Northern San Andreas Seismotectonic Setting

The San Andreas Fault is probably the best-known transform system in the world. Extending along the west coast of North America, from the Salton Sea to Cape Mendocino, it is the largest component of a complex and wide plate boundary that extends eastward to encompass numerous other strike-slip fault strands and interactions with the Basin and Range extensional province. The Mendocino Triple junction lies at the termination of the northern San Andreas, and has migrated northward since about 25-28 Ma. As the triple junction moves, the former subduction forearc transitions to right lateral transform motion.

West of the Sierra Nevada block, three main fault systems accommodate ~75% of the Pacific-North America plate motion, distributed over a 100 km wide zone (Argus and Gordon, 1991). The remainder is carried by the Eastern California Shear Zone (Argus and Gordon, 1991; Sauber, 1994). The northern San Andreas is the main system, accommodating about 25 mm/yr of the ~34 mm/yr distributed across western California. Most of the remainder is taken up on the parallel Hayward-Rogers Creek system, and the slightly divergent Calaveras Fault system further to the east. The Hayward and Calaveras systems become the Maacama and Bartlett Springs faults respectively in northernmost California. These faults may merge with thrust faults on similar trends north of the southern limit of Gorda plate subduction (Castillo and Ellsworth, 1993). South of San Francisco, the transform system becomes more complex, and includes the offshore San Gregorio fault, which joins the Northern San Andreas at Olema, just north of San Francisco. Between San Francisco and Cape Mendocino, the main strand of the San Andreas is a relatively simple system.
with most strain localized on the main strand. Several uncertain faults exist offshore, but the age and activity of these faults is unknown (Jennings, 1994). Seismicity offshore is virtually nil, with the exception of the Mendocino triple junction region. Since the 1906 rupture, the main San Andreas has been nearly aseismic, with only a few small events near Pt. Arena.

Northern San Andreas Onshore Paleoseismicity

The San Andreas system has been intensively studied on land, and has been divided into segments based on its historical record of earthquake behavior. The northern segment ruptured in the 1906 Mw 7.8 earthquake, and rupture extended from at least San Francisco north to Shelter Cove near Point Delgada. The paleoseismic history of the northern San Andreas system is presently under investigation using trenching and marsh coring. The 1906 earthquake clearly ruptured the surface along the San Francisco Peninsula to as far north as Point Arena (Lawson, 1908). Based on bedrock mapping, some debate exists regarding the full length of the 1906 rupture (McLaughlin et al., 1979; 1983). Original investigations of surface rupture are summarized in Lawson (1908), and included a description of surface rupture as far north as Shelter Cove. Seismological evidence does not require slip on the San Andreas north of Point Arena, though Thatcher et al. (1997) infers from geodetic data that ~8.6 m of slip occurred on the fault in the Shelter cove area. Brown (1995) re-examined surface morphology and the original field reports by F.E. Mathes from 1906, and concluded that the original reports of surface rupture were correct, and that many effects of the rupture are still observable today. Most recently, Prentice et al. (1999) also re-examined Mathes’ field notes and photographs and trenched along the 1906 rupture. Like Brown (1995), they conclude that abundant evidence for 1906 rupture exists, and estimate a minimum slip-rate of 14 mm/yr for the northern San Andreas based on a 180 m offset of colluvial deposits dated at 13,180 ± 170 cal yrs bp. The southern end of the rupture extends as far south as the Santa Cruz mountains (Schwartz et al., 1998), giving a minimum rupture length of ~470 km. The paleoseismology of the northern San Andreas has been investigated at Olema, 45 km north of San Francisco, at Dogtown, close to the Olema site, at Point Arena, and at Grizzly Flats in the Santa Cruz mountains. At the Vedanta site near Olema, Niemi and Hall (1992) found that offset stream channels showed that the fault ruptured along a single main strand, and offset stream deposits dated at 1800 ± 78 yrs by 40-45m. The maximum late Holocene slip rate derived from these data is 24± 3 mm/yr, in good agreement with geodetic data. They estimate that if the 4-5 m slip event recorded in 1906 is characteristic, the recurrence time for such events would be 221 ± 40 yrs. At point Arena, 145 km to the northwest, Prentice (1989) recognized four events that offset a Holocene alluvial fan channel 64 ± 2m. The maximum slip rate calculated at Point Arena is 25.5 mm/yr., in excellent agreement with the Olema data. The average slip per event at Point Arena implies a recurrence time of 200-400 yrs (Prentice, 1989). Dated offset terrace deposits suggest that this rate has not changed by more than about 20% since Pliocene time. The best age derived for the penultimate event is the mid 1600’s (Schwartz et al., 1998), and the most likely ages for the previous three events were: #3 ~1300 (post AD 1150, pre AD 1650), and two events pre AD 1210 and post AD 1. Totaling five events in 2000 years (Prentice, 1989, 2000; Niemi and Zhang, 2000). Schwartz et al., 1998 also show an additional event at several sites in the early-mid 1500’s. Niemi (2002) now reports new evidence from the Vedanta site of 10 events during the past 2500 years (Niemi et al., 2002). Radiocarbon dates of the individual events are not yet available as of this writing (T. Niemi, Pers. Comm. 4/02).

A controversial aspect of Northern San Andreas tectonics has been the whether the fault is segmented, with variable behavior for each segment, or whether the 1906 rupture was characteristic. The consistent slip rates found north of the Golden Gate, slow to about 15 mm/yr south of the Golden Gate. This and a lower co-seismic slip south of the Golden Gate (Segall and Lisowski, 1990; Thatcher et al., 1997; Prentice and Ponti, 1997) led investigators to conclude that the fault is segmented near the Golden Gate. The Working Group on California Earthquake Probabilities (1990) applied a uniform slip rate to the fault, and concluded that segments with lower-co-seismic slip in 1906 should have more frequent events to fill the slip deficit. Schwartz et al. (1998) argues that the segmentation is simply a reflection that the offshore San Gregorio fault absorbs some of the slip, and the slip-rate on the main San Andreas is correspondingly reduced. They argue that the through going rupture in 1906 is not segmented, and further, that the penultimate event, which occurred in the mid-1600’s, ruptured approximately the same distance and magnitude as the 1906 event. The partitioning of slip to the San Gregorio fault is supported by estimates of 5-10 mm/yr of slip on that fault, approximately equal to the drop in slip rate along the main SAF from ~ 25 to ~ 15 mm/yr south of the Golden Gate (e.g. Clahan, 1996; Clark, 1999).
New Results 1999 and 2002 Cores: Northern San Andreas Turbidite Record

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. We did this both to test the distance at which large ruptures would generate turbidites, and to investigate whether the northern San Andreas had generated a turbidite record of its own. In Core PC49, 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 and fourth event are lumped together, as there is no hemipelagic sediment between them. The age of this event is AD 1524 (1445-1664), though we are not certain whether this event represents one event or two. The fifth event age is AD 1304 (1057 - 1319), and the sixth 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 ~ 1500-1600, and a fourth event ~ 1300. Our record contains 11 events in the last ~2500 years, while Niemi et al. (2002) report 10 events during that time at the Vedanta site. The close agreement in number of events between the onshore and offshore records suggests a possible correspondence between the two records.

These data are quite consistent with estimates of time intervals between recurrent northern San Andreas earthquakes at Pt. Arena and Olema. At Pt Arena, Prentice (1989) estimated a 200-400 year recurrence time, and the interval was estimated to be 221 years at Olema. We are encouraged at the close agreement with these preliminary data, and believe that this also supports the hypothesis that the San Andreas is the principal, and perhaps only trigger for turbidites along this segment of the margin. The preliminary results from Noyo Channel indicated the potential for this study to collect additional cores from other channels.

During June and July, 2002, we collected 69 piston, gravity and Kasten cores from channel and canyon systems draining the northern California margin (Figure 1). We operated 24 hours a day for 30 days with an international science party of 37 scientists and students from the US, Russia, England, France, Belgium, Germany and Spain. We mapped channel systems with the newly installed Simrad EM-120 multibeam sonar. This system provides both high-resolution bathymetry and backscatter data essential for analysis of channel morphology, sedimentation patterns, and core siting. Prior to the cruise we compiled existing bathymetry for California, including all multibeam data from archives of NOAA, Scripps, USGS and other academic institutions, and combined these data with sounding and trackline data from NGDC. This grid was re-processed many times during the cruise as we collected new data so that the best compilation of data was always readily available. For this purpose we took to sea a fast processing computer, and full 3D GIS capabilities for visualization.

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 turbidity currents. 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, and finally 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.

Unlike Cascadia, the northern California margin does not appear to have a regional stratigraphic datum, thus correlating events and testing for an earthquake origin depends more heavily on stratigraphic correlation, tests of synchronicity, and possibly other methods of distinguishing earthquake triggered turbidites from those triggered by other mechanisms.
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. 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 feeder channels. Rather than separate events from each provenance, we see either doublet or triplet sand pulses in a continuous turbidite, with no hemipelagic sediment between the events; or we find bimodal sand fractions in the turbidites, each peak representing a separate provenance. Since the sand fractions of turbidites settle out in minutes to hours, the couplets and bimodal distributions indicate little or no time passage during deposition. Because these coarser pulses occur in a generally continuous graded turbidite, it is unlikely that a convenient degree of basal erosion of the upper event created the same stratigraphy. Synchronous deposition in turn suggests a synchronous timing of the triggering of the source events. Few, if any, triggering events other than earthquakes can satisfy the very short time requirements for synchronous initiation of turbidity currents separated by large distances along the margin. This test of synchronicity is similar to the one used Adams (1990) and later by us in Cascadia. 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). A second possible “synchronous” origin might include storm generated flows, which could conceivably produce flows in separate canyons that were triggered within hours of each other. However, channel systems in northern California, like Cascadia, are mostly separated from river systems in the coastal mountains by a broad continental shelf. On the California margin, storm surges are generally swept to the north by the Davidson current during the winter months in which they occur, and these deposits mostly do not reach the canyon heads directly (Cacchione and Drake, 1990). Our preliminary investigations thus suggest that at least some of the events observed in our initial look at these cores are probably earthquake triggered.

Do the northern California turbidites represent San Andreas earthquakes exclusively? One of the strengths of the success in Cascadia is that synchronicity of the records in widely separated channels systems strongly supports earthquake triggering. If the San Andreas system is characterized by large 1906 type ruptures, then the northern California turbidite record should strongly reflect this, with little variability from channel to channel. A question of greater importance for the San Andreas than for Cascadia is the minimum magnitude and triggering distance from the earthquake hypocenter. Presently, our limited knowledge is empirical. Shiki et al. (2000) observed that earthquakes less than M=7.4 do not trigger turbidites in the Japan Sea or Lake Biwa. A question is whether San Andreas events will trigger turbidites along the southern part of the 1906 segment from Pt. Arena to San Francisco, where the distance from the fault to major canyon heads is 15-45 km, greater than at Noyo Canyon. We were initially concerned about this issue, but our initial correlations seem to defuse this as an issue, though we do see it as decreased turbidite size southward as the shelf widens.

2003 Results

Shore-based analysis of the cores and data has continued through 2002-2003. We have now completed X-ray imaging of about 90% of the cores, and completed a more detailed micropaleontologic stratigraphy for all cores. We have completed color reflectance analysis of the cores using the high-resolution imagery from the GeoTek system, and integrated these data with digital core logs. We done a detailed petrologic analysis of the sand fraction of the turbidites in selected cores, focusing on heavy mineral assemblages. Within the three major mineralogic provinces we identified at sea, we were concerned that we would have difficulty distinguishing between adjacent channel systems within the same province. The heavy mineral data however shows that we can reliably distinguish between the channels that should be the most alike, based on consistent differences in the heavy minerals. These differences are maintained down core and down channel, and thus are proving to be robust fingerprints of each system.

Another method we are testing for correlation is the use of high-resolution magnetic, density and color reflectance data. Both of these records provide a very high-resolution record of core stratigraphy that shows strong correlation to the turbidites. The magnetic data reflects the magnetite content of the turbidite sands, and the color data reflect the color changes between turbidites and the lighter colored hemipelagic sediment. We first began to correlate events down each channel using these data, and found that much like electric well log data, the magnetic and color data showed that each event down channel had a distinctive “signature” wiggle pattern in the data that persisted from core to core. While we expected to see similar numbers for turbidites, and hoped that we could correlate them, we found that robust correlation could be done using the “wiggle patterns” in these data. What surprises us even more is that this distinctive wiggle pattern not only persists down channels, but seems to persist along the margin from one channel to another.
We have made a preliminary correlation based on “wiggle matching” that extends along much of the continental slope in the study area. Most events can be correlated with magnetic and density data, with supporting correlations using the color data. Given that individual turbid flows in separate canyons with different sediment supply, bathymetry, configuration and other parameters have little in common, it’s difficult to understand why these wiggle traces in the magnetic data would look as similar as they do.

The correlation using patterns in imagery and physical properties suggests that, as we found in Cascadia, many turbid events appear to be recording large earthquakes rather than other possible triggers of these flows. Correlation of events along the margin for large distances suggests an earthquake origin for these turbidites, since other potential triggering mechanisms (except very large storms) operate in only single channels. Such synchronous triggering, only possible with earthquakes, is shown for many events. Channels from separate mineralogic provenances come together at confluences, below which we see either doublets, with no intervening time between them, or bimodal coarse fractions in the turbidites, each peak representing a separate provenance. Perhaps of equal or greater importance, the regional correlation of events implies that the physical property “wiggles” contain information about the earthquakes themselves, since the turbidites located in widely separated and non-communicating channels have, to our knowledge, nothing else in common.

Based on initial AMS 14C results, we find that regional correlation is possible for the last ~ 6200 years, and identify 35 events above this datum for the entire region. Of these, 10 events can be correlated along the length of the study region, from the northern limit of the SAF to south of San Francisco. Twelve events correlate along a northern “segment” and nine events correlate along a southern “segment” We find no events that occur clearly in only one channel, and only four events that are found in two and three channels only. These events are in close proximity to the seismically active Mendocino Triple Junction. Having worked extensively with these correlations, we believe that the data are telling us that these separate channels are recording information about the individual events that generated the turbidites. We tentatively postulate that the distinctive “wiggles” that correlate from channel to channel may in effect be seismograms, recording energy release patterns and perhaps aftershocks that result in distinctive turbidite deposits whose main character can be identified in the deposits of separate channels. We can presently think of no other parameters that these channels have in common, other than the periodic shaking from earthquakes, that could cause this. A distant possibility though, would be large storms. However these can be distinguished (if present) through use of synchronicity tests and sedimentological tests if needed.

Publications from this grant:


7 additional abstracts from GSA, AGU, AAPG and other meetings.
**Student support**
One PhD student, Joel Johnson has been partially supported by this grant.
19 graduate and undergraduate students participated in this project, including original fieldwork and data analysis. They received training in multibeam mapping, coring techniques, sediment data analysis, correlation and other techniques.

**Non-Technical Summary**
Past Great Earthquakes along the San Andreas Fault have left a record of submarine landslides spanning more than 10,000 years. Dating of these events has shown that the average repeat time is variable, ~200-300 years. Correlation between landslide deposits suggests that most of not all were triggered by earthquakes. We see that the Northern San Andreas history includes a number of “full ruptures” similar to 1906, and ruptures of a northern, and also a southern segment. The boundary between these segments appears to lie between Pt. Reyes and Pt. Arena. The southern segment may include ruptures on the San Gregorio fault.