Paleoseismicity and Crustal Deformation along the Northern San Andreas Fault, Fort Ross to Point Arena, California

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INTRODUCTION

The primary goals of this project were to constrain rates of slip, timing of paleoseismic events, and rates and styles of deformation along the northern San Andreas fault (SAF) from Fort Ross to Point Arena in coastal California (Figure 1). A crew of 17 geology students, professors, government scientists, and private consultants used a variety of techniques to assess rates and styles of deformation along the SAF. Methods of analysis included backhoe excavations across the SAF; mapping of geologic units, fault structures, and offset geomorphic features along the SAF with aerial photos, satellite images, and a total geodetic station; and surveying of uplifted marine terraces along the fault with GPS equipment.

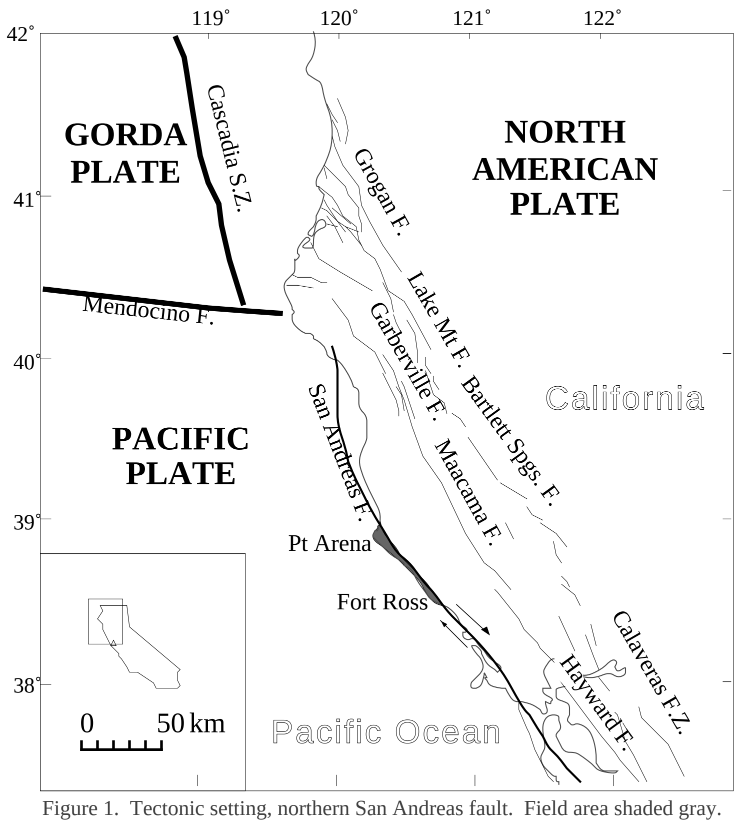

Figure 1. Tectonic setting, northern San Andreas fault. Field area shaded gray.

THE SAN ANDREAS FAULT IN NORTHERN CALIFORNIA

The San Andreas Fault (SAF) is a transform boundary separating the Pacific and North American plates (Figure 1). It formed about 26-28 m.y. ago, when part of the ancestral spreading center of the Farallon (present-day Gorda) plate was subducted beneath the North American plate (Atwater, 1970). In northern California, the SAF separates Franciscan-bearing terranes to the east from a block of late Mesozoic to late Cenozoic volcanic and sedimentary rocks that were depsted in a shoaling basin along the plate margin. This block, named the Gualala Block, has been translated hundreds of kilometers to the north by right-lateral slip along the SAF.

Although the general details and history of the evolution of the SAF have been determined by many geologists over the past century, a number of problems remain. Here, we focus on those problems pertinent to the coastal area between Forth Ross and Point Arena, spanning the entire length of the Gualala block. This area was the focus of a Ph. D. dissertation by Dr. Carol Prentice at California Institute of Technology (Prentice, 1989). Our work here builds upon her investigation.

A fundamental geologic problem regards the occurrence of isolated, anomalous exposures of rocks typical of the Franciscan Complex west of the SAF, within the Gualala Block. If they are indeed Franciscan rocks, then their incorporation into material west of the SAF requires a more complex model of fault evolution than simple right-lateral slip. Relevant to this issue of the nature of deformation along the SAF is the existence of compressional structures and uplifted Quaternary marine terraces at several locations along the northern segment of the fault. One of these locations is the Gualala block, which is flanked along its western perimeter by a flight of wave-cut marine platforms that vary in altitude, indicating both uplift and differential tilting since the time of formation. At Point Arena, extensive outcrops of thrust faults indicate that compression is occurring, even though the orientation of the SAF at this location, which makes a slight clockwise bend, would suggest that extension might occur, not compression. Another significant problem is related to the timing and rate of slip along the right-lateral fault. Only one historic event has occurred on the northern segment of the SAF. The rupture trace of this event, the 1906 San Francisco earthquake, was about 435 km, from San Juan Bautista to Point Delgada (Prentice et al., 1999). (Recent determination that rupture did indeed extend all the way to Point Delgada was the result of a 1995 Keck project (see Merritts and Beutner, 1996).) Several workers have used paleoseismological methods to determine slip rates based on several earthquake events (e.g., Prentice, 1989; Niemi and Hall, 1992). Most rates are on the order of 19-25 mm/yr, but much more information is needed to fully understand the history of seismic activity along the northern segment of the SAF.

STUDENT PROJECTS

Students worked on each of these different fundamental problems related to deformation along the northern SAF. Two students worked on projects that used paleoseismological techniques to constrain slip rates. With guidance from paleoseismologists Carol Prentice and Rob Landgridge of the USGS, Chris Crosby excavated three trenches near a stream that appeared to be offset at Fort Ross, where the SAF comes onshore. Historic photos indicated that several meters of offset occured during the 1906 earthquake; however, the trenching investigation found no evidence of offset in late Holocene deposits. After detailed surveying with a total geodetic station, and careful reoccupation of 1906 photo sites, the trio of investigators determined that the 1906 rupture--and the offset stream seen in historic photos--is now hidden beneath Highway 1 (the Coastal Highway). The ~7-m, right-jog in the stream at Fort Ross appears to indicate right-lateral offset, but in fact is not related to faulting. Crosby determined, instead, that it is due to landsliding that deflected the stream, a conclusion that many will find intriguing, since the site is a common stop for examining an offset stream along the “San Andreas fault”.

Aletha Lee worked with two geologists from William Lettis and Associates, John Baldwin and Keith Knudsen, to excavate several trenches across and along the SAF at Point Arena, in a fluvial terrace deposit of Alder Creek. The trenches were sited in order to match piercing points across the fault so as to estimate slip rates. Numerous samples of charcoal were taken to establish age control of the strata exposed in the trench walls. Aletha analyzed samples of sediment from the trench walls and exposures along Alder Creek to assess preliminary correlations of piercing points from the logging. By comparing the sedimentologic analysis with her highly detailed (and beautiful!) trench logs, she concludes that a single channel has indeed been offset by repeated faulting.

David Allderdice collected samples of rocks that appeared to be Franciscan both east and west of the trace of the SAF. He benefited from much guidance by Robert McLaughlin of the USGS, an expert on Franciscan rocks and geologic mapping along the San Andreas fault. From his petrologic analysis, Allderdice concludes that rocks which contain little or no potassium feldspar, sampled from locations close to the SAF, can be readily correlated to other terranes east of the fault, in the Franciscan Central Belt. Furthermore, rocks with Franciscan affinities close to the SAF are relatively unsheared and coherent, suggesting that they were incorporated as large discreet blocks. Allderdice concludes that the blocks might have been emplaced in the Gualala block along widely spaced faults, with little post-lithification internal deformation.

In another project related to the issue of complex deformation along the SAF, Meadow Koslen worked with Michael Rymer of the USGS to complete detailed structural analyses of numerous exposures of thrust faults near Point Arena. Rymer has extensive experience with detailed structural analysis elsewhere along the SAF where deformation is highly complex. Koslen cleaned five exposures of thrust faults along the faces of cliffs and sinkholes that reveal thrusting of Miocene-age Point Arena Formation over Quaternary-age terrace deposits. Koslen concludes from detailed logging of these exposures that the faults are a single, low-angle thrust sheet with a curviplanar geometry. Her detailed topographic surveying reveals up to 24 cm of surface deformation above this thrust sheet. In addition, her analysis of both fold and fault structures enabled her to develop a history of compressional strain along the SAF, revealing a change in direction of compressional deformation during late Quaternary time.

The remaining five projects were related closely to one another, and all dealt with the problem of vertical deformation and differential tilting along the coastline. One of the best methods of assessing rates of uplift, and variations in such rates, is analysis of the inner edge altitudes of wave-cut, bedrock marine platforms. However, the method relies upon correlation of these platforms with sea-level highstands. As a consequence, one student—Jessica Darter—did a thorough literature review in order to compile an up-to-date sea-level curve. This curve, with data on the timing and altitude of numerous late-Quaternary highstands, is essential to the work of four other students. These students divided the coastline into separate regions. Each student used GPS equipment and a coastal beacon signal to acquire highly detailed surveys with excellent vertical and horizontal control (submeter resolution for vertical, and cm-resolution for horizontal position). In the south, Erica Richardson surveyed flights of marine terraces between the Russian River, just south of Fort Ross, and the town of Gualala, about midway along the Gualala block. Richardson found that uplift rates are low (between 0.5 and 1 m/ky), but slightly higher than rates determined farther south along the SAF. In addition, she determined that uplift rates increase gradually to the north. In a novel manner, she was able to calculate a slip rate for the SAF by matching a marine terrace west of the SAF Fort Ross with its corollary to the south, near the Russian River.

Stacy Tellinghuisen worked from the town of Gualala northward to Point Arena, at the edge of the SAF. She determined that uplift rates remain fairly low, between about 0.5 and 0.7 m/ky, however, she found several locations where terraces are faulted—sometimes many meters—and hence occur at elevations much lower than elsewhere nearby. Her findings provide clues for where to look for active faults. Furthermore, the terrace elevations and uplift rates drop significantly at Point Arena, as they near the San Andreas Fault. Tellinghuisen proposes the existence of a south-dipping thrust or reverse fault in the vicinity of the Coast Guard Station that is dropping the Gualala Block down on the north side of the fault. This fault might well be that mapped in such detail by Koslen.

Charles Hampton worked from just north of the SAF northward to the town of Mendocino. All of his marine terrace survey transects were on the North American plate, whereas those of Tellinghuisen and Richardson were on the Pacific Plate (with exception of Richardson's survey transect south of Fort Ross near the Russian River). Hampton determined that uplift rates increase from north to south; in essence, this is a mirror image of what was found by Richardson. Hampton's surveys included some particularly extensive marine terraces with excellent exposures of inner edges, and he was able to acquire an exceptional amount of control on the variation in inner-edge altitude along the coast. Combining his data with that of Richardson and Tellinghuisen produces a span of surveyed coastline some 100 km in length. Immediately north of where Hampton completed his last transect, Merritts (1989) has completed similar types of analyses all the way to the end of the SAF, at the Mendocino triple junction, an additional distance of 140 km. We now have the most complete database (in terms of distance and quality of altitudinal control) of terrace deformation that exists along the SAF, and perhaps anywhere in the world.

As is clear from the summary of the marine terrace work of Richardson, Tellinghuisen, and Hampton, vertical deformation is most intense close to the SAF as it approaches shore at Point Arena. In this complex area, numerous reverse and thrust faults occur, and marine terraces are laterally offset as well as vertically disrupted by faulting and perhaps even folding. Michael Toomey tackled this complex area, striving to correlate marine terraces across the SAF in order to determine how rates of uplift change. He concluded that uplift rates do indeed increase markedly from west to east across the fault, and furthermore that the terrace inner edges are offset laterally. Carol Prentice had done preliminary work on this idea, and Toomey followed up on her suggestion to do detailed GPS surveying along the terrace inner edges. Toomey derived a possible slip rate based on his estimates of plausible terrace ages and amount of terrace offset. His rate is similar to that of other workers on the northern San Andreas fault, but spans a much greater time period of tens of thousands to hundreds of thousands of years, whereas those from trench excavations span only a few thousand years at most.

INTERACTIONS WITH SCIENTISTS FROM OUTSIDE THE PROJECT

The first day of the project was spent at the USGS in Menlo Park in order to orient students to the research questions. Dr. Carl Wentworth, USGS, gave one of several presentations. He completed a Ph.D. at Stanford based on a structural geologic analysis of rocks in the Fort Ross to Point Arena area. John Baldwin and Carol Prentice summarized their research in the Fort Ross to Point Arena area, and Dorothy Merritts explained the variety of possible research projects. The second day was spent with Jeff Hamilton, a specialist in GPS surveying. He provided five hours of hands-on training in the use of differential GPS methods to all members of the project. The next few days were spent completing a reconnaissance of the project areas, under the guidance of Dr. Tom Anderson of Sonoma State University. An expert in sedimentary rocks in the area, Tom provided an excellent foundation for our work. As a local geologist with much mapping experience, he knew of many excellent places to point out specific geologic features. Exposures of Tertiary turbidites were particularly impressive.

After the first few days, students began to select and develop their individual projects. At this time, Noah Snyder of MIT visited for several days. He was instrumental in helping several students to define their project goals and agendas, and he accompanied several students to their field areas. Bob McLaughlin of the USGS visited for one day near the end of the field season in order to work with Dave Allderdice on mapping Franciscan rocks.

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