FINAL TECHNICAL REPORT

Project Title:

Assessment of late Quaternary deformation, eastern Santa Clara Valley, San Francisco Bay region

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ABSTRACT

A series of northwest-trending reverse faults that bound the eastern margin of Santa Clara Valley are aligned with the southern termination of the Hayward fault, and have been interpreted as structures that may transfer slip from the San Andreas and Calaveras faults to the Hayward fault. Uplift of the East Bay structural domain east of Santa Clara Valley is accommodated by this thrust fault system, which includes the east-dipping Piercy, Coyote Creek, Evergreen, Quimby, Berryessa, Crosley, and Warm Springs faults.

Our study provides an evaluation of the near-surface geometry and late Quaternary surficial deformation related to reverse faulting in the eastern Santa Clara Valley. Retrodeformable geologic cross sections provide constraints on the down-dip geometry and depth of interaction between east dipping faults of the eastern Santa Clara Valley and Calaveras fault system. These cross sections show that the Evergreen and Quimby faults are likely secondary structures which root into the Calaveras fault system at relatively shallow (<5km) depths. We conclude that these faults are likely not independent seismic sources but rather probably rupture in response to large earthquakes on the Calaveras fault. Based on scarp profiling and offset of a fluvial terrace across the Evergreen Fault near the Evergreen Valley Community College, we obtain a minimum vertical separation across the fault of 7.3 m. Based on radiocarbon dates from the upper terrace deposits, we obtain a vertical separation rate on Evergreen fault of 3.8 mm/yr. Similarly, based on 1 m of offset of a correlative terrace across the Quimby fault, we obtain a vertical separation rate of 0.5 mm/yr. However, we believe that the offset terraces likely are late Pleistocene or early Holocene and thus the actual slip rate on the fault likely is up to an order of magnitude less.

A field exposure of the Silver Creek fault shows the fault to be a west-dipping structure with reverse displacement. The observed geomorphic pattern of uplift within Santa Clara Valley above the west-dipping Silver Creek fault is distinct from, and different than, the observed pattern of localized uplift of the hills east of the Evergreen, Quimby, and other east-dipping faults that bound the eastern margin of Santa Clara Valley. Because the Silver Creek fault dips more steeply than the east-dipping faults, appears to have significant fault slip per event, and is a more significant structural discontinuity, it likely is a seismogenic feature capable of producing independent earthquakes.

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1.0 INTRODUCTION

During the past several decades, several moderate to large earthquakes in California have occurred on reverse faults. Prior to the earthquakes, these faults generally were not recognized as potential seismic sources. These earthquakes (e.g., 1983 Coalinga, 1987 Whittier Narrows, 1994 Northridge) demonstrate that buried or 'blind' reverse faults are significant, and often unforeseen, sources of damaging earthquakes. Where these faults underlie densely populated urban areas, reverse faults may actually constitute a greater hazard for locally intense ground motions than high-slip rate (but more distant), larger strike-slip faults.

Potentially active reverse (or oblique slip) faults present along the eastern margin of the Santa Clara Valley include the Silver Creek, Piercy, Coyote Creek, San Jose, Evergreen, Quimby, Berryessa, Crosley, and Warm Springs faults (Figures 1 and 2). A moderate earthquake generated by any one of these faults within the densely populated Santa Clara Valley would be potentially damaging. To date, these reverse faults that underlie the eastern Santa Clara Valley are poorly characterized. Although several of these faults were originally zoned as potentially active by the California Geological Survey (CGS), and despite several investigations that have identified potential Quaternary activity (Bryant, 1981), the basic seismic source characteristics of these faults remain largely unknown. Late Pleistocene or Holocene slip rates for most of the faults have not been determined, and despite recent studies of the structure of the East Bay Hills, the subsurface geometry, sense of vergence, and degree of interaction with the Hayward and Calaveras faults is poorly constrained.

1.1 Significance and Purpose

This study evaluates the near-surface geometry and late Quaternary deformation related to buried, potentially seismogenic sources in the eastern Santa Clara Valley. Reverse faults bounding the east Valley likely play a prominent role in uplift of the hills east of San Jose and strain transfer in the San Francisco Bay area. Understanding rates and style of deformation on these faults, therefore, contributes directly toward assessing the distribution of strain along the plate boundary in the San Francisco Bay area, in general, and the location and cause(s) of crustal shortening in the southern Bay area, in particular. In this study, we focused on: (1) evaluating the structural setting and style of deformation of the east Valley reverse faults, including their relationship to, and interaction with, the San Andreas, Hayward, and Calaveras strike-slip faults; and (2) evaluating the rate and recency of potential fault activity based on detailed Quaternary geomorphic mapping and geomorphic analyses.

Determining the structural association of reverse faults beneath the Santa Clara Valley to the San Andreas, Hayward, and Calaveras faults is critical for assessing the transfer of slip (strain) between these faults. Reverse faults beneath the eastern valley are aligned along the southern termination of the Hayward fault, and several have been interpreted as structures that may transfer slip from the southern Hayward fault to the Calaveras fault (Graymer, 1995). If true, the cumulative rate of deformation on these faults may locally approach the rate of slip transferred between the Hayward and Calaveras faults. However, it is unclear just where and how slip is distributed at the southern end of the Hayward fault and whether the slip is transferred via: (1) coseismic displacement on the reverse faults during large earthquakes on the Hayward or Calaveras faults; or (2) by means of slower strain buildup resulting in moderate, independent earthquakes on the reverse faults.

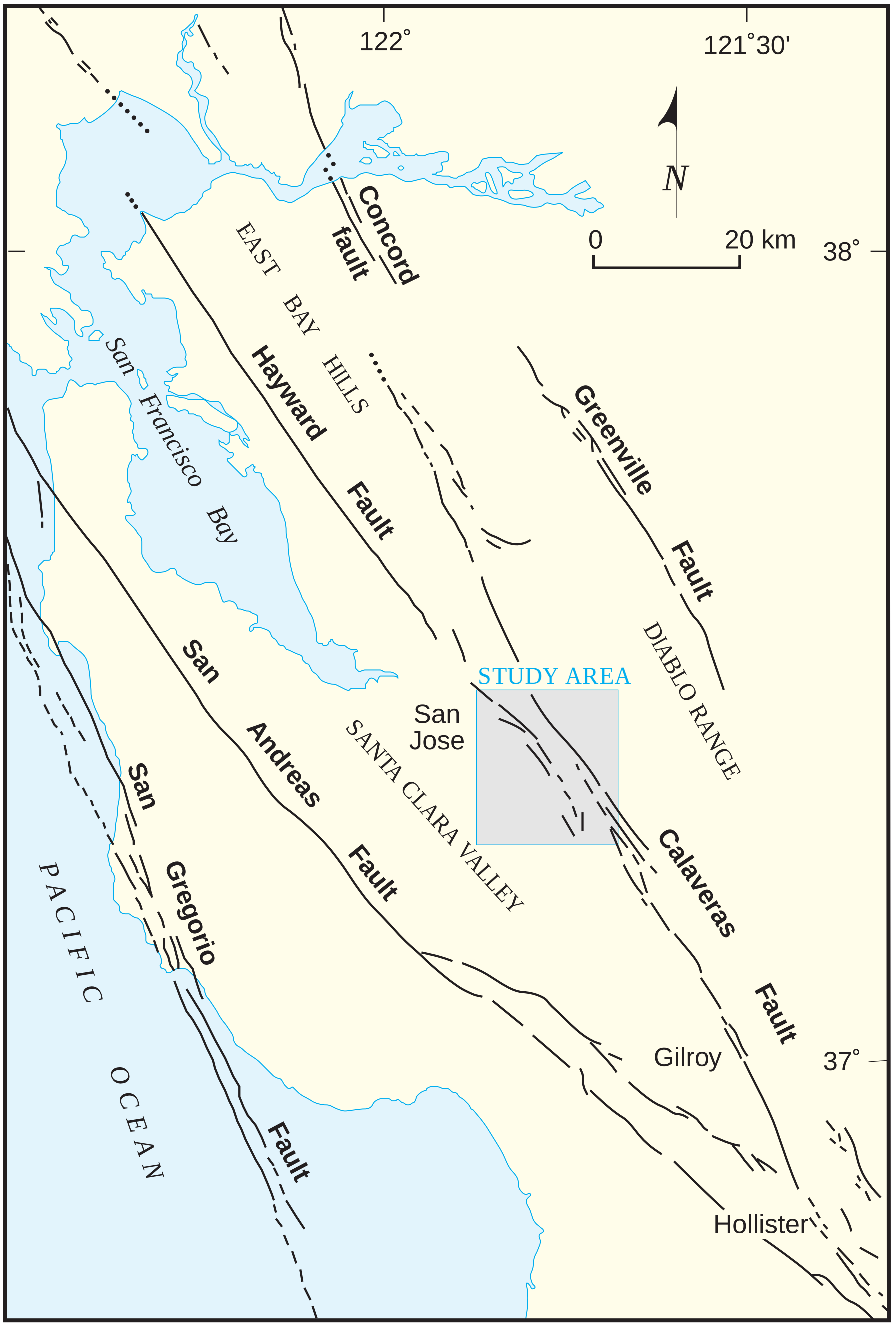

Figure 1. Regional map of the San Francisco Bay area showing major strike-slip faults and the eastern Santa Clara Valley study area.

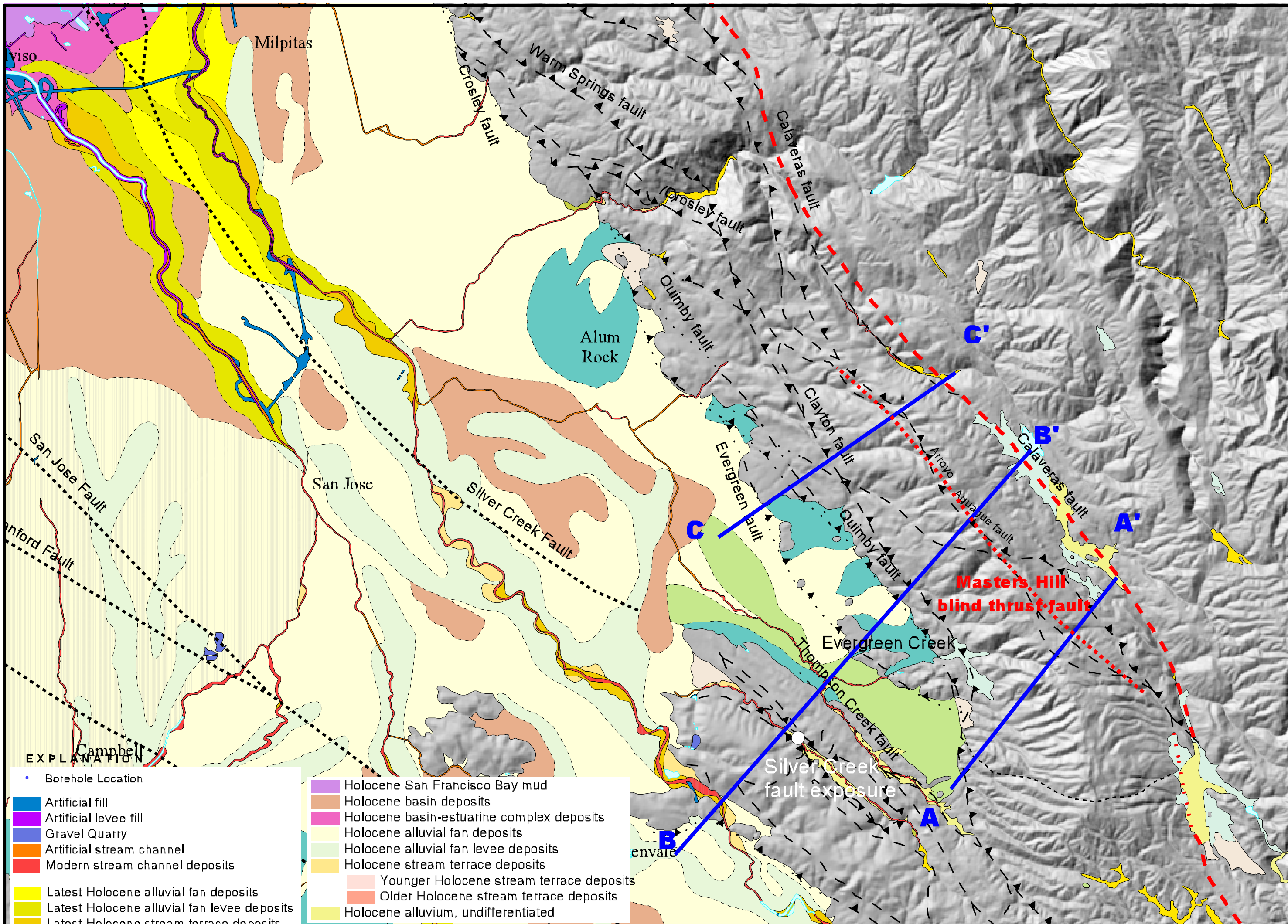

Figure 2. Location map showing cross section locations.

The question of whether observed surface deformation associated with reverse faults beneath the Santa Clara Valley is the result of primary slip during moderate earthquakes on the underlying thrust fault system, or secondary, aseismic deformation that is triggered by, or associated with, large earthquakes on nearby major strike-slip faults is critical for evaluating the earthquake hazard posed by the reverse faults. Because the faults traverse the densely populated communities of San Jose and Milpitas, they pose potentially significant primary surface fault rupture and ground motion hazards to these communities. Hitchcock and Kelson (1999) observed that slip on similar thrust faults within the Foothills thrust fault system along the west side of the Santa Clara Valley may occur entirely during large earthquakes on the adjacent San Andreas fault, and thus documented late Quaternary deformation above these faults may reflect repeated episodes of aseismic triggered slip and postseismic creep rather than independent seismic activity.

However, if the reverse faults beneath the Santa Clara Valley are capable of independently generating earthquakes, the recurrence of moderate to large-magnitude earthquakes on these faults, as calculated from the long-term average slip rate, is heavily dependent upon the percentage of triggered slip and postseismic creep contributed during large earthquakes on nearby strike-slip faults. Regardless of the tectonic mechanism, primary or secondary ground rupture caused by triggered slip along the reverse faults will cause localized damage and requires documentation. Based on the coincidence of zones of damage along the western margin of the valley produced during the 1989 Loma Prieta earthquake (Haugerud and Ellen, 1990; Schmidt et al., 1995), with potentially fault-related geomorphic features (Hitchcock et al, 1994; Hitchcock and Kelson, 1999), even minor triggered slip during large earthquakes on nearby strike-slip faults can cause significant localized damage updip of reverse faults underlying the urbanized Santa Clara Valley.

1.2 Summary of Results

The major results of this study include the following:

1) Retrodeformable structural cross sections provide constraints on the style and geometry of potentially active reverse faults beneath the eastern Santa Clara Valley. The cross sections indicate that the east-dipping Quimby and Evergreen reverse faults most likely intersect the Calaveras fault at depths of about 4-5 km (12000-15000 feet); thus these faults probably are limited to the upper crust and do not extend to depths at which moderate to large earthquakes (>M5) typically nucleate. Based on our structural interpretation, these reverse faults most likely are not primary seismic sources capable of large earthquakes. However, because these faults intersect the Calaveras at relatively shallow depths, they may rupture in conjunction with, or triggered by, a large earthquake on the Calaveras fault.

2) We interpret structural repetition of bedrock units caused by a series of northwest-trending anticlines and synclines within the hills east of Santa Clara Valley as fault-propagation folds caused by an underlying blind thrust fault, which we term the Masters Hill blind thrust.

3) Longitudinal profiles of Pleistocene and younger stream terraces show localized uplift and folding across the east-dipping Quimby and Evergreen faults consistent with that inferred from our structural cross sections. Morphometric analysis of regional topography, incorporating GIS analysis of available digital elevation data (DEMs), shows patterns of topographic residuals coincident with mapped east-dipping reverse faults, including the Quimby, Evergreen, and other sub-parallel faults. Assuming that regional stream incision is a proxy for regional uplift, the observed pattern is consistent with localized late Quaternary uplift above the faults.

In addition, a prominent area of high topographic residuals coincides with the fold axis of the fault propagation fold inferred to lie above the Masters Hill blind thrust fault from our structural cross-sections. Topography and inferred regional incision patterns suggest that recent uplift of the hills west of the Calaveras fault may have been at least partially accomplished by uplift in the hanging walls of the reverse faults and above the blind thrust fault.

4) Based on outcrop evidence that the Silver Creek is a west-dipping reverse or oblique-slip fault and because it has a different orientation than the other reverse faults in the eastern Santa Clara Valley, we interpret that the Silver Creek fault is distinct from the east-dipping reverse faults that bound the eastern margin of Santa Clara Valley. In addition, the observed geomorphic pattern of uplift within Santa Clara Valley above the west-dipping Silver Creek fault is distinct from, and different than, the observed pattern of localized uplift of the hills east of the Evergreen, Quimby, and other east-dipping faults that bound the eastern margin of Santa Clara Valley. Changes in stream valley morphology along major streams that cross the Silver Creek fault and profiles of terraces along Coyote Creek are consistent with late Pleistocene, and possibly Holocene, uplift within the inferred hanging wall of a west-dipping reverse fault.

5) Structural, geologic, and geomorphic evidence support the interpretation that the Silver Creek fault may be part of the Foothills Thrust Fault System, influenced by the 'big bend' in the San Andreas fault within the Santa Cruz Mountains. Assuming that the Silver Creek fault is a west-dipping fault distinct from the east-dipping faults bounding the eastern margin of the Santa Clara Valley, interaction between the two sets of reverse faults likely controls the structure of the eastern Santa Clara Valley. In particular, the north-trending Evergreen structural depression (located east of San Jose) may have formed due to tectonic subsidence between the convergent thrust fault systems. Our proposed structural model is non-unique as a recently presented model by Jachens et al. (2002) also is consistent with much of the geologic, structural, and geomorphic data that we present. Jachens et al (2002) suggest that the Evergreen basin may be a pull-apart basin between a predominately strike-slip Silver Creek fault and the southern Hayward fault.

6) Based on radiocarbon dating of organic material within a faulted colluvial wedge obtained from an exposure of the Silver Creek fault, it is probable that the Silver Creek fault has experienced displacement during the Holocene and thus is Holocene active.

7) Based on scarp profiling and offset of a fluvial terrace across the Evergreen Fault near Evergreen Valley Community College, we obtain a minimum vertical separation of 7.3 m across the fault of a late Quaternary stream terrace surface. Based on radiocarbon dates from the upper terrace deposits, we obtain a vertical separation rate on Evergreen fault of 3.8 mm/yr. Similarly we document 1 m of offset of a correlative terrace across the Quimby fault, and obtain a vertical separation rate of 0.5 mm/yr. However, we believe that the offset terrace likely is late Pleistocene or early Holocene and thus the actual slip rates on the faults likely are an order of magnitude less.

1.3 Acknowledgements

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2.1 Structural Setting

Santa Clara Valley is a structural and topographic low bounded on the west by the San Andreas fault and on the east by the Hayward and Calaveras faults (Olson and Zoback, 1998; Figure 1). The valley is located at the southern end of, and is part of, the larger San Francisco Bay basin. Santa Clara Valley is bordered on the west by the Santa Cruz Mountains and on the east by the rugged East Bay Hills. Both western and eastern margins of the valley are defined by a series of reverse faults that bound the rangefronts.

On the eastern margin of Santa Clara Valley, reverse faults separate the valley margin from the uplifted East bay structural domain to the east (Figure 2; Aydin and Page, 1984). This system of anastamosing, east-dipping reverse faults trending northwest-southeast along the base of the foothills includes the Piercy, Coyote Creek, Evergreen, Quimby, Berryessa, Crosley, and Warm Springs faults (Figure 2). The faults strike about 10º to 15º more westerly than the main traces of the Hayward and Calaveras faults. These structures were originally mapped by Dibblee (1972 a,b,c;1973), Crane (1985), and Page et al. (1998) primarily on the basis of bedrock exposures and aerial photo lineaments.

2.1.1 Major Faults in the Study Region

Santa Clara Valley has been shaped, in large part, by the San Andreas, Calaveras, and Hayward right-lateral strike-slip fault systems. These major fault systems accommodate much of the movement along the plate boundary between the Pacific and North American plates. Local, and possibly regional, compressional deformation associated with these faults hypothetically may have three main possible origins: (1) shortening attributed to the orthogonal component of relative motion between the Pacific and North American plates, (2) shortening occurring at restraining bends and stopovers in dextral fault systems, and (3) shortening caused by rotation of large crustal blocks.

The central Calaveras fault plays a major role in accommodating plate-motion slip the region. In the vicinity of the study area, east of the southern Santa Clara Valley, fully half of the slip along the plate margin is accommodated by strike-slip displacement on the fault (Kelson et al., 1992). Geodetic modeling and historical creep data suggest a present-day slip rate of about 16 mm/yr and paleoseismic studies suggest a late Holocene slip rate of about 14±5 mm/yr (Kelson and Lettis, 1992; Kelson et al, 1996). Interactions and slip transfer between the San Andreas and Calaveras/Hayward right-lateral strike-slip fault systems, and the influence of local restraining bends, result in localized net shortening within this region.

Across the region, crustal shortening is accommodated, in part, by belts of northeast- and southwest-vergent thrust faults on the southwest and northeast margins of the Santa Clara Valley. These faults accommodate uplift of the flanking ranges of the Santa Cruz Mountains and hills east of San Jose. Although the marginal thrust faults exhibit much lower slip rates than adjacent strike-slip faults, they are integral parts of the overall strike-slip fault system and play an important role in the transfer of slip across the Bay Area. As such, the activity and slip rates on these faults are a crucial part of the puzzle required for understanding of the behavior and interaction between the major strike-slip faults that bisect the Bay Area.

2.1.2 Reverse Faults of the Eastern Santa Clara Valley

Rapid uplift of hills within the East Bay structural domain east of Santa Clara Valley likely is accommodated, at least in part, by east-dipping reverse faults trending northwest-southeast along the base of the foothills. The uplifted East Bay structural domain, located between the southern Hayward fault and the Calaveras fault near Niles, has experienced late Pleistocene uplift rates of 1.5 ± 0.5 mm/yr (Kelson and Simpson, 1996), This system of faults includes the Piercy, Coyote Creek, Evergreen, Quimby, Berryessa, Crosley, and Warm Springs faults (Figure 2). The faults strike about 10° to 15° more westerly than the main traces of the Hayward and Calaveras faults. The Crosley, Warm Springs, and Piercy faults are aligned with the southern termination of the Hayward fault, and have been previously interpreted as structures that may transfer slip from the southern Hayward fault to the Calaveras fault (Graymer, 1995). These structures were mapped by Dibblee (1972 a,b,c;1973), Crane (1985), and Page et al. (1998) primarily on the basis of bedrock exposures and aerial photo lineaments.

Cross-sections of relocated microearthquake hypocenters, although sparse, also indicate that the faults dip moderately to the east (Woodward-Clyde Consultants, 1994; Fenton and Hitchcock, in press). Earthquake focal mechanisms indicate predominately reverse motion on northwest-striking faults. No large, historical earthquakes have been conclusively attributed to the thrust faults along the eastern Santa Clara Valley margin (Oppenheimer et al., 1990). Jaumé and Sykes (1996) suggest that the 1 July 1911, M6.2 earthquake may have occurred on a thrust fault parallel to the Calaveras fault; however, anecdotal intensity data indicates that this event likely occurred on the Calaveras fault (Bakun, 1999; Toppozada, 1984).

In the Evergreen region of east San Jose, the Evergreen and Quimby faults are interpreted as moderately east-dipping faults which are primary structures in the rangefront and cause significant stratigraphic repetition of the Cretaceous and Tertiary section (Figure 2). Trenching at the Evergreen Valley Community College by Woodward-Clyde Consultants (Woodward-Clyde Consultants, 1994; Fenton et al., 1995) documented that the Evergreen fault is a moderate to low-angle (less than 45°) east-dipping thrust fault that displaces Knoxville Shale east-side-up against Santa Clara Formation gravels. The fault plane was observed to offset Santa Clara Formation gravels and internal paleosol horizons estimated to be late Pleistocene in age (Fenton and Hitchcock, in press; Figure 3). Overlying gravels of unknown age are also warped. Woodward-Clyde Consultants (1994) interpreted evidence for minor repeated offsets within the trench exposures at Evergreen Valley Community College as suggestive that the Evergreen fault may have experienced incremental coseismic rupture (‘triggered slip’) during the late Pleistocene and possibly Holocene.

Specifically, progressive steepening of bedding within Santa Clara Formation gravels towards the fault in the hangingwall, and the relatively minor amount of displacement on the exposed fault (approximately 0.15 m) suggests that displacement on the Evergreen fault may be incremental and possibly due to “triggered slip” rather than due to primary rupture (Fenton and Hitchcock, in press). However, Woodward-Clyde Consultants (1994) concluded that it is unlikely that the rupture reached the surface. Based on the trench exposures, rupture likely flattened near the surface, with repeated displacements producing the observed fault scarp.

Alquist-Priolo trenching studies have refined the locations of several of the faults, but in general recent attempts to determine their Holocene activity have been inconclusive . Jones et al (1994) interpret these faults as a steeply-dipping zone of thrusts that roots in the Calaveras fault at approximately 10 km depth. However, outcrop mapping suggests that many of these faults are moderate to relatively low-angle features that may root into the Calaveras fault at shallower depths (Fenton and Hitchcock, in press).

Faults that extend beneath Santa Clara Valley, including the northern section of the Silver Creek fault and the San Jose fault, are mapped based on inferred offset of buried stream channels identified in water-well logs (California Department of Water Resources (DWR), 1967, 1975). These inferred faults are buried under Holocene alluvium and have no documented geomorphic expression. There is no evidence that the Silver Creek and San Jose faults, and nearby secondary fault splays, influence the flow of groundwater beneath Santa Clara Valley (California Department of Water Resources, 1975). Thus, the presence of these faults remains speculative. However, the presence of these faults beneath much of San Jose, as currently mapped, suggest that, if active, they may pose a potential seismic hazard to the city.

2.2 Stratigraphy

Geologic units exposed within the study area provide a record of sedimentation, erosion, and regional deformation. Past researchers have used these bedrock units and Quaternary deposits to map major faults and folds. In addition, the composition of geologic units exposed within the study area has directly influenced the geomorphic evolution of the region and influence ongoing erosional and depositional processes.

The bedrock geology of the area has been mapped by numerous workers, including Dibblee (1972 a,b,c;1973), Crane (1985), and Page et al. (1998). Bedrock in the area consists of a sequence of Cretaceous and Tertiary marine sedimentary rocks that have been uplifted and deformed intensely by faulting and folding. The bedrock structure consists of generally northwest-trending faults and folds, with bedrock dipping moderately to steeply to the northeast. The low-lying Santa Clara Valley is filled with Quaternary alluvial sediments. Landslide deposits obscure the valley margin in many places along the valley margin, roughly coincident with the bedrock/alluvium contact.

The surficial Quaternary geology of the proposed study area has been mapped in detail (1:24,000 scale) by William Lettis & Associates as part of a NEHRP-funded liquefaction susceptibility study (Sowers et al., 1994; Knudsen et al., 2000). While the Quaternary sediments and basin deposits cover and obscure the underlying bedrock and structures, numerous boreholes have been drilled for water wells in the valley (Fio and Leighton, 1994) and for geotechnical and environmental studies (CDMG, 2001; Hitchcock and Helley, 2002). These data provide control on depth to bedrock and Holocene sediment thickness in the San Jose area.

2.3 Regional Geomorphic Setting

The eastern Santa Clara Valley has been shaped by regionally extensive erosional and depositional processes, complicated by active faulting, and associated uplift, along the valley margin. Although primarily shaped by recent fluvial processes, the eastern Santa Clara Valley contains preserved remnants of older alluvium that record earlier pulses of deposition along the valley margin and, possibly, ongoing active faulting. The Evergreen area, located southeast of San Jose, is dominated by a broad piedmont that extends westward of an abrupt northwest-trending rangefront. This piedmont, although mantled in some areas by a thin veneer of Holocene alluvium, principally is underlain by, and composed of, deeply Pleistocene fan deposits with isolated bedrock knolls.

Crittenden (1951) documented topographic evidence preserved along the canyon slopes of Penitenticia Creek that suggested a broad valley once was the dominant geomorphic feature of the Alum Rock Canyon area. The present elevation of the remnants of this former valley ranges between about 1,100 (380 m) to 1,500 feet (450 m) based on mapping by Coyle (1984). Coyle (1984) noted broad erosional surfaces that he interpreted as predating the Santa Clara Formation and which may have been the source area for at least the upper portion of the Formation. Clasts within the Santa Clara Gravels include material derived from the bedrock units that underlie the inferred erosional surfaces, including Monterey Group and Briones Formations (Coyle, 1984).

Quaternary mapping, field reconnaissance, and geomorphic analyses were utilized to assess the location, style, and, where possible, estimated rates of late Quaternary contractional deformation. Structural cross sections were used to constrain the possible fault geometry and style of deformation. Combined with geomorphic analyses, the balanced cross sections provide an estimate of the amounts and rates of shortening on these faults. The initial phase of study involved stereoscopic interpretation of conventional aerial photographs. Air photo interpretation was used to identify and map Quaternary geomorphic surfaces, develop a Quaternary stratigraphic framework for the study area, and identify sites for field reconnaissance. Two vintages of aerial photographs, flown at various dates and various scales, were incorporated into the mapping (Table 1).

Table 1. List of Aerial Photography Used in Reconnaissance Mapping.

Date/Series	Approx. Scale	Image Type	Agency	USGS 7.5' Quadrangles
7/31/32 CIV series	1:20,000	Black-and-white	USDA	San Jose East, San Jose West
4/14/1999 WAC-C-99CA series	1:22,000	Color	WAC (Western Aerial Surveys, Inc.)	San Jose East, San Jose West

3.1 Geomorphic Investigations

Reverse faults may not extend to the ground surface, and thus it is difficult to identify these faults and interpret their often subtle pattern of surface deformation (Lettis et al., 1997). Paleoseismic investigations of many of the faults within the proposed study area have been inconclusive, and in some cases it is unclear whether the mapped 'fault' trace is of tectonic or landslide origin (Bryant, 1981). In other cases fault trenches documented fault rupture at depth that is not apparent at the ground surface. For example, Woodward-Clyde Consultants (1994) interpreted trench exposures of the Evergreen fault at Evergreen Valley Community College as shallow subsurface warping above a blind thrust fault at depth. At this location, the Evergreen fault is distinguished by a prominent west-facing scarp (Fenton et al., 1995).

Although reverse faults may be difficult to locate and characterize via conventional paleoseismic trenching, their association with warped or faulted landforms enables them to be evaluated using existing Quaternary mapping and geomorphic analysis techniques. Quantitative geomorphic analyses provide a proven approach to the determination of the distribution, style, and rate of surficial deformation associated with near-surface thrust faults (Bullard and Lettis, 1993; Hitchcock et al., 1994; Angell et al., 1998; Hitchcock and Kelson, 1999). When these techniques are integrated with restorable cross sections, the nature and geometry (i.e., rupture dimensions) of buried reverse faults can be evaluated.

Based on the similarity of geomorphic features in the eastern Santa Clara Valley with fault-controlled geomorphic features in the western Santa Clara Valley (Hitchcock et al, 1994; Hitchcock and Kelson, 1999), we applied similar established geomorphic and geologic techniques used in our previous studies to identify and characterize potential seismogenic sources in the eastern Santa Clara Valley.

First, we mapped landforms and surfaces along major creeks. Geomorphic features identified on the aerial photographs were transferred to 1:24,000-scale topographic maps and supplemented by field reconnaissance. Field reconnaissance helped verify and refine geologic contacts and collection of information on deposits associated with mapped geomorphic surfaces in readily accessible exposures (e.g., stream banks and roadcuts). Quaternary surfaces identified on the aerial photographs were verified in the field, where possible, and correlated using geomorphic and stratigraphic position, relative degree of surface modification, physical continuity within drainage basins, and, to a limited extent, relative degree of soil-profile development.

Second, we conducted geomorphic analyses of the mapped Quaternary surfaces to: (1) evaluate possible tectonic influences on the geomorphic development of the study area; (2) assess evidence for late Quaternary growth of folds; and (3) constrain uplift rates across folds and faults. Analyses performed for this study include construction of longitudinal terrace and stream channel profiles, analysis of stream channel morphology using stream-gradient index, evaluation of transverse stream valley morphology across the study area, and assessment of the late Quaternary evolution of fluvial drainages across the region. Results from these techniques were integrated with our review of published literature and field reconnaissance to assess evidence for late Quaternary deformation.

As part of our study, we examined the distribution of terraces along major drainages within the study area including Evergreen and Coyote Creek. These drainages contain distinct, well-preserved sequences of fluvial terraces and flow nearly orthogonal to and across the reverse faults. Surficial geologic maps of fluvial terraces and other geomorphic surfaces were used to construct the longitudinal terrace profiles. We used two-foot topographic maps of major streams obtained from the Santa Clara Valley Water District to map surficial deposits and landforms along the streams and to construct stream terrace and stream thalweg profiles. These topographic maps incorporate survey data collected prior to substantial stream channel modifications and thus provide excellent base maps for our analyses. Deviations in the profile from an initially graded terrace profile were used to identify loci of tectonic deformation and, when integrated with age constraints, provide a basis for estimating rates of Quaternary deformation. Combined with results of radiocarbon analyses of charcoal samples obtained from stream terraces, the terrace profiles provide valuable constraints on late Quaternary uplift rates on reverse faults within the eastern Santa Clara Valley thrust system.

As part of our analysis of late Quaternary deformation, we also constructed longitudinal profiles of stream channels along major drainages to help identify the location and style of deformation. Field studies by Burnett and Schumm (1983), Merritts and Vincent (1989), Bullard and Lettis (1993), and Marple and Talwani (1993) show that changes in stream channel gradient may record tectonic uplift. Along streams that are unaffected by regional or localized uplift, stream gradient generally decreases with distance downstream, typically in an exponential or logarithmic manner producing a characteristic convex graded profile (Hack, 1957; Schumm, 1977). Longitudinal profiles of stream channels within homogeneous terrain typically are convex upward across an axis of uplift (e.g. Figure 5). Thus downstream variations in channel gradient that are not logarithmic or exponential, typically expressed as a local convexity or concavity in the channel profile, may be related to localized uplift or subsidence.

In addition, localized uplift or subsidence may change the stream channel gradient, upsetting the equilibrium between channel gradient and hydraulic properties of the stream (Ouchi, 1985). Localized disruption of these properties may be expressed as straightening of the channel on the upstream side of an uplift and incision across the central reach of the uplift with associated development of a series of fluvial terraces (Ouchi, 1985; Figure 5). Often these terraces are absent, or poorly preserved, elsewhere along the stream channel. These terraces can be diagnostic of localized uplift and useful in evaluating the amount of folding or faulting across the uplift. Downstream of an axis of uplift, stream sinuosity generally increases as the stream attempts to maintain a uniform stream gradient on the steepened slope. For this study, the stream-gradient index (Hack, 1973), that relates channel gradient to channel length is used to analyze the longitudinal stream profiles. As defined by Hack (1973), the stream-gradient index is equal to the product of the channel slope at a point and total stream length from the drainage divide to that point as shown:

$$SL \text{ (stream gradient index)} = \Delta H/\Delta L*L \qquad (1)$$

where $\Delta H/\Delta L$ is the channel slope or gradient (ΔH is the change in elevation of the stream reach and ΔL is the length of the reach), and L is the total channel length from the stream divide.

The stream-gradient index is a means of quantifying stream power, with higher index values representing stream reaches with greater available power to incise and transport sediment. The stream-gradient index is very sensitive to changes in channel gradient, which generally correspond to differences in bedrock strength, particle size, and load supplied to the stream. Where climatic factors and lithological controls on the fluvial system are effectively constant, anomalously high stream-gradient values typically are interpreted to indicate localized uplift (Keller and Pinter, 1996). Unfortunately, rock strength varies significantly across the study area, and this technique must be used with caution. Based on outcrop and topographic expression, the most resistant rocks in the study area are rocks of the Franciscan Complex. The Franciscan Complex is considerably more resistant than younger Quaternary gravel deposits, including the Santa Clara Gravels. For this reason, we present index data only as one line of evidence among several. Where presented, the stream-gradient index is calculated for stream reaches underlain by similar bedrock units and any variations between reaches are identified and discussed.

Topographic residual maps are a means of evaluating regional variations in erosional relief associated with stream incision. If it is assumed that erosional relief is a response to tectonic uplift, then residual maps indirectly document the loci and magnitude of uplift. Residual relief maps are derived from “envelope” and “sub-envelope” maps, using methods developed by Strahler (1952). An envelope map is an interpretation of the pre-incision landscape that is created by interpolating a smooth surface that connects interfluves and flattish summit surfaces. It is essentially a reconstruction of the pre-incision topography. The sub-envelope map is a smooth surface formed by interpolating among the thalwegs of second-order drainages, and is interpreted to represent the current level of stream incision. The “residual” topography is derived by subtracting the elevation of the envelope surface from the sub-envelope surface at a point; a residual map is the contoured values of the residuals at many points.

We applied a standard algorithm, developed based on work by George Hilley of Arizona State University (pers. comm., G. Hilley, 2000; Hilley and Arrowsmith, 2000) for computing the envelope, subenvelope, and residual surfaces from 30-meter Digital Elevation Models (DEMs). The topographic residual map was calculated by subtracting two derived surfaces, the envelope and the subenvelope surfaces. The upper envelope surface is calculated by taking elevations from ridgelines in a landscape, derived from DEM data, and interpolating a gridded surface from these points. The subenvelope surface is calculated by first calculating approximate stream channel bottoms and then interpolating a gridded surface between those points. By subtracting the lower subenvelope surface from the upper envelope surface, the relief within drainage basins is quantified. Our computations are performed with the aid of ArcView 3.2 and Surfer 7 running on a Windows NT operating system.

3.2 Interpretation of Subsurface Data

Morphometric analysis of the regionally extensive top of Pleistocene surface underlying the Santa Clara Valley provides estimates of minimum regional uplift and locations of folding and faulting. The top of buried Pleistocene deposits represents a landscape surface exposed prior to the rise of seawater through the Golden Gate at the beginning of the Holocene (Atwater and others, 1977; Helley and Lajoie, 1979). Hitchcock and Helley (2002) have contoured and reconstructed this laterally extensive surface in the Evergreen Basin area (San Jose East USGS quadrangle) to provide information on the loci of possible Holocene fault and fold deformation. Reconstructing the top of the buried Pleistocene surface provides a significant strain gauge for fault evaluation with the potential to add new knowledge about faults and folds previously inferred beneath the Santa Clara solely on the basis of groundwater data (e.g., DWR, 1967, 1975), geophysics, and geomorphic mapping (e.g., Hitchcock and Kelson, 1999). Contour maps of the top of Pleistocene deposits within the study area shows irregularities in the Pleistocene surface that may correspond to fault displacements.

3.3 Structural Cross-sections

After collecting and reviewing the surface and subsurface data, we constructed a series of three retrodeformable structural geologic cross sections across reverse faults of the eastern Santa Clara Valley (Figure 2). These sections incorporated the compiled surface data from 1:24,000 scale geologic maps from the area (Dibblee, 1972 a,b,c;1973; Crane, 1985; and Page et al. 1998). Our goals in constructing these cross sections were to (1) constrain the subsurface fault geometry, (2) evaluate the style and sense of vergence of crustal shortening beneath the eastern Santa Clara Valley; and (3) to provide an estimate of the amounts and rates of shortening on these faults. Cross sections were constructed using conventional and accepted techniques for balanced and retrodeformable cross sections. Surface stratigraphic and bedding dip data were projected to depth using the kink-fold method of Suppe (1983) and Suppe and Medwedeff (1990). The section lines were oriented perpendicular to the strike of contractional structures, in order to illustrate the geometry of faults and folds with a minimum of geometric distortion. Various fault models were tested for compatibility with the shallow fold geometry.

Cross sections were constructed in the Evergreen region of San Jose and the adjacent hills to the north, east, and south. We focused on this area because it coincides with good bedding orientation data from published geologic maps and well-constrained fault locations from our geologic and geomorphic mapping. The cross sections illustrate the location and style of deformation to the west of the Calaveras fault. Because the Calaveras fault forms a regional structural boundary we infer that any structures west of the fault would be truncated by, or would root into, the Calaveras fault zone. In developing the cross sections, we assume that all deformation occurs within the plane of the section and that strike slip deformation in and out of the plane of the section is minimal. While strike-slip motion on the reverse faults would result in out-of-plane deformation, and resulting errors on the cross sections, we believe that the majority of the displacement on the faults has been reverse to oblique-reverse, and will not compromise the cross sections. Similar cross section construction techniques have been applied successfully in the interpretation of faults and folds adjacent to the San Andreas Fault (Angell and Crampton, 1996). While the balanced cross sections do not result in unique solutions to the geometry of subsurface faults and folds, we believe that they allow for the testing of various hypotheses and the construction of well-constrained, geologically realistic and plausible interpretations.

Several models to account for the fold and fault geometries were considered in the construction of the cross sections. For example, we considered fault bend folding (e.g. Suppe, 1983; 1985), fault propagation folding (Suppe and Medwedeff, 1990), and imbricate thrust models (Suppe, 1983; Shaw et al., 1999) as possible kinematic models to account for the observed deformation. In addition, we considered the possibility that none of these models is consistent with the available data and thus that the construction of balanced cross sections across these structures would not be possible or representative of the deformation. Of all the models considered, the fault propagation fold model best fits the geologic and stratigraphic data.

3.4 Field Investigations

During our field mapping, we cleaned and logged a fresh exposure of the Silver Creek fault excavated during construction of a golf course along upper Silver Creek (Figure 2). The exposure enabled us to examine native sediments previously covered by artificial fill and obscured by recent development. The original ground surface, now removed by grading, preserved a subtle but clearly defined east-facing scarp which trended north-south. The excavation exposed bedrock faulted against scarp-derived colluvium and older alluvial gravels of unknown age (likely Pleistocene). The age of the faulted colluvium was estimated based on radiocarbon analyses of two representative samples of charcoal collected from the colluvial deposits.

We also mapped stream terraces along Evergreen Creek, across the Quimby and Evergreen faults, and along Coyote Creek, across the Silver Creek fault. We examined exposures along Evergreen Creek of older stream terrace deposits and collected charcoal samples from these deposits.

4.0 RESULTS

Balanced structural cross sections help constrain the subsurface fault geometry and evaluate the style and sense of vergence of crustal shortening beneath the eastern Santa Clara Valley. In conjunction with the cross sections, we conducted detailed geologic and geomorphic mapping to locate and characterize faults, and to identify Quaternary deposits and surfaces that overlie the faults. Where we documented potential fault-related deformation, we performed detailed geomorphic analyses to assess the style of related faulting and characterize the timing of the deformation related to buried, potentially seismogenic sources in the eastern Santa Clara Valley. We conducted field reconnaissance to check our preliminary interpretations, collect datable material to provide age constraints on the deposits and surfaces, and, where possible, document fault exposures that might provide information on the major faults within the eastern Santa Clara Valley. We describe the results of our integrated studies below.

4.1 Structural Cross-Sections

Three regional cross sections are shown in Figures 3 through 5, and show similar structural styles of deformation. The cross section which best illustrates the overall geometry of the faults bounding the eastern margin of the Santa Clara Valley is cross section B-B', which extends northeastward across the area of Evergreen Community College, immediately north of Yerba Buena Creek (Figure 2). This section incorporates well-defined surface fault locations and bedding data along its entire length. The overall geometry of the structure in this cross section is of a primarily northeast-dipping Cretaceous and Tertiary stratigraphic section, with structural repetition of units caused by northwest-trending anticlines and synclines. We interpret the observed anticline-syncline pair as fault-propagation folds caused by an underlying blind thrust fault, which we herein term the Masters Hill blind thrust.

The Evergreen and Quimby faults are interpreted as bed-parallel, decollement-style faults that accommodate contractional strain along weak strata. The Quimby fault appears to occur within the Oakland conglomerate; the strata in the footwall of the Evergreen fault is unknown, though most likely the Evergreen fault occurs within the Knoxville shale. The Masters Hill blind thrust fault is interpreted to root at the stratigraphic level within the Cretaceous section that corresponds to the Quimby fault further to the west.

Cross section A-A' is located south of B-B', and shows a similar geometry of fault and fold structures (Figure 4). The anticline-syncline pair are present in a similar relationship as that given in B-B', although the units present at the surface are slightly older and deeper stratigraphically. This indicates that this fold plunges gently to the north. The blind thrust underlying the fault propagation fold is confined to similar stratigraphic levels as in A-A', with the tip of the fault interpreted to occur within the Cretaceous section. The Quimby and Evergreen faults again are interpreted as bedding-parallel structures, although in this cross section the Quimby fault is located at the boundary between the Knoxville shale and the overlying Oakland conglomerate. Thus it appears that the Quimby fault cuts downsection slightly along strike to the south. The Evergreen fault occurs within the Knoxville shale or at the contact with the underlying strata; the footwall stratigraphy is not exposed.

Cross section C-C' is located just to the north of B-B', and again shows the characteristic anticline-syncline fault propagation fold geometry within the Cretaceous and Tertiary section (Figure 5). The anticline has a tighter geometry than is present to the south, and the

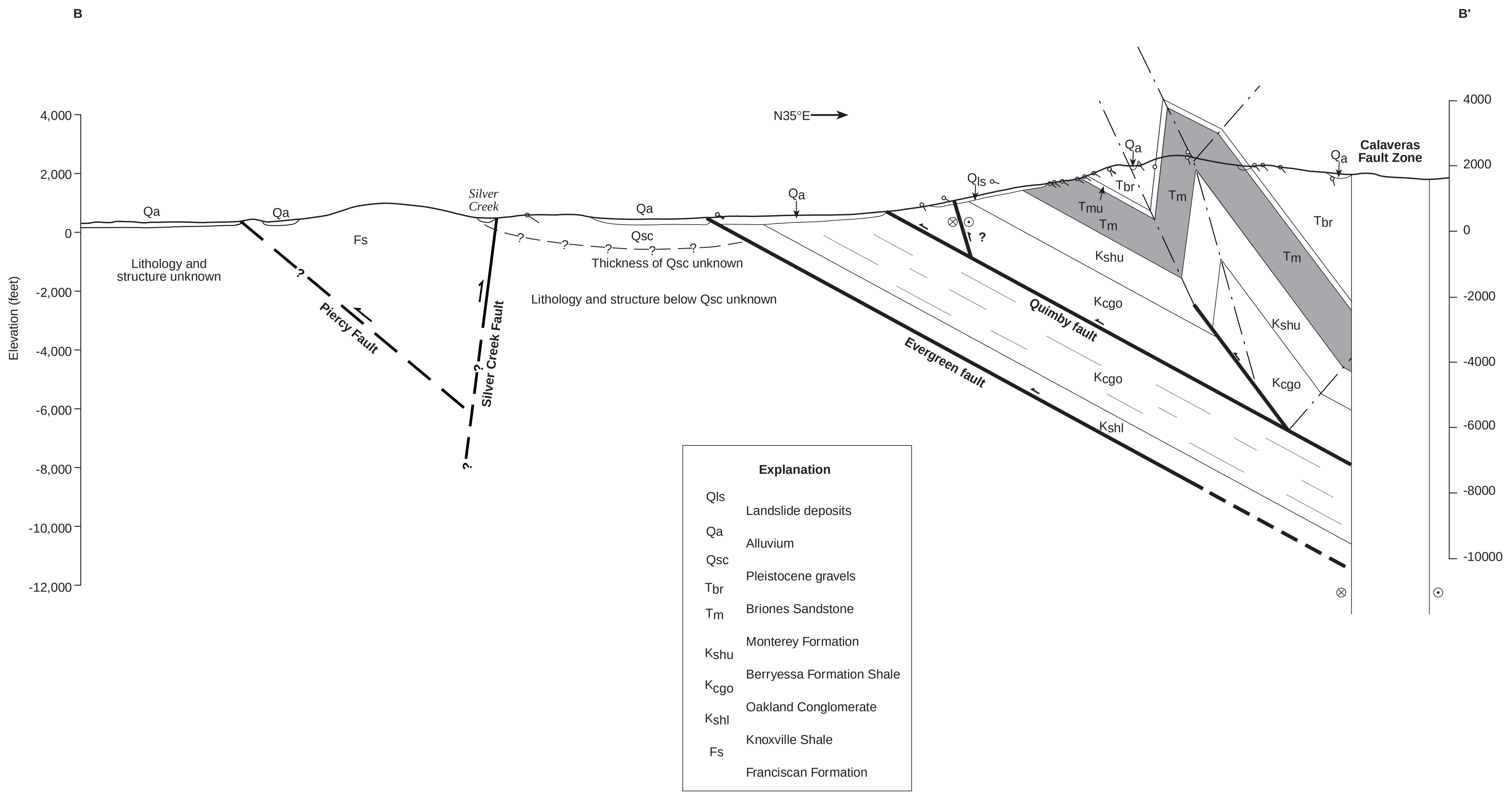


Figure 3. East-west cross-section B-B' through East Bay Hills. See Figure 2 for cross section location.

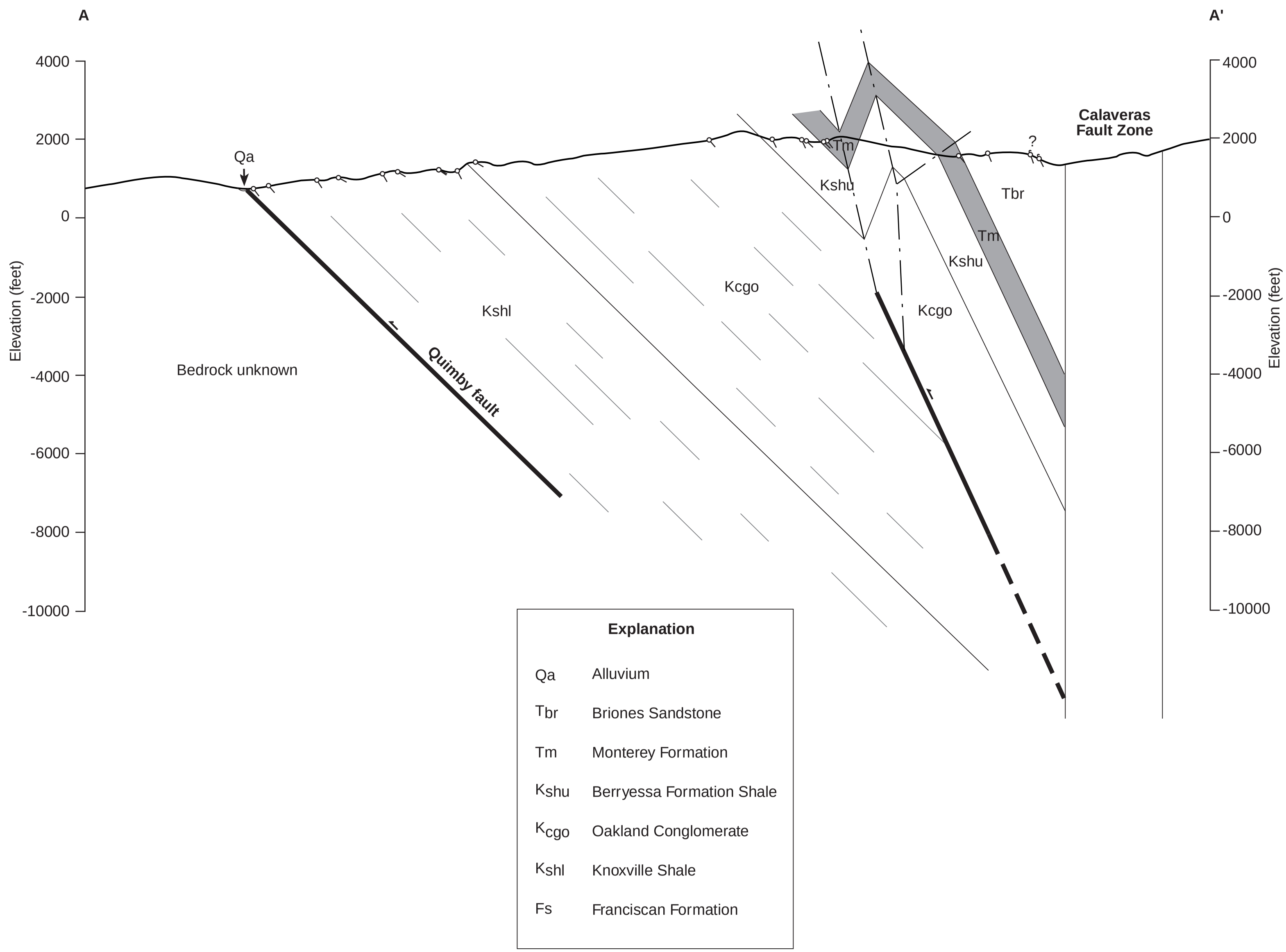


Figure 4. East-west cross-section A-A'. See Figure 2 for cross-section location.

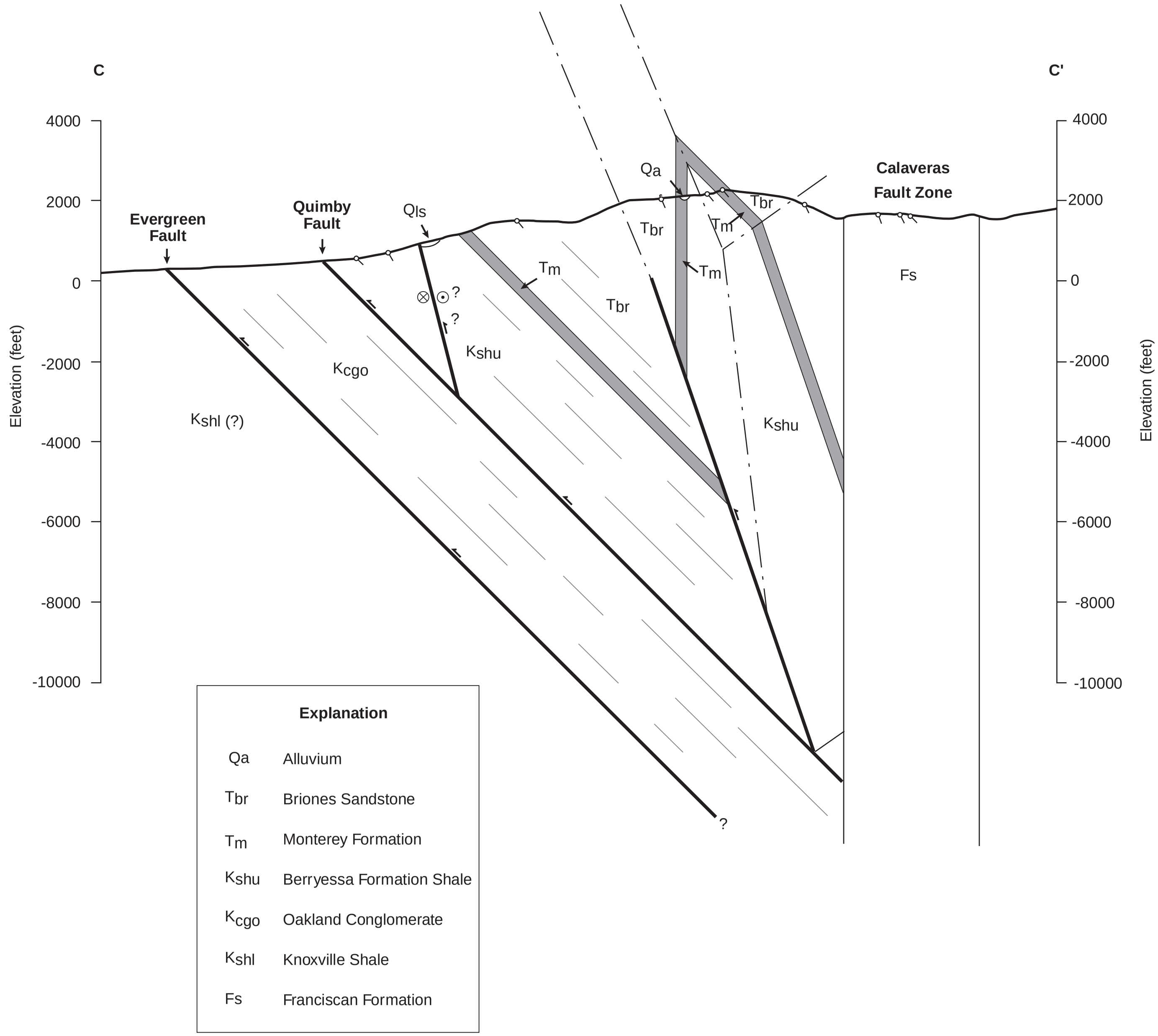


Figure 5. East-west cross-section C-C'. See Figure 2 for cross-section location.

blind thrust fault is interpreted to be larger, extending deeper to its intersection with the Quimby fault. Similar to the other cross sections, the Quimby and Evergreen faults are shown as bedding parallel structures, though here the Quimby fault occurs along the contact between the Oakland conglomerate and the overlying Berryessa shale unit. The Evergreen fault may occur within the Oakland conglomerate, or at the contact between the Oakland conglomerate and the Knoxville shale; as above, the footwall strata are not exposed along this section and are buried under alluvium.

These cross sections are idealizations of a complicated structural region, and slight deviations from the shown structure do occur. For example, bedding attitudes from very small areas along the cross sections often vary by as much as 20 degrees. In these areas, we used an average bedding dip or a dip that fit the majority of the data. Because of this, there are some portions of the cross sections that contradict local bedding data. However, these cross sections are meant to depict the large scale structural geometry and not local perturbations such as small outcrop scale structures such as small faults and folds. Although not a unique interpretation, we believe that these cross sections best honor the available data.

Our structural cross-sections provide evidence of a large fault propagation fold located beneath in the hills west of the Calaveras fault. This fold is apparent in the mapping by Dibblee (1972a) and is a regionally extensive feature, extending approximately 10 km subparallel to the strike of the reverse faults bounding the hills and diverging from the Calaveras fault at an angle of about 5-10 degrees. We interpret that the fold indicates the presence of a blind fault at depth, termed herein the Masters Hill blind thrust fault. Extrapolating the stratigraphy along bedding and following the methodology of Suppe and Medwedeff (1990), we infer the geometry of the blind fault responsible for the fold. The fault is a thrust fault that originates as a bedding parallel, decollment-style detachment within the Cretaceous section. Based on the geometric relationship with other structures, we infer that this detachment is the same structure that forms the Quimby fault further to the west.

We originally hoped that we would be able to constrain fault slip rates on reverse faults across the study area on the basis of the cross sections. Unfortunately, our interpretation of the Evergreen and Quimby faults as bedding-parallel structures does not allow us to calculate slip rates. Based on geomorphic evidence alone, such as relatively subdued and difficult to trace fault scarps, we suspect that the Evergreen and Quimby faults are relatively young and have experienced only minor displacement and/or relatively low slip rates. However, lack of large fault related folds indicates that neither the Quimby nor the Evergreen faults appears to have total displacements near the magnitude of the blind thrust fault that underlies the East Bay Hills.

We emphasize that these cross sections were drawn using only surface geology, and lack subsurface data to constrain the geometries of the faults and folds. While the cross sections were drawn using proven techniques, the lack of subsurface data is an acknowledged limitation of this interpretation. The relative sparseness of geologic and structural data within the area surrounding the Evergreen and Silver Creek faults, made constraining the subsurface geometry of these structures difficult. Few bedrock outcrops exist in this area, particularly in the area surrounding the Evergreen fault, and so the interpretation of the downdip extent of the fault is largely conjectural. However, we note that projection of the Evergreen fault downdip as a bedding-parallel decollment fault results in fault geometry similar to that of the Quimby fault, thus providing an internally consistent model for the style of faulting.

4.2 Geomorphic Analyses

Because of the reconnaissance nature of our study, we focused our mapping and field investigations along major streams that cross the study area. Urbanization covers or modifies much of the original landscape and native deposits within the eastern Santa Clara Valley. However, where unaltered, streams preserve portions of the original geomorphic setting (i.e. stream terraces and levees) and provide fresh exposures of native sediments. In addition, parks and greenbelts in the eastern Santa Clara Valley, typically established adjacent to streams, contain unmodified areas of the natural land surface. Changes in terrace surface gradients and stream channel gradients along these streams provide a direct means of assessing the presence or absence of Quaternary deformation associated with these structures and, if present, documenting the location, amount and pattern of deformation.

Geologic and geomorphic features identified on aerial photographs and topographic maps were examined in the field, where urbanization does not cover or obscure relations. We examined localities with geologic deposits and geomorphic surfaces that extend across mapped faults in order to: (1) document the presence or absence of late Quaternary deformation; and, if present, (2) assess the amount of fault offset. We also attempted, with limited success, to obtain datable material within deposits from which to estimate the ages of associated deformed and faulted geomorphic surfaces. Adequate age control on these deposits is required to derive the timing and rates of fault displacement.

On a more regional scale, our analyses of digital elevation data (derived from USGS DEMs) quantify the relief due to stream incision (surface dissection). This stream incision is an indirect measure of tectonic uplift, allowing us to evaluate how closely regional uplift is related to the mapped and inferred structures. In addition, uplift patterns likely are a good proxy for identifying and evaluating where and how strain is transferred between the Calaveras and Hayward faults.

4.2.1 Fluvial Terrace Longitudinal Profiles

Fluvial terrace profiles provide a means of assessing both regional and localized deformation across specific folds and faults. Detailed longitudinal profiles of terraces along two of the streams that cross the study area (Evergreen and Coyote Creeks) were constructed from available topographic maps. Departures from a concave profile (i.e., local convexities) were assessed for evidence of activity, specifically possible localized uplift.

4.2.1.1 Evergreen Creek

Evergreen Creek has its headwaters currently within the East Bay Hills east of the Evergreen valley. The Evergreen Creek stream profile was constructed using two-foot contour maps from a Santa Clara Water District topographic survey of the creek in 1971. The profile extends from within the rangefront upstream of the Quimby fault to Evergreen College, west of the Evergreen fault (Figure 6).

We identify a sequence of two distinct terraces (units Qht1 and Qht2) along Evergreen Creek (Figure 6). The oldest, and most laterally extensive, terrace (Qht) is inset into Pleistocene alluvial fan deposits. This terrace likely is late Pleistocene or early Holocene age based on a moderately well-developed soil in stream exposures. We collected charcoal samples (EG-1 and EG-2) from deposits within the upper portion of Qht1. We obtained two similar dates of 1930±40 BP and 1940±40 BP (Table 1). These late Holocene dates are younger than we anticipated and may represent overbank deposits. It is not known whether the geomorphic surface that we profile, i.e. the stream terrace surface, is in fact as young as the dates suggest. These dates may represent the minimum age of the deposits, not necessarily the actual age of the deformed surface. More age information is required to

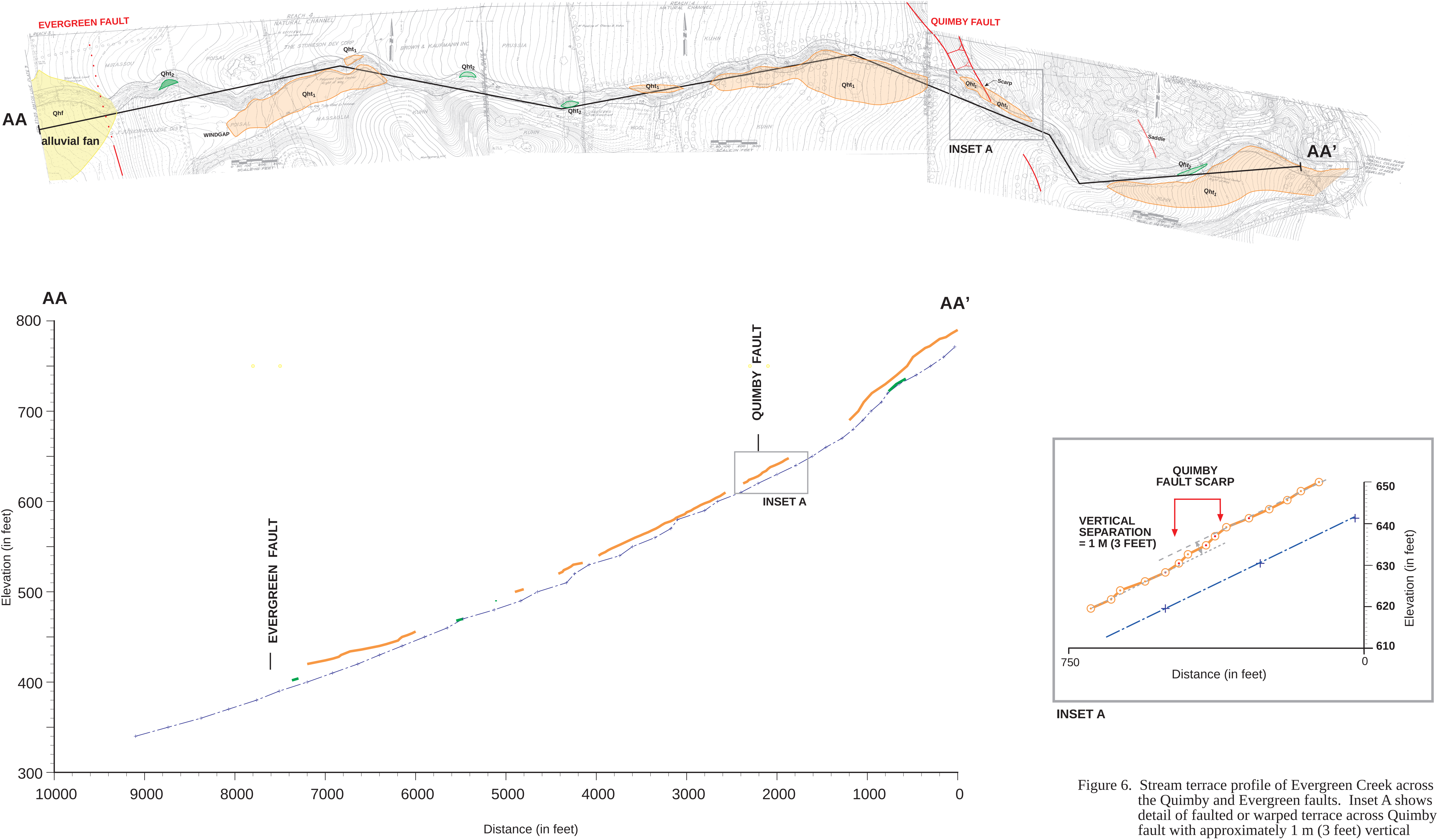


Figure 6. Stream terrace profile of Evergreen Creek across the Quimby and Evergreen faults. Inset A shows detail of faulted or warped terrace across Quimby fault with approximately 1 m (3 feet) vertical separation.

better constrain the age of the terrace deposits, preferably from a test pit or other fresh exposure deeper within the deposits.

We interpret a well-defined convexity in the oldest terrace (Qht1) and inset younger terraces (Qht2) in the longitudinal profile of fluvial terraces along Evergreen Creek as evidence for progressive warping and uplift in late Pleistocene through Holocene time (Figure 6). The Qht1 terrace diverges from the modern stream channel in two significant locations. Upstream of the Quimby fault, the terrace is located much higher above the stream channel than downstream of the fault. Upstream of the Evergreen fault, the same terrace diverges from the stream channel profile and appears to have been backtilted. We document approximately 1 m of offset and/or warping of the Qht1 terrace surface across the Quimby fault, consistent with east-dipping reverse displacement (Inset A; Figure 6). We interpret these relations as evidence for late Pleistocene and possibly Holocene activity on the underlying Evergreen and Quimby faults.

Based on the SCWD two-foot contour maps of Evergreen Creek, we have constructed a detailed scarp profile across the Evergreen fault (Figure 7). We tentatively correlate the surface of the faulted Qht1 terrace across the fault with the land surface west of the fault. Based on this correlation, we obtain a total minimum vertical offset of the Qht1 surface of 7.3 m (24 feet). This is a minimum because the surface may be buried west of the fault by younger deposits, including the alluvial fan deposits that are mapped just north of the scarp profile. Using the calculated vertical separation and dates obtained from the Qht1 terrace deposits along Evergreen Creek (Figure 7; Table 1), we obtain a late Holocene vertical separation rate of 3.8 mm/yr. Similarly we document 1 m of offset of a correlative terrace across the Quimby fault, and obtain a vertical separation rate of 0.5 mm/yr (Figure 6). However, we believe that the offset terrace likely is late Pleistocene or early Holocene and thus the actual slip rates on the faults likely are an order of magnitude less.

TABLE 1. RADIOCARBON DATES FROM SILVER CREEK FAULT EXPOSURE AND EVERGREEN CREEK STREAM TERRACE

Field Sample No.	Laboratory Sample Number	Sample Material	^{14}C Date[1]	Dendro-corrected Age
Evergreen Creek Terrace				
EG-1	Beta-167272	charcoal	*1920 ± 40*	*1940±40*
EG-2	Beta-167273	charcoal	*1930 ± 40*	*1930±40*
Silver Creek fault				
SC-1	Beta-167274	organic	*2660 ± 330*	*2620 ±330*
SC-2	Beta-167275	organic	*2190± 40*	*2180±40*

1) Delta ^{13}C values are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977) when given without decimal places. Values measured for the material itself are given with a single decimal place. The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (ibid.).

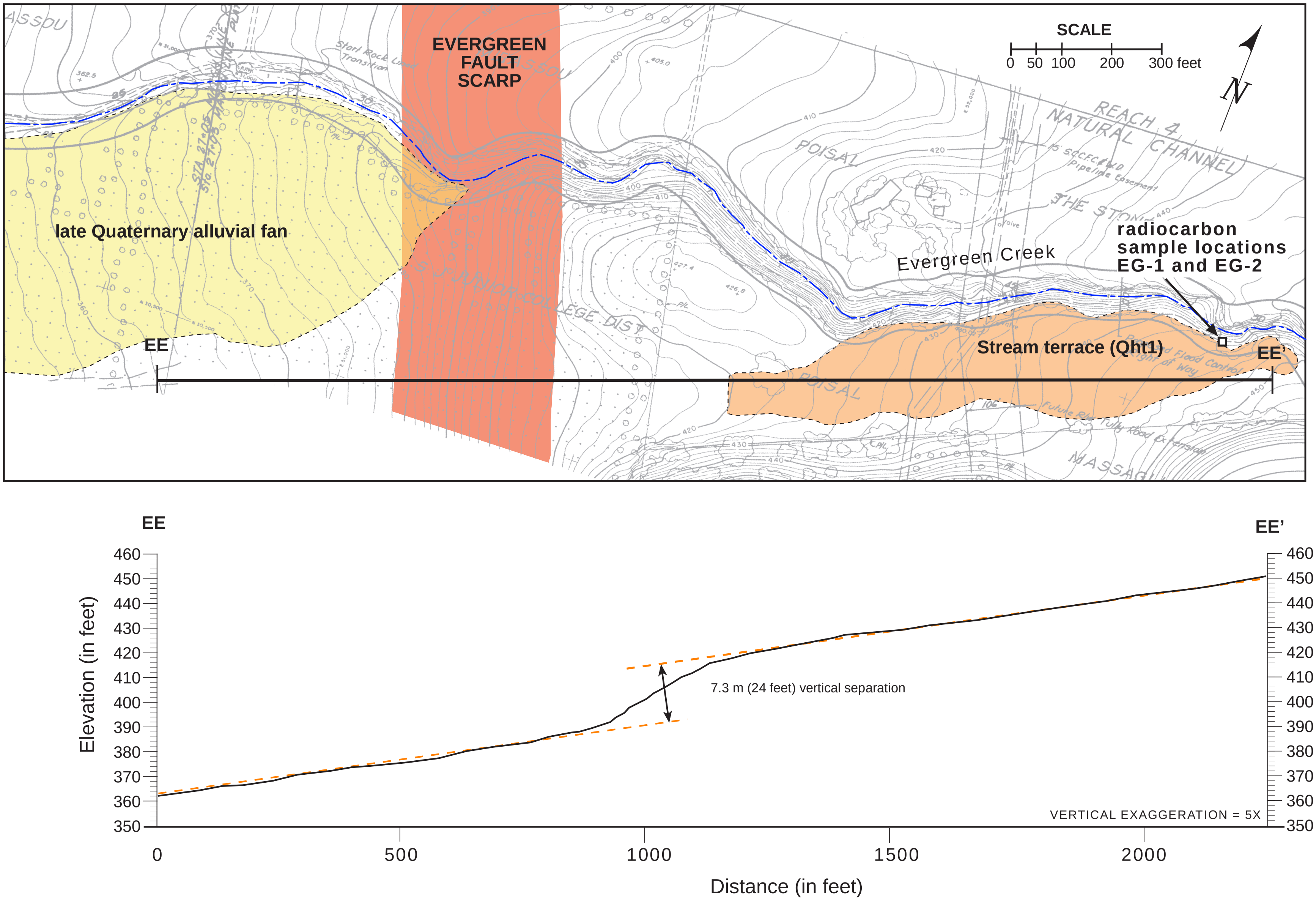


Figure 7. Evergreen scarp profile constructed from 2-foot topographic map from stream survey by the Santa Clara Water District in 1971 (SCWD project 40045). Orange dashed line is best fit to faulted surface used to calculated vertical separation.

4.2.1.2.Coyote Creek Stream Terrace Profile
Coyote Creek flows northwestward across the inferred trace of the Silver Creek fault before turning northward (Figure 8). We identify a sequence of at least distinct terraces (units Qt2 and Qt1) along Coyote Creek based on mapping by Knudsen et al (2000). The longitudinal terrace profile shows maximum elevations of the fluvial terraces upstream of the Silver Creek fault (within the inferred hanging wall of the fault).

The terrace profile is suggestive of Holocene uplift in the hangingwall of a west-dipping Silver Creek fault. Based on changes in the heights of the Holocene terraces above the active stream channel across the fault, it appears that incision and possibly associated uplift has continued into the Holocene. An alternative explanation is late Pleistocene and/or Holocene subsidence of the Evergreen basin has lowered the base level of the creek, resulting in the observed incision and apparent terrace formation pattern.

4.2.3 Fluvial Channel Profiles
Detailed longitudinal profiles of major streams that drain the eastern margin of the Santa Clara Valley (Evergreen and Coyote Creeks) were constructed from Santa Clara Water District topographic maps (2-foot-contours) and 1:24,000-scale USGS topographic maps (five-foot-contours). For this study, average stream-gradient index values were calculated for stream reaches with similar gradients, which are associated with linear slopes on semi-logarithmic stream profiles.

The longitudinal profile of Evergreen Creek shows no marked convexities across the Quimby or Evergreen faults (Figure 9). The overall stream channel pattern is consistent with broad uplift based on the convex channel profile in semilog form (Figure 9a), but there are no notable local variations in the active stream that would consistent with localized uplift. Thus, we interpret that Evergreen Creek, although crossing an area of active regional uplift, has been able to incise across local changes caused by minor coseismic uplift on the Quimby and Evergreen faults, as interpreted from trench logs (Woodward-Clyde Consultants, 1994; Fenton et al., 1995) and from the fluvial terrace profile (Figure 7).

The longitudinal profile of Coyote Creek shows a broad convexity across the inferred buried Silver Creek fault (Figure 10). The profile convexity may be related to near-surface anticlinal folding in the hanging wall of the Silver Creek fault fault. The profile convexity downstream of the range front is located entirely within alluvial sediments in Santa Clara Valley and coincides with a marked change in the incision of Coyote Creek within the valley floor (Figure 10). The change in incision across the fault also coincides with a change in the late Holocene depositional pattern from stream terrace formation within the inferred hangingwall of the fault to alluvial fan and levee formation within the inferred footwall.

4.2.4 Topographic Residual Map
Regional envelope and sub-envelope maps of the region between the Calaveras and Hayward faults (using second-order drainages) were constructed using digital elevation model (DEM) data following methods developed by Strahler (1952) and Stearns (1967). An envelope map is an interpretation of the pre-incision landscape that is created by interpolating a smooth surface that connects interfluves and flattish summit surfaces (Figure 11). The reconstructed landscape consists of remnants of once regionally extensive erosional surfaces. These surfaces likely are the original source areas of Plio-Pleistocene gravels, including the Plio-Pleistocene (4 ma) Santa Clara Gravels (Coyle, 1994).

The sub-envelope map is a surface formed by interpolating among the thalwegs of second-order drainages, and is interpreted to represent the current level of stream incision (Figure 12). The “residual” relief is derived by subtracting the elevation of the envelope surface from the sub-envelope surface at a point; a residual map is the contoured values of the

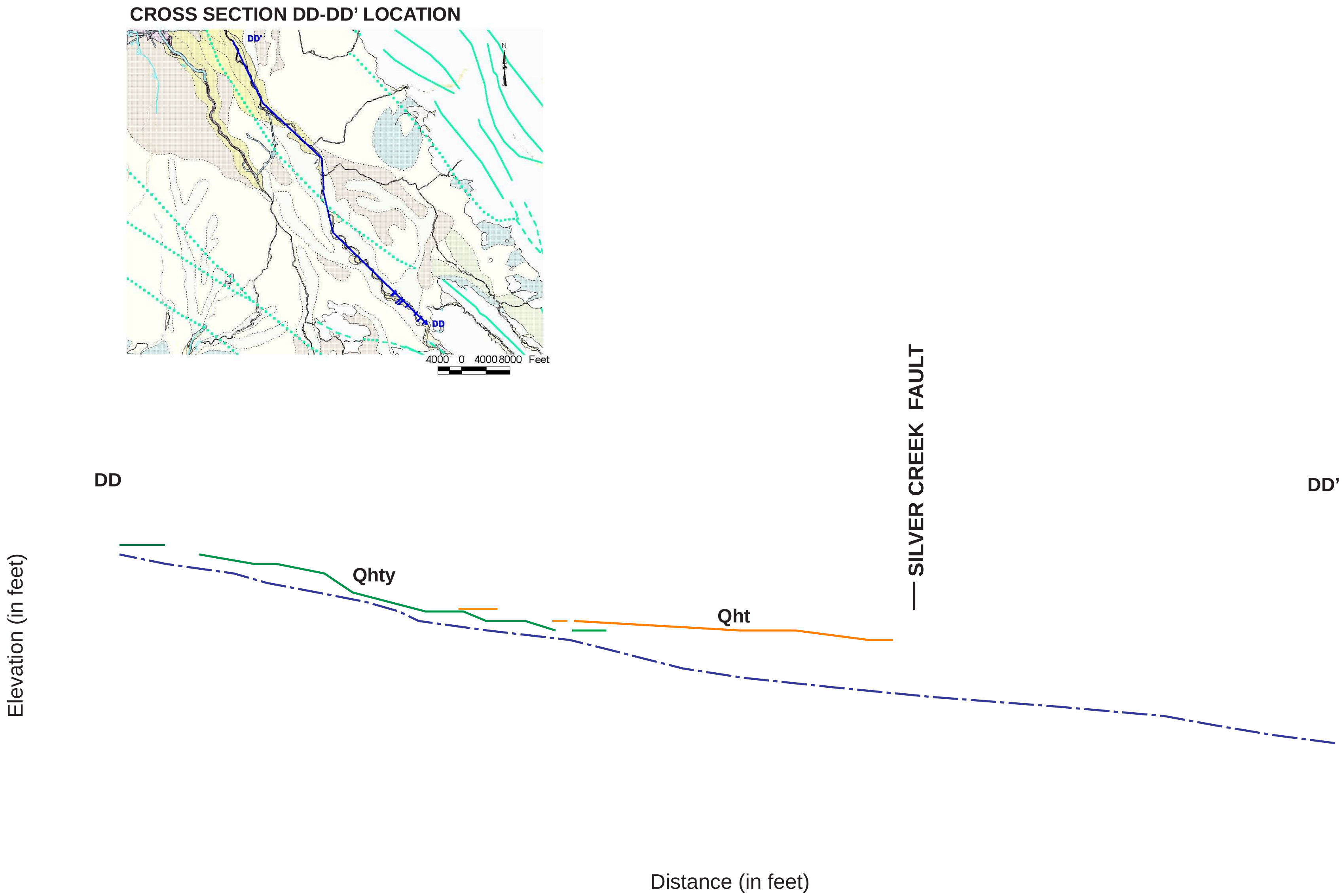


Figure 8. Stream terrace profile of Coyote Creek across the Silver Creek fault.

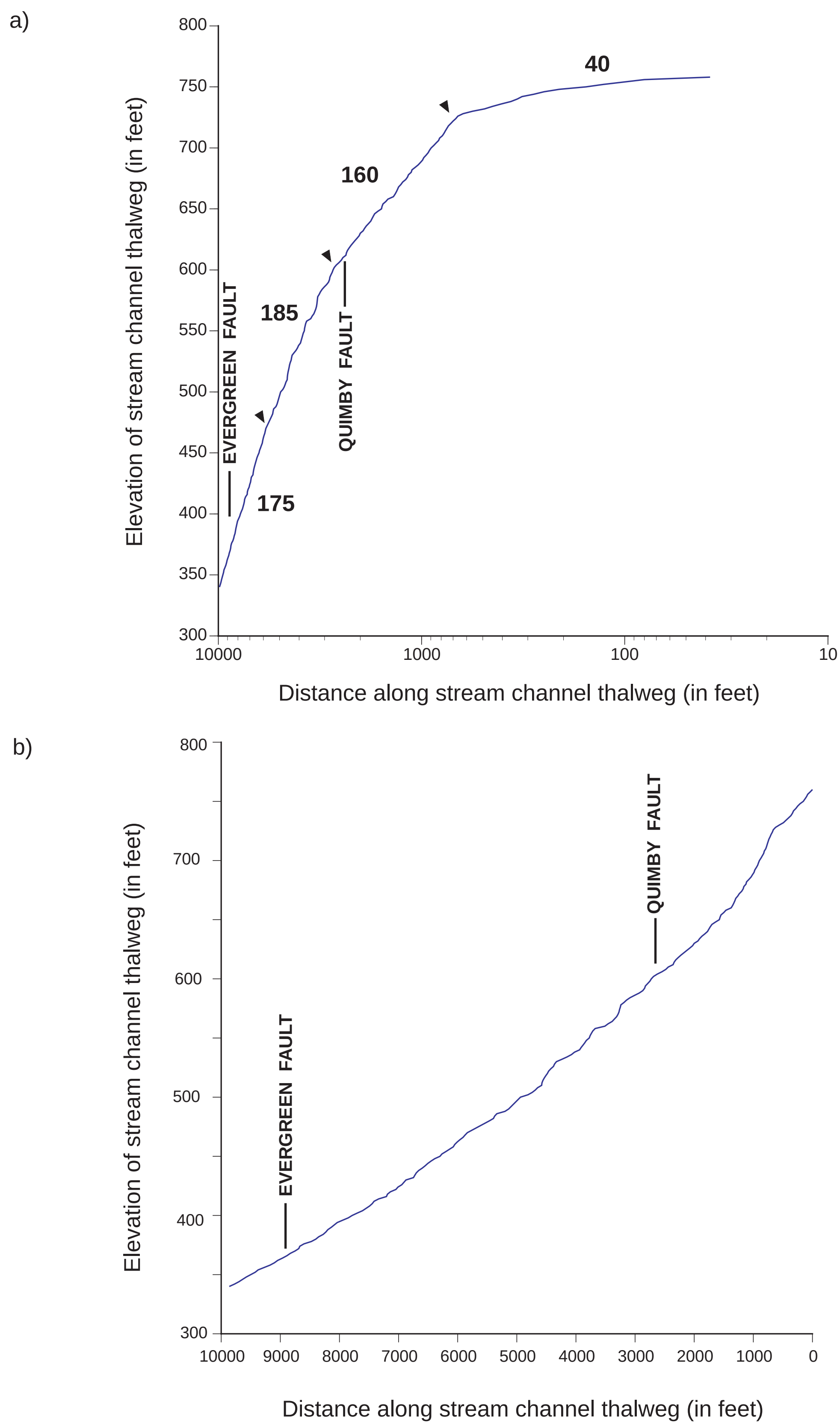


Figure 9. Stream channel profile of Evergreen creek shown on, (a) semilogarithmic plot and, (b) linear plot. Average stream-gradient index values are shown on the left of each stream reach.

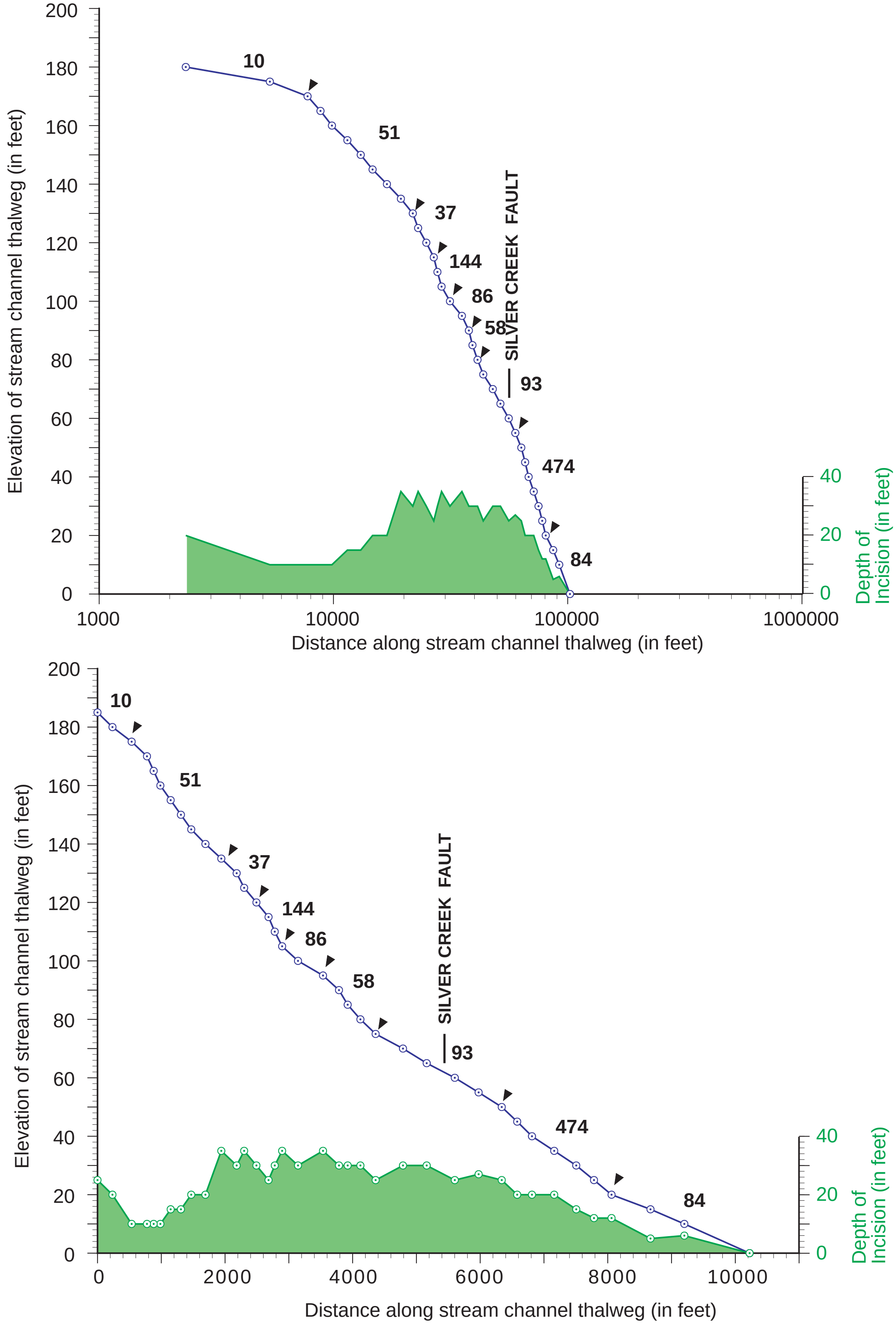
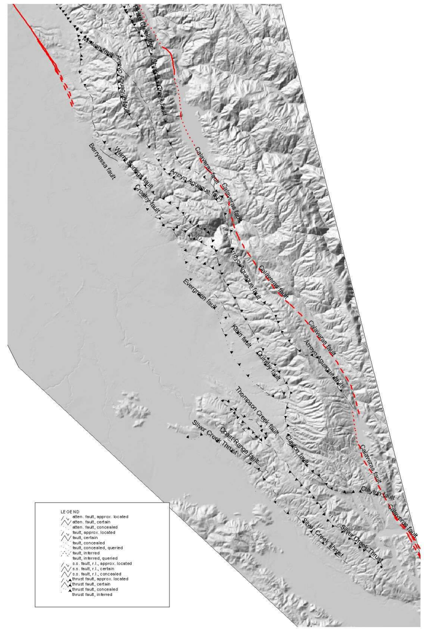


Figure 10. Stream channel profile of Coyote Creek shown on, (a) semilogarithmic plot and, (b) linear plot. Average stream-gradient index values are shown on the right of each stream reach. Depth of stream incision below present ground surface shown in green at base with legend to right of graph.

a)



b)

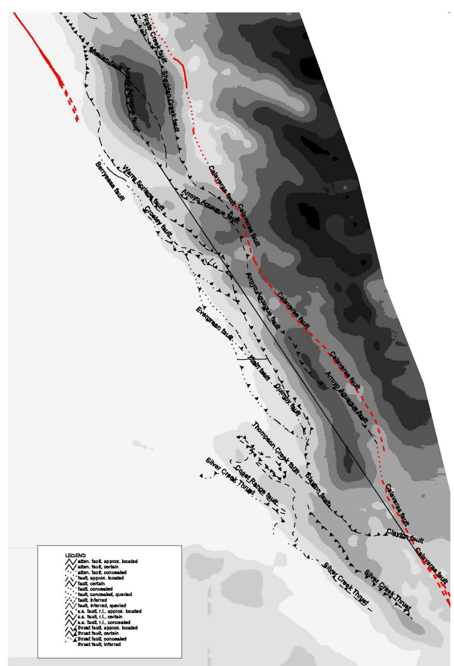


Figure 11. Digital Elevation Model (DEM) of study area and (b) topographic envelope map, derived via GIS analyses.

residuals at many points (Figure 13). A topographic residual map produced by subtracting the sub-envelope from the envelope thus quantifies, in a generalized sense, the relief due to stream incision (surface dissection). If it is assumed that erosional relief is, at least in part, a response to tectonic uplift, then residual maps indirectly document the loci and magnitude of uplift.

The topographic residual map of the study area confirms field observations of rugged topography and deep incision suggestive of continuing uplift. The residual map shows high residual values that coincide with an area of rugged topography above the inferred tip of the Masters Hill blind master thrust (Figure 13). The magnitude of the residual erosional relief is at least 750 feet (229 m). The localized high incision values are bounded by the east-dipping reverse faults including the Evergreen and Quimby faults. High residual values of 300 feet (90 m) or more also are associated with an active area of uplift associated with the East bay structural domain (Kelson and Simpson, 1992). The correlation of anomalous incision with previously identified studied active anticline lends additional confidence to our interpretation that high residual values are associated with localized Quaternary uplift.

Although we cannot date the timing of the uplift and fluvial incision of the hills located between the Calaveras fault and the southern end of the Hayward fault, the deep, narrow morphology of the canyons further suggest that incision is on-going.

4.3 Silver Creek fault exposure

During our field reconnaissance, we cleaned and logged an exposure of the Silver Creek fault excavated during construction of a golf course. The fault exposure, exposed between September 16th and 18th, 2001, and now covered by fill, was located approximately 500 feet southeast of a newly constructed bridge across Silver Creek near the intersection of Silver Creek Valley Road and Stonyford Circle (Figure 14). The temporary excavation, cut along the back edge of an active grading operation, exposed 45 m (approx. 145 feet) of bedrock faulted over Quaternary gravels (Figure 15). Our field mapping confirmed that the fault within the logged exposure is a major fault strand, likely the main strand, of the Silver Creek fault and documented the presence of a deformed late Quaternary stream terrace surface within the hanging wall of the fault.

The original ground surface at the site of the excavation, subsequently removed by grading and covered by backfilling, preserved a subtle but clearly defined east-facing scarp that trends north-south, sub-parallel to Silver Creek, and coincident with the mapped trace of the Silver Creek fault (Figure 14). The scarp ranged in height from 0.5 to 0.75 m along a zone 1 to 1.5 m wide within a distinctly warped geomorphic surface. The east-facing scarp coincides with a major west-dipping reverse fault exposed in the excavation.

The excavation enabled us to examine faulted bedrock and native sediments previously covered by artificial fill and obscured by recent development. The 2- to 4-m-high (6- to 12-foot-high), north-facing vertical cut trended 210°, orthogonal to the trend of the Silver Creek fault. The cut exposed sheared Franciscan bedrock thrust over older alluvial gravels of unknown age (likely Pleistocene) and scarp-derived colluvium (Figures 14, 15, and 16). The faulted gravels and colluvial wedge are covered by recent alluvial deposits with a weakly developed soil.

Bedrock west of the fault contact consisted of intensely sheared serpentinite and bedded chert. Internal fault contacts between the chert and serpentinite bodies are west dipping as are the general shear fabric and other shear indicators, including slickensides along fault planes. The main fault that juxtaposes Franciscan bedrock over fluvial gravels dips approximately 60° to the west (Figure 16). Several major sub-parallel west-dipping faults

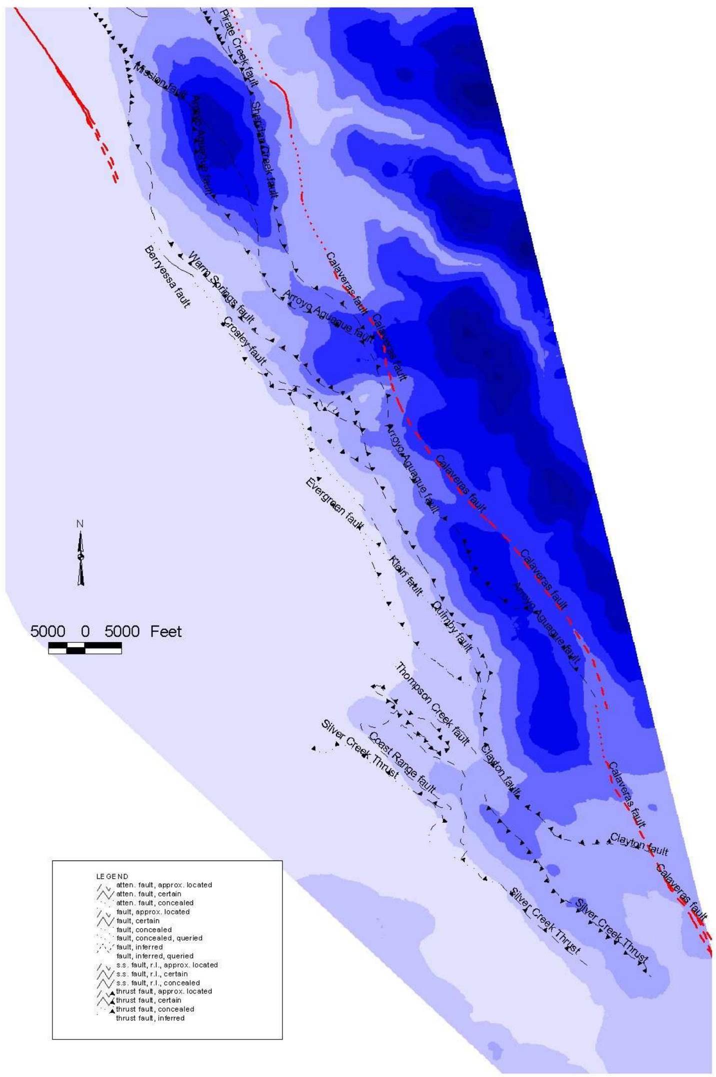


Figure 12. Subenvelope map of study area derived via GIS analyses.

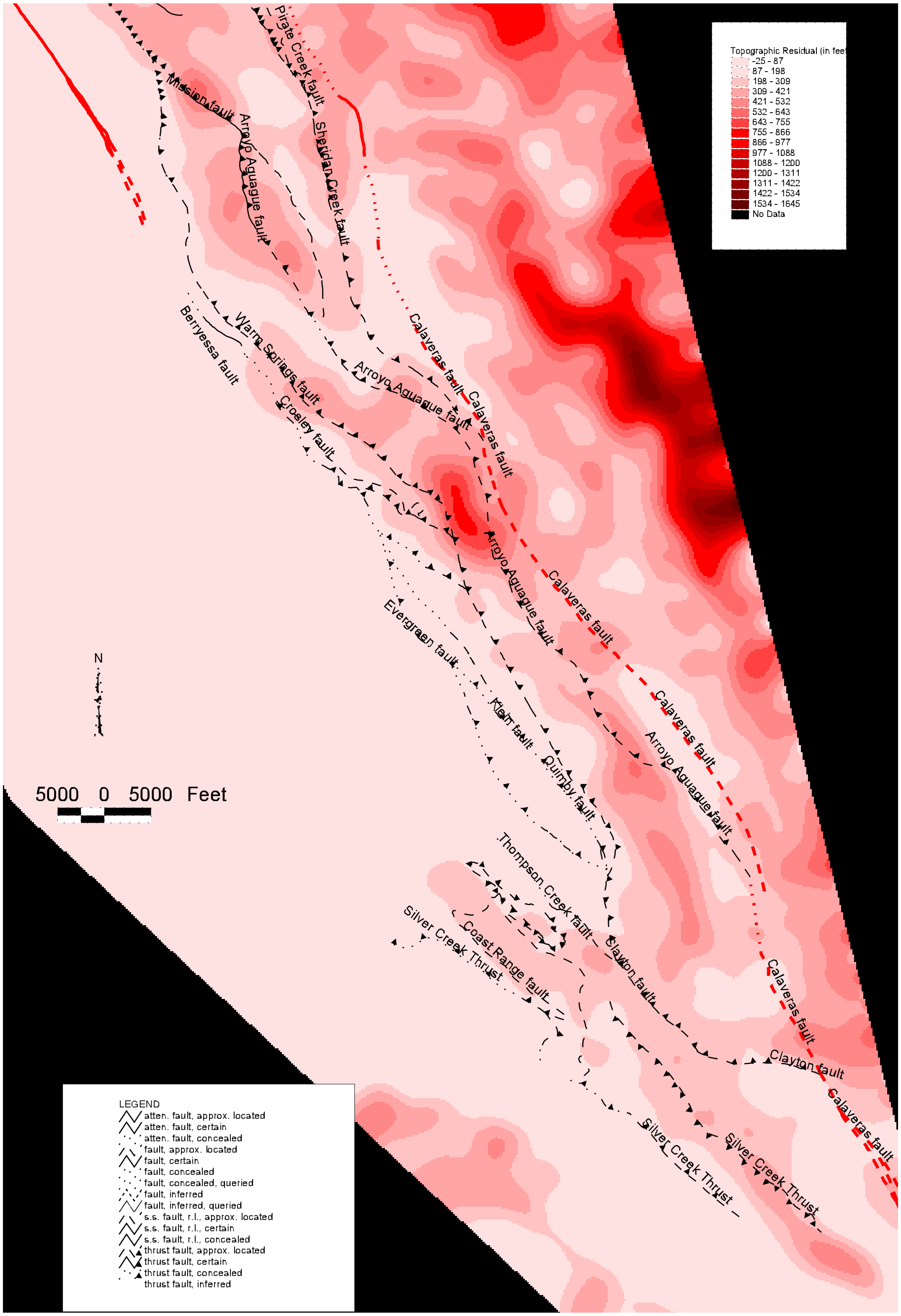


Figure 13. Topographic residual map of study area derived via GIS analyses.

Figure 14. Location map (a) and aerial photograph (b) of Silver Creek fault exposure. Photograph (c) is looking to the south. Photograph (d) is looking to the southeast and shows the east-facing topographic scarp associated with the fault.

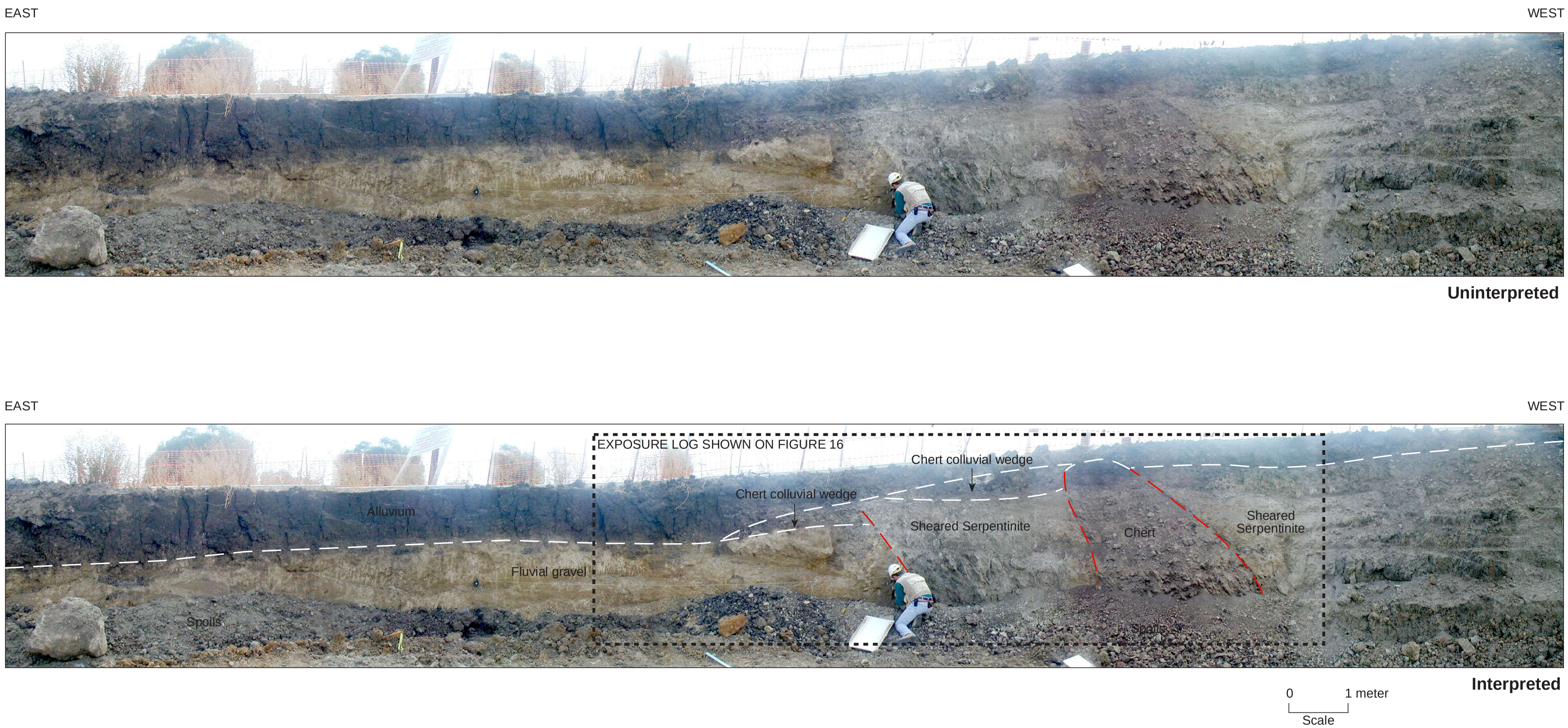


Figure 15. Photo mosaic of east-west exposure of the Silver Creek fault. Photos taken on September 18, 2001.

that bound chert and serpentinite bodies within sheared Franciscan bedrock within the Silver Creek fault zone west of the inferred main strand steepen with depth from 60° near the surface to as much as 70° at the base of the exposure.

A faulted colluvial wedge is present east of, and adjacent to, the interpreted main fault strand, and consists of large (>3-4 cm diameter), angular chert fragments within a serpentinite matrix (Figures 16 and 17). The colluvial wedge is clast supported, poorly graded, and lacks internal stratification. It appears to consist of a single deposit with no internal contacts that would indicate multiple colluvial episodes. Chert within the wedge is identical to bedded chert exposed in the chert body 3 m to the west (Figure 16). We believe that the fault-bounded chert body is the source of the colluvial wedge.

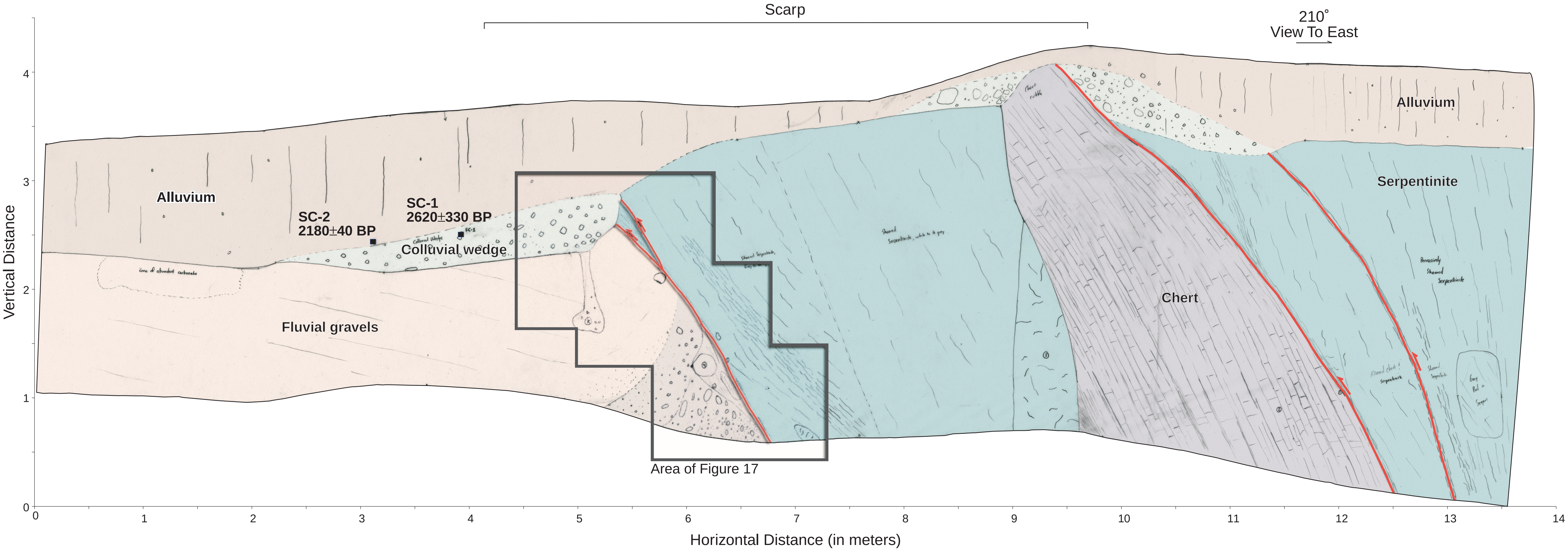
The exposure provides information on sense of slip and probable style of faulting on the Silver Creek fault. Bedding within the faulted gravels is warped upwards against the fault, consistent with drag folding due to reverse displacement on the fault. Although we can not preclude a component of strike-slip displacement, the predominant sense of slip appears to be reverse.

Based on the presence of the faulted colluvial wedge above the faulted fluvial gravels, we interpret at least two distinct surface faulting events. It is likely that the colluvial wedge is derived from an east-facing scarp developed during the penultimate event. The wedge has, in turn, been faulted by a subsequent event. The colluvial wedge, and adjacent scarp, appears to have been subsequently stripped and covered by recent fluvial deposits.

The observed colluvial wedge stratigraphy is not consistent with incremental uplift during triggered or coseismic movement on the Silver Creek fault. Minimum vertical fault displacement of about 0.5 m is required based on the faulted colluvial wedge. As observed above, this wedge does not contain internal stratification or other evidence of multiple colluvial episodes but rather appears to be distinct unit, likely representing a fault displacement of similar size or larger.

Results of radiocarbon analyses of charcoal and organic material sampled from the faulted colluvial deposits and overlying, apparently unfaulted fluvial deposits provide preliminary constraints on the timing of the most recent event. The age of the faulted colluvium was estimated from a very small sample (0.9 mg; sample SC-1; Table 1) that we submitted, along with the other three samples, to Beta Analytic in Florida. The date of sample SC-1 was obtained by diluting the sample carbon with dead CO2 to obtain a full size sample for the AMS detection. This is known as “isotope dilution”. A “dilution factor” was calculated and used to derive the net activity of the sample. A reference sample with a known age of 4500 +/- 40 BP which was analyzed simultaneously using the same methodology yielded a statistically comparable age of 4750 +/- 160 BP (0.8 sigma agreement) inferring validation. The result does indicate an age of < 10,000 BP even with the indeterminant error (e.g. the indeterminant error is not large enough to make the date older than 10,000 BP). Radiometric analysis of organic material from the base of the overlying fluvial deposits resulted in an age estimate of 2180±40 BP (Table 1).

Although based on the results of the radiocarbon analyses it is possible that the faulted colluvial wedge is Holocene, the uncertainty in the age and similarity in the date obtained from the colluvial deposits to the overlying deposits requires that further age control on the timing of earthquakes on the Silver Creek fault be obtained prior to concluding that the fault is in fact Holocene active. The faulted colluvial wedge appears to have been eroded prior to deposition of the overlying Holocene deposits, suggesting, but not requiring, that there may be a significant hiatus following the deposition and subsequent faulting of the colluvial deposits, prior to burial by the overlying Holocene fluvial deposits.



SILVER CREEK FAULT

Log of September 18, 2001 Exposure

WLA William Lettis & Associates, Inc. | Figure 16

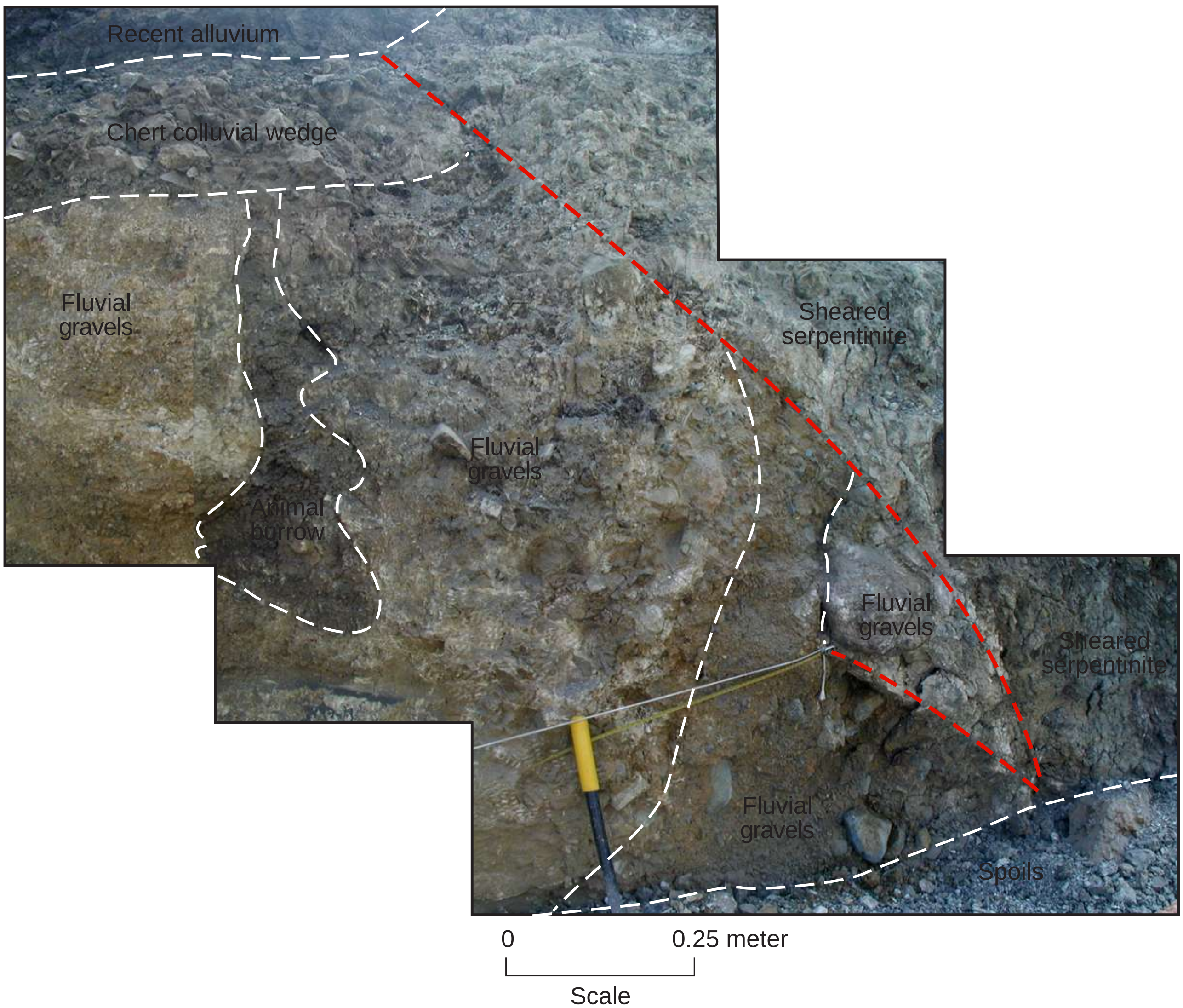


Figure 17. Close-up photograph of Silver Creek fault exposure taken on September 18, 2001.

5.0 DISCUSSION

Based on our structural cross sections and geomorphic profiles, east-dipping reverse faults bounding the eastern Santa Clara Valley play a prominent role in uplift of the hills east of San Jose. It is also likely that these faults accommodate strain transfer between the Calaveras and Hayward fault systems. However, based on our cross sections, the Quimby and Evergreen faults intersect the Calaveras fault at depths of about 4-5 km (12000-15000 feet). Therefore these faults likely are limited to the upper crust and do not extend to depths at which moderate to large earthquakes (>M5) typically nucleate. Because these faults intersect the Calaveras at relatively shallow depths, they may rupture in conjunction with, or are triggered by, a large earthquake on the Calaveras fault.

The Silver Creek fault, located west of the east-dipping reverse faults that bound the hills along the margin of Santa Clara Valley, is a major fault that bounds the western margin of the Evergreen structural basin (Jachens et al. 2002). Field exposure of the Silver Creek fault shows a west-dipping structure with reverse displacement. The observed geomorphic pattern of uplift within Santa Clara Valley above the west-dipping Silver Creek fault is distinct from, and different than, the observed pattern of localized uplift of the hills east of the Evergreen, Quimby, and other east-dipping faults that bound the eastern margin of Santa Clara Valley. Because the Silver Creek faults dips more steeply than the east-dipping faults, appear to have significant fault slip per event, and is a more significant structural discontinuity, it likely is a seismogenic feature capable of producing independent earthquakes.

Although preliminary, our results contribute information on the style and rates of deformation on these faults. We document a pattern of incision and stream terrace formation within the broad piedmont upstream of the Evergreen fault, and deposition of Holocene alluvial fans downstream. We interpret these relations as evidence of late Pleistocene, and possibly younger, uplift within the hanging-walls of east-dipping reverse faults. This interpretation is consistent with our GIS-based topographic analysis that shows regionally extensive erosional surfaces in the East Bay Hills have been subsequently uplifted and segmented by tectonic uplift.

5.1 Structural and Kinematic Model

Jachens et al. (2002) proposed that the Silver Creek fault is a predominately strike-slip fault with up to 40 km of right-lateral displacement. They interpreted that slip may be transferred to the Hayward fault by strike-slip displacement along the Silver Creek fault and that the Evergreen basin is an extensional pull-apart basin between the Silver Creek and southern Hayward faults (Jachens et al, 2002).

We present an alternative structural model. Based our interpretation of the Silver Creek fault as a west-dipping fault with predominately reverse displacement and the faults bounding the eastern Santa Clara as east-dipping reverse faults, we believe that the Evergreen basin may have formed between two vergent reverse fault systems (e.g. Figure 3).

A lack of reliable structural data in the area prevents us from constructing balanced cross sections to interpret the subsurface geometry of the Silver Creek fault or to definitively exclude one or the other interpretation. Geomorphic evidence for apparent late Quaternary uplift in the hangingwall of the west-dipping Silver Creek fault can also be explained by lowering of stream levels due to subsidence of the Evergreen basin, including that produced by tectonically driven extension across a pull-apart basin as argued by Jachens et al. (2002). Regardless, based on either interpretation, the Silver Creek fault likely is a major, crustal-scale structure that should be considered a possible independent seismic source.

Within the East Bay Hills, the geometry of the Masters Hill blind thrust fault and the extent to which it has broken upward from the master detachment, as well as the amount of slip that the blind thrust has accommodated, changes from north to south. In the southern portion of the study area, the fold exposes Cretaceous strata in the core of the anticline; further north, the same structural position exposes Miocene units. In addition, the magnitude of inferred slip along the interpreted blind thrust fault increases from south to north, based on the structural relief of the fault propagation anticline and the increasing length of the back-dip panel of the anticline. From these features we estimate the amount of shortening on these structures to be on the order of a maximum of 2,500 m (8000 feet). This estimate does not include any bed-parallel shortening that may have occurred. Such shortening can not be estimated from the available structural data and interpretation.

Construction of cross sections north of cross-section C-C' was attempted but was not successful using any of the considered balanced cross-section methods. We infer that to the north, the increasing component of strike-slip associated with the southern termination of the Hayward fault has produced out-of-section displacements that cannot be accounted for in the standard kinematic models.

5.2 Regional Rates of Quaternary Deformation

Melting and retreat of glacial ice at the end of the Pleistocene caused sea level to rise and invade the valleys now occupied by the San Francisco Bay (Atwater and others, 1977). Rapid rise in base level should have substantially reduced the ability of streams to continue downcutting. Indeed, within Santa Clara Valley and elsewhere along the Bay margins, the irregular Pleistocene landscape has been covered by relatively flat-lying Holocene deposits (Hitchcock and Helley, in prep.). Deeply incised Pleistocene stream channels have been infilled by thick packages of Holocene fluvial deposits.

However, the presence of inset Holocene stream terraces and deeply incised stream channels provide direct evidence that creeks are actively downcutting, despite the rise in base level during the Holocene. Either streams have not yet adjusted to the new base level conditions or Holocene uplift has exceeded the rate at which base level (sea level and infilling of San Francisco Bay) has rose. Patterns of incision and terrace development along major streams are not uniform as would be expected with a pure fluvial response to base level rise. For example, the transition between incision and deposition along Coyote Creek (Figures 8 and 10), likely corresponds to development of the Evergreen structural basin and thus is tectonically controlled. Similarly, changes in streams across the Quimby and Evergreen faults likely correspond to localized and regional uplift bounded by these faults.

Assuming that stream incision rates are equivalent to, or less than, uplift rates, we can estimate regional rates of Quaternary uplift rates. Within the study area, channel incision rates likely reflect a combination of factors, and incision rates can therefore be used only to constrain the maximum uplift rate. Therefore, given the reconnaissance nature of this study, and the lack of absolute ages for the fluvial deposits, these rates should be regarded as order-of-magnitude estimates only. Additional age dating studies are required to refine our estimated deformation rates.

The topographic residual map of the study area confirms field observations of rugged topography and deep incision suggestive of long-term uplift. The residual map shows high residual values that coincide with an area of rugged topography above the inferred tip of the

Masters Hill blind thrust (Figure 13). Topographic residuals consistent with localized uplift are coincident with mapped reverse faults. These erosional surfaces likely are the original source areas of Plio-Pleistocene gravels, including the Santa Clara Gravels (Coyle, 1994). Although we do not have dates on the ages of the regional surfaces, they likely roughly correspond to the ages of the Plio-Pleistocene gravels (about 4 ma). In addition, these gravels are folded and faulted by the reverse faults along the rangefront and the Silver Creek fault providing evidence for continuing local and regional deformation.

5.3 Hazard Assessment of Seismogenic Sources

Our structural and geomorphic analyses provides important new information on the reverse faults that bound the eastern Santa Clara Valley, in particular the Evergreen, Quimby, and Silver Creek faults. Based on our interpretive cross sections, the Evergreen and Quimby faults most likely intersect the Calaveras fault at depths of about 4-5 km (12000-15000 feet). Thus these faults are limited to the upper crust and likely do not extend to depths at which earthquakes typically nucleate. However, the fact that these faults intersect the Calaveras at relatively shallow depths may indicate that they could rupture in conjunction with, or triggered by, a large earthquake on the Calaveras fault.

As described above, for the construction of these cross sections we assumed that no major strike-slip displacements were present on the east-dipping reverse faults. It is possible that these faults may accommodate some strike-slip displacements transferred from the southern termination of the Hayward fault. However, the balanced cross sections support the interpretation that the primary mode of deformation on these structures is contractional, and thus that the primary sense of slip on these range-bounding faults is reverse.

Our interpretation is that the Evergreen and Quimby faults are bedding-parallel detachment-style faults that are relatively young and immature compared to the larger-scale folds and faults that occur eastward in the East Bay Hills. We believe that the majority of the crustal shortening and deformation has been accommodated within the East Bay Hills by the propagation of the Masters Hill blind thrust and the associated anticlinal folding above the fault tip. In contrast, the lack of large folds or dramatic fault scarps west of the range front, in the area of the Evergreen fault, indicate that these faults likely are young.

Our observations are consistent with previous trench exposures of the Evergreen fault that documented relatively minor amount of displacement on the exposed fault (Fenton and Hitchcock, in press). These data indicate that strain likely is partitioned in this area, with shear strain being taken up by the Calaveras fault and compressional strain accommodated by the Evergreen, Quimby, and other east-dipping reverse faults. Based on our cross-sections, it appears that the Evergreen fault is the youngest of the faults, having the least pronounced topographic scarp and occurring about 1 km west of the main mountain front.

Based on outcrop evidence that the Silver Creek is a west-dipping reverse or oblique-slip fault and because it has a different orientation than the other reverse faults in the eastern Santa Clara Valley, we interpret that the Silver Creek fault is distinct from the east-dipping reverse faults that bound the eastern margin of Santa Clara Valley. In addition, the observed geomorphic pattern of uplift within Santa Clara Valley above the west-dipping Silver Creek fault is distinct from, and different than, the observed pattern of localized uplift of the hills east of the Evergreen, Quimby, and other east-dipping faults that bound the eastern margin of Santa Clara Valley.

Because of the steep west-dip of the Silver Creek fault through the seismogenic crust and the presence of significant slip per event, we interpret the fault to be a potentially significant seismic source. In addition, the Silver Creek fault bounds the Evergreen structural basin and, as noted by Jachens et al. (2002), likely plays a significant role in transferring slip between the larger strike-slip faults in the region. We have documented displacement of Plio-Pleistocene gravels and younger scarp-derived colluvial deposits. Preliminary radiocarbon analyses suggest that the faulted colluvial deposits may be Holocene although we do not believe that there are sufficient constraints on the ages of the faulted deposits. Additional detailed study is necessary to better constrain the timing of past earthquakes on the Silver Creek fault. Pending more detailed research, we believe that the geomorphic and preliminary paleoseismic evidence is sufficient to consider the Silver Creek fault potentially active.

6.0 CONCLUSIONS

Reverse faults bounding the east Valley likely play a prominent role in uplift of the hills east of San Jose and strain transfer in the San Francisco Bay area. Our study provides new information on the near-surface geometry, style of deformation, and late Quaternary deformation of the east Valley reverse faults. In addition, we provide information on the rate and recency of potential fault activity based on faulted and/or deformed late Quaternary deposits and surfaces.

Retrodeformable structural cross sections across the East Valley thrust system indicate that the Quimby and Evergreen faults of the East Valley Thrust System most likely intersect the Calaveras fault at depths of about 4-5 km (12000-15000 feet). Thus these faults of the most likely are not primary seismic sources capable of large earthquakes. However, because these faults intersect the Calaveras at relatively shallow depths, they may rupture in conjunction with, or triggered by, a large earthquake on the Calaveras fault. Morphometric analysis of regional topography, incorporating GIS analysis of available digital elevation models (DEMs) shows patterns of topographic residuals coincident with the east-dipping reverse faults, and consistent with localized late Quaternary uplift of the hills east of the faults.

We interpret a series of northwest-trending anticlines and synclines within the hills east of Santa Clara Valley as fault-propagation folds caused by the underlying Masters Hill blind thrust. The fold axis of a prominent fault propagation fold inferred from our structural cross-section closely matches an area of high topographic residuals. The coincidence of the topographic residuals above a master blind thrust fault suggests that recent uplift of the hills west of the Calaveras fault may have been at least partially accomplished by folding above the blind thrust fault.

Based on outcrop evidence that the Silver Creek is a west-dipping reverse fault, and because it has a different orientation than the other reverse faults in the eastern Santa Clara Valley, we interpret that the Silver Creek fault is distinct from the east-dipping reverse faults that bound the eastern margin of Santa Clara Valley. In addition, the observed geomorphic pattern of uplift within Santa Clara Valley above the west-dipping Silver Creek fault is distinct from, and different than, the observed pattern of localized uplift of the hills east of the Evergreen, Quimby, and other east-dipping faults that bound the eastern margin of Santa Clara Valley. Changes in stream valley morphology along major streams that cross the Silver Creek fault and profiles of terraces along Coyote Creek are consistent with late Pleistocene, and possibly Holocene, uplift within the inferred hanging wall of a west-dipping reverse fault.

Based on our interpretation that the Silver Creek fault is a west-dipping fault distinct from the east-dipping faults bounding the eastern margin of the Santa Clara Valley, we believe that interaction between the two sets of reverse faults likely controls the structure of the eastern Santa Clara Valley. In particular, the north-trending Evergreen structural depression likely has formed as a subsiding basin between the convergent thrust fault systems.

Based on scarp profiling and offset of a late Quaternary fluvial terrace along Evergreen Creek, we obtain a minimum vertical separation of 8 m on the Evergreen fault and 1 m on the Quimby fault. Based on radiocarbon dates from the upper terrace deposits, we obtain a vertical separation rate on Evergreen fault of 3.8 mm/yr and on the Quimby fault of 0.5 mm/yr. However, we believe that the offset terrace likely is early Holocene and thus the actual rate on the faults likely an order of magnitude less.

The Silver Creek fault bounds the Evergreen structural basin and plays a significant role in transferring slip between the larger strike-slip faults in the region. We have documented displacement of Plio-Pleistocene gravels and younger scarp-derived colluvial deposits. Radiocarbon analyses suggest that the Silver Creek may displace Holocene deposits and thus, pending more detailed research, should be considered potentially active.

7.0
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APPENDIX A: REPORTS OF RADIOCARBON DATING ANALYSES