Holocene Seismicity of the Northern San Andreas Fault Based on the Turbidite Event Record

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San Andreas Fault Record

Earthquakes represent one of the largest releases of energy on earth. However, quantifying the temporal and spatial patterns of these great events remains elusive because our observations often span only one or even less than one seismic cycle. Recent rapid advances in Global Positioning System (GPS) technology now make it possible to measure crustal motion associated with elastic strain accumulation at plate boundaries with a high degree of certainty in only a few years. However, real-time strain measurements can only represent a fraction of one strain cycle. Fundamental questions such as the utility of the seismic gap hypothesis, clustering, and the applicability of slip-predictable or time-predictable models remain problematic because we rarely have a long enough earthquake record to effectively address these issues. Recently, stress-triggering models have called into question the validity of characteristic earthquake models on which these hypotheses are based. The applicability of stress models and characteristic earthquake models is a fundamental and controversial topic in tectonics worldwide. What is most needed to address this issue is more time-history data over longer time spans, and in a variety of tectonic systems.

Paleoseismology has the potential to address these questions directly using a larger time span than available to geodesists. Cascadia has become a leading example. Discovery of rapidly buried marsh deposits and associated tsunami sands along the Pacific Coast has led to the recognition that Cascadia has generated great (Mw 8-9) earthquakes in the past. The questions of how large and how frequent these megathrust earthquakes are, and how these events occur spatially and temporally have only recently been addressed using turbidite paleoseismology. Unlike more typical paleoseismologic techniques, neither uses fault outcrops, and both must demonstrate that the observed events are uniquely generated by earthquakes and not some other natural phenomenon. Nevertheless, these problems can be overcome, and both techniques can be powerful tools for deciphering the seismic history along a submarine fault system.

We have begun to apply the paleoseismologic technique we have used in Cascadia to the turbidite history along the Northern San Andreas transform margin. The northern San Andreas system shares many of the same favorable oceanographic and physiographic features that made Cascadia ideal. New core data show that continental margin channels have recorded a Holocene history of regional submarine slides probably triggered by great earthquakes. We plan to collect piston cores in these channels to develop a Holocene event stratigraphy that we infer is a good representation of the earthquake record over the last ~10,000 years. This event history can then be compared with the shorter land record in northern California.

The ofshore segment between San Francisco and Shelter Cove is recognized as distinct in its seismic behavior from fault segments further south, and is characterized by a single main fault strand, simplifying the problem of multiple fault sources for the turbidites. The San Andreas is at or near the coast for its full length, making it an ideal trigger for margin turbidites. Cores collected in during 1999 in Noyo channel suggest that the northern San Andreas Fault may in fact be the only trigger for margin turbidites. We infer that it is possible to establish the Holocene event chronology along the Northern San Andreas Fault system from San Francisco to Cape Mendocino by directly dating planktonic forams immediately below each turbidite as we have done in Cascadia. Additionally, we will establish the chronostratigraphic record using use AMS dates, oxygen isotopes, and radiolarian biostratigraphy to define the Holocene/Pleistocene boundary (and other datums if possible) to provide a supporting age control.

The Noyo Channel cores near the offshore northern San Andreas fault show a good cyclic record of turbidite beds. Thirty-one turbidite beds are found above the Holocene/Pleistocene boundary as determined by radiolarian/foram ratios (see below for further explanation; Nelson and Goldfinger, 1999). At the base of slope off southern Oregon, the age of this boundary averages 12,400 cal. yr. B.P. (age reported in Goldfinger et al., 1997 and unpublished 2000 dates). If we assume that the age is the same in the base of slope region of the Noyo Channel, then the average time interval between turbidite events is about 400 cal. yr B.P. This recurrence interval appears to be quite consistent based on independent evidence of the hemipelagic sediment thickness between turbidite intervals.

The first run of AMS ages from core 49PC in Noyo Canyon give the calendar age of the penultimate event as 1663 AD (1 sigma +44 -107; Calibration method of Stuiver and Reimer, 1993). This places the event in the mid-1600's, similar to the time range derived by Schwartz et al. 1998) for widely separated sites studied by numerous investigators. We are encouraged at the close agreement with these preliminary data, and believe that this also supports our suggestion that the San Andreas is the principal, and perhaps only trigger for turbidites along this segment of the margin

Hemipelagis sediment thickness between turbidites can also be used to cross-check the AMS radiocarbon ages. Thus far, the hemipelagic thickness has only been examined carefully in the upper meter of the PC-49 trigger and piston cores from Noyo Channel. The hemipelagic thickness varies from 5 to 7 cm between the first 6 turbidite events and the average is 5.83 cm in the trigger core; the range of thickness also is 5 to 7 cm, but the average thickness is 6.4 cm in the piston core. The reduced thickness of the hemipelagic beds in the trigger core is expected because the trigger core is a gravity core that undergoes more compaction during the coring process than does the piston core.

Based upon core lithology and MST data, the total hemipelagic sediment thickness of piston core 49 from the surface to the Holocene/Pleistocene boundary (12,400 yr) is 145 cm. This yields a hemipelagic sedimentation rate of 11.6 cm/ka. Dividing this average rate into the average 6.4 cm thickness of hemipelagic sediment in the upper meter of the piston core gives an age of about 550 years for each hemipelagic sediment interval. This estimate is about 150 years greater than the time estimate of 400 yr based on the total number of Holocene turbidites since the 12,400 cal yr B.P. datum. However, this age difference is expected because the deeper core sediment is compacted relative to the near-surface sediment. This compaction effect needs to be evaluated from the density data from the core sediment logger, which will adjust the hemipelagic age estimate downward. For example, the average hemipelagic interval between turbidite events in the upper meter of the piston core is 6.4 cm, whereas in the meter above the Holocene/Pleistocene boundary the average thickness is 5.66 or 12% less. Adjusting the upper meter for this estimated compaction effect reduces the average time interval to 485 years based on hemipelagic sedimentation rates.

Our preliminary hemipelagic sedimentation rates also show a reasonable estimate for the age of the youngest T1 turbidite event. The hemipelagic thickness above T1 is 2.5 cm in the gravity core, which has the least disturbed surface sediment. This 2.5 cm/5.83 average thickness of hemipelagic sediment between turbidites =.43 X 400 yr average time between turbidite events suggests an uncorrected age of 172 years for the youngest turbidite. We infer an additional compaction of about 12% in the first 10 cm of hemipelagic sediment where the most rapid consolidation of hemipelagic sediment typically takes place. This 24% compaction adjustment suggests a corrected age of the uppermost event of 151 yr based on hemipelagic sedimentation rates. Considering that the youngest turbidite probably is related to the 1906 San Francisco earthquake, the usefulness of hemipelagic sediment thickness analysis is clear. Similarly, if we apply this method, the estimated time between the 1906 event and the penultimate event would be ~250 years (5 cm hemipelagic interval) in agreement with the AMS age in the mid 1600's. The preliminary results from Noyo Channel indicate the great potential for the application of this study to additional cores from other channels.

Implications for Cascadia

Through the Noyo Canyon and Cascadia data, some additionl observations can be made from the joint datasets. Though we do not know what the threshold is interms of earthquake magnitude for turbidite generation, we suspect that is is highly site-specific. Nevertheless, we observe that in two box cores, taken at the same site in Mendocino channel in 1986 and 1999 there is no surface turbidite observed. This channel drains the southern part of the Gorda margin that was the site of the 1992 Petrolia Mw 7.1 event. This even was apparently insufficient to generate a turbidite in Mendocino channel. Additionally, we now have good evidence that the 1906 SAF event, and the penultimate event ~1660, did generate turbidites in Noyo Canyon and Mendocino Channel. The 1906 event was M~ 8, and the 1660 event is suspected to have been similar in rupture length, and thus in magintude (Schwartz et al., 1998). The significance for Cascadia is that the turbidite record there indicates only regular occurrence of M9 events, an apparent violation of G-R laws that seem to work for most faults. Are we not detecting the M8 and smaller events that should be occurring if Cascadia behaves as it should? Since the SAF events of M~8 do generate turbidites, and we detect no "extra" events from Cascadia, what are the prospects for undetected M~8 events there? We suggest that M8 events from Cascadia are unlikely to go undetected. The sediment supply in Cascadia is far greater, and the recurrence time longer than Noyo Canyon, suggesting that if Noyo records most or all of the large events there, Cascadia should do the same or better since the availability of unstable sedimens is greater. Cascadia does just the opposite, with the "anomalous" cores having missing events, most of which can be explained by channel processes.

Lastly, the closeness in time of the penultimate SAF event in the mid1600's, and the most recent Cascadia megathrust event in 1700 AD raises the question of whether these two events could be related in more than time. We have evaluated a preliminary Coulomb stress model (Toda et al., 1998) that considers the effects of stress changes due to a 1906 style rupture of the SAF on the southern Cascadia subduction zone. We find that a 1906 rupture (~8.6 m at Shelter Cove) will bring the shallow part megathrust closer to Coulomb failure, loading this adjacent fault. The deeper part of the megathrust is at the same time unloaded. This simple model does not consider crustal thickness variations, or changes in rheology across the major plate boundaries. While the average recurrence time of Cascadia is longer than the SAF (600 vs 400 years), these structures are in phase, using average repeat times, every 1200 years, such that triggering may occationally occur.