CALIFORNIA GEOLOGICAL SURVEY
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EASTERN SAN CAYETANO FAULT
in the Piru Quadrangle

Ventura County
California

by
Brian P.E. Olson
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INTRODUCTION

The San Cayetano Fault is a major east-west-trending north-dipping reverse fault, which partially bounds the northern edge of the Santa Clara River valley along the base of the Topatopa* Mountains (Figures 1 and 2). The mapped strands of the San Cayetano Fault are found mainly in the foothills along the southern flank of the mountains and in the alluvium near the base of the hills (CSWRB, 1956; Cordova, 1956; Weber et al., 1973; Çemen, 1977; Rockwell, 1983; Dibblee, 1991; Huftile and Yeats, 1995; and Yerkes and Campbell, 1995). The overall fault system (Figure 2) extends from Upper Ojai Valley eastward to Fillmore, and then along the base of the Topatopa Mountains where it ultimately loses separation and dies out in the subsurface approximately 5 km east of Piru (Çemen, 1977). The fault is divided into two sections based on a prominent right-step in the fault trace forming a lateral ramp at Sespe Creek near the town of Fillmore, west of the study area (Rockwell, 1988). The eastern segment, or Modelo lobe, is located within the Piru quadrangle and bifurcates into two strands near the mouth of Hopper Canyon (Çemen, 1977; Huftile and Yeats, 1995; Yerkes and Campbell, 1995). The Main strand is located in the foothills of the mountain front and the Piru strand trends along the northern edge of the Santa Clara River Valley (Figures 2 and 3).

The Main Strand from Upper Ojai Valley (i.e. western segment) to Piru Canyon was previously evaluated in Fault Evaluation Report FER-19 (Smith, 1977). Kahle (1985 and 1986) later zoned the portion of the San Cayetano Fault west of Sespe Creek in FER-174. The Piru Strand has not previously been evaluated.

Both the Main and Piru strands of the San Cayetano Fault in the Piru quadrangle study area are evaluated as part of the statewide effort to evaluate faults for surface rupture hazard. Those faults determined to be sufficiently active (surface displacement during Holocene time) and well-defined are zoned by the State Geologist as directed by the Alquist-Priolo Earthquake Fault Zoning Act (Bryant and Hart, 2007).

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* The mountains immediately north of the study area are not formally named; however, to maintain consistency with various workers in the Ventura Basin, CGS uses the name "Topatopa Mountains".

SUMMARY OF AVAILABLE DATA

The Piru study area is located in the southwest portion of the Transverse Ranges geomorphic province. In this area, deformation is dominated by roughly east-west trending low-angle reverse faulting and folding driven by north-south tectonic compression (Shaw and Suppe, 1994).

Bedrock in the southern half of the Piru quadrangle is dominated by the Miocene Modelo Formation, Pliocene Fernando Formation and Plio-Pleistocene Saugus Formation, which are faulted and folded in a series of anticlines and synclines whose fold axes generally trend east-west (Cordova, 1956; Weber et al., 1973; Çemen, 1977; Dibblee, 1991; Huftile and Yeats, 1995; Yerkes and Campbell, 1995). The Modelo Formation consists mainly of sandstone and shale, while the Fernando Formation (Pico Member) is composed chiefly of marine siltstone. The Saugus Formation is informally divided into two members: a lower marine member composed of conglomerate, silty sandstone with minor siltstone beds and a non-marine upper member consisting of chiefly massive sandstone and pebble conglomerate (Huftile and Yeats, 1995). Late Quaternary alluvium is mapped in the Santa Clara River and Piru Creek alluvial valleys and as coalescing alluvial fans emanating from the various north-south trending canyons in the mountains north of the Santa Clara River valley (Cordova, 1956; Weber et al., 1973; Çemen, 1977; Dibblee, 1991; Huftile and Yeats, 1995; William Lettis and Associates, 2000; Yerkes and Campbell, 1995).

Topography in the study area is generally mountainous to the north, with the relatively flat Santa Clara River valley draining from east to west across the southern part of the quadrangle. The Topatopa Mountains form a roughly east-west trending mountain range with east-west and north-south trending canyons, which ultimately drain south into the Santa Clara River.

LITERATURE REVIEW

The San Cayetano Fault is characterized as a thrust fault due to the relatively low dip angles and reverse separation of stratigraphic units. Based on geologic mapping and well data, workers indicate the fault plane dips at a very low angle in the shallow subsurface and becomes gradually steeper with depth (Çemen, 1977, 1989; Yeats, 1983; Yeats et al., 1994; Nicholson et al., 2007). Measured and inferred dips for the near-surface portion of the fault range from as little as 5° to 10° (Yeats, 1983 and Çemen, 1989) up to 18° to 30° (Dolan and Rockwell, 2001; Dolan, 2009). Çemen (1989) indicates both the Main and Piru strands merge at depth into a single fault plane that gradually increases in dip up to 45°.

Cumulative dip-slip displacement on the San Cayetano Fault has proven difficult to determine because the oldest units in the hanging wall have yet to be encountered in any wells drilled to date in the footwall of the fault (Çemen, 1977 and 1989). Rockwell (1988) and Çemen (1989) both calculate approximately 7,500 meters of total stratigraphic separation on the Modelo lobe segment of the fault using the maximum thickness of the bedrock units in both the hanging wall and footwall. Separation decreases notably to the east on both strands, such that the Main strand dies out under Piru Canyon and approximately 2 km east of the quadrangle boundary the Piru strand is completely lost as the fault transitions into the East Ventura fold belt (Huftile and Yeats, 1995).

Quaternary slip rates for the Modelo lobe of the fault range from 7.3 to 7.5 mm/yr (Rockwell, 1988; Çemen, 1989; Huftile and Yeats, 1996), which is significantly higher than rates calculated for the western portion of approximately 1 to 3.6 mm/yr (Rockwell, 1988). Dolan and Rockwell (2001) note this is one of the highest slip rates of any reverse fault known in California.

Workers who have mapped this portion of the San Cayetano Fault include: CSWRB (1956), Cordova (1956), Weber et al. (1973), Weber et al. (1975), Çemen (1977 and 1989), Rockwell (1983 and 1988), Dibblee (1991), Huftile and Yeats (1995), and Yerkes and Campbell (1995). Two fault trenches were also excavated and logged across the Piru strand by Dolan and Rockwell (2001) and Dolan (2009). Other researchers who have worked on regional tectonics studies involving the San Cayetano Fault characteristics are Yeats (1983), Huftile (1993), Huftile and Yeats (1996), and Nicholson et al. (2007).

The San Cayetano Fault system was previously evaluated under the guidelines of the Alquist-Piriolo Earthquake Fault Zoning Act (Bryant and Hart, 2007) in 1977 and 1985. For the initial fault evaluation, Smith (1977) reviewed the fault in its entirety from Ojai to Piru. In the current study area he relied mainly on mapping by Weber et al. (1973 and 1975) who only mapped the Main strand of the fault offsetting bedrock in the hills northwest of Piru, placing Miocene Modelo Formation over Plio-Pleistocene Fernando Formation. Where the Main strand was mapped across the alluvium of the foothill canyons and in the alluvium south of the hills, it was shown as buried. A photo-lineament was noted by Weber et al. (1975) and by Smith (1977) in the area of the Piru strand in the alluvium away from mountain front. Zoning was not recommended by Smith for any portion of the San Cayetano Fault because "[w]hile Holocene activity has been suggested, it has not been proven."

Using newer data, which included geologic mapping by Çemen (1977) and Rockwell (1983), the San Cayetano Fault was re-evaluated by Kahle (1985 and 1986) and an Alquist-Priolo Earthquake Fault Zone was established for the Main Strand of the San Cayetano Fault from Upper Ojai Canyon to Sespe Creek, just north of Fillmore. Neither of the fault strands in the Piru Quadrangle were included in the scope of that re-evaluation.

This current fault evaluation utilizes additional mapping and subsurface data resources not incorporated in previous FERs. These are described in more detail below.

Çemen (1977)

Çemen (1977), in his Master's thesis, mapped traces of the San Cayetano Fault in the Sespe-Piru Creek area from the Fillmore area to approximately 7 km east of Piru, including both strands within the study area. Where the Main strand is mapped in the alluvium west of Hopper Canyon, it is delineated based on a difference in soil color visible in aerial photographs. The Main strand offsets Tertiary bedrock in the foothills east of Hopper Canyon but is depicted as buried under the young alluvium of the Santa Clara River valley and Piru Canyon. The youngest bedrock unit offset by the Main strand in the study region is the Pico Member of the Fernando Formation (Plio-Pleistocene). Çemen also maps the Piru strand within the alluvium south of the mountain front based on noted "warping" in the alluvial sediments between Hopper Canyon and Piru Creek and then by soil color changes east of Piru Creek. However, the Piru strand is not mapped offsetting any alluvial units at the surface.

Using oil well data, Çemen measures approximately 5,200 to 7,300 m of stratigraphic separation on the Main strand of the San Cayetano Fault about 1.5 km west of Hopper Canyon using "the minimum and maximum thicknesses of the rock units stratigraphically between the lower sandstone member of the Modelo Formation and the base of the Saugus Formation." Separation steadily decreases on both strands to the east such that approximately 1.5 km east of Piru, separation on the Piru strand is about 1,400 m using the same stratigraphic correlation (Çemen, 1989). Approximately 1 km east of the Piru quadrangle boundary, vertical separation is only 750 m and the Piru strand loses separation completely and dies out into the Santa Clara Valley syncline 1.3 km farther east.

Çemen notes older alluvial fan deposits were mapped as offset by the fault to the west of and outside the study area and concludes the San Cayetano Fault should only be considered potentially active.

Çemen (1989)

Çemen later published a paper on the near-surface expression of the eastern San Cayetano Fault (Çemen, 1989) based mainly on data gathered from his earlier thesis, new regional groundwater data, and subsequent studies by others including Rockwell (1983 and 1988). Here, Çemen postulates the cause of the color changes in the soil used to map the near-surface trace of the fault are related to changes in groundwater levels, possibly due to the fault acting as a groundwater barrier in the young alluvium. Based on this data, he ultimately concludes the warping in the alluvium and changes in soil color along the trace of the Piru strand are "suggestive of recent movements along the San Cayetano fault" (Çemen, 1989).

Dibblee (1991)

Dibblee mapped traces of the San Cayetano Fault as part of his geologic map of the Piru quadrangle. This mapping was originally performed by Dibblee between 1939 and 1940 and was supplemented by field work from 1979 to 1982 and again in 1990. The San Cayetano Fault is divided into two strands at Hopper Canyon, similar to previous mappers; however, Dibblee maps the Main strand splitting into three subparallel faults in the bedrock hill immediately east of Hopper Canyon (Figure 3). Here Dibblee maps the Main strand thrusting Miocene Sisquoc Formation ultimately over Plio-Pleistocene Saugus Formation with a sliver of Pliocene Pico Formation between the southern two fault splays. These Main strand fault splays join back into a single strand just west of Real Canyon where Sisquoc Formation overlies Pico Formation. Fault plane dips range from 50° to 65° on the northernmost portion of the Main Strand, between Hopper and Edwards Canyons. The Piru strand is mapped at the base of the foothills until Real Canyon, where the trace shifts more easterly and continues through Piru to the base of the low hills east of Piru Creek.

Similar to previous mappers, no strands or splays of the fault are shown to offset Quaternary alluvial sediments.

Huftile and Yeats (1995)

Both traces of the San Cayetano Fault were mapped by Huftile and Yeats in their study of the Cenozoic structure of the Piru quadrangle. The traces of both the Main and Piru strands generally follow those of Çemen (1977), except at the eastern end of the Main strand in Piru Canyon. Near the Modelo Canyon alluvial fan the authors map the fault trace turning more to the northeast following Piru Canyon Road across the fan (Figure 3). The authors report the dip of the fault in the western lobate portion (i.e. Modelo lobe) of the Main strand ranges from 22°-34°, steepens to about 40° just east of Hopper Canyon, and increases further to 66° near the eastern terminus. The Piru strand has a much shallower dip at its western end, near Hopper Canyon, and steepens up to 54° at the eastern end. Fault displacement is apparently transferred to the Eastern Ventura fold belt, in the eastern portion of the study area, where both strands ultimately lose separation.

Huftile and Yeats conclude both strands of the fault have evidence of Late Quaternary activity based on offsets noted in well logs and surficial mapping. They observe aerial photographic evidence showing drainages in the upper portion of the Modelo Canyon alluvial fan, northwest of the Main trace, are more incised than those to the southeast suggesting active uplift to the west. Also, Huftile and Yeats indicate the Modelo fan "appears" to be cut by the Main trace; however, they do not cite any direct field evidence. Bedrock units exposed on the west side of Piru Canyon are much older than the bedrock units on the east side, which the authors take to suggest a component of left-lateral movement on the eastern portion of the Main strand. They also indicate offset of drainages increases to the south "where dip-slip offset should be greater" and some of the drainages in the foothills appear left-laterally offset; however, no specific drainages or other localities were cited as examples to support these observations. The authors state these two observations imply oblique motion for this portion of the fault. Huftile and Yeats also note the warped alluvium near the base of the mountains as an indicator of recent activity on Piru strand. As a result, the authors conclude both strands of the San Cayetano Fault appear to have areas where Holocene deposits are offset.

Dolan and Rockwell (2001)

Dolan and Rockwell performed the first known paleoseismic study of the San Cayetano fault in August 1999. They focused on the tectonic geomorphology of both strands to identify suitable sites for fault trenching. They noted the Main strand does not exhibit any recognizable geomorphic evidence for recent faulting despite the clear evidence for several kilometers of stratigraphic offset. The Piru strand, however, exhibits a notably well-defined scarp in the alluvial fan sediments south of the mountain front, which was first documented by Çemen (1977). This scarp is up to 8 m high and was traced by the authors for over 2 km west of Piru. They also noted the scarp has marked topographic inflection points at the top and bottom, with up to 15° surficial slope angles. Based on the lack of geomorphic evidence for recent activity on the Main strand, only the prominent scarp along the Piru strand was selected for a trenching study.

The trench site is located on a small alluvial fan just west of Edwards Canyon (Figure 3 and 8). A 59-meter long and up to 4.5-meter deep trench (SCF1) was excavated across the fault scarp of the Piru strand, approximately 2 km west-southwest of the town of Piru and 1.5 km east of Hopper Canyon. Seven Holocene-age stratigraphic units were encountered in the trench (Figure A-1). The units were dated using pedogenic analyses and radiocarbon dating of detrital charcoal samples. Ages of the units range from historic alluvium containing man-made debris with an approximate age of late nineteenth to early twentieth century (Unit 1) to no older than 2,000 BC (Unit 7). The youngest pre-historic stratum (Unit 2) is a 60- to 120-cm thick fine-grained sand dated as no older than 1660 AD.

Four distinct faults (Faults 1 through 4) were exposed in the trench. Faults 1 through 3 are generally planar with single shear zones all dipping between 18° and 25° north. These three faults all offset the prehistoric sediments and terminate at the base of Unit 1. Fault 4 consists of several closely-spaced minor subparallel faults in a zone up to 1.7 m wide. Due to increased disturbance of the soils near the surface, it was unclear whether or not Fault 4 extended all the way up to the base of Unit 1, similar to the other three faults; however, the authors were able to determine this fault did offset the Unit 6/7 contact.

Based on multiple measurements of separation between the different stratigraphic units exposed in the trench, Dolan and Rockwell conclude Faults 1 through 3 accommodated approximately 4.3 m of total reverse slip, which likely occurred during a single earthquake event after 1660 AD (the approximate age of Unit 2). Displacement along Fault 4 was more difficult to measure due to bioturbation and the absence of Units 2 through 5 due to erosion above the fault, but amounted to about 90 cm. It is not clear though whether or not Fault 4 also ruptured at this time or was formed during an earlier earthquake event.

Dolan and Rockwell concluded the Piru strand of the San Cayetano ruptured to the surface as a result of a very large late Holocene earthquake. Their trench investigation also confirmed, at least in the vicinity of the trench site, the warped alluvium mapped by

Çemen (1977) is a fault scarp related to active faulting on the Piru strand and relocated the mapped trace of the Piru strand based on their findings (Figure 3).

Nicholson et al. (2007)

Noting the San Cayetano Fault thrusts Neogene bedrock over younger unconsolidated sediments, Nicholson et al. (2007) explored the manner in which non-elastic deformational processes in the footwall may contribute to the high rates of crustal shortening measured in the Ventura Basin (Donnellan et al., 1993; Huftile and Yeats, 1996). The authors note the San Cayetano and other basin-bounding reverse faults in this area have rotated nonplanar three-dimensional geometries based on structural cross sections. To explain this, they suggest differential compaction and subsidence of the unconsolidated footwall sediments, induced by the overlying Miocene to Pliocene bedrock units, is causing collapse and rotation of the near-surface portion of the San Cayetano fault plane toward the basin. This differential compaction, subsidence, and fault plane rotation can also generate apparent vertical offset via flexural slip. This non-seismic fault slip may explain the high slip rate calculated for the San Cayetano Fault, especially in the Modelo Lobe region.

As a result of the footwall compaction and subsidence, coupled with on-going hanging wall uplift and basinward tilting, Nicholson et al. also suggest there is an increased potential for gravity sliding toward the basin, which can add to the nonplanar fault plane geometry and total vertical offset. They postulate this is the case with the Modelo lobe portion of the San Cayetano Fault (Figure 2). Here they state the three-dimensional geometry of the fault plane, derived from structure contour maps and detailed cross sections, is reminiscent of a thrust nappe. Their postulated model proposes the Modelo lobe was formed by a "deep-seated, gravity-driven failure" and the near-surface displacements on the shallow-dipping Modelo lobe portion of the San Cayetano Fault are caused by both fault slip at depth and sliding of the uplifted bedrock in the hanging wall. The authors claim this "mega-slide" most likely failed within the Rincon Formation, which is a weak shale bedrock unit prone to bedding plane and detachment slip and underlies the Modelo Formation.

The authors conclude if their proposed footwall subsidence/compaction and gravity-induced sliding model is correct, it has significant implications for fault modeling and concomitant seismic hazard analysis. They summarize that non-elastic deformation, mainly in the form of compaction, subsidence, and gravity sliding, may be accommodating regional tectonic strain in the Ventura Basin. Also in this model, compaction of the young sediments in the footwall alone can produce fault plane deformation, increased vertical separation, and horizontal motion mimicking co-seismic fault slip. Therefore, Nicholson et al. conclude these effects would contribute to the horizontal and vertical motions seen in the geologic data and measured in geodetic surveys, which could result in an overestimation of the inferred seismic hazard for these basin-bounding faults.

Dolan (2009)

Dolan returned to the area west of Piru in 2002 to conduct another paleoseismic study on the Piru strand of the San Cayetano Fault. A trench investigation was conducted approximately 100 m east of the Dolan and Rockwell (2001) site, where the previously identified fault scarp reaches a maximum height of approximately 8 meters. The author also drilled three large-diameter bucket-auger borings through the faulted zone to observe the older sediments too deep to expose in the trench and help interpret the geometry of the faulted strata.

A 32-meter long trench (SCF2) with up to 6 meters of vertical exposure was excavated on the same small alluvial fan emanating from the mouth of Edwards Canyon as the previous fault trench (SCF1) studied by Dolan and Rockwell (2001) (Figure 3 and 8). Seven major stratigraphic units were identified in the trench (Figure A-2). Due to the similarity between these units and those exposed in the prior Dolan and Rockwell (2001) study, the unit number designations from the prior trench investigation were used to label the strata in this study. Unit 3 from the previous study was not encountered but an additional deeper sand layer (Unit 8) was exposed in the borings at this location that was not in the trench to the west (SCF1) because it did not extend deep enough. Stratigraphic units were dated using pedogenic analyses and radiocarbon dating of detrital charcoal samples. Because of the near-identical sequence of stratigraphic units in SCF1 and this trench, age data from SCF1 was used to constrain the ages of the units in this study. The ages of the sediments (Units 1 through 8) were determined to be latest Holocene.

Similar to SCF1, four distinct faults were observed in the SCF2 trench. The individual faults were not as planar as in the SCF1 trench but were composed of multiple strands forming discrete narrow fault zones, which dipped from 18° to 30° north. Based on the dip range, the author concluded it is likely these faults all merge together downdip below the trench. Each of these faults extends up to within a few centimeters of the existing ground surface and offset the pre-historic stratigraphic units (Units 2-8). Restoration of the upper and lower contacts of Unit 4 indicates a total of approximately 5 m of total slip for the most recent event. After this restoration, Dolan noted the strata below Unit 4 are in lateral continuity indicating the slip from the most recent earthquake event affected all units by the same amount, suggesting this displacement occurred during a single event (i.e. Event 1). The units below Unit 4 after restoration, however, are notably folded indicating at least one additional slip event (i.e. Event 2) occurred prior to the most recent event. Based on the age dating of the various stratigraphic layers exposed in the trench and the large amount of offset, Dolan concluded both Events 1 and 2 were likely large magnitude earthquakes ($M_W > 7$), which occurred after 1660 AD. Using the top of Unit 6 as a restoration horizon, Dolan determined a minimum of 5 m of slip was needed to generate the folding observed in Unit 6. He also noted the geometry of Unit 6 suggests it was deposited above a pre-existing fault scarp, which likely developed during the deposition of Units 7 or 8 suggesting an ante-penultimate event (i.e. Event 3) also during the latest Holocene.

Building on the previous investigation by Dolan and Rockwell (2001), this study concludes the Piru strand of the San Cayetano Fault has generated at least two, and likely three, earthquake events during the latest Holocene that resulted in significant surface deformation.

Dolan does consider the model proposed by Nicholson et al. (2007), which suggests the Modelo lobe was formed as part of a mega-landslide and some of the measured offset at the SCF2 location could be related to gravity sliding. He notes the evidence is generally consistent with the gravity slide model; however, even if the mega-landslide exists, the activity of the proposed slidemass and possibility of recurrent movement are not documented. Therefore, Dolan states there is no evidence the mega-landslide is active or has been active in recent time. If landslide activity and recurrent slip were documented, then Dolan agrees the measured displacements at SCF2 should not be used to calculate magnitudes of paleo-earthquakes on the San Cayetano Fault. In the absence of such evidence, he thinks the offsets measured during this study and by Dolan and Rockwell (2001) most likely represent co-seismic fault slip and are appropriate for use in evaluating the seismic hazard potential of the area.

AERIAL PHOTOGRAPHIC INTERPRETATION AND FIELD INSPECTION

Aerial photographic interpretation was performed primarily to look for visual and geomorphic features suggestive of active faulting and also to verify the location and activity of the fault traces mapped by others (Figure 3). This was accomplished using aerial photographs from the USDA (1938, 1953), USGS (1947, 1969), and NASA (1994). Fault traces mapped by others were also checked against these photos for geomorphic evidence of Holocene activity and location accuracy. The various mapped traces and lineaments are annotated and included on Figure 4. This study also utilized a recently flown Light Detection and Ranging (LiDAR) survey of the Santa Clara River Valley (Earthscope, 2008). From this point-cloud data a hillshade map of the study area was generated (Figures 6 through 8). Traces of the San Cayetano Fault identified from this study were plotted directly in ArcGIS using the LiDAR-generated hillshade map and contours.

Three field visits were made in October and November 2010 and February 2012 to check various lineaments identified in the aerial photographs, as well as observe the mapped traces of the fault and associated topographic features. Field observation annotations are included in Figure 4. Various field visits were also performed as part of the original fault evaluation (Smith, 1977) and pertinent notes are also included on Figure 4.

The aerial imagery interpretation and field observations indicate much of the San Cayetano Fault is moderately well-defined in the areas where the fault is located in the alluvium near the base of the mountain front, with several low scarps and breaks in slope visible (Figure 4). Because the fault traces, especially the Modelo lobe portion of the Main strand and the entire Piru strand, are located immediately adjacent to the Santa Clara River, there is some difficulty and ambiguity in differentiating fault-related scarps from fluvial scarps. The aerial photos were used to interpret those scarps and lineaments, which were most likely related to fluvial deposition and/or erosion. In the bedrock foothills east of Hopper Canyon, the location of the Main strand of the fault is chiefly defined by linear drainages and benches, as well as tonal contrasts, but overall these features do not suggest Holocene activity.

Main Strand

Soil color changes in the alluvium noted by Çemen (1977) at the base of the Modelo lobe in the western portion of the quadrangle were not readily observable on the aerial photographs reviewed. However, various scarps and other geomorphic indicators were observed and mapped near this tonal lineament, which are interpreted as features related to active faulting along the Main strand of the San Cayetano Fault (see Locality 1 on Figure 4). South-facing scarps were mapped outboard of the bedrock-alluvium interface, which are interpreted as related to active faulting. Based on geologic mapping by William Lettis and Associates (2000) these scarps also tend to be located within distinct alluvial units and therefore are not likely artifacts representing contacts between different generations of alluvial fans or related to fluvial erosion and/or deposition. Landsliding along the front of the foothills has also obscured some of the scarps as evidenced by their abrupt termination along the lateral margins and toe of the slide masses. The increasingly left-laterally offset drainages noted by Huftile and Yeats (1995) were not readily observed in the aerial photographs.

Near the apex of the Fairview Canyon alluvial fan, one of the scarps is associated with a distinct change in bedding attitudes within the bedrock exposed on the western canyon wall (Figure 4). This same scarp also bounds an upstream incision in an alluvial terrace (Figure 6). Two low scarps were also noted near the mouth of Hopper Canyon in the central portion of the study area (Figure 4). There is some ambiguity as to whether these scarps are the result of hanging wall faulting or fluvial processes from the adjacent Hopper Creek. Relict meander bends trending roughly east-west are faintly visible just south of these scarps in the oldest aerial photographs for this area, prior to agriculture development at the mouth of the canyon. Therefore, it is possible these scarps are erosional remnants of local stream meanders within the channel margins.

In the foothills of the Topatopa Mountains east of Hopper Canyon, the Main strand of the San Cayetano Fault is delineated by a relatively narrow zone of faulting; however, Dibblee (1991) mapped the Main strand branching into three substrands between Hopper and Edwards Canyons (Figure 3). Here Dibblee maps a fault zone consisting of a basal thrust fault and two intra-hanging wall faults. In this area, the trace is best defined by linear benches, topographic breaks in the southerly-trending ridgelines, linear drainages, and tonal contrasts between different bedrock units on either side of the fault. However, based on aerial photographic interpretation, these features do not appear to reflect recent activity. They are mainly limited to older uplifted geomorphic surfaces and tend to be absent in areas of young active surface processes, such as the alluvial-filled canyons and areas of hillslope erosion (Figure 4). Also, this portion of the Main strand does not appear to deform or deflect any of the active canyon drainages. Dolan and Rockwell (2001) also came to this conclusion noting a general lack of "discernable geomorphic evidence for recent reverse slip" despite evidence that the fault accommodated several kilometers of reverse slip in the past.

A possible scarp across the Modelo Canyon alluvial fan and observation of apparent deeper incision in alluvial drainages found in the upper fan surface were thought to be suggestive of recent activity along the Main strand in Piru Canyon by Huftile and Yeats (1995) (See Locality 2 on Figure 4). Geologic mapping by William Lettis and Associates (2000) shows the proximal portion of this fan is underlain by Holocene and late Pleistocene alluvial-fan deposits. The distal portion of the fan, generally southeast of Piru Canyon Road, is mapped as young alluvial terrace deposits of similar age along with a slightly younger alluvial fan deposit overlying both older units (Figure 5). Weber et al. (1973) also mapped the Main strand of the fault cutting the western portion of this fan. Smith (1977) field checked this area and stated there were "no faults visible in [the] roadcuts" and "no topographic evidence [was] noted" (Plate 3). Dolan and Rockwell note this scarp is subparallel to Piru Creek and may be related to fluvial processes, not faulting. All other workers (Cordova, 1956; Weber et al., 1975; Çemen, 1977, 1989; Dibblee, 1991) map the Main strand as buried under the Piru Creek alluvium. No evidence was observed during our field visits to support the interpretation that the scarp is fault-related. The deeper incised drainages on the upper surface would be expected in any stepped terrace surface as headward erosion deepens and extends the channel away from a scarp; be it fluvial or fault-related. Other workers (Çemen, 1977 and 1989; Huftile, 1993) performing surficial geologic mapping and reviewing subsurface data from oil well logs, note the San Cayetano Fault consistently loses stratigraphic separation from west to east until it dies out just beyond the eastern quadrangle boundary. Also, as noted above, there is a lack of evidence to suggest recent offset along the Main strand of the San Cayetano Fault east of Hopper Canyon. Therefore, it appears unlikely to have such a notable scarp located at the extreme eastern end of the fault, just before it dies out.

Based on the aerial photographic review and field inspection, several scarps and other features along the Main strand of the San Cayetano Fault west of Hopper Canyon exhibit geomorphic evidence of recent movement; however, east of Hopper Canyon where the Main strand is located in the bedrock foothills, no evidence of recent activity was observed.

Piru Strand

The majority of the photo-lineaments identified in the alluvial plain south of the foothills tend to be related to fluvial process associated with Piru Creek and the Santa Clara River. However, there are notable deformational and tonal contrasts in the alluvium, which are considered to be associated with the Piru strand of the San Cayetano Fault (See Locality 3 on Figure 4). Weber et al (1975) and Smith (1977) noted a photo-lineament near the mapped trace of the Piru strand and Çemen (1977) was the first to note the "warped alluvium" and soil color changes. Field inspection verified the existence of the scarp near where it was mapped by others and the reported maximum height of approximately 8m (Dolan and Rockwell, 2001; Dolan, 2009). The mapped trace of the Piru strand for this study was drawn at the base of these scarps.

Other prominent slopes were observed at the east end of Camulos Street and northwest of Piru Canyon Road (See Locality 4 on Figure 4). Because of the location, freshness and height of both of these slopes, it is most likely they are modified fluvial terrace benches related to Piru Creek outflow. The slope along Camulos Street is located within a landscaping contractor's property and appears to have been modified by grading.

The Piru strand turns to the southeast at Piru and trends along the base of a low east-west trending ridge. Çemen (1977, 1989) notes a color change and warping along the fault trace east of Piru but neither color changes nor geomorphic features suggestive of active faulting were observed in the aerial photographs or during field reconnaissance in this area. The scarps mapped in this area are located along the northern edge of the Santa Clara River and are indiscernible from fluvial scarps (Figure 4). The disagreement in fault locations mapped by previous workers (Figure 3) is evidence of its poor definition here.

South-facing scarps and other breaks in slope were also observed on the north side of the bedrock ridge, east of Piru (See Locality 5 on Figure 4). The southernmost breaks in slope along the top of the ridgeline, as well as other features visible along the ridgeline, suggest these features are most likely related to ridgetop-spreading (i.e. sackungen) and differential weathering of resistant beds within the Fernando Formation. There are also south-facing scarps visible in elevated older alluvial deposits overlying the bedrock. The origin of these scarp features is unclear. There is no mapped fault trace, which coincides with the scarps or breaks in slope. Weber et al. (1975) and Çemen (1977) both map the westernmost strand of the Del Valle Fault trending east-west and dying out under the alluvium of Piru Creek. This mapped trace is over 200 meters north of the northernmost scarp at Locality 5; however, the existence of this fault is not well-supported as neither Dibblee (1991), Huftile and Yeats (1995), nor Yerkes and Campbell (1995) include this fault in their geologic map of the Piru Quadrangle. There is not sufficient data to conclude these features are fault-related. They parallel bedding and it is possible they were produced by earthquake shaking and are related to the sackungen features noted at the top of the adjacent ridgeline.

LIGHT DETECTION AND RANGING DIGITAL ELEVATION MODEL

Available optical remote sensing imagery was used to more accurately evaluate the geomorphology associated with the San Cayetano Fault in the study area (Earthscope, 2008). An airborne Light Detection and Ranging (LiDAR) survey was taken of the Santa Clara Valley on April 12, 2008 as part of a regional study of southern California fault zones. The LiDAR survey consisted of scanning the ground surface with a pulsing laser mounted in an airplane. The distance from the laser source to the ground surface is measured based on the time required for the laser beam to be reflected back to the source. Based on the various arrival times a digital model of the ground surface can be generated. For the survey of the Santa Clara River study area, the aircraft flew at an above ground altitude of 700m with a 100 KHz laser pulse frequency resulting in a "point cloud" dataset with approximately 6 to 8 point measurements per square meter.

From the point cloud data a digital elevation model (DEM) with 1-meter resolution was generated and imported into the GIS dataset. To filter out vegetation and man-made objects, the minimum elevation value within each 1-meter grid was used to create the DEM. From this, hillshade relief maps (Figures 6 through 8) were derived. The hillshade map was processed with a 315° illumination angle at 30° above the horizontal.

The LiDAR hillshade map proved to be most helpful in interpreting the Main and Piru strand scarps in the alluvium. The "shadows" generated by the scarps are clearly visible in the alluvium from the western quadrangle boundary to Warring Wash channel, just west of Piru in the hillshade maps (Figure 6 through 8). The portions of the fault trace symbolized as "certain" were drawn at the base of these scarps (Figure 9).

SEISMICITY

Yerkes and Lee (1979) listed the epicenters of several earthquakes, which occurred between 1970 and 1978 in the western Transverse Ranges. Two of these events were associated with the San Cayetano and had focal plane solutions derived for them. The data indicate a fault plane dipping 40° to 58° north from approximately 6.5 to 12 km deep with slightly oblique thrust motion. A plot of seismicity ($M_L \geq 2.0$) from 1936 through 2008 (Figure 10) shows limited, low magnitude earthquakes north of the southernmost surface trace of the San Cayetano Fault. The largest event was a M4.1 with an epicenter just north of the mouth of Hopper Canyon. Rockwell (1988) points out clearly "the historic seismicity does not represent the long-term activity."

CONCLUSIONS

The surface trace of the San Cayetano Fault zone extends approximately 42 km from eastern Ojai to beyond Piru (Figure 2). The fault is a nearly pure reverse thrust fault with up to 7,500 meters of cumulative offset within the study area and a calculated slip rate of approximately 7.5 mm per year (Çemen, 1977; Rockwell, 1988). Near Hopper Canyon, the fault splits into two distinct fault strands: the Main and the Piru, which both lose stratigraphic separation and die out east of the town of Piru. West of Hopper Canyon, the San Cayetano Fault is located along the base of the mountains. Numerous scarps and breaks in slope within the Quaternary alluvium suggest this portion of the fault zone is active. Geomorphic evidence of activity across the Hopper Canyon alluvial fan, where the fault bifurcates, is mostly masked by erosion and/or deposition; however, there are some tonal contrast lineaments suggesting the presence of the fault in the shallow subsurface, which are in line with fault-related geomorphic features on either side of the canyon mouth. The Main strand, east of Hopper Canyon, is located within the foothills of the Topatopa Mountains and has not likely been active within the Holocene, based on the lack of geomorphic expression associated with active faulting. Within this area, it appears the Main strand offsets the Plio-Pleistocene Pico Member of the Fernando Formation but not the late Pleistocene terrace deposits along Piru Creek, the Holocene alluvium in Hopper, Edwards, Real, Warring or Piru Canyons or the alluvial fan emanating from Modelo Canyon (Cordova, 1956; Çemen, 1977; Dibblee, 1991). The Piru strand, however, demonstrably ruptures latest Holocene alluvium to the west of Piru (Dolan and Rockwell, 2001; Dolan, 2009) producing a well-defined scarp. The Piru strand southeast of Piru, however, is not well-defined.

RECOMMENDATIONS

Recommendations for establishing Earthquake Fault Zones are based on the criteria of "sufficiently active" and "well-defined" (Bryant and Hart, 2007).

The Main strand of the San Cayetano Fault was previously reviewed by Smith (1977) and was determined to be neither well-defined nor sufficiently active in the current study area to merit the establishment of an earthquake fault zone. Based on the interpretation of aerial photographs, LiDAR imagery, and field inspection several fault-related scarps were documented in the Quaternary alluvium along portions of both the Main and Piru strands of the fault zone. As a result, the Main strand of the San Cayetano Fault from the western quadrangle boundary along the base of the foothills to Hopper Canyon and the Piru strand from Hopper Canyon to the town of Piru should be one continuous zone (Figure 9). The segment of the Piru strand between Hopper Canyon and the town of Piru is based on geomorphic expression visible in LiDAR imagery and aerial photographs, as well as the fault studies of Dolan and Rockwell (2001) and Dolan (2009). The remaining mapped portions of the Main and Piru strands do not have geomorphic evidence to suggest activity during the Holocene and as such cannot be considered "sufficiently active". Furthermore, the Piru strand southeast of Piru is not well-defined.

Report reviewed
and approved.
Jerome
CEG 1035
3/29/12

Brian Olson
Engineering Geologist
PG 7923, CEG 2429

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AERIAL PHOTOGRAPHS REVIEWED

USDA (U.S. Department of Agriculture) b/w 1:800 (approx.)

Flight	frames	date
AXI-20	13, 15, 17, 19, 21	5/10/1938

USGS (US Geological Survey) b/w 9x9 1:24,000

Flight	frames	date
EM	3-37 to 3-39	8/16/1947

USDA (U.S. Department of Agriculture) b/w 9x9 1:24,000 (approx.)

Flight	frames	date
AXI-3K	47,181,182	1/3/1953
AXI-10K	91-94	10/3/1953
AXI-11K	10-12,72-76	10/19/1953

USGS (US Geological Survey) b/w 9x9 1:30,000 (approx.)

Flight	frames	date
GS-VCHC	1-65 – 1-70	7/25/1969

NASA (National Aeronautics and Space Administration) b/w 9x9 1:16,250 (approx.)

Flight	frames	date
04689	463-465	1/22/1994
	517-526	1/22/1994
	604-613	1/22/1994
	663-668	1/22/1994

LIST OF FIGURES