QUATERNARY INVESTIGATIONS TO EVALUATE SEISMIC SOURCE CHARACTERISTICS OF THE FRONTAL THRUST BELT, PALO ALTO REGION, CALIFORNIA:
Collaborative Research with Desert Research Institute and Geomatrix Consultants

External Award Number
01HQGR0015 (Desert Research Institute)
01HQGR0016 (Geomatrix Consultants)

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Program Element I
Key Words: Quaternary Fault Behavior, Surface Deformation, Age Dating

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ABSTRACT
Active blind and emergent faults that occur in a zone of deformation adjacent to and east of the San Andreas fault (the Frontal thrust fault system) pose a seismic hazard to communities and infrastructure in the Palo Alto and adjoining regions of the San Francisco Peninsula. Prominent expression of deformation in the landscape led to geomorphic analysis and targeting efforts for mapping of Quaternary deposits and surfaces that have been deformed across this zone. The mapping and analyses provide information that can be used to evaluate the location and activity of individual faults and the expected style of deformation that may occur in future earthquakes. This study updates and refines a model of the kinematics and geometry of faulting in this region based on preliminary Quaternary terrace mapping combined with analysis of bedrock structure and construction of a retrodeformable cross section (Angell and others, 1997). This earlier study showed that the structures in this area have been active during the latest Pleistocene and possibly the Holocene. Preliminary age estimates and vertical separations of the terraces suggested relative uplift rates of 0.15 m/kyr for the Hermit fault, 0.15 to 0.2 m/kyr for the Pulgas fault, and 0.4 to 0.6 m/kyr for the Stanford fault zone. The current study incorporates available radiocarbon analyses, detailed topographic survey data, archaeological information, and geomorphic analysis, have focused on the latest Pleistocene and Holocene terraces along San Francisquito Creek (Bullard and Hanson, 2001). Geomorphic expression of deformation across the active structures includes prominent topographic relief aligned above growing folds, warped geomorphic surfaces, stream profile inflections, and stream pattern change. Refinements of the terrace mapping in the vicinity of the Stanford Golf Course across the Pulgas fault and Stanford fault zone show that latest Pleistocene terraces are folded across the Stanford fault zone, but do not appear to be displaced across the Pulgas fault as previously thought. More detailed measurement of the vertical deformation of three terraces (Qt3b, Qt3c, and $Qt3c_L$) based on survey data and age estimates for the terraces based on correlation to the terrace at the previously dated Stanford Man II archaeological site indicate that the uplift rate across the Stanford fault zone is approximately 0.6 ± 0.05 mm/yr.

INTRODUCTION

The Frontal thrust belt system comprises a series of contractional faults adjacent to and east of the San Francisco Peninsula segment of the San Andreas fault (SAF). Quaternary tectonic activity on these faults in the vicinity of Palo Alto, California is expressed by localized deformation (folding and faulting) of Plio-Pleistocene deposits, uplift and preservation of Quaternary alluvial deposits and geomorphic surfaces, and the instrumental record of earthquake activity (Figures 1 and 2). A model of the kinematics and geometry of faulting in this region has been developed based on preliminary Quaternary investigations combined with analysis of bedrock structure and construction of a retrodeformable cross section (Angell and others, 1997) (Figure 3). This study showed that the structures in this area have been active during the latest Pleistocene and possibly the Holocene. Preliminary age estimates and vertical separations of the terraces from this earlier study suggest relative uplift rates of 0.15 m/kyr for the Hermit fault, 0.15 to 0.2 m/kyr for the Pulgas fault, and 0.4 to 0.6 m/kyr for the Stanford fault zone.

Additional geologic and geomorphic studies conducted in 2001 to 2002 utilized the established Quaternary framework to improve slip rate estimates with more detailed topographic survey data and tectonic geomorphic analyses. The results of these studies, which are described below, provide additional constraints on the location and amount of latest Pleistocene to Holocene deformation across individual faults within the Frontal thrust fault system.

DETAILED TERRACE MAPPING AND TOPOGRAPHIC SURVEY—SAN FRANCISQUITO CREEK

Longitudinal terrace and stream profiles along San Francisquito and Los Trancos creeks presented by Angell and others (1997) were constructed based on inspection of 1:24,000-scale USGS topographic maps (20-foot contour interval data) and hand-level surveys of the lower terraces at a few localities. These profiles revealed evidence for different amounts of vertical uplift across narrow zones associated with the Hermit fault, the Pulgas fault, and the Stanford fault zones. The preliminary correlation and estimates of the elevations of the older terrace remnants also suggested regions of backtilting associated with the Pulgas anticline.

Field investigations completed as part of the current study focused on refining the correlation of the latest Pleistocene and Holocene terraces along San Francisquito Creek across the Pulgas fault and the Stanford fault zone. The following data were collected and used to improve the mapping of latest Pleistocene to Holocene fluvial terraces across the entire deformation front.

1. Stanford archaeologist, Dr. Laura Jones provided available radiocarbon analyses, topographic survey data, and archaeological information on the lower Holocene terraces along San Francisquito Creek from the Pulgas fault east to the vicinity of the Stanford man site (Figure 2).

2. Pre-building construction survey and archaeological survey data provide detailed topography (contour interval of 1 and 2 ft) of terrace remnants in the Oak Creek apartment and Stanford West apartment complexes northwest of Sand Hill Road east of the bridge crossing San Francisquito Creek.

3. Detailed mapping of the terraces within the Stanford Golf Course was completed from just upstream of the Pulgas fault eastward across the Stanford deformation zone (Plate 1). Terrace heights measured using a stadia rod and hand level provided preliminary elevation data that was used to supplement more detailed topographic survey data.

4. A series of longitudinal and cross valley profiles were measured using a Nikon DTM 450 total station to more accurately map the heights of latest Pleistocene to Holocene terrace remnant along San Francisquito Creek across the Pulgas fault and Stanford deformation zone. Measured elevations from this survey are shown on Plate 1.

Four low terraces (Qt3a, Qt3b, Qt3c, and Qt3d) and undifferentiated additional terraces present within the narrow modern fluvial channel (designated as Qt3y) were previously mapped by Angell and others (1997) along this reach of San Francisquito Creek. The additional mapping and detailed topographic profile data from the more recent studies provide an improved basis for correlating terraces across the Pulgas fault and Stanford fault zone deformation front. Terrace correlation is based largely on the elevation above base (creek) level, relative altitudinal spacing, and, to a lesser degree, general geomorphic characteristics of the terrace remnants. An updated map showing the distribution of terraces along San Francisquito Creek in the vicinity of the Pulgas fault and Stanford fault zone is shown on Plate 1. Longitudinal and cross valley profiles showing the continuity and altitudes of terrace remnants in this area are shown on Figure 4.

DESCRIPTION OF TERRACES

Five terraces are differentiated on Plate 1 (oldest to youngest: Qt3a, Qt3b, Qt3c, $Qt3c_L$, and Qt3d) and are described below. Younger terraces incised below Qt3d were observed locally, but were not mapped in detail. Upstream of the Pulgas fault at the confluence of Los Trancos Creek and San Francisquito Creek, three lower terraces at altitudes of 1.37 m (bedrock strath), 3.57 m, and 4.88 m were measured along Los Trancos Creek (Figures 1 and 5). Downstream of the Pulgas fault at field locality P11, terraces at 0.48 m, 1.13m, and 2.26 m were measured below the 6.1 m –high Qt3d terrace (Figure 2).

Along most of San Francisquito Creek upstream of the Pulgas fault the channel is scoured to bedrock. Modern alluvium (Qa) in this reach generally consists of thin (<1 m) laterally discontinuous bar and point bar deposits that exist only locally and generally are associated with the tight bends in the river channel, such as at the western base of Jasper Ridge, at the tight bend west of Highway 280, and north of the confluence with Los Trancos Creek (Figure 1). Downstream of the Pulgas fault bedrock is much more scarce. The north-easternmost outcrop of bedrock in the channel of San Francisquito Creek occurs approximately 300 m downstream of Junipero Serra Boulevard (Plate 1). The top of bedrock exposed in the left bank of the stream for a distance of approximately 25 m is 3.4 m above the modern channel.

Qt3a terrace

Qt3a terrace remnants are mapped along both San Francisquito and Los Trancos creeks. As described by Angell and others (1997) the Qt3a terrace along San Francisquito Creek consists of discontinuous isolated remnants that are 18 to 30 m (60 to 100 feet) above the creek, with heights increasing upstream across the Hermit fault. A broad, continuous Qt3a terrace occurs near the confluence of San Francisquito and Los Trancos creeks. The Qt3a terrace is relatively continuous in the upper part of Los Trancos Creek. A remnant of the Qt3a terrace is mapped along San Francisquito Creek south of Junipero Serra Road. Based on elevation contours from the 1:24,000 USGS quadrangle map, the altitude of this terrace remnant is 58 ± 3 m (190 ± 10 ft) (Plate 1). Remnants of the terrace have not been recognized north of the Pulgas fault. Few natural exposures of intact Qt3a deposits occur in the area; however, near the intersection of Sand Hill and Whiskey roads small exposures show rounded gravel and cobbles unconformable on the underlying bedrock unit (mapped as Whiskey Hill Formation by Pampeyan, 1993).

Qt3b terrace

Qt3b is the most extensive terrace along both San Francisquito Creek and the lower part of Los Trancos Creek. It forms a narrow, relatively continuous surface that lies along the margins of the valley floor approximately 11 to 12 m (35 to 40 ft) above the creek channel. Outcrops on the north side of Alpine Road near the confluence of Los Trancos Creek and San Francisquito Creek show well-rounded gravel up to 20 cm b-axis diameter resting on bedrock mapped by Pampeyan (1993) as the Miocene Page Mill Basalt and Ladera Sandstone. A well-developed soil having a reddened B_t horizon (7.5YR to 5 YR hue) at least 1 m thick is formed on the Qt3b deposits. Qt3b is well preserved along the northwest side of San Francisquito Creek west of the confluence with the Los Trancos Creek and along both sides of the creek between its confluence with Los Trancos Creek and the range front. A remnant of this terrace on the west side of the creek just upstream (south) of the Pulgas fault was previously mapped as part of Qt3c (Angell and others, 1997). Maintenance and office facilities for the Stanford Golf Course and Stock Farm horse ranch occupy this terrace directly northeast of the Pulgas fault (which approximately coincides with Junipero Serra Road in the vicinity of the golf course). The terrace, which is monoclinally folded across the Stanford fault zone, can be traced into the vicinity of the Stanford mall where it merges with the broad undifferentiated Qoa fan surface.

Qt3b is a fill terrace composed of poorly sorted, matrix-supported alluvium. Deposits within the upper part of this terrace were partially exposed in a golf course trail cut leading up from the bridge between hole 4 and tee 5 on the golf course (Figure 6; P13, Plate 1). At this location, approximately 8 m (about 26 ft) of poorly sorted matrix-supported gravelly alluvium overlies an irregular erosional surface cut on bedrock that dips 65° to 75° southeast. A well-developed soil is present on the Qt3b surface. Although the Qt3b terrace surface has been modified to varying degrees within the Stanford Golf Course, locally there are areas within the Golf Course where the original surface does not appear to be significantly modified.

Qt3c and Qt3c$_L$ terrace

Angell and others (1997) identified Terraces Qt3c and Qt3d as a closely spaced couplet that could be mapped from the northern margin of Jasper ridge to the confluence of Los Trancos Creek. They mapped the Qt3c and Qt3d terraces west of the Hermit fault at heights of approximately 12.2 and 9.1 m (40 and 30 ft), respectively, above the modern channel. The terraces east of the Hermit fault were judged to be slightly lower, at approximately 7.6 and 6 m (25 and 20 ft), respectively. Detailed surveying of the terraces to confirm the correlations across the Hermit fault were not completed as part of this study.

Based on more detailed mapping and survey data in the vicinity of the Pulgas fault and Stanford deformation front, we have differentiated Qt3c, a slightly lower terrace that we refer to as Qt3c$_L$

and Qt3d. Terrace Qt3c remnants occur at heights of approximately 9 to as much as11.2 m above present stream level where they cross the axis of an active anticline in the hanging wall of the Stanford fault zone. The broad monoclinal flexure in the terrace across the Stanford fault zone is preserved east of Sand Hill Road downstream of the Sand Hill Road bridge crossing. The Qt3c surface broadens into a more general fan shape from this point eastward. The more distal parts of the fan merge with the older Qt3b surface to the east and the contact is only approximately known. Incision by younger drainages has modified both the upper surfaces of the Qt3b and Qt3c terraces and the contact between them.

The $Qt3c_L$ terrace is about 1 m lower than Qt3c. Terrace remnants adjacent to and downstream of the Pulgas fault previously mapped by Angell and others (1997) as undifferentiated Qt3y correlate to terraces $Qt3c_{L.}$ and Qt3d. The Qty surfaces mapped by Angell and others (1997) in the Oak Creek apartment complex area are interpreted to be the $Qt3c_L$ terrace surface monoclinally warped across an en echelon trace of the Stanford fault zone that is offset slightly to the north of the monoclinal flexure east of Sand Hill Road (Plate 1). The $Qt3c_L$ surface continues to the east into the Stanford West apartment complex. In the Stanford West complex, bones (Stanford Man I) collected at a depth of 6.1 m were dated at 5130 ± 70 ^{14}C years B.P.) and bones (Stanford Man II) collected at a depth of 5.2 m were dated at 4350 ±135 ^{14}C yr B.P and 4400 ± 270 ^{14}C yr B.P. Calibrated ages for these samples are provided in Table 1. The deposits associated with this surface are well exposed at field locality P8, which is located at the western end of the Stanford West complex area (Figure 2). The stratigraphic sequence at this locality is shown in Figure 7. The upper 3.74 m unit is a massive fine to medium sand with scattered pebbles that represents cut and fill into an approximately 1 m thick older fine-grained unit having an organic rich layer with abundant charcoal. This unit overlies a basal poorly sorted, pebble to cobble gravel unit. The organic layer lies at a depth slightly less but comparable to the radiocarbon dated samples from the Stanford Man II site further to the east. Based on these relationships, the $Qt3c_L$ terrace is inferred to be approximately middle Holocene in age (5 ka).

Qt3d terrace

The Qt3d terrace remnants mapped upstream of the Sand Hill bridge crossing are 6 to 7 m above the level of the present stream channel. They are best expressed along the stretch of San Francisquito Creek between the Pulgas fault and Sand Hill Road. Terrace remnants inset below the Qt3c terrace were noted upstream of the Pulgas fault, but they were not differentiated on the map. Directly upstream of the Pulgas fault a possible terrace remnant of the Qt3d terrace, which is occupied by a large oak at the border of one of the heavily modified golf greens, is at a height of 7.26 m above present level. Due to the extensive modification of the area in the vicinity of the tee at this location, the height of the terrace is questionable.

Downstream of the Sand Hill bridge, terrace heights of approximately 7.3 m (P4 and P6) and 7.9 m (P7) were measured from stream level up to the highest prominent terrace adjacent to the creek on the right (southeast) bank. The 7.3 m high remnants are tentatively correlated to the Qt3d terrace. The higher terrace surface at field locality P7 likely is the $Qt3c_L$ terrace.

Stratigraphy in the Qt3d terrace at field station P8 is shown on Figure 7. Approximately 1.5 m (5 ft) of imbricated, upward-fining gravel at the base of the exposure (unit d of Figure 7) is overlain by a package of about 2.5 m (8 ft) of weakly cross-bedded fine to medium sand (unit c of Figure

7). At the contact of the gravel and sand unit, a thin (15 to 20 cm) darkened horizon contains fragments of organic material and charcoal. A sharp erosional contact and remnants of a weakly developed soil (B_w to B_{tj} horizon about 20 cm thick) appears at the top of the sand unit (b of Figure 7). Approximately 4 m (13 ft) of primarily massive, poorly to moderately sorted fine to medium grained subangular sand, silty sand, and 5 to 15 cm thick gravel lenses overlie the erosional contact (unit a of Figure 7). Small paleochannels in unit a (Figure 7) contain a basal pebble lag and evidence of weak bedding as thin interbeds of fine sand and silt. Figure 7 also shows the lower inset terraces that are present throughout the system.

Longitudinal Terrace Profiles

The detailed survey of stream terraces along San Francisquito Creek was performed on February 21-22, and March 25-26, 2002, using a Nikon DTM 450 total station. The survey was registered to the "Sherwood" benchmark[1], National Geodetic Survey Benchmark B151, elevation 144.67 ft (NAD 1927). Measured elevations are shown on Plate 1. Terrace profiles were constructed using only data obtained from this survey, with the exception of Profile 3 (Figure 4). The north end of Profile 3 was extended to the north to incorporate the broad surface of the Qt3c terrace north of and below the monocline shown on Plate 1. We used topography from the US Geological Survey 7.5 minute Palo Alto Quadrangle and from a site-specific survey of the Stanford West Apartment Complex (Received March 22, 2002) to extend Profile 3. Elevations of contours from the Palo Alto Quadrangle were raised 1.22 meters (4 feet) to account for discrepancies between those contours, topography from the Stanford West Apartment Complex, and the survey done for this study. This adjustment removes artificial steps in the profile, and provides a smoother profile that more accurately reflects topography observed in the field.

Additional elevation control for terraces and stream base level was obtained from surveys using a stadia rod and hand level. The elevation of the modern stream channel was estimated at several locations using data from the hand surveys and the total station survey points. The height of terrace remnants above modern stream level as measured from the hand surveys is indicated for selected field stations on Plate 1.

Three topographic profiles (Figure 4) were constructed to illustrate relationships among the various terraces and locations of Quaternary deformation. Locations of the profiles are shown on Figure 2. Profiles 1 and 3 are longitudinal profiles constructed on terraces Qt3b and Qt3c, respectively, across the Stanford deformation front. Profile 2 is a cross valley profile showing the relative elevation of the two terraces and a younger terrace Qt3d in the vicinity of the Stanford Golf course due east of the Pulgas fault.

In both Profile 1 and 3, deformation of the terraces is expressed chiefly as broad fold. The most prominent feature in each of these profiles is the east-facing monoclinal flexure associated with the Stanford deformation front. The older Qt3b terrace surface appears to be vertically displaced approximately 5 to 8.3 m across the deformation front. Mapping this terrace surface east of the profile is complicated by a number of factors: the more distal parts of the Qt3b and Qt3c surface appear to merge and are more difficult to differentiate on the footwall block of the Stanford fault

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[1] We refer to this benchmark as "Sherwood" because it is mounted into the base of a statue of a horse named Sherwood adjacent to the main maintenance buildings for the Stanford Golf Course.

zone, channel incision and construction activities related to the Stanford shopping mall have disrupted the original terrace surface. The apparent slight dip in the Qt3b surface between 400 and 600 m distance likely is related to post-terrace incision.

The Qt3c profile (Profile 1) shows a similar pattern of deformation across the deformation front. The total vertical displacement across the east-facing monocline appears to be slightly less (3 to 5 m). Slight inflections in the profile are noted at distances of 925, 1150, and 1550 (indicated by arrows on Figure 4). The inflection at 925 may result from post-terrace gullying and incision. However, topographic relationships in the nearby Oak Creek apartment complex west of Sand Hill Road suggest that a secondary tectonic scarp may project into this area. The topographic inflection at 1150 marks the base of the primary monoclinal flexure. The inflection at 1550 lies along the projected trend of the northernmost trace of the deformation front that is better expressed west of Sand Hill Road (Figure 2). If tectonic, the subtle expression at the distance of 1550 suggests this trace is dying out to the east. Major displacement appears to step southward to the major flexure shown on Profiles 1 and 3.

Profile 3 also shows an apparent secondary fold (anticline) in the hanging wall of the Stanford fault zone that is centered approximately 700 m from the southwest end of the profile. Although somewhat modified by construction of the golf course holes and fairways, this topographic anomaly appears to extend east from Profile 3 a distance of approximately 200 m. The anomaly, however, is not readily apparent in Profile 1 suggesting that the structure is dying out in this direction.

Profile 3 extends across the Pulgas fault, and as shown on Figure 4, there is no indication of vertical deformation of the Qt3c terrace across this fault. The apparent vertical displacement noted by Angell and others (1997) across this fault zone resulted from miscorrelation of terrace remnants across the fault. Based on the more detailed mapping conducted for this study, the upper part of a terrace previously mapped as Qt3c is now correlated to Qt3b. The relative heights of both terraces Qt3b and Qt3c above present stream level do not vary significantly across the Pulgas fault, suggesting that the fault has not been active in the latest Pleistocene to Holocene.

Based on pre-development topography the Qt3cL terrace is vertically displaced about 3 m across the monoclinal flexure in the Oak Creek apartment complex.

GEOMORPHIC ANALYSIS

In the study area, tectonic deformation has notably affected many geomorphic features. We used regional-scale geomorphic features to quantify the relative magnitude deformation and to help identify other subtle geomorphic indicators of tectonic activity that could then be investigated in the field. The geomorphic expression of deformation in the area includes abrupt changes in topography and alignments of positive topographic features, changes in stream gradient, changes in stream pattern, and deformed geomorphic surfaces. The behavior of stream systems in tectonic environments is particularly important and applicable to this study. The behavior of streams has been shown to reflect tectonic activity to the extent that characterizing the stream morphometry of a region can help to identify potential locations of active or recent deformation and reveal clues regarding tectonic framework and styles of deformation (e.g., Bull and

McFadden, 1977; Keller and Rockwell, 1984; Schumm, 1986; Wells et al., 1988; Bullard and Lettis, 1993; Keller and Pinter, 1996; Bullard, 2002; Schumm et al., 2000). For example, spatial change in stream gradient and stream network development may reflect the location and magnitude of regional tilting (e.g., Hare and Gardner, 1985; Merritts and Vincent, 1989; Merritts and Hesterberg, 1994). Abrupt changes in stream gradient and stream network development may indicate locations of active structures, in particular active faults and folds (Burnett and Schumm, 1983; Ouchi, 1985). Because gradient and channel pattern are commonly related (e.g., Knighton, 1998; Ritter et al, 2002), measurable changes in stream gradient and channel pattern can provide a measure of spatial variation in location and magnitude of disturbance. This study was cognizant of factors that are capable of complicating the interpretation of geomorphic data, such as the potential effects of lithology (e.g., Hack, 1973) and climate change on hydrology, sediment yield, and geomorphic processes (e.g., Bull, 1991; Pazzaglia et al., 1998). For example, during field investigations, attention was given to the thicknesses and distribution of depositional units over bedrock strath surfaces that may result from geomorphic responses to climate change, such as an increase in sediment load that provokes aggradation and might tend to diminish or inhibit channel incision in response to uplift (e.g., Pazzaglia et al., 1998).

Geomorphic analyses for this study included stream morphometry (longitudinal profile, stream gradient, and channel pattern), assessing spatial differences in stream incision across the piedmont, and topographic analysis (slope maps, drainage asymmetry to detect block tilting) (e.g., Keller and Pinter, 1996) including techniques designed to highlight geomorphic indicators of longer-term surface deformation (topographic envelope and subenvelope maps and derivative products such as the topographic residual map) (e.g., Bullard and Lettis, 1993).

Figure 8 summarizes the results for selected morphometric analyses including the topographic envelope-subenvelope-residual results. Relief associated with long-term deformation can be depicted by the topographic residual, which is obtained by contouring the differences between the topographic subenvelope and the envelope tangential to the land surface. The general premise is that in a tectonic environment, the difference in relief between a hypothetical enveloping surface and a surface tangential to stream channels (the topographic residual) represents a measure of the magnitude of tectonic uplift (Stearns, 1967; Bullard and Lettis, 1993; Golts and Rosenthal, 1993) assuming that downcutting keeps pace with uplift. The distribution of the topographic residual, commonly depicted as contoured data, provides a sense of the location and activity on underlying geologic structure. When the residual map is compared with the tectonic map of the area, the residual highs are approximately aligned with mapped fold axes (Angell and others, 1997).

Shaded reaches of San Francisquito, Los Trancos, and Matadero creeks (shown on Figure 8) depict areas of stream gradient and channel sinuosity values that are distinctly greater than the gradient and sinuosity of adjacent upstream and downstream reaches. Field reconnaissance indicated possible spatial variability in depth of stream incision; however, prior to the detailed mapping it was not possible to make accurate measurements. The locations of these identified reaches of higher gradient and high sinuosity are approximately coincident with axes of long-term deformation (e.g., Telescope ridge area; Hermit Fault, etc) and areas northeast of the deformation front on the northern edge of the Stanford fault zone. In studies of fluvial response to contractional deformation Burnett and Schumm (1983) and Ouchi (1985) found that the zone of influence on fluvial processes extends upstream and downstream of the axes of deformation. Depending upon the spatial relation to the underlying structure, streams may incise or agrade and a number of complex geomorphic responses related to changes in gradient and sediment load may follow (e.g., Schumm, 1977, 1986).

As previously noted, factors other than tectonic deformation can result in variable depths of incision and changes in stream gradient and sinuosity, and further investigation is necessary to distinguish the causative factors. For example, increases in gradient can result from a variety of causes including local base level change, resistant bedrock, aggradation or incision, or tectonic deformation. Similarly, sinuosity can be influenced by a number of fluvial geomorphic factors including discharge, sediment load, and change in slope.

In the study area, proximity to sea level and documented change in Holocene climate may play a role in geomorphic responses and fluvial behavior to the extent that a definitive cause for changes in sinuosity and stream gradient cannot be demonstrated without additional detailed stratigraphic and stream analyses; however, the association of fluvial geomorphic anomalies with known structural features strongly suggests a relation between the geomorphology and deformation. We have attempted to take into consideration variability in bedrock through the area. Bedrock is relatively homogeneous north of the Oak Creek Apartments (north of the Pulgas fault zone) and is relatively variable south of the Pulgas fault zone. The association of known structures with fluvial geomorphic indicators rather than bedrock type suggests that tectonic deformation exerts a stronger control on fluvial geomorphology than bedrock type does.

STYLE AND RATE OF QUATERNARY DEFORMATION

The results of the studies described above provide better constraints on the location and amount of Quaternary deformation associated with the Frontal thrust system in the vicinity of Palo Alto.

- The Pulgas fault was modeled by Angell and others (1997) as a reactivated normal fault in the hanging wall of the Stanford fault zone that was accommodating some of the contractional strain across the Foothills thrust system. Based on more detailed mapping and profiling of late Pleistocene terraces across this fault zone, there is evidence of no vertical deformation of terraces Qt3b and Qt3a across the Pulgas fault, suggesting that this fault has not been active in latest Pleistocene to Holocene time.

- The major locus of activity in latest Pleistocene to Holocene time has been across the Stanford fault zone, which is expressed at the surface by a broad monoclinal flexure in the majority of the field area (the region of Figure 2 southeast of the Oak Creek apartment complex). Vertical displacement of the Qt3b terrace, estimated to be ~15 ka (Angell and others, 1997), across the monocline is 5 to 8.3 m. The younger Qt3c terrace appears to be displaced slightly less (3 to 5m). No direct ages are available for either of these terraces.

- The $Qt3c_L$ terrace, which is estimated to be approximately 5 ka based on radiocarbon dates from the Stanford Man 'II' locality, is displaced approximately 3 m vertically across the major trace of the deformation front in the Oak Creek apartment complex. The uplift rate across the deformation front implied by the estimated age and deformation of the $Qt3c_L$ terrace is 0.6 ± 0.05 mm/yr.

- The en echelon step in the monocline in the vicinity of Sand Hill Road roughly coincides with a north-trending fault inferred from geophysical data as reported by Oliver (1990) (Plate 1 in Angell and others, 1997).

- Ages inferred for the Qt3c and Qt3b terraces based on the slip rate estimated from the $Qt3c_L$ terrace and the range of vertical offset are 5 to 8.3 ka and 8.3 to 14 ka, respectively. There remain uncertainties in the correlation of the terrace surfaces to the sediments within the Stanford West Apartment complex area that were sampled at depth and dated with radiocarbon analysis. Limited exposures along San Francisquito Creek near the boundary between the Oak Creek and Stanford West apartment complexes indicate that sediments that likely correlate to the dated material (Stanford Man II) lie beneath a buried soil. We assume that the overlying sediments correlate to the Qt3d terrace, but additional dating is needed to confirm this assumption. Further investigation is needed to verify the preliminary ages inferred for the Qt3c and Qt3b surfaces. These studies would include soil test pits on selected surfaces to evaluate relative ages and soil profile development and to provide exposures for sampling of radiocarbon dating

STRUCTURAL MODEL

The style and geometry of deformation exhibited in the Palo Alto region are consistent with localized transpression due to both local and regional contractional discontinuities and/or asperities along the San Andreas fault (Angell and others, 1997) (Figure 1). Alternative structural models have been presented by McLaughlin and others (1996, 2000) and Angell and others (1997) to explain the structural relationships between the northeast-vergent thrust faults of the Frontal thrust fault system and the San Andreas fault. The faults in the Palo Alto region play an important role in the northwest-tapering geometry of the Foothills thrust fault system, because they coincide with an apparent transfer oblique slip between outlying thrust faults and steeply-dipping faults adjacent to the San Andreas fault. This mechanism produces a distinctive, style of deformation that is observed at both the northern end of the Monte Vista thrust fault where it interacts with the Hermit fault, and the northern end of Jasper Ridge, where the southern Hermit fault interacts with the northern Hermit fault (also known as the Cañada fault) (Figure 1). We infer that these complexities in the Hermit and Monte Vista faults represent regions where oblique slip is transferred from an “outlying” fault such as the Monte Vista fault to a fault segment more closely linked to the strike-slip deformation on the San Andreas fault proper. The reverse component of slip either is consumed by folding in the hanging wall of the outlying fault (e.g., Arastradero and Hermit anticlines), or is transferred to another portion of the fault system. Gravity and magnetic data recently obtained by the USGS can be used to test the proposed structural models. Preliminary modeling of these data by the USGS (V. Langenheim, written communication, August 2000) and comparison to calculated profiles based on the structural cross section presented by Angell and others (1997) suggests that the structural model proposed by Angell and others (1997) (Figure 3) may need to be revised. Re-evaluation of the structural model using the new geophysical data, combined with updated seismicity data for the area is needed to provide constraints on reasonable seismic source characterization models that can be incorporated into seismic hazard analyses.

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TABLES

Table 1. Radiocarbon ages and calibrated ages in years Before Present for three samples contained in alluvium at the Stanford Man II archaeological site

Sample Number	Material Analyzed	Quaternary Unit	Radiocarbon Age, yr BP	Calibrated Age, yrBP, (2 sigma)
UCLA-1425A	Stanford Man II, bone, 5.2 m depth in alluvium	$Qt3c_L$	4400 +/- 270	4259 – 4269 4283 – 5653
UCLA-1425B	Stanford Man II, bone, 5.2 m depth in alluvium	$Qt3c_L$	4350 +/- 135	4533 – 4536 4548 – 4558 4569 – 5315
SMA-269	Stanford Man I, bone, 6.1 m depth in alluvium	$Qt3c_L$	5130 +/- 70	5661 – 5672 5679 – 5688 5707 – 5996 6080 – 6089 6101 – 6105 6151 – 6166

FIGURES

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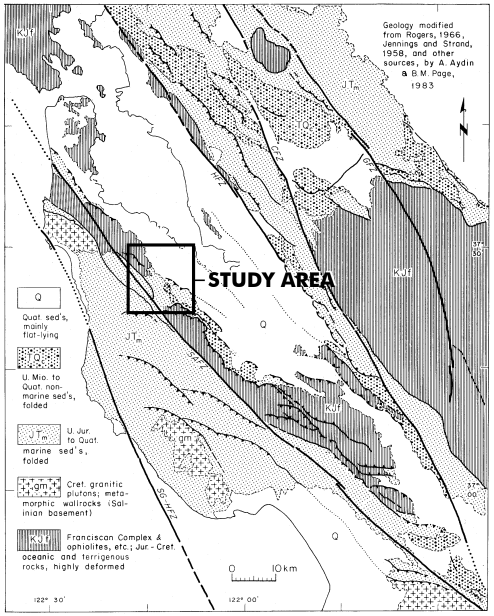
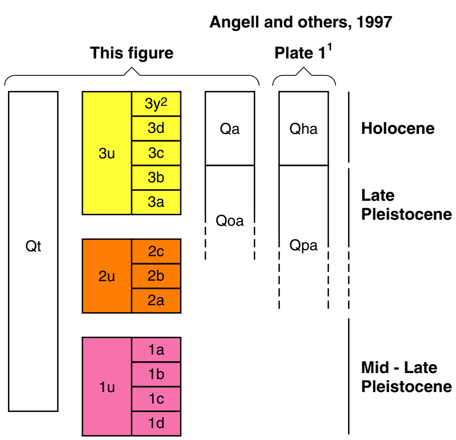


Correlation of Quaternary Units



[1] from Helley and Lajoie, 1979

[2] San Francisquito Creek longitudinal profile B only.

MAP SYMBOLS

Fault Arrow indicates dip direction of high-angle reverse fault; teeth on upper plate of thrust fault; half arrows indicate sense of lateral slip; dashed where approximately located; dip in degrees

Scarp Ticks indicate slope direction of scarp face; x's indicate bedrock scarp along range front; deformation front defined by northeastern-most scarps in alluvium.

Ridge Topographic feature within alluvial deposits northeast of range front. Locally coincident with anticlinal structures and reverse faults.

Basin Circular to elongate localized depression within alluvial deposits northeast of range front and southwest of deformation front; contains fine-grained, "ponded" alluvial deposits.

Terrace Fluvial terrace geomorphic landform; circles indicate presence of gravel on Qt2 and Qt1 surfaces; dashed where uncertain.

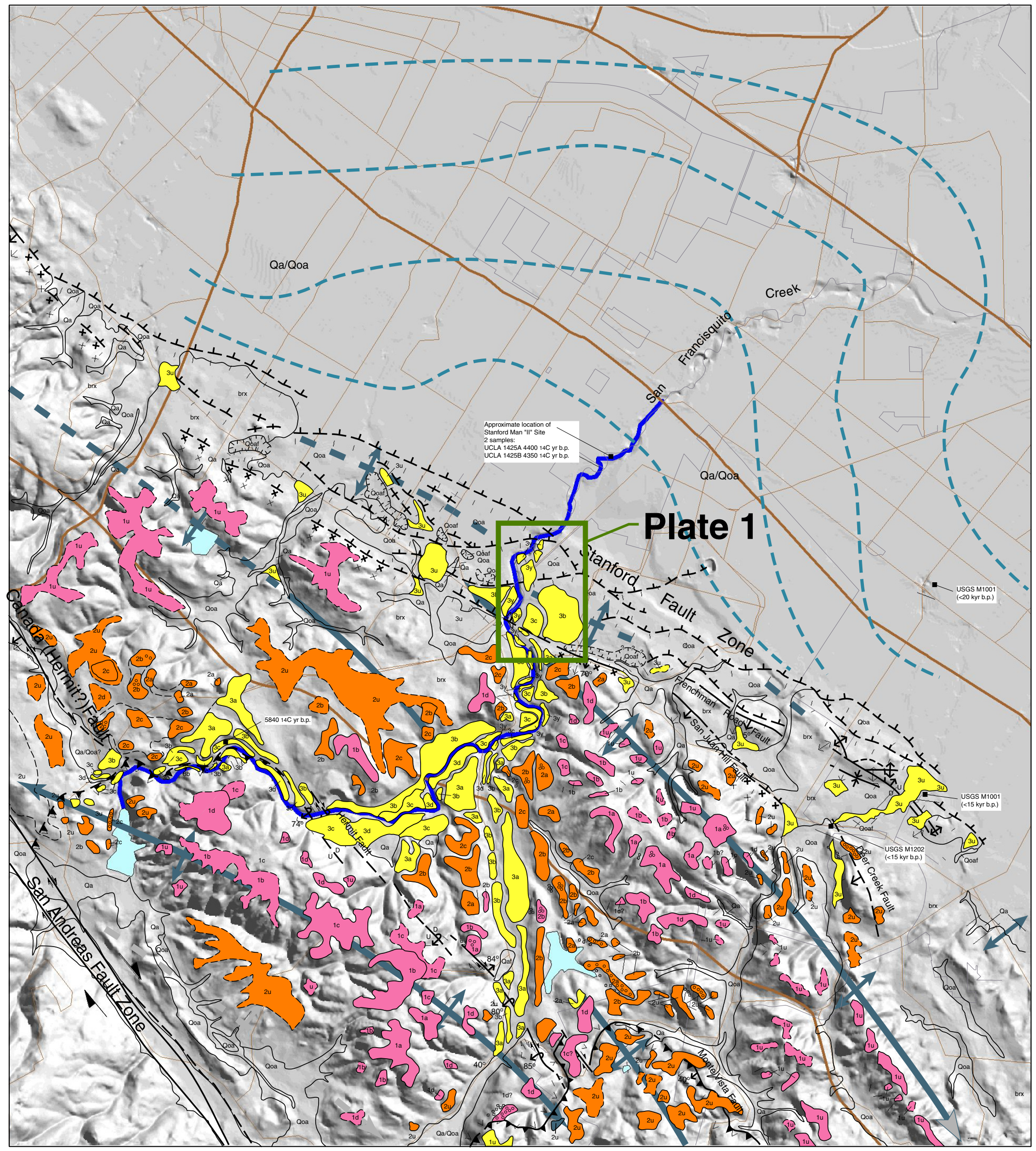
Uplift Axis Approximate axis of Quaternary uplift defined by distribution of Quaternary landforms, deposits and structural features; dashed where uncertain.

Anticline Location of Quaternary anticline defined by structural data within Quaternary alluvium.

Syncline Location of Quaternary syncline defined by structural data within Quaternary alluvium.

Generalized contours of San Francisquito Creek alluvial fan; represents late Pleistocene fan surface.

Age-date sample locality



(from Plate 2, Angell and others, 1997)

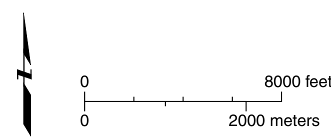
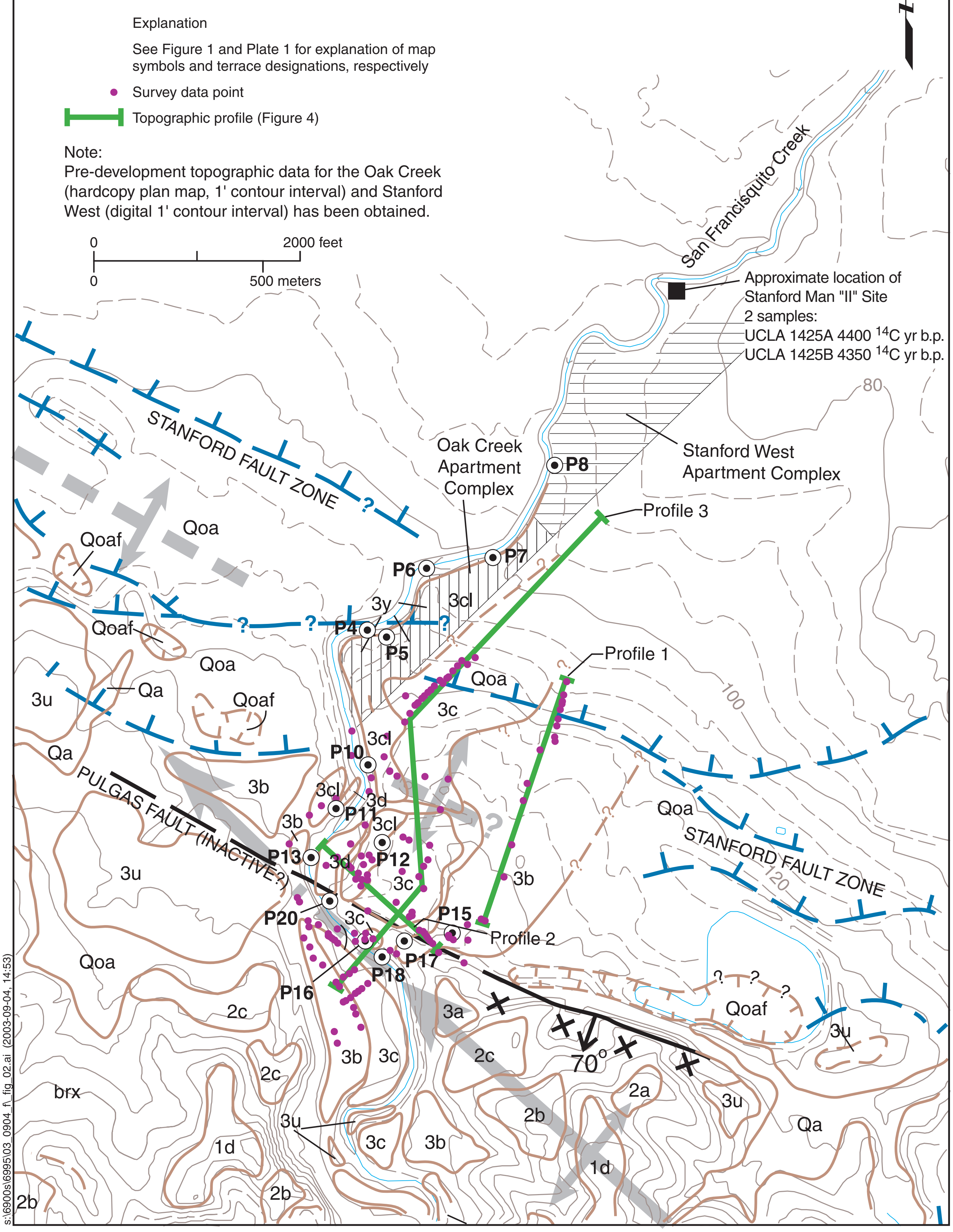


Figure 1. Location of study area and the Quaternary geology of the Palo Alto quadrangle

Figure 2
Quaternary geology of Frontal thrust fault system at San Francisquito Creek



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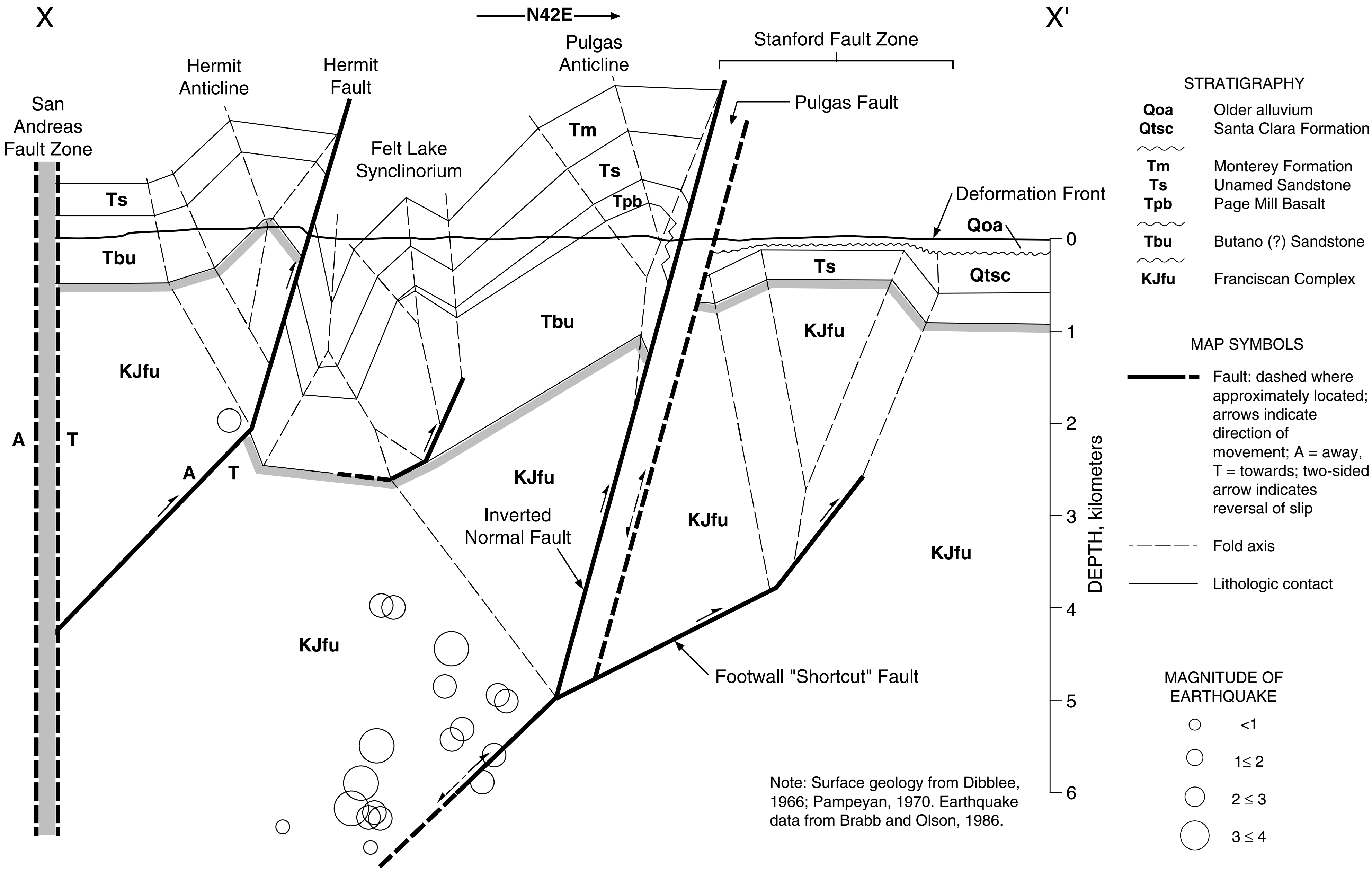
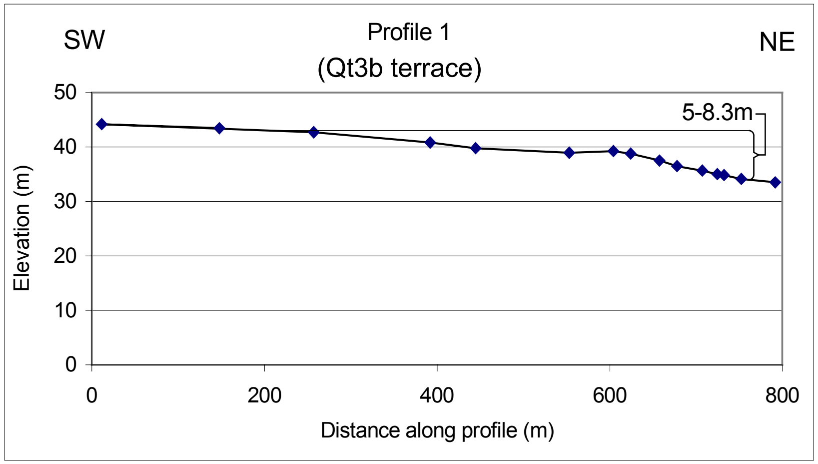
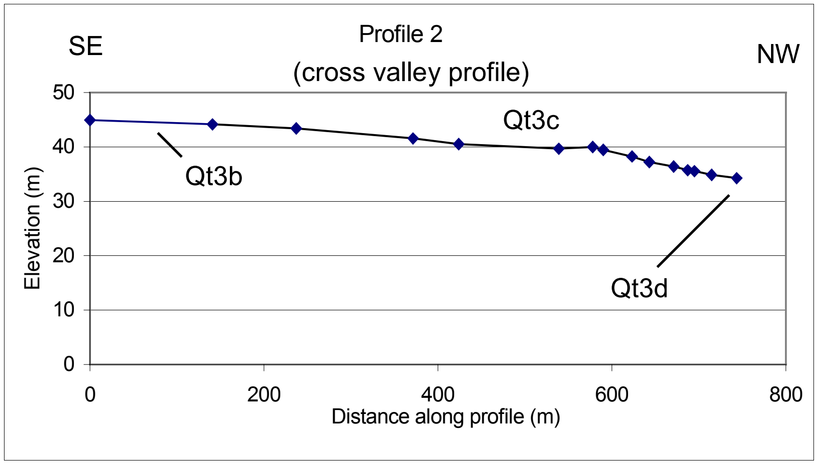
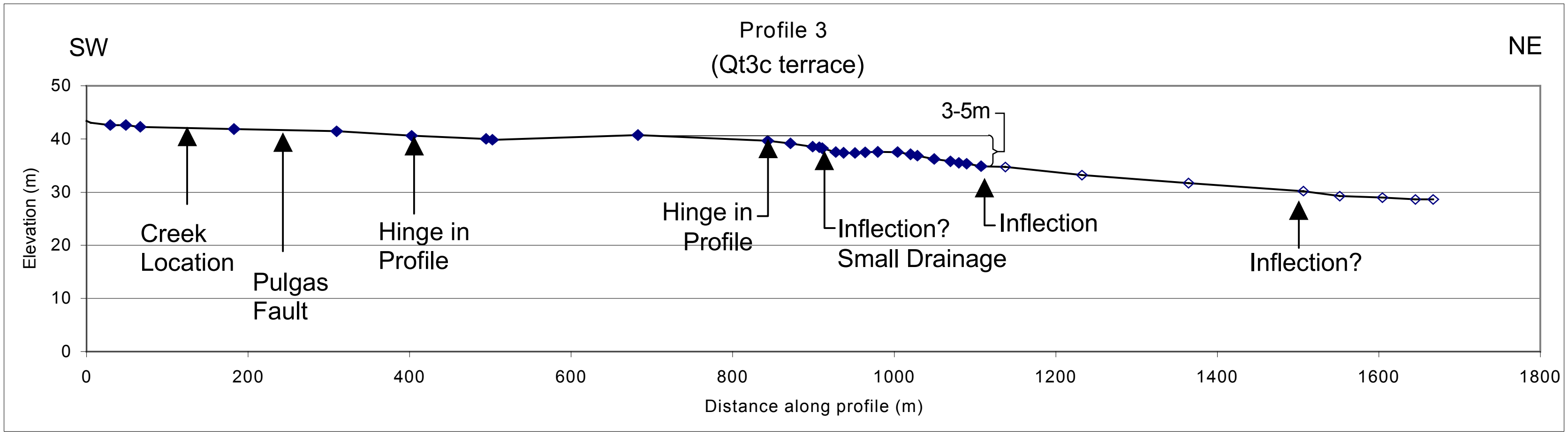


Figure 3. Regional cross section X - X' from Woodside to Palo Alto (from Angell and others, 1997)







◆ Measured elevation (Total Station Survey)

◇ Elevation from U.S.G.S Palo Alto 7.5' topographic quadrangle (corrected to control bench mark), and survey data from Stanford West Apartment Complex

Notes:

1) Survey elevations are registered to "Sherwood" benchmark; NGS Benchmark B151, elevation 144.67 (NAD 29)
2) Contour elevations from U.S.G.S Palo Alto 7.5' topographic quadrangle were adjusted upward 1.22 meters (4 feet) to match survey done for this study and survey from the Stanford West Apartment Complex.

Figure 4: Profiles of stream terraces along San Francisquito Creek. Profile locations are shown on Figure 2.

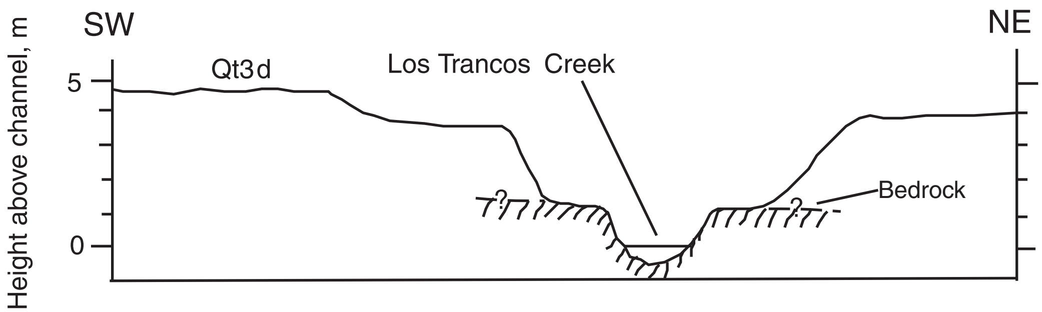


Figure 5: Topographic profile across Los Trancos Creek near the confluence with San Francisquito Creek showing about 1.5 m of channel incision into bedrock.

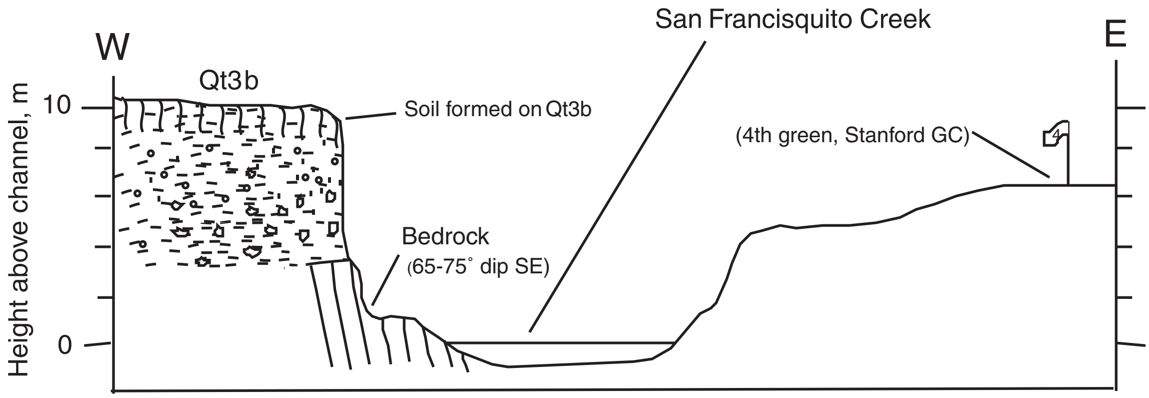


Figure 6: Topographic profile across San Francisquito Creek near the point where the trace of the Pulgas fault crosses. Channel incision into steeply dipping bedrock is observed at this site near the 4th green of the Stanford Golf Course. About 6 m of poorly stratified deposits overlie a bedrock erosional surface approximately 3 m above the modern channel. A soil having a well-developed Bt horizon is formed on the deposits, which we identify as Qt3b.

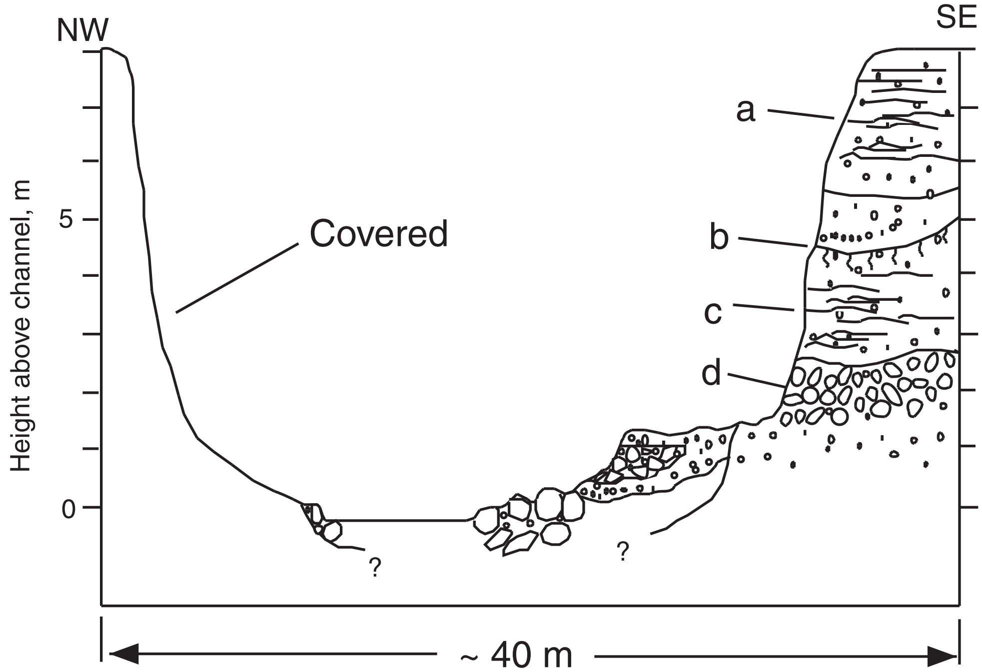


Figure 7: Composite Stratigraphic Section At Field Station P-8, San Francisquito Creek

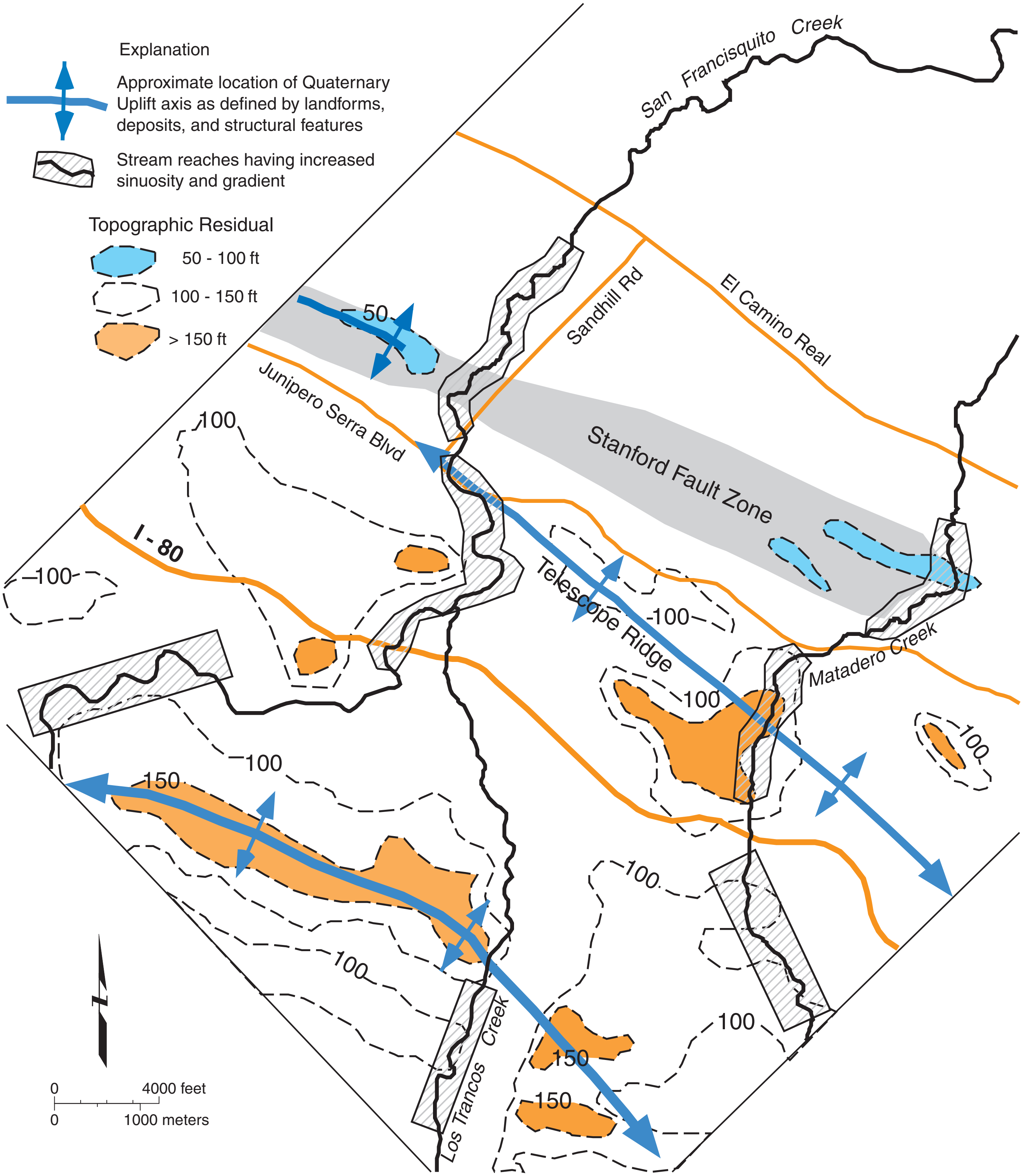


Figure 8. Summary of tectonic geomorphic analyses carried out in the region. Shaded reaches of San Francisquito, Los Trancos, and Matadero creeks depict areas of stream gradient and channel sinuosity values that are distinctly greater than the gradient and sinuosity of adjacent upstream and downstream reaches. These reaches approximately coincide with axes of long-term deformation (e.g., Telescope ridge area; Hermit Fault, etc), areas northeast of the deformation front, and the zone of monoclinal folding on the north edge of the Stanford fault zone. Results of the topographic envelope-subenvelope-residual map analysis show axes of long-term uplift coincident with mapped structures as well as a zone of deformation in the vicinity of the Stanford fault zone.

PLATES

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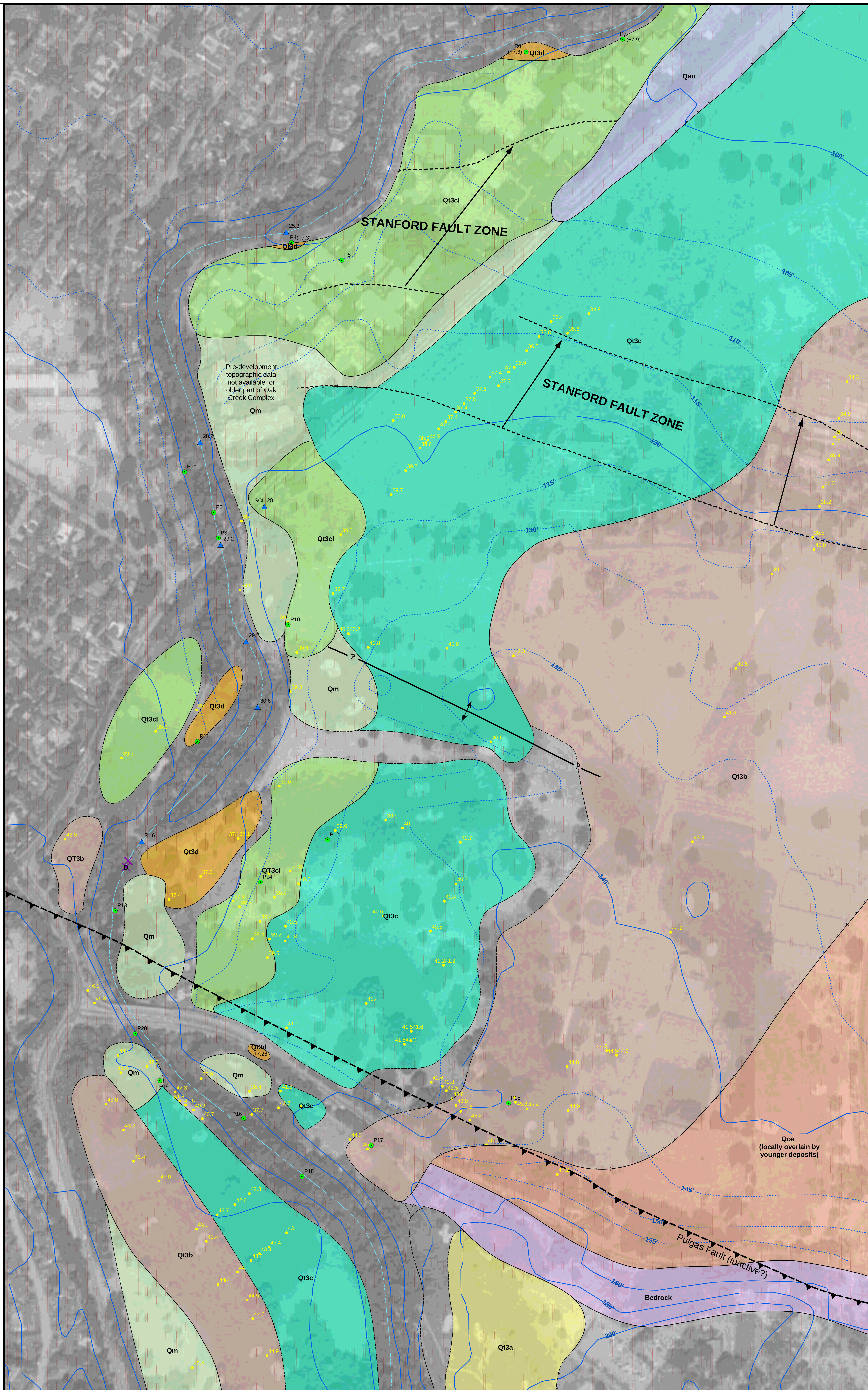

Explanation

Unit	Description
Qm	(disturbed or signifcantly modified)
Qau	(undifferentiated younger alluvium)
Qt3d	
Qt3cl	
Qt3c	
Qt3b	
Qt3a	
Qoa	
Bedrock	(X indicates bedrock outcrop)

- Thrust fault
- Anticline, queried where uncertain
- Monocline, arrow towards base of inflection in slope
- Terrace boundary, dashed where approximate, queried where uncertain
- San Francisquito Creek
- 31.6 Approximate elevation of stream (meters)
- (+7) Field stations (height of terrace above stream channel, meters)
- Surveyed elevations (meters)

0 50 100 Meters

Notes:
1. Contours (blue lines) are from the USGS Palo Alto 7.5 minute Quadrangle Digital Line Graph. Major contour interval is 20 feet. Minor contour interval is 5 feet.
2. Base map is the USGS Palo Alto 7.5 minute Digital Orthophoto Quadrangle.

MAP OF QUATERNARY STRUCTURES AND FLUVIAL TERRACES ALONG SAN FRANCISQUITO CREEK
Stanford Fault Zone, Frontal Thrust Fault System
Palo Alto, California

GEOMATRIX	Project No.	Plate
	6995	1