FINAL TECHNICAL REPORT

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CRITICAL EVALUATION OF THE NORTHERN TERMINATION OF THE CALAVERAS FAULT, EASTERN SAN FRANCISCO BAY AREA, CALIFORNIA

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ABSTRACT

Dextral slip on the northern Calaveras fault, which dies out as a significant strike-slip fault somewhere in the vicinity of Danville, California, is transferred to the interior of the northern East Bay hills by a complex system of poorly integrated strike-slip faults and shear zones that are connected by restraining stepovers. At the northern end of the Calaveras fault, the majority of dextral slip steps west across the Las Trampas anticline (and associated blind thrust fault) onto the dextral Reliez Valley and Lafayette faults. Based on detailed air photo analysis and field reconnaissance, we identify several NNW-trending lineament zones west of the Lafayette-Reliez Valley faults that may accommodate distributed dextral shear: Russell Peak, Briones, McEwen Road-Dillon Point, and Ozol-Columbus Parkway lineament zones. These lineament zones are associated with geomorphic features suggestive of fault movement, and they appear to truncate/displace non-striking bedding and northwest-striking reverse faults and folds. The Briones lineament is associated with the "Briones swarm", a cluster of small earthquakes that form a NNW-trending alignment, and which exhibit dextral slip on NNW-striking nodal planes. The "Briones swarm" provides strong evidence that these lineaments are active and potentially seismogenic strike-slip faults. Slip is transferred onto these structures from the Lafayette-Reliez Valley faults through a series of short restraining stepovers in the Briones hills region. Associated crustal shortening is responsible for creating the high topography of the Briones hills. Some slip on the Lafayette-Reliez Valley fault system also may be transferred northward onto the Franklin and Southhampton faults; alternatively, these faults may be pre-existing thrust structures that are cross-cut and deformed by younger strike-slip faults. Some dextral slip may continue north-northwest along the trend of the Calaveras fault to the Mt. Diablo thrust fault/Saklan fault, onto the Larkey lineament in downtown Pleasant Hill, then onto Southhampton fault, which steps westward into the East Bay hills.

Collectively, these relations suggest that strain in the East Bay hills north and west of the northern Calaveras fault is accommodated through complex deformation along discontinuous, north-striking dextral slip faults, northwest-striking reverse faults and folds, and possibly blind faults. The pattern of mixed strike-slip faulting and shortening deformation is consistent with a braided strike-slip duplex within an overall transpressional tectonic setting. Similar patterns of deformation have been produced in analog sandbox models of transpression. Strain appears to be distributed over a broad

region of the northern East Bay hills, but collectively may accommodate all, or most, of the 4 to 7 mm/yr of dextral slip on the Northern Calaveras.

Based on analysis of map-scale geologic structure, about 11 to 13 km of post-Miocene slip on the northern Calaveras fault has been accommodated by shortening and distributed strike-slip faulting in the northern East Bay hills. This estimate is within the 12-16 km range of total post-Miocene offset on the fault, and suggests that all or most of the slip steps westward into the interior of the East Bay hills. Slip on the northern Calaveras fault is not transferred eastward in a releasing geometry to the Concord fault.

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1.0
INTRODUCTION

This study is an investigation of the northern termination of the Calaveras fault, a major strand of the San Andreas fault system in the eastern San Francisco Bay area. Existing mapping and geologic analyses suggest that the Calaveras fault dies out as a significant strike-slip fault somewhere in the vicinity of Danville, California (Figure 1). The actual location and nature of the fault termination, however, are not known. Two alternative models have been advanced to explain the fault termination:

(1) Slip on the Calaveras fault transfers to the southern Concord fault via a right-releasing stepover ("releasing stepover model"); and

(2) Slip on the fault transfers onto heretofore poorly characterized strike-slip faults in the northern East Bay hills via a left-restraining stepover ("restraining stepover model").

The presence of a releasing stepover has long been *assumed* to link the northern Calaveras and Concord faults (e.g., Wills and Hart, 1992; Smith, 1992; Oppenheimer and Macgregor-Scott, 1992). To date, however, no compelling evidence for such a stepover has been documented. If the releasing stepover model is correct, then it suggests that unidentified active faults must be present beneath Walnut Creek and Ygnacio Valley to accommodate approximately 4 to 7 mm/yr of distributed dextral slip between the northern Calaveras and Concord faults.

Alternatively, if the releasing stepover model is incorrect, then slip on the northern Calaveras fault may be transferred westward to strike-slip faults and thrust faults in the northern East Bay hills (e.g., Aydin, 1982; Unruh and Lettis, 1998). This alternative hypothesis (i.e., the “restraining stepover model”) suggests that uncharacterized strike-slip and thrust faults in the northern East Bay hills may have slip rates approaching 1 to 3 mm/yr, and thus may be more significant sources of potential earthquakes than previously assumed (i.e., Working Group, 1999).

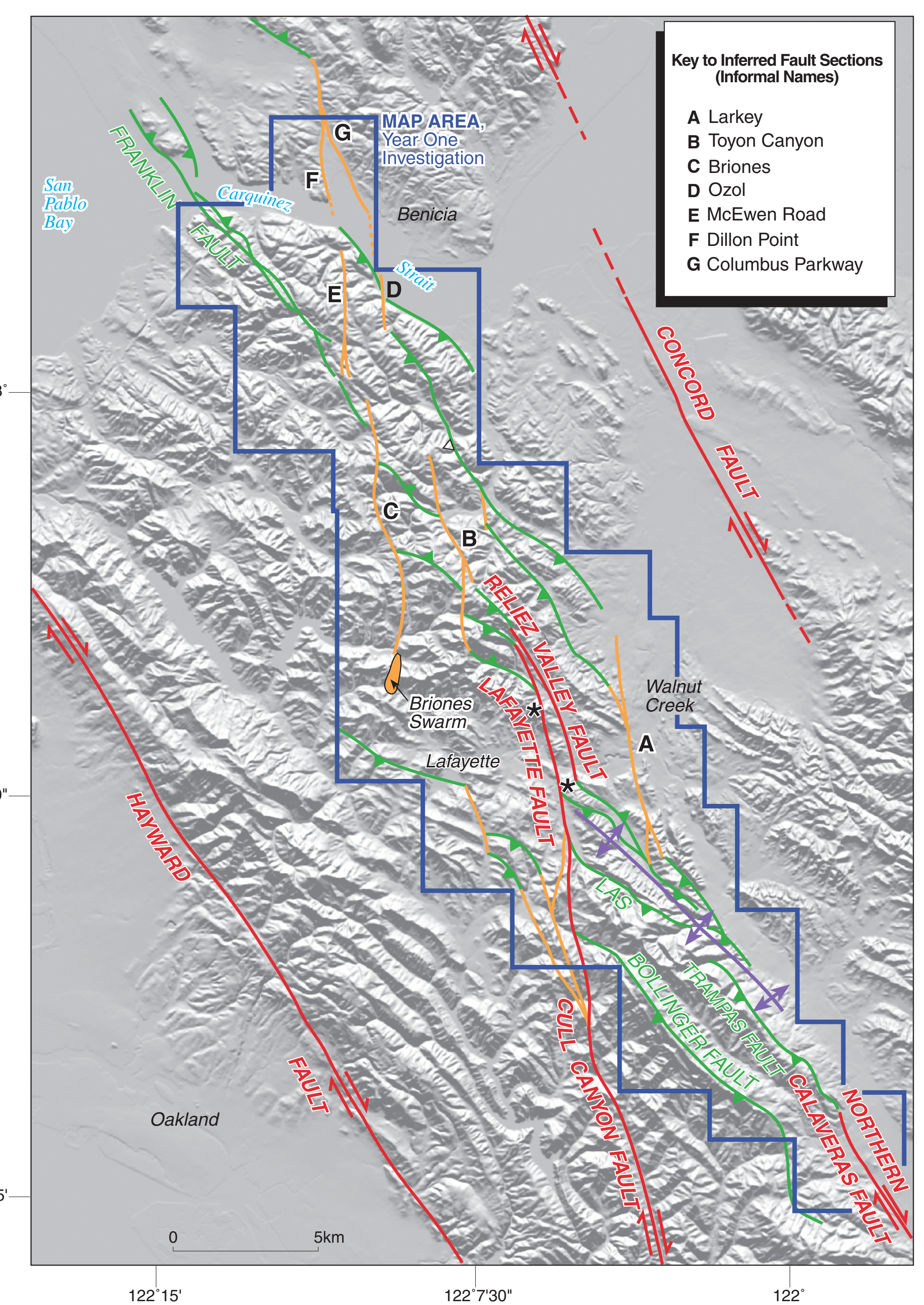

Figure 1. Regional tectonic map of the northern East Bay Hills, showing our recent map area, major fault traces, and inferred fault sections generalized from 1:24,000 mapping. Green shows inferred faults with reverse or oblique movement, red lines show previously mapped strike-slip faults, and orange lines show inferred faults with lateral movement. Asterisks (*) shows stratigraphic contact between the Neogene Neroly and Cierbo Formations which are offset in a right-lateral sense by the Lafayette fault.

This study specifically evaluates the restraining stepover model by investigating late Cenozoic structure and tectonic geomorphology of the northern East Bay hills. The main objectives of this study include the following:

- Map geomorphic features and tectonic lineaments associated with potentially active strike-slip faults in the interior of the northern East Bay hills;

- Assess the relationship of strike-slip faults to thrust faults and folds in the northern East Bay hills, with emphasis on identifying contractional structures that comprise restraining stepovers;

- Assess the magnitude of late Cenozoic shortening across the northern East Bay hills for comparison with estimates of post-Neogene offset on the northern Calaveras fault;

- Relocate earthquakes in the northern East Bay hills and assess their relationship, if any, to late Cenozoic strike-slip faults;

- Identify sites for future paleoseismic trench investigations to evaluate the activity or non-activity of strike-slip faults in the interior of the northern East Bay hills.

Evaluating the presence or absence of Holocene faulting on strike-slip faults in the northern East Bay hills is critical for interpreting the style and kinematics of regional deformation. Should the strike-slip faults be considered independent seismic sources, or should they be considered elements of a complex, segmented Calaveras fault? In the latter case, the northern Calaveras fault could be interpreted as being perhaps 60 km long or longer, and thus may be capable of producing earthquakes larger than is commonly used in seismic source characterizations for the San Francisco Bay region (**M**6.5 to 7; WGNCEP, 1999; Kelson, 2002). Characterization of the strike-slip faults also may provide information about the activity of blind thrust faults in the northern East Bay hills, particularly where a kinematic relationship between the two classes of structures can be demonstrated. As discussed by Unruh and Lettis (1998), positive evidence for activity of strike-slip faults bounding a restraining stepover can be used as indirect evidence for activity of thrust faults and folds accommodating shortening within the stepover region.

The study area includes the towns of San Ramon on the south, Lafayette on the west, Crockett on the north, and Pleasant Hill on the east. Within this regional map area, we focused more detailed efforts on the Lafayette-Reliez Valley fault system, which includes faults previously mapped in the area north and west of the northern end of the Calaveras fault (Figure 1). Our investigative approach included analysis of vintage aerial photography, aerial reconnaissance, field reconnaissance, and construction of geologic cross sections. The primary map products of this effort encompass the area of the Lafayette and Reliez Valley fault system, and show (a) the late Quaternary surficial geologic deposits, and (b) potentially fault-related lineaments, including annotations on the type and prominence of the lineaments. We present geologic and geomorphic evidence of late Quaternary deformation in the northern East Bay hills, and discuss potential sites for future paleoseismic investigation.

2.0
GEOLOGIC SETTING OF THE NORTHERN EAST BAY HILLS

2.1 LATE CENOZOIC TECTONIC SETTING OF THE EAST BAY HILLS

The East Bay hills is a belt of youthful, elevated topography bounded by the Hayward fault on the west and the northern Calaveras fault on the east (Figure 1). The late Cenozoic structure of the hills is characterized by northwest-trending folds and thrust faults, (Crane, 1995) and by previously unrecognized NNW-striking dextral faults that locally offset the contractional structures. Major fold-thrust structures in the northern East Bay hills, such as the Bollinger thrust fault and the Las Trampas anticline, are oriented about 45° more westerly than the northern Calaveras fault, and exhibit a right-stepping, en echelon geometry typical of dextral wrench folds (Figure 1; Aydin, 1982; Unruh and Lettis, 1998). The folds and thrust faults locally are truncated by, or terminate against, north-northwest-striking faults that that are similar in strike to the Calaveras fault, and which locally offset Neogene stratigraphic units in a right-lateral sense. Aydin (1982) interpreted this pattern of late Cenozoic faulting and folding in the East Bay hills to reflect transpressional deformation.

The northern East Bay hills are characterized by a moderate level of background seismicity. In 1977, a swarm of small earthquakes occurred in the northern East Bay hills along an approximately 6 km long, north-northwest-trending alignment subparallel to the northern Calaveras fault (Ellsworth et al., 1982; Oppenheimer and Macgregor-Scott, 1992). These events are located in the general vicinity of Briones Regional Park and Briones Reservoir, and are informally referred to as the “Briones swarm”. A cross section of hypocenters normal to the trend of the swarm (Figure 3 in Oppenheimer and Macgregor-Scott, 1992) shows a well-defined planar alignment in the 6 to 12 km depth range. Focal mechanisms from these events indicate dextral faulting on north-northwest-striking nodal planes. The Briones swarm clearly shows that blind or previously unrecognized strike-slip faults are present in the northern East Bay hills that may accommodate distributed dextral shear north of the termination of the Calaveras fault.

2.2 GEOLOGIC CONSTRAINTS ON THE MAGNITUDE AND DISTRIBUTION OF SLIP ON THE NORTHERN CALAVERAS FAULT

Previous workers have used a variety of geologic markers to infer a total of 16 to 24 km of late Cenozoic dextral displacement on the northern Calaveras fault south of Danville (see discussion in Page, 1982). One marker is the southern extent of late Neogene strata deposited in the ancestral Livermore-Contra Costa basin. The north- to northeast-dipping contact between the late Neogene strata and underlying Mesozoic rocks south of Livermore Valley and in the southern East Bay hills generally demarcates the southwestern margin of the NW-SE-trending Neogene basin; this contact is displaced about 12 to 16 km in a dextral sense by the northern Calaveras fault (Figure 2). If all of this slip is transferred in a releasing stepover to the Concord fault, then coeval strata representing the northern margin of the basin, which are present along the southwestern edge of Mt. Diablo and in the northern East Bay hills, should show comparable displacement across the northern projection of the northern Calaveras fault through the Walnut Creek area. The presence or absence of this predicted offset, therefore, provides a test of the "releasing stepover" hypothesis for the northern Calaveras fault.

We evaluate this model by analyzing the northern extent of the late Miocene Neroly Formation, which is a distinctive volcaniclastic sandstone found near the base of the San Pablo Group on both sides of the Calaveras fault (Figure 2; see discussion of stratigraphy in the following section). The basal Neroly Formation contact can be traced from Livermore Valley northwest along the base of Mt. Diablo to the southern Walnut Creek area, where it is gently folded about the axis of an unnamed syncline southwest of Shell Ridge. Although the Neroly Formation cannot be traced continuously beneath northern San Ramon Valley, it is present in the northern East Bay hills directly west of the unnamed syncline, across the hypothesized northern projection of the Calaveras fault in the releasing stepover model (location "C"; Figure 2). Farther west, the Neroly Formation is offset in a dextral sense across the Lafayette-Reliez Valley strike-slip faults (location "B"; Figure 2). Although locally folded, the northern limit of the Neroly Formation in the East Bay hills generally is on trend with outcrops along the southwestern flank of Mt. Diablo. These observations provide stratigraphic evidence that the northern extent of the Neroly

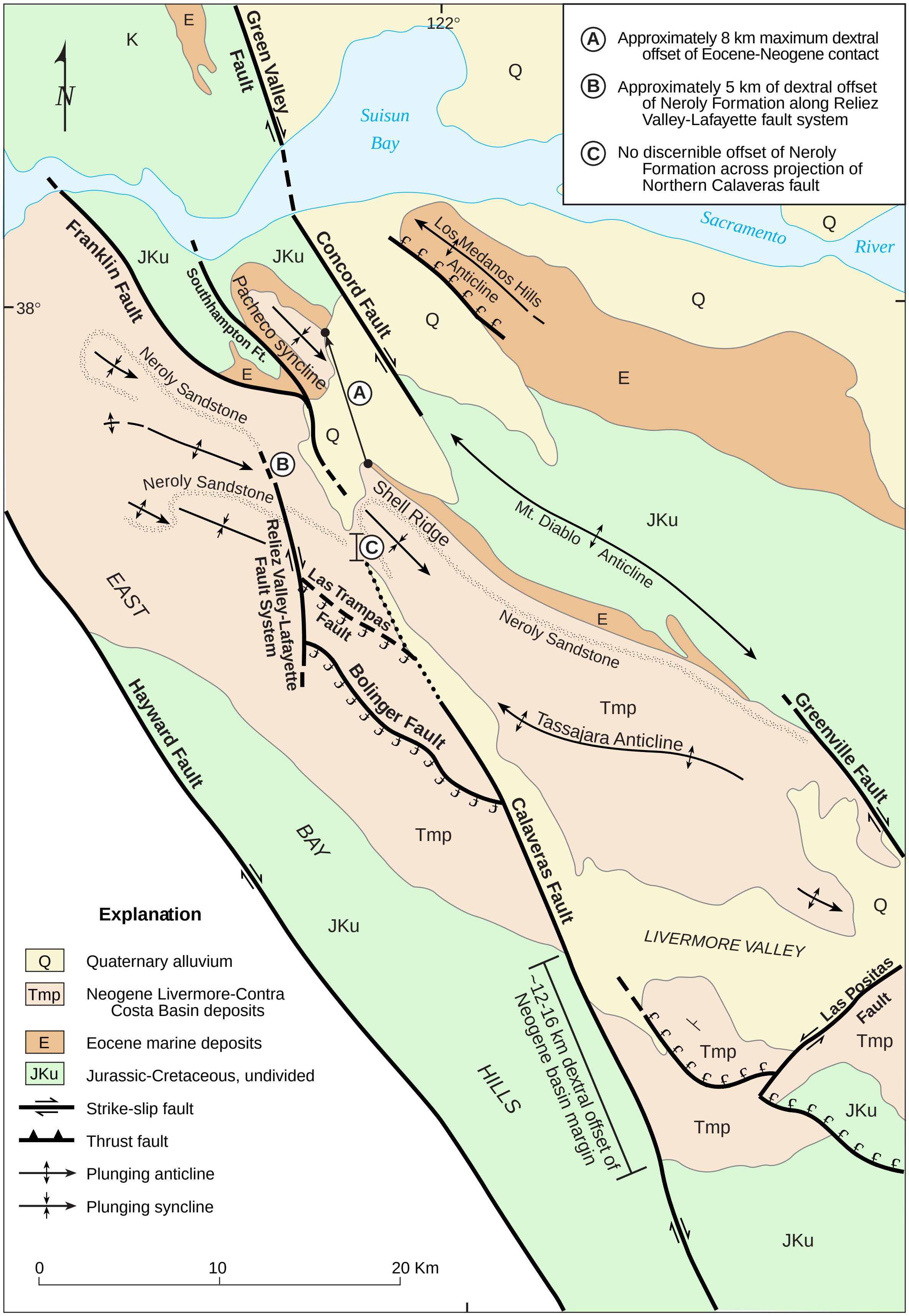

Figure 2. Generalized geology east of the Hayward fault showing stratigraphic contraints on the distribution of slip at the northern termination of the Calaveras fault.

Formation is offset less than 12 to 14 km in a dextral sense by any known or postulated fault that may link the northern Calaveras and Concord faults.

A similar argument can be made for lack of substantial dextral offset of the contact between the older Neogene Livermore-Contra Costa basin fill and underlying Eocene strata across the hypothesized northern projection of the Calaveras fault. Direct mapping of this contact across the northern projection of the Calaveras fault is problematic because the Neogene strata rest unconformably on Eocene rocks southwest of Mt. Diablo, but are in fault contact with Eocene and Cretaceous rocks across the Franklin fault in the northern East Bay hills. Nevertheless, the *maximum* dextral offset of the Eocene-Neogene contact permitted by map relations is about 8 to 9 km (location “A”; Figure 2), which requires correlating the Eocene-Neogene contact in the Shell Ridge area with an Eocene-Neogene contact in the Pacheco syncline west of the Concord fault. An alternative correlation of the basal Neogene strata at Shell Ridge with its stratigraphically similar counterpart south of the Franklin fault implies that substantially less than 8 km of dextral offset, if any, occurs north of Danville (Figure 2). Collectively, these relations provide a *prima facie* case for transfer of at least 8 km, and probably all, of the post-Miocene dextral slip on the northern Calaveras fault south of Danville (Figure 2) westward into the northern East Bay hills. The stratigraphic map relations do not support transfer of slip from the northern Calaveras fault to the Concord fault in a right-releasing stepover within the Walnut Creek/Ygnacio Valley area.

These geologic relations are consistent with new paleoseismic data from the Greenville fault south of Mt. Diablo that refines the known distribution of tectonic strain in the East Bay area. Based on right-lateral offset of Holocene strata, Sawyer and Unruh (2002) conclude that the Holocene slip rate on the Greenville fault is about 4 $\pm$ 2 mm/yr, which is significantly higher than previous estimates of 0.1 to 0.3 mm/yr of slip for this fault (e.g., Wright et al., 1982). The implication of these results for the present study is that all of the 3.4 $\pm$ 0.3 mm/yr Holocene slip rate on the Concord fault (Borchardt et al., 1999) can be accounted for by transfer of slip from the Greenville fault across the Mt. Diablo anticline (a restraining stepover; Unruh and Sawyer, 1995), rather than in a releasing stepover from the northern Calaveras fault as assumed by previous workers (Smith, 1992; Oppenheimer and Macgregor-Scott, 1992). In short, recently obtained geologic data remove the presumed requirement for slip transfer from the northern Calaveras fault onto the Concord fault, and, in fact, suggest that much of the slip on the northern Calaveras does not transfer to the Concord Fault.

2.3 STRATIGRAPHIC RELATIONS RELEVANT TO ASSESSING DEFORMATION IN THE NORTHERN EAST BAY HILLS

We use stratigraphic units in the northern East Bay hills as geologic markers to evaluate late Cenozoic fold geometry, tectonic shortening, fault offsets, and Quaternary fault activity. In the following section, we describe major stratigraphic units in the study area, with emphasis on correlations among units established by previous workers that are significant to interpreting basin geometry and structure prior to the onset of late Cenozoic shortening.

2.3.1 Bedrock Units

For the purposes of this study, "bedrock" units in the East Bay hills are Mesozoic and early Tertiary rocks that represent the deformed remnants of the ancestral western California convergent margin. The structurally lowest bedrock unit is the Mesozoic Franciscan complex, which consists of metamorphosed basalt, chert, shale and sandstone that accumulated in an accretionary wedge above an east-dipping subduction zone. Exposures of the Franciscan complex are confined to the western margin of the East Bay hills south of Berkeley. The Franciscan complex is structurally overlain by the Mesozoic Coast Range ophiolite, which represents the basement of the ancestral fore-arc region. The Coast Range ophiolite is present as fault-bounded blocks of serpentinite, metavolcanics and gabbro. In the Oakland East 7.5' quadrangle (Crane, 1988), the Franciscan rocks and Coast Range ophiolite appear to be tectonically interleaved.

Structurally overlying both the Franciscan complex and ophiolitic rocks in the western East Bay hills are Mesozoic and Tertiary marine fore-arc basin deposits. Mesozoic strata range from Jurassic to Late Cretaceous in age and are referred to collectively as the Great Valley Group. The Great Valley Group section exposed in outcrop along the eastern margin of the Diablo Range is in excess of about 5 km thick (Moxon, 1990). In the East Bay hills, the Great Valley

Group section is highly attenuated and present as a series of fault-bounded slivers. Crane (1988) describes the fault-bounded Great Valley Group rocks in the Oakland East 7.5' quadrangle as an "imbricate zone". Bedding dips in these faulted rocks define a NW-SE-trending synclinorium.

The major structural contact between the Great Valley Group rocks and Coast Range ophiolite in the western East Bay hills is the Chabot fault. This structure locally juxtaposes Great Valley Group rocks against blueschist-facies Franciscan complex, indicating that a significant thickness of intervening crust (including the forearc basement; i.e., Coast Range ophiolite) is missing across it. Similar structural relations are present in the Mt. Diablo region to the east, where the Franciscan-ophiolite-Great Valley structural contracts are demonstrably older than late Cenozoic in age, and folded about the axis of the late Cenozoic Mt. Diablo anticline (Unruh, 2000). The Chabot fault thus may be a pre-existing bedrock structure that has been uplifted and deformed during late Cenozoic growth of the East Bay hills.

2.3.2 Eocene Strata

Eocene marine deposits of the ancestral fore-arc basin unconformably overlie the Mesozoic Great Valley Group rocks. The Eocene strata have been grouped into two packages by Moxon (1990). The lower package is referred to as "EP-1" and is locally represented by the Martinez and Capay Formations in the northeastern East Bay hills west of Pacheco. The upper package, called "EP-2" (Moxon, 1990), rests unconformably on EP-1 and is represented (in ascending order) by the Domengine, Nortonville and Markley Formations. The Domengine Formation is a transgressive, quartz-rich sandstone that marks a regional Eocene angular unconformity (Moxon, 1990), and is an important early Tertiary marker horizon in the East Bay hills and Mt. Diablo regions. Strata of package EP-2 are best preserved in the "Pacheco syncline" along the northeastern flank of the East Bay hills (Figure 2).

2.3.3 Neogene Strata

Mesozoic and early Tertiary rocks in the East Bay hills are unconformably overlain by a section of Miocene to Quaternary marine and terrestrial deposits that span the transition from convergent margin tectonics to transpressional motion along the Pacific-North American plate boundary (Graham et al., 1983; Nilsen and Clark, 1989). Descriptions of Neogene strata in the greater eastern San Francisco Bay region are presented in Fox (1983), Graham et al. (1983), Nilsen and Clarke (1989), Isaacson and Andersen (1992), Crane (1995), and Andersen et al. (1995). In general, we follow the conventions of Graham et al. (1983) for grouping stratigraphic units in the northern East Bay hills. Of particular importance for this study are late Neogene strata that were deposited in a deep northwest-southeast-trending basin that originally extended from Livermore Valley to west of the Hayward fault. Strike-slip faulting and transpressive crustal shortening associated with the modern San Andreas system subsequently deformed this basin (Graham et al., 1983).

2.3.3.1 Monterey Group

Basal Neogene strata of the East Bay hills are correlated with the middle Miocene Monterey Group (Graham et al., 1983). These rocks are represented in the western East Bay hills by siliceous shale, chert and porcellanite. The strata coarsen eastward to sandstones and shales in the eastern East Bay hills, and age-equivalent rocks in the Mt. Diablo area primarily are represented by sandstones and conglomerates. According to Graham et al. (1983), foraminifera from Monterey Group strata in the western East Bay hills suggest deposition in water depths of 500 m to 1500 m. Analysis of Monterey Group strata to the east suggest a shelf environment grading to an inner shelf environment in the vicinity of Mt. Diablo. Graham et al. (1983) concluded that the Monterey strata in this region accumulated along a west-facing marine paleoslope.

Monterey Group strata are most extensively preserved and exposed in the northern East Bay hills. The thickness and completeness of the exposed Monterey Group section increases eastward across the hills, suggesting that uplift and erosion may have occurred in this region prior to deposition of overlying Neogene strata (Graham et al., 1983).

2.3.3.2 Middle to Late Miocene Strata

The most extensively exposed rocks in the northern East Bay hills are middle to late Miocene (14-5 Ma) strata of the Contra Costa and San Pablo Groups. These rocks are equivalent to the lower part of the Neogene Livermore basin section exposed on the southwestern flank of Mt. Diablo and the hills north of Livermore Valley (Isaacson and Anderson, 1992; Anderson et al., 1995). The Contra Costa Group is characterized by subaerial fluvial deposits interbedded with volcanic flows and lacustrine deposits, and it primarily crops out in the western East Bay hills. The age-equivalent San Pablo Group consists primarily of marine sandstones and shales, and is present in the northeastern East Bay hills and in the Mt. Diablo-Livermore area. The facies transition between the non-marine Contra Costa and marine San Pablo rocks locally is exposed in the central East Bay hills in the axis of the Mullholland syncline (Graham et al., 1983). The combined middle to late Miocene section (Contra Costa and San Pablo Groups) thickens eastward across the East Bay hills, presumably toward the axis of the ancestral Neogene basin, near what is now Livermore Valley. Seismic refraction studies in Livermore Valley indicate that the maximum thickness of the Neogene section there approaches 5 km (Meltzer, 1988).

Exact correlation of the Contra Costa and San Pablo sections is difficult given the change in facies and depositional environment across the East Bay hills. One of the best stratigraphic markers for correlating the Neogene sections units is the late Miocene Neroly Formation, a distinctive volcaniclastic sandstone that is exposed in the Mt. Diablo region and northeastern East Bay hills. Stratigraphic relations with dated tephra in the Mt. Diablo region indicate that the Neroly Formation is between 11 Ma and 6.2 Ma in age. Marine fossils date Neroly deposition at about 9 to 10 million years. This is similar to the age of the Grizzly Peak basalt (about 9-10 Ma; Graham et al., 1983), which is interbedded with the non-marine Contra Costa Group sediments in the western East Bay hills.

2.3.3.3 Late Neogene Strata

Late Miocene-Pliocene strata in the East Bay hills overlying Contra Costa and San Pablo group rocks are mapped generally as unit “TP” by Crane (1988). The late Neogene deposits are fully involved in folding and thrust faulting in the East Bay hills. These deposits have not been studied to the same level of detail as the Contra Costa Group and San Pablo Group rocks, however, and it is not known if significant unconformities are present in the late Neogene section that may indicate the onset of shortening deformation during the deposition. Stratigraphically, the post-Neroly section in the East Bay hills is equivalent to the Sycamore Formation exposed on the southwestern flank of Mt. Diablo anticline (Issacson and Andersen, 1992; Andersen et al., 1995). The Sycamore Formation, which contains several tephra ranging in age from 6.2 to 3.3

Ma (Graymer et al., 1994; Isaccson and Andersen, 1992; J. Walker, personal communication, 1999), is at least 3000 m thick and primarily characterized by continental fluvial deposits. The Sycamore Formation thickens westward and the late Neogene strata in the East Bay hills thicken eastward, indicating that the axis of the late Neogene basin lies between the two regions; i.e., near or beneath San Ramon Valley.

2.3.4 Quaternary Deposits

Quaternary deposits in the northern East Bay hills consist primarily of alluvial-fan, channel alluvium, stream terrace and landslide deposits (Plate 1). Previous mapping of these deposits was performed in the northern East Bay hills by Simpson et al. (1992), Knudsen et al. (2000), and R. Witter and J. Sowers (unpublished mapping, in prep.). During this study, we refined and built upon these earlier studies and prepared detailed Quaternary maps at a scale of 1:24,000 within parts of the Las Trampas, Walnut Creek and Briones Valley 7.5-minute quadrangles (Plate 1). Our mapping also covers parts of the Oakland East, Dublin and Benicia quadrangles at a scale of 1:24,000. Generalized descriptions of the Quaternary surficial deposits are given in Table 1.

Delineation of surficial deposits and lineaments was completed primarily through analysis of vintage aerial photography, supplemented by field and aerial reconnaissance. Because much of the study area is extensively urbanized, we analyzed black-and-white, stereo-paired aerial photography taken in 1939 and printed at a scale of approximately 1:20,000 (Table 2). We also analyzed other, more detailed, photography of selected areas. Data from analysis of air photos and field reconnaissance was complied at a scale of 1:24,000 and entered into a Geographic Information System (GIS) database.

Table 1. Descriptions of Quaternary surficial deposits.

Map Symbol	Unit Name and Description
	HOLOCENE (<10,000 years)
Qhf	**Holocene alluvial fan deposits.** Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains as debris flows, mudflows, or stream flows. Alluvial fan sediment includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size and general particle size typically decreases downslope from the fan apex. Alluvial fan deposits are identified primarily on the basis of fan morphology and topographic expression. Holocene alluvial fans are relatively undissected, compared to older alluvial fans. Soils typically are entisols, inceptisols, mollisols, and vertisols.
Qht	**Holocene alluvial fan deposits.** Stream terrace deposits that were deposited in point bar and overbank settings. Terrace deposits include sand, gravel, silt and minor clay, and are moderately to well sorted, and moderately to well bedded. Typically, this unit is mapped where relatively smooth, undissected terraces are less than 30 ft above the active stream channel. Soils typically are entisols, inceptisols, and mollisols. Terrace deposits that are too small to be shown at the map scale, such as those along small creeks, are included within the undifferentiated alluvium (Qha) map unit.
Qha	**Holocene alluvium, undifferentiated.** Alluvium deposited in fan, terrace, or basin settings. This unit is mapped where separate types of alluvial deposits could not be delineated either due to complex interfingering of depositional environments or the small size of the area. Typically, undifferentiated alluvium is mapped in relatively flat, smooth valley bottoms of small- to medium-sized drainages. The planar and smooth geomorphic surfaces, with little or no dissection, indicate that there has been little modification of the surface, and the deposits therefore are interpreted to be Holocene in age. These deposits are intercalated sand, gravel, silt, and clay, and are moderately to well sorted, and moderately to well bedded. Soils typically are entisols, inceptisols, mollisols, and vertisols.
Qls	**Holocene landslide deposits.** Sediments deposited in hillside settings, as debris flow, rotational slide, translational slide, or other mass-wasting deposit. Only easily distinguishable landslide deposits are delineated; map is not a comprehensive landslide inventory. Typically, landslide deposits are associated with hummocky topography in areas of moderate or steep slopes. These deposits are poorly sorted sand, pebbles, and boulders, as well as large blocks of bedrock that locally are coherent.
	PLEISTOCENE (10,000 years to 1.6 m.y.)
Qof	**Pleistocene alluvial fan deposits.** Moderately to deeply dissected alluvial deposits, laid down by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains as debris flows, mudflows, or stream flow. Alluvial fan sediment typically includes sand, gravel, silt, and clay, and is moderately to poorly sorted, and moderately to poorly bedded. Sediment clast size and general particle size typically decrease downstream from fan apex. This unit differs from undifferentiated Pleistocene alluvium in that some original fan surface morphology is preserved.

Map Symbol	Unit Name and Description
Qoa	**Pleistocene alluvial deposits, undifferentiated.** This unit is mapped on gently sloping to level alluvial fan or terrace surfaces. The deposits are slightly too deeply dissected, and may be associated with gently rolling topography with little or none of the original planar alluvial surface preserved. Deposits within this unit include alluvial fan, stream terrace, basin, and channel deposits, and are mapped in small valleys where separate fan, terrace, or basin deposits could not be delineated at the mapping scale. The deposits consist of sand, gravel, silt, and clay, and are moderately to poorly sorted, and moderately to poorly bedded.

Modified from Knudsen et al. (2000)

Table 2. Partial list of aerial photographs analyzed (all photographs black and-white, circa 1939).

Roll Number	Frame Numbers	Geographic Area
BUU - 289	76 to 81	Hercules to Vallejo
BUU - 289	28 to 33	Vallejo to Highway 4
BUU - 283	66 to 77	Benicia to Lafayette
BUU - 280	98 to 108	St. Mary's College to Martinez
BUU - 280	86 to 93	Pleasant Hill to Burton Valley
BUU - 283	44 to 45	Las Trampas Peak
BUU - 280	58 to 63	Alamo to Walnut Creek
BUU-BUT - 282	38 to 42	Las Trampas Ridge
BUU - 281	90 to 94	Danville to San Ramon
BUT-BUU - 280	7 to 10	San Ramon

Surficial geologic mapping utilized the general stratigraphic framework provided by Knudsen et al. (2000). Quaternary map units are divided into three generalized groups of surficial deposits: Holocene (<11,000 years old), late Pleistocene (<30,000 years old), and Quaternary (>30,000 years old) (Plate 1). The ages of these deposits are poorly constrained because there are few or no numerical data available for deposit ages, and thus should be considered estimates only. We acknowledge that individual surficial map units may contain components of older or younger deposits that are too small to show at the 1:24,000 map scale. We do not differentiate map units with modern (<150 years) or late Holocene estimated ages (<1,000 years), nor do we differentiate "latest Pleistocene" deposits (10,000 to 30,000 years old) from late Pleistocene deposits; these distinctions are not critical to the goal of delineating late Quaternary fault-related deformation.

Within each surficial-deposit age group, we identified units that are attributed to alluvial-fan or fluvial-terrace depositional processes (labeled with "f" or "t" suffixes, respectively; Plate 1). Where this distinction was not made, we labeled units with an "a" suffix to indicate undifferentiated alluvium (Plate 1). Landslide deposits were delineated only where distinct and easily identifiable; Plate 1 does not represent a comprehensive inventory of landslide deposits in the area. At several selected localities, the map units identified via analysis of aerial photography were reviewed in the field and revised as appropriate. The general distribution of map units agrees well with similar maps by Knudsen et al. (2000) and Witter and Sowers (unpubl. mapping, 2001), but the detailed distribution of surficial deposits differs locally from these earlier mapping efforts.

3.0
GEOLOGIC STRUCTURE

3.1 Introduction

This investigation focused on interpreting the structural framework of the area between the western margin of the San Ramon Valley near the town of San Ramon to the Carquinez Strait near the town of Vallejo, as shown on Figure 1. Within this area, we mapped late Quaternary deposits and geomorphic features in the area between the town of Alamo and Franklin Canyon (Plate 1), which covers parts of the Briones Valley, Walnut Creek, and Las Trampas Ridge 7.5' quadrangles. This area includes the previously mapped Lafayette and Reliez Valley faults (Dibblee, 1980a), which are primary geologic structures that require better characterization. Additionally, we identify several candidate faults and folds in the northern East Bay hills that may accommodate dextral slip transferred westward from the northern Calaveras fault (Figure 1). Many of these structures coincide with faults or folds that have been mapped by previous workers (Lawson, 1914; Ham, 1952; Saul, 1973; Woodward-Clyde Consultants, 1976, 1978, 1979a, 1979b; Herd, 1978; Wagner, 1978; Dibblee, 1980; Crane, 1988, 1995).

In this section, we describe map-scale folds and faults in the northern East Bay hills, with emphasis on structures that appear to transfer dextral slip from the northern Calaveras fault westward into the interior of the hills. Although there are many synclines and anticlines in the East Bay hills, not all of these structures are equally significant. Here, we focus on folds with mapped axial lengths of several kilometers or more, and with amplitudes in excess of 1000 m, on the assumption that these structures have accommodated significant shortening and are most likely to be underlain by blind thrust faults capable of generating moderate-magnitude or larger earthquakes. We also relocated background earthquakes in the northern East Bay hills to assess the relationship of the 1977 "Briones swarm" events, if any, to neotectonic features and lineaments mapped during this study.

3.2 Methods

3.2.1 Geologic Cross Sections

Geologic cross-sections were prepared to assess the geometry of late Cenozoic folds and thrust faults in the northern East Bay hills, and estimate the horizontal shortening accommodated by these structures. The cross sections were constructed using bedrock geologic map compilations by Crane (1988, 1995), supplemented by mapping of Dibblee (1980a, 1980b), Wagner (1978), Saul (1973), Ham (1952), and Lawson (1914). Our approach to constructing the cross-sections is similar to that recommended by Woodward et al. (1989). We began by choosing and orienting the section lines so that they are perpendicular to the strike or trend of fold-thrust structures. After constructing the topographic profile and adding the surface geology, we projected the limbs and axes of large, map-scale folds to 3 to 4 km depth using the kink-fold method (e.g., Suppe and Medwedeff, 1990). Various models for the underlying thrust geometry then were tested for compatibility with the shallow fold geometry. The interpretation was guided by the following principals, which generally apply to other well-studied fold-and-thrust belts (Woodward et al., 1989):

(1) Asymmetric anticlines typically are underlain by blind thrust faults, or otherwise are decoupled above a detachment horizon;
(2) Blind thrust faults are assumed to dip in the same direction as the back limb of the asymmetric fold developed in the hanging wall; and
(3) Depth to the detachment must be compatible with the scale of the overlying folds, as defined by projecting hinges at the base of the backlimb and the top of the forelimb to depth.

We emphasize that in order to complete the cross-sections it was necessary to project stratigraphic and structural relations to depth, as well as above the current level of erosion. In both cases, the constraints on the geology available for this study were limited to surface mapping. Thus, we acknowledge a high degree of uncertainty in the details of our interpretations. Nevertheless, the structural models honor the available map data, and they provide a preliminary basis for estimating a range of average late Cenozoic shortening rates across the northern East Bay hills.

3.2.2. Earthquake Relocations

We relocated hypocenters of 346 earthquakes that occurred in the East Bay hills region during the period 1970-2000. We selected only those events with magnitudes greater than M_L 2 to provide sufficient seismic data for relocations. Earthquake P-wave arrival data were collected by the Northern California Seismic Network and obtained from the data repository at the Northern California Earthquake Data Center, maintained by the Berkeley Seismological Laboratory of the University of California. The data consist of 14,327 arrival times gathered at 440 seismic stations in northern California.

Hypocenter relocations were performed using the program VELEST (Kissling, 1994). The program performs a simultaneous inversion of local P-wave arrival time data for one-dimensional p-wave crustal velocity structure and earthquake hypocenter locations. Using the initial one-dimensional P-wave gradient velocity model (Concord-Calaveras model) used for creating U.S. Geological Survey hypocenter catalogs (A. Michael, personal communication, 1997), we performed two separate inversions to obtain the relocated hypocenters. First, we performed an iterative inversion to estimate the local one-dimensional p-wave velocity model with station corrections for the East Bay hills. This velocity model did not differ significantly from the original one-dimensional velocity model. Next, we performed an iterative inversion for the earthquake hypocenter relocations, holding the velocity model and station corrections fixed. Overall, the relocation inversions resulted in a reduction in the root-mean-square error of 89% (from 1.23 to 0.135 s^2), with a root-mean-square residual of 0.48 s^2.

3.2.3 Delineation of Potentially Fault-related Lineaments

We identified and mapped geomorphic features indicative of potentially active faults through analysis of aerial photography and field reconnaissance. Our geomorphic mapping refined the previous mapping of Simpson et al. (1992), and documents a greater level of detail regarding lineament type (i.e., linear troughs, saddles, vegetation alignments) and degree of expression (strong, distinct, weak; per Lienkaemper, 1992, and Witter and Kelson, in prep.). We also document the strike and dip direction of prominent bedding (based on air-photo interpretation) that provides information to interpret zones of structural discontinuities and folding. In many parts of the study area, resistant sandstone beds form prominent strike ridges that are as much as several kilometers long (Plate 1), and which are excellent stratigraphic markers delineating areas unaffected by cross-strike faulting. Collectively, the compilation of potential fault-related lineaments, continuous and discontinuous bedrock strata, and previous bedrock and Quaternary geologic mapping provide information to identify areas of potentially active faulting.

Surficial deposits and potential fault-related lineaments derived from analysis of aerial photography, and field and aerial reconnaissance was compiled on mylar overlays on 1:24,000-scale topographic base maps, which were then scanned, digitized, and entered into a GIS database using ArcView (version 3.2). As shown on Plate 1, the lineaments have attributes within the GIS database that address the type and prominence of the feature.

3.3 Late Cenozoic Structures of the Northern East Bay hills

3.3.1 Northern Calaveras Fault

The Calaveras fault is mapped along the eastern margin of the East Bay hills in San Ramon and Alamo by several workers (Lawson, 1914; Ham, 1952; Herd, 1978; Simpson et al., 1992; Crane, 1995). CDMG (Hart, 1981) classifies the fault as an inactive (pre-Holocene) structure northwest of San Ramon; this evaluation is supported, in part, by results of trenching across an apparently undisplaced latest Pleistocene alluvial fan in Alamo (Simpson et al., 1992). Nevertheless, numerous linear hill fronts and tonal lineaments in alluvial deposits (Plate 1) characterize the eastern margin of the East Bay hills in Alamo. Analysis of aerial photography and field reconnaissance for this study suggests that the lineaments along the hill front are similar to those along the northern part of the Calaveras fault in San Ramon. We interpret that the northern Calaveras fault extends as far northwest as the southern end of Castle Hill (Plate 1), although we do not confirm or deny that the Holocene active section of the fault ends in San Ramon (as mapped by Hart, 1981). Several northwest-trending linear valleys extend into the East Bay hills from Alamo, and appear to merge with the Las Trampas fault, faults bordering Tice Valley (including the Saklan fault of Woodward-Clyde, 1976), and the Mt. Diablo fault mapped by

Crane (1995) in the vicinity of Castle Hill. The relatively sinuous eastern front of Castle Hill in Alamo and Walnut Creek, and the absence of similar distinct fault-related air-photo lineaments in this area, suggests that the northern Calaveras fault does not continue along this front. Instead, the northernmost part of the northern Calaveras fault may merge with or intersect the Las Trampas, Saklan, and/or Mt. Diablo faults, and/or Las Trampas anticline (Figure 3).

3.3.2 Knife Anticline

The Knife anticline is part of a clustered group of northwest-trending folds on the west of the Calaveras fault, directly opposite San Ramon Village (Figure 3). These northwest-trending structures are significant because they represent the southernmost set of map-scale folds in the East Bay hills that trend northwest, distinctly oblique to the north-northwest strike of the Calaveras fault (Figure 3). In contrast, structural trends (i.e., bedding strike, trends of fold axes) in the East Bay hills south of Knife anticline are more parallel to the strike of the Calaveras fault. Thus, we consider the Knife anticline and related structures to mark the southern boundary of the northern East Bay hills structural domain. These structures also are significant because they are well expressed in late Neogene strata (i.e., lower San Pablo Group), and thus are unequivocally late Cenozoic in age. There are no rocks younger than Mesozoic in the southern East Bay hills; therefore, young fold deformation between the Hayward and Calaveras faults is difficult to establish south of the Knife anticline.

Based on compilation mapping by Crane (1988), the axis of the Knife anticline is about 9 km long. A cross section of the Knife anticline (Figure 4) indicates that the width of the fold (or wavelength) is about 3 km, and the amplitude measured on Neogene bedding contacts is about 3,400 m. The Knife anticline is slightly asymmetric and vergent to the northeast. As mapped by Crane (1988), the axis of the anticline is displaced about 1 km in a dextral sense by an unnamed north-northwest-striking fault along the southeast margin of the fold (Figure 3).

Other folds associated with the Knife anticline include the Kaiser Creek syncline and Donlan Canyon anticline (Figure 3). These northwest-plunging folds terminate abruptly to the southeast against the Calaveras fault and plunge out to the northwest. The Kaiser Creek syncline separates the Knife anticline from the Donlan Canyon anticline to the southeast. The Donlan Canyon

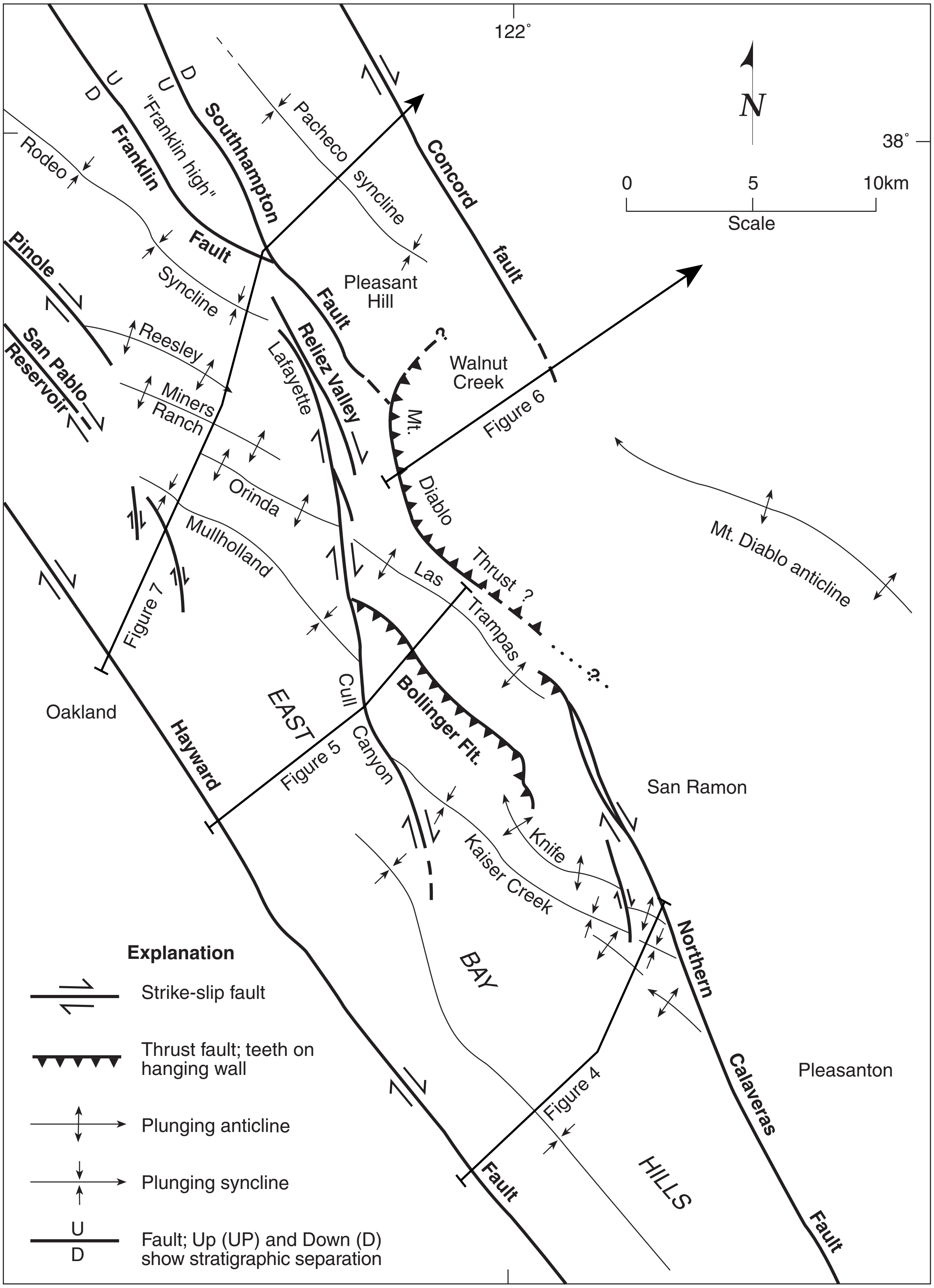

Figure 3. Generalized structure map of the northern East Bay hills (modified from Crane, 1988).

anticline has a width of about 1.2 km and an amplitude of about 1,200 m, and based on cross-section construction it appears to be vergent to the southwest (Figure 4).

We interpret the Knife anticline to be a fault-propagation fold developed above a blind, southwest-dipping thrust fault (Figure 4). The Donlan Canyon anticline also is interpreted to be a fault-propagation fold. Given its smaller size and opposite sense of vergence, we infer that the Donlan Canyon anticline formed by buckling within the panel of northeast-dipping Neogene strata that forms the west limb of the Kaiser Creek syncline (Figure 4). This northeast-dipping panel may be the forelimb of a larger northeast-vergent anticline above the blind thrust fault interpreted to dip west beneath all of these folds. However, Neogene strata are not present in the East Bay hills to the southwest to test this hypothesis. The significance of the southwest dip of Cretaceous strata west of the Donlan Canyon anticline is difficult to assess because pre-Neogene structure in this region is not well understood. For example, the abrupt reversal in dip across the northeast-dipping Neogene/Cretaceous contact on the west limb of the Kaiser Creek syncline (Figure 4) is the local expression of a regional angular unconformity at the base of the Monterey Group section. Variations in bedding dip across this contact in the southern and western East Bay hills (documented in compilation mapping by Crane, 1988) show that that Cretaceous strata were dipping east or northeast at the time the Neogene strata were deposited. These relations indicate at least some of the structure in the Cretaceous strata southwest of Knife anticline formed prior to the Middle Miocene.

Based on the line length of deformed Neogene contacts in the plane of the cross section (Figure 4), horizontal northeast-vergent shortening across the Knife anticline and related folds is about 4 km. As noted above, Neogene shortening southwest of the Donlan Canyon anticline cannot be evaluated with confidence.

3.3.3 Bollinger Fault

The Bollinger fault is a northwest-striking, southwest-dipping thrust fault, the trace of which is located a few tens of meters east of the crest of Bollinger ridge between the northern Calaveras fault and the southern end of the Lafayette fault. Ham (1952) shows that the Bollinger fault is truncated at its southeast end by a northeast-striking, high-angle fault. In contrast, Crane (1988)

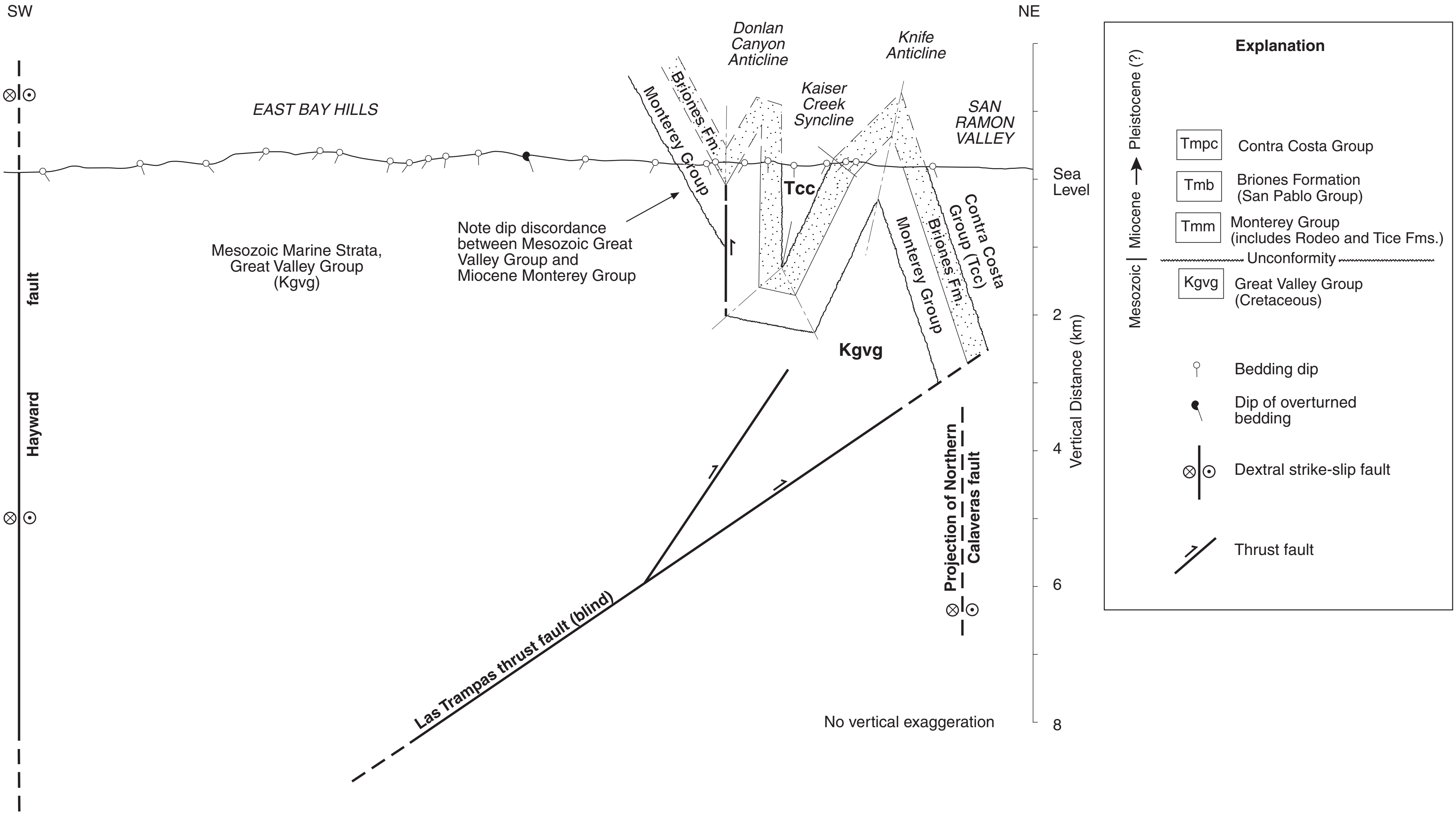
SW
NE
EAST BAY HILLS
Donlan Canyon Anticline
Kaiser Creek Syncline
Knife Anticline
SAN RAMON VALLEY
Monterey Group
Briones Fm.
Tcc
Contra Costa Group (Tcc)
Sea Level
Mesozoic Marine Strata, Great Valley Group (Kgvg)
Note dip discordance between Mesozoic Great Valley Group and Miocene Monterey Group
Kgvg
Hayward fault
Las Trampas thrust fault (blind)
Projection of Northern Calaveras fault
No vertical exaggeration
Vertical Distance (km)
2
4
6
8
Explanation
Mesozoic | Miocene → Pleistocene (?)
Tmpc
Contra Costa Group
Tmb
Briones Formation (San Pablo Group)
Tmm
Monterey Group (includes Rodeo and Tice Fms.)
Unconformity
Kgvg
Great Valley Group (Cretaceous)
Bedding dip
Dip of overturned bedding
Dextral strike-slip fault
Thrust fault

Figure 4□

shows that the fault terminates to the southeast in a complex, faulted anticline (Figure 3). Total length of the fault trace, as mapped by Ham (1952) and Crane (1988), is about 13 km.

Ham (1952) and Crane (1988) both show that the Bollinger fault strikes parallel to bedding and places Briones Formation over undifferentiated upper Contra Costa Group strata (Figure 5). Bedding in the hanging wall of the fault dips moderately to steeply southwest. In contrast to the Las Trampas fault, which is mapped as a thrust fault by Crane (1988) but does not repeat a significant thickness of stratigraphic section, the Bollinger Canyon fault repeats a minimum of about 2 km of the Neogene section (Figure 5) and thus likely has a minimum displacement on the order of about 3 km.

The Bollinger fault is very well expressed as a geomorphic feature. Multiple coalescent landslides are abundant along the northeastern flank of Rocky Ridge (the southwestern side of Bollinger Canyon), and are developed in the weaker Contra Costa Group strata. The more resistant rocks of the Briones Formation on the hanging wall form the headwalls of many of these landslides. Because of this, the Bollinger Canyon fault is very well expressed as far northwest as the headwaters of Las Trampas Creek (Plate 1). In the vicinity of Las Trampas Creek valley (upstream of St. Mary's College, Plate 1), the Bollinger fault merges with or intersects the Lafayette and/or Cull Canyon faults. Northwest of Las Trampas Creek, there is no geomorphic expression suggestive of the Bollinger fault.

3.3.4 Bollinger Canyon Fault

The Bollinger Canyon fault (mapped by Crane, 1988, but not named) coincides with a nearly continuous vegetation and tonal lineament along the northeastern valley wall of Bollinger Canyon, from the vicinity of Las Trampas Peak to western San Ramon. Bollinger Canyon itself is a major linear valley that is parallel to the regional strike of bedding and likely is a result of different erosional resistances of bedrock (and shear zones) juxtaposed along the Bollinger Canyon fault. Las Trampas Ridge consists of resistant, steeply dipping to vertical sandstone strata of the Briones Formation, and is essentially a strike ridge from San Ramon on the south to Las Trampas Peak on the north. Analysis of aerial photography confirms mapping by previous workers showing that Las Trampas Ridge, and the parallel Rocky Ridge to the southwest, are essentially unbroken by cross-faults, and make up a distinct geologic-structural domain within the East Bay hills. In the vicinity of Las Trampas Creek valley (along western Bollinger Canyon Road and upstream of St. Mary's College, Plate 1), the Bollinger Canyon fault merges with or intersects the Lafayette and/or Cull Canyon faults. Northwest of Las Trampas Creek, there is no prominent geomorphic expression of the Bollinger Canyon fault.

3.3.5 Las Trampas Anticline

Las Trampas anticline is an asymmetric, northeast-vergent fold that trends northwest from the northern end of the Calaveras fault. The fold was first recognized and mapped by Ham (1952). The Miocene Briones Formation of the San Pablo Group is present on both limbs of the fold and can be reasonably projected parallel to bedding dip across the fold axis (Figure 5). The core of the anticline exposes Miocene Monterey Group strata (i.e., the Tice and Rodeo Formations). The anticline axis terminates to the northwest against the Lafayette-Reliez Valley fault system. The maximum length of the anticline is about 12 km.

Based on cross-section analysis, the Las Trampas anticline is about 3 km wide and has an amplitude of about 3000 m. The forelimb varies from dipping steeply northeast to being overturned and dipping steeply southwest. Backlimb dips range from about 45° to 65° southwest. Based on the asymmetry of the fold, we interpret the Las Trampas anticline to be a northeast-vergent fault-propagation fold underlain by a blind, southwest-dipping thrust fault, similar to the Knife anticline to the southeast (Section 3.3.2).

The Las Trampas anticline is associated with a localized, northwest-trending belt of high topography that, like the fold, is bounded by the northern Calaveras fault to the east and Lafayette and Reliez Valley faults to the west. The Las Trampas anticline underlies "Las Trampas Ridge", which rises abruptly to elevations about 560 m and is about 400 m higher than the floor of San Ramon Valley to the east. The potential tectonic significance of the high topography in this region is discussed in Section 4. The prominent, northeast-facing topographic escarpment that defines the eastern margin of the East Bay hills at this latitude is coincident with the forelimb of Las Trampas anticline.

3.3.6 Las Trampas Fault

The Las Trampas fault is a northwest-striking fault on Las Trampas Ridge west of the town of Alamo. Crane (1988) maps the Las Trampas fault as a southwest-dipping thrust fault whose map trace closely follows topographic contours, suggesting a relatively shallow dip. As mapped by Crane (1988), the Las Trampas fault lies entirely within the Rodeo shale of the Monterey Group, and does not repeat the stratigraphic section. In contrast, Ham's map (1952) of the Las Trampas Ridge area does not show a continuous strike-parallel fault within the Rodeo shale. Instead, the Las Trampas fault of Ham (1952) strikes obliquely across bedding and cuts across the anticline axis (Figure 3).

The Las Trampas fault is marked clearly by a distinct, nearly continuous 3-km-long vegetation and tonal lineament within the southeastern part of Grizzly Creek Valley (Plate 1). This lineament coincides with the different rock types that are juxtaposed along the Las Trampas fault, and the linear creek valley likely is related to erosion along the strike of less resistant beds on the southwestern side of the fault. To the northwest, the lineaments along the Las Trampas fault appear to merge with lineaments along the Lafayette fault in the lower Grizzly Creek valley (Burton Valley) (Plate 1). To the southeast, linear valleys coincident with the mapped traces of the Las Trampas fault (Ham, 1952) appear to merge with lineaments along the margin of the East Bay hills in the town of Alamo, which, as noted above, may be related to the northern Calaveras fault (Plate 1). In general, the geomorphic features described above correspond to the trace of the Las Trampas fault as mapped by Lawson (1914) and Ham (1952).

The Las Trampas fault does not appear to have accommodated significant late Cenozoic thrust displacement because there is no repetition of section across it. A cross section across Las Trampas anticline (Figure 5) shows that the Briones-Cierbo contact can be projected from the limbs over the fold axis, and requires less than a 100 m of separation across the trace of the Las Trampas fault as mapped by Crane (1988). This is easily within the error of the cross-section construction technique, and it can plausibly be argued that there is no thrust offset across the Las Trampas fault. The thickness of the Neogene units appears to differ from southwest to northeast

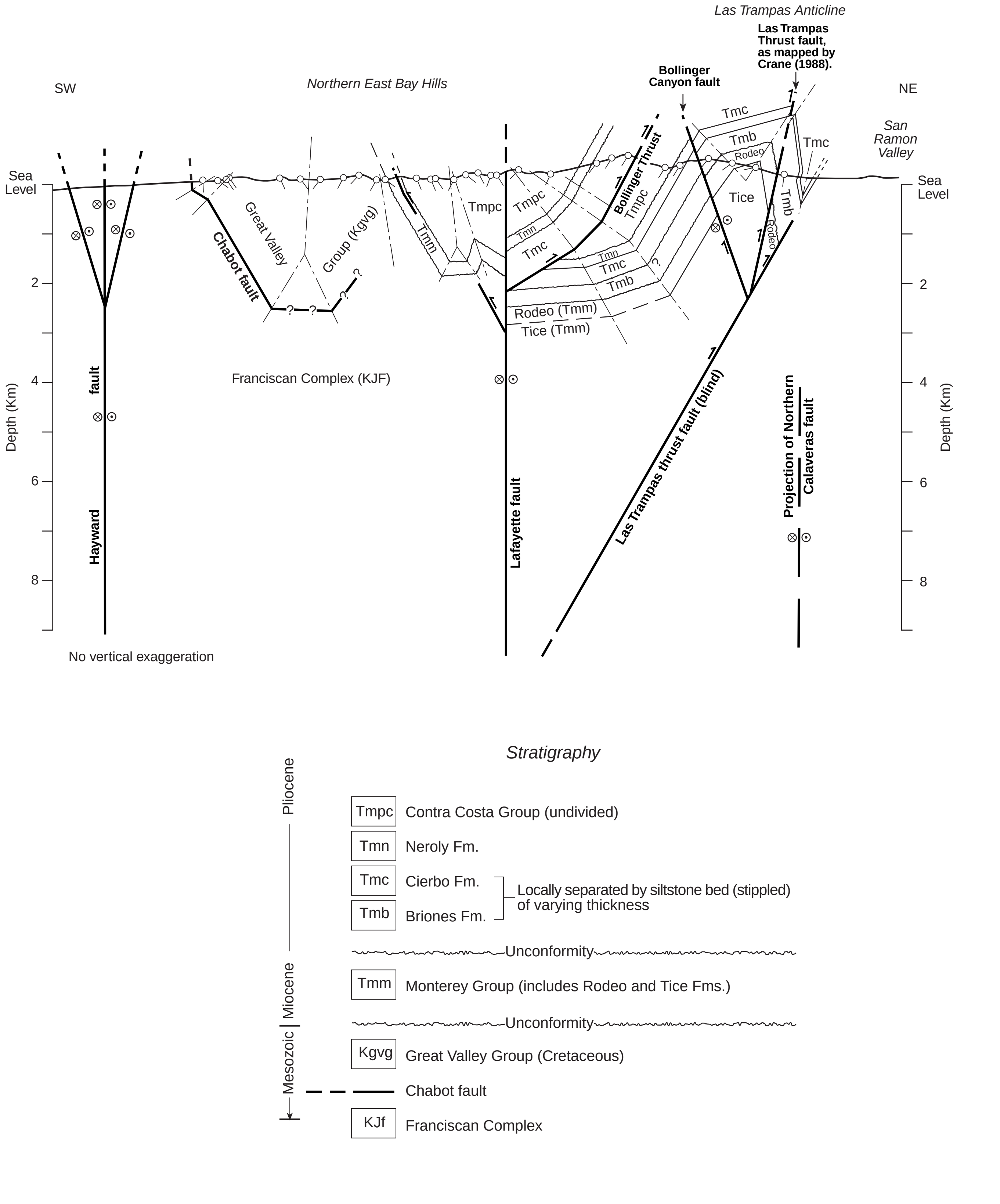

Figure 5. Geologic cross section across the northern East Bay hills, showing relationship between the Lafayette fault, the Las Trampas fault, the northern Calaveras fault, and the Las Trampas anticline.

across the fold and trace of the fault, which may be evidence for Neogene syndepositional activity. The trace as mapped by Crane suggests that the fault may be subparallel to bedding; if this is correct, then the fault probably is folded along the backlimb of Las Trampas anticline. In general, we believe that the map depiction of the "Las Trampas fault" by Ham (1952) is more geologically plausible and consistent with other structures mapped nearby.

3.3.7 Mt. Diablo Thrust Fault

The Mt. Diablo thrust fault herein refers to the previously mapped structure that extends from an intersection with the northern Calaveras fault at the southern end of Castle Hill (Figure 3), northwestward to an intersection with the Saklan fault of Woodward-Clyde (1979). This fault was mapped by Ham (1952), Woodward-Clyde (1975, 1979a), and Wagner (1978) as the southern part of the Franklin fault, which Lawson (1914) connects with the Calaveras fault. Saul (1973) maps this structure as part of the Calaveras fault, and Crane (1995) interprets it as the Mt. Diablo thrust fault. Crane (1995) shows the Mt. Diablo thrust fault extending to the north of Tice Creek and Las Trampas Creek, through the City of Walnut Creek, as a buried structure.

As mapped, the Mt. Diablo thrust fault juxtaposes steeply east-dipping to vertical Eocene strata on the east juxtaposed against southwest-dipping Neogene rocks on the west (Crane, 1988). The relatively straight surface trace of the fault across substantial topographic relief indicates that the fault in this area is steeply dipping to vertical. Several paleoseismic trenches by Woodward-Clyde (1979b) demonstrate the presence of sheared and deformed bedrock along this fault. These workers concluded that the fault is not active on the basis of undisplaced colluvial deposits, and interpreted that the deformation may be related to folding of the bedrock or secondary faulting.

A cross-section interpretion of the Mt. Diablo thrust fault is shown in Figure 6. The fault is interpreted to dip about 40° to the northeast in the subsurface beneath the northwestern end of the Mt. Diablo anticline. At Castle Hill, however, the Mt. Diablo fault plane has been uplifted and tilted eastward in the upper crust by the forelimb of an unnamed anticline east of the Reliez Valley fault. We interpret that the anticline is a northeast-vergent fault-propagation fold developed above a blind, southwest-dipping thrust fault. The inferred thrust is on trend with the

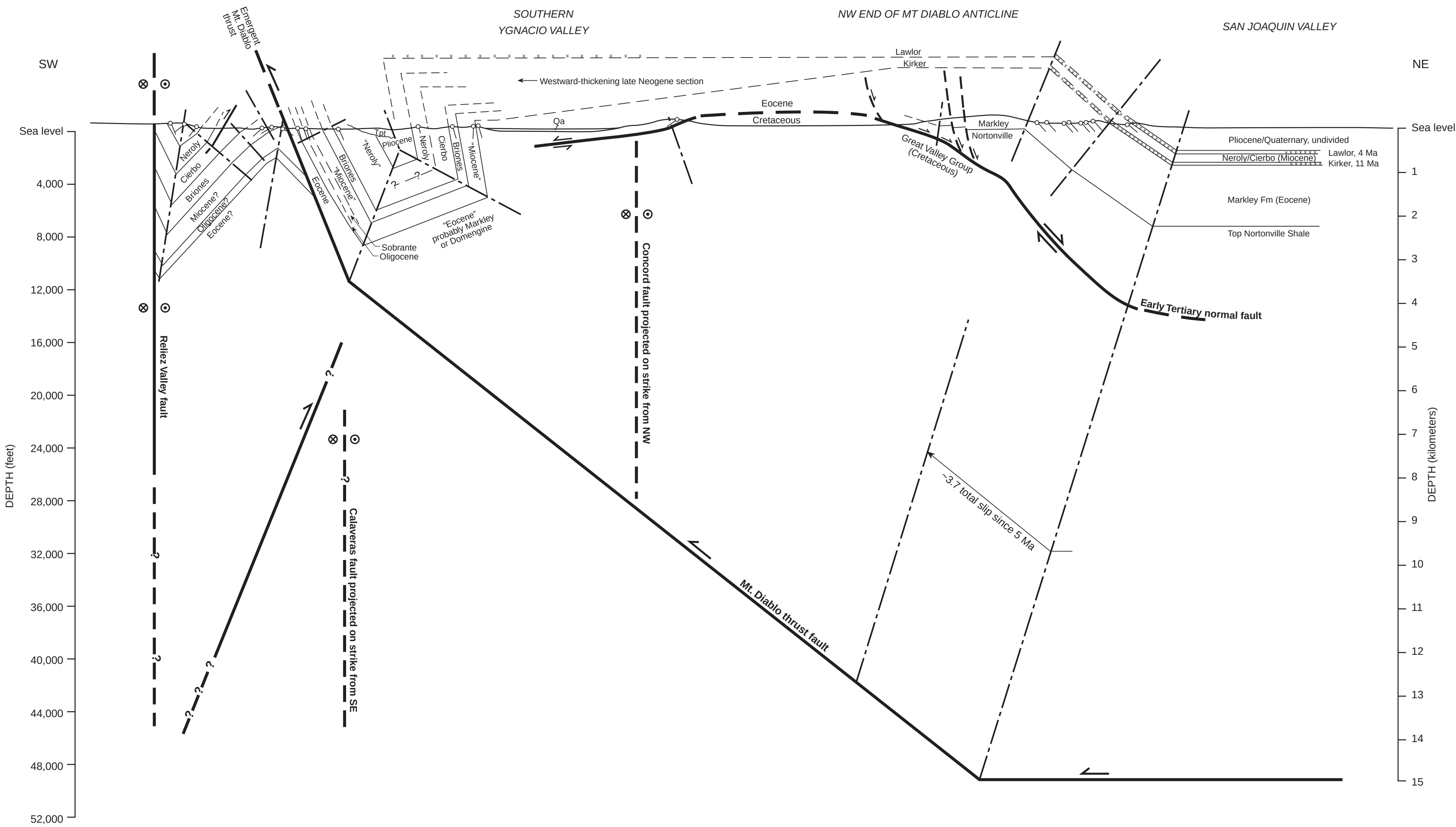

Figure 6. Geologic cross section across northern end of Mt. Diablo anticline.

projection of the Calaveras fault, and may have a en echelon, right-stepping geometry relative to the Las Trampas anticline to the south. Analysis of aerial photography and field reconnaissance shows the presence of several strongly pronounced to distinct geomorphic features along the mapped trace of the Mt. Diablo thrust fault, including side-hill benches, saddles, linear drainages, and vegetation and tonal lineaments (Plate 1). South of Castle Hill, the fault lies within a narrow, linear valley; north of Castle Hill the fault is associated with a series of pronounced benches and tonal lineaments (Plate 1). Most of these features are present within bedrock terrane, and thus may be related to lithologic controls on erosion and weathering, rather than late Quaternary fault movement. However, we consider that the prominent geomorphic expression of the fault, its apparent connection with other regional structures, and its favorable orientation suggest that the fault may have had late Quaternary movement.

3.3.8 Saklan Fault

Woodward-Clyde (1976, 1978b, 1978c) mapped a north-striking "Fault A" from the southern end of Tice Valley, obliquely across the ridge separating Tice Valley from Castle Hill. Woodward-Clyde (1979a) referred to this fault as the Saklan fault, and showed it as a west-vergent thrust fault along the eastern margin of Tice Valley. These workers also show that the fault connects to the north with the Franklin fault of Wagner (1978) (which is also the Calaveras fault of Saul [1973] and the Mt. Diablo thrust fault of Crane [1988]). Geologic trenches by Woodward-Clyde (1976, 1978b, 1979a) across the Saklan fault exposed sheared and deformed bedrock.

Our analysis of 1939 aerial photography shows the presence of several strongly pronounced geomorphic features along the fault trace, including saddles, linear drainages, and vegetation and tonal lineaments (Plate 1). Most of these features are present within bedrock terrane, and thus may be related to lithologic controls on erosion and weathering, rather than late Quaternary fault movement. The southern end of the Saklan fault merges with or intersects the Tice Valley fault (Section 3.3.9), whereas we interpret that the northern end of the Saklan fault merges with the Mt. Diablo fault north of Tice Valley, and may continue northward into the cities of Walnut Creek and Pleasant Hill as the “Larkey lineament zone” (Section 3.3.10).

3.3.9 Tice Valley Lineaments

Tice Valley is a flat-floored, northwest-trending intermontane valley within the East Bay hills that parallels the regional structural trend (Plate 1). The valley contains several strongly pronounced and distinct lineaments along both its eastern and western margins (Plate 1). Herd (1978) identified many of these same features and interpreted them as evidence of Quaternary faulting. On the 1939 aerial photography, the lineaments are strongly pronounced or distinct tonal features that occur on bedrock units, Holocene alluvial-fan deposits shed into the valley, and Holocene alluvium on the valley floor. Bedrock comprising the valley walls consists of steep, southwest-dipping to vertical sandstone strata of the Neroly and Briones Formations (Wagner, 1978). The air-photo lineaments are parallel with the strike of these strata and, where located in bedrock terrane, are likely related to variations in lithology within the bedrock formations. However, many of the lineaments occur on alluvial surfaces, and thus may be related to late Quaternary fault movement. At the southern end of the valley, air-photo interpretation shows truncated sandstone bedding along the projection of these lineaments, and there are several linear drainage valleys that extend to the southeast from Tice Valley toward Alamo (Plate 1). Extensive development within Tice Valley has destroyed the lineaments identified on alluvial deposits, and precludes field verification of these features.

At the southern end of Tice Valley, Woodward-Clyde (1979b) completed four geologic trenches across the lineaments identified by Herd (1978) as possible Quaternary faults. Of the three trenches that exposed bedrock, one showed an absence of faulting, one showed distributed deformation of shale units, and one showed a juxtaposition of shale and sandstone bedrock units along a vertical, N49°W-striking shear. Because none of the trenches provided evidence of faulted alluvial deposits, Woodward-Clyde (1979b) concluded that the faults mapped by Herd (1978) do not exist. In contrast, we interpret that the presence of the series of prominent lineaments at the southern end of Tice Valley, and the faulted bedrock in trench 2 of Woodward-Clyde (1979b), suggest that the lineaments are related, at least in part, to fault movement. These lineaments extend to the southeast to an intersection with the northern Calaveras fault in the town of Alamo (Plate 1).

At the northern end of Tice valley, two strongly pronounced linear drainages coincide with the northern projections of the valley margins (Plate 1). The eastern of these northwest-trending linear valleys projects into the Reliez Valley fault (Dibblee, 1980; Crane, 1988), and the western linear drainage has a slightly more westerly trend and projects to an intersection with the Lafayette fault (Dibblee, 1980; Crane, 1988) at the northern end of Burton Valley (Plate 1).

The Tice Valley lineaments may be the geomorphic expression of faults that transfer strain from the northern Calaveras fault near the southern end of Castle Hill, through Tice Valley, and then onto both or either the Reliez Valley and Lafayette faults. The possible fault traces between Alamo and Tice Valley have a trend of about N45°W (as shown on Plate 1 and also mapped by Herd, 1978). In contrast, the traces bordering the valley have a trend of about N30°W, and the traces connecting with the Reliez Valley and Lafayette faults have a trend of about N60°W. Given these variations in fault orientation and the broad, alluviated characteristics of Tice Valley, we speculate that Tice Valley may be a local pull-apart basin related to a 1-km-wide right stepover. We further speculate that the west-northwest-trending fault segments between Tice Valley and the Calaveras fault and between Tice Valley and the Reliez Valley fault are likely to have had oblique reverse slip if active in the present tectonic setting.

3.3.10 Larkey Lineament Zone

We identify a 0.5-km-wide, discontinuous zone of lineaments that extends at least 6.5 km north from the northern end of the mapped trace of the Saklan fault of Woodward-Clyde (1979a) into the City of Pleasant Hill (Plate 1). This lineament zone also is coincident with the Mt. Diablo thrust fault mapped by Crane (1995) through the City of Walnut Creek. The zone includes two sets of lineaments in the bedrock terrane between Tice Creek and Las Trampas Creek, and discontinuous, possible fault-related geomorphic features flanking the eastern margin of the East Bay hills in the cities of Walnut Creek and Pleasant Hill (Plate 1). This zone of discontinuous lineaments may be related to influences of shallow bedrock on geomorphic features and/or to possible movements on the northern continuation of the Saklan/Mt. Diablo faults.

Geomorphic features indicative of potential fault activity within the Larkey lineament zone are well expressed in the bedrock terrane between Tice Creek and Las Trampas Creek (Plate 1).

Directly south of Parkmead (Doris Eaton) School, a set of lineaments traverses a topographic low coincident with the trace of the Mt. Diablo thrust fault (Crane, 1988), and consists of multiple saddles, benches, and linear drainages. Along the northern projection of these lineaments, alluviated areas flanking Tice Creek and Las Trampas Creek in the City of Walnut Creek contain only a few isolated tonal lineaments suggestive of possible late Quaternary fault movement. However, this alignment coincides with the truncation of a prominent northwest-striking ridge composed of Briones Formation sandstone on the northern side of the Las Trampas Creek valley, at the intersection of Highways 680 and 24 (Plate 1). Crane (1988) maps the Mt. Diablo thrust fault east of this sandstone ridge, and continues the fault to the north-northeast beneath the urbanized, alluviated valley of Walnut Creek in the cities of Pleasant Hill and Concord. The east-facing front of the East Bay hills through the City of Walnut Creek and into Pleasant Hill also contain numerous tonal lineaments, truncated ridge spurs, linear fronts, and topographic saddles (Plate 1). These lineaments, in places, coincide with the mapped location of the northern Calaveras fault as mapped by Dibblee (1980), and the southern end of the Franklin fault as mapped by Geomatrix (1999).

East of the Mt. Diablo thrust fault (Crane 1988), the bedrock ridge between Tice Creek and Las Trampas Creek trends north and is bordered on the east by a series of tonal lineaments, saddles, and truncated ridge spurs (Plate 1). These features border a north-trending ridge underlain by San Pablo Group rocks, and likely are related to lithologic influences on erosion, but may in part be related to fault movement. Along the northern projection of these lineaments, 1939 air photos show the presence of possible fault-related lineaments within Holocene alluvium adjacent to Las Trampas Creek directly downstream of Highway 680 (Plate 1). Urban modification of this area precludes field verification of these lineaments. North of Las Trampas Creek, a few north-trending tonal lineaments that may be fault-related also are present in late Pleistocene alluvium in downtown Walnut Creek (Plate 1). These lineaments appear to coincide with the northern Calaveras fault as mapped by Graymer et al. (1994).

Farther north, the 1939 air photos show possible fault-related features within the Larkey lineament zone in Walnut Creek and possibly as far north as the Mokelumne Aqueduct in the town of Pleasant Hill (Plate 1). We map a prominent east-facing scarp in late Pleistocene older alluvium from about 3rd Avenue on the south to Geary Road on the north (Plate 1). This east-facing scarp is oriented across the local slope of the dissected older alluvium, and gradually increases in height from south to north. Where the scarp crosses the Mokelumne Aqueduct in Larkey Park, it is about 4 to 5 m high. Based on field reconnaissance observations and discussions with park maintenance personnel, we believe that the scarp is developed on alluvium, although we cannot at this time preclude the presence of shallow bedrock that might account for the existence of the scarp. North of Geary Road, the scarp does not continue into topographically lower areas underlain by younger (Holocene) alluvium. The presence of this scarp in alluvium is significant because it raises the possibility of Quaternary faulting along a fault bordering the eastern piedmont of the northern East Bay hills. This location coincides roughly with the Southhampton fault mapped by Crane (1988) and an unnamed fault mapped by Graymer et al. (1994).

3.3.11 Lafayette, Reliez Valley and Cull Canyon Faults

The Lafayette, Reliez Valley and Cull Canyon faults collectively comprise a 25-km-long, north-northwest-trending zone of late Cenozoic dextral faulting in the northern East Bay hills. Attributes of the individual faults within this zone are described below.

The Lafayette and Reliez Valley faults are north-northwest-striking high-angle faults that can be traced from northwestern end of the Las Trampas anticline to the eastern margin of the Franklin High structural culmination in the Briones hills area. The two faults are subparallel at their southern ends and separated by approximately 250 m to 500 m; the faults merge at their northern end.

The Lafayette fault extends from the vicinity of Las Trampas Creek near St Mary's College to about the Maricich Lagoons in Briones Regional Park, for a total length of about 13 km (8 mi), including its northernmost section coincident with the Reliez Valley fault (Plate 1). As identified by Dibblee (1980), Crane (1988) and Graymer et al. (1994), the N15°W-striking fault has predominantly dextral strike slip, displaces sandstone beds within the Briones and Neroly Formations, and merges with the Reliez Valley fault at its northern end. The southern end of the fault may merge with the Cull Canyon fault east of St Mary's College (Plate 1).

The Lafayette fault is associated with strongly pronounced geomorphic features suggestive of possible Quaternary activity along most of its entire length. Its southernmost end, between its intersections with the Bollinger fault (on the south) and the Las Trampas fault (on the north), is a broad (1-km-wide) zone of distinct saddles and tonal lineaments, and abundant landslides (Plate 1). However, north of its intersection with the Las Trampas fault at the southern end of Burton Valley, the fault is associated with multiple tonal lineaments in alluvium, saddles, linear valley margins, and vegetation alignments. Burton Valley has a broad, N15°W-trending alluviated valley floor and linear valley margins. Lineaments along both valley margins suggest that this valley may be a linear tectonic pull-apart basin within the dextral fault zone, in some ways similar to the NW-trending Tice Valley.

North of Burton Valley, the Lafayette fault displaces sandstone strata underlying Snake Hill (Plate 1), and is associated with tonal lineaments across Holocene deposits in Las Trampas Creek valley. The fault is mapped along a series of large linear troughs in bedrock terrane north of Las Trampas Creek (Plate 1). These linear troughs are occupied by Janet Lane, and are associated with displacement of San Pablo Group contacts (Dibblee, 1980; Crane, 1988). These linear troughs project to the north across Highway 24 to another strongly pronounced linear trough ("Lafayette Ridge site", Plate 1). This prominent, alluviated trough is described in more detail in Section 5.1.

North of Highway 24, the Lafayette fault is associated with multiple strongly pronounced or distinct tonal lineaments, vegetation alignments, and linear drainages within Briones Regional Park (Plate 1). These features continue across Springhill Canyon, and, near the upper end of Reliez Valley, the Lafayette and Reliez Valley faults appear to merge. These faults together are expressed as a series of saddles, side-hill benches, and linear drainages along the strongly dissected, high-relief eastern flank of the Briones hills. The northernmost part of the combined Lafayette-Reliez Valley fault is associated with a series of prominent closed depressions within an apparent local right-stepover in the fault zone ("Maricich Lagoon Site", Plate 1). These closed depressions are described in detail in Section 5.2.

We identify two areas where geomorphic features suggest the presence of more westerly striking reverse faults branching away from the Lafayette fault. One is a linear valley margin on the southern side of the Las Trampas Creek valley, directly north of Burton Valley, along St Mary's Road (Plate 1). Crane (1988) maps an unnamed reverse fault along this valley margin, which has linear hill fronts and truncated spur ridges that may be fault related. Las Trampas Creek valley also contains several northwest-trending tonal lineaments across Holocene valley-floor alluvium, particularly in the area now occupied by Stanley School (Plate 1). Second, in the area directly north of the Lafayette Ridge Site, Crane (1988) maps a reverse fault within Springhill Canyon, which branches to the northwest from Reliez Valley (Plate 1). The southern margin of Springhill Canyon is linear and merges with other possible fault-related features along the Lafayette fault (vegetation alignments, saddles, benches). In addition, the lineaments within Springhill Canyon coincide with distinct differences in bedrock orientation on both sides of the canyon, as shown by northerly strikes on the northern side of the canyon and westerly strikes on the southern side (Plate 1; Crane, 1988). If the features in Springhill Canyon and in Las Trampas Creek valley near Stanley School are fault related, we speculate that they may represent some component of slip transferring from the Lafayette fault the over to the Russell Peak lineament (described in Section 3.3.14, below).

The Reliez Valley fault extends from the vicinity of Las Trampas Creek in western Walnut Creek to about the Maricich Lagoons in Briones Regional Park, for a total length of about 8 km (5 mi) (Plate 1). As identified by Dibblee (1980) and Crane (1988), the N15°W-striking fault has predominantly dextral strike slip, displaces sandstone beds within the San Pablo Group, and merges with the Lafayette fault at its northern end. As described in Section 3.3.9 above, the southern end of the fault may merge with possible faults along the margins of Tice Valley (Plate 1).

The Reliez Valley fault is associated with prominent fault-related geomorphic features. Reliez Valley itself is a linear, S15°E-trending valley that cuts across the structural grain of the region, and has a broad, gently sloping alluviated floor and linear valley margins. Although these linear margins may be a result of fluvial erosion or lithologic control, the lack of any sinuous sections along the valley margins suggests a tectonic, rather than fluvial, origin for the valley. The prominent lineaments along both valley margins suggest that this valley may be a linear tectonic pull-apart basin within the dextral fault zone. North of Springhill Canyon (and Pleasant Hill Road), Reliez Valley is slightly narrower and both valley margins have linear sections as much as 1 km long. Also, upper Reliez Valley (upstream of Springhill Canyon) is broad (more than 250 m wide), alleviated, and does not contain an active stream channel. These relations suggest that the upper Reliez Valley is an "underfit" valley, and is at least partially tectonic in origin. Northwest of the alluviated part of upper Reliez Valley, the Reliez Valley fault is associated with multiple strongly pronounced to distinct geomorphic features, including saddles, side-hill benches, tonal and vegetation lineaments, and linear drainages (Plate 1). These features continue along the strongly dissected, high-relief eastern flank of the Briones hills domain.

The Cull Canyon fault is mapped by Crane (1988) as a north-northwest-striking fault, the trace of which is on trend with the southern end of the Lafayette fault. The Cull Canyon fault forms the western structural boundary of Bollinger ridge, and is mapped by Crane (1988) along the linear, north-northwest-trending valley of Cull Creek south of the Lafayette fault. The axis of the Kaiser Creek syncline and several short west-northwest-trending folds on trend with the Knife anticline terminate westward against the Cull Canyon fault. Clear evidence of dextral offset of stratigraphic units is not apparent on existing geologic maps of this region (i.e., Crane, 1988; Dibblee, 1980); however, the northwest-trending unconformity between the Neogene Livermore basin strata and Cretaceous Great Valley Group strata may be dragged or sheared about 2 km in a dextral sense near the southern end of the fault. Total length of the Cull Canyon fault is about 14 km.

Our air-photo analysis addressed only the northernmost part of this fault in the area between Las Trampas Creek (upstream of St. Mary's College) and the headwaters of Cull Creek. This area contains multiple discontinuous, distinct to weakly pronounced north-trending lineaments, including linear drainages, saddles and tonal lineaments within a zone about 1 km wide (Plate 1). The northerly strike of bedrock strata within this zone, where perceptible from aerial photography, differs from the prominent northwest-striking bedrock strata east and west of the zone. Also, as noted above, regional topography is generally higher in the area east of the Cull Canyon fault than west of the fault.

3.3.12 Briones Hills

The Briones hills is an area of locally high topography that stands several hundred feet above adjacent regions. The hills are bordered on the east by the Lafayette-Reliez Valley fault zone, and some of the highest summit elevations in this region are directly associated with the northern termination of these faults.

In addition to relatively high topography, the Briones hills is an area of relatively high structural relief in the northern East Bay hills (Figure 7). The Reesley anticline and Rodeo syncline are two major folds that trend through the Briones hills, and the Monterey Group strata are exposed across both structures. In contrast, major folds directly southwest of the Briones hills expose much shallower parts of the Neogene section. The different levels of stratigraphic exposure indicate about 1-3 km of positive structural relief in the Briones hills relative to areas directly southwest.

3.3.13 Franklin and Southhampton Faults

3.3.13.1 Bedrock Map Relations

As mapped by Crane (1988; 1995), the NNW-SSE- to NW-SE-striking Franklin and Southhampton faults form the boundaries of the "Franklin High" structural block (Crane, 1995). The Franklin fault is the southwestern structural margin of this block, and it juxtaposes older rocks on the northeast (Cretaceous and Eocene marine strata) against Miocene strata of the Monterey and San Pablo Groups to the southwest. Crane (1995) shows the Franklin fault to be a northeast-dipping thrust or reverse fault. The Southhampton fault is the northeastern structural boundary of the "Franklin High", and is mapped by Crane (1995) as a southwest-dipping thrust fault.

Patterns of folding and regional variations in depth of stratigraphic exposure indicate that the Franklin High is a significant structural culmination in the northern East Bay hills. Moving from the Mullholland syncline northeast towards the Briones hills, progressively deeper parts of the Neogene section are exposed in the cores of synclines (Figure 7). The basal San Pablo group contact is present in the Rodeo syncline and Pacheco syncline on opposite sides of the Franklin

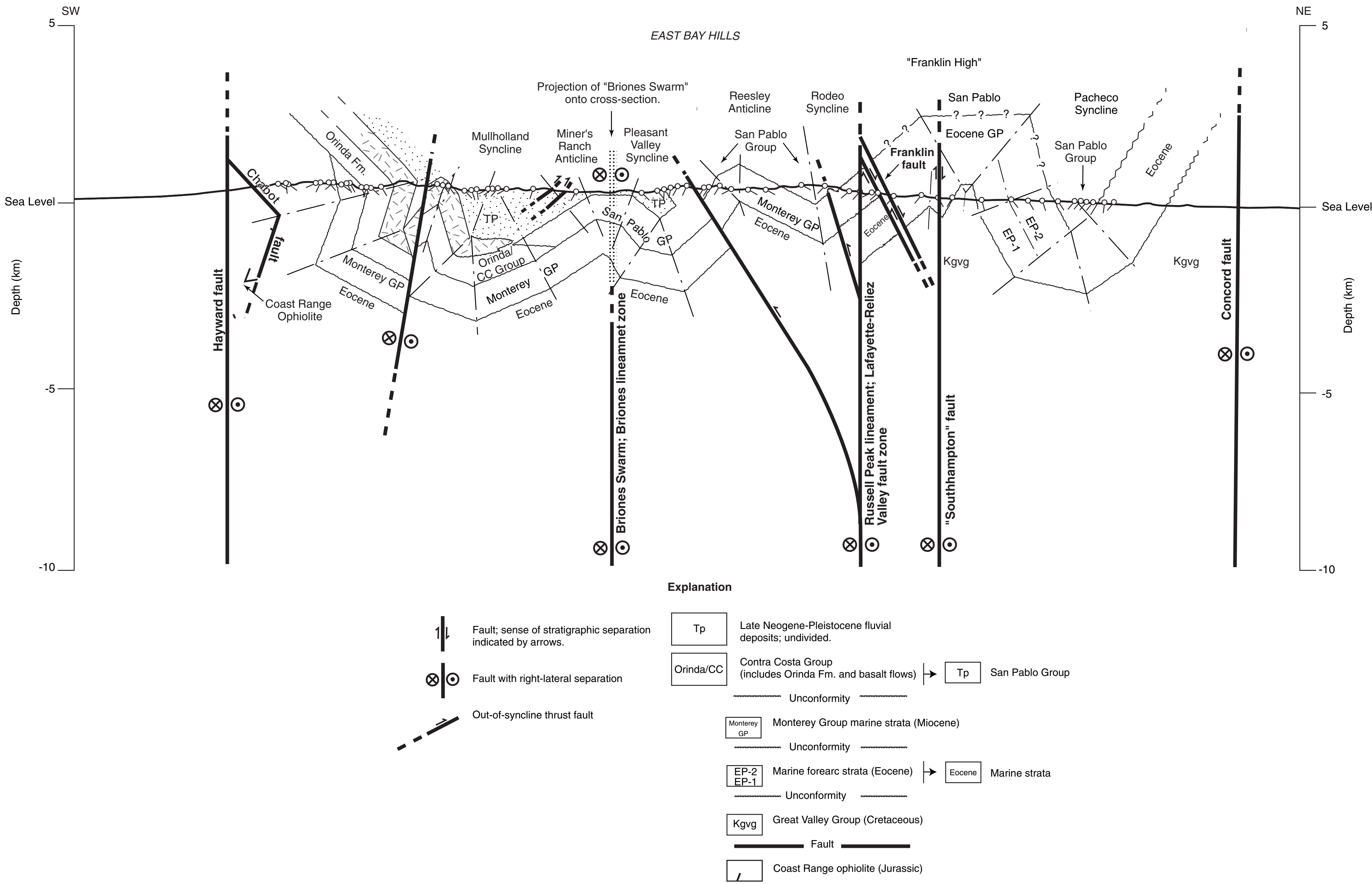

Figure 7. NE-SW cross-section through the northern East Bay hills.

High. The basal San Pablo contact can be projected from the limbs of these synclines over the axis of the Franklin High, parallel to bedding dips in the folded Cretaceous rocks in the axis of the structure (Figure 7). If this interpretation is correct, then the Franklin high is a late Cenozoic anticlinorium with a total of about 4.5 km of structural relief on the basal San Pablo contact relative to the Mullholland syncline.

The role of the Franklin and Southhampton faults in the development of the Franklin High antiformal culmination is poorly understood. For example, San Pablo strata overlie Monterey Group strata in the Rodeo syncline on the southern margin of the Franklin High, but overlie Eocene strata in the Pacheco syncline north of the Franklin High. These relations indicate that the Monterey Group strata are missing over the axis of the Franklin High anticlinorium. It is possible that structural relief on Eocene and Cretaceous rocks in the Franklin high is greater than on the San Pablo Group; thus, the Franklin and/or Southhampton faults may have a history of movement prior to deposition of the San Pablo group in late Miocene time that elevated the block between them relative to surrounding regions. Also, there are inconsistencies between the mapping and interpretation of the faults (particularly the Southhampton fault) that suggest these structures are incorrectly mapped, or may have a more complex history than previously inferred. These inconsistencies are described in detail as follows.

The southern reach of the Southhampton fault is mapped along the northeastern margin of Acalanes Ridge in western Walnut Creek and western Pleasant Hill. The Southhampton fault juxtaposes Eocene strata on the northeast against Miocene Monterey Group strata to the southwest, implying relative northeast-side-up movement. However, Crane (1988; Walnut Creek 7.5' quadrangle) shows the fault dipping to the southwest, which implies that the footwall is up relative to the hanging wall. The stratigraphic separation on the fault is inconsistent with the interpretation of the fault as a southwest-dipping thrust.

North of Acalanes Ridge, the Southhampton fault is mapped along the western edge of an unnamed stream that drains southeast into Diablo Valley at Pleasant Hill. According to Crane (1988), the fault lies within the Eocene Martinez Formation. Although there is no significant stratigraphic separation along the fault formally mapped as the "Southhampton" in this reach, Crane (1988) shows a subsidiary or secondary splay several hundred meters to the west that dips northeast and juxtaposes Martinez Formation on the northeast against Monterey Group strata to the southwest. Moving northwest along strike, the fault mapped as the Southhampton and secondary trace rejoin. Directly northwest of this point, the Franklin fault is mapped by Crane (1988) as branching west-northwest from the Southhampton fault.

As mapped by Crane (1988), the reach of the Southhampton fault directly north of the branch point with the Franklin fault is a southwest-dipping thrust or reverse fault. Both the hanging wall and footwall blocks are Eocene Martinez Formation, indicating no significant stratigraphic separation. Several kilometers north of the branch point, the fault juxtaposes Martinez Formation on the southwest against Cretaceous rocks to the northeast. Here again the stratigraphic separation is opposite the expected sense of slip for a southwest-dipping thrust fault. Farther north the fault is entirely in Cretaceous rocks, and net stratigraphic separation cannot be discerned.

3.3.13.2 Lineaments Associated with the Map Traces of the Franklin and Southhampton Faults

Weakly pronounced geomorphic features are present along many parts of the mapped traces of the Franklin and Southhampton faults, but strongly pronounced to distinct lineaments occur within four north-northwest-trending zones. These zones contain numerous linear drainages, linear troughs, truncated bedding, saddles, springs, and vegetation alignments, and appear to represent north-northwest-trending strike-slip shear zones that are oblique to the general northwest strike of the Franklin and Southhampton faults. We informally refer to these zones as the Ozol, McEwen Road, Dillon Point, and Columbus Parkway lineament zones (Figure 1; Plate 1).

The Ozol lineament zone is relatively short (1.2 km), and extends from an unnamed tributary valley on the south to the Carquinez Strait on the north (Figure 1). This north-northwest-trending zone of lineaments includes tonal lineaments, linear drainage sections, and a topographic saddle, and is associated with truncated cretaceous strata. The zone lies along the northwest-trending Southhampton fault as mapped by Crane (1995), although the Ozol lineament zone as identified herein lies along a NNW-striking section of the Southhampton fault. We interpret that the Ozol lineament zone may represent a small, right displacement of the

Southhampton fault. The Ozol lineament zone is parallel to, and about 1.5 km east of, the McEwen Road lineament zone (see below).

The McEwen Road lineament zone is about 5 km long, and extends from the Franklin fault near the ATSF railroad tunnel on the south, to the Southhampton fault near the village of Port Costa on the north (Figure 1). This zone consists of multiple strongly pronounced to distinct linear drainages, saddles, topographic scarps and tonal lineaments within a zone about 0.5 km wide. The alignment of these features in bedrock terrane dominated by northwest-striking resistant bedding strongly suggests that the lineaments represent displacement along a north-trending fault zone. The zone includes a prominent, east-facing topographic scarp directly south of McEwen Road, about 1 km north of Highway 4. This scarp lies within a zone of linear drainages, linear troughs, and tonal lineaments that appear to be associated with truncated sandstone strata. The geomorphic pattern of this lineament zone is comparable to that of the Briones lineament zone (Section 3.3.15), but slightly less continuous and less well expressed.

The Dillon Point and Columbus Parkway lineament zones are located on the northern side of the Carquinez Strait, and are at least 4 km long (Figure 1). The Dillon Point lineament is identified primarily as the linear, north-trending western margin of Southhampton Bay, and extends from the Carquinez Strait on the south to perhaps the intersection of Springs Road and Columbus Parkway on the north, in the town of Vallejo (Figure 1). The Columbus Parkway lineament zone is identified informally herein as the eastern margin of Southhampton Bay, which trends more westerly than the western margin and intersects the Dillon Point lineament about 0.5 km north of Highway 780 (Figure 1). Both lineaments coincide with dextral faults mapped by Crane (1995). Bathymetric and shallow borehole data from within Southhampton Bay show the presence of a prominent, east-facing escarpment along the Dillon Point lineament (C. Hitchcock, WLA, personal communication, 2002). We do not know the northern extent of the Dillon Point-Columbus Parkway lineament because they extend beyond the limits of this study area. On the south, we suspect that the Dillon Point lineament zone may merge with the McEwen Road lineament zone, forming a zone at least 10 km long. Similarly, we suspect that the Columbus Parkway lineament zone projects to the south and may merge with the Ozol lineament zone, forming a zone also at least 10 km long.

3.3.13.3 Interpretation of the Franklin and Southhampton Faults

We interpret that the north-northwest trending lineament zones described in the previous section are associated with short, potentially active dextral strike-slip faults. The faults appear to coincide with northerly striking sections of the Franklin or Southhampton faults, although the lineament zones extend to the north and south beyond the mapped traces of these structures. An interpretation that is consistent with these relations, and generally consistent with mapping by Crane (1988) and Graymer et al. (1994), is that the northwest-striking Franklin and Southhampton faults are displaced in a right-lateral sense along north-trending strike-slip fault zones associated with the lineaments. The Franklin and Southhampton faults may be pre-existing, northwest-striking Tertiary structures that have been deformed by late Cenozoic NNW strike-slip displacement, or they may be have formed entirely in the late Cenozoic as complex zones consisting of alternating reaches of strike-slip and reverse faulting.

3.3.14 Russell Peak Lineament Zone

The Russell Peak lineament zone is about 6.5 km (4 mi) long, and extends from Happy Valley on the south to Alhambra Valley on the north (Figure 1, Plate 1). This zone coincides with an unnamed, 8-km-long fault mapped by Graymer et al (1994) that has dextral offset of Neogene strata west of the Lafayette fault. This north-trending zone consists of several clusters of north-trending, discontinous tonal lineaments, linear drainages, saddles, and vegetation lineaments. On both sides of the zone, resistant bedding of the San Pablo Group form prominent, west-northwest-trending ridges. Within the lineament zone, however, this regional, lithologically controlled topographic grain is disrupted. Field reconnaissance confirmed that the lineaments are coincident with a broad, 0.5-km-wide zone of shearing and deformation within bedrock units in the area between the Maricich Lagoons and Bear Creek (Plate 1). Locally, small offsets in ridgetops are present and appear to be related to fault displacement, although our field reconnaissance did not confirm all of these detailed geologic relations. Near Maricich Lagoons, the lineament zone appears to merge with the Lafayette-Reliez Valley fault system, and continue northward within the steep, linear, narrow Toyon Canyon toward Alhambra Valley (Plate 1). Directly north of Alhambra Valley, we interpret that the Russell Peak lineament zone intersects or merges with the northwest-striking Franklin fault (Crane, 1988, Graymer et al., 1994).

3.3.15 Briones Lineament Zone

The Briones lineament zone is about 8 km (5 mi) long, and extends from Bear Creek Valley on the south to the ATSF railroad tunnel on the north (Figure 1, Plate 1). This zone is about 0.5 to 1.0 km wide, and is about 2 km west of and parallel to the Russell Peak lineament zone. Its northern projection is close to, if not coincident, with the southern end of the McEwen Road lineament zone (Figure 1). The Briones lineament zone is similar to the Russell Peak zone, as it also contains several clusters of north-trending, discontinous tonal lineaments, linear drainages, saddles, and vegetation lineaments. In the vicinity of Bear Creek, the zone is associated with a mapped fault that offsets stratigraphic contacts in a dextral sense (Wagner, 1978; Graymer et al. 1994). Our field reconnaissance within the zone directly north of Bear Creek did not identify any specific exposures or field evidence of late Quaternary fault displacement. The northern end of the Briones lineament zone merges with the northwest-striking Franklin fault (Graymer et al, 1994; Crane, 1988), particularly in the vicinity of the ATSF railroad tunnel directly west of Franklin Canyon (Plate 1). Our analysis of aerial photography identifies several lineaments in a broad, 0.5-km-wide zone encompassing the mapped trace of the Franklin fault.

The Briones lineament zone is spatially associated with the "Briones swarm", a north-northwest-trending zone of earthquakes with strike-slip focal mechanisms (Oppenheimer and Macgregor-Scott, 1992). As described previously, epicenters of this swarm occurred in a linear, north-trending zone between Bear Creek and Happy Valley, directly south of and along the southerly projection of the Briones lineament zone. Our relocation of the hypocenters from this swarm shows that, in cross-section, the earthquakes form a north-northwest-striking planar alignment in the 6 to 11 km depth range.

4.0
INTERPRETATION

The northern Calaveras fault ends as a well-defined geomorphic feature at the latitude of Danville, although the fault may continue as far north as Alamo (Dibblee, 1980; Hart, 1981; Simpson et al., 1992; Kelson, 2002). The northern termination of the Calaveras fault coincides with the southern end of the Las Trampas anticline (Ham, 1952), a northeast-vergent fold associated with the Las Trampas and Bollinger faults (Figure 1). We interpret the Las Trampas anticline to be a fault-propagation fold underlain by a blind, southwest-dipping thrust fault (Figure 5). The anticline and inferred underlying thrust fault terminate to the northwest against the north-northwest-striking Lafayette and Reliez Valley faults, which displace stratigraphic contacts several kilometers in a dextral sense (Figure 2).

The area between the northern end of the Calaveras fault in Danville and the Lafayette-Reliez Valley fault system is a local topographic high with summit elevations that are several hundred feet higher than surrounding regions. For convenience, we refer to this area as the "Las Trampas domain" (Figure 8). This area is dominated by two northwest-trending ridges (i.e., "Rocky Ridge" and "Las Trampas Ridge"), which are spatially associated with the Bollinger fault and Las Trampas anticline (Figure 1). Las Trampas Peak (elevation 1827 ft, 557 m) and Rock 2 peak (elevation 2024 ft, 617 m) are the topographic culminations of these topographically high ridges, which terminate against the Lafayette-Reliez Valley fault system near the southern ends of Tice Valley and Burton Valley (Figure 1). Analysis of the Digital Elevation Model (DEM) of this domain indicates that elevations range from 355 to 2027 ft, with a mean elevation of 1046 ft (Figure 9). We interpret that the Las Trampas anticline and associated blind thrust faults transfer slip from the northern Calaveras fault to the Lafayette-Reliez Valley fault system (Figure 3). The associated high topography of the Las Trampas domain is a reflection of localized uplift and folding across the restraining stepover between the strike-slip faults (Figure 1).

The combined Lafayette-Reliez Valley fault system extends for a length of about 13 km north of the Las Trampas anticline and terminates in Briones Regional Park, about 4 km east of Walnut

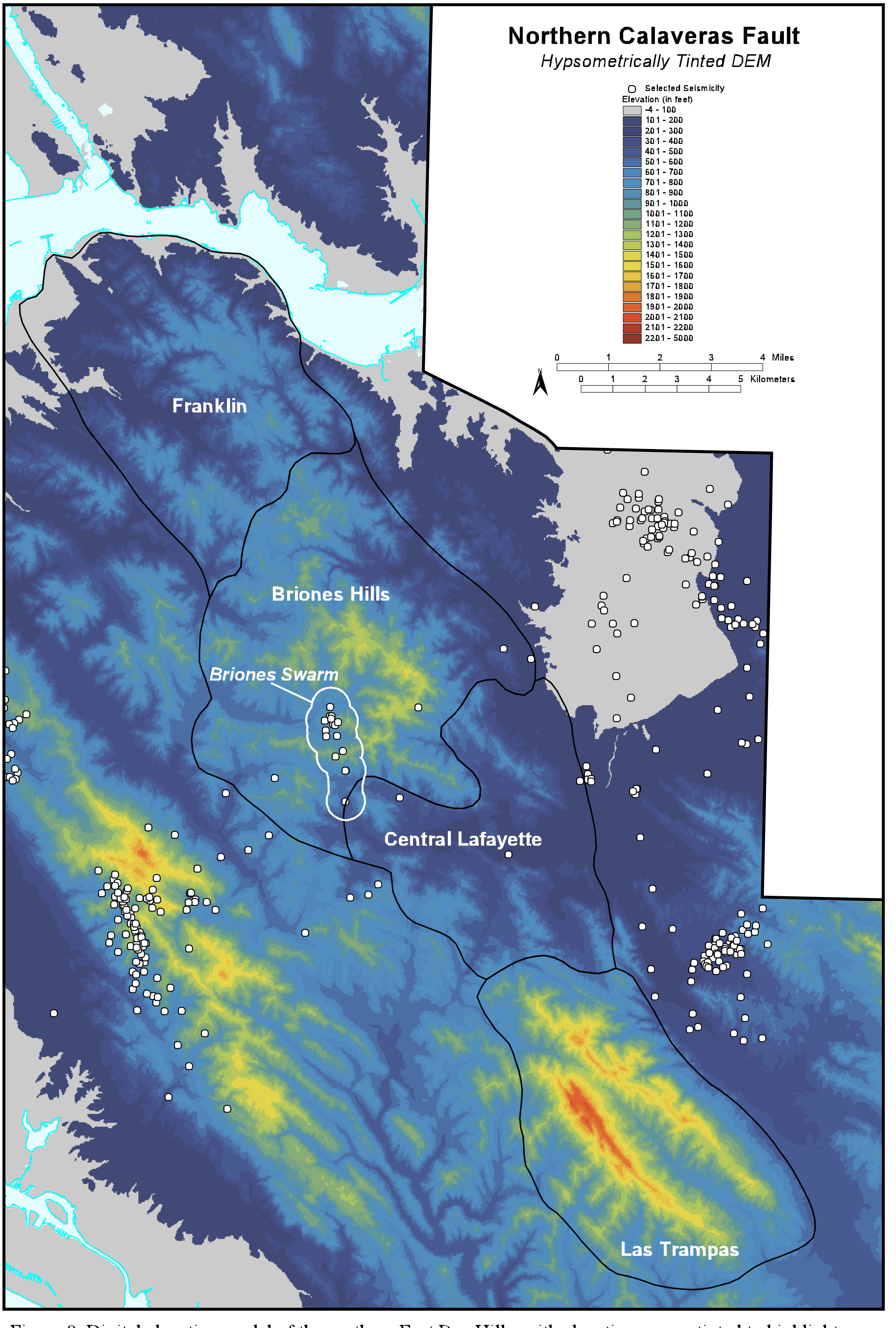

Figure 8. Digital elevation model of the northern East Bay Hills, with elevation ranges tinted to highlight areas of relatively high topography. Four physiographic domains within the study area (Franklin, Briones Hills, Central Lafayette, and Las Trampas) are discussed in text.

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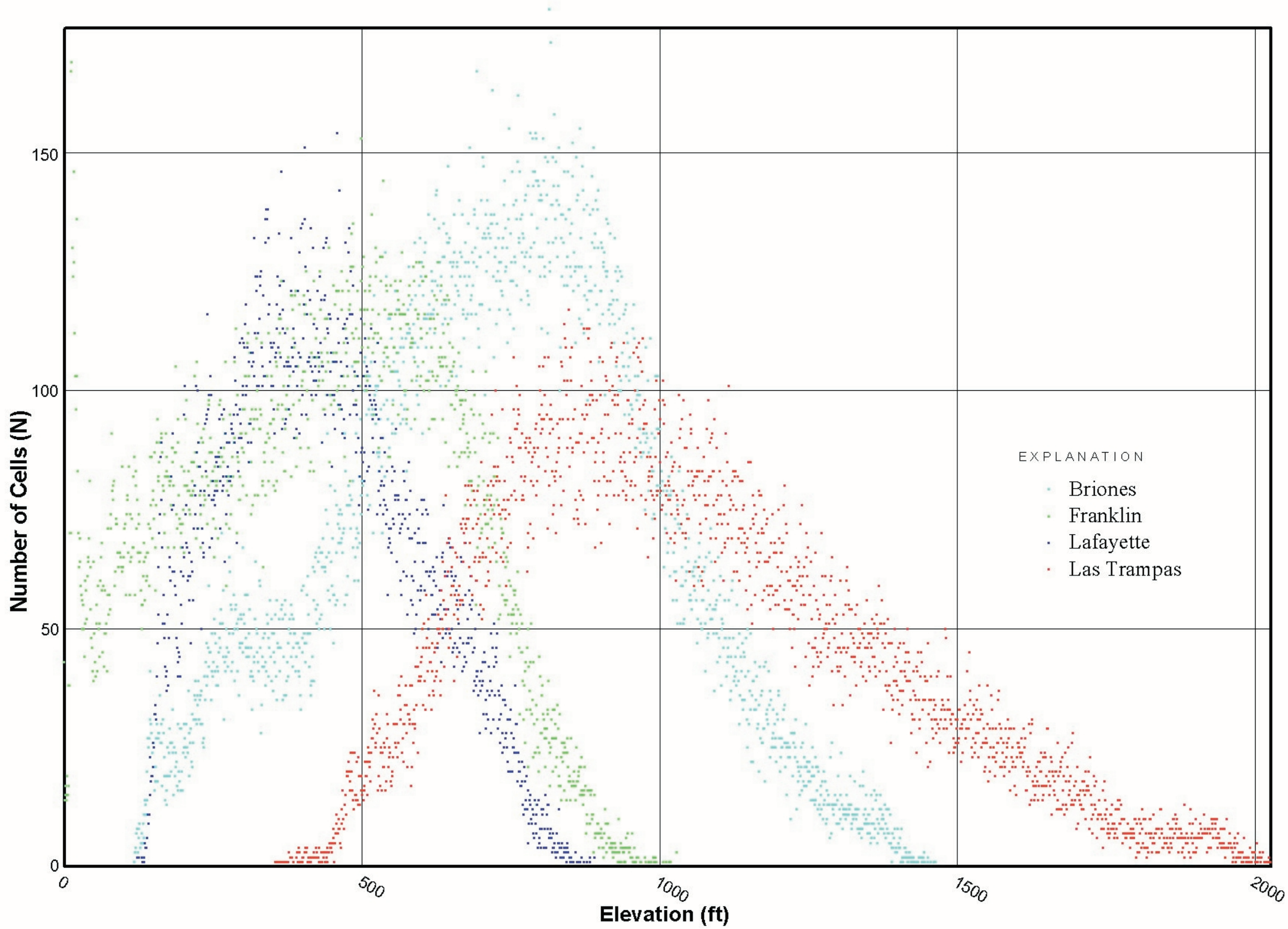

Figure 9. Histogram of the Briones, Franklin, Lafayette, and Las Trampas areas shown in Figure 8.

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Creek (Figure 1). The area traversed by the Lafayette-Reliez Valley fault system directly north of the Las Trampas domain is characterized by relatively low relief. We refer to this area, which includes Tice Valley, Burton Valley, central Lafayette, and Reliez Valley, as the Central Lafayette domain (Figure 8). This topographically low domain is drained by Las Trampas Creek and its major tributaries (e.g., Grizzly Creek, Tice Creek, Reliez Valley Creek), which flow in relatively broad, gently sloping alluviated valleys. In general, Las Trampas Creek flows easterly, across the overall northwest-trending geologic structure; whereas its major tributaries flow either northerly or southerly, oblique to the geologic fabric. This area of relatively moderate relief has ridge tops less than about 900 ft (274 m) in elevation, which are substantially lower than the areas directly to the south and north. Analysis of the DEM of this domain indicates that elevations range from 123 to 891 ft, with a mean elevation of 432 ft (Figure 9). We interpret the Central Lafayette domain to be dominated by dextral strike slip along the Lafayette and Reliez Valley faults, and possibly along the Larkey lineament zone. We speculate that Tice Valley, Burton Valley, and the southern part of Happy Valley may be local pull-apart basins along the strike slip faults. Lateral slip on these faults has resulted in the creation of multiple north-trending, linear alleviated valleys and, collectively has resulted in the low topography of the Central Lafayette domain, relative to the adjacent Las Trampas and Briones hills domains.

The northern end of the Lafayette-Reliez Valley fault system is the eastern structural boundary of the Briones hills, an area that stands several hundred feet above the Central Lafayette domain and surrounding regions. We refer to this area of local high topography as the Briones hills domain (Figure 8). This domain includes Lafayette Ridge and most of Briones Regional Park and contains several high peaks, including Russell Peak (1357 ft, 357 m), Briones Peak (1483 ft, 452 m), and several other unnamed peaks above 1400 ft (427 m). Valleys in this area are narrow and deeply incised, and generally contain bedrock-floored stream channels flanked by thin terrace or alluvial-fan deposits. Our analysis of the DEM of this domain indicates that elevations range from 261 to 1464 ft, with a mean elevation of 805 ft (Figure 9).

We interpret the Briones hills domain to be a zone of shortening at the northern termination of the Lafayette-Reliez Valley fault system (Figure 1). The Briones hills geomorphic domain and associated structural culmination are traversed by the north-northwest-trending Russell Peak and Briones lineament zones as defined herein. Slip is transferred from the Lafayette and Reliez Valley faults westward to the Briones lineament zone. We interpret the intervening restraining stepover region to be a positive flower structure (Figure 7). The Briones and related lineament zones contain numerous linear drainages, linear troughs, truncated bedding, saddles, springs, and vegetation alignments, and appear to represent north-northwest-trending strike-slip shear zones. These zones are associated with mapped faults that offset stratigraphic contacts in a dextral sense (Wagner, 1978; Crane, 1988; Graymer, 1994). The Briones lineament zone is associated with the “Briones swarm”, a group of earthquakes that define a seismogenic strike-slip fault (Oppenheimer and Macgregor-Scott, 1992). We interpret these data as evidence that the north-northwest trending lineament zones are associated with short, locally seismogenic, and potentially active strike-slip faults.

We informally refer to the area north of the Briones hills domain as the Franklin domain (Figure 8). The primary topographic high in this domain is the northwest-trending Franklin Ridge. Valleys in this area are narrow and deeply incised, and generally contain bedrock-floored stream channels flanked by thin terrace or alluvial-fan deposits. The northern border of this domain is the Carquinez Strait, at sea level. Our analysis of the DEM of this domain indicates that elevations range from 0 to 1029 ft, with a mean elevation of 425 ft (Figure 9). This domain is traversed by the northwest-striking Franklin fault and the north-trending McEwen Road and Ozol lineament zones, and is bordered on the northeast by the Southhampton fault.

We interpret that a significant proportion of present-day slip on the northern Calaveras fault is consumed by distributed strike-slip faulting and crustal shortening in the East Bay hills north of the Las Trampas domain. Potentially active strike-slip faults include the Lafayette and Reliez Valley faults, as well as short, unnamed strike-slip faults associated with the Columbus Parkway-Ozol lineament zone, the Dillon Point-McEwen Road lineament zone, the Russell Peak lineament zone, and the Larkey lineament zone (see Figure 1).

We generalize the interpreted tectonic pattern in the northern East Bay hills as a series of reverse faults and related folds traversed by several moderate length (5 to 10 km long) dextral slip faults

(Figure 10). This generalized pattern explains the observed geologic and geomorphic features in the area, resolves several problems noted by previous workers, including numerous reversals in fault dip and fold vergence in the Briones hills (see discussion in Section 3.3.13). We interpret that slip on the northern Calaveras fault is accommodated through complex deformation along strike-slip faults, reverse faults, blind faults, and folds comprising the northern East Bay hills. Strain, therefore, may be distributed throughout the hills, rather than concentrated on any specific structure. Collectively, however, the suite of structures may accommodate all or most of the 4 to 7 mm/yr of slip on the northern Calaveras fault.

This tectonic model also provides an explanation for the complex map patterns of the Franklin and Southhampton faults (Section 3.3.13). Both of these faults have alternating reaches that strike northwest and north-northwest (NNW). Several of the NNW-striking reaches are coincident or generally associated with NNW-trending lineament zones that we interpret to be strike-slip faults. For example, the NNW-striking reach of the Southhampton fault north of Alhambra Valley (Briones Valley 7.5' quadrangle; Crane, 1988) is parallel to a northwest-trending lineament (Plate 1), and bedrock map relations suggest that the unconformable contact between the Eocene Martinez Formation and Cretaceous Great Valley Group is offset about 800 meters in a dextral sense (this is not a unique interpretation of the map relations, however). Similarly, a NNW-striking reach of the Franklin fault along the western border of Franklin Ridge is parallel to and generally coincident with NNW-trending lineaments of the Briones lineament zone. We favor the interpretation that the Franklin and Southhampton faults were pre-existing, northwest-striking faults that have been sheared and offset in a dextral sense by movement on NNW-striking faults represented by the Briones, Russell Peak and related lineament zones.

The structural linkages between strike-slip faults and folds outlined above is typical of restraining strike-slip duplexes (Twiss and Moores, 1992). In particular, the Las Trampas anticline and related structures in the left step between the northern Calaveras and Cull Canyon-Lafayette-Reliez Valley fault system are similar to those created in scaled analog sandbox models of restraining stepovers (Bonora and McClay, 2001). Elements of the braided duplex pattern in the East Bay hills north of the Las Trampas domain (Figure 10) are replicated by sandbox models of distributed transpression where slip is not confined to principal displacement

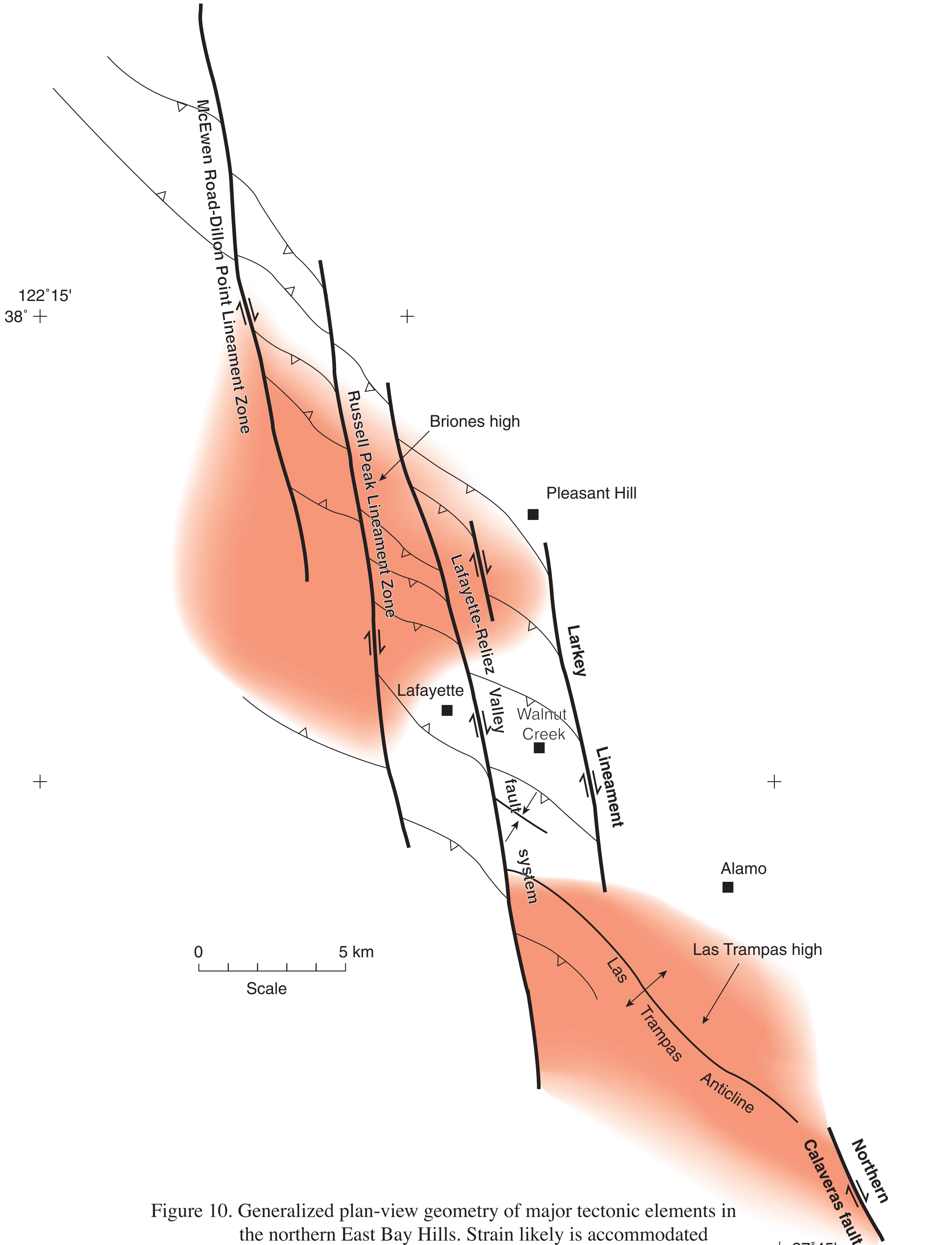

Figure 10. Generalized plan-view geometry of major tectonic elements in the northern East Bay Hills. Strain likely is accommodated through complex deformation along strike-slip faulting, reverse faulting, and folding in a series of strike-slip duplexes.

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zones and discrete stepovers at the base of the model (Schreurs and Colletta, 1998). The sandbox models provide insights into the possible down-dip geometry of blind thrust faults and their relationship to strike-slip faults at depth. The strike-slip and thrust faults typically branch upward from common displacement zones at the base of the models (Bonora and McClay, 2001). If the models accurately mimic natural structures, then for example we would expect the blind thrust faults beneath the Knife anticline and Las Trampas anticline to dip southwest and intersect the base of the brittle crust at the downdip termination of the Cull Canyon-Lafayette-Reliez Valley fault zone.

Based on its mapped length and apparent structural continuity, the Las Trampas anticline may be underlain by a 12-km-long blind thrust fault. We interpret the locally high mean elevation of the Las Trampas geomorphic domain (Figures 8 and 9) as evidence for the presence of this fault, as well as for late Cenozoic activity. If it is assumed that an earthquake on the fault will have a minimum 1:1 rupture aspect ratio, then the blind Las Trampas thrust fault may be capable of generating a maximum M_w 6.2 earthquake (per empirical relations in Wells and Coppersmith, 1994). In contrast, folds and thrust faults north of the Las Trampas domain appear to be shorter in length. In general, the northern East Bay hills appear to be characterized by a series of strike-slip faults bordering narrow (1- to 3-km-wide) blocks that are internally deformed by reverse faulting and northeast- and southwest-vergent folding (e.g., Figure 7). We expect that blind thrust faults associated with these narrow blocks are unlikely to be sources of M6 (or larger) earthquakes, but may be sources of smaller “background” earthquakes. Because restraining transfer of slip north of the Las Trampas domain is distributed across smaller stepovers there is correspondingly less localized shortening, consistent with the lower mean elevation of the Briones hills domain relative to the Las Trampas domain (Figure 9).

Several major fold structures in the northern East Bay hills appear to be sheared and offset by northwest-striking dextral faults and lineament zones. For example, the northwest-trending axes of the Rodeo anticline, Rodeo syncline and Reesley anticline rotate to a NNW trend as they cross the Briones lineament zone, then resume a northwest trend in the block between the Briones and Russell Peak lineament zones. If it is assumed that at least some of the folds predate shearing along the dextral lineament zones, then deflection or offset of the fold axes can be used to evaluate distributed dextral shear north in the interior of the East Bay hills north of the Calaveras fault. Correlation of several different structures and stratigraphic contacts across NNW-striking faults and lineaments in the northern East Bay hills supports the interpretation, illustrated in Figure 2, that about 5 km of dextral shear has been accommodated by the Reliez Valley-Lafayette fault zone and related structures:

- The Rodeo syncline axis can be traced confidently across the Briones lineament zone, Russell Peak lineament zone and the Lafayette-Reliez Valley fault due to the distinctive stratigraphic sequence exposed in the limbs of the fold. We estimate total right lateral offset of the syncline axis to be about 4.6 km.

- A distinctive unconformable contact between the Briones Formation (San Pablo Group) and Rodeo shale (Monterey Group) is exposed in the southwest limb of the Rodeo syncline. The contact is dextrally offset about 3 km across the Briones lineament zone and about 2 km across the Reliez Valley-Lafayette fault zone, for a total of about 5 km.

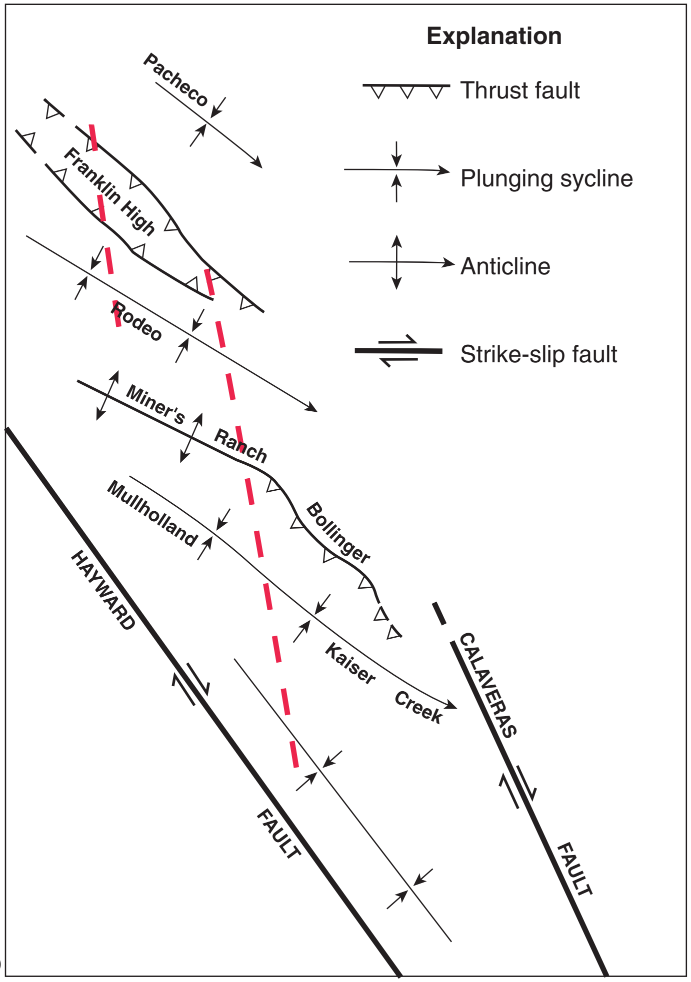
- Similarly, the contact between the Briones and Cierbo Formations, also exposed in the southwest limb of the Rodeo syncline, is dextrally offset about 2.5 km across the Briones lineament zone and about 2.5 km across the Reliez Valley-Lafayette fault zone, for a total of about 5 km.

- Farther south, the unconformable contact between undivided “Pliocene strata” (Unit Tp of Crane, 1988) and the Neroly Formation is exposed in the southwest-dipping section in the northern limb of the Pleasant Valley syncline, west of the Cull Canyon fault. The Tp/Neroly contact also is exposed in a southwest-dipping section on the northern side of Bollinger canyon, east of the Cull Canyon fault. If these contacts (and associated stratigraphic sections) are correlative, then the right-lateral separation across the Cull Canyon fault is about 5.2 km. An alternative correlation east of the Cull Canyon fault is with the Tp/Neroly contact in the southwest-dipping stratigraphic section west of Tice Valley, which yields a significantly lower estimate of about 2 km of right-lateral separation. We do not favor this correlation because the thickness of the Tp section in Tice Valley is much less than that in Pleasant Valley, indicating that two the stratigraphic sections probably are not the same.

We propose a two-stage model to account for the total 12 to 16 km of late Cenozoic dextral offset on the northern Calaveras fault (Figure 11). In Stage 1, slip on the northern Calaveras fault was consumed by formation of a fold-thrust belt in the northern East Bay hills. The folds had a right-stepping, en echelon geometry, typical of dextral wrench folds and similar to the pattern of structures in the Mt. Diablo fold-and-thrust belt to the east (Unruh and Sawyer, 1997). We infer that the Cull Canyon-Lafayette-Reliez Valley system of dextral faults had not yet formed during Stage 1. By restoring 5 km of slip dextral slip on this system (Figure 11a), we interpret that: (1) the Mullholland and Kaiser Creek synclines were originally continuous; (2) the Bollinger thrust fault and Miner's Range anticline were once part of a contiguous structural culmination; (3) the Rodeo syncline originally had a linear, northwest-trending axis; and (4) the 'Franklin High" had a simple NW trend uninterrupted by NNW-trending reaches. Based on line-length restoration of stratigraphic contacts in Figure 7, total NE-SW shortening accommodated by these structures is about 8 to 10 km. Resolved parallel to the NNW strike of the northern Calaveras fault, 8 to 10 km of shortening is equivalent to about 6 to 8 kilometers of dextral shear.

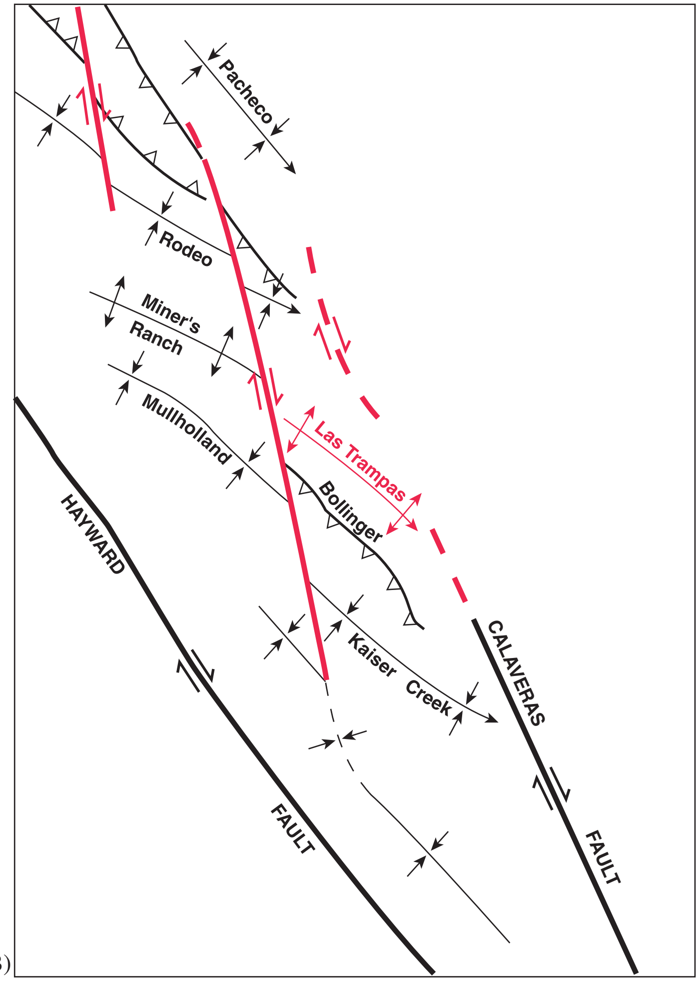
In Stage 2 (Figure 11b), these structures are systematically cut and dextrally offset by NNW-striking faults, including the Cull Canyon-Lafayette-Reliez Valley system and lineament zones in the northern East Bay hills. Total dextral displacement of the pre-existing folds and thrust faults during Stage 2 is about 5 km. We thus estimate total northern Calaveras fault slip absorbed by late Cenozoic deformation in the East Bay hills during Stage 1 and Stage 2 to be about 11 to 13 km, which is within the 12 to 16 km range of total slip discussed in Section 2.2.

This two-stage kinematic model for the East Bay hills is consistent with progressive development of transpressional structures in analog sandbox experiments. McClay and Bonora (2001) found that folds, thrust faults and pop-up blocks tend to develop first, followed at higher strains by strike-slip faults (i.e., "trans pop-up cross fault systems") that cross-cut and displace some of the early formed structures. The strike-slip faults comprise the primarily kinematic linkage between the principal displacement zones at the base of the models, and apparently represent a mature stage in the development of restraining stepovers (McClay and Bonora, 2001).



A)

Stage 1: Development of right-stepping, en echelon folds and thrust faults. Shortening consumes about 7 to 10 km of slip on the Calaveras fault.



B)

Stage 2: Fold-thrust structures sheared by dextral faults. Shearing in the East Bay hills accommodates about 5 km of slip on the Calaveras fault.

Figure 11. Kinematic model for accommodation of late Cenozoic slip on the northern Calaveras fault.

5.0
IDENTIFICATION OF POTENTIAL PALEOSEISMIC INVESTIGATION SITES

A primary goal of this investigation was to identify potential sites for future paleoseismic trenching to document the presence or absence of late Quaternary activity on strike-slip faults within the northern East Bay hills. Our investigation focused on the Lafayette - Reliez Valley fault system, which exhibits relatively prominent geomorphic expression of potential fault activity. Through air-photo analysis, aerial reconnaissance, and field mapping, we identify two sites along the Lafayette fault that exhibit prominent geomorphic evidence of possible late Quaternary surface rupture: the Lafayette Ridge site, and the Maricich Lagoon site (Figure 12). Both of these sites are within a linear swale or valley that contains Holocene colluvium and have not been disturbed by cultural development. Although the fault is geomorphically well expressed by multiple linear valleys, scarps, vegetation alignments and tonal lineaments on vintage (1939) aerial photography, most other parts of the fault trace have been altered by suburban development in Lafayette. In addition, much of the fault lies within steep, linear drainages or is covered by landslide deposits, therefore providing only a limited availability of viable investigation sites. The following sections briefly describe the Lafayette Ridge and Maricich Lagoon sites.

5.1 Lafayette Ridge Site

The Lafayette Ridge site is along the most prominent, continuous lineament associated with the Lafayette fault, on the northern side of Highway 24 and Deer Hill Road (Figures 12 and 13). The lineament consists of a series of fault-related features, including a linear margin of an alluvial-fan deposit at the southern end of a linear, south-trending drainage, a linear trough bordered by bedrock on both the east and west, and a prominent side-hill bench (Figure 14A). Directly north of the site, the fault is associated with a vegetation alignment, a linear landslide-headscarp, and a linear drainage extending north toward Springhill Road. The sandstone bedrock bordering the linear trough strikes west-northwest and is oblique to the valley trend, suggesting that the linearity of the valley is not related to erosion parallel to bedding strike. The southern part of the linear trough is about 100 feet wide and is undisturbed by cultural activity

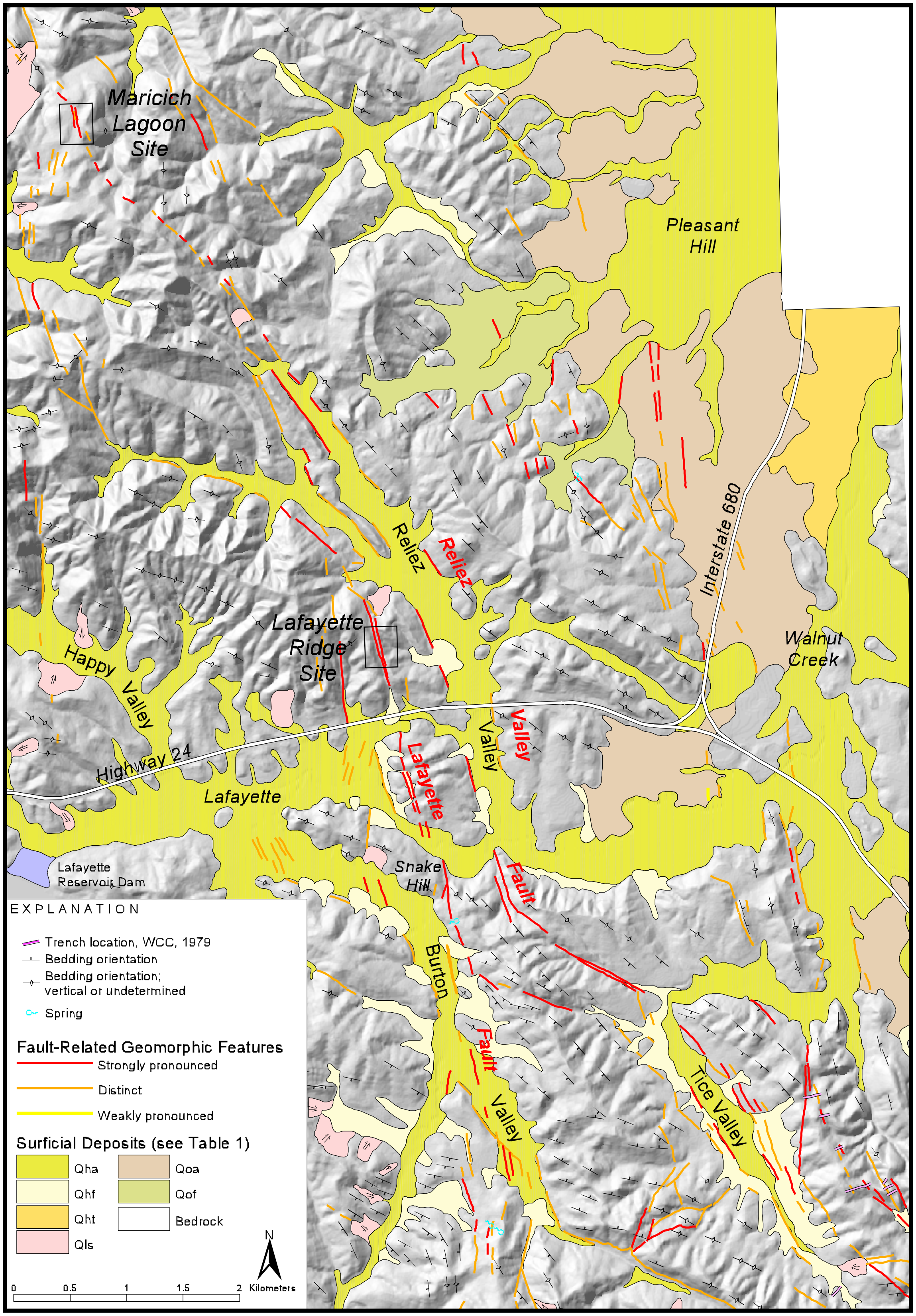


Figure 12. Map of lineaments and surficial deposits along the Lafayette-Reliez Valley fault system, showing possible fault-related geomorphic features and proposed investigation sites.

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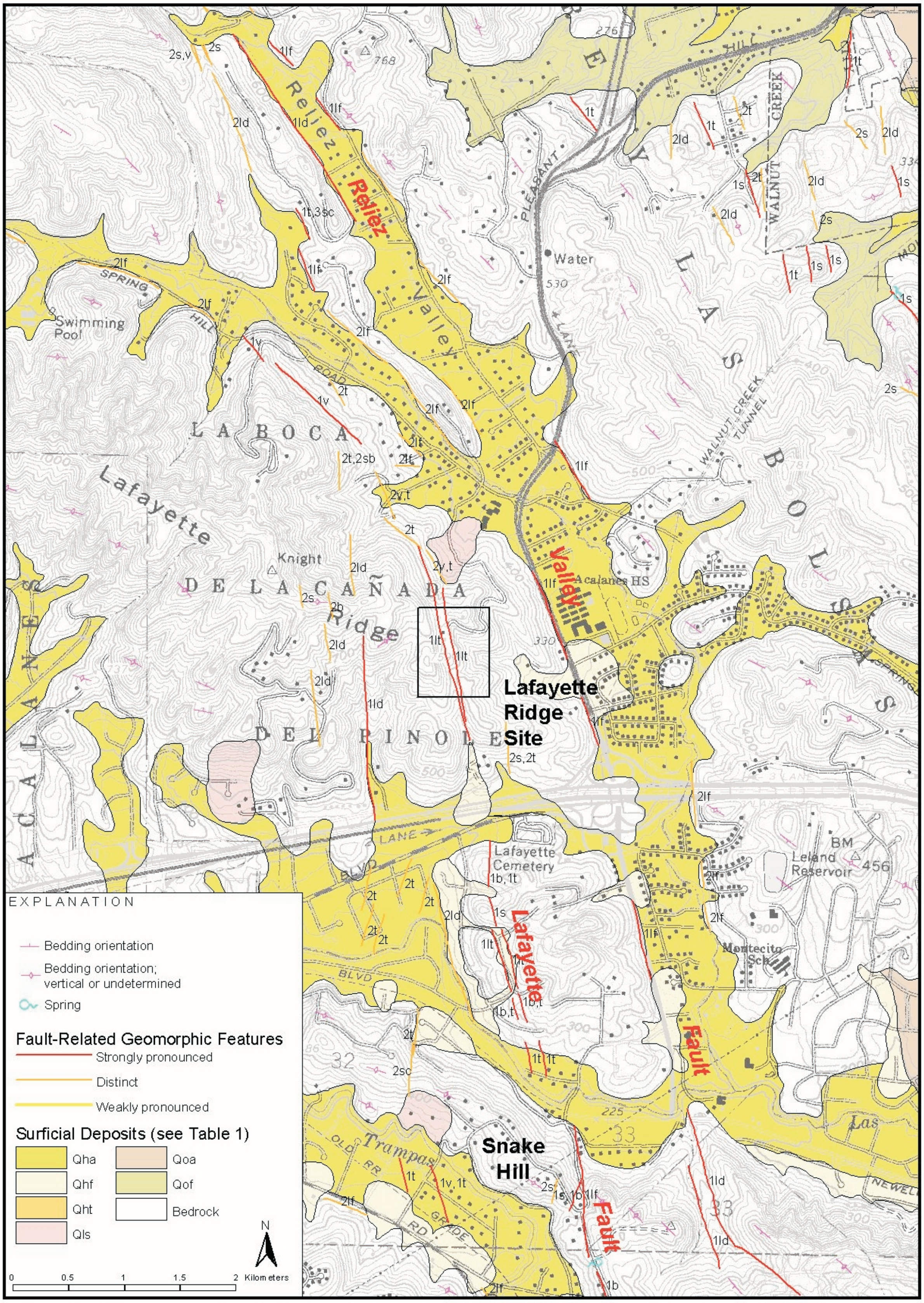

Figure 13. Lineament and surficial deposit map of of the area encompassing the Lafayette Ridge site. Key to lineament descriptors: 1 - strongly pronounced, 2 - distinct, 3 - weakly pronounced; b - bench, f - offset bedrock strata, ld - linear drainage, lf - linear hillfront, s - saddle, sc - scarp, t - tonal contrast, v - vegetation alignment.

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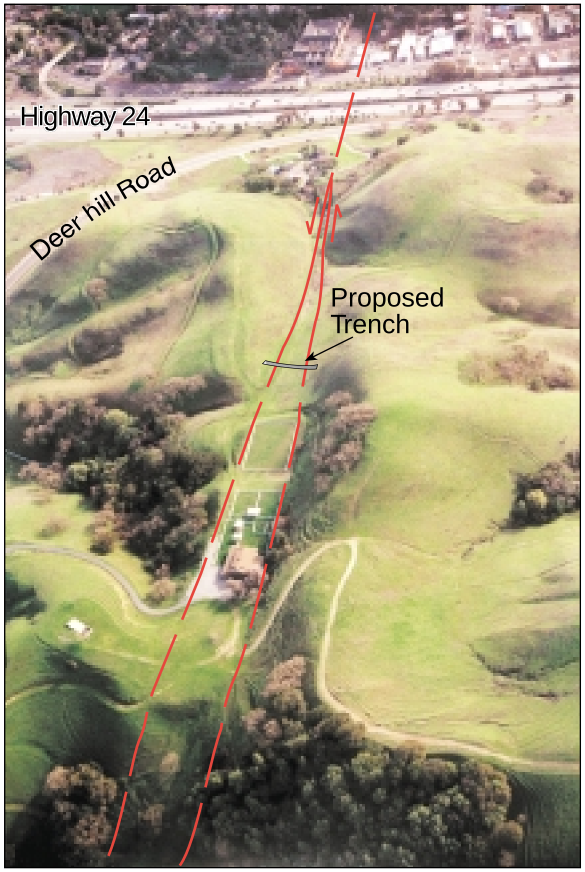
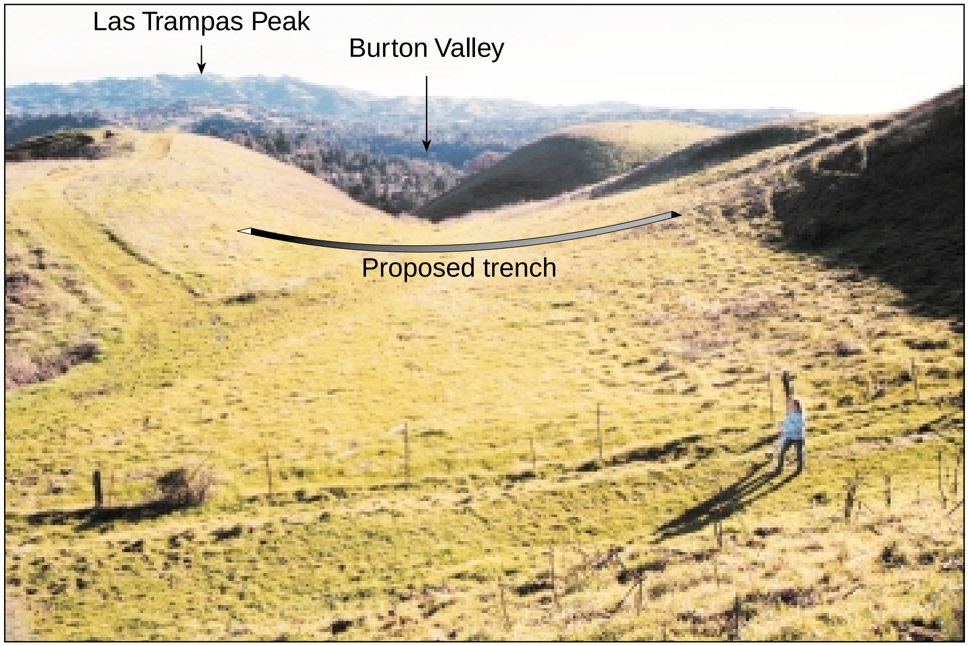


A)



B)

Figure 14. Photographs of the Lafayette Ridge site, showing location of Lafayette fault and proposed trench site. A) Oblique air photograph looking south; taken 1/10/02. B) Ground photograph looking south; taken 1/27/02.

(Figure 14B). The northern part of the trough has been modified by the placement of cut-and-fill pads for horse corrals and a barn, and the prominent bench appears to have been cut. Thus, the southern part of the trough is preferable for paleoseismic investigation. On the basis of our air-photo interpretation and aerial reconnaissance, we interpret that the Lafayette fault may consist of two strands through the site, forming the linear trough (as shown on Figure 14A), or it may consist of a single, mid-valley strand.

The linear trough contains colluvial sediments derived from the western and eastern walls of the valley; the site geomorphology and adjacent in-place bedrock strike document the absence of landslide deposits in the trough. The colluvial sediments likely are massive or poorly bedded sandy clay or clayey sand, based on local bedrock type and field observations. Although these sediments commonly are less desirable than interbedded alluvial sediments for assessing the number and timing of multiple surface ruptures, the site should provide a means to identify the presence or absence of Holocene activity on the fault. We believe that if the sediments in the trough are thick (more than about 10 ft), there is a reasonable chance that they will include middle Holocene and possibly late Pleistocene deposits. In contrast, if the sediments are thin (a few feet), then a trench may expose bedrock and provide the exact location of any bedrock faulting overlain by late Holocene deposits. In general, the site contains late Holocene (and older?) deposits that will likely provide data on whether or not the Lafayette fault has experienced Holocene surface rupture.

5.2. Maricich Lagoon Site

The Maricich Lagoon site is an excellent location to assess the presence or absence of Holocene activity the Lafayette fault. The site lies at the intersection of the Lafayette-Reliez Valley fault system (Figures 1 and 15) and provides a good opportunity to assess possible Holocene surface rupture on the Lafayette-Reliez Valley fault system. The site contains two linear ponds ("lagoons") (Figure 16) that lie within a short, linear trough bordered by steeply dipping sandstone bedrock. The southern pond lies within an unmodified, natural closed depression along the fault trace. The northern pond is formed, in part, by a small berm and culvert, and thus is partially enhanced by cultural modifications. The rest of the site appears to be undisturbed by

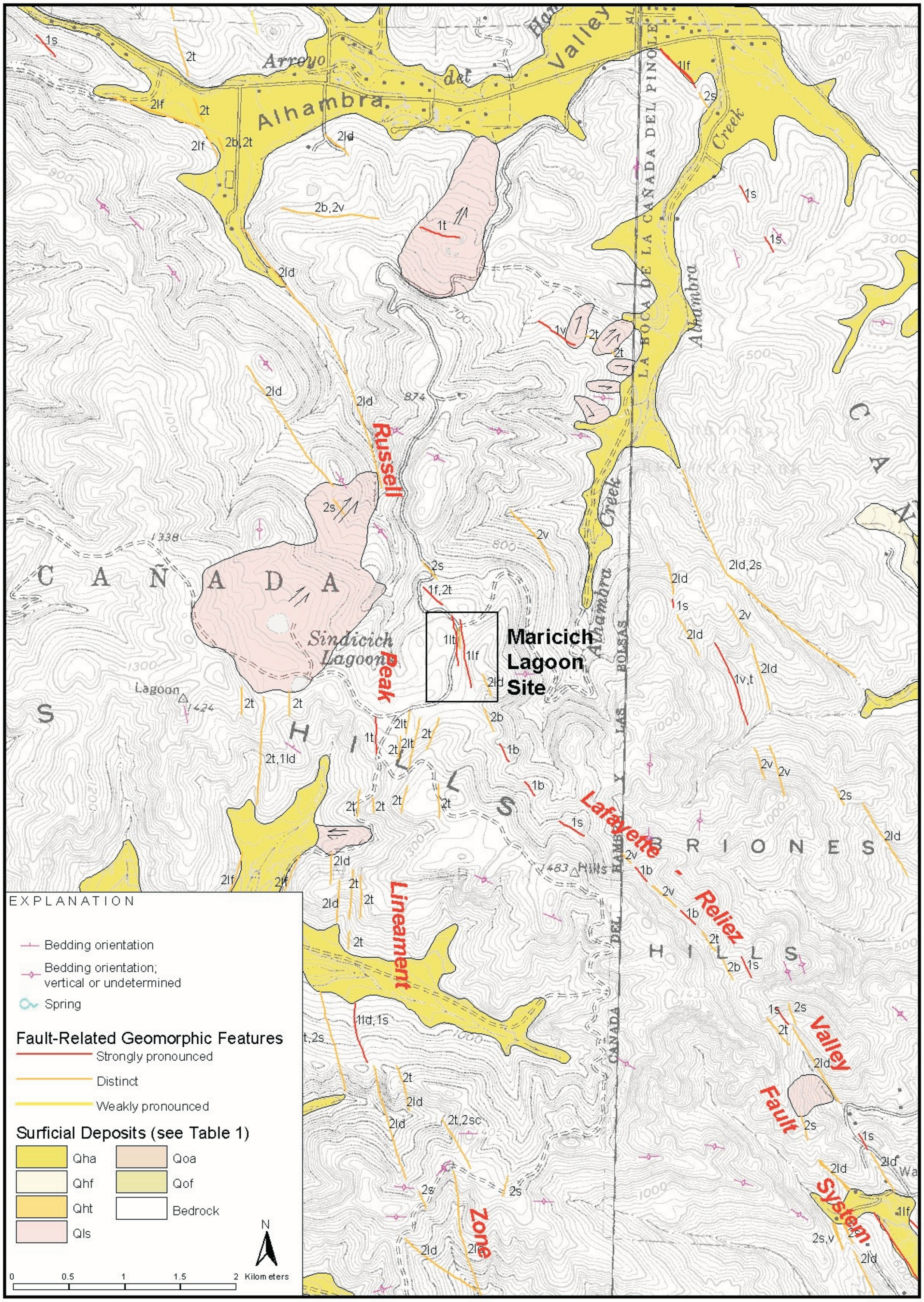


Figure 15. Lineament and surficial deposit map of of the area encompassing the Maricich Lagoon site. Key to lineament descriptors: 1 - strongly pronounced, 2 - distinct, 3 - weakly pronounced; b - bench, f - offset bedrock strata, ld - linear drainage, lf - linear hillfront, s - saddle, sc - scarp, t - tonal contrast, v - vegetation alignment.

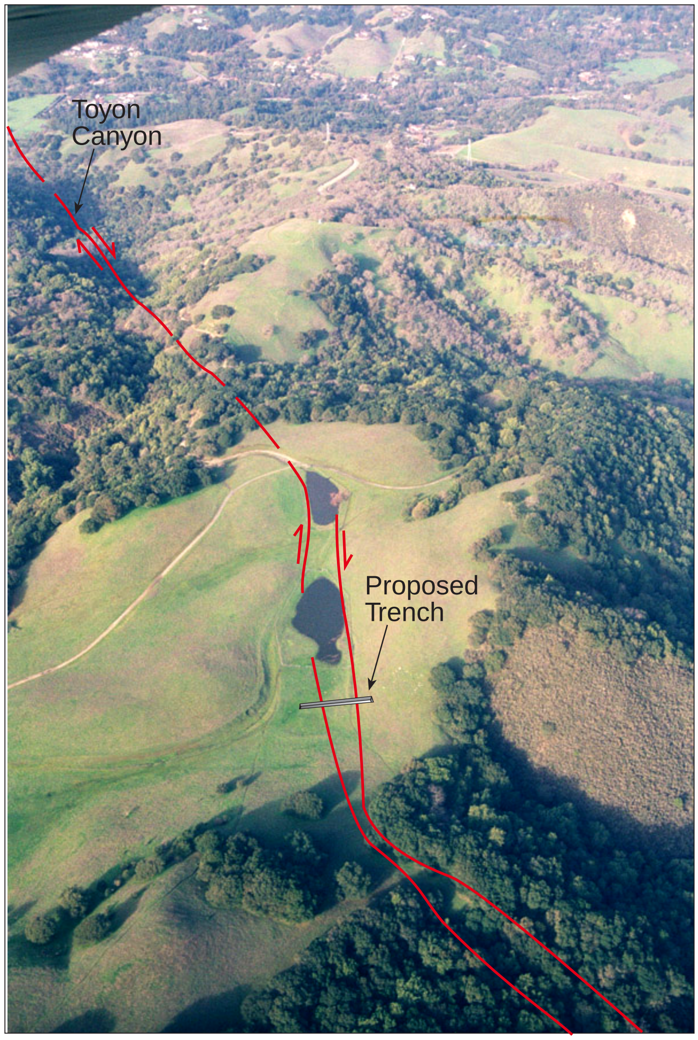


Figure 16. Oblique air photograph of the Maricich Lagoon site in Briones Regional Park, looking north, showing location of Lafayette - Reliez Valley fault and proposed trench site. Photograph taken 1/10/02.

cultural activities. The linear trough within which both of the ponds lies is filled with colluvium derived from adjacent hillsides, and likely is clayey sand or sandy clay. Based on our field observations, the Holocene strata also may contain cobbles and pebbles derived from sandstone bedrock outcrops on adjacent hillslopes. The geomorphology of the site suggests that it is characterized by local "transtension", and may contain fault strands along the eastern and/or western margins of the linear trough, or within the trough. We expect that the site contains late Holocene (and older?) deposits that may provide information to assess the presence or absence of Holocene surface rupture.

6.0
CONCLUSIONS AND RECOMMENDED WORK

The major conclusions of this study are summarized as follows:

- Geologic relations suggest that at about 11 to 13 km of post-Miocene slip on the northern Calaveras fault has been accommodated by shortening and distributed strike-slip faulting in the northern East Bay hills. This estimate is within the 12-16 km range of total post-Miocene offset on the fault, and suggests that all or most of the slip steps westward into the interior of the East Bay hills. Slip on the northern Calaveras fault is not transferred eastward in a releasing geometry to the Concord fault.

- Our analyses identify the presence of several possible strike-slip faults within the northern East Bay hills, including Russell Peak, Briones, McEwen Road, Dillon Point, and Ozol-Columbus Parkway lineament zones. These lineament zones are associated with geomorphic features suggestive of fault movement; the north-trending zones appear to truncate/displace non-striking bedding and northwest-striking reverse faults and folds. The zones are discontinuous or geologically young structure.

- The Las Trampas anticline and associated thrust fault transfer slip in a restraining step from the northern Calaveras fault onto Reliez Valley and Lafayette faults, which form a relatively broad zone of distributed strike slip within the East Bay hills. Other structures that probably accommodate dextral slip in the northern East Bay hills include the Russell Peak and Briones lineament zones, and the McEwen Road-Dillon Point and Ozol-Columbus Parkway lineaments. Some dextral slip may continue to the north along Mt. Diablo thrust fault/Saklan fault, onto Larkey lineament, then onto Southhampton fault.

- Slip on the Lafayette-Reliez Valley fault system transfers onto Franklin and Southhampton faults, or may cross-cut and deform these structures.

- Collectively, these relations suggest that strain in the East Bay hills north and west of the northern Calaveras fault is accommodated through complex deformation along discontinuous, north-striking dextral slip faults, northwest-striking reverse faults and folds, and possibly blind faults. The pattern of mixed strike-slip faulting and shortening deformation is consistent with a braided strike-slip duplex within an overall transpressional tectonic setting. Strain appears to be distributed over a broad region of the East Bay hills, but collectively may accommodate all, or most, of the 4 to 7 mm/yr of dextral slip on the Northern Calaveras.

To test our model for slip transfer, we suggest a second year of investigation to evaluate the presence or absence of Holocene surface rupture on the most continuous and prominent of these north-striking strike-slip faults, the Lafayette fault. Evaluating the presence or absence of Holocene faulting on this fault is critical for interpreting the role of the Lafayette fault in the deformation of the East Bay hills, and thus for interpreting the style and kinematics of regional deformation. We have reasonable confidence that either the Lafayette Ridge or Maricich Lagoon sites will provide the means to assess the presence or absence of Holocene surface rupture along the Lafayette fault. If evidence of such a rupture is present, and if geologic conditions are appropriate, these sites may yield data on the number and timing of multiple Holocene ruptures. Importantly, information on Holocene activity (or non-activity) on the Lafayette-Reliez Valley fault system will allow for better characterization of seismic sources in the eastern San Francisco Bay region, including blind thrust faults in restraining stepovers between strike-slip faults. As noted by Unruh and Lettis (1998), activity of strike-slip faults that bound thrust and reverse faults in restraining stepovers can be used as indirect evidence for activity of the contractional structures. The information that could be developed at either the Lafayette Ridge or Maricich Lagoons sites would directly address whether the Lafayette-Reliez Valley fault, as well as other similar faults in the East Bay hills, should be considered active seismic sources. Overall, it is our opinion that detailed information on the timing of earthquake rupture along the Lafayette - Reliez Valley fault will provide a much greater understanding of the potential seismic sources zones in the eastern San Francisco Bay region.

7.0
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