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Geomorphic Investigations of Deformation Along the Northeastern Margin of the Santa Cruz Mountains

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ABSTRACT

The October 17, 1989 Loma Prieta earthquake produced coseismic ground deformation in the urbanized area along the northeastern flank of the Santa Cruz Mountains. This ground deformation was coincident with the general trend and locations of the Berrocal, Monte Vista, and Shannon faults, and is consistent with coseismic movement on these structures (Haugerud and Ellen, 1990). These faults are part of a series of southwest-dipping reverse faults that border the Santa Cruz Mountains range front and traverse the communities of Los Gatos, Saratoga, Cupertino, and Los Altos Hills. These faults, which deform the Pliocene and Pleistocene Santa Clara Formation and overlying Quaternary deposits, pose a potentially significant earthquake hazard to Santa Clara Valley. Possible movement along these faults during the 1989 Loma Prieta earthquake, and similar reported surface deformation during the 1906 earthquake (Lawson, 1908), suggests that the range-front faults may be Holocene active faults related at depth to the San Andreas fault. This research provides a basic geologic and geomorphic framework to address whether these faults are independent seismic sources, or if displacement occurs only as secondary deformation during large-magnitude events on the San Andreas fault.

The primary objective of this study is to determine the nature and pattern of late Quaternary tectonic deformation along the eastern Santa Cruz Mountains range front. Our mapping of late Quaternary deposits between Los Altos Hills and Los Gatos shows that several potentially fault-related geomorphic features are present along the range front coincident with the previously mapped Monte Vista and Shannon faults. In addition, there is substantial geomorphic evidence of surficial deformation in coalescent alluvial-fan deposits northeast of the range front coincident with the inferred Cascade fault (California Department of Water Resources [CDWR], 1975). The pattern of *en echelon* topographic and vegetation lineaments are evidence of distributed contractional deformation within a zone at least 5 km wide northeast of the range front.

Longitudinal profiles of late Quaternary fluvial terraces preserved along Saratoga, Stevens, and Los Gatos Creeks are used to identify the locations of deformation across the range front. Terraces flanking Stevens Creek and topographic lineaments mapped during this study constrain the southwest dip of the main trace of the Monte Vista fault between about 40° and 50°. Minimum vertical separation across the range front of the highest late Pleistocene terrace within Stevens Creek canyon is 12 ± 1 m. Based on previous age-estimates of this terrace and a correlative fan surface, we estimate a late Pleistocene uplift rate of 0.3 ± 0.2 mm/yr for the Monte Vista fault. Based on a fault dip of about 45° southwest, a reverse dip-slip rate for the Monte Vista fault of 0.4 ± 0.3 mm/yr is estimated.

Northwest-trending zones of anomalous stream gradients located about 4 to 6 km northeast of the range front are spatially coincident with potentially fault-related lineaments. Longitudinal profiles of streams crossing the lineament zones show local convexities consistent with tectonic uplift. Changes in stream sinuosity and fan distribution across the zones are also consistent with tectonic uplift. The deformed geomorphic surfaces and probable fault-related topographic lineaments mapped during this study provide strong evidence of late Quaternary faults located further east of the range front than previously recognized. The geomorphic features are consistent with deformation within the hanging walls of buried thrust faults east of previously mapped faults.

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1.0 INTRODUCTION

The 1989 Loma Prieta earthquake produced coseismic contractional deformation in several northwest-trending, elongate zones along the northeastern flank of the Santa Cruz Mountains in the southern San Francisco Bay region (Fig. 1) (Haugerud and Ellen, 1990). This deformation occurred along, or subparallel to, the previously mapped Monte Vista, Shannon and Berrocal faults (Bailey and Everhart, 1964; Sorg and McLaughlin, 1975). Possible activation of these faults during the 1989 Loma Prieta earthquake suggests that they may be related at depth to the San Andreas fault. It is not known whether displacement on these faults occurs only as secondary coseismic deformation resulting from movement along the San Andreas fault during large-magnitude events, or if these faults are themselves potential seismic sources.

The Berrocal, Shannon, and Monte Vista faults are located along the northeastern margin of the Santa Cruz Mountains and traverse the heavily populated areas of Los Gatos, Saratoga, Cupertino and Los Altos Hills in the southern San Francisco Bay area. Because active uplift of the southern Santa Cruz Mountains occurs, in part, by displacement along faults bordering the northeastern margin of the range, these faults likely pose a significant earthquake hazard to the southern San Francisco Bay region. However, the amount and timing of late Quaternary movement along these faults is poorly constrained. The location of the range front fault system in this densely populated area stresses the need for: 1) more accurate determination of the nature and locations of late Quaternary faulting and folding, 2) well-constrained data on the timing of fault movements, 3) an appraisal of the expected type and amount of ground disturbance associated with future episodes of thrust faulting, and 4) an understanding of the structural relationship between this range-front deformation and the San Andreas fault.

1.1 Purpose and Scope

The primary goal of this research is to assess the pattern of late Quaternary tectonic deformation across the northeastern margin of the southern Santa Cruz Mountains between Los Altos Hills and Los Gatos (Fig. 1). We assess the location and style of deformation of late Quaternary geomorphic surfaces and surficial deposits along the range front by analysis of aerial photography, field mapping, and quantitative geomorphic analyses. In this report, we present the results and conclusions of our geomorphic investigations, and speculate whether the range-front faults are independent seismic sources or dependent structures related to the San Andreas fault. This report presents a compilation of previous geologic mapping and pertinent exploratory trench locations along the range front at 1:24,000 scale (Plate 1), and provides a 1:24,000-scale map of surficial deposits, geomorphic surfaces, and fault-related lineaments along the range front (Plate 2). In addition, this report provides longitudinal profiles of stream channels and geomorphic surfaces across the range front, and stream-channel gradients and sinuosities along reaches that cross potential fault traces. These data allow interpretation of the locations, amounts, and styles of surficial deformation across the northeastern margin of the southern Santa Cruz Mountains, and provide an initial characterization of some potential seismic sources in the southern part of the San Francisco Bay region. The following sections present a brief synthesis of pertinent previous investigations, followed by the results and discussion of our assessment of the late Quaternary deformation along the range front.

1.2 Previous Investigations

The topographic relief of the southern Santa Cruz Mountains east of the San Andreas fault is, in part, a result of fault-normal contraction across a left-stepping restraining bend in the San Andreas fault (Anderson, 1990; Arrowsmith et al., 1992 ; Bürgmann et al., 1993).

Uplift of the Southern Santa Cruz Mountains has occurred, in part, along faults bordering the northeastern margin of the range front. These faults are a complex zone of anastomosing, curvilinear strands mapped as the Berrocal, Monte Vista, and Shannon faults, which dip moderately to the southwest toward the San Andreas fault (Fig. 2; Plate 1). The range front itself is curvilinear between Los Altos Hills and Los Gatos, with a large embayment in the range block between Saratoga and Los Gatos. This embayment is informally referred to here as the Saratoga-Los Gatos embayment.

These southwest-dipping faults have thrust Jurassic and Cretaceous rocks of the Franciscan Complex northeastward over Pliocene and Pleistocene alluvial sediments of the Santa Clara Formation and younger Quaternary deposits (Sorg and McLaughlin, 1975; Wesling and Helley, 1989; McLaughlin et al., 1991). In addition, water-well data suggest the presence of northwest-trending faults located beneath Santa Clara Valley, approximately 2 to 7 km northeast of the range front (California Department of Water Resources [CDWR], 1975). We consider all of these faults as significant tectonic features herein informally referred to as the range-front fault zone. Structural relations and gravity data suggest that up to 3 km of shortening and uplift, and 4.2 km of reverse slip, has occurred across some of the range-front faults within the past 10 Ma (R. L. McLaughlin, pers. comm., 1993). A cumulative slip rate of 2 to 3 mm/yr on the range-front faults is required to explain uplift rates of ~0.8 mm/yr based on geomorphic evidence and fission track data (Bürgmann et al., 1993). Shortening and uplift across the range front has been accommodated by both folding and thrust or reverse faulting (Sorg and McLaughlin, 1975).

The Monte Vista fault is one of the primary range-front faults that mark the boundary between the southern Santa Cruz Mountains and the western margin of Santa Clara Valley (Fig. 2; Sorg and McLaughlin, 1975). Northwest of the study area, through the towns of Los Altos and Palo Alto, the Monte Vista fault consists of a belt of imbricate northeast-vergent thrust faults (Dibblee, 1966; William Cotton and Associates, 1978). Within the study area, the Monte Vista fault lies at the base of a prominent northeast-facing escarpment between the towns of Los Altos Hills and Cupertino (Plate 1). South of Cupertino, the range front trends more southerly between Calabazas Creek and Saratoga. In this area, fold axes within the Santa Clara Formation west of the range front also have southerly trends (Plate 1), suggesting that the Monte Vista fault changes strike, curves to the south, and joins the Berrocal fault along the range front near Saratoga (Cotton et al., 1980; McLaughlin, 1974; Sorg and McLaughlin, 1975). However, well logs show that a fault, possibly the southern extension of the Monte Vista fault, displaces bedrock and buried stream channels between Calabazas Creek and Vasona Reservoir (CDWR, 1975), along the eastern edge of the Saratoga-Los Gatos embayment (Plate 1). Gravity data also suggest that bedrock is offset beneath alluvium between Calabazas Creek and Vasona Reservoir (Taylor, 1956). The Monte Vista fault therefore may extend southeastward from the range front and join the Shannon fault mapped south of Vasona Reservoir by Bailey and Everhart (1964).

Based on results of limited exploratory trenching, the Monte Vista fault has had late Quaternary and possibly Holocene displacement. Directly downstream of the range front, Permanente Creek parallels the Monte Vista fault and is bordered on the southwest by a series of prominent linear fronts and faceted ridge spurs (Plate 2). Exploratory trenching across the fault trace at the base of these facets exposed colluvial deposits thrust over fluvial gravel deposited by Permanente Creek (Earth Systems Consultants, unpublished data). Based on relatively little soil development, the soil developed on the colluvial deposits was interpreted as Holocene (W. McCormick, Earth Systems Consultants, pers. comm., 1992). In addition, four discontinuous fault traces, expressed as linear depressions or saddles in the Santa Clara Formation exposed north of Cupertino, were trenched 0.8 km east of the main trace of the Monte Vista fault (Earth Science Associates, 1979; Plate 1). Northeast-dipping shear zones exposed in two trenches offset soil horizons estimated as three to five thousand years old based on interpretation of soil-profile development (Earth Science Associates, 1979). The shear zones may represent the surface expression of a southwest-vergent backthrust rooted in a thrust fault east of the trenches.

The Berrocal fault is located along the range front between Saratoga and Los Gatos, and extends to the northwest and southeast within the range block (Plate 1). Southeast of the study area, the Berrocal fault merges with, or intersects, the Sargent fault. The Berrocal fault dips moderately to the southwest, although some strands are steeply dipping and some dip moderately to the northeast possibly due to rotation of fault planes (R. L. McLaughlin, pers. comm., 1993). At Wood Road, near downtown Los Gatos, late Pleistocene fluvial deposits are displaced by the Berrocal fault (R. L. McLaughlin, pers. comm., 1993; this study).

The Shannon fault, which extends south from Los Gatos to Coyote Creek near New Almaden, consists of several southwest-dipping, thrust or reverse fault strands and several subsidiary northeast-dipping normal fault strands. The Shannon fault is mapped northwest of Los Gatos Creek as four parallel strands striking N 50° W, based on linear stream valleys and other topographic anomalies within the Santa Clara Formation (Bailey and Everhart, 1964; McLaughlin et al., 1991). South of Los Gatos Creek, the northeasternmost strand of the Shannon fault is located at the base of Blossom Hill, an uplifted fold developed in Tertiary rocks (Fig. 2). Based on trench exposures at the Senator mine west of New Almaden, about 6 km southeast of Vasona Reservoir, the Shannon fault deforms Miocene rock and cuts a paleosol with an estimated age less than 20 ka (R. McLaughlin, pers. comm., 1993).

There is substantial geological and geophysical evidence for faults northeast of the range front, beneath alluvium in Santa Clara Valley. Based on gravity data, Taylor (1956) inferred several narrow, northwest-trending fault blocks with large vertical displacements northeast of the range front, which he interpreted as horst-and-graben fault blocks. Based on displaced buried stream channels interpreted from well logs, CDWR (1975) mapped several northwest-trending faults beneath Santa Clara Valley, including the Cascade and Santa Clara faults (Fig. 2; Plate 1). Although CDWR (1975) showed these faults as vertical features in the uppermost crust, decreases in vertical separation of basement on progressively more easterly faults is consistent with the interpretation that these faults are east-vergent thrust or reverse faults related at depth to other range-front faults. For example, there is approximately 150 m of vertical separation of basement across the Monte Vista fault east of Saratoga, about 30 m of vertical separation across the Cascade fault, and less than 25 m of vertical separation across the easternmost Santa Clara fault (CDWR, 1975). Wesling and Helley (1989) also map a west-trending fault trace about 4 to 6 km northeast of the range front (Plate 1). In addition, based on detailed bedrock mapping throughout the southern Santa Cruz Mountains and along the margin of Santa Clara Valley, R. L. McLaughlin (pers. comm., 1993) interprets that movement on active blind thrusts beneath Santa Clara Valley northeast of the range front has rotated the Monte Vista fault into a steeper, southwest-dipping orientation. Results of our investigation, as described below, provide geomorphic evidence for late Quaternary folding and possible faulting on subsurface faults northeast of the range front.

There is seismologic evidence that the range-front faults are potential seismic sources. Historical records show that a M6.5 earthquake in 1865 may have occurred on a fault east of the San Andreas fault, possibly along the northeastern flank of the Santa Cruz Mountains (Tuttle and Sykes, 1992). Focal mechanisms interpreted from instrumental microseismicity northwest of Cupertino are consistent with motion on low-angle, southwest-dipping thrust faults (Sorg and McLaughlin, 1975). Kovach and Beroza (1993) estimate that the Monte Vista fault has the potential for a M > 6 earthquake based on contemporary microseismicity and potential rupture length.

2.1 Reconnaissance Surficial Mapping

Geomorphic map units were delineated on black-and-white, 1:22,000-scale aerial photographs taken in 1939 (USDA-CIV series). After field checking and final compilation, geologic contacts identified on air photos were transferred manually to standard, 1:24,000-scale USGS topographic maps. Surficial deposits mapped within parts of the Cupertino, San Jose West, Los Gatos, and Castle Rock Ridge 7.5-minute topographic quadrangles are shown on Plate 2.

Field reconnaissance mapping within the study area consisted of examining stream drainages, road cuts, and other exposures within the study area. For example, we examined road cuts exposed during construction of Highway 85 between Saratoga-Sunnyvale Road and University Avenue in Los Gatos. The main trace of the Monte Vista fault mapped by Rogers and Williams (1974) northeast of Vasona Reservoir (Plate 1) was crossed by 7-m-deep exposures north and south of University Avenue. Late Pleistocene fluvial deposits exposed in these road cuts were not displaced across the mapped trace of the fault. Based on our field reconnaissance within the study area, extensive cultural modification has either covered or destroyed many potentially fault-related geomorphic features. Where possible, field mapping was combined with interpretation of detailed topographic maps and soil maps to revise contacts established on air photos. However, Plate 2 is only a reconnaissance surficial geologic map and should not be used in place of site-specifc geologic or geotechnical investigations.

Geomorphic Surfaces and Surficial Deposits

In general, the area northeast of the Santa Cruz Mountains range front in the study area consists of a complex series of coalescent alluvial fans and fluvial terraces; whereas the mountainous areas contain few fan and terrace remnants. Northeast of the range front, fans include an older, moderately-dissected piedmont surface as well as younger, nested, undissected fans that open to the northeast toward San Francisco Bay (Helley and Brabb, 1971; Wesling and Helley, 1989). Helley and Brabb (1971) grouped Quaternary alluvial fan deposits into Quaternary younger fan deposits (Qyf), older fan deposits (Qof), and older dissected alluvial fan deposits (Qofd). Based on additional detailed analyses of aerial photography, soil surveys, and well-log data, Wesling and Helley (1989) identify two Holocene fan deposits ($Qhaf_1$ and $Qhaf_2$) and a Pleistocene fan deposit (Qpaf). This study identifies five major alluvial fan surfaces and numerous undifferentiated minor alluvial fans along the range front (Plate 2), which generally coincide with alluvial fan deposits identified by Helley and Brabb (1971) and Wesling and Helley (1989). Fluvial terraces preserved along steep canyon walls west of the range front and along present-day stream channels in Santa Clara Valley provide a record of episodic incision and terrace development. Previous investigations did not differentiate among terrace deposits, with most workers grouping terrace deposits as "older alluvium" (Helley and Brabb, 1971; Wesling and Helley, 1989; McLaughlin et al., 1991). This study identifies remnants of five distinct fluvial geomorphic surfaces, including four terraces and the modern flood plain, along major streams within the study area (Plate 2).

Our delineation of geomorphic surfaces and surficial deposits, as shown in Plate 2, is intended to build on previous surficial mapping by Helley and Brabb (1971), Wesling and Helley (1989), and McLaughlin et al. (1991), and to provide sufficient detail from which to assess near-surface deformation along the range-front fault zone. Based on geomorphic features observed on aerial photography and in the field, we identify multiple fan surfaces, fluvial terraces, and active flood plains and channels within the Permanente, Stevens, Regnart, Calabazas, Saratoga, San Tomas de Aquinas, and Los Gatos drainage systems (Plate 2). Because the characteristics of each terrace or fan surface differs among drainages, we differentiate among surfacse only within each drainage. As shown on Plate 2, the lower-case letter at the end of the map unit designation indicates the drainage system. For example, map unit Qf_2s is the second-oldest fan deposited by Stevens Creek, as denoted by the "s", whereas map unit Qf_2p is the second-oldest fan deposited by Permanente Creek, as denoted by the "p".

We identify remnants of five fluvial terraces and remnants of four alluvial fans in most of the drainages. Within each drainage system, fluvial terraces that grade into alluvial fan surfaces are interpreted as correlative and are assigned similar relative-age designations (Table 1). For example, within the Stevens Creek drainage system, terraces Qt_1s, Qt_2s, and Qt_4s grade into alluvial fan surfaces Qf_1s, Qf_2s, and Qf_4s, respectively. Terrace Qt_3 is present only locally within the study area and does not have a correlative fan surface (Table 1).

The relative ages of alluvial fan surfaces are based on geomorphic expression, air photo characteristics, degree of dissection, and stratigraphic position. Qf_1 and Qf_2 are correlative with Quaternary older fan deposits of Helley and Brabb (1971). On black-and-white 1939 air photos, these older fan surfaces are darker and more mottled than younger fan surfaces, which is most likely related to well-developed soil profiles. Qf_1 is moderately dissected throughout the study area and locally is extensively dissected. Qf_2 is lighter and has more topographic relief than Qf_1, and locally sediments associated with Qf_2 cover Qf_1. Alluvial fan surfaces Qf_4 and Qf_5 are a uniform color with some lighter, disturbed areas that may be related to local debris flows.

Remnants of four major stream terraces are preserved along the margins of Stevens, Saratoga, and Los Gatos canyons. The terrace remnants, which range up to 30 m above the present-day stream channels, typically are underlain by unconsolidated fluvial gravels containing pebble to cobble-sized clasts. We informally designate these surfaces Qt_1 to Qt_4, from oldest to youngest respectively.

The relative ages of terraces are based on geomorphic expression, air photo characteristics, relative spacing and height above the present-day channel, and surface morphology. The height above the active stream channel of the four major terraces, Qt_1 through Qt_4, is similar for all three major drainages (Table 1). Qt_1, the oldest terrace, is a paired fill terrace characterized by well-preserved remnants at the range front. Qt_2 is a paired fill terrace preserved as broad surfaces on both sides of streams. Qt_3 is a poorly preserved, unpaired terrace present locally on the inside of valley meanders, and is inset into Qt_2. Qt_4 is a paired fill terrace preserved as broad surfaces along stream banks. The present-day flood plain, Qfp, is typically 1 to 1.5 m above the present-day stream channel.

An old, extensively dissected surface (Qp) is preserved as isolated remnants across the Santa Clara Formation within the study area (Plate 2). The discontinuous surface is present on both sides of the range front and appears to represent a piedmont or erosional surface developed on the Santa Clara Formation. The most extensive remnants of Qp are present along the northwest side of Los Gatos Creek (Plate 2).

Surficial deposits identified on Plate 2 also include undifferentiated stream alluvium, deposits of the Santa Clara Formation, pre-Quaternary rocks, and landslide deposits. Undifferentiated stream alluvium includes deposits beneath various geomorphic surfaces mapped during this study and along various streams within the field area. Deposits of the

Santa Clara Formation northeast of the range front were mapped via air photo interpretation and field mapping during this study. Deposits of the Santa Clara Formation southwest of the range front were compiled from previous mapping by Sorg and McLaughlin (1975) and McLaughlin et al. (1991). Pre-Quaternary rocks shown on Plate 2 are compiled from previous mapping by Sorg and McLaughlin (1975) and McLaughlin et al. (1991). Landslide deposits are mapped along the range front and selected drainages where landslides may be confused with terrace deposits or cover relevant geomorphic features. This study does not provide a comprehensive map of all landslides within the study area.

Potentially Fault-related Geomorphic Features

Along the range front of the Santa Cruz Mountains, potentially fault-related topographic lineaments include saddles, linear depressions, scarps, deflected drainages, triangular faceted spurs, and linear fronts. Vegetation lineaments are distinguished by tonal contrasts and the absence or sparsity of vegetation. Potentially fault-related lineaments are particularly well expressed in dissected uplands underlain by the Santa Clara Formation between Cupertino and Los Altos Hills and between Saratoga and Los Gatos. In areas in which the Santa Clara Formation is exposed, northwest-trending lineaments consisting of saddles, linear depression, topographic scarps, and linear fronts are common (Plate 2). These lineaments were observed on black-and-white, 1939 aerial photographs (USDA-CIV series) taken before extensive urban development.

East of the range front, many vegetation and topographic lineaments are present within late Quaternary alluvial deposits, and likely are related to late Quaternary deformation. In general, individual lineaments are up to a few hundred meters long and occur in several distinct N40°W-trending zones up to 500-m wide, 5 km long, and up to 6 km northeast of the range front (Plate 1). In surficial deposits northeast of the range front, the northwest-trending lineaments primarily are vegetation or tonal contrasts, although linear drainages, linear closed depressions, and topographic scarps are also present (Plate 2). Vegetation lineaments typically are lighter color than surrounding areas, and coincide with linear depressions or deflected drainages. Several individual lineaments cross field boundaries in areas under cultivation in 1939, based on interpretation of the 1939 air photos.

The most prominent lineament present within alluvial deposits northeast of the range front is a 1-km-long, northeast-facing topographic scarp north of Regnart Creek in Cupertino (Plate 2). This scarp is present in the highest fan surface associated with Regnart Creek (Qf1r), and, based on profiles constructed from 2-foot-contour topographic maps provided by the City of Cupertino, is approximately 6 m high. Vertical separation of the Qf1r surface is about 2 m. Approximately 1 km west of the scarp, the range front is a linear topographic escarpment whose base is veneered by an apron of colluvial and possibly fluvial deposits. An exploratory trench across the base of the escarpment at the western end of Rainbow Drive, west of the scarp, showed that the Plio-Pleistocene Santa Clara Formation is strongly deformed and overlain by at least two distinct sheets of Quaternary colluvium and a surficial soil (W. Cotton, pers. comm., 1993). Colluvial deposits are progressively more tilted with depth in the trench, strongly suggesting progressive late Quaternary uplift and tilting or folding of the range front. A possible interpretation for these stratigraphic and structural relationships is that the site is on the hanging wall of a reverse or thrust fault. The scarp near Regnart Creek may be the surface expression of this fault.

2.2 Fluvial Terrace Profiles

The geomorphic surfaces present along the northeastern margin of the Santa Cruz Mountains provide the opportunity to assess the amount, style, location, and timing of deformation across the range-front fault zone. Deformed and undeformed geomorphic surfaces help constrain the locations and amounts of folding and faulting across the range front between Los Altos Hills and Los Gatos. We concentrated our analysis on the assessment of deformation of fluvial terraces flanking the three largest drainages in the study area: Stevens, Saratoga, and Los Gatos Creeks. Along the three creeks, longitudinal terrace profiles show that changes in profile gradient and heights correspond to previously mapped fault traces and fold axes (Dibblee, 1966; Sorg and McLaughlin, 1975; CDWR, 1975) and zones of lineaments identified in this study (Plate 1). In addition, we analyze the present-day gradients and sinuosities of these creeks from the range front to downstream of the lineament zones (see section 2.3). Changes in channel gradients and sinuosities also correspond to previously mapped fault traces, and to lineaments identified in this study.

Los Gatos, Saratoga, and Stevens Creeks have headwaters in the southern Santa Cruz Mountains, flow northeast across the range front, and empty onto the coalescent alluvial fan complex along the western side of Santa Clara Valley. The creeks traverse areas within which coseismic deformation occurred during the 1989 Loma Prieta earthquake. Late Quaternary fluvial terrace remnants preserved along the creeks provide a means of assessing locations and amounts of vertical deformation along the range front and within Santa Clara Valley. The main goals of this part of our study are to establish preliminary correlations among terraces flanking Los Gatos, Saratoga, and Stevens Creeks southwest and northeast of the range front, and thus identify and assess late Quaternary deformation across the Monte Vista fault in Cupertino and northeast of the range front in Saratoga and Los Gatos.

Delineation of late Quaternary fluvial terraces and terrace remnants along Stevens, Saratoga, and Los Gatos Creeks was completed initially by analysis of aerial photography taken in 1939 at a scale of approximately 1:20,000. The terrace remnants were checked and revised via field mapping at scales of 1:2,400 to 1:24,000. Surface remnants were correlated on the basis of height above the present-day channel, lateral extent, and surface morphology. Because a comprehensive chronostratigraphy is beyond the scope of this study, the terrace correlations presented herein are preliminary. Fluvial terraces along other major creeks that drain the southern Santa Cruz Mountains such as Permanente, Regnart, Calabazas, and San Tomas de Aquinas Creeks, were mapped on air photos at a scale of approximately 1:20,000 and compiled at a scale of 1:24,000. Longitudinal profiles of terraces along these creeks were not constructed because detailed topographic maps were not available at the time of our analysis.

Terrace remnants were mapped along Stevens Creek on 5-ft-contour interval, 1:2,400-scale topographic maps obtained from the City of Cupertino (Wahlen Aerial Surveys, No. W6833). Terrace remnants along Saratoga Creek were mapped on a 5-ft-contour interval, 1:7,200-scale topographic storm drainage map of Saratoga provided by the Saratoga Public Works Department. Additional vertical control of terrace elevations was provided by 2-ft-contour interval, 1:600-scale Santa Clara Valley Water District strip maps of Saratoga Creek (Project No. 2021). Terrace remnants along Los Gatos Creek were mapped on 10-ft-contour interval, 1:24,000-scale USGS quadrangles and on 2-ft-interval, 1:1,200-scale Santa Clara Valley Water District maps of Los Gatos Creek (Project No. 3020). Because higher terraces along Los Gatos Creek (Qt_1lg and Qt_2lg; Plate 2) generally are located outside of the areas covered by the detailed, 2-ft-contour maps, elevations of these higher terrace remnants have greater uncertainties than elevations of the lower terraces (Qt_3lg and Qt_4lg).

Stevens Creek

In contrast to the other drainages in the study area, the Stevens Creek drainage is well-suited for detailed investigation because fluvial terraces are preserved on both sides of the Monte Vista fault. Stevens Creek canyon is not as steep walled as others in the study area and numerous terraces are preserved west of the range front, upstream of the Monte Vista fault. Fluvial terraces within the Stevens Creek drainage were used by Sorg and McLaughlin (1975) and more recently by R. McLaughlin (pers. comm., 1993) to constrain the amount of deformation across the Monte Vista fault.

Based on analysis of aerial photography and detailed field mapping, we recognize five fluvial geomorphic surfaces in Stevens Creek canyon downstream of Stevens Creek Reservoir (Plate 2). These surfaces include the present-day flood plain (Qfps) and four major terraces (Qt1s, Qt2s, Qt3s, and Qt4s) (Plate 2). Unconsolidated terrace gravels that underlie these terraces contain pebble- to cobble-sized clasts within a sandy matrix. Fluvial gravels associated with these remnants unconformably overlie the Santa Clara Formation and older Tertiary rocks.

Remnants of terrace Qt1s are preserved upstream and downstream of the mountain front, with the largest remnant preserved on the southeastern side of Stevens Creek just downstream from Stevens Creek Reservoir (Plate 2). In general, Qt1s remnants are 15 to 30 m above the present-day stream channel (Table 2). Based on our mapping at a scale of 1:2,400, the Qt1s terrace is deformed by synclinal folding between Stevens Creek Reservoir and the Monte Vista fault, and by anticlinal folding directly upstream of the fault (Fig. 3). Both of these folds are within the hanging wall of the Monte Vista fault. Thus, synformal deformation noted by R. McLaughlin (pers. comm., 1993) of the broad Qt1s surface upstream of the range front is supported by our longitudinal profiles. Based on longitudinal profiles of terrace remnants along Stevens Creek, Qt1s within Stevens Creek Canyon is correlative the Qf1s fan surface, directly downstream of the range front, as noted by Sorg and McLaughlin (1975). Based on the longitudinal profiles of fan and terrace remnants across the Monte Vista fault, we estimate a vertical separation of 12 m of the Qt1s/Qf1s surface (Fig. 3).

Remnants of terrace Qt2s are relatively well preserved along Stevens Creek in comparison to other terrace remnants. Upstream of the Monte Vista fault, Qt2s remnants are relatively discontinuous, whereas downstream of the fault Qt2s is a nearly continuous remnant between the range front and Stevens Creek Boulevard (Plate 2). Downstream of Stevens Creek Boulevard, the correlative Qf2s fan surface is present on the northwestern side of the creek (Plate 2). Qt2s remnants and the Qf2s surface typically are about 12 to 14 m above Stevens Creek (Table 2). In the immediate vicinity of the Monte Vista fault, we identify remnants of Qt2s on both sides of the fault (Fig. 4). The longitudinal terrace profiles along Stevens Creek shows about 3 m of vertical separation of these remnants across the fault, as well as substantial synclinal and anticlinal deformation in the hanging wall of the fault (Fig. 3).

Remnants of terrace Qt3s are poorly preserved along Stevens Creek. Small isolated remnants are present upstream and downstream of the range front (Figs. 3 and 4, Plate 2). There is no fan surface identified as correlative to the Qt3s terrace remnants. Qt3s remnants typically are about 6 to 8 m above Stevens Creek (Table 1). The lack of continuity of Qt3s remnants precludes assessment of the amount of displacement of Qt3s across the Monte Vista fault, although the longitudinal terrace profile along Stevens Creek does show changes in terrace heights and gradients consistent with anticlinal deformation and/or uplift in the hanging wall of the fault (Fig. 3).

Similarly, remnants of terrace Qt4s are poorly preserved along Stevens Creek across the range front, with only small isolated remnants preserved upstream and downstream of the range front (Fig. 4). Qt4s remnants typically are about 3 to 4.5 m above Stevens Creek (Table 1). The lack of continuity of Qt4s remnants precludes assessment of the presence or absence of deformation of Qt4s across the Monte Vista fault.

Longitudinal profiles of terraces along Stevens Creek help assess the location of the Monte Vista fault. Previous mapping shows the main trace of the Monte Vista fault west of Riverside Drive and Anza Circle, on strike with linear fronts and faceted spurs to the north and south (Plate 1). However, based on the distribution of displaced and undisplaced terrace remnants and vegetation and topographic lineaments, the location of the Monte Vista fault trace at the mouth of Stevens Creek Canyon is east of Riverside Drive and Anza Circle and the dip of the Monte Vista is constrained between about 40° and 50° to the southwest (Fig. 4). In this interpretation, the fault trace coincides with a prominent right-stepping bend in Stevens Creek, and may be associated with fractures within Miocene sandstone in bluffs above Linda Vista Park (Fig. 4).

<u>Saratoga Creek</u>

Terraces along Saratoga Creek provide a record of late Quaternary deformation east of the range front near Saratoga (Plate 2). Terraces preserved upstream of Saratoga are insufficient for assessing deformation across the Berrocal fault at the range front. However, a relatively well preserved flight of terraces northeast of the range front cross the range front embayment between Saratoga and Los Gatos. Numerous topographic lineaments including linear fronts and linear depressions in dissected uplands underlain by the Santa Clara Formation within the Saratoga-Los Gatos embayment provide evidence of substantial late Pleistocene deformation. Alluvial fan deposits and terraces inset into the Santa Clara Formation allow identification of late Quaternary deformation in the embayment. Terraces and fan surfaces also cross the inferred southeastern extension of the Monte Vista fault south of Calabazas Creek mapped by Rogers and Williams (1974) (Plate 1).

Based on analysis of aerial photography and field mapping, we recognize five fluvial geomorphic surfaces along Saratoga Creek, within the Saratoga-Los Gatos embayment (Plate 2). Remnants of four terraces (Qt1st, Qt2st, Qt3st, and Qt4st) and the present-day flood plain (Qfpst) are present along Saratoga Creek. Qt1st, the highest terrace, is represented by a remnant on the north side of Saratoga Creek at the base of the range front (Fig. 5). The Qt1st remnant is about 15 m above the Saratoga Creek channel (Table 2). Based on the downstream projection of the Qt1st surface to the Qf1st surface, Qt1st is correlative with Qf1st preserved along the north side of Saratoga Creek (Fig. 5).

Qt2st is present on both sides of Saratoga Creek as broad, fairly continuous remnants about 10 to 12 m above the Saratoga Creek channel (Plate 2; Table 2). Much of downtown Saratoga occupies remnants of Qt2st near the range front. Downstream of Saratoga, Qt2st is preserved as isolated surfaces inset into Qf1st on the north side of Saratoga Creek. Qt2st grades into Qf2st on the south side of Saratoga Creek, east of Saratoga-Sunnyvale Road (Plate 2). Qt3st is only preserved as a surface remnant on the north side of Saratoga Creek within Saratoga. Qt3st is about 6 m above the Saratoga Creek channel. Qt4s is present on both sides of Saratoga Creek as broad, relatively continuous surfaces approximately 4 km downstream of the range front (Plate 2). Qt4st is about 3 m above the Saratoga Creek channel and grades into Qf$_4$st. The present-day flood-plain, Qfpst, is inset into Qt$_4$st and preserved as isolated remnants along the stream course.

Near the range front, within downtown Saratoga, there is evidence of possible tectonic deformation of Qt$_1$st and Qt$_2$st. The longitudinal terrace profile of Saratoga Creek (Fig. 5) shows that the gradient of Qt$_1$st is greater than that of the present channel gradient, possibly reflecting tilting of Qt$_1$st. Qt$_2$st beneath downtown Saratoga, on the southern bank of Saratoga Creek, also changes gradient and may be slightly warped. The anomalous gradients of Qf$_1$st and Qt$_2$st coincide with the projected trace of an anticline mapped in the Santa Clara Formation by Sorg and McLaughlin (1975) (Plate 1, Fig. 5).

Downstream of Saratoga, no prominent deformation of terrace or fan surfaces is observed in the Saratoga Creek longitudinal terrace profiles. Qf$_1$st, an alluvial fan surface on the north side of Saratoga Creek, has substantial changes in surface gradient and height above the stream channel, although this may simply reflect moderate dissection and natural undulations of the fan surface (Fig. 5). No discernible pattern of deformation in Qt1st is obvious. Qt$_2$st and Qf$_2$st show only minor changes in gradient or height above the stream channel downstream of Saratoga (Fig. 5). Qt$_2$st and Qf$_2$st are slightly convex upstream of the projected trace of the Monte Vista fault mapped by Rogers and Williams (1974). However, it is unclear if the convexity is due to tectonic deformation. There is no deformation of terraces across the inferred trace of the Monte Vista fault mapped by Dibblee (1966) and Rogers and Williams (1974). Overall, the longitudinal terrace profile of Saratoga Creek suggests that if deformation has occurred between Saratoga and the projected trace of the Monte Vista fault, across the Saratoga-Los Gatos embayment, then it is broad deforamtion that may not be perceptible given the resolution of 5-ft contour interval topographic maps. However, the profiles are permissive of an interpretation of folding near the range front in downtown Saratoga.

<u>Los Gatos Creek</u>

Los Gatos Creek is the largest stream in the study area and has a well-preserved sequence of terraces east of the range front (Plate 2; Fig. 6). However, because Los Gatos Creek flows in a narrow, deep canyon below Lexington Reservoir, few terraces are preserved west of the range front, upstream of the Berrocal fault. Therefore, the longitudinal profiles of terraces along Los Gatos Creek are insufficient to assess the late Quaternary deformation across the Berrocal fault. However, longitudinal profiles cross one trace of the Berrocal fault mapped by Sorg and McLaughlin (1975) and four traces of the Shannon fault mapped by Bailey and Everhart (1964) and McLaughlin et al. (1991). Los Gatos Creek also crosses the Saratoga-Los Gatos embayment and, thus allows assessment of late Pleistocene and possibly Holocene deformation.

Based on analysis of aerial photography and field mapping, we recognize five fluvial geomorphic surfaces along Los Gatos Creek. Four terraces (Qt$_1$lg, Qt$_2$lg, Qt$_3$lg, and Qt$_4$lg) and the modern flood plain are represented by surface remnants preserved along the margins of Los Gatos Creek (Plate 2). Very discontinuous remnants of Qt$_1$lg are preserved in downtown Los Gatos, northwest of Los Gatos Creek, near the base of the range front. A large remnant of Qt$_1$lg is preserved northwest of Vasona Reservoir. Remnants of Qf$_1$lg are about 20 to 30 m above Los Gatos Creek (Table 2).

Qt$_2$lg is present on both sides of Los Gatos Creek as broad, continuous surfaces extending east of the range front to about 2 km downstream of Vasona Reservoir (Plate 2; Fig. 6). Much of downtown Los Gatos is built on Qt$_2$lg, which is about 14 m above the creek channel (Table 2). As along Stevens and Saratoga Creeks, remnants of Qt$_3$lg are very discontinuous. The only preserved remnant of Qt$_{3}$lg is located 1 km northeast of Vasona Reservoir (Plate 2), and is about 6 m above the creek (Table 2). Qt$_{4}$lg is present on both sides of Los Gatos Creek as isolated remnants about 3 m above Los Gatos Creek. The present-day flood plain, Qfplg, is inset into Qt$_{4}$lg and is relatively continuous along the stream course.

The longitudinal terrace profile along Los Gatos Creek shows subtle evidence of contractional deformation between the range front and the easternmost trace of the Shannon fault at Vasona Reservoir mapped by McLaughlin et al. (1991). Minor height and gradient changes in Qt$_{2}$lg mapped on 2-ft contours just upstream of Vasona Reservoir may represent a convexity that coincides with a trace of the Shannon fault mapped by Bailey and Everhart (1964) and McLaughlin et al. (1991). However, evidence of deformation of the older Qt$_{1}$lg or Qf$_{1}$lg surfaces is not present across this fault trace, most likely because the 10-ft contours used to map Qt$_{1}$lg and Qf$_{1}$lg do not provide sufficient resolution to detect the possible broad deformation interpreted from the Qt$_{2}$lg profile. R. L. McLaughlin (pers. comm., 1993) notes that a strand of the Berrocal fault may displace fluvial deposits associated with Qt$_{1}$lg.

2.3 Channel Longitudinal Profiles and Sinuosities

As part of our analysis of late Quaternary deformation along the northeastern margin of the Santa Cruz Mountains, we constructed longitudinal profiles of stream channels and evaluated stream sinuosities along major drainages that cross the range front. 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 and sinuosity may record tectonic uplift. Along streams that are unaffected by tectonism, stream gradient generally decreases with distance downstream, typically in an exponential or logarithmic manner (Hack, 1957; Schumm, 1977). Downstream variations in channel gradient that are not logarithmic or exponential, such as a local steepening or shallowing, may be related to uplift or subsidence. Tectonic deformation may change the stream channel gradient, upsetting the equilibrium between channel gradient and hydraulic properties of the stream (Ouchi, 1985). For example, longitudinal profiles of channels typically are convex upward across an axis of uplift (Fig. 7). On the upstream side of an uplift, channel straightening and meander cutoffs may form while the damming effects of the uplift may cause net aggradation (Ouchi, 1985). In the central reach of the uplift, however, a channel typically incises into underlying deposits and may produce a series of fluvial terraces. Downstream of an axis of uplift, stream sinuosity generally increases as the stream attempts to maintain a uniform stream gradient on the steepened slope. Thus, because of the presence of reverse faults along and northeast of the range front, our approach is to use channel profiles and sinuosities to help identify the location and style of deformation. The main emphasis of this investigation was on channel reaches downstream of the range front, primarily because the area northeast of the range front: (1) is underlain by relatively homogeneous alluvial sediments of the Santa Clara Valley, (2) contains multiple lineaments that are potentially related to surficial deformation, and (3) is covered by topographic maps of sufficient detail (10-ft supplemental contour intervals) that enable reasonable assessment of channel gradients.

Longitudinal profiles of six streams (Permanente, Regnart, Stevens, Calabazas, Saratoga, and Los Gatos) were constructed from 1:24,000-scale USGS topographic maps (1961 vintage) having 40-ft contour intervals and 10-ft supplemental contours. Stream sinuosities are based on photogeomorphic mapping of channels on 1939 black-and-white, 1:20,000-scale aerial photographs. Sinuosity values were determined by dividing stream channel length along a given reach of the stream by the straight-line distance between the two ends of the reach. Thus, a perfectly straight channel has a sinuosity of 1.0, and sinuosities greater than 1.0 indicate channels with greater degrees of meandering. The endpoints of reaches are based on qualitative assessment of channel morphology, valley width, and the presence or absence of lineaments. Based on the results from each drainage, as described below from northwest to southeast, we interpret that changes in stream channel gradient and sinuosity are consistent with linear zones of surficial deformation northeast of the southern Santa Cruz Mountains range front.

Permanente Creek

The longitudinal profile of Permanente Creek shows two convexities, one that is spatially associated with the Monte Vista fault at the range front, and another coincident with the trace of the Cascade fault, approximately 5 km northeast of the range front (Fig. 8). The profile convexity at the upstream end of the profile probably is related to differences in bedrock erodibility on either side of the fault, with more resistant bedrock in the hanging wall (Plate 1). Alternatively, the convexity may be related to near-surface anticlinal folding in the hanging wall of the Monte Vista fault. The profile convexity downstream of the range front is located entirely within alluvial sediments in Santa Clara Valley (Fig. 8; Plate 2). For about 2 km downstream of the range front, the channel has a gradient of about 16 m/km, which then shallows to about 6 m/km for another kilometer or so. About 3 km downstream of the range front, the gradient steepens to about 13 m/km for another kilometer (Fig. 8). Although the drainage has been modified downstream of this steep reach, the overall gradient is about 6 to 8 m/km. The anomalously steep gradient coincides with the mapped trace of the Cascade fault (CDWR, 1975), as well as a zone of lineaments that is potentially related to surficial deformation (Fig. 8; Plate 1). If the profile convexity is related to uplift, there is about 3 m of uplift over approximately 1.7 km. The stream-profile convexity and associated zone of lineaments along Permanente Creek are along the northwestern projection of similar convexities and zones of lineaments identified along Stevens, Regnart, and Calabazas Creeks (Fig. 9).

Channel sinuosity also varies along Permanente Creek, with dimensionless values of 1.1 to 1.2 along reaches that are crossed by zones of lineaments, and values of 1.2 to 1.5 along reaches directly downstream of zones of lineaments (Fig. 8). For example, between 3 and 4 km downstream of the range front (reach EF, Fig. 8), sinuosity is 1.1, whereas directly downstream of the range front, sinuosity is 1.5. Low sinuosity probably is related to active downcutting, perhaps in response to uplift (Ouchi, 1985). High sinuosity values probably are related to fluvial response to steepened gradients, also perhaps in response to uplift. These relations are consistent with adjustments of the stream channel to tectonic uplift associated with the zone of lineaments and thus, perhaps, with the Cascade fault.

Stevens Creek

The longitudinal profile of Stevens Creek shows a broad convexity that is spatially associated with the trace of the Cascade fault approximately 6 km northeast of the range front, within alluvial sediments of Santa Clara Valley (Fig. 10). For about 3.5 km downstream of the range front, the channel has an overall gradient of about 7 m/km. Between about 3.5 and 6 km downstream, shallows to about 5 m/km, then steepens to a gradient of about 11 m/km (Fig. 10). Below this relatively steep reach, the channel shallows and has a gradient of about 5 m/km. This broad convexity coincides in a general sense with two zones of lineaments that are potentially related to surficial deformation (Fig. 10; Plate 2). The mapped trace of the Cascade fault coincides with the central part of the convexity, whereas the zones of lineaments cross Stevens Creek in the central and downstream parts of the convexity. If the profile convexity is related to uplift, there is about 6 m of uplift over approximately 4.3 km. As noted above, the mapped trace of the Cascade fault and the zone of lineaments are continuous to the northwest and southeast, and are associated with channel gradient changes along Permanente and Calabazas Creeks (Fig. 9).

Channel sinuosity varies substantially along Stevens Creek, although there is not as much correlation as along Permanente Creek between sinuosity values and potentially deformation-related lineaments. Sinuosity values of 1.1, 1.7, and 1.1 are present along reaches that are crossed by zones of lineaments, and values of 2.1 and 1.3 are present along reaches directly downstream of zones of lineaments (Fig. 10). For example, between 1 and 1.5 km downstream of the range front (reach BC, Fig. 10), the sinuosity value is 1.1, whereas directly downstream, the value is 2.1. As along Permanente Creek, these relations are consistent with adjustments of the stream channel to tectonic uplift perhaps associated the Monte Vista and Cascade faults. The large variability in sinuosity values along Stevens Creek downstream of the mountain front (between 3.5 and 8 km, Fig. 10), likely is related to broad deformation over a zone about 4 to 5 km wide, perhaps characterized by anticlinal and synclinal folding and/or multiple fault strands.

The plan view pattern of Stevens Creek also supports the interpretation that the profile convexity downstream of the range front is a result of surficial deformation. Within the upstream part of the profile convexity, directly upstream of the Southern Pacific railroad tracks, the trend of Stevens Creek changes from north to northwest (Fig. 10; Plate 2). Of the major streams that drain the southern Santa Cruz Mountains, this is the only reach in the Santa Clara Valley that trends northwest for more than 0.5 km. If there is uplift of the area along the Cascade fault and the zones of lineaments identified herein, then it is likely that the change in trend of Stevens Creek reflects deflection of the channel to the northwest. Similar channel deflection and migration of point-bar sequences along the Mississippi River have been attributed to active deformation of the Lake County uplift in the New Madrid Seismic Zone (Kelson et al., 1993).

<u>Regnart Creek</u>

Regnart Creek drains a small, predominantly range-front basin between Stevens Creek and Calabazas Creek (Plate 2). Downstream of the range front, the creek flows in a shallow channel for approximately 2 km before dissipating into alluvial deposits of the coalescent fan complex in Santa Clara Valley. Approximately 1 km downstream of the range front, Regnart Creek crosses a prominent, 3-m-high topographic scarp (Fig. 11; Plate 2). Directly upstream of this scarp, the longitudinal profile of Regnart Creek clearly shows a convexity (Fig. 11). The stream gradient upstream and downstream of the scarp is about 15 to 18 m/km, whereas the gradient at the scarp is about 23 m/km. However, the steepest part of the stream channel is approximately 200 m upstream of the scarp face where it is developed in alluvial fan deposits northwest of the creek, suggesting that there has been headward erosion into the scarp by Regnart Creek.

<u>Calabazas Creek</u>

The longitudinal profile of Calabazas Creek shows two subtle convexities that coincide with the southern extension of the Regnart scarp and the surface trace of the Cascade fault (Fig. 12; Plate 2). Both of these convexities are more subtle than those along Permanente, Stevens, and Regnart Creeks. The upstream convexity is located at the range front, although to the southeast of Calabazas Creek the range front changes orientation to a more southerly trend, and Calabazas Creek flows parallel to the range front (Plate 2). The stream gradient upstream of the upper convexity is about 14 m/km, which shallows to about 9 m/km and then steepens to about 15 m/km (Fig. 12). This convexity is along the southeastern projection of the scarp near Regnart Creek, and likely is related to deformation along the range front.

Downstream of the upper convexity, Calabazas Creek has a gradient of about 10 m/km, shallows to about 8 m/km, and then steepens to 11 m/km (Fig. 12). Below this lower convexity, Calabazas Creek has a gradient of about 7 m/km. These gradient changes reflect a convexity that is about 2 km wide and is located between 1 and 3 km downstream of the range front. The trace of the Cascade fault coincides with the base of the steep part of this lower convexity. Several lineaments, including a closed depression, are located adjacent to the upstream part of the lower convexity (Fig. 12). A northwestward projection of this lower convexity coincides with the lower, more northeasterly convexity identified along Stevens and Permanente Creeks (Fig. 9).

Calabazas Creek has low sinuosity values across the zones of lineaments relative to areas upstream and downstream of the lineaments. For example, reaches AB and EF (Fig. 12) are associated with multiple lineaments and have sinuosities of 1.2, and reaches directly downstream of these reaches have sinuosities of 1.7 and 1.9, respectively. The low sinuosity values are probably related to active downcutting, perhaps in response to uplift, and the high sinuosity values probably are related to fluvial response to steepened gradients, also perhaps in response to uplift. These relations are consistent with adjustments of the stream channel to tectonic uplift associated the zone of lineaments and thus, perhaps, with the Cascade fault.

Saratoga Creek

The longitudinal profile of Saratoga Creek downstream of the range front shows two subtle convexities (Fig. 13). The upper convexity is 2 km wide and is located essentially at the mountain front and along the projection of an anticline mapped by Sorg and McLaughlin (1975) (Fig. 9; Plate 1). The channel gradient across this zone changes from about 24 m/km above the range front, to about 20 m/km in the upstream part of the convexity, to about 27 m/km in the steeper, downstream part of the convexity. The gradient below the convexity is about 17 m/km (Fig. 13). This convexity probably is related to near-surface anticlinal folding in the hanging wall of the Monte Vista fault.

A second, very subtle convexity is present along Saratoga Creek approximately 4 to 6 km downstream of the range front (Fig. 13). This 2-km-wide convexity is located entirely within alluvial sediments, and is coincident with the trace of the Monte Vista fault as mapped by Dibblee (1966) and zones of lineaments identified in this study (Fig. 9). The channel gradient across this zone changes from about 13 m/km above the convexity, to about 8 m/km in the upstream part of the convexity, to about 10 m/km in the downstream part of the convexity (Fig. 13). A shallow gradient of about 8 m/km is present below the steeper downstream end of the convexity. If the profile convexity is related to uplift, there is less than about 3 m of uplift over approximately 2 km. This convexity is along the southeastern projection of the upper convexities identified along Permanente, Regnart, and Calabazas Creeks (Fig. 9). However, the Saratoga Creek profile shows no evidence of convexity across the trace of the Cascade fault, or across the southeastern projection of convexities about 2 km downstream of the range front along Stevens and Calabazas Creeks (Fig. 9).

Channel sinuosity values along Saratoga Creek are generally low, although two stream reaches with higher sinuosities are located at or directly below zones of lineaments (Fig. 13). Roughly 0.5 km downstream from the range front, sinuosity increases slightly from 1.2 to 1.3, an increase that occurs directly downstream from a narrow zone of lineaments and a previously mapped fault (Plate 1). Roughly 2 km northeast of the range front, sinuosity shows an increase from 1.1 to 1.3, with the increase taking place upstream of a well-defined zone of vegetation lineaments. The majority of the more sinuous reach lies downstream of the lineament zone. These relations, although subtle, are consistent with adjustments of the stream channel to tectonic uplift associated with the range front faults. Downstream of these two reaches, Saratoga Creek maintains a relatively straight course across three more zones of lineaments, including one coincident with a mapped trace of the Monte Vista fault (Plate 1).

Los Gatos Creek

Because of extensive cultural modifications prior to 1961, the longitudinal profile of Los Gatos Creek may not accurately reflect pre-urbanization channel gradients. For example, construction of Vasona Reservoir extensively altered the stream channel and its profile, and channel modifications related to several percolation ponds downstream of Vasona Reservoir are extensive. With these exceptions, however, it is likely that modifications were small enough so that the longitudinal profile may still reflect possible tectonic influences on channel gradients. There are two convexities in the Los Gatos Creek profile downstream of the range front, one that coincides with traces of the Shannon fault above Vasona Reservoir, and one that coincides with the trace of the Cascade fault below Vasona Reservoir (Fig. 14).

The upper convexity along Los Gatos Creek is about 1.5 km wide and is located downstream of the range front (Fig. 14). The channel gradient changes from about 5 m/km to about 12 m/km across the convexity. Three traces of the Shannon fault are mapped across Los Gatos Creek along this reach. The lower convexity is about 3 km wide and is located between about 4 and 7 km downstream of the range front (Fig. 14). This convexity is characterized by a gradient change of about 4 m/km in the upstream reach, directly downstream of Vasona Dam, to about 12 m/km in the downstream reach. Downstream of the steeper northeast side, the channel gradient is about 5 m/km (Fig. 14). The trace of the Cascade fault crosses the steeper, downstream side of the convexity. However, in contrast to convexities along other major streams, this convexity is not coincident with zones of lineaments identified on aerial photography (Fig. 9). Because of substantial channelization, stream sinuosities were not determined for Los Gatos Creek.

Summary

Several of the longitudinal profiles of major creeks draining across the northeastern margin of the southern Santa Cruz Mountains show convexities that likely are related to near-surface deformation. Most of these convexities are coincident with either the range front, previously mapped traces of the Monte Vista, Shannon, or Cascade faults, or zones of lineaments identified herein (Fig. 9; Plate 1). Convexities typically consist of a relatively shallow-gradient reach, followed by a steeper reach that generally is coincident with mapped fault traces or zones of lineaments. Profile convexities typically are collinear among most of the major drainages, providing evidence of two or three zones of deformation at and northeast of the range front. High stream sinuosities typically are associated with relatively steep stream reaches, and with reaches directly downstream of zones of lineaments or mapped faults. The upstream, shallow-gradient reaches of convexities typically have low sinuosities, which is probably a response of the streams to equilibrate channel gradients across the convexity. These relations provide evidence that the zones of lineaments and profile convexities are spatially associated with zones of uplift.

3.0 DEFORMATION ASSOCIATED WITH THE NORTHEASTERN MARGIN OF THE SANTA CRUZ MOUNTAINS

Northeast of the San Andreas fault, the structure of the San Francisco Bay region is characterized by large blocks bordered by major southwest-dipping faults with northwest-trending orientations (Fig. 1; Bailey and Everhart, 1964; R. L. McLaughlin, pers. comm., 1993). These southwest-dipping faults include the Monte Vista, Berrocal, and Shannon faults, which exhibit northeast-vergent reverse displacement of Miocene and younger deposits and generally are located along the northeastern margin of the Santa Cruz Mountains (Sorg and McLaughlin, 1975). In addition, there is abundant geologic and geomorphic evidence that several fault traces are present northeast of the range front that deform Pliocene and younger deposits (Dibblee, 1966; CDWR, 1975; Sorg and McLaughlin, 1975; Helley and Wesling, 1989). This report delineates late Pleistocene and Holocene geomorphic surfaces along and northeast of the northeastern margin of the Santa Cruz Mountains, and uses these surfaces, along with potentially fault-related lineaments, channel profiles, and stream sinuosities to assess the distribution and style of deformation across the range-front fault zone. As described above, several faults deform late Pleistocene surfaces and influence major fluvial systems crossing the range front. It is likely that these faults are potential seismic sources and, in part, are responsible for uplift of the Santa Cruz Mountains. The following discussion addresses the late Pleistocene deformation along and northeast of the range front, compares the pattern of this long-term deformation with ground cracking that occurred during historic earthquakes, and speculates on the relationship between reverse faults along the margin of the range and the San Andreas fault.

3.1 Deformation Along the Range Front

The northeastern margin of the Santa Cruz Mountains is bordered by the Monte Vista fault between Palo Alto and Cupertino, and the Berrocal fault between Saratoga and Los Gatos, both of which dip to the southwest and exhibit geologic evidence of Pliocene and later reverse displacement (Sorg and McLaughlin, 1975). Our investigations provide information on the location and style of late Pleistocene and possibly Holocene deformation along these faults.

<u>Monte Vista Fault</u>

Based on detailed mapping of fluvial terraces in the vicinity of the range front, there is about 12 m of vertical separation of the Qt_1 terrace across the Monte Vista fault at Stevens Creek. An estimated age for this terrace is about 120 ka (E. Helley, cited in Sorg and McLaughlin, 1975). These data suggest that the Monte Vista fault has a late Pleistocene uplift rate of about 0.1 mm/yr. However, the age of this terrace is poorly constrained, and may be considerably younger than 120 ka. For the sake of argument, the terrace may be as young as 23 ka, which is the age estimated by Sieh (1975), for the correlative Qf1r alluvial fan along Regnart Creek (Plate 2). Assuming a 23 ka age estimate for the displaced terrace along Stevens Creek, the estimated uplift rate across the Monte Vista fault is about 0.5 mm/yr. Given the large uncertainty in the age of the terrace, we estimate a late Pleistocene uplift rate across the Monte Vista fault of 0.3 ± 0.2 mm/yr. Assuming an average dip for the fault of 45°, these relations yield an estimated late Pleistocene dip-slip rate of 0.4 ± 0.3 mm/yr. Considering that the fault likely is an oblique-slip fault with some unknown component of lateral slip, this value is a minimum for the net slip rate along the Monte Vista fault.

Our estimated uplift rate of 0.3 ± 0.2 mm/yr across the Monte Vista fault is comparable to the 0.36 mm/yr rate estimated by Sorg and McLaughlin (1975) and R.L. McLaughlin (pers. comm., 1993). Although our value of 12 m of vertical separation is lower than the 43 m estimated by these previous workers, it is based on detailed delineation of terrace and fan-surface remnants on 5-ft-contour topographic maps, and on surface offset rather than terrace height above Stevens Creek. The estimated late Pleistocene uplift rate of 0.3 ± 0.2 mm/yr across the Monte Vista fault is less than the post-10 Ma uplift rate for the range block of 0.8 to 1.0 mm/yr based on fission-track data (Arrowsmith et al., 1992; R. Bürgmann et al., in press, 1993). This difference may be attributed to a decrease in uplift rate during the late Pleistocene. Alternatively these data may show that uplift has occurred on faults other than the Monte Vista fault northeast of the range front during the late Pleistocene and possibly Holocene.

There are several geomorphic features (e.g., zones of lineaments, stream convexities and sinuosities) that provide substantial evidence for the presence of late Pleistocene and possibly Holocene deformation northeast of the range front. Because this deformation probably is a result of movement along faults that dip moderately to the southwest and merge or intersect with structurally higher reverse faults (i.e., the Berrocal or Monte Vista faults) or the San Andreas fault, they contribute, in part, to uplift of the Santa Cruz Mountains. Thus, faults northeast of the range front likely take up some of the "discrepancy" between the uplift rate for the range and the uplift rate estimated for the Monte Vista fault. The cumulative rate of uplift along all of the many faults northeast of the San Andreas fault, including the Monte Vista, Shannon, and Berrocal faults and faults within the Santa Clara Valley northeast of the range, may be as high as the rate suggested by fission track data (0.8 mm/yr, Bürgmann et al., in press, 1993).

Additional information on the late Pleistocene uplift rate along the Monte Vista fault is provided by a prominent topographic scarp flanking Regnart Creek about 0.5 km northeast of the range front. This scarp is developed on a fan surface estimated to be 23 ka (Sieh, 1975), which we map as the highest alluvial fan associated with Regnart Creek (Qf1r, Plate 2). Based on 2-ft-contour maps of the central part of the scarp, there is about 2 m of vertical separation of the fan surface. These data yield a late Pleistocene uplift rate across this strand of the Monte Vista fault of about 0.1 mm/yr. However, we have low confidence in this estimated rate because the age-estimate of the fan surface is poorly constrained and because the scarp probably represents only one strand of the Monte Vista fault. The scarp is located about 0.5 km northeast of the mapped trace of the Monte Vista fault (Sorg and McLaughlin, 1975). Based on the presence of multiple lineaments and a prominent linear range front, there probably are additional post-late Pleistocene strands and subsidiary strands between the mapped trace and the topographic scarp. Thus, the estimated uplift rate for this fault strand likely is a minimum for the entire Monte Vista fault.

The total length of this scarp is only about 1.5 km, including a very subtle scarp on the southeast side of Regnart Creek near Regnart School (Plate 2). The short, yet prominent scarp in alluvium may represent a section of the Monte Vista fault over which distinct surface rupture has occurred outboard of the range front. Deformation along other sections to the northwest and southeast of the scarp probably occurs as folding or distributed faulting. Also, R.L. McLaughlin (pers. comm., 1993) interprets the Monte Vista as a former blind thrust fault that has breached the axis of its hanging wall anticline, reached the surface, and rotated to a steeper southwest-dipping orientation. If so, the Regnart scarp may be a result of fault rupture up through its hanging wall anticline and to the surface, with anticlinal deformation occurring to the northwest and southeast of the ends of the scarp.

The distribution of lineaments, scarps, and other geomorphic features potentially related to deformation along the range front provides additional information on the southeastern extent of the Monte Vista fault. As shown on Plate 1, previous workers map the Monte

Vista fault along the base of the range front between Permanente Creek and Calabazas Creek. Analysis of aerial photography conducted during this study shows that several lineaments are present along this range front (Plate 2). South of Calabazas Creek, the range front changes trend to a more southerly orientation, as do fold axes within the Santa Clara Formation (Plate 1). Previous workers interpret that the Monte Vista fault also changes strike, coincides with the range front, and joins the Berrocal fault near Saratoga (Sorg and McLaughlin, 1975; Cotton et al., 1980; R.L. McLaughlin, pers. comm., 1993). However, our interpretation of aerial photography shows that many of the lineaments identified adjacent to the range front northwest of Calabazas Creek continue to the southeast into the central part of the range-front embayment occupied by Saratoga and Los Gatos (Plate 2). In general, the northwest trend of lineaments is consistent throughout the study area, including the south-trending section of the range front between Calabazas Creek and Saratoga. This overall pattern provides evidence that the Monte Vista fault, as a late Pleistocene structure, continues from Calabazas Creek into the Saratoga-Los Gatos embayment, rather than following the range front to the south toward Saratoga. In addition, subsurface well data show that a possible southeastern extension of the Monte Vista fault displaces bedrock and buried stream channels between Calabazas Creek and Vasona Reservoir (CDWR, 1975). Thus, it appears that the late Pleistocene Monte Vista fault is not continuous with the Berrocal fault near Saratoga, but instead either dies out in the Saratoga-Los Gatos embayment, splays into several fault traces within the embayment, or joins the Shannon fault (Plate 1). Nevertheless, a trace of the Monte Vista fault may be present along the south-trending range front between Calabazas Creek and Saratoga (Sorg and McLaughlin, 1975; Cotton et al., 1980; R.L. McLaughlin, pers. comm., 1993), although this trace shows much less geomorphic expression of late Pleistocene movement (Plate 2).

All of the major streams between Los Altos Hills and Cupertino show longitudinal-profile convexities and/or high stream sinuosities at or adjacent to the range front (Fig. 9). The Permanente Creek profile shows a prominent convexity directly upstream of the Monte Vista fault (Fig. 8). This convexity probably is related to differences in bedrock erodibility within the range block and/or anticlinal folding in the hanging wall of the Monte Vista fault. Directly downstream of the convexity, the stream flows parallel to the fault and within a zone of lineaments (Fig. 9). This 1.5-km-long, linear reach is bordered on the southwest by a series of prominent linear fronts and faceted ridge spurs (Plate 2). The position of the stream within this linear, fault-parallel valley probably accounts for the lack of a high stream sinuosity directly downstream of the range front (Fig. 9).

The longitudinal profile of Stevens Creek also shows a convexity directly upstream of the range front and the Monte Vista fault (Figs. 3 and 9). This may also be a result of differences in bedrock erodibility within the range block and/or anticlinal folding in the hanging wall of the Monte Vista fault. Substantial anticlinal folding of the Qt1s, Qt2s, and possibly Qt3s terraces are coincident with this convexity, and the lowest terrace (Qt4s) is located only downstream of the profile convexity (Fig. 3). These relations strongly support the interpretation that the convexity is a result of anticlinal folding in the hanging wall of the Monte Vista fault. Stream sinuosity directly downstream of the convexity is relatively high (Figs. 9 and 10), which provides evidence that the fault influences the valley gradient.

Regnart Creek shows a profile convexity directly downstream of the range front, which contrasts with the position of the convexities along Permanente and Stevens Creek upstream of the range front (Fig. 9). However, the Regnart Creek convexity is coincident with the prominent scarp in the highest alluvial fan surface, and likely is related to deformation about 0.5 km downstream of the range front. The crest of the convexity is a few hundred meters upstream of the crest of the scarp, suggesting that there has been headward erosion of Regnart Creek into the scarp. These relations could be interpreted to show that the scarp has some antiquity (late Pleistocene?), although the rate of headward erosion is unknown for a stream having the discharge and sediment load characteristics of Regnart Creek.

Calabazas Creek shows a profile convexity approximately at the range front (Figs. 9 and 12). The convexity extends for about 0.5 km downstream of the range front and thus is similar in geomorphic position to the convexity along Regnart Creek. Multiple lineaments that coincide with the convexity provide evidence that the convexity is a result of near-surface deformation, most likely along the southeastern projection of the Monte Vista fault toward the Saratoga-Los Gatos embayment. Stream sinuosity is relatively high across the crest of the convexity, and directly downstream of the convexity (Fig. 12), which probably is related to deformation at or near the range front.

Berrocal Fault

The Berrocal fault is located along the southwestern margin of the Saratoga-Los Gatos embayment (Plate 1). Between Los Gatos and Saratoga, the fault separates the Santa Clara Formation and older alluvial fan deposits. Strands of the Berrocal fault also cut Franciscan bedrock. Near Saratoga, the fault is mapped within the range block (Sorg and McLaughlin, 1975). South of Los Gatos, the Berrocal fault has a more southwesterly trend than the range front and is mapped within the range block (McLaughlin et al., 1991).

The distribution of lineaments, scarps, and other geomorphic features potentially related to deformation between Los Gatos and Saratoga constrain the location of the Berrocal fault to the base of the range front. Lineaments include linear fronts, linear depressions, and scarps along the range front. In general, lineaments between Los Gatos and Saratoga trend northwest, parallel to the range front. However, topographic lineaments are present along the range front through Saratoga, providing evidence that the range front may be controlled by faulting to the northeast of the Berrocal fault. Longitudinal profiles of fluvial terraces along Saratoga Creek show anomalous gradients that coincide with a mapped anticline northeast of the Berrocal fault (Fig. 5). Deformation of the stream terraces coincides with a convexity in the longitudinal stream profile (Fig. 13). Deformation within Saratoga, northeast of the Berrocal fault, may be associated with a previously unidentified strand of the Berrocal fault or a different, previously unmapped range-front fault.

The uplift rate across the Berrocal fault between Saratoga and Los Gatos is unknown. However, minor scarps and other topographic lineaments associated with the Berrocal fault displace Qf$_1$st northeast of the range front, between Saratoga and Los Gatos. In addition, Pleistocene terrace deposits underlying Qt$_1$lg are displaced by a strand of the Berrocal fault that dips about 60° to the southwest, northwest of the intersection of Wood Road and Santa Cruz avenue in Los Gatos (R. L. McLaughlin, pers. comm., 1993) (Plate 1). Rock within the Franciscan Complex has been thrust to the northeast over terrace gravels. Based on the outcrop, the estimated minimum offset of Qt$_1$lg across the Berrocal fault is 0.7 m (R. L. McLaughlin, pers. comm., 1993). However, the longitudinal terrace profile of Los Gatos Creek does not show vertical offset of Qt$_1$lg across the strand of the Berrocal fault mapped by McLaughlin et al. (1991) at Wood Road (Fig. 6). The maximum offset of Qt$_1$lg is therefore less than or equal to the 3-m resolution of the contour intervals used to map Qt$_1$lg.

3.2 Deformation Northeast of the Range Front

The Santa Clara Valley borders the northeastern margin of the Santa Cruz Mountains and is underlain primarily by alluvial sediments deposited by major streams and range-front tributaries flowing to the northeast out of the mountains. Several previous workers mapped faults northeast of the range front on the basis of gravity data, water well logs, or linear geomorphic features (Dibblee, 1966; CDWR, 1975; Wesling and Helley, 1989). All of the faults previously identified northeast of the range front are mapped as buried or concealed (Plate 1), and prior to the 1989 Loma Prieta earthquake none of the faults were considered significant seismic sources. The concept of active thrust faulting along the margins of major range blocks in the urbanized San Francisco Bay region was brought to light by the occurrence of the 1983 Coalinga earthquake along a thrust fault northeast of the San Andreas fault, and by substantial contractional deformation northeast of the San Andreas fault during the 1989 Loma Prieta earthquake (R.L. McLaughlin, pers. comm., 1993) .

Between the towns of Los Altos Hills and Los Gatos, the major mapped faults northeast of the range front are the Cascade fault (CDWR, 1975), which originally was interpreted as a vertical fault based on well data, and the Shannon fault (Bailey and Everhart, 1964; Sorg and McLaughlin, 1975), which is a southwest-dipping reverse fault consisting of several splays in the Saratoga-Los Gatos embayment. As noted above, the southeastern projection of the Monte Vista fault merges with splays of the Shannon fault between Saratoga and Los Gatos (Plate 1). Our investigations provide information on the location and style of late Pleistocene and possibly Holocene deformation along the Cascade and Shannon faults.

Cascade Fault

The Cascade fault traverses the coalescent alluvial-fan complex underlying the Santa Clara Valley approximately 2 to 6 km northeast of the Santa Cruz Mountains range front (Plate 1). Our investigations show a strong correlation between the mapped trace of the Cascade fault and potentially fault-related geomorphic features, including vegetation lineaments, closed depressions, linear drainages, stream profile convexities, and high-sinuosity stream reaches. These geomorphic features are developed in late Pleistocene and possibly Holocene deposits, and therefore provide evidence of late Pleistocene (and possibly Holocene) displacement along the Cascade fault. Although this research provides little or no information on the sense of slip and the amount and direction of fault dip, it is likely that the Cascade fault is a southwest-dipping, northeast-vergent reverse fault similar to, but perhaps having a shallower dip in the near surface than, the Monte Vista, Berrocal, and Shannon faults. R. L. McLaughlin (pers. comm., 1993) notes that there may be faults beneath the Santa Clara Valley northeast of the range front that root into the Monte Vista or the San Andreas at depth. It is likely that the Cascade fault is such a fault.

In a general sense, zones of lineaments identified via analysis of aerial photography are coincident with the surface trace of the Cascade fault in Los Altos and Cupertino, but not between Calabazas and Los Gatos Creeks (Plate 1). These lineaments likely are related to tectonic deformation based on their consistent northwest trends, *en echelon* pattern, and spatial coincidence with potentially fault-related geomorphic lineaments (Plate 2). The lineaments also are spatially associated with the apices of similar-age alluvial fans deposited by each of the major streams that cross the fault trace. For example, near the intersection of Highways 280 and 85 in Cupertino, Stevens Creek crosses the trace of the Cascade fault and a series of vegetation lineaments developed in the Qf1s, Qf2s, and Qf4s fan surfaces (Fig. 15; Plate 2). Directly downstream of the fault and the zone of lineaments are the apices of the two youngest fan surfaces (Qf4s and Qf5s), which are inset into the Qf1s surfaces (Fig. 15). Although the location of fan apices may be unrelated to tectonic deformation, the correspondence between the Qf4s and Qf5s apices and the Cascade fault trace, the zone of lineaments, inset terraces, and a profile convexity (see below), strongly suggests that the development of the fans is related to deformation along the Cascade fault. Importantly, a similar pattern is present for many of the other major streams that cross the Cascade fault and its associated zones of lineaments, including Permanente, Calabazas, and

Saratoga Creeks (Plate 2). These relations provide evidence that there has been late Pleistocene uplift located about 5 to 6 km northeast of the range front, probably along the Cascade fault between Los Altos and Cupertino.

Most of the major streams between Los Altos Hills and Los Gatos show longitudinal-profile convexities where they cross the Cascade fault trace, with the exception being Saratoga Creek (Fig. 9). In general, the crests of the convexities coincide with the zone of lineaments (Figs. 8, 10, 11, and 12). The convexities range in width from about 1.5 km to about 3.5 km, with wider convexities associated with wider or multiple zones of lineaments, such as along Los Gatos or Stevens Creek (Fig. 9). The crest of the convexities are located about 3 to 5 km northeast of the range front, and occur along reaches underlain by alluvial sediments of the Santa Clara Valley. Convexities along Permanente, Stevens, and Calabazas Creeks are associated with relatively high values of stream sinuosity directly downstream of the convexity (Fig. 9). The variations in sinuosity along each of these streams likely are related to anticlinal deformation, with less sinuous reaches present across the upstream sides of the uplifts, and more sinuous reaches along the steeper, downstream sides of the uplift (Fig. 7; Ouchi, 1985). These relations support our interpretation of late Pleistocene uplift along the Cascade fault between Los Altos and Cupertino.

Shannon Fault

Southeast of Los Gatos Creek, the Shannon fault consists of several southwest-dipping strands that exhibit northeast-vergent reverse displacement between the Santa Teresa Hills and the Berrocal fault (Bailey and Everhart, 1964; R.L. McLaughlin, pers. comm., 1993). Within the Saratoga-Los Gatos embayment, the fault consists of four strands that presumably also are southwest-dipping, northeast-vergent reverse faults (McLaughlin et al., 1991). Because mapping by Bailey and Everhart (1964) and McLaughlin et al. (1991) covered only the Los Gatos quadrangle, the northwestern extent of the Shannon fault into the Saratoga area is unpublished (Plate 1). Our investigations in the Saratoga-Los Gatos embayment between Los Gatos and Calabazas Creek provide additional information on possible locations of strands of the Shannon fault, and provide evidence of probable late Pleistocene deformation associated with these strands.

The distribution of lineaments within the Saratoga-Los Gatos embayment is complex, consisting of multiple anastomosing zones (Plates 1 and 2; Fig. 9). In the Los Gatos quadrangle, previously mapped traces of the Shannon fault show a general correspondence with the orientations of the zones of lineaments, although there is not a consistent relation between the zones and mapped fault traces (Plate 1). However, the amount of uncertainty in the locations of the mapped traces probably is permissive of the interpretation that the zones of lineaments represent surface deformation associated with traces of the Shannon fault. Spatial association of coseismic deformation during the 1989 Loma Prieta earthquake with traces of the Shannon fault (Haugerud and Ellen, 1990) and with zones of lineaments (see below) support this interpretation.

Based on profiles constructed from 2-ft-contour interval maps, fluvial terraces along Los Gatos Creek exhibit evidence of deformation along the Shannon fault (Fig. 6). In particular, terrace Qt_2lg shows a convexity directly upstream of a trace of Vasona Reservoir that is coincident with the convexity of the present-day channel (Fig. 14). If related to tectonic uplift, the terrace provides evidence of about 3 to 4 m of uplift distributed over a reach about 1.5 km long, whereas the channel profile exhibits less than about 2 m of vertical relief over a reach about 1 km long. The profile of the higher, older terrace Qt_1lg is based on 10-ft contours, which probably do not enable resolution of the possible deformation exhibited by the Qt_2lg terrace. Inset into terrace Qt_2lg are discontinuous remnants of the lowest terrace (Qt4lg, Fig. 6), which show possible evidence of deformation. The Qt4lg profile is shows a slight convexity and a possible oversteepened remnant approximately 1.5 km downstream of the range front (Fig. 6). Although the age of terrace Qt4lg is unknown, its geomorphic position along the floor of the Los Gatos Creek valley suggest that it is Holocene or possibly latest Pleistocene. Considered together, the spatial association of traces of the Shannon fault with zones of photogeologic lineaments and convexities in the terrace and present-day channel profiles proved evidence of late Pleistocene and possibly Holocene surficial deformation.

The zones of lineaments identified near Los Gatos Creek continue along northwesterly trends toward Saratoga Creek (Plates 1 and 2; Fig. 9). Considering that traces of the Shannon fault most likely continue to the northwest into the Saratoga area, the distribution of lineaments suggest that traces of the Shannon fault probably continue to the northwest across Saratoga Creek and possibly as far northwest as Calabazas Creek. Near Calabazas Creek the zones of lineaments appear to merge with those along the base of the range front associated with the Monte Vista fault (Fig. 9; Plate 1). Thus, it is reasonable to interpret that strands of the Monte Vista and Shannon faults merge within the Saratoga-Los Gatos embayment.

Based on profiles constructed from 2-ft-contour interval maps, fluvial terraces along Saratoga Creek exhibit possible evidence of deformation across the Monte Vista/Shannon fault (Fig. 5). In particular, terrace Qt2st shows a broad convexity between about 2 and 3.5 km downstream of the range front (Fig. 5). This possible terrace deformation is downstream of a broad convexity in the present-day channel (Fig. 13). The crest of this convexity lies along the southeastern projection of other convexity crests associated with the range front (and thus the Monte Vista fault) along Calabazas, Regnart, and Permanente Creeks (Fig. 9). The reach characterized by convexities in the Qt2st terrace is upstream of the trace of the Monte Vista fault, whereas the present-day channel convexity is coincident with the fault trace (Figs. 5 and 13). Given that the Shannon fault consists of multiple splays near Los Gatos, it is reasonable to interpret that the convexity is associated with one or more traces of the Monte Vista and/or Shannon faults. These relations provide additional evidence that the Shannon fault has had late Pleistocene displacement.

3.3 Relative Timing of Deformation at and Northeast of the Range Front

Assessment of the timing of deformation along the Monte Vista, Berrocal, Shannon, and Cascade faults requires well-constrained estimates of the ages of deformed and undeformed geomorphic surfaces and surficial deposits. Unfortunately, we have no additional information on the ages of surfaces or deposits in the study area, and have had to rely on previous, poorly constrained age-estimates that are available only for a few surfaces. With the exception of displacement along the Monte Vista fault at Stevens Creek, we choose to not estimate uplift rates or slip rates for structures in the study area. However, several relations between geomorphic surfaces and potentially fault-related lineaments identified via analysis of aerial photography yield information on the relative timing of deformation among faults at and northeast of the Santa Cruz Mountains range front. These relations may provide insight into the kinematics of faulting along the range front, and on the relative seismic hazards posed by faults bordering the range.

Along the range front in the vicinity of Permanente Creek, lineaments are present in areas underlain by the Santa Clara Formation and across relatively low terrace surfaces (Qtu, Plate 2). Downstream of the range front and in the vicinity of the Cascade fault, lineaments also are present across older and younger fan remnants (Qf1p, Qf2p, and Qf4p). Along Stevens and Regnart Creeks near the range front, lineaments are present across older fan surfaces (Qf1s and Qf1r), but not across younger, inset terraces (Qt2s and Qt4s, Plate 2).

About 2.5 km downstream of the range front, lineaments cross the Qt2s surface but not the younger Qt4s surface (Fig. 15). Near the Cascade fault about 4 km downstream of the range front, lineaments cross all of the surfaces, including the Qf4s fan surface (Plate 2). Surfaces along Saratoga Creek show a similar pattern, with lineaments present across progressively younger surfaces in a downstream direction. These relations support an interpretation that deformation across the faults northeast of the range has progressed outward from the range front to the northeast.

In contrast, however, surfaces along Los Gatos Creek show the opposite pattern (Plate 2). At the range front, lineaments are present across areas underlain by the Santa Clara Formation, across the Qt2lg terrace, and across the lowest, youngest Qt4lg terrace. Downstream of Vasona Reservoir, about 4 km downstream of the range front, lineaments are present across areas underlain by the Santa Clara Formation (QTsc), across the highest fan surface (Qf1lg), and very locally across the Qt2lg terrace (Plate 2). Further to the northeast and about 5 km downstream of the mountain front, lineaments are not present across broad, well preserved remnants of both the Qt2lg and Qt4lg terraces (Plate 2). These relations suggest that faults at the range front near Los Gatos have had more recent deformation than those further to the northeast.

3.4 Fault-related Geomorphic Features and Historic Ground Deformation

The 1989 Loma Prieta earthquake produced coseismic contractional deformation in several northwest-trending zones along the northeastern flank of the Santa Cruz Mountains (Haugerud and Ellen, 1990). The linear trend of the deformation zones and spatial coincidence with mapped traces of the Shannon and Monte Vista faults suggest that the deformation was caused by tectonic movement. Correlation of the 1989 coseismic deformation with potentially fault-related geomorphic features and lineaments mapped during this study further supports a tectonic origin for the coseismic deformation.

A general correlation exists between zones of potentially fault-related geomorphic features, such as vegetation lineaments, topographic scarps, and stream profile convexities, and the distribution of coseismic deformation associated with the 1989 Loma Prieta earthquake. Localized zones of damage within Los Gatos, between Blossom Hill and Vasona Reservoir, and near Regnart School in Cupertino coincide with fault-related lineaments mapped during this study. These zones of deformation closely coincide with previously mapped traces of the Monte Vista, Shannon, and Berrocal faults (Haugerud and Ellen, 1990). In addition, deformation during the 1989 earthquake occurred in similar locations, as best as can be determined, as during the 1906 earthquake on the San Andreas fault (Lawson, 1908).

In downtown Los Gatos, the 1989 Loma Prieta earthquake produced a zone of broken and buckled concrete curbs and sidewalks (Haugerud and Ellen, 1990). Deformation of grates and utility boxes recorded northeast-southwest shortening, and broken concrete slabs lining Los Gatos Creek recorded up to about 17 cm of northeast-southwest contraction (Peterson et al., unpublished data). These breaks coincide with the projections of vegetation lineaments in Qt4lg and linear depressions in Qt2lg on both the northwestern and southeastern sides of Los Gatos Creek. Deformation associated with the 1906 earthquake, in the area that is now downtown Los Gatos, consisted of "about a dozen upheavals of sidewalks, mostly on north and south streets" (Lawson, 1908, p. 274).

Northeast-trending lineaments near Blossom Hill coincide with a band of 1989 coseismic deformation between Blossom Hill and Vasona Reservoir (Haugerud and Ellen, 1990). Numerous prominent vegetation and topographic lineaments are present at the base of Blossom Hill, where there was considerable localized deformation during the 1989 Loma

Prieta earthquake (Fig. 16). In particular, the pattern of deformation near Blossom Hill as a result of the 1989 earthquake is coincident with vegetation lineaments and a closed depression mapped on 1939 air photos during this study (Fig. 16).

The Loma Prieta earthquake caused intensive cracking and buckling of concrete sidewalks and curbs on alluvial fan deposits west of the Regnart scarp (S. Ellen, pers. comm., 1993; W. Cotton, pers. comm., 1993). A 50-m-wide, N40°W-trending zone of cracks that formed in asphalt at Regnart School during the 1989 earthquake coincides with the southern end of the Regnart scarp (S. Ellen, pers. comm., 1993) and is located along the southeastern projection of the Regnart Creek profile convexity (Fig. 11). Following the 1906 earthquake on the San Andreas fault, Lawson et al. (1908, p. 262) reported that "...0.5 mile southeast of Stevens Creek...a large area of ground, extending for 150 feet (*46 m*), had been torn up in a direction of N3°W". Youd and Hoose (1978) placed Lawson's observations east of the range front near Regnart School, but attributed the cracking to lateral spreading. Considering that lateral spreading toward the northeast is unlikely at this locality, ground cracking associated with both earthquakes probably was caused by coseismic movement along the fault strand also responsible for the formation of the Regnart scarp.

Coseismic contractional deformation associated with the 1989 Loma Prieta event was recorded almost entirely within brittle concrete curbs and sidewalks. Except for isolated exceptions, ground rupture was rare. Where ground rupture did occur, there is a close association with potentially fault-related lineaments. However, it is unclear whether repeated secondary coseismic deformation is sufficient to form prominent lineaments, especially distinct features like the Regnart scarp. Observations of deformation associated with the 1906 and the 1989 earthquakes are insufficient to provide a clear answer.

4.0
CONCLUSIONS

Coseismic contractional deformation occurred during the 1989 Loma Prieta earthquake in an area traversed by several southwest-dipping, northwest-trending reverse faults, including the Monte Vista, Shannon, and Berrocal faults (Haugerud and Ellen, 1990). These faults, which border the northeastern margin of the southern Santa Cruz Mountains, are responsible, in part, for uplift of the range block. In addition, movement along faults that traverse the Santa Clara Valley to the northeast of the range front, such as the Cascade fault, may also contribute to uplift of the range and the southwestern margin of the Santa Clara Valley.

Based on analysis of aerial photography and field reconnaissance between Los Altos Hills and Los Gatos, we delineate potentially fault-related lineaments, multiple alluvial fan surfaces, fluvial terraces, and other geomorphic features, in order to assess the pattern of deformation along and adjacent to the range front. Several zones of potentially fault-related lineaments are present along and northeast of the range front between Los Altos Hills and Los Gatos, and are coincident with previously mapped or postulated traces of the Monte Vista, Shannon, Berrocal, and Cascade faults. In particular, zones of lineaments located about 2 to 3 km northeast of the range front are up to 0.5 km wide and 5 km long, and include vegetation lineaments, topographic scarps, closed depressions, tonal contrasts linear drainages, and other linear geomorphic features. These zones of lineaments generally coincide with the previously mapped trace of the Cascade fault in Los Altos and Cupertino, and with mapped traces of the Shannon fault in Saratoga and Los Gatos. Based on their discontinuous, curvilinear pattern, the zones of lineaments probably are related to oblique dextral slip along moderately to shallow dipping, northeast-vergent reverse or thrust faults.

Up to as many as four fluvial terraces and four alluvial fans are identified along the major streams that drain the Santa Cruz Mountains and flow northeast into Santa Clara Valley. Longitudinal profiles of fluvial terraces along Stevens Creek show that there is about 12 m of vertical separation across the Monte Vista fault of a high terrace and a correlative alluvial fan surface. This terrace and the next two younger terraces show synclinal and anticlinal deformation in the hanging wall of the Monte Vista fault, as previously noted by Sorg and McLaughlin (1975). The ages of these surfaces are poorly constrained, although they most likely are late Pleistocene. Based on previous age-estimates of 23 to 120 ka for the highest terrace and its correlative fan surface, and on the 12 m of vertical separation, we estimate a late Pleistocene uplift rate for the Monte Vista fault of 0.3 ± 0.2 mm/yr. Based on a fault dip of about 45° derived from detailed field mapping along Stevens Creek, a reverse dip-slip rate of 0.4 ± 0.3 mm/yr is estimated for the Monte Vista fault. Both of these values are comparable to previous estimates derived from the same area but based on different assumptions of surface ages and displacements (Sorg and McLaughlin, 1975; R.L. McLaughlin, pers. comm., 1993).

Terraces and alluvial fans along Saratoga Creek show evidence of late Pleistocene deformation across the Berrocal fault at the range front, although a lack of surface continuity precludes a well-constrained assessment of the amount of deformation. Downstream of the range front, Saratoga Creek flows across the 3-km-wide Saratoga-Los Gatos embayment. Across the embayment, Saratoga Creek terraces exhibit evidence of possible deformation across traces of the Shannon fault. Although terrace longitudinal profiles along Los Gatos Creek exhibit no prominent evidence of deformation across the Berrocal fault, multiple lineaments across older and younger surfaces adjacent to the range front and possible faulting of fluvial deposits associated with the highest terrace near Los

Gatos (R.L. McLaughlin, pers. comm., 1993) show that the Berrocal fault probably has had late Pleistocene displacement. Terrace profiles along Los Gatos Creek within the Saratoga-Los Gatos embayment show a broad convexity probably related to uplift along traces of the Shannon fault directly upstream of Vasona Reservoir. Thus, fluvial terraces and alluvial-fan surfaces along all of the major streams that cross the range front and the Saratoga-Los Gatos embayment show evidence of probable late Pleistocene deformation.

Several longitudinal profiles of major creeks draining across the northeastern margin of the southern Santa Cruz Mountains show convexities that likely are related to near-surface deformation. Most of these convexities are coincident with previously mapped traces of the Monte Vista, Shannon, Berrocal, or Cascade faults, or with zones of lineaments identified herein. Convexities typically consist of a relatively shallow-gradient reach, followed by a steeper reach coincident with mapped fault traces or zones of lineaments. Profile convexities typically are collinear between major streams, providing evidence of three zones of deformation at and northeast of the range front. These zones occur (1) along the range front between Saratoga and Los Gatos (coincident with the Berrocal fault), (2) along the range front between Los Altos Hills and Cupertino (coincident with the Monte Vista fault and its southeastern projection), and (3) about 2 to 6 km northeast of the range front (coincident with the Cascade fault). These convexities also coincide, in a general way, with stream reaches characterized by relatively high sinuosity. The upstream, shallow-gradient reaches of convexities typically have low sinuosities, and the steeper reaches typically have high sinuosities, both of which are probably responses of the streams to equilibrate channel gradients across the convexity. The coincidence of mapped faults, zones of lineaments, terrace convexities, channel convexities, and anomalous channel sinuosities strongly suggest that faults along and northeast of the range front have had late Pleistocene and possibly Holocene deformation.

Analysis of aerial photography and field reconnaissance provides evidence that the Monte Vista fault merges with a trace or traces of the Shannon fault within the Saratoga-Los Gatos embayment. Northwest-trending, potentially fault-related geomorphic features along the range front between Los Altos Hills and Cupertino continue to the southeast into the embayment, rather than following the range front to the south toward Saratoga. Thus, we interpret that the late Pleistocene Monte Vista fault is not continuous with the Berrocal fault near Saratoga, but instead either dies out in the Saratoga-Los Gatos embayment or merges with traces of the Shannon fault. Considering the continuity of zones of lineaments between the Monte Vista fault in Cupertino and traces of the Shannon fault in Los Gatos, we interpret that the Monte Vista fault probably splays southward and merges with traces of the Shannon fault.

The distribution of lineaments across geomorphic surfaces of different relative ages provides information on the relative timing of deformation within the range-front fault zone as a whole. For example, lineaments crossing Stevens, Calabazas, and Saratoga Creeks are present on progressively younger surfaces in a downstream direction, to the northeast. These relations suggest that deformation has progressed through time from southwest to northeast, from the range front toward San Francisco Bay. In contrast, the distribution of lineaments on surfaces associated with Los Gatos Creek suggests that the deformation may have progressed from northeast to southwest, with the most recent deformation located closer to the range front, near downtown Los Gatos. These relations are consistent with the distribution of concentrated damage in downtown Los Gatos during the 1989 Loma Prieta earthquake.

Overall, the distribution of lineaments helps assess likely locations of future ruptures along the Monte Vista, Shannon, Berrocal, and Cascade faults. Based on the distribution of all potentially fault-related geomorphic features identified in this study, it is likely that the southeasternmost extent of future ruptures on the Cascade fault would be located in Cupertino, rather than in Los Gatos or further southeast. In addition, deformation on the Monte Vista fault extends into the Saratoga-Los Gatos embayment, where deformation is broader than along the range front in Los Altos Hills and Cupertino. Depending on earthquake magnitude and location, and perhaps many other factors, rupture on the Monte Vista fault may or may not extend to the Shannon fault proper. Based on numerous northwest-trending lineaments in the Saratoga-Los Gatos embayment, surface rupture on the Berrocal fault likely would not extend along the north-trending section of the range front between Saratoga and Cupertino, and thus probably would not merge with the Monte Vista fault. However, folds in the Santa Clara Formation west of this range front highlight the possibility of continued surficial deformation between Cupertino and Saratoga.

5.0 ACKNOWLEDGMENTS

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Permanente Creek		Stevens Creek		Regnart Creek		Calabazas Creek		Saratoga Creek		San Thomas de Aquinas Creek		Los Gatos Creek	
		Qfps	Qf_5s				Qf_5c	Qfpst	Qf_5st	Qfpa	Qf_5a	Qfplg	
	Qf_4p	Qt_4s	Qf_4s				Qf_4c	Qt_4st	Qf_4st		Qt_4a	Qt_4lg	Qt_4lg
		Qt_3s						Qt_3st				Qt_3lg	
	Qf_2p	Qt_2s	Qf_2s		Qf_2r		Qf_2c	Qt_2st	Qf_2st		Qt_2a	Qt_2lg	Qt_2lg
	Qf_1p	Qt_1s	Qf_1s		Qf_1r		Qf_1c	Qt_1st	Qf_1st		Qt_1a	Qt_1lg	Qt_1lg
Qtu						Qtu		Qtu		Qtu			
	Qfu		Qfu		Qfu		Qfu		Qfu		Qfu		Qfu
	Qp								Qp		Qp		Qp

Table 1. Correlation chart showing inferred age correlations between units for major drainages along the northeastern range front of the Santa Cruz Mountains. Units on the same line are believed to have similar relative ages.

	Qt_1	Qt_2	Qt_3	Qt_4	Qfp
Stevens Creek	15-30 m (50-100 ft)	12-14 m (40-45 ft)	6-8 m (20-25 ft)	3-4.5 m (10-15 ft)	1.5 m-3 m (5-10 ft)
Saratoga Creek	13-15 m (45-50 ft)	10.5-12 m (35-40 ft)	6 m (20 ft)	3 m (10 ft)	1.5-2 m (5-7 ft)
Los Gatos Creek	20-30 m (70-100 ft)	13.5-20 m (45-70 ft)	6 m (20 ft)	3 m (10 ft)	1.5-2 m (5-7 ft)

Table 2. Average heights of terrace remnants above the present day stream channel.

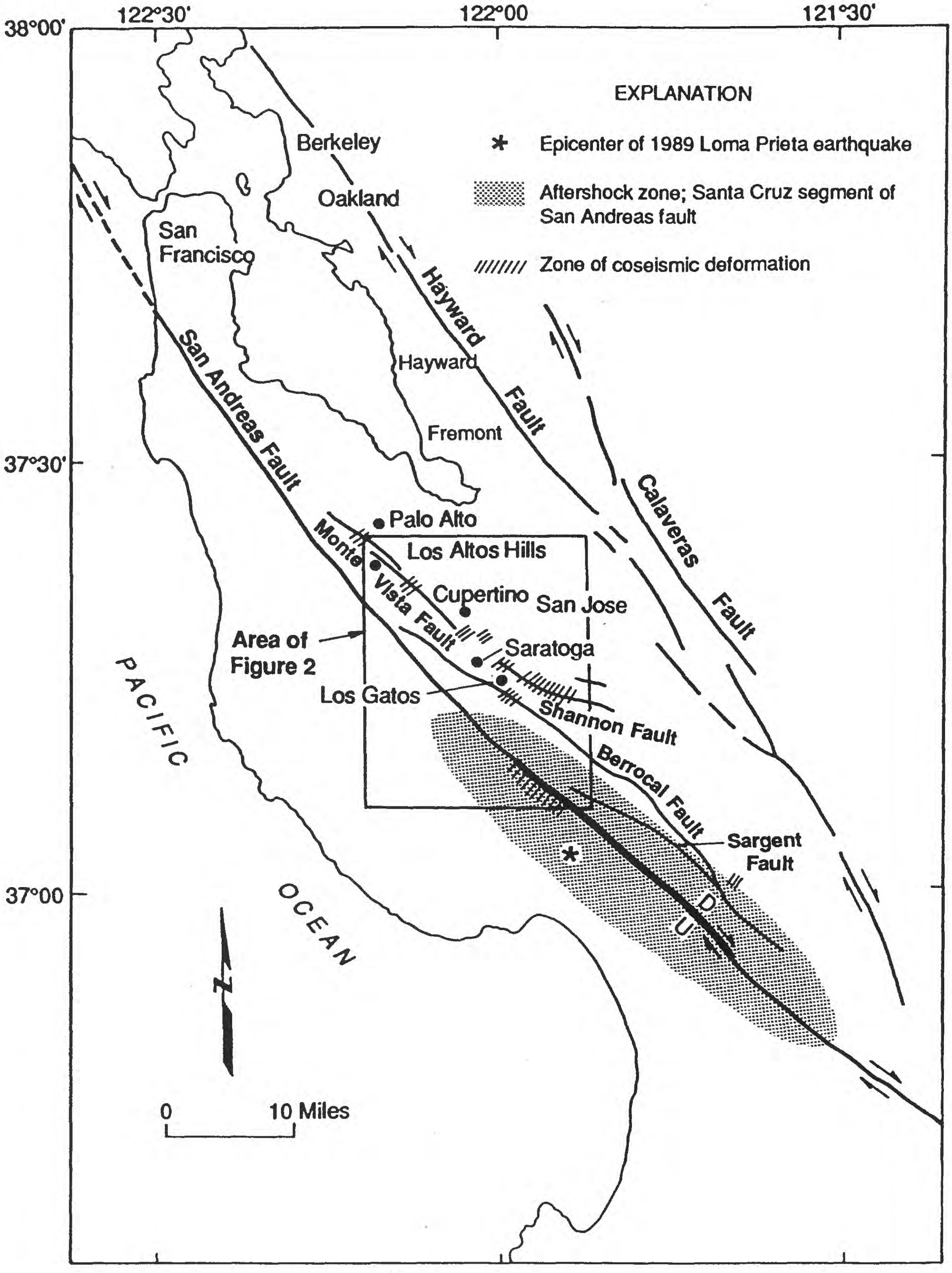


Figure 1. Regional fault map of the southern San Francisco Bay region and the Loma Prieta earthquake aftershock zone.

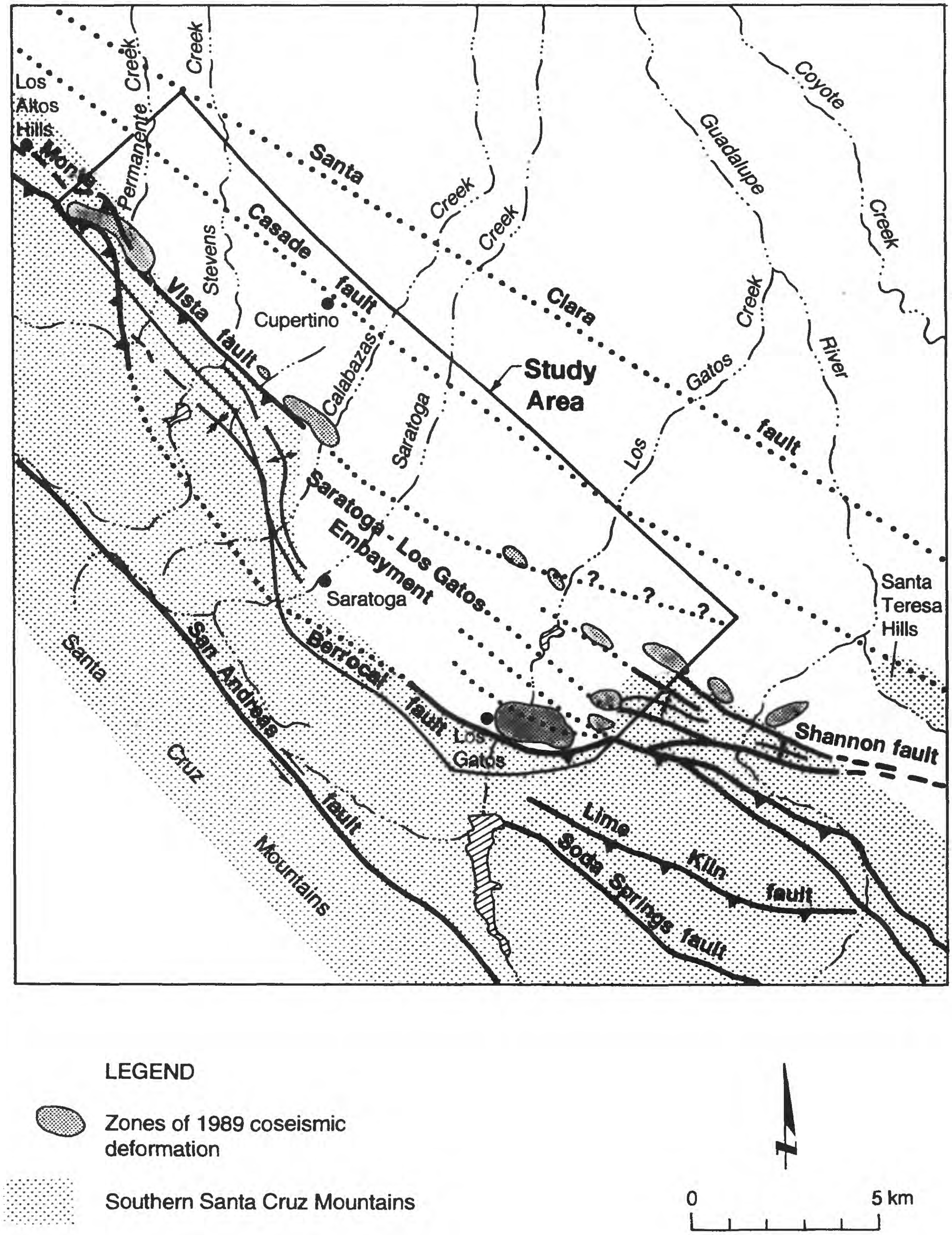


Figure 2. Regional map of the southern Santa Cruz Mountains and southwestern Santa Clara Valley showing major faults along the northeastern margin of the range. Zones of 1989 coseismic deformation are from Haugerud and Ellen (1990).

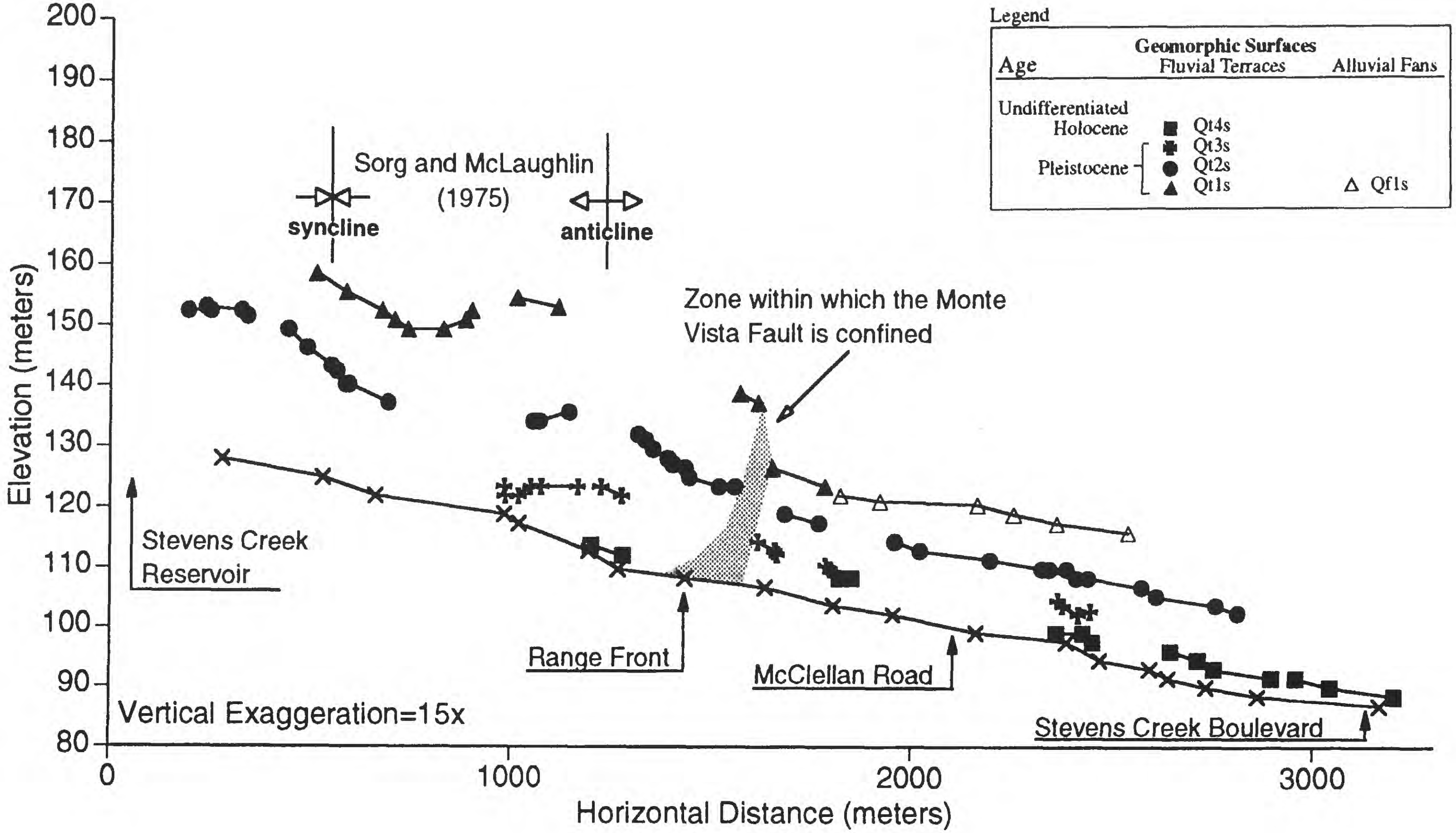


Figure 3. Longitudinal profile of geomorphic surfaces along Stevens Creek east of Stevens Creek Reservoir. Anticline and syncline traces shown on profile are projected from mapping by Sorg and McLaughlin (1975).

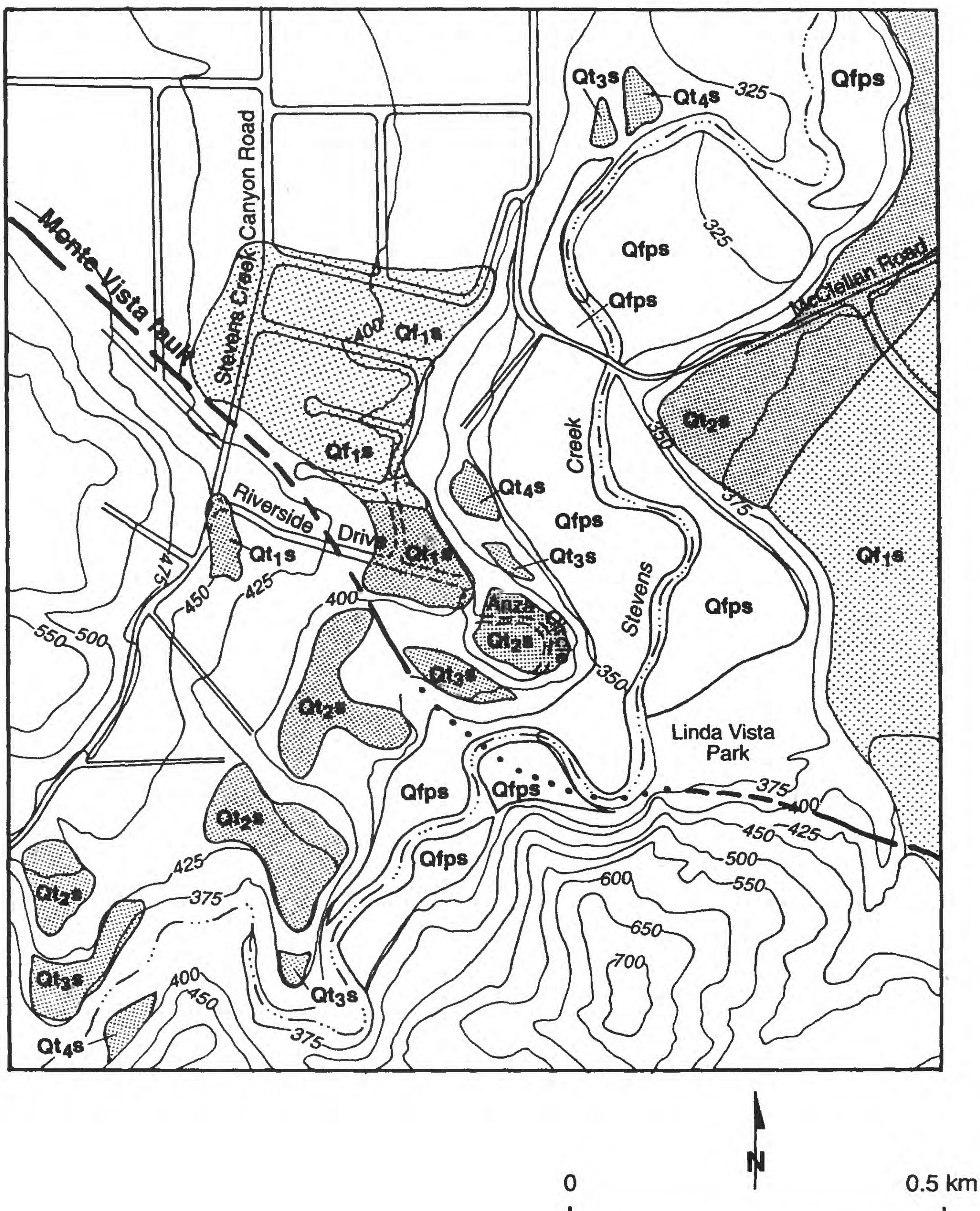


Figure 4. Map of geomorphic surfaces along Stevens Creek at the range front. The Monte Vista fault trace is dashed where inferred based on undisplaced terraces and topographic lineaments and dotted where covered by flood plains. Terraces are darkly shaded and fans are lightly shaded.

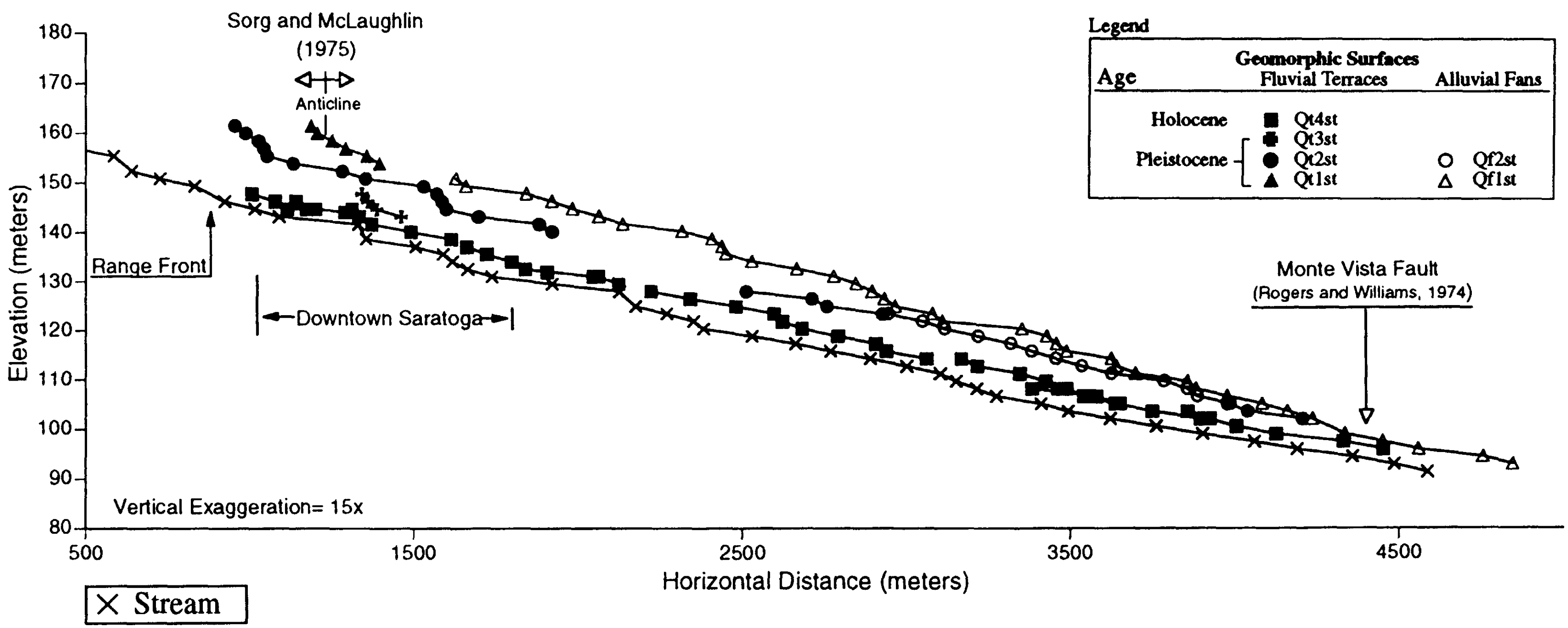


Figure 5. Longitudinal profile of geomorphic surfaces along Saratoga Creek east of the range front. Anticline shown on profile is projected from mapping by Sorg and McLaughlin (1975).

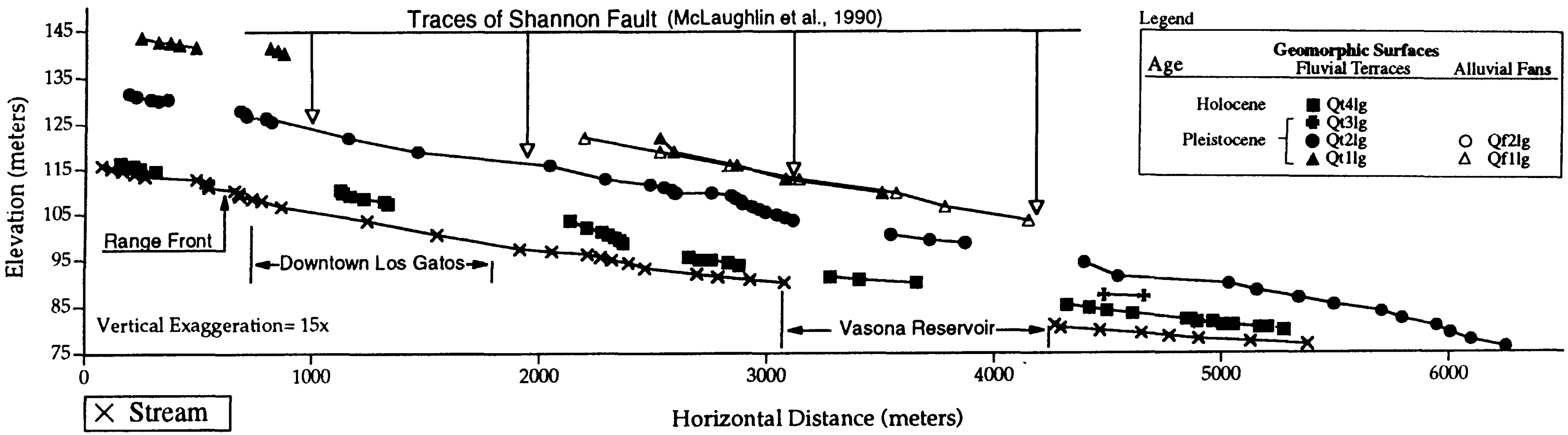


Figure 6. Longitudinal profile of geomorphic surfaces along Los Gatos Creek east of Stevens Creek Reservoir. Fault traces shown on profile are from mapping by McLaughlin and others (1990).

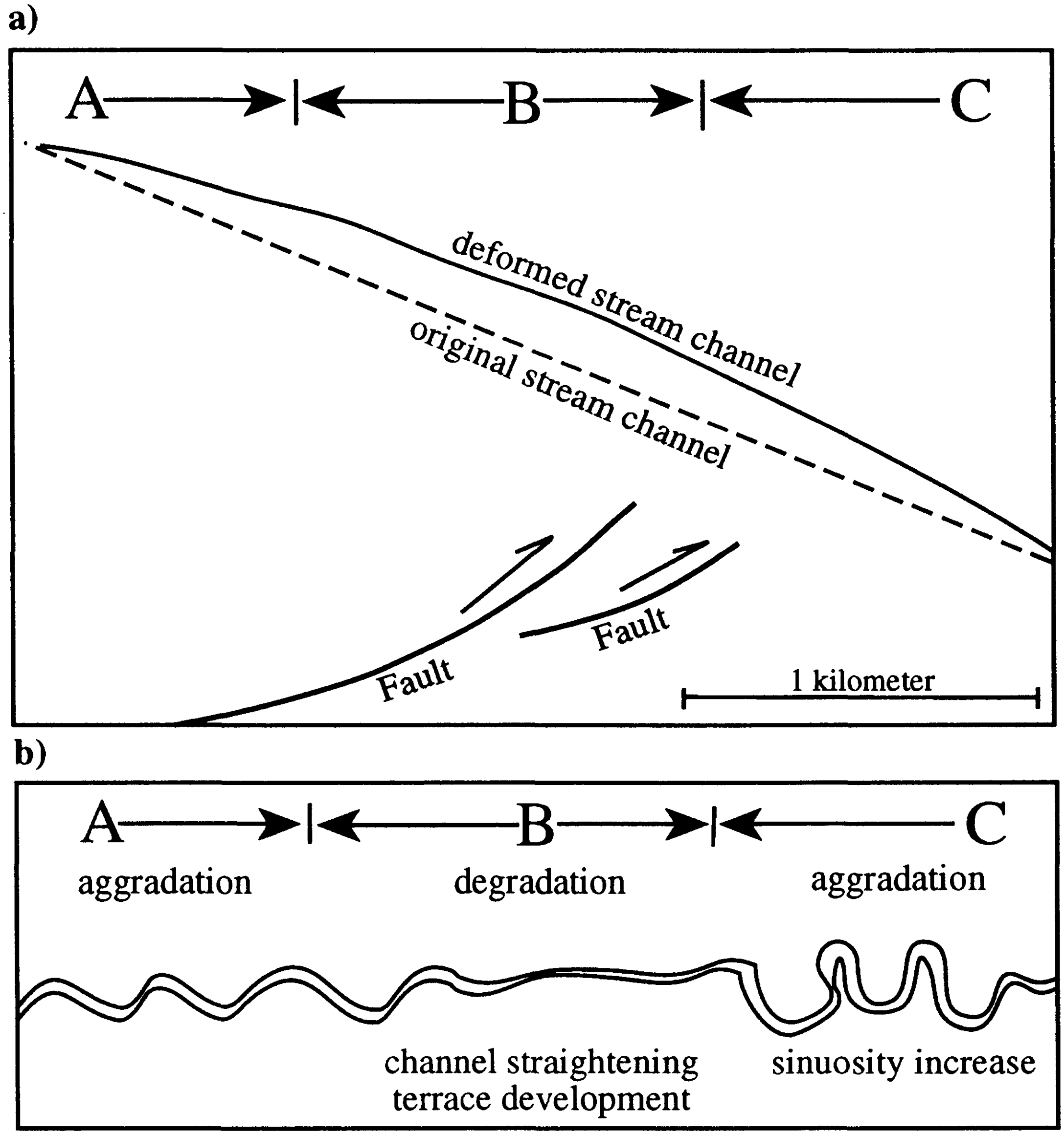
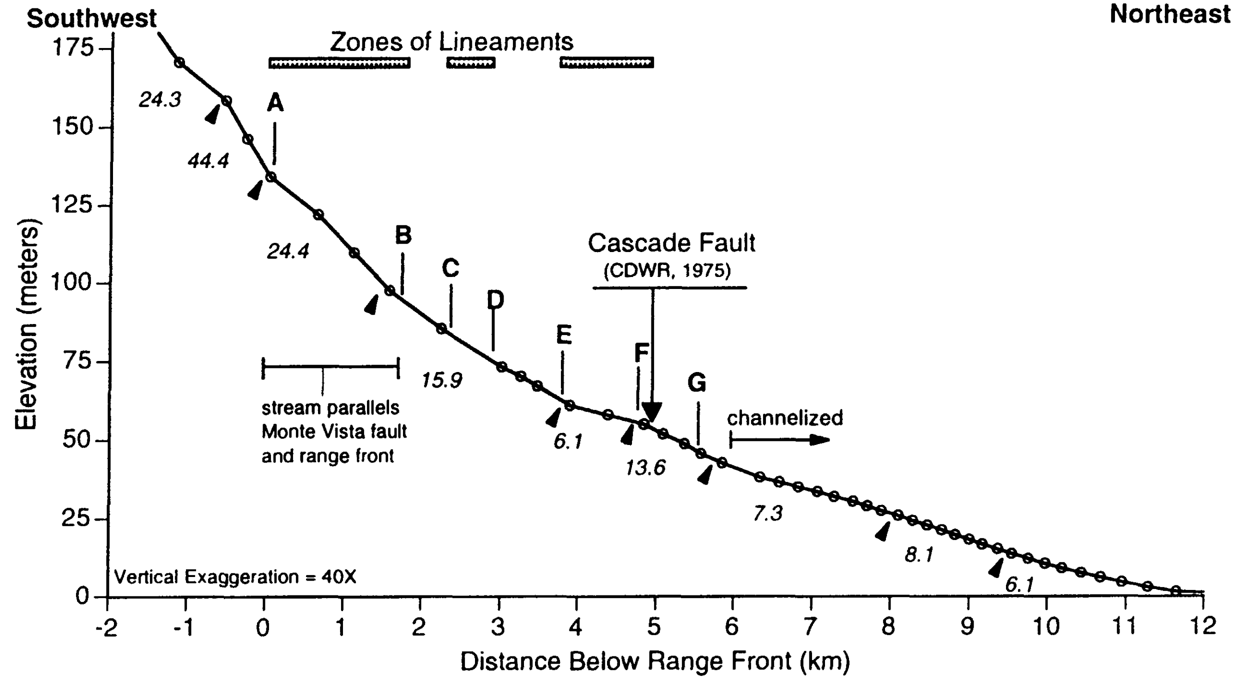


Figure 7. Inferred adjustment of a meandering stream to anticlinal uplift. (a) Cross-section of thrust faults and resultant convex longitudinal stream profile. (b) Plan view of stream channel changes. Modified from Ouchi (1985).

(a)



(b)

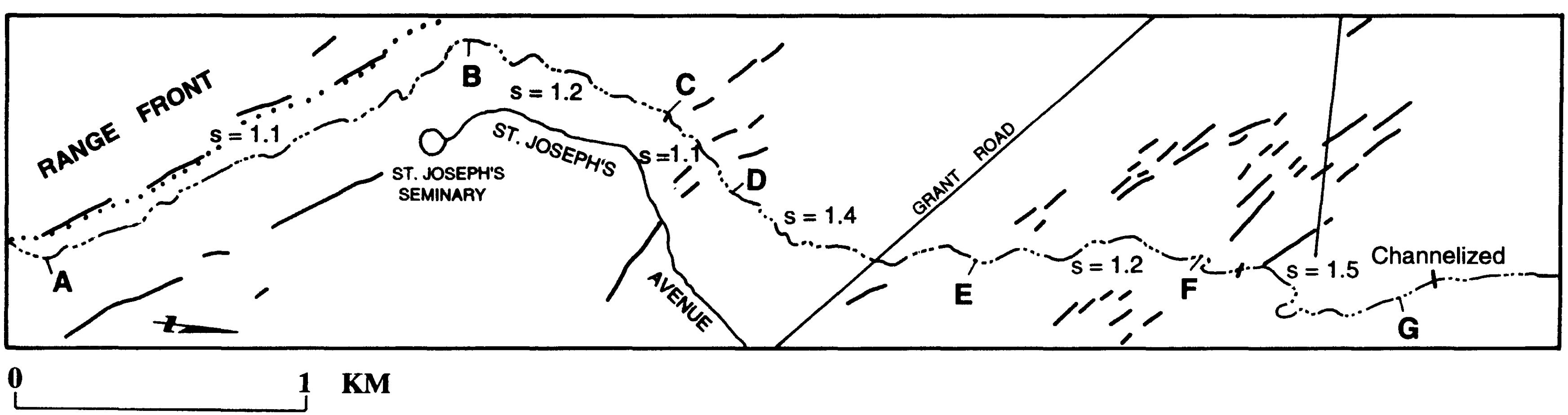


Figure 8. (a) Longitudinal stream profile of Permanente Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Permanente Creek showing stream channel interpreted from 1939 air photos, locations of lineaments and major roads, and stream sinuosity values.

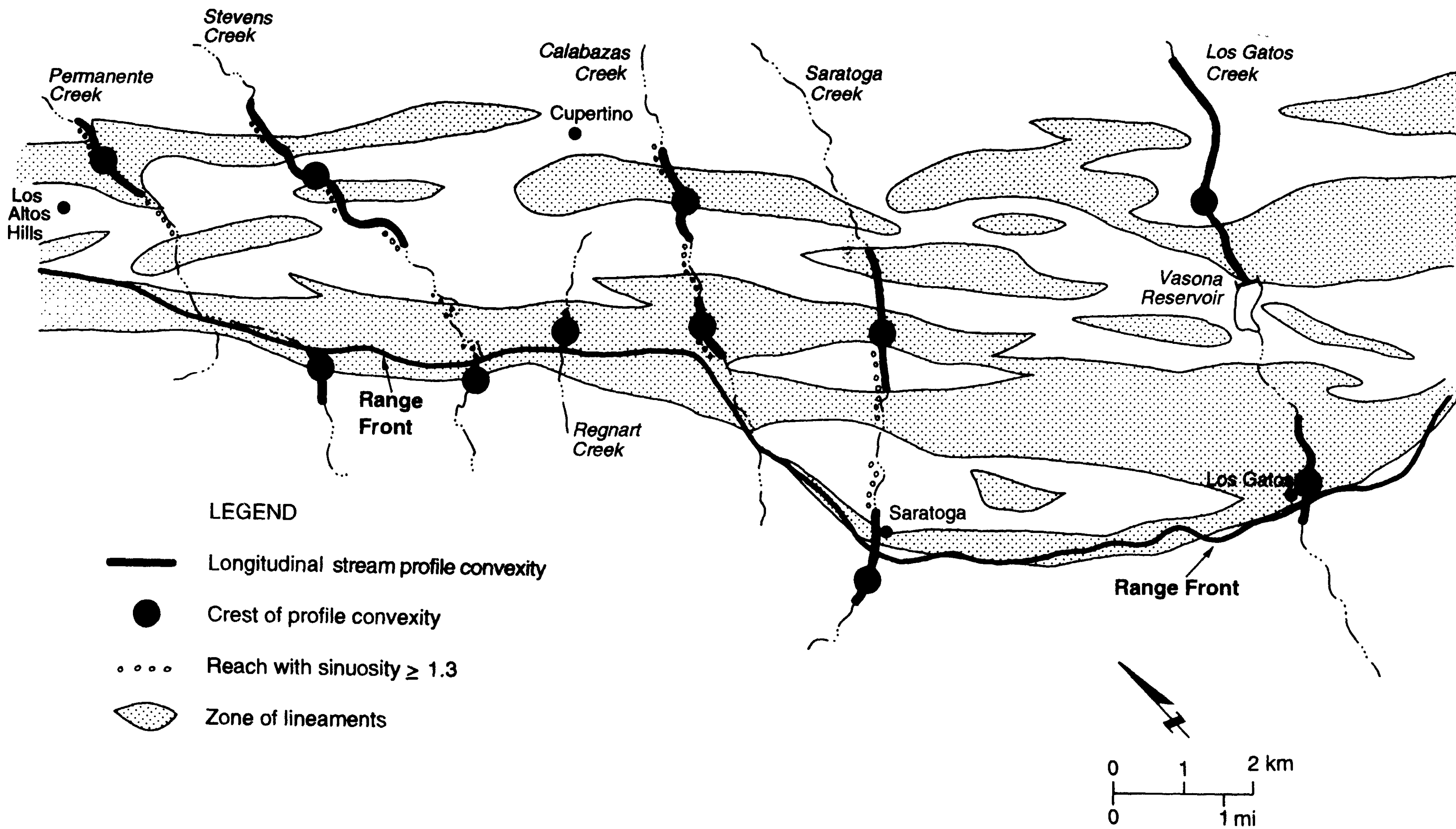


Figure 9 Map of northeastern margin of Santa Cruz Mountains, showing major streams, zones of lineaments (generalized from Plate 1), stream profile convexities, and reaches of high stream sinuosities. No sinuosity data are available for Los Gatos Creek.

(a)

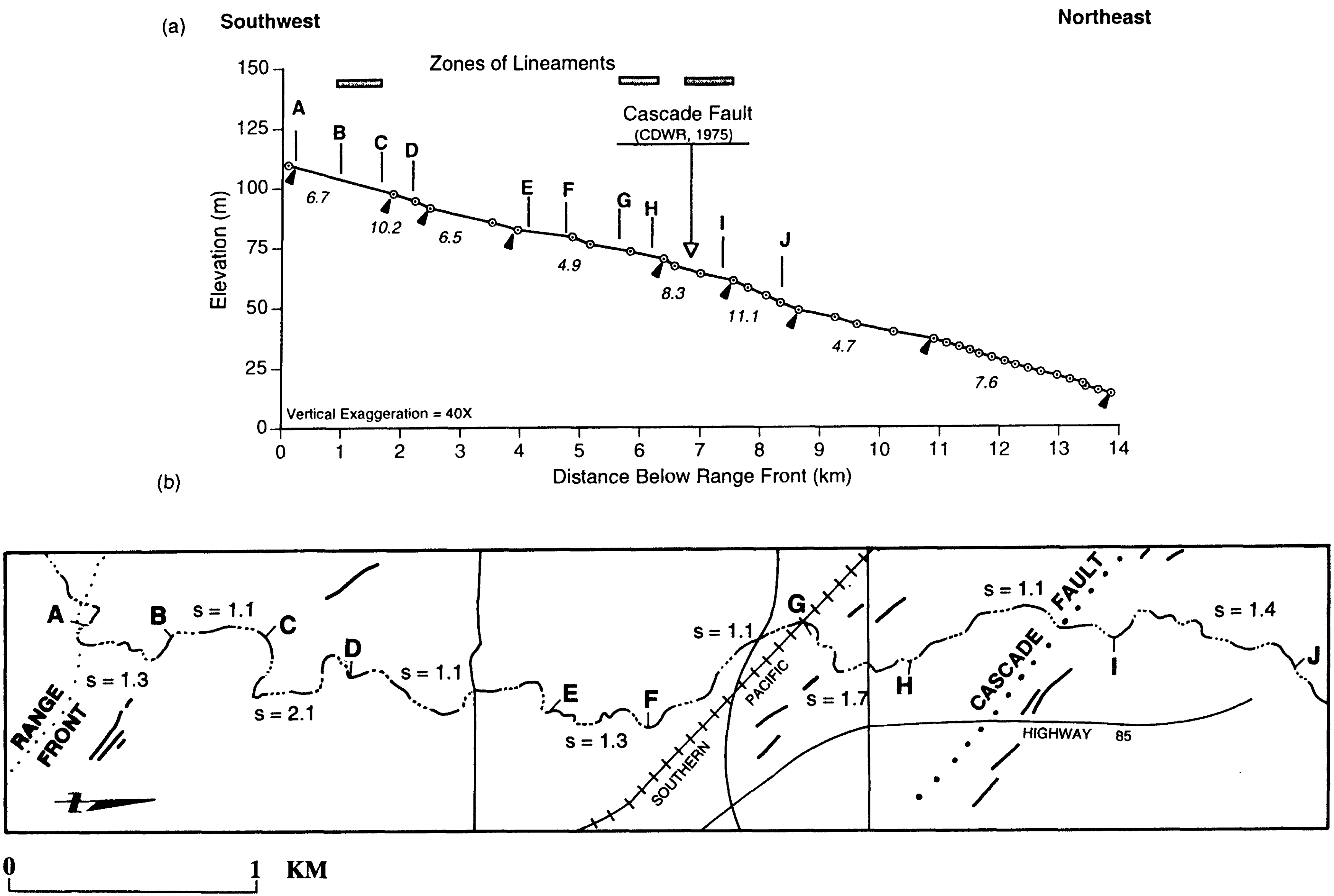
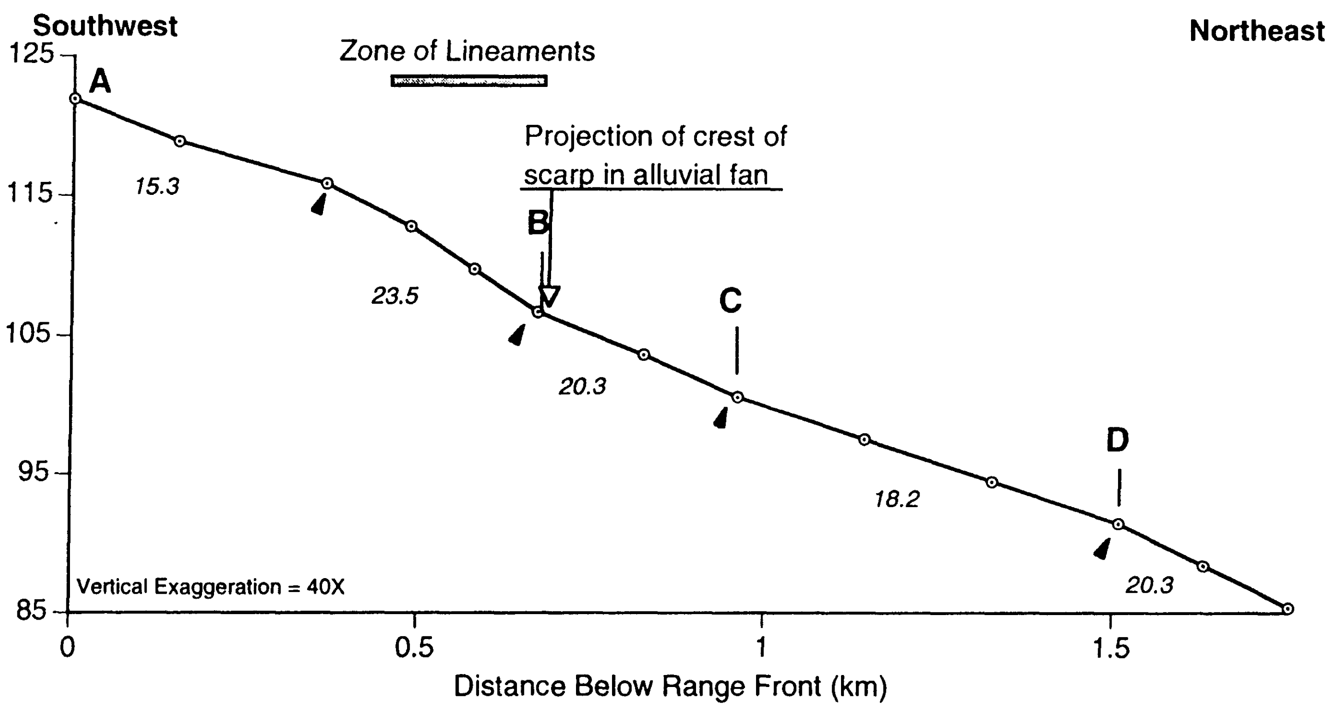


Figure 10. (a) Longitudinal stream profile of Stevens Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Stevens Creek showing stream channel interpreted from 1939 air photos, locations of lineaments and major roads, and stream sinuosity values.

(a)



(b)

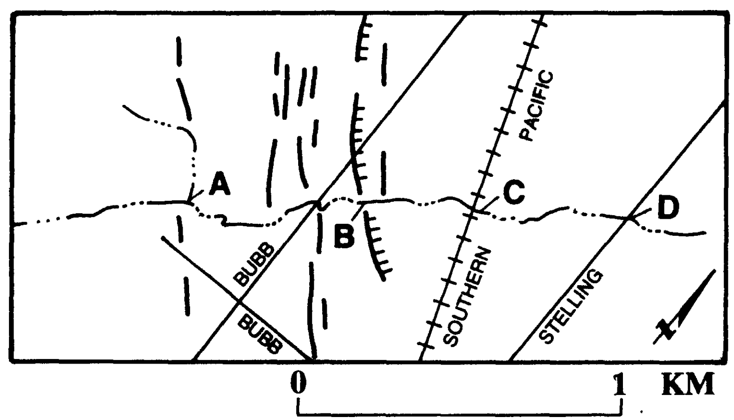
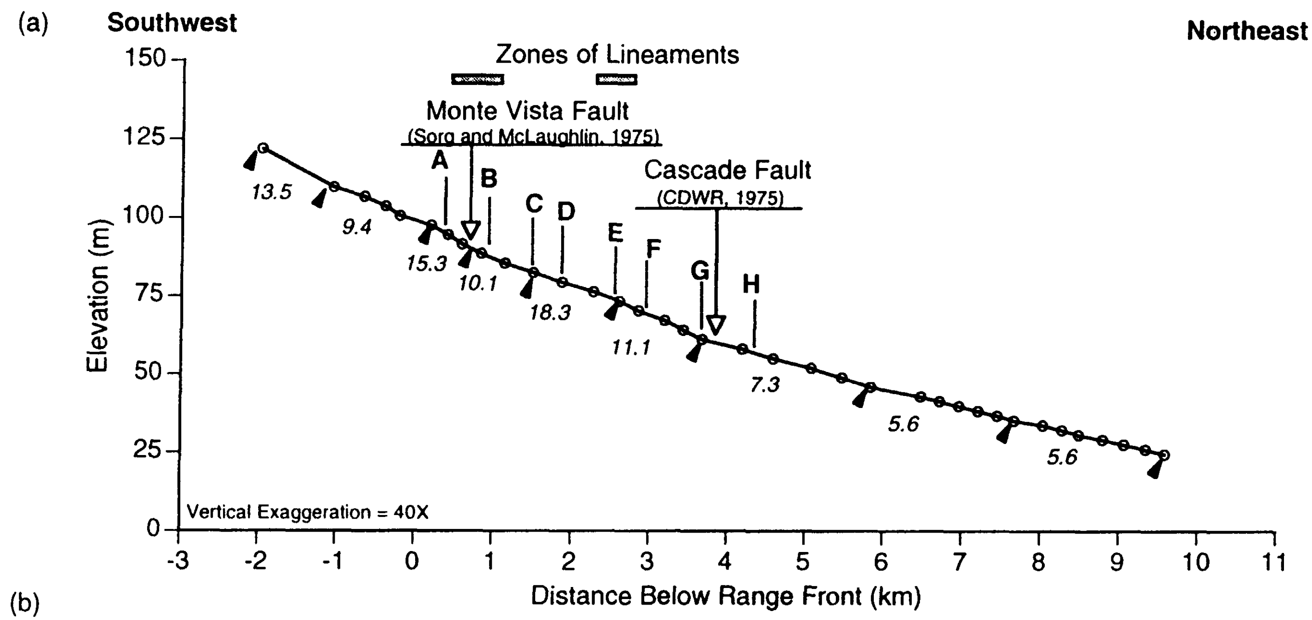


Figure 11. (a) Longitudinal stream profile of Regnart Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Regnart Creek showing stream channel interpreted from 1939 air photos, and locations of lineaments and major roads.



(b)

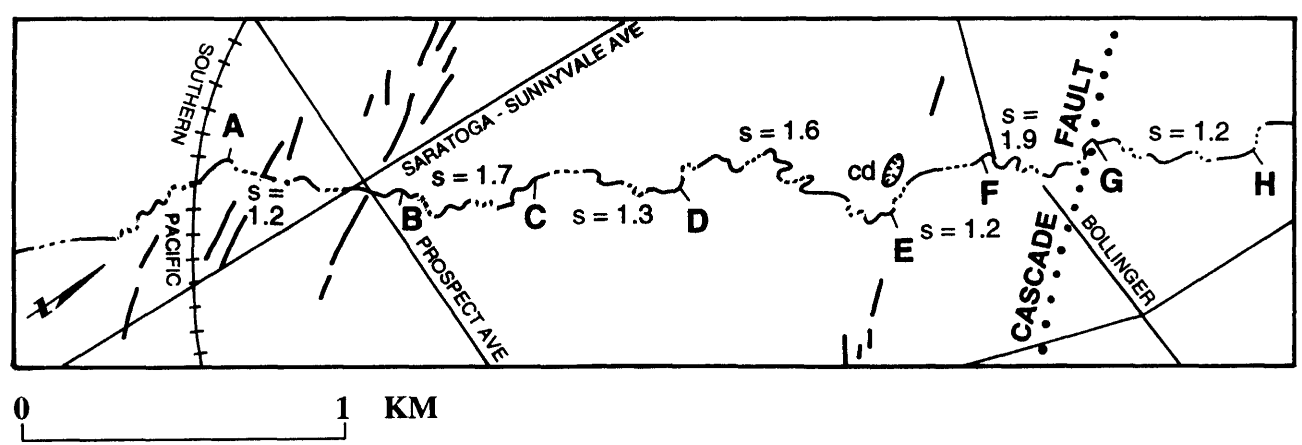


Figure 12. (a) Longitudinal stream profile of Calabazas Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Calabazas Creek showing stream channel interpreted from 1939 air photos, locations of lineaments and major roads, and stream sinuosity values.

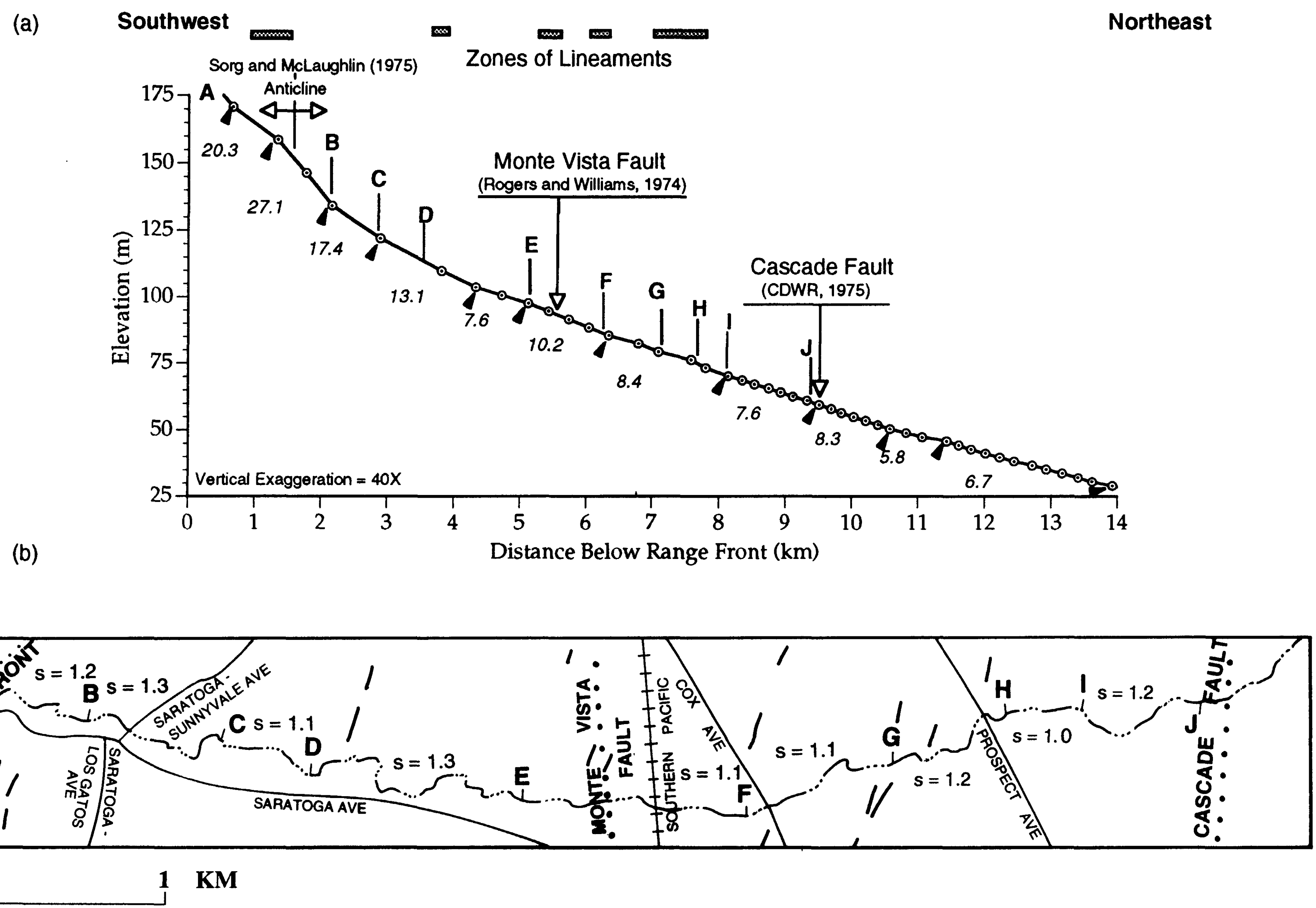


Figure 13. (a) Longitudinal stream profile of Saratoga Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Saratoga Creek showing stream channel interpreted from 1939 air photos, locations of lineaments and major roads, and stream sinuosity values.

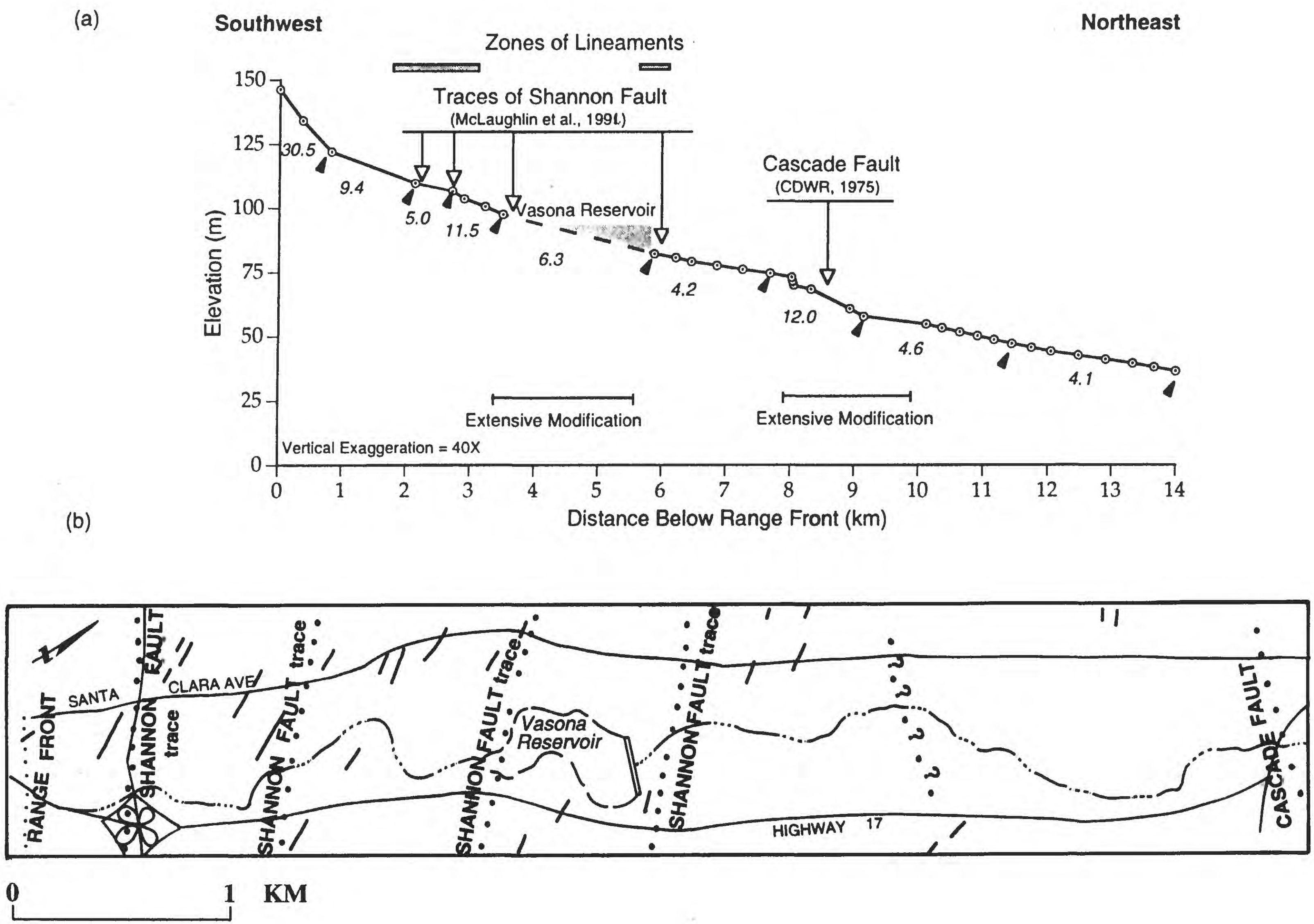


Figure 14. (a) Longitudinal stream profile of Los Gatos Creek east of the range front showing stream gradients (*in italics*), and locations of faults and zones of lineaments.
(b) Map of Los Gatos Creek showing stream channel interpreted from 1939 air photos, locations of lineaments and major roads, and stream sinuosity values.

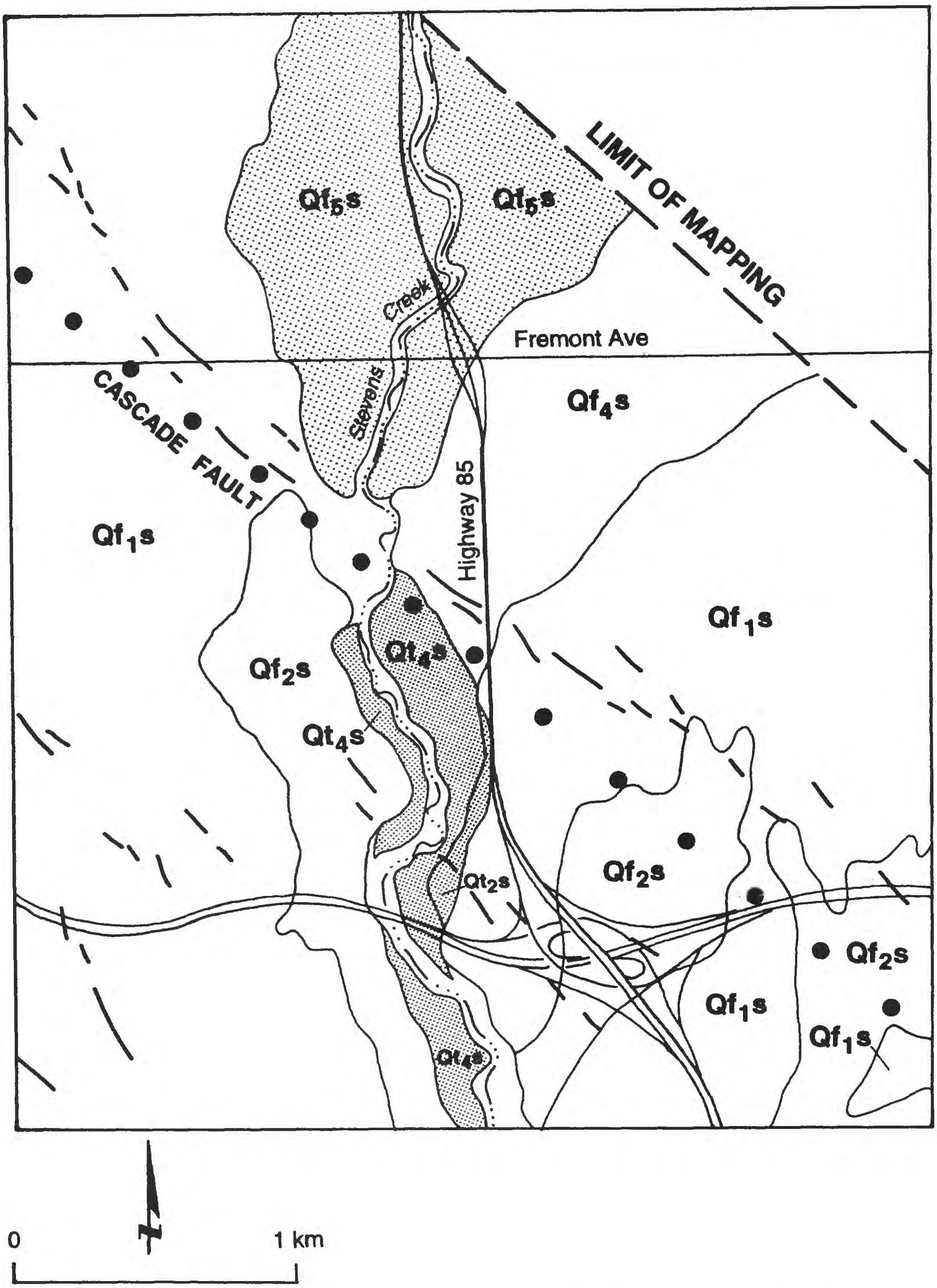


Figure 15. Map of geomorphic surfaces associated with Stevens Creek east of the range front. Terraces are darkly shaded and the youngest fan surface (Qf5s) is lightly shaded. Potentially fault-related vegetative lineaments are solid lines. The Cascade fault location is from CDWR (1975). Note the coincidence of lineaments, fan boundaries with the location of the Cascade fault.

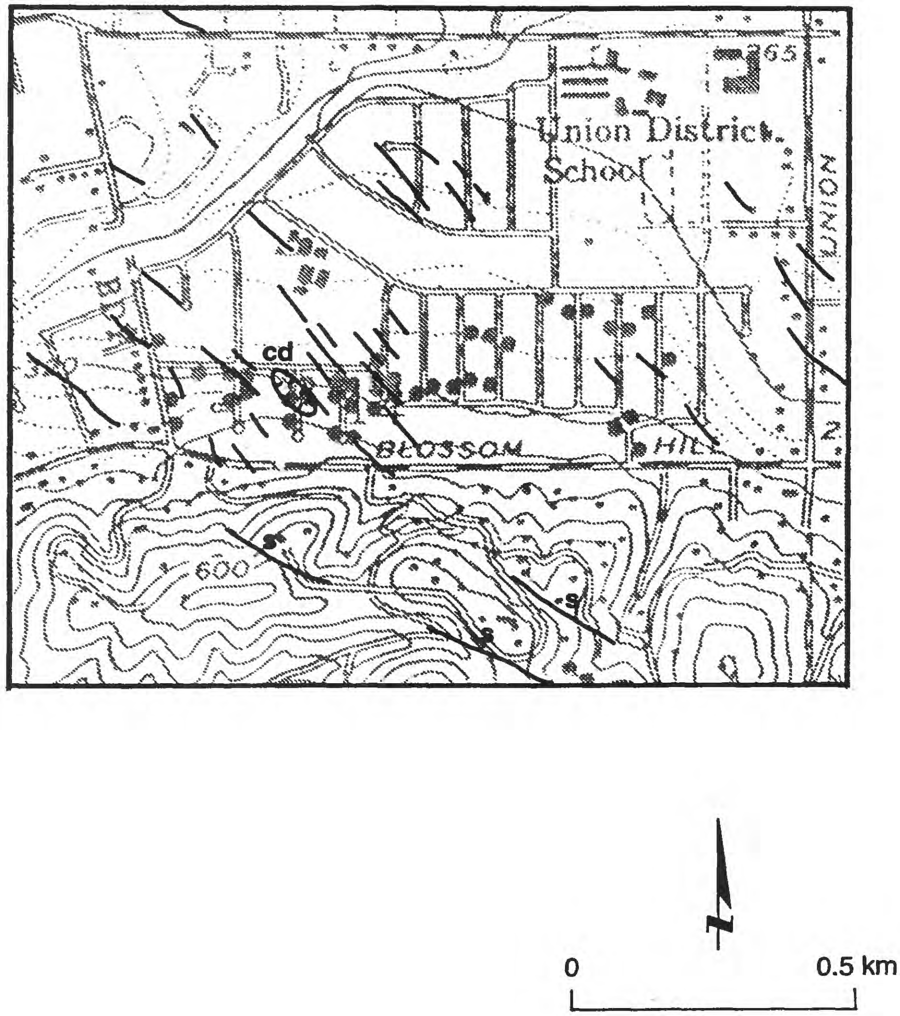


Figure 16. Map showing ground deformation along the base of Blossom Hill, southeast of Los Gatos, following the 1989 Loma Prieta earthquake and potentially fault-related vegetation and topographic lineaments mapped on 1939 air photos during this study. Black circles represent deformed pavement associated with the Loma Prieta earthquake (Haugerud and Ellen, 1990). Dark lines represent vegetation and topographic lineaments. Topographic lineaments are labeled and include a closed depression (cd) and saddles (s). Modified from Haugerud and Ellen (1990).