NEHRP FINAL TECHNICAL REPORT, 2004

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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). Multiple tributary slope canyons and proximal channels join downstream into large channels, and all systems are dominated by the deposition of turbidite silt and sand beds. Our research focus is to: 1) evaluate the hypothesis that synchronous turbidites along the margin result from turbidity currents triggered by great earthquakes on the SAF and 2) thus define a paleoseismic record. Several lines of evidence suggest that there is synchronous SAF triggering of turbidites. Channels below tributary confluences are characterized by many single-event turbidite beds with multiple coarse-grained sediment pulses that contain different mineralogy from tributary source canyons. The rate of turbidite bed deposition (number/m) above and below channel tributary confluences typically is the same and not additive in downstream channels. Geotek log signatures of turbidites from different channel systems correlate along the margin and our present limited number of 14C ages suggest correlative events. The most complete and reliable turbidite record is found in Noyo Channel where the canyon head source of turbidites is directly underlain by the SAF. Most important, we want to outline the recurrence history of paleoseismic events. We utilize multiple cores with 24 correlative turbidite events from the Noyo channel to define event recurrence time between turbidites. We base this time on two independent methods: 1) hemipelagic sediment thickness (H) between two consecutive turbidites (i.e. H/sedimentation rate =recurrence time) (24 events), and 2) ^{14}C ages (i.e. difference in ages between two consecutive turbidites= recurrence time)(6 events). The average recurrence time we find between events is 220 yr (H method) and 215 yr (^{14}C age method). ^{14}C data show greater minimum (110 yr) and maximum (400 yr) recurrence time variation compared to hemipelagic thickness (H) data that show 150 yr minimum and 300 yr maximum recurrence times. Both methods show that 75% of recurrence times are between 150 yr and 225 yr. With three major assumptions that 1) Noyo Channel turbidites represent great earthquakes on the SAF, 2) the hemipelagic (H) record is more accurate and 3) the Noyo recurrence pattern continues into the future, the Noyo recurrence data suggests that we are not yet in a window for another great earthquake on the northernmost SAF. This statement is based on present evidence indicating that in the Noyo Channel area: 1) an earthquake greater than 7.2 magnitude is necessary to trigger a turbidity current, 2) minimum recurrence times are 150 yr based on H, and 3) the great earthquake in 1906 triggered the youngest turbidite (Nelson et al, 2004).

FY 2004 Investigations Undertaken

The objective of this project is to test the hypothesis that turbidites deposited in channel systems along the northern California continental margin resulted from turbity currents triggered by earthquakes on the northern San Andreas Fault. Previous work on the Cascadia margin has shown that turbidites there were most likely the exclusive result of earthquake triggering of turbid currents. Along the north coast of California, the northern segment of the San Andreas lies close to the coast or just offshore between San Francisco and Point Delgada, near the Mendocino Triple Junction. Favorable physiography of both fault and channel systems suggested 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 (**Figure 1**).

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. 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. Simultaneously, samples were taken for mineralogy, and were analyzed for heavy minerals at sea to attempt to distinguish channels systems by their mineralogic characteristics.

FY 2004 Results

In Core PC49, where our date thus far are most complete, we find thirty-one turbidite beds above the Holocene/Pleistocene faunal “datum”. Thus far, we have determined ages for 20 (of 38) events including the uppermost 5 events from cores 49PC/TC and adjacent box core 50BC using AMS methods. The uppermost event returns a "modern" age, which we interpret is likely the 1906 San Andreas earthquake. The penultimate event returns an intercept age of AD 1663 (2 sigma range 1505 - 1822). The third event age is AD 1524 (1445-1664. This event appears not to have a correlative in the land record, however there is no land record as far north as the Noyo Canyon site, so this may be a more local or non-seismic event. The fourth event age is AD 1304 (1057 - 1319), and the fifth event age is AD 1049 (981-1188). These early results are in relatively good agreement with the onshore work to date which indicates an age for the penultimate event in the mid -1600's, the most likely age for the third event of ~ 1200-1300 AD. Our record contains 11 events in ~2500 years, while Niemi et al. (2002) report 10 events during that time at the Vedanta site (**Figure 2**).

Channel Confluences and Mineralogy:

Unlike Cascadia, the Northern California margin does not appear to have a strong regional stratigraphic datum, thus correlating events and testing for an earthquake origin depends more heavily on stratigraphic correlation, and tests of synchroneity. Preliminary mineralogic data suggest a synchronous origin for at least some of the events examined thus far. We have been able to distinguish three heavy mineral provenances in the cores, well linked to the onshore source geology (**Figure 1**). Channels from these distinct provenances come together at confluences on the abyssal plain, below which we clearly see mixed provenance, or stacked and distinct layers of the components of provenance represented in the tributaries. Rather than separate events from each provenance, we see either doublet and triplet coarse-grained pulses in a single turbidite event, with no hemipelagic sediment between the events, or bimodal coarse fractions in the more distal turbidites, each peak representing a separate provenance (Goldfinger et al., 2004; Morey-Ross et al., 2003). Cores 24-31downstream of the confluence show this relationship **(Figure 1).** Although we do not yet have radiocarbon ages for some cores, we see that if the correlations are correct, the total number of events in a given span of the cores both above and below the confluence remains the same. If this is correct, events at this confluence pass a strict test of synchroneity, and we would argue they must be of earthquake origin. The use of mineral provenance to fingerprint source channels to test for earthquake origin has also been used in the Sea of Japan by Shiki et al. (2000).

Event correlation and $_{14}$C dating

With our colleagues at Oregon State University (OSU) we continue our radiocarbon dating and analysis of physical property signatures as we work toward a stratigraphic framework for the Northern San Andreas System. At University of Granada, we are working with a semi-independent time series for SAF events based on the hemipelagic sediment thickness (H) deposited between turbidite events. The volume of samples and limited funding precludes a quantitative grain size or composition analysis of hemipelagic thickness for each event in each core. Also, our collegues at OSU, 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. They do this in two ways:

1) Magnetic susceptibility, color reflectance, and density plots are compared with the logged hemipelagic intervals. These three datasets demonstrate that these turbidite tail-hemipelagic boundary can in most cases be accurately determined from the inflection point where fining upward turbidite tail clay grades upward into hemipelagic sediment. In the physical property plots, this point is marked by a flattening of all three curves (susceptibility, density, and RGB variance from the digital imagery) at this point. This estimate is effective in ~ 70% of the turbidite events.

2) After arriving at a final determination of hemipelagic thickness as above, we plot cumulative hemipelagic thickness in the core vs. age. These plots reflect the near constant local sedimentation rate, which changes subtly if at all during the Holocene for most sites. Sedimentation rates can be derived from regression of these data, and are in turn used to make corrections to the 14C ages due to the thickness of sample use **(Figure 3)**. These plots are also used to calculate ages based on sedimentation rates for which $_{14}$C ages can't be determined (**Figure 4). Figure 3** shows detail of the calculation of the age of the uppermost two events from Noyo Channel using these methods and radiocarbon ages. The hemipelagic age for the 1906 earthquake is calculated by two methods to be 1892, or 1904 respectively (omitting errors analysis for this report). This serves as a check on the hemipelagic methods, which work very well for events where basal erosion is not a factor. Where basal erosion is a factor, if there are multiple cores at a site, this erosion can be detected. Them, as described below, resulting corrections can be made for H analysis and RC ages obtained from eroded hemipelagic layers.

Hemipelagic Thickness (H) Analysis

In FY 2004 at University of Granada we developed 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 (Nelson et al, in reniew).
- 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 T event from multiple cores at each location compared to a single incomplete set of radiocarbon ages at each location.

The following extensive set of techniques (A-F) have been developed from the hemipelagic sediment thickness data:

A. Best hemipelagic thickness (HBT)

We measured hemipelagic sediment thickness between every turbidite for all 2002 cores at the sites of Noyo, Gualala, Bodega, Farallon and Pioneer channels. We then determined the best hemipelagic thickness (HBT) between each turbidite by calculating the average thickness of the two thickest layers. By using the two layers our error is biased towards maximum thickness and reduces the potential effect of hemipelagic erosion by turbidity currents. By averaging two layers we are also reducing the effect of variance in core logger observations, which appear to range between +/- 0.5 to 1 cm in total thickness of the hemipelagic interval between turbidites.

B. Hemipelagic sedimentation rates

To calculate sedimentation rates down core, we utilize ^{14}C ages for individual T events. The sedimentation rate with depth at each site is calculated by adding up the total HBT increments above each datum or (^{14}C) age and dividing by the age. Because of the resulting moving average of ages, age errors have only a slight effect on sedimentation rates **(Table 1, Figure 4).**

C. Recurrence times and Ages based on HBT and sedimentation rates

With the ^{14}C ages corrected for sample depth and sedimentation rate, we calculated recurrence times between each turbidite based on HBT/sedimentation rate. The maximum and minimum recurrence times vary less for HBT data than those obtained with ^{14}C ages.We added the HBT recurrence interval times consecutively with depth to determine the age of each turbidite.

D. Effects of hemipelagic sediment erosion on RC and HBT data

Because both ^{14}C samples and measurement of hemipelagic thickness are obtained from the hemipelagic sediment below turbidites, any erosion from the top of the hemipelagic layer will result in ^{14}C ages that are anomalously old and H recurrence times that are anomalously young. Our HBT analysis from multiple cores compensates for differential erosion that may have affected HBT recurrence intervals or HBT ages at any of our key sites.

E. Erosion correction of ^{14}C ages and recurrence intervals

Erosion of hemipelagic sediment at each site was determined by comparing all hemipelagic intervals between each correlative turbidite event in multiple cores at a site. When a ^{14}C sample has been obtained from an anomalously thin eroded H the missing H time can be calculated to correct the ^{14}C age. This erosion correction for the ^{14}C ages brings the recurrence intervals based on ^{14}C ages into much closer agreement with the intervals calculated from HBT.

F. Correction of minimum recurrence times based on HBT

It is of utmost importance to define accurate minimum recurrence times for great earthquakes on the San Andreas Fault. Because of the constant rate of hemipelagic sedimentation at each location (Nelson, 1976, Nelson et al., 2003 AGU, Nelson et al., in review) minimum ^{14}C recurrence intervals should be no less than the minimum HBT stratigraphic time represented by multiple cores at each location. This correction method is important because the coastal paleoseismic stratigraphic record has no independent method like hemipelagic sediment thickness to assess reliability of minimum recurrence times based only on ^{14}C ages.

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

The most complete and reliable turbidite record is found in Noyo Channel where the canyon head source of turbidites is directly underlain by the SAF. The five youngest turbidite ^{14}C ages of Noyo show general agreement with the SAF paleoseismic record on land. This apparent correlation suggests that Noyo Channel may provide a much longer paleoseismic record for 24 events on the SAF during the past ~ 6,000 yr. We utilize multiple cores with 24 correlative turbidite events from the channel to define event recurrence time between turbidites. We base this time on two independent methods: 1) hemipelagic sediment thickness (H) between two consecutive turbidites (i.e. H/sedimentation rate =recurrence time) (24 events), and 2) ^{14}C ages (i.e. difference in ages between two consecutive turbidites= recurrence time) (8 events). The average recurrence time we find between events is 220 yr (H method) and 215 yr (^{14}C age method). ^{14}C data show greater minimum (110 yr) and maximum (400 yr) recurrence time variation compared to hemipelagic thickness (H) data that show 150 yr minimum and 300 yr maximum recurrence times. Both methods show that 75% of recurrence times are between 150 yr and 225 yr **(Table1)**. With three major assumptions that 1) Noyo Channel turbidites represent great earthquakes on the SAF, 2) the hemipelagic (H) record is more accurate and 3) the Noyo recurrence pattern continues into the future, the Noyo recurrence data suggests that we are not yet in a window for another great earthquake on the northernmost SAF. This statement is based on present evidence indicating that in the Noyo Channel area: 1) an earthquake greater than 7.2 magnitude is necessary to trigger a turbidity current, 2) minimum recurrence times are 150 yr based on H, and 3) the great earthquake in 1906 triggered the youngest turbidite (Nelson et al, 2004).

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 210 yr for the past ~ 6000 years with a minimum time of 150 years between earthquakes. However, more cores and land records must be examined to verify this preliminary record of earthquakes.

Published Results

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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.

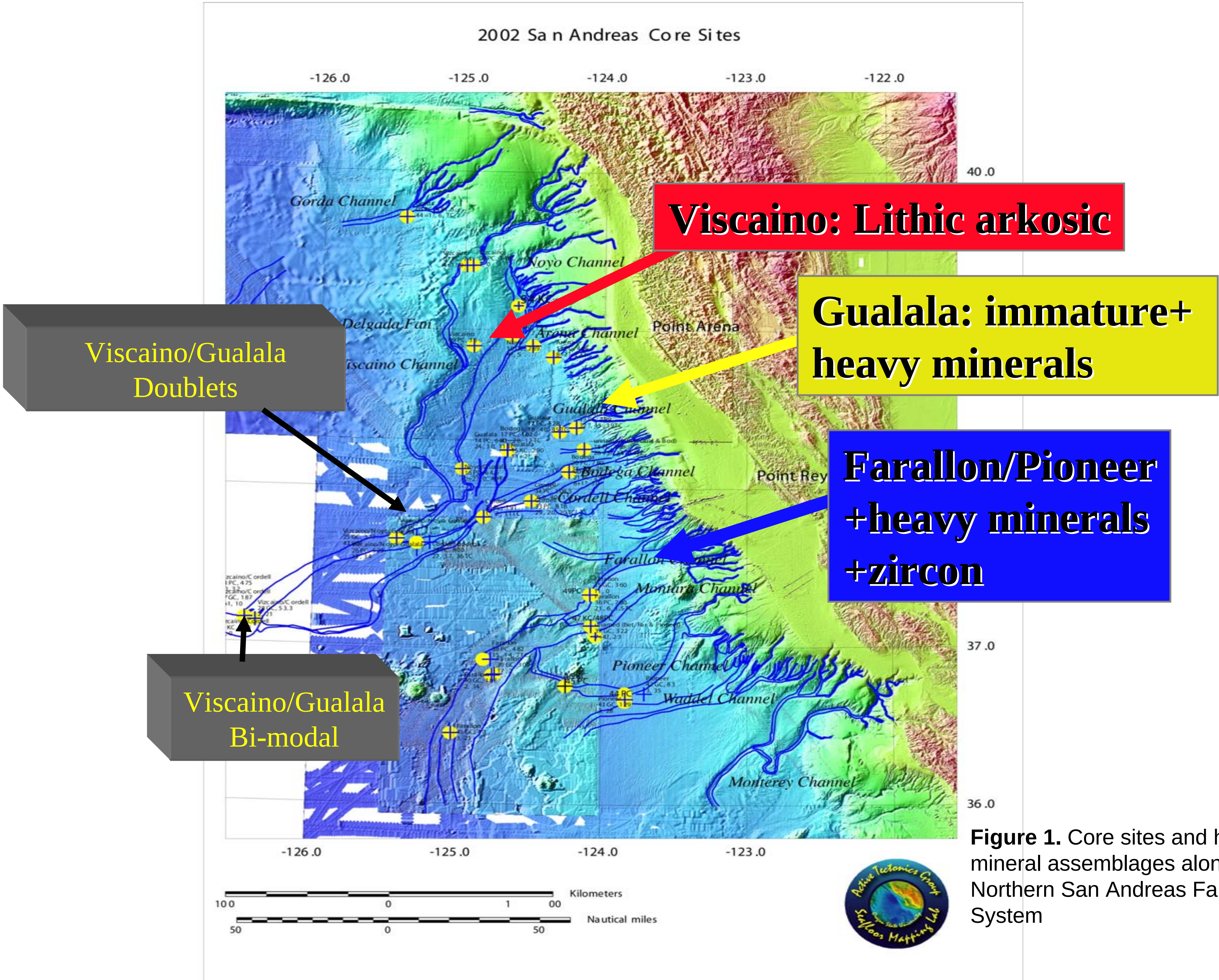

Figure 1. Core sites and heavy mineral assemblages along the Northern San Andreas Fault System

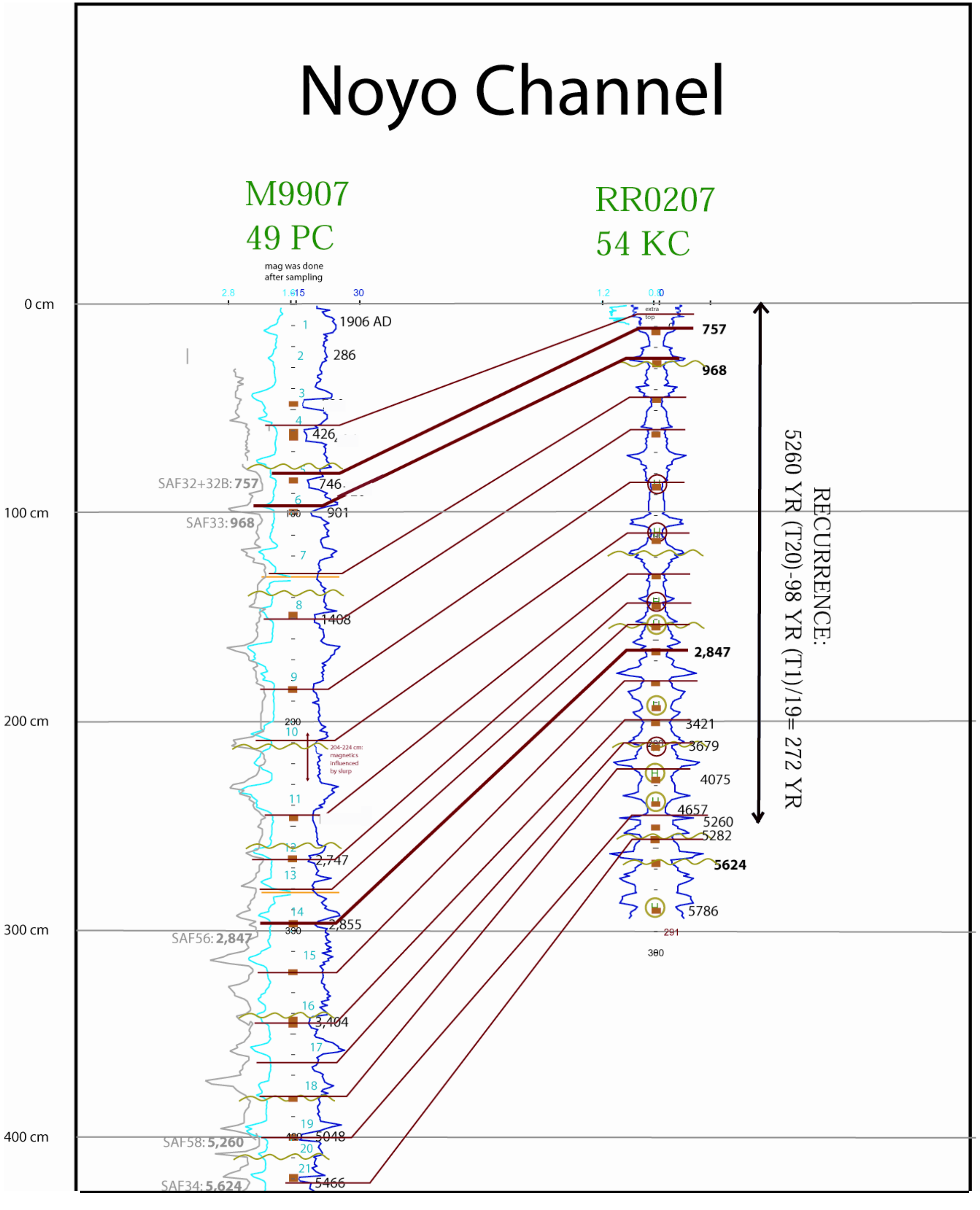

Figure 2. Noyo Correlation diagram. Density (light blue) and magnetic sus traces are shown (dark blue). Radiocarbon years calibrated from bp 1950 using CALIB 4.4

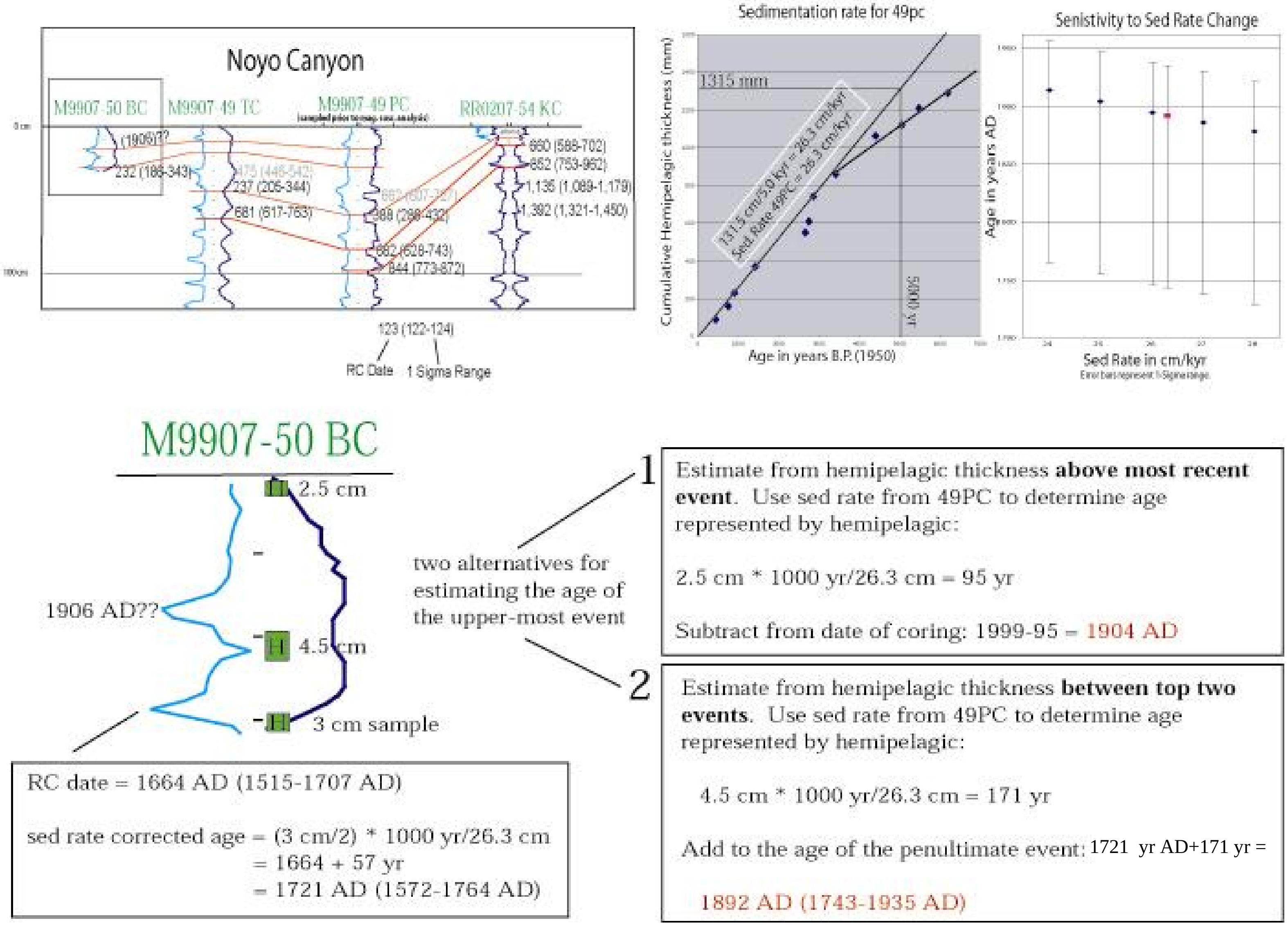

Figure 3. A. Core top correlation of the youngest SAF events in Noyo Channel.
B. Regression determined sedimentation rate calculation for Noyo channel, and sensitivity to sedimentation rate change.
C. Calculation of ages of uppermost two events and correlation to 1906.

TABLE 1.COMPARISON OF 14C AND HEMIPELAGIC SEDIMENT (H) RECURRENCE TIMES

NOYO SITE
49PC/54KC

TURBIDITE	^{14}C Ages (yr)	^{14}C Rec (yr)	H(cm)	accum.H	sed.rate cm/1000 yr	ave.sed.rate cm/1000 yr	H Rec	H Ages
			3,5		35,7	33,7		
1	98 (H)	158	5,8	9,3	36,3	33,7	172	98
2	256	109	6,9	15,1	38,2	33,7	205	270
3-4	395	311	7,4	22	31,16	33,7	220	475
5	706	183,5	6,8	29,4	33,1	33,7	202	695
6	889,5		8	36,2		33,7	237	897
7			6,3	44,2	32,6	33,7	187	1134
8	1354		5,6	50,5		33,7	166	1321
9			7,3	56,1		33,7	217	1487
10			7,8	63,4		27,9	280	1704
11			6,8	71,2	26,5	27,9	244	1983
12	2688		5,5	78		27,9	197	2227
13			7	83,5	30,0	27,9	251	2424
14	2781		5,5	90,5		27,9	197	2675
15			5,4	96	28,6	27,9	194	2872
16	3361	258	5,2	101,4	28,0	27,9	186	3066
17	3619	394	7,25	106,6	26,6	27,9	260	3252
18	4013	584	4,6	113,85	24,8	23,5	196	3512
19	4597	603 *	6,4	118,45	22,8	23,5	272	3708
20	5200	110 *	6,85	124,85	23,5	23,5	291	3980
21	5310	254	5,8	131,7	23,7	23,5	247	4272
22	5564	162	6,6	137,5	24,0	23,5	281	4519
23	5726		4,6	144,1		23,5	196	4799
24			3,6	148,7	22,3	23,5	153	4995
25	6675		5,6	152,3		23,5	238	5148

* T19 and T20 14C ages and RC data after this are not considered reliable because H thickness is ~ 6.5 cm in each interval but 14C recurrences vary by 500 yrs.

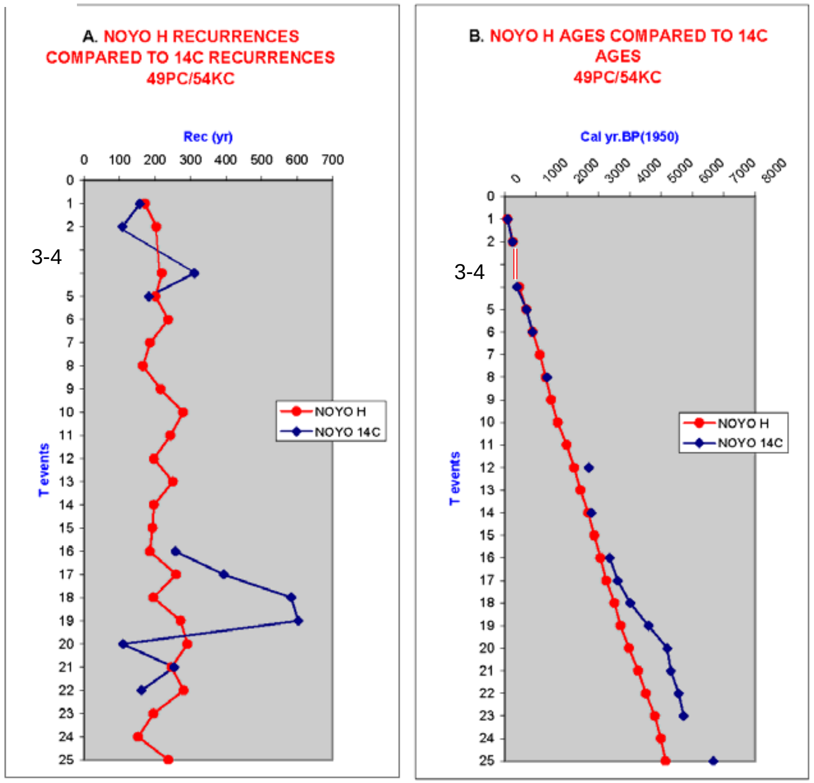

Figure 4. Comparison of age and recurrence times based on AMS radiocarbon age (RC) and hemipelagic thickness (BT) data sets for T1 to T25 Holocene earthquakes at Noyo site at San Andreas margin. Left plot **A** shows comparative RC and BT ages vs T events.Rigth plot **B shows** recurrence interval times at Noyo site, for both RC and BT data sets.

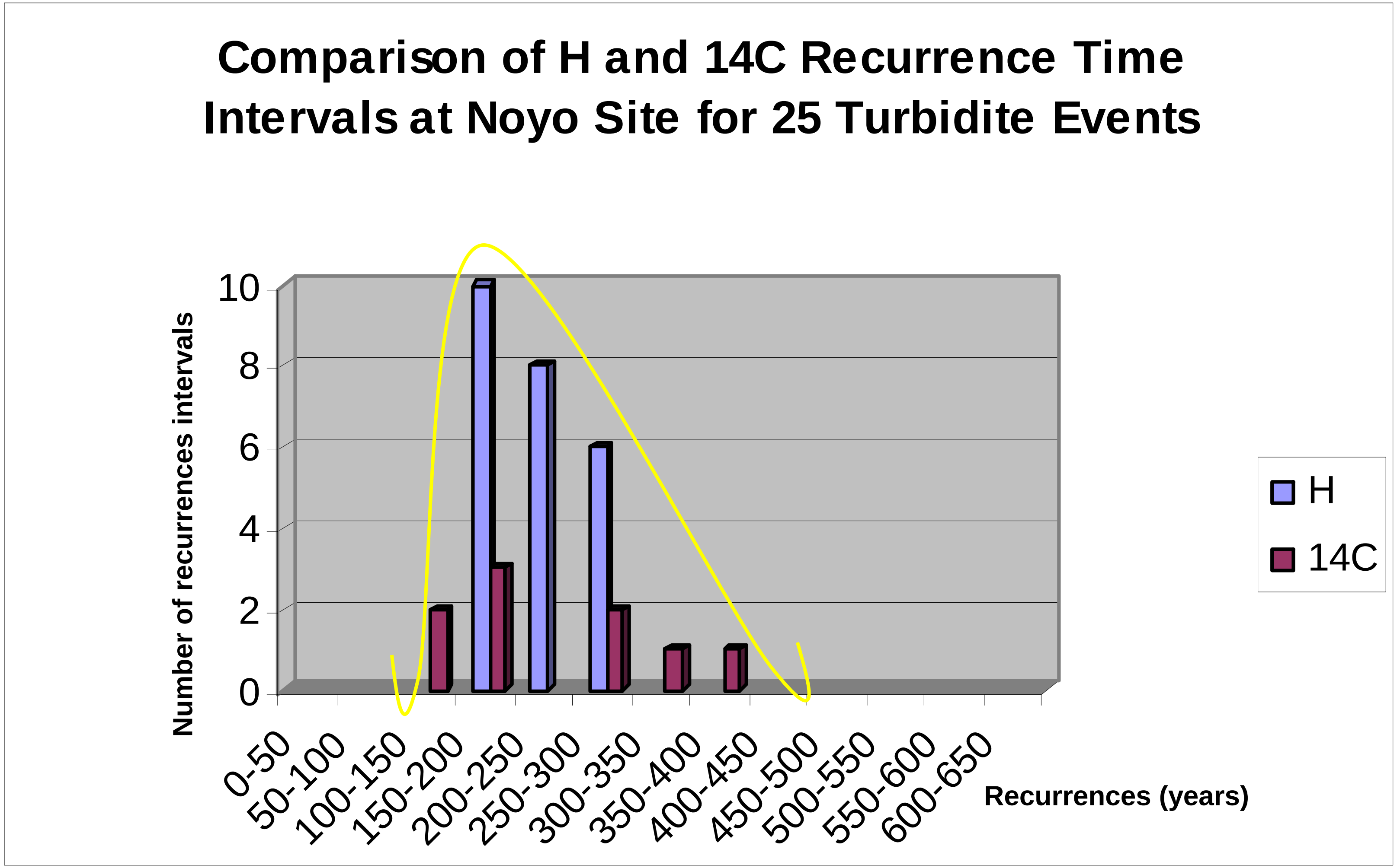

Figure 5. Comparison of the frequency distribution of recurrences times from T1 to T25 turbidite events at the Noyo site. The histogram shows the number of recurrences times observed in each 50 yr interval class. Both H and 14C data shows a normal distribution of recurrences that are sligthly skewed to older recurrence times, however minimun and maximun times have a greater variation for 14C data, with a maximum between 250-300 yr and a minimum betwween 150 and 200 yr.