NEOGENE PALEOGEOGRAPHIES IN THE GREATER SAN FRANCISCO BAY AREA

10 Ma
Contraction-corrected
(1 mm/yr, onset at 5 Ma)

Anna V. Buising, editor
4 May 1996
NEOGENE PALEOGEOGRAPHIES
IN THE GREATER SAN FRANCISCO BAY AREA

Guidebook for
Northern California Geological Society Spring Field Trip
4 May 1996

editor:

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"Who's on first? -- Strike slip, contraction, and Neogene paleogeographies in the greater San Francisco Bay area"

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Introduction

The purpose of this field trip is to address the sedimentary record for Neogene tectonic and structural evolution in the greater Bay Area, with a particular focus on structure and sedimentation in the East Bay region since ~15 Ma. The material presented in this roadlog represents a partial progress report on several current projects of the CSU Hayward Bay Area Neogene Tectonics and Sedimentation working group.

We have recently begun to use palinspastic paleogeographic reconstructions as a tool for attempting to identify the structural styles controlling Neogene landscape evolution and sedimentation in the greater Bay area (see Buising and Walker, 1995, reprinted in this volume). We have been particularly interested in assessing the relative roles of strike-slip effects sensu lato and plate boundary-normal contraction in sculpting the Neogene landscapes of the Bay area. The kinematic and temporal relationships between the two structural styles remain largely unclear in the Bay area as in much of the rest of the California Coast Range; resolving this issue in the Bay area has broader applications to addressing the history and significance of compression/contraction along the full length of the Pacific-North American plate boundary.

We currently prefer a version of our paleogeographic reconstructions which suggests that dextral strike slip was the primary control on basin evolution in the Bay area between ~15 Ma and ~6 Ma. Contraction driven by Pacific-North American plate convergence may have become important as early as ~5-7 Ma, somewhat earlier than the date implied by the plate-tectonic datasets of previous workers (e.g., Cox and Engebretson, 1985; Harbert and Cox, 1989). In addition, new structural data from the Rocky Ridge area, Las Trampas 7.5' quadrangle, suggest that in at least parts of the East Bay fold and thrust belt, dextral slip and reverse slip are not discretely partitioned but rather combine to produce oblique slip (see Klinck, this volume).
Figure 1. Map showing approximate locations of field trip stops with respect to regional tectonic elements of the greater Bay area. SAF=San Andreas fault, HF=Hayward fault, RCF=Rodgers Creek fault, CalF=Calaveras fault, ConF=Concord fault, GF=Greenville fault. BB=Bay block, EBHB=East Bay hills block, LB=Livermore block, ECRB=eastern Coast Ranges block. For additional discussion, see Buising and Walker (1995, reprinted in this volume).
Figure 2. Generalized correlation chart for Neogene units of the greater Bay area (from Buising and Walker, 1995; see Figure 1 for geography). SAF=San Andreas fault, HF=Hayward fault, CF=Calaveras fault, GF=Greenville fault. BB=Bay block, EBHB=East Bay Hills block, LB=Livermore block, ECRB=Eastern Coast Ranges block. NoSPB=north of modern San Pablo Bay; SoSPB=south of modern San Pablo Bay; PenN=peninsula north of ~Palo Alto; PenS=peninsula south of ~Palo Alto.
Figure 3. Stops 1, 3, 4, and 5 located with respect to 10-Ma paleogeography of Buisung and Walker (1995). Stops have been shown on the chronologically and paleogeographically most appropriate map, although not all units examined are precisely 10 Ma. Arrows represent inferred transport directions, based on paleocurrent and provenance data. Faults shown are, from west to east: San Andreas, Hayward, Rodgers Creek, Calaveras, Concord, and Greenville. Note that only the San Andreas and Hayward faults are active at 10 Ma; future locations of other faults are given for geographic reference. BB=Bay block, EBHB=East Bay Hills block, LB=Livermore block, ECRB=Eastern Coast Ranges block.
15 Ma  
Contraction-corrected  
(1 mm/yr, onset at 5 Ma)  

Figure 4. Stop 2 located with respect to 15-Ma paleogeography of Busing and Walker (1995). Arrows represent inferred transport directions, based on paleocurrent and provenance data. Faults shown are, from west to east: San Andreas, Hayward, Rodgers Creek, Calaveras, Concord, and Greenville. Note that only the San Andreas fault is active at 15 Ma; future locations of other faults are given for geographic reference. BB= Bay block, EBHB=East Bay Hills block, LB=Livermore block, ECRB=Eastern Coast Ranges block.
Stop 1: Overview of Monterey-San Pablo section and traverse through San Pablo Group, northern Diablo foothills

This traverse includes an overview of the upper units of the Monterey Group (Hambre Sandstone and what we interpret as the Rodeo Shale) and a traverse through excellent exposures of the San Pablo Group (Briones and Neroly Formations) (figures 5, 6).

Monterey subsidence likely represents precursory strike-slip effects heralding the arrival of the Mendocino Triple Junction at the latitude of the Bay area in mid-Miocene time (Buisinng and Walker, 1995). Shallow-marine Monterey strata near modern Mt. Diablo (Oursan Sandstone and coeval parts of the Sobrante Sandstone) are equivalent to the upper bathyal Claremont Shale in the East Bay hills west of the Calaveras fault (Hill, 1979); the entire package may record development of a deep silled basin or complex of basins in a borderland-style topographic setting (figure 4; Buisinng and Walker, 1995).

By San Pablo time, significant uplift approximately along the modern Hayward fault trend had elevated the region between the Hayward and San Andreas faults ("Bay block" of Graham and others, 1984; see figure 1), walling off a large marine/estuarine embayment which occupied much of what is now the East Bay region (figure 3). We have referred to this system as the San Pablo embayment (Buisinng and Walker, 1995). Subsidence in the San Pablo embayment was likely due to transtensional normal faulting (see discussion in Buisinng and Walker, 1995). San Pablo strata in the Diablo foothills were deposited at and near the eastern margin of the San Pablo embayment.

The upper Monterey Group is a fining-upward shallow-marine sequence. Mudrocks of what we interpret as the Rodeo Shale (for an alternative nomenclature, see Crane and Lyon, 1994) are overlain by coarse-grained and pebbly sandstones of the basal San Pablo Group (Briones Formation). The San Pablo Group overall represents a slightly upward-coarsening shallow- to marginal-marine sequence. Interestingly, the Monterey and San Pablo appear to be in conformable contact in this vicinity: although significant uplift took place west of the modern Hayward fault trend during and after the Monterey-San Pablo transition, there was apparently little disturbance in the east. Note also that the provenance of coarse-clastic detritus changes upsection from the upper Monterey to the Neroly Formation. Coarse clasts in the Hambre consist largely if not exclusively of metamorphic materials likely derived from the Sierra Nevada and/or Sierran foothills. The Briones Formation also contains a conspicuous percentage of probable Sierran material but includes in addition detritus of likely Coast Range derivation. The Neroly, and in particular the middle and upper Neroly, is characterized by andesitic Sierran detritus, although, like the Briones, it also contains a Coast Range-derived admixture. Clearly, drainage from the east was important throughout Monterey and San Pablo time; this trend likely continued into Contra Costa time as well (see discussion under Stop 4 below). Abundant Franciscan material in both the San Pablo and Contra Costa Groups attests to the significance of westerly uplifts as sediment sources as well.
Figure 5. Location of Stop 1 traverse to examine Neogene stratigraphy (focus on San Pablo Group), Shell Ridge-Indian Valley area. Topographic base from USGS Walnut Creek 7.5' quadrangle.
**Composite columnar section**

**Neogene units, Shell Ridge-Indian Valley**

**Contra Costa County, CA**

<table>
<thead>
<tr>
<th>Pliocene</th>
<th>Sycamore Formation</th>
<th>Neroly Formation</th>
<th>Briones Formation</th>
<th>(?) Rodeo Shale</th>
<th>Hambre Sandstone</th>
</tr>
</thead>
</table>

| 570 m | 762 m | 52 m | 213 m | Base of section not exposed. |

**Explanation:**

- Conglomerate
- Sandstone
- Siltstone
- Shell hash
- Scour
- Amalgamation
- Plant fossils

**Vertical Scale:** 0 - 500 m

**Figure 6.** Generalized stratigraphy of the Neogene section exposed in Shell Ridge-Indian Valley area (units examined on Stop 1 traverse).
Directions to Stop 1a

Enter Shell Ridge Open Space at the Indian Valley trailhead. The steep-sided northwest-trending ridge on the east side of Indian Valley (east of the trailhead) is Shell Ridge. Take the trail northeast (see figure 5). At the first corner, take a sharp right so you loop around the curve of the hill and turn back to the southeast. Two right turns are possible at this corner; take the upper trail. You are now walking approximately along strike in conglomerate, sandstone and shell hash of the Briones Formation (lower San Pablo Group; see stratigraphic column in figure 6). The sharp break in slope downhill, to your left if you are facing south, is approximately the base of the Briones Formation. The trail below you follows a swale defined by the Rodeo Shale (uppermost Monterey Group). Looking across the Rodeo Shale, the near series of low hills, which make up a disconnected strike ridge, represent outcrops of the more resistant Hambre Sandstone, which underlies the Rodeo Shale.

Stop 1a: Overview of Monterey and San Pablo Groups, northern Diablo foothills

Stop at or slightly before the first switchback and gaze to the southeast. The irregular topography of the north- and northeast-trending spurs (see figure 7) reflects intercalation of resistant sandy and coarse-clastic units with less resistant mudrocks in the upper Monterey Group and lower San Pablo Group.

Directions to stop 1b

Continue along the trail toward the ridge top. These strata are slightly overturned and dip steeply northeast; stratigraphic up is actually to the west, so as you climb the ridge, you are making your way upsection through the Briones Formation. When you reach the ridge top, turn right (north) and continue along the ridge top to the prominent water tank (EBMUD's Muir Reservoir). You will be walking along strike in pebbly shell hashes of the Briones Formation. We recommend first examining the Briones shell hashes and associated sandstones in the roadcuts adjacent to Muir Reservoir tank, and then if time permits backtracking the beds along the ridge.

Stop 1b: Briones Formation at Muir Reservoir

Outcrop Description

The Briones Formation at Muir Reservoir consists of sandstone and shell hash. At the northeast end of the wall facing the water tank, a well-defined erosive surface marks the base of a conspicuous packet which fines upward from shell hash and pebbly shell hash to interbedded sandstone and shell hash. If you walk downhill to the west, you will find that sandstone and pebbly shell hash in turn pass upward into finer-grained sandstone and siltstone.
Figure 7. View to southeast from Stop 1a, showing irregular topography supported by shallow-marine units of the upper Monterey Group and lower San Pablo Group.
At Muir Reservoir, Briones Formation shell hashes are commonly amalgamated. Individual beds are erosive-based, lenticular on a scale of several m along strike, and are predominantly between 1 dm and 0.5 m thick. Hashes range from matrix-supported to shell-supported, and are commonly pebbly; along strike on the ridge crest to the south, pebbles dominate some coarse-clastic beds. Matrix consists of poorly sorted medium- to coarse-grained lithic-rich yellow sandstone. Shell hashes locally grade upward into overlying sandstone. Internally, shell hash and conglomerate beds commonly show a crude planar fabric defined by alignment of shell fragments. In some cases, laminae are curviplanar and suggest poorly defined large-scale trough cross-bedding. Internal laminae in individual beds commonly exhibit a gentle angular discordance with laminae in adjacent beds; the effect resembles channel-fill cross-bedding, or a coarse-grained version of beach cross-stratification.

Coarse clasts in Briones shell hash beds are typically subangular to subrounded, with subangular clasts predominating. Clasts range from granule grade to several cm in diameter. A wide variety of clast lithologies is present at Muir Reservoir, including: white vein quartz; fine-grained green metasediments; black, green, and red cherts; a distinctive plagioclase-bearing metaporphry with a red, hematite-rich groundmass; and gray quartzose metamorphic rocks. To the south along strike on the ridge crest, grey ?andesitic porphyry containing phenocrysts of plagioclase or plagioclase and hornblende also occurs. The green chert, black chert, white vein quartz, and gray quartzose high-grade metamorphics are indistinguishable in outcrop from those found in the conglomerates of the Hambre Sandstone.

Fossils in the Briones shell hashes occur both as fragments and as disarticulated valves. They include: very large (15-20 cm long), heavy-shelled oysters (*Ostrea titan*?); clams (to 5-8 cm); sand dollars (*Astrodapsis* spp.?); pectens (*Lyropecten* sp., to several cm); and, very rarely, mussels and calcareous worm tubes. On the ridge crest, small (1-2 cm) low-spired gastropods (*Natica* sp.) are also present.

Oysters are most common near the base of the Muir Reservoir fining-upward packet. The relative proportion of different types of fossils varies from bed to bed and along strike. In many cases, adjacent beds are dominated by different organisms, although no rhythm or cyclicity is evident.

Sandstones in the Briones at Muir Reservoir and on the adjacent ridge crest are typically yellow, medium-grained, subangular and poorly sorted. They contain abundant dark-colored lithic fragments. Most commonly, sandstones are internally un laminated, although in some cases faint internal lamination is present, primarily on a scale of one to several mm.

**Interpretation**

The fossils of the Briones Formation at Muir tank represent a shallow shoreface to intertidal assemblage. Although shells are commonly broken, and thus clearly represent a redeposited (death) assemblage, they are unmixed with deeper-water fauna; we therefore infer that the hashes and associated sandstones at the base of the Muir Reservoir sequence were
deposited in a very shallow marine setting. This sequence thus probably reflects conditions near the eastern shoreline of the Miocene San Pablo embayment.

Lenticular, erosive-based shell hashes at Muir Reservoir are probably storm lags. This seems particularly likely where they grade upward into overlying sands and pebbly sands, which we interpret as recording fairweather deposition on the shallow San Pablo shoreface. Briones shell hashes bear some resemblance to shell beds described by various workers from modern San Francisco Bay (e.g., Anima and others, 1995); the San Pablo examples are thicker and coarser-grained, suggesting that currents in the San Pablo embayment were stronger than those of modern San Francisco Bay. This may imply greater fetch, i.e., that the San Pablo embayment was significantly larger in at least one dimension than the modern Bay, which is consistent with our paleogeographic reconstructions (Busing and Walker, 1995 and unpublished data).

The upward-fining sequence at Muir Reservoir likely records an upsection deepening trend. Fossil evidence is extremely sparse in fine sandstones and siltstones of the Briones at this locality; however, based on the overall stratigraphic sequence (see below), we infer that the maximum depth was no greater than middle to lower shoreface.

The mixture of detritus in Briones coarse-clastic units at Muir Reservoir indicates that during Briones time, the San Pablo embayment received input from both easterly (Sierran) and and westerly (Coast Range sensu lato) highlands. Conglomerates and pebbly sands of the upper Monterey in this vicinity are characterized by a largely if not exclusively Sierran/Sierran foothills clast assemblage; during Monterey time, the most important drainage systems were westward-flowing, draining from headwaters in the Sierran massif. While these westward-flowing systems clearly continued to operate during deposition of the San Pablo Group (cf. interpretations of Graham and others, 1984), it is clear that during Briones time, topographic relief to the west also became important. We ascribe this, as previous workers have done (see Graham and others, 1984), to uplift of Franciscan terranes along the young Hayward fault trend.

**Directions to stop 1c:**

Leaving Muir Reservoir, follow the paved road downhill. When you reach the bottom of Shell Ridge, turn left at the steep switchback and return to the trailhead gate. At the trailhead gate, continue downhill (roughly west) across Indian Valley. Notice sparse outcrops of Briones sandstone and shell hash on the west-facing slope of Shell Ridge; in the Briones Formation, small-scale fining-upward cycles like that at Muir Reservoir are superposed on the overall upward-coarsening trend of the San Pablo Group.

Follow the trail across Indian Valley. The western part of the valley is incised into thick-bedded, internally un laminated sandstones of what we refer to as the upper Briones Formation (Cierbo Formation of Crane and Lyon, 1994); the resistant beds on the skyline at the west side of the valley are exposures of the Neroly Formation. Cross the stream in the axis of Indian Valley and continue uphill along the trail until you come to resistant "finny" outcrops of gray sandstone, conglomerate and shell hash. This is the basal Neroly Formation. We recommend examining
the basal Neroly Formation (Stop 1c on figure 5) and then walking uphill to look at the conspicuous quarry outcrops of the middle Neroly.

Stop 1c: Neroly Formation on west side of Indian Valley.

Outcrop description

The Neroly Formation on the west side of Indian Valley consists of sandstone, conglomerate and shell hash. All three lithologies typically occur in m-scale erosive-based beds; as in the underlying Briones, amalgamation is a hallmark of the Neroly. Beds in the Neroly amalgamated packets are arrhythmically stacked. Like those in the Briones Formation, Neroly shell hashes contain varying admixtures of terrigenous coarse clasts; however, the Neroly is more conglomerate-rich overall than the Briones, and maximum clast size in the Neroly conglomerates is greater than in those of the Briones. Similarly, the thickness of individual beds (sandstone, conglomerate and shell hash) is greater on the average in the Neroly than in the Briones. This represents a subtle coarsening- and thickening-upward trend; this trend is even more pronounced in the San Pablo Group to the southeast, particularly in the vicinity of Macedo Ranch (see Walker and others, this volume).

Conglomerates, conglomeratic shell hashes, and shell hashes are all clast-supported and matrix-rich. They are typically ungraded and internally massive. The matrix consists of very poorly sorted, angular, coarse-grained sandstone containing abundant volcanic rock fragments. Coarse clasts range from granules to cobbles, and are predominantly subangular with some subrounded examples.

Coarse clasts in the Neroly Formation at Indian Valley represent at least two distinct source terranes: Franciscan/Coast Range and Sierran. Red cherts are probably of Franciscan origin. Black and green cherts may also be derived from Franciscan sources, but a Sierran or Sierran foothills source is perhaps more probable, particularly for the black cherts. Yellow quartzites, white quartzites, and a variety of quartzofeldspathic metamorphics were probably derived from Sierran or Sierran foothills sources. Metamorphies may have come from Sierran sources, or they may be recycled from Mesozoic coarse-clastic rocks in the Coast Range region; clast angularity suggests that the former is more likely.

Several types of fresh, unmetamorphosed volcanic rocks are also present in the Neroly Formation at Indian Valley. Distinctive pyroxene-bearing basalts with a red, hematitic groundmass strongly resemble some phases of the Miocene Grizzly Peak volcanics in the East Bay (see Walker and others, this volume). Grey andesites with conspicuous phenocrysts of hornblende and plagioclase were almost certainly derived from the Mehrten Formation of the northern Sierra. Fresh volcanic rocks increase in abundance upsection, while Sierran/Sierran foothills clasts become less abundant upsection; this is evident if you compare the clast assemblage in the basal conglomerate to that in the strata exposed in the quarry outcrops.

The Neroly shell hashes and shelly conglomerates at Indian Valley are overwhelmingly
dominated by large (4-8 cm), heavy-shelled clams. Very sparse heavy-shelled gastropods are also present. Near the base of the section, smaller, ornamented clams also occur.

Neroly sandstones at Indian Valley range from medium- to coarse-grained and from poorly to moderately sorted. Grains are angular to subangular. Sands are yellowish to gray near the base of the section and show an increasingly blue cast upsection. Sands at the quarry outcrops are distinctly blue, although not as strongly colored as those described to the southeast by Walker and others (this volume). Basally, Neroly sands in this vicinity contain a conspicuous percentage of monocrystalline quartz and feldspar; the percentage of monocrystalline quartz and feldspar decreases upsection, as the sands become increasingly volcaniclastic. Neroly sandstones include both internally unlaminated beds and beds containing poorly defined medium- to large-scale trough cross-beds. Where present, laminae are typically several mm thick and are defined by changes in grain size.

**Interpretation**

The heavy-shelled clams which predominate in shell hashes of the Neroly Formation at Indian Valley reflect comparatively high-energy shallow-marine (beach face?) conditions. The predominance of broken valves indicates a reworked assemblage. However, since the hashes are dominated by a single type of shallow-water organism, which occur without admixture of deeper-water fauna, it seems likely that these beds were in fact deposited in very shallow water. Sandstones probably represent normal background sedimentation on the shallow shoreface slightly below sea level. The Neroly Formation at Macedo Ranch, approximately 5 km to the southeast along strike, was probably deposited at sea level (see Walker and others, this volume). This implies a slight along-strike deepening trend from Macedo Ranch northwest to Indian Valley.

The conglomerates and shell hashes of the Neroly clearly reflect a significant intermittent increase in depositional energy; strongly scoured bases and amalgamation of conglomerate beds indicate turbulent, erosive current activity. We interpret the conglomerate and shell hash beds as recording storm events. As in the underlying Briones Formation, Neroly shell hashes are comparatively coarse, thick beds, suggesting strong storm-generated currents. This in turn suggests a fair distance of open-water fetch, possibly greater than in the modern Bay.

The dominance of Sierran- and Sierran foothills-derived materials in the Neroly indicates that during Neroly time the San Pablo embayment received large amounts of detritus from the east via a westward-flowing drainage or system of drainages. The shift from a clast assemblage dominated by metamorphic lithologies to a volcanic-dominated one likely reflects events in the upstream evolution of the drainage system, perhaps headward erosion and/or stream piracy permitting drainages to tap into new sources of detritus. By contrast, the occurrence of volcanic clasts of probable East Bay derivation on the eastern margin of the San Pablo embayment is paleogeographically rather difficult to explain.

After examining the Neroly Formation, return via the same trail to the vehicles and depart
in caravan for Stop 2.

**Directions from Stop 1 to Stop 2:**

Turn around where Marshall Drive dead-ends at the Indian Valley trailhead, and follow Marshall Drive back out to Homestead Drive (1.2 mi). Turn right on Homestead and proceed 0.2 mi to Ygnacio Valley Road. Turn left onto Ygnacio Valley Road and follow it through Walnut Creek to 680; you will pass intersections with Walnut, North Civic, and North Broadway, and immediately before 680, on the right (northeast) side of the street—you will pass the Walnut Creek BART station. Proceed under the 680 overpass and get on westbound, headed for the Caldecott Tunnel and Berkeley. From 680, take 24 West and proceed through the Caldecott Tunnel, a total distance of about 10 mi from the point where you got on the freeway.

Just east of the Caldecott Tunnel, notice the beautiful exposures of Contra Costa Group strata. The gray and red units are gravelly fluvial strata (gray) and floodplain silts (red) of the Orinda Formation; these are overlain by dark-colored, blocky-fracturing outcrops of the Grizzly Peak basalts. Note that these units are repeated across the axis of the Neogene Siesta Syncline.

When you emerge on the west side of the Caldecott tunnel, take the right-hand exit marked 13 North (Berkeley). Savor the view of the Bay as you come to a stop at the light. Proceed straight through the light and continue on 13 (now Ashby Avenue), downhill past the Claremont Hotel on the right (east) side of the road. The Claremont is located at the corner of Ashby and Domingo; you should be in the right lane at this point. Continue straight through the intersection of Ashby and Domingo and take the next right on Claremont Avenue, at the Coast Gasoline station.

Follow Claremont Avenue along a winding route up the canyon for a total distance of about 1.5 mi. You will pass signs for Tilden and Sibley regional parks. The sporadically exposed yellow sandstones which you may glimpse in roadcuts for about the first 0.5 mi are Cretaceous deep-marine sediments belonging to the Great Valley Group. At about 0.9 mi up the canyon, you will begin to notice thin-bedded, light-colored units in outcrop, especially on the left (north) side of the road. These are porcellanites of the Miocene Claremont Shale.

At 1.5 mi, turn out in the fire road pullout on the right side of the road. We will cross the road (carefully!) and examine the quarry outcrop immediately across from the fire road.

**Stop 2: Claremont "Shale," Claremont Canyon**

**Outcrop description**

This small quarry exposes porcellanite and shale (ch:sh ∼ 10:1) of the rather deceptively-named Claremont Shale, in the the north limb of a tight, boxy, northwest-trending anticline.
These strata are slightly overturned and dip steeply to the southwest (figure 8a).

Claremont porcellanite at this outcrop occurs in beds 3-7 cm thick intercalated with shaley partings to ~3 cm thick; one thicker (1.75 m) shale interval is also present (figure 8a, 8b). At least one siltstone bed containing conspicuous, nearly euhedral medium to coarse sand-grade feldspar grains is also present. The extreme angularity of the feldspar grains, and the abundance of clay in the matrix, suggests that this bed may contain tuffaceous material.

Cherty laminae in the Claremont commonly pinch and swell along strike. Some beds have irregular bases resembling scour surfaces; beds also coalesce along irregular surfaces in a manner resembling amalgamation. However, much of this may be due to volume changes during silica diagenesis. Claremont cherts are typically light gray to brown on fresh surfaces and orange-, buff- or rusty-weathering; mm-scale internal lamination is commonly defined by darker horizons.

Shale interbeds in the Claremont are typically porcellaneous and rather coarsely fissile. Abundant macroscopic fossil fragments are present in some beds, including fish scales and fish bone fragments.

**Interpretation**

Previous workers (see Hill, 1979; Graham and others, 1984) suggest that the Claremont Shale was deposited at upper bathyal depths (~500 m). These strata represent the downslope equivalent of shallow-marine Monterey rocks exposed in the Diablo foothills and San Ramon Valley (Oursan Sandstone and coeval parts of the Sobrante Sandstone; see Hill, 1979 and Crane and Lyon, 1994) (figure 4). Graham and others (1984) interpreted the Claremont as representing deposition in the deep, largely starved portion of the Great Valley (*sensu lato*) forearc basin during the last phases of arc activity at this latitude. We have suggested alternatively that the Claremont records the earliest phases of strike slip-controlled "borderland"-style subsidence associated with the approach of the Mendocino Triple Junction to the Bay area (Buising and Walker, 1995). Regionally in the East Bay, the basal Monterey unconformably overlies either Eocene deep-marine strata, or Jura-Cretaceous Franciscan and Great Valley rocks. Underlying strata must have been first uplifted and exposed, and then downdropped below sea level in order to initiate marine Monterey deposition. This implies that Monterey deposition took place in a tectonic regime distinct from that which governed formation of the underlying units.

**Directions from Stop 2 to Stop 3:**

Use extreme caution in pulling back out onto Claremont Boulevard; the road is blind and very heavily traveled. Continue uphill (roughly east) on Claremont. Almost immediately after leaving the fire road parking space, you will begin to see roadcut outcrops of yellowish and gray-brown gravelly units of the Orinda Formation.
Figure 8a. Porcellanite (light-colored) and shale (dark-colored) of Claremont Shale in Claremont Canyon, Stop 2. Conspicuous shale interval on left side of photo is approximately 1.75 m thick.

Figure 8b. Rhythmic stratification in Claremont porcellanite and shale beds, Stop 2.
Follow Claremont Boulevard about 0.6 mi uphill to the "four corners" intersection with Grizzly Peak Drive and Fish Ranch Road. Turn left onto Grizzly Peak Boulevard and follow the switchbacks uphill. Notice that the beds are now upright, striking northwest and dipping northeast. At about 0.4 mi past “four corners,” you will pass a conspicuous roadcut outcrop of Orinda gravels overlain by black, blocky-fracturing basalts of the Grizzly Peak Formation. Immediately past this outcrop, there is a pullout on the right-hand side of the road. The first few vehicles should park in this pullout. If additional parking space is needed, the rest of the caravan should continue to the next pullouts. The first is located another 0.1 mi along on the right-hand side of the road, adjacent to the conspicuous roadcut outcrop of a 2-3 m white tuff marker bed. The second is an overlook located in the apex of the next curve, another 0.05 mi along on the left side of the road. When you have parked your vehicle, return to the first pullout, where we will convene and walk back to the adjacent Orinda and Grizzly Peak outcrops.

**Stop 3: Orinda Formation, Grizzly Peak Drive**

Here we will examine excellent roadcut exposures of the Orinda Formation (basal Contra Costa Group) and overlying Grizzly Peak basalts. The Orinda Formation records uplift of Franciscan terrane along the trend of the young Hayward fault during mid- to late Miocene time (see Graham and others, 1984; Buising and Walker, 1995). This westerly uplift contributed to the development of the San Pablo embayment by creating a large topographic barrier on the west side of the embayment, geographically reinforcing the separation of bay/estuarine waters from the open waters of the Pacific (figure 3). This uplift also resulted in the progradation of an extensive clastic wedge eastward into the San Pablo embayment, where continental and estuarine strata of the Contra Costa Group interfinger with shallow-marine and estuarine units of the San Pablo Group (Wagner, 1978; Graham and others, 1984; Buising and Walker, 1995).

Previous workers have also related the eruption of the overlying Grizzly Peak basalts to early rupturing along the Hayward fault at ~10 Ma (Graham and others, 1984). However, uplift along the Hayward fault trend appears to have preceded the appearance of the Grizzly Peak volcanics by some 3 m.y. (dates per Graham and others, 1984). Could this imply that Grizzly Peak volcanism was not in fact an early sign of strike slip in the East Bay, but rather the manifestation of a well-established strike-slip regime? This is certainly the case in other well-developed strike-slip basins such as the modern Salton Trough (e.g., Robinson and others, 1976; Fuis and Kohler, 1984; see also Crowell, 1974), although we are not suggesting that volcanism in the East Bay approached the scale of activity documented in the Salton Trough.

We recommend that you begin contemplating this outcrop at the downhill side (stratigraphically lowest convenient point possible). Watch for auto and bicycle traffic -- this is a busy road!
Outcrop description

In the stratigraphically lower portion of this exposure, the Orinda Formation consists of tan cobble to boulder conglomerate with minor interlenses of pebble conglomerate and sandstone. Conglomerate is typically crudely stratified on a scale of 0.5-1 m; stratification is locally defined by sand-rich lenses to 3 dm thick and several m long along strike. Internally, conglomerates show a crude planar fabric defined by clast alignment. Conglomerate is typically clast-supported but comparatively matrix-rich. The Orinda section exposed here fines and thins upward; the uppermost 3-4 m, immediately below the conspicuous baked contact with the overlying Grizzly Peak basalt flows, comprises pebble conglomerate overlain by brown, spheroidally weathering siltstones with pebbly interbeds 2-3 dm thick.

Clasts in these Orinda conglomerates range from granules to boulders and from angular to subrounded. The clast assemblage here is extremely diverse. Many clast lithologies in these beds reflect derivation from Franciscan sources in the Coast Range: e.g., graywacke, blueschist (including distinctive epidote-bearing blueschists), red chert, greenstone, epidote-rich metamorphic rocks, and serpentinite. Grey siltstone and argillite are less distinctive but are probably also of Franciscan derivation. Quartzose and quartzofeldspathic metamorphic rocks, white vein quartz, white marble, black chert, and green chert could be either Coast Range-derived or Sierran-derived, although the Orinda is an eastward-thinning clastic wedge (Wagner, 1978) and it would be difficult to account for the presence of westward-transported material in this part of the section (note that this is not the case for the younger conglomerates of the Contra Costa Group; see discussion of strata at Cull Canyon below). Plagioclase-bearing metaporphyreries in the Orinda resemble some of likely Sierran origin which occur as clasts in local Cretaceous strata (e.g., Oakland Conglomerate). The Orinda metaporphyreries may thus be recycled from Cretaceous Coast Range sources rather than representing material transported directly from the Sierra. However, clasts in the potential Cretaceous source rocks are significantly better rounded on the whole than Orinda clasts of similar lithologies; direct derivation from a Sierran source seems more likely than recycling from Cretaceous sedimentary sources.

Interpretation

Fossil evidence reported by a number of previous workers suggests a terrestrial environment of deposition for the Orinda Formation (see Wagner, 1978; Graham and others, 1984). The gravelly nature of the deposit implies a fairly high-gradient system; based on clast size (coarse but not extremely coarse) and rounding (angular but not extremely angular), we infer moderately proximal deposition. Clast-supported, comparatively well-organized strata imply dilute flow deposition. We suggest that the lower portion of the Orinda Formation, as exposed on Grizzly Peak Boulevard, records deposition in a fairly high-gradient braided stream similar to the Scott-type system of Miall (1977), but lacking the debris-flow strata characteristic of the classic Scott-type river.

Clast composition indicates that the overwhelming majority of the detritus in these beds
was derived from Franciscan and related sources in the Coast Range. As stated above, we concur with Graham and others' (1984) interpretation that the basal Orinda reflects uplift associated with early motion on the Hayward fault. In terms of reconstructing the geometry of basin and fault scarp, however, it is important to point out that the Orinda Formation on Grizzly Peak Boulevard is not a proximal fault-scarp breccia. By comparison with examples of proximal fault-scarp breccias from other strike-slip depositional settings (e.g., the Violin Breccia of Ridge Basin in southern California; see Crowell, 1982; also Busing and Walker, unpublished data), the Orinda is both significantly finer-grained (both maximum and average clast size) and significantly better-organized. Thus, while the sediment making up these Orinda strata was almost certainly derived from a fault-bounded highland, and was probably deposited fairly proximal to its source, this material is insufficiently coarse and far too well-organized to have been deposited immediately adjacent to the young Hayward fault scarp. Thus, the active fault scarp must have been somewhat west of the Miocene location of these outcrops, and perhaps even somewhat west of its active Holocene trace. We are currently carrying out clast geometry studies aimed at quantifying the distance between the Orinda basin and the paleo-Hayward fault scarp.

Directions from Stop 3 to Lunch:

Pull gingerly back out into traffic headed uphill on Grizzly Peak Boulevard and continue up the grade to the top of the ridge, about 0.8 mi past Stop 3. Admire the amazing view of the Bay and peninsula!

After the road flattens out on top the ridge you will see a sign on the right side that says "Steam Trains." Turn right here; the street name is Lomas Cantadas. Make an immediate left into the steam trains parking lot. If there is sufficient space (difficult to predict on a weekend!), all vehicles can park in the main lot. If more room is needed, some vehicles may wish to continue about 0.2 mi up the road to the overflow parking area (marked "Employee Parking"). We will eat lunch in the picnic area across from the main steam trains parking lot; privies are available in the main parking lot.

Directions from Lunch to Stop 4:

After lunch, turn right from the steam trains parking lot onto Lomas Cantadas and then immediately left onto Grizzly Peak Boulevard. We will backtrack downhill to the "four corners" intersection and turn left on Fish Ranch Road. Follow Fish Ranch downhill and get on 24 westbound. Watch out -- the entrance to the onramp is a left turn before you reach the bottom of the hill.

Once on 24, go through the Caldecott Tunnel (again!) and follow the signs for 13 South (Hayward). Highway 13 follows a narrow valley defined by the active trace(s) of the Hayward fault through the Montclair district. Proceed south on 13 (about 9 mi) to the interchange with 580, then take 580 East. Continue on 580 East (actually more south) through the remainder of
Oakland and San Leandro.

Don't take 238 to Hayward! Stay on 580 (signs will say 580 Stockton) through Castro Valley, and get off at the Crow Canyon/Center Street exit, about 10 mi “south” of the 13-580 interchange. You will want to be in the middle lane on this three-lane exit. Turn left onto Center Street, go over the freeway to the east, and take the first right onto Castro Valley Boulevard. Go downhill to the first light, and turn left onto Crow Canyon.

Follow Crow Canyon about 0.6 mi, and turn left onto Cull Canyon Road; the fire station on the northeast corner of the intersection makes a good landmark. We will continue up Cull Canyon to the end of the paved road, a distance of about 6.3 mi from the intersection with Crow Canyon.

The lower part of Cull Canyon (slightly more than 2 mi by the road) is cut into by now familiar yellow sandstone and interbedded olive shale of the Cretaceous Great Valley Group. The canyon widens and flattens slightly as it passes through the more friable sandstones of the Monterey and San Pablo Groups (about 1.4 mi by the road). In the middle and upper reaches of the drainage (beginning about 3.5 mi after the turnoff from Crow Canyon Road) friable-appearing light-colored sandstones and red-brown conglomerates of the Contra Costa Group are exposed in roadcut outcrops.

Drive all the way to the end of the paved part of Cull Canyon Road; stay off the dirt continuation because this part of the road is private. Park in the pullout area at the end of the road.

Stop 4: Contra Costa Group strata, Cull Canyon

Roadcuts in the last 0.5 mi of Cull Canyon Road provide excellent exposures of strata typical of the Contra Costa Group in the vicinity of Upper San Leandro Reservoir. The Contra Costa strata exposed in Cull Canyon are probably between ~8 and ~6 Ma in age, somewhat younger than the outcrops of basal Orinda we examined in the Berkeley hills (see Graham and others, 1984; Buising and Walker, 1995).

We follow Buising’s (1992) informal field stratigraphy for the Contra Costa Group, which distinguishes five complexly intercalated mappable lithofacies. The conglomerate-dominated, sandstone-dominated, and interbedded conglomerate, sandstone, and siltstone lithofacies represent fluvial channel and floodplain deposits; the sandstone + mudstone lithofacies represents lacustrine-deltaic and shallow-lacustrine deposits; the shale lithofacies records open-lacustrine deposition. Fluvial deposits are areally, and probably also volumetrically, dominant in the Contra Costa Group in this vicinity. Open-lacustrine shales occur in stratigraphically isolated lenses ranging in length from more than 1 km to less than 100 m along strike. This suggests numerous small lakes on a broad fluviodeltaic drainage plain which probably emptied into the San Pablo embayment (see Liniecki-Laporte and Andersen,
Clast composition in both sand and coarse-clast fractions suggests that the Contra Costa Group in the Cull Canyon area comprises sediment derived from both western (Franciscan/Coast Range) and eastern (Sierran/Sierran foothills) sources, rather than being exclusively Coast Range-derived as previous workers have suggested. Buising (1995) used a combination of Gazzi-Dickinson (for sand bulk composition) and “Indiana” (for detailed rock fragment data) techniques to perform 400-point point-counts on a suite of K-stained Contra Costa thin sections. Sands from the lower Contra Costa Group (~215 m above the base of the unit) plot in the recycled orogen field of $Q_{m}FL$, and $Q_{m}FL$ plots; however, point-count data from the overlying 1200 m of the Contra Costa Group show intercalation of recycled orogen- and arc-provenance sands in packets 50-300 m thick. The angularity of sand grains seems to preclude significant sediment recycling. Buising (1995) inferred that most of the material in the Contra Costa represents first-cycle detritus; compositional results are thus probably reasonably indicative of provenance.

Both arc and recycled orogen sands of the Contra Costa Group are closely associated with Coast Range-derived coarse clasts in outcrop; some arc sands also include sand grains of probable Coast Range derivation. Coast Range coarse clasts include: ?Franciscan sandstone and chert; white vein quartz; Claremont Shale; and mafic volcanic rocks. Coarse clasts of possible Sierran origin include black chert, argillite, mica schist, and some volcanic and metavolcanic clasts. Coast Range-derived sand-grade rock fragments include Franciscan blueschist, sandstones and metasandstones, as well as distinctive Miocene (Grizzly Peak?) basalts from the Berkeley Hills. Sand-grade rock fragments of likely Sierran derivation include abundant quartz-rich, quartzofeldspathic, and pelitic metamorphic rocks.

Buising (1995) interpreted arc sands of the Contra Costa Group as recording periods when the bulk of the sediment reaching the Contra Costa depocenter was derived from the Sierra: the westward-flowing drainage which characterized much of San Pablo time must have continued to be important during deposition of the Contra Costa Group. Sand composition in the “arc” intervals reflects the volumetric dominance of Sierran detritus, while the presence of Coast Range-derived material attests to uplift within the Coast Range during Contra Costa time. By contrast, intervals dominated by sands with a recycled orogen compositional signature were derived from Franciscan-Great Valley-Coast Range Ophiolite source rocks west of the Hayward fault trend, and likely record times when Sierran detritus was diverted from reaching the Contra Costa basin, either by structurally controlled changes in the evolving landscape or by autocyclic processes.

Overview of Contra Costa Group exposures in Cull Canyon

The stratigraphic section exposed below the west-dipping Cull Creek fault (figures 9, 10) in Cull Canyon exposes three of the five mappable lithofacies of Buising (1992): the sandstone-dominated facies (figure 11a), the sandstone + mudstone facies ("S" in figure 11b; figure 11e), and the shale facies ("O" in figure 11b; figure 11d).
Figure 9. Location of Stop 4 traverse through younger Contra Costa Group strata adjacent to trace of Cull Creek fault. Topographic base from USGS Las Trampas Ridge 7.5' quadrangle.
**Measured section of a portion of the Contra Costa Group**
east of Cull Creek fault, Cull Canyon, Alameda County, California

<table>
<thead>
<tr>
<th>Age</th>
<th>Unit Thkns</th>
<th>Prov</th>
<th>Graphic Column</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 m</td>
<td></td>
<td></td>
<td></td>
<td>Gray calcareous shale with minor dm-thick interbeds of micritic limestone; limestones buff to tan on fresh surfaces, weather cream or white. Ostracodes common. Volcaniclastic interbed: medium to coarse sand-grade andesitic-basaltic rock fragments and highly angular, nearly euhedral plagioclase in a distinctive hematite-rich cement. <strong>Open-lacustrine.</strong></td>
</tr>
<tr>
<td>38 m</td>
<td></td>
<td></td>
<td></td>
<td>Interbedded brown ss and siltstr and olive to gray sh; sh increasingly gray upsilon. Ss and silt beds one to several dm, very commonly show internal lamination on mm to cm scale. Symmetrical ripples very common (wavelength 2-4 cm, amplitude &lt;1-2 cm). Ss's locally erosive-based. Abnt fossil material (plant fragments to several mm long, ostracodes), disseminated and as lags/partings. Ss dikes common. <strong>Shallow-lacustrine and lake-marginal.</strong></td>
</tr>
<tr>
<td>36 m</td>
<td></td>
<td></td>
<td></td>
<td>Interval covered.</td>
</tr>
<tr>
<td>26 m</td>
<td></td>
<td></td>
<td></td>
<td>Lower ~10 m tan ss and pebbly ss. Ss beds ~1 cm to ~1 m thick, lenticular on several-m scale, amalgamated (erosional surfaces, horizons of concentrated mud rip-ups to ~5 cm diam), w/ large-scale trough cross-bedding or mm-scale parallel laminae. (In thicker beds, parallel laminae pass upsilon into massive ss). Carbonized plant fragments common, to 2-3 cm long, on partings and disseminated. <strong>Fluvial channel.</strong> Upper ~15 m tan and olive siltstr, mudstr and sh w/ erosive-based yellow ss interbeds to ~1 m thick. <strong>Floodplain.</strong></td>
</tr>
</tbody>
</table>

**EXPLANATION**
- pebbly sandstone
- sandstone
- siltstone
- shale
- limestone
- volaniclastic material
- plant fragments
- ostracodes
- amalgamation
- symmetrical ripples
- arc-provenance sands
- recycled orogen-provenance sands

*Individual bed thicknesses exaggerated to show detail; see text for detailed descriptions.*

**Figure 10.** Contra Costa Group stratigraphy exposed along traverse at Stop 4, Cull Canyon. This partial measured section represents the uppermost 126 m of the approximately 270 m of continuous section exposed structurally below the Cull Creek fault in Cull Canyon.
We will examine in detail only the upper part of the Contra Costa Group section exposed below (east of) the Cull Creek fault. Our traverse begins about 146 m stratigraphically above the base of the section (location marked on map in figure 9). The strata covered in our traverse include three distinct depositional associations: a lower amalgamated sandstone + pebbly sandstone association (sandstone-dominated lithofacies of Buising, 1992), interbedded sandstone and siltstone with shaley partings and pervasive oscillation ripple marks (sandstone + mudstone lithofacies), and gray calcareous shale (shale lithofacies) (figure 10).

Description of lower amalgamated sandstone/pebbly sandstone interval

At about 146 m above the base of the section, a prominent scour surface marks the base of ~10 m dominated by tan sandstone and pebbly sandstone (figure 10, 11a). Sandstone beds range from ~1 cm to >1 m thick; individual beds are lenticular on a scale of several m along strike. Beds show large-scale trough cross-lamination or are internally parallel-laminated on a mm scale; in thicker beds, parallel laminae pass upsection into internally un laminated sands. Partings containing abundant concentrations of carbonized plant fragments to 2-3 cm long are common (figure 11c); disseminated organic material also occurs locally. Erosional surfaces and horizons of concentrated mud rip-ups to ~5 cm in diameter suggest amalgamation.

The lower amalgamated sand/pebbly sand section is overlain by ~15 m of tan and olive siltstone, mudstone and shale with erosive-based yellow sandstone interbeds to almost 1 m thick. This interval becomes increasingly poorly exposed upsection and passes upward into ~35 m of covered section.

Interpretation of lower amalgamated sandstone interval

Sandstone and pebbly sandstone of this interval probably record fluvial channel deposition in the Contra Costa-San Pablo estuarine system. Pebbly sands and large-scale trough cross-beds attest to strong current activity, while scour and amalgamation imply turbulent starved currents. Mudrock strata probably record interchannel or floodplain conditions.

Description of rippled sandstone + mudstone interval

Above the covered section is approximately 38 m of interbedded brown sandstone and siltstone and olive to gray shale; shale becomes increasingly gray upsection (figure 10; "S" in figure 11b). Sandstones are primarily fine-grained; grains are fairly angular. Sand and silt occur in beds from one to several dm thick; beds very commonly show internal lamination on a scale of mm to cm. Symmetrical ripples are very common throughout this interval; wavelength typically ranges from 2-4 cm and amplitude is generally <1-2 cm. In some cases sands have erosive bases, although amalgamation is rare or absent. Sandstone dikes are common, and sand in the dikes is generally somewhat coarser than the dominant grain size for this interval.
Figure 11a. Amalgamated fluvial sandstones in upper Contra Costa Group, near base of stop 4 traverse, Cull Canyon.

Figure 11b. Lacustrine strata in upper Contra Costa Group, near top of stop 4 traverse, Cull Canyon. $S =$ shallow-lacustrine units, $O =$ open-lacustrine units.
Figure 11c. Concentration of plant fragments on parting in amalgamated sandstone, Contra Costa Group, Cull Canyon.

Figure 11d. Decimeter-thick buff micrite interbeds in gray open-lacustrine shale, Contra Costa Group, upper portion of stop 4 traverse, Cull Canyon.
Figure 11e. Symmetrical ripples in shallow-lacustrine beds, Contra Costa Group, upper portion of stop 4 traverse, Cull Canyon.
Fossil material is abundant in the rippled sandstone + mudstone association. Carbonized plant fragments to several mm long are common, particularly in the lower third of the interval, where they occur both on parting surfaces and finely disseminated. Ostracodes are also common throughout, especially in sandy/silty units; they occur both disseminated and in beds to several mm thick which resemble very thin winnowed or lag deposits.

**Interpretation of rippled sandstone + mudstone interval**

Liniecki (1986) has identified the ostracodes of the Cull Canyon section as a freshwater assemblage. The rippled sandstone + mudstone association probably represents a shallow-lacustrine and lake-marginal setting, with symmetrical ripples recording low-energy orbital/oscillatory wave currents. Erosive-based sands may document storm events. Similarly, plant-rich parting horizons may reflect storm run-off conditions. Sandstone dikes attest to syn- or early post-depositional disturbance of unconsolidated, water-rich sediments, probably by earthquakes.

**Description of gray shale interval**

The upper ~26 m of section, immediately below the trace of the Cull Creek fault, consist of gray calcareous shale (figure 10; “O” in figure 11b). Minor micritic limestone occurs in sparse decimeter-thick interbeds (figure 11d); limestones are buff to tan on fresh surfaces but weather cream or white. At least one thin (0.7 dm) volcanioclastic interbed is present about halfway through the interval. It consists of medium to coarse sand-grade andesitic-basaltic rock fragments and highly angular, nearly euhedral plagioclase in a distinctive hematite-rich cement. Ostracodes are common throughout the gray shale interval.

**Interpretation of gray shale interval**

Both Liniecki (1986; on fossil grounds) and Buising (1992; based on sedimentological evidence) have interpreted the gray shales as lacustrine deposits. We suggest that they record open-lacustrine conditions. Micrite interbeds may be algal bloom deposits; their sparseness and lack of periodicity, however, suggest that they represent atypical, non-cyclic events. We interpret the volcanioclastic interbed as a distal mass-flow deposit.

**Directions from Stop 4 to Stop 5:**

After examining exposures of the Contra Costa Group in Cull Canyon, return to the vehicles and drive back down Cull Canyon Road to the intersection with Crow Canyon (about 6.3 mi). Turn left on Crow Canyon Road and proceed about 6.9 mi. This winding and scenic drive will take you over the northwest-trending ridge which separates Castro Valley from San
Ramon Valley.

For about the first 1.9 mi of the drive over Crow Canyon, you will be in familiar-appearing outcrops of Cretaceous Great Valley Group sandstone and shale. From about mile 1.9 to just before the intersection with Norris Canyon Road, Crow Canyon runs through the Monterey Group, but these strata are not well exposed in the road. Just past the intersection with Norris Canyon Road, you will begin to see conglomerate and sandstone of the Contra Costa Group in sparse roadcut outcrops. Notice also the abundance of slope failure (both ancient and recent!) in steep slopes developed on the Contra Costa Group.

Continue along Crow Canyon Road over the crest of the hill, and begin the descent into the San Ramon Valley. Turn left at Bollinger Canyon Road. Bollinger Canyon is incised into comparatively recessive strata of the Contra Costa Group. Rocky Ridge to the west (figure 13), and Las Trampas Ridge to the east, are supported by resistant shell hash units of the San Pablo Group; the San Pablo-Contra Costa section is repeated by the Bollinger fault, which is visible as the strong break in slope parallel to and just below the ridge crest on the east flank of Rocky Ridge. As you drive up Bollinger Canyon Road, watch for zebras in a paddock on the right (east) side of the road, and an ostrich farm on the left (west) side.

About 4 mi after turning onto Bollinger from Crow Canyon, you will come to East Bay Regional Park District gates. Drive through the gates and proceed to the EBRPD parking lot on the left side at the end of the road. Enter the parking lot and follow the caravan through the fire road gate on the immediate right. (NOTE: this is a locked, restricted-access gate. If you are using this road log at a time other than with the NCGS field trip, you will not be able to drive through this gate. However, you can walk to the top of Rocky Ridge following the paved fire road. It is a steep climb and a one-way distance of about 1.2 mi, so be sure to allow plenty of time!)

After entering the locked gate, follow the caravan up the paved fire road through two additional gates (one locked, one not) to the top of Rocky Ridge. We will park adjacent to the microwave tower enclosure on top of Rocky Ridge. Please be careful to minimize impact on the watershed!

Stop 5: Rocky Ridge overview --
San Pablo Group west of the Calaveras fault;
Neogene structure in the vicinity of Upper San Leandro Reservoir

Once we have parked the vehicles and congregated, we will traverse to stop 5a, shown on the map in figure 12. If possible, we will go straight through the microwave tower enclosure; otherwise, we will detour around it, following the trail shown on the map.
Figure 12. Location of Stop 5 traverse to examine San Pablo Group stratigraphy and previously unmapped faults on Rocky Ridge. Topographic base from USGS Las Trampas Ridge 7.5' quadrangle.
Figure 13. View to southeast showing westward-facing dipslopes of San Pablo Group sandstone and shell hash on Rocky Ridge.

Figure 14. View to southeast along crest of Rocky Ridge, showing crestline valley defined by “Rocky Ridge” faults of Klinck (this volume).
Stop 5a: Neogene structure, including previously unmapped faults, on and near Rocky Ridge

Stop 5a offers an excellent view both to the northwest and southeast along strike of two previously unmapped faults which define a broad swale between the two parallel crests of Rocky Ridge (figure 14). CSUH MS student Richard Klinck, who is currently carrying out 1:12,000 lithofacies mapping on Rocky Ridge and Las Trampas Ridge, has recently identified these structures based on alignment of geomorphic features, springs, and slickensided outcrops (for discussion, see Klinck, this volume). These northwest-striking, southwest-dipping structures are roughly parallel to the Miller Creek, Cull Creek and Bollinger faults; we follow Klinck (this volume) in tentatively interpreting them as previously unrecognized strands of the East Bay hills reverse fault system. This implies that the geometries of the reverse fault system of the East Bay hills may be more complex than previously appreciated.

Slickensides on exposed fault plane surfaces of the Rocky Ridge faults indicate northeast-vergent dextral oblique reverse slip. Klinck (this volume) interprets this to mean that in at least some parts of the East Bay hills contractile belt, strike slip and contractile slip have occurred simultaneously, and have been accommodated on the same plane(s) of rupture, rather than being discretely partitioned in space and/or time. This further implies that, since strike slip is demonstrably active in the East Bay, contractile structures in this part of the East Bay may also be active.

Directions from Stop 5a to Stop 5b:

Backtrack to the main trail and follow it to the ridge crest south of the microwave tower. Continue south along the ridge crest (see figure 12).

Stop 5b: Briones Formation pebbly shell hashes; San Pablo Group west of the Calaveras fault

The San Pablo Group at Rocky Ridge (and west of the Calaveras fault in general) both resembles and differs from the more "classic" San Pablo east of the Calaveras, exemplified by exposures in the Diablo foothills. Like those in the Diablo foothills, San Pablo outcrops on Rocky and Las Trampas ridges consist of interbedded sandstone, conglomerate, and shell hash, which is commonly pebbly or conglomeratic. Fossil assemblages west of the Calaveras generally reflect shallow marine and perhaps also brackish-estuarine conditions of deposition (figure 3); fluvial and fluvio-deltaic deposits like those at Macedo Ranch (see Walker and others, this volume) have not been recognized to date west of the Calaveras fault.

The most striking difference between the eastern and western tracts of San Pablo Group outcrop is compositional. This is most evident in the Neroly Formation. East of the Calaveras fault, the Neroly is characterized by andesitic bluesands and by conglomerates containing an overwhelming majority of andesitic coarse clasts. West of the Calaveras fault, bluesands are
absent, and andesitic detritus in general is extremely sparse. This implies that andesitic Sierran detritus failed to reach the westerly portion of the San Pablo embayment; our ongoing provenance and sedimentologic studies in the San Pablo Group and coeval portions of the Contra Costa Group may help to-delineate drainage patterns from Sierran and Coast Range source terranes as well as sediment mixing patterns within the embayment.

Outcrop description

At this outcrop, we will examine the resistant shell hashes and sandstones of the Briones Formation which support Rocky Ridge. Briones shell hashes at Rocky Ridge occur in stacked packets of amalgamated beds. Beds range from 1 dm to ~0.3 m thick, and commonly vary in thickness along strike on a scale of several m. No grain size or bed thickness trend is discernible at this outcrop. Shell hash beds are locally separated by lenticular sandy partings to ~2 cm thick. Both sands in the matrix of shell hashes and those in sandy interbeds are yellow, medium- to coarse-grained, angular, poorly sorted and quite lithic rich.

The shell assemblage of these hashes is dominated by heavy-shelled clams between 1.5 and 4 cm wide. Pectens to about 2.5 cm also occur but are much less common. Shells are typically badly broken, and are commonly nested and closely packed.

Coarse clasts range from granules to ~1 cm in diameter and are primarily angular to subrounded. Red (Franciscan?) chert and white vein quartz almost certainly reflect derivation from Coast Range sources. Dark gray fine-grained metasediments and/or metavolcanics may also be of Coast Range origin but could be Sierran-derived. Green chert and quartzose metamorphics could be either Sierran- or Franciscan-derived.

Interpretation

Fossils in this part of the San Pablo section at Rocky Ridge suggest shallow marine conditions. They are badly fragmented, and clearly represent a transported, reworked assemblage, but since only shallow-marine taxa are present, we infer that these beds were in fact deposited in a shallow-marine environment. Erosive-based coarse-clastic units probably record deposition by turbulent, high-energy storm currents. These exposures likely record conditions near the western margin of the Miocene San Pablo embayment (figure 3).

The view from Rocky Ridge (or, on a clear day, you can see forever . . .)

While we are up on top of Rocky Ridge, take a moment to enjoy the view. This is an ideal spot for contemplating the relationship between structure (both strike slip and contractile) and topography in the modern Bay area. It’s also an ideal spot for contemplating the extent of the Miocene San Pablo embayment and related topography.
The last directions we’re going to give you

When you have looked your fill, we will return to the vehicles, and drive out the way we came in. We will need to caravan to the base of the hill, in order to get all the vehicles back out through the locked gates on the fire road. From the EBRPD parking lot, we will proceed back out along Bollinger Canyon (take a final look at the Bollinger fault!) to Crow Canyon, and turn left on Crow Canyon to head for 680. We will return to Chevron and re-shuffle the vehicles from this point.

This concludes the field trip -- thanks for joining us!

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Evidence for two previously unmapped faults on Rocky Ridge, Contra Costa County, California

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Introduction

This paper is a progress report on the preliminary findings of an ongoing MS thesis research project in the East Bay Hills (map 1). Continued work on the project to further support these findings will be forthcoming.

Slip partitioning in time and space between strike slip and contractile faults over the last 5 m.y. is one of the big uncertainties in our understanding of East Bay geology (e.g., Busing and Walker, 1995). Recent field data described herein suggest that strike slip and reverse slip may not be discretely partitioned, but may instead be combined to produce oblique reverse displacements.

Lithofacies mapping at a scale of 1:12,000 in the East Bay Hills has revealed evidence for two previously unmapped and potentially significant faults on Rocky Ridge in the Las Trampas Ridge 7.5' quadrangle (map 2). The newly identified structures are roughly parallel to and may be genetically related to the Miller Creek, Cull Creek, and Bollinger faults. Slickensides on an exposed slip surface of one of the "Rocky Ridge" faults indicate oblique reverse displacement toward approximately N25E. If dextral and reverse slip have combined to produce this oblique reverse faulting in the past, there is perhaps reason to believe that these and other reverse faults in the East Bay Hills are active in the present transform environment.

Field evidence

There are several lines of evidence which suggest the presence of two bedding-parallel faults within the upper member of the Briones Formation on Rocky Ridge (stratigraphy of Ham, 1952). The faults appear to lie between beds and parallel or sub-parallel to bedding so there are no obvious offsets of beds to provide unequivocal evidence of faulting but other field criteria detailed below are strongly suggestive.

Stratigraphic evidence

The upper member of the Briones Formation on Rocky Ridge consists of about 225 m of
fine-grained sandstone lying in a valley which trends along the crest line of the ridge (figure 1 sec. A-A'). This sandstone has a low resistance to weathering and does not tend to crop out. It is typically mantled with thick soil and covered with grasses. Intercalated in this sandstone there are at least five marker beds 2 m to 15 m thick which are more resistant and crop out locally, providing some topographic expression of structure. These marker beds appear to be lithologically similar to the surrounding softer sandstone except for their greater hardness and local calcareous concretions found near the fault traces (figure 1 sec. B-B'). The hardness of the marker beds is probably due to non-calcareous cementation.

**Geomorphic evidence**

The topography of Rocky Ridge is somewhat unusual. There is a valley trending along what would normally be the crest line of the ridge (figure 1 sec. A-A'). Ham (1952) attributes this valley to the incompetence of the upper member of the Briones Formation which occupies the valley. However, the same member is exposed on Las Trampas Ridge to the east of Rocky Ridge but on that ridge there is no analogous valley. I suggest that the crest line valley on Rocky Ridge is a result of erosion along the two faults that lie within it (map 2).

Additional geomorphic evidence for the presence of the two faults includes: abrupt breaks in slope angle; notches eroded into saddles which cross the crest line valley; and mass wasting and gullying along the inferred traces of the faults. There are two very distinct slope breaks at the upper contacts of two of the markerbeds (figure 1 sec. B-B'). These may be a result of the resistance of the markerbeds but there are three other similar beds which have no such topographic manifestation. Moreover, all of the other field evidence is found at, or in line with, these slope breaks. Therefore I tentatively interpret these slope breaks as fault-line scarps.

The crest line valley formed by the upper member of the Briones Formation is transected by several saddles between the two ridge-forming units that border the valley: the middle member of the Briones Formation to the east and the Cierbo Formation to the west (map 2 sec. B-B' lies on one of these saddles). These saddles typically have two low spots or notches eroded into their profile (figure 1 sec. B-B'). The flanks of the saddles are commonly incised along the two fault traces where the trunk drainage of the valley splits and becomes two-headed on both sides of a saddle. The notches in the saddles and the gullying on their flanks line up along the apparent fault traces, suggesting preferential erosion due to faulting.

**Hydrologic evidence**

A number of springs and seeps lie directly on the inferred map traces of the faults (map 2). One very large spring on the eastern fault is the headwater for Bolinas Creek, a large perennial stream. The abundance of springs may be due to flow through fracture permeability along the faults or ponding of the water table behind impermeable fault gouge. Further hydrologic study of the catchment area and hydraulic conductivity of the upper Briones sandstones may determine which mechanism produces the springs. However they arise, their
MAP 2:
Traces of inferred faults on Rocky Ridge

EXPLANATION

- fault
- spring
- slickenside locality
- $AA'$ line of section for cross sections shown on Figure 1

Scale

0 0.5 km

40
abundance and their linear alignment suggests a fault-controlled origin.

**Structural evidence**

A detailed cross-section of one of the saddles crossing the upper Briones member (figure 1 sec. B-B') shows a very abrupt change in bedding attitudes separated by a zone of disturbed bedding, where attitudes are very disrupted. The bedding attitudes appear to change at the base of one of the two inferred fault-line scarp. The change in attitudes is not great, amounting to about 20 degrees change in dip, but measurements taken stratigraphically above and below the disrupted zone are quite consistent, suggesting that the scarp demarcates two distinct structural domains.

A few slickensided surfaces have been found in place along the fault traces; measurements of slickenside attitudes on those surfaces, listed in Table 1, are remarkably consistent. While mapping the length of the crest line valley I have also encountered numerous pieces of float rock with slickensided surfaces lying near the fault traces. Slickensides may just be a result of inter-bed slip during folding, but mapping in the Contra Costa Group nearby has not revealed any similar features even though those beds are more tightly folded than the San Pablo Group on Rocky Ridge (A. V. Buising, pers. comm., 1996).

The coup de theatre of structural evidence is a large sandstone outcrop in the north end of the crest line valley (site S1, map 2) which was exposed in a soil slip during the storms of 1995. This outcrop has a deeply scored slickensided surface of about 0.5 m² which clearly shows the rough direction of the slickensides, indicating displacement of the upper plate toward 025 on a fault plane oriented 340/45-60 SW, i.e. oblique reverse faulting. These may be the first kinematic indicators found in the East Bay Hills west of the Calaveras fault and they are strong evidence for a local dextral oblique contractile environments.

**TABLE 1**

<table>
<thead>
<tr>
<th>Attitudes of slickensided surfaces found in place</th>
<th>(Map # refers to site locations on map 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Map#</strong></td>
<td><strong>Attitude of Surface</strong></td>
</tr>
<tr>
<td>S1</td>
<td>326/45W</td>
</tr>
<tr>
<td>S2</td>
<td>330/58W</td>
</tr>
<tr>
<td>S3</td>
<td>341/60W</td>
</tr>
<tr>
<td>S4</td>
<td>322/81W</td>
</tr>
<tr>
<td>S5</td>
<td>321/68W</td>
</tr>
</tbody>
</table>
**FIGURE 1**

Structural cross sections of Rocky Ridge, Contra Costa County, California.
Geology after Ham (1952) and Klinck (unpublished field data).
Conclusions

If my interpretation of these faults as oblique reverse structures is correct, they may have significant implications for the timing of faulting and the seismic potential of the many similar structures in the East Bay Hills. Oblique reverse displacement may indicate that contractile and dextral stresses are acting simultaneously in the crustal block between the Hayward and Calaveras faults. Perhaps strike slip and reverse slip are not partitioned onto discrete dextral and reverse rupture surfaces, but instead combine to produce oblique reverse motion. This suggests that contractile deformation in the East Bay Hills is concomitant with the strike slip displacement we know to be active on the Hayward and Calaveras faults. If this is true, than any one of the many reverse faults in the East Bay Hills may have the potential to slip in response to this combination of stresses.

References cited


Stratigraphy and tephrochronology of the Neogene section at Shell Ridge, Contra Costa County, California

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¹Department of Geological Sciences, California State University, Hayward, Calif.  

Introduction

Shell Ridge is one of several parallel, linear, northwest-trending ridges that extend west of Mount Diablo, in eastern Contra Costa County (figure 1). The sedimentary strata that form these ridges are steeply inclined to slightly overturned by the uplift of Mount Diablo. The Neogene section on the southwest flank of Mt. Diablo includes, in stratigraphic order, the Miocene Monterey and San Pablo Groups, and the Miocene-Pliocene Sycamore Formation (figure 2). North of Pine Canyon, the Neogene section includes both the Monterey and San Pablo Groups in conformable contact. At the latitude of Pine Canyon the Monterey Group is missing. The combined average thickness of the Monterey and San Pablo Groups is approximately 1.6 km.

Monterey Group

The Middle to Upper Miocene Monterey Group is represented in the Shell Ridge area by the Hambre Sandstone and the Rodeo (?) Shale (figure 2). In this section, the two formations compose a general upward-finining trend. The Hambre Sandstone makes up the low ridges to the east of Shell Ridge. The Rodeo (?) Shale is represented in this area by a siltstone that occupies the saddle between the low ridges of Hambre Sandstone to the east and Shell Ridge (composed of the Briones Formation) to the west (figure 1).

Hambre Sandstone

The Hambre Sandstone is approximately 213 m thick; it is composed of buff to light-gray sandstone. Compositionally, the Hambre is a very fine- to medium-grained lithic-rich quartzofeldspathic sandstone. Contained within the Hambre are resistant, buff carbonate lenses that underlie the ridge directly east of Shell Ridge. At roughly the same stratigraphic level as the carbonates, lenses of shell hash occur locally. At one location, pieces of fossilized wood as much as 80 cm in length and from 10 cm in diameter tapering to less than 5 cm have been found. The pieces appear to be gnarled branches with intact bark. Conglomerate lenses are present in the Hambre; they commonly show internal cross-bedding and in turn are cross-bedded with the surrounding sands.

The Hambre shell hashes are typically ~50 cm thick. They contain high-spired gastropods 15-20 mm long, heavy-shelled pelecypods, and ridged pelecypods 2-3 cm wide. Some of the pelecypods appear to be intact while others have been damaged. This is a markedly different assemblage than that found in the stratigraphically higher Briones Formation.

The clasts found in the Hambre conglomerate lenses are in the pebble size range. They are primarily metavolcanic and metasedimentary pebbles. Other significant
Figure 1.

Geologic Map:
Neogene section of Mount Diablo Foothills
Contra Costa County, California

James P. Walker

Scale

North
1 KM

Location of map area

ML Grinks

Tps

Macedo Ranch

Tem
## Composite columnar section of the Neogene at Diablo Foothills
Contra Costa County, California

<table>
<thead>
<tr>
<th>Unit / Time</th>
<th>Age</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top not exposed</td>
<td>4.1 Ma</td>
<td>Sycamore Formation — Siltstone. Light tan in outcrop. Unidentified razor clams and plant material (rushes?) present.</td>
</tr>
<tr>
<td>&gt;5.2 Ma</td>
<td></td>
<td>Neroly Formation — Fine- to coarse-grained volcano-lithic sandstone. Blue in outcrop. In general, coarsens upward. Lower portion is trough cross-beded. Fossil leaf material present at various horizons. Decimeter-scale shell hash. Fossils include: Glycines septemalis (?), Protolitica paphia, and Cardium sp. Conglomerates dominate the upper portion.</td>
</tr>
<tr>
<td>570 m</td>
<td></td>
<td>Briones Formation — Fine- to coarse-grained lithic-rich quartzofeldspathic sandstone. Yellow-gray in outcrop. ~140 m above base are coalescing shell hash lenses several less extensive shell hashes upsection. Shell hashes contain: heavy-shelled pelecypods to 6 cm long, oysters approximately 20 cm long, Natica sp., Astrodapsis sp., and Astrodapsis carboensis. Conglomerate lenses are common.</td>
</tr>
<tr>
<td>762 m</td>
<td>11.3 Ma</td>
<td>Rodeo Shale — Poorly cemented siltstone in limited exposures. Contains clams of the genus Tagelus.</td>
</tr>
<tr>
<td>52 m</td>
<td></td>
<td>Humbre Sandstone — Very fine- to medium-grained lithic-rich quartzofeldspathic sandstone. Buff to light gray in outcrop. Lenses of conglomerate, carbonate, and shell hash. Fossilized wood (branches with bark?). Shell hash lenses contain gastropods 15-20 mm long, heavily-shelled, and ridged pelecypods 2-3 cm long. Conglomerate lenses are internally cross-beded and cross-beded with the surrounding sands.</td>
</tr>
</tbody>
</table>

**Key:**
- Siltstone
- Sandstone
- Trough cross-beded Sandstone
- Tuff
- Carbonate
- Conglomerate
- Shell hash
- Fossil
- Wood
- Leaves

**Scale:** 200 m

Figure 2.
components are black chert and white vein quartz. Additional clast lithologies include: fine-grained metasediments, metavolcanics, grey quartzite, fine-grained igneous intrusive rocks, micaceous quartzite, yellow metasiltstone, graywacke, felsic metaporphry, green chert, and fine-grained white felsic porphyry containing quartz, plagioclase, and mica. Two light gray clasts containing monocristalline quartz have been found in two different conglomerate lenses. These last-mentioned pebbles resemble clasts found in the Delleker Formation tuffs in the Northern Sierra Nevada (Durrell, 1987).

Rodeo (?) Shale

The Hambre Sandstone grades upward into a lithologically similar siltstone that may be the shoreface equivalent of the Rodeo Shale, a formation present further to the west and north of Shell Ridge. The average thickness of the unit is 52 m. The siltstone is poorly cemented and consequently exposures are limited. Small razor clams of the genus Tagelus, indicative of an environment below wave base (J. W. Durham, pers. comm., 1994), have been collected in this study.

San Pablo Group

The San Pablo Group comprises the Briones and Neroly Formations, following Wagners' (1978) grouping of these formations. At the base of the San Pablo Group is the Briones Formation, which is in conformable contact with the underlying Rodeo (?) Shale (figure 2). The Briones forms Shell Ridge and the valley directly west of it. The Neroly Formation underlies the next set of ridges to the west of Shell Ridge (figure 1). The average thickness of the San Pablo Group is 1334 m.

Briones Formation

The Briones Formation is 762 m thick and is composed of yellow-gray sandstones. The Briones is a fine- to coarse-grained, quartzofeldspathic, lithic-rich sandstone. Approximately 140 m above the base of the Briones is a series of coalescing, resistant shellhash lenses that form the crest of Shell Ridge. There are also several less extensive shell hashes higher in the section. Conglomerate lenses are also common in the Briones and are stratigraphically scattered throughout the section. Both the shell hashes and conglomerates may contain significant proportions of either clastic or biogenic material, and the one grades into the other.

The composition of the shell hashes varies along strike and with stratigraphic position. Endemic to all, though, are heavy-shelled pelecypods as much as 6 cm long. Present in the stratigraphically lower shell hashes are oyster valves as much as 20 cm long (Ostrea titan?). Less stratigraphically restricted are gastropods of the genus Natica, and the echinoderms Astrodapsis sp. In one of the upper shell hashes Astrodapsis cierboensis is present, indicating an environment just below the surf zone (J. W. Durham, pers. comm., 1994).

The Briones conglomerates are massive and commonly contain varying amounts of broken shell material. Clast size varies within the conglomerates from granules to pebbles 6 cm in diameter. The lithologies represented by the pebbles are: red and black chert; vein quartz; white felsic porphyry with plagioclase and hornblende; dark grey porphyry with plagioclase and hornblende; grey quartzose metamorphic rocks; light gray tuff (?) with
plagioclase and hornblende; and green metavolcanics with saussuritized plagioclase. In contrast to the Monterey conglomerates, the Briones conglomerates contain a significantly greater proportion of volcanic clasts.

At approximately 180 m below the Briones-Neroly contact is a previously unmapped tuff. Analysis of volcanic glass shards separated from this tuff (table 1) provides a method of correlating this tuff to other localities. Results of electron-microprobe analysis of this tuff (samples 8 and 9, table 1) indicate that it is correlative with a tuff found in the Briones (?) or Cierbo (?) Formation, in essentially the same stratigraphic position below the Neroly Formation, on the north side of the Mount Diablo anticlinorium, in the Los Medanos Hills (sample 10, table 1). We also tentatively correlate this tuff with a tuff in the Aldrich Station Formation in west-central Nevada, near Walker Lake (sample 11, table 1; see Sarna-Wojciecki and others, 1991). At the latter locality, massive tuffs each underlie and overlie the tuff of sample 11, and are in turn correlated to another section at Trapper Creek, Idaho (see Perkins and others, 1995). At the last locality, the tuffs have been dated by the laser-fusion 40Ar/39Ar method, providing an interpolated, correlated age of ~11.5 Ma for the tuff in the Briones Formation.

The tuff is a sandy cross-bedded unit that grades from an underlying light gray, very fine-grained tuffaceous sand into the pumiceous lapilli tuff. Present in the tuff are rare pelecypod fossils. The sand component of the tuff is medium- to coarse-grained, poorly sorted, and rich in monocrystalline quartz. The tuff grades into an overlying very fine-grained tuffaceous sand containing fossils of the genus Tagelus, indicative of an environment just below wave base (J. W. Durham, pers. comm., 1993).

Neroly Formation

The Neroly Formation conformably overlies the Briones Formation. The Neroly Formation is approximately 570 m thick and is composed of fine- to coarse-grained sands, which show a general upward coarsening trend. Compositionally, the Neroly is a volcaniclastic sandstone, with quartz and feldspar making up the other major constituents; brown hornblende is a significant minor constituent. The sands have a characteristic blue color in outcrop, due to a coating of montmorillonite clay on the grains (Hill, 1979). Much of the lower portion of the Neroly is trough cross-bedded. In the upper portions of the Neroly, conglomerates dominate. The conglomerates are commonly interbedded with muds and sands in packets that show a general upward-finings trend in contrast to the overall upward-coarsening trend in the formation. Shell hashes are present in the Neroly, though they represent a smaller percentage of the unit than they do in the Hambre or Briones Formations. In contrast, conglomerates make up a greater proportion of the Neroly than they do in either the Hambre or Briones. The Neroly also contains fossil leaf material at various horizons.

Shell hashes in the Neroly are thinner than those in the underlying units; they are commonly ~10 cm thick. Fossils in the Neroly include Glycimeris septenalis (?), Protodroclus paphia, and Cardium sp., which are indicative of an environment just below the surf zone (J. W. Durham pers. comm., 1993).

Conglomerates in the Neroly contain a higher percentage of sand-size matrix than the conglomerates in the underlying units. Clasts in the Neroly conglomerates include the following lithologies: red, green, and black chert; white vein quartz; yellow quartzite; green metavolcanics with saussuritized plagioclase phenocrysts; fine-grained quartzose metamorphic rocks; gray basalts; basalts with a red hematite groundmass and pyroxene phenocrysts; and hornblende andesites.
### Table 1. Chemical composition of volcanic glass shards determined by electron-microprobe analysis of Neogene tuffs from Shell Ridge, and correlated reference samples. Values given are in weight-percent oxide, recalculated to 100 percent. About 15 individual glass shards were analyzed for each sample. S.C. - similarity coefficient for comparison of samples 1, 6, 8, and 9, with similar reference samples; a value of 1 represents a perfect match. Average values of analyses of a homogenous glass standard are given to provide estimate of precision. C. E. Meyer, U.S.G.S., Menlo Park, analyst.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>MnO</th>
<th>CaO</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>S.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. MRT-2</td>
<td>73.4</td>
<td>14.3</td>
<td>2.16</td>
<td>0.09</td>
<td>0.03</td>
<td>0.87</td>
<td>0.16</td>
<td>4.31</td>
<td>4.60</td>
<td>1.000</td>
</tr>
<tr>
<td>2. WC-B3B</td>
<td>73.8</td>
<td>13.9</td>
<td>2.17</td>
<td>0.09</td>
<td>0.07</td>
<td>0.93</td>
<td>0.17</td>
<td>4.30</td>
<td>4.55</td>
<td>0.973</td>
</tr>
<tr>
<td>3. 758-141A(2)</td>
<td>73.4</td>
<td>14.3</td>
<td>2.16</td>
<td>0.09</td>
<td>0.04</td>
<td>0.88</td>
<td>0.17</td>
<td>3.67</td>
<td>5.30</td>
<td>0.987</td>
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<tr>
<td>4. 758-156A</td>
<td>73.6</td>
<td>14.3</td>
<td>2.17</td>
<td>0.08</td>
<td>0.04</td>
<td>0.89</td>
<td>0.16</td>
<td>4.71</td>
<td>4.11</td>
<td>0.976</td>
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<tr>
<td>5. LAWLER-1</td>
<td>73.2</td>
<td>14.3</td>
<td>2.15</td>
<td>0.09</td>
<td>0.04</td>
<td>0.84</td>
<td>0.18</td>
<td>4.83</td>
<td>4.37</td>
<td>0.974</td>
</tr>
</tbody>
</table>

3. Lawlor Tuff (4.1 Ma); Sycamore Fm., Shell Ridge, this study (1), Isaacson and Andersen (1992) (2), and Lawlor Tuff exposed on north flank of Los Medanos Hills, north of Mount Diablo and the study area (3-5); sample (5) is from the type locality in Lawlor Canyon (Sarna-Wojicki and others, 1991).

2. Tuff near the base of the Sycamore Fm. (>6.25 Ma), Macedo Ranch (Isaacson and Andersen, 1992) (6) and near the base of the Sycamore Fm., 2 miles east of Tassajara, south of Mt. Diablo (7) (Sarna-Wojicki, 1971).

1. Tuff in the Briones (?) Fm. (~11.5 Ma), Shell Ridge, this study (8, 9), tuff in the Briones (?) Fm., Los Medanos Hills north of Mt. Diablo (10), and tuff near the top of the Aldrich Station Fm., west of Walker Lake, Nev. (11); the latter tuff is underlain and overlain by two tephra layers that are correlated to the Trapper Creek section, Ida.; the two tephra layers at the latter locality are dated directly by the 40Ar/39Ar method (Perkins and others, 1995).

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>MnO</th>
<th>CaO</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>%</th>
<th>Natural glass standard used as monitor in analysis (electron-microprobe analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. MRT-3A</td>
<td>78.7</td>
<td>13.6</td>
<td>0.58</td>
<td>0.08</td>
<td>0.07</td>
<td>0.54</td>
<td>0.09</td>
<td>2.31</td>
<td>4.02</td>
<td>1.000</td>
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<tr>
<td>9. MRT-3B</td>
<td>78.7</td>
<td>13.6</td>
<td>0.58</td>
<td>0.08</td>
<td>0.07</td>
<td>0.54</td>
<td>0.09</td>
<td>2.34</td>
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<tr>
<td>10. 920609-2</td>
<td>78.0</td>
<td>13.3</td>
<td>0.55</td>
<td>0.08</td>
<td>0.06</td>
<td>0.54</td>
<td>0.10</td>
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<td>4.61</td>
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<tr>
<td>11. BE-25</td>
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<td>0.56</td>
<td>0.07</td>
<td>0.07</td>
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<td>0.10</td>
<td>1.40</td>
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</table>

Natural glass standard used as monitor in analysis (electron-microprobe analysis)

<table>
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<tr>
<th>RLS 132 (n=18)</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>MnO</th>
<th>CaO</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>%</th>
<th>Natural glass standard used as monitor in analysis (wet-chemical analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75.4</td>
<td>11.3</td>
<td>2.12¹</td>
<td>0.06</td>
<td>0.16</td>
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<td>0.19</td>
<td>4.9</td>
<td>4.4</td>
<td>1.000</td>
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<tr>
<td>± 1 σ:</td>
<td>0.1</td>
<td>0.2</td>
<td>0.04</td>
<td>0.01</td>
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<td>0.1</td>
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<td></td>
</tr>
<tr>
<td>% σ:</td>
<td>0.2</td>
<td>1.4</td>
<td>1.9</td>
<td>17</td>
<td>6.3</td>
<td>9</td>
<td>5.3</td>
<td>2.7</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

³Iron reported as FeO for the standard.
The basalt clasts with a red hematite groundmass and pyroxene phenocrysts match basalts in the Grizzly Peak Formation (this study), while the hornblende andesite clasts are derived from the Merhten Formation in the northern Sierra Nevada (E. R. Brooks, pers. comm., 1994). The presence of these two clast types in the same conglomerate packets indicates provenances from both the east and the west. The Grizzly Peak Formation basalts would have had to be transported from west to east across an embayment larger than modern San Francisco Bay in order to occur in their present position near the eastern shore of the embayment; however, the eastern shore of this embayment was dominated by deposition of Sierran material coming from the east, as indicated by the composition of sands in the Neroly Formation (Graham et al., 1984; Buising and Walker, 1995). The association of these two clast lithologies thus presents an unresolved challenge to paleogeographic reconstructions for the East Bay region.

Deposition of the Neroly Formation lasted from about 11.2 Ma to about 9.8 Ma, based on correlated ages of tephra layers in the Neroly Formation in the Los Medanos Hills, north of Mount Diablo (Sarna-Wojcicki, unpublished data).

**Sycamore Formation**

The Sycamore Formation unconformably overlies the Neroly. The lower portion of the Sycamore Formation is predominantly composed of a light tan siltstone containing unidentified razor clams and plant material (rushes?). For a more detailed discussion of the Sycamore Formation, see Isaacson and Andersen (1992).

A lithic-rich tuff is present at the base of the Sycamore Formation near Macedo Ranch (sample 6, table 1). The groundmass of the tuff is composed of a very poorly sorted, angular, granule conglomerate, with pumice lapilli. Analysis of volcanic glass from this tuff indicates that it is correlative with a tuff found to the east, near Tassajara, also near the base of the Sycamore Fm (sample 7, table 1). This tuff underlies the Roblar tuff of Sarna-Wojcicki (1992), dated recently at 6.25 Ma by the laser-fusion $^{40}$Ar/$^{39}$Ar method (R. J. Fleck, pers. comm., 1995).

Approximately 3.2 km northwest of Macedo Ranch and 230 m above the Neroly-Sycamore contact is a second tuff. This tuff is 2-3 m thick and contains minor interbeds of mud and unidentified pelecypod fossils. Analysis of the tuff indicates that it is the 4.1-Ma Lawlor Tuff (sample 1, table 1). The tuff had been previously reported as the Lafayette Tuff by Wagner (1978).

**Conclusions**

Based on fossil data, the Monterey Group near Mt. Diablo appears to have been deposited in a shelf environment of not more than 60 m depth. Shell hashes and conglomerates suggest a fairly high-energy environment. Based on fossil and sedimentologic data, the paleoshoreline was probably west of the present-day location of Mt. Diablo. The data from the Monterey conglomerate clasts suggest the most likely provenance for the Monterey Group was the Sierra Nevada, specifically, Sierran roof-ependant metamorphics or the western foothills metamorphic belt. It is also quite possible that Franciscan outcrops to the north were a secondary source (Buising and Walker, 1995).

Paleoenvironmental conditions do not appear to have changed greatly from the
Monterey Group to the Briones Formation, at least in the vicinity of Mt. Diablo. Fossil and tuff data from the Briones Formation suggest a slightly shallower environment at 11.5 Ma than during Monterey Group time.

The Neroly Formation over most of the area is fluvial at and near its base. However, in the section at Macedo Ranch, the packets of conglomerate interbedded with muds and sands that show a general upward-fining trend are interpreted as having formed from a migrating-channel delta. The complete lack of marine fossils in the conglomerate packets in an environment that has abundant shell material, as evidenced by the shell hashes in the intervening sand units, together with leaf fossils found in the conglomerates, suggests a supratidal environment of deposition for the conglomerate packets. The above, coupled with the fossil evidence found in the intervening sands, suggests that the Neroly Formation at Macedo Ranch was deposited alternately immediately above and immediately below sea level.

Exposures of the Sycamore Formation, while sparse, suggest a nearshore environment of lesser energy. Poor sorting and angular clasts suggest source terranes that were more proximal to the depositional basin than was the case for the underlying units. As suggested by the tuff dates from the Sycamore Formation, the base of the Sycamore appears to be slightly older to the south, suggesting that early uplift of Mt. Diablo first manifested itself west of the present crest of the mountain.

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PRELIMINARY PALINSPASTIC PALEOGEOGRAPHIC RECONSTRUCTIONS FOR THE GREATER SAN FRANCISCO BAY AREA, 15 Ma - 5 Ma

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ABSTRACT

This paper presents preliminary versions of palinspastic paleogeographic reconstructions for the greater San Francisco Bay area at 15, 10, and 5 Ma. Our reconstructions rely largely on the available sedimentologic, stratigraphic, and geochronologic literature for the Miocene and early Pliocene record in the greater Bay area east of the San Andreas fault zone; we have also integrated results of ongoing California State University, Hayward field studies. We have made a first-order attempt to restore both strike-slip and contractile deformation. Our reconstructions suggest that the primary control on basin evolution in the Bay area between ~15 Ma and ~6 Ma was right-lateral strike slip; contraction driven by Pacific-North American plate convergence was probably not important until 5-7 Ma. Deposition of bathyal sediments (Claremont Shale and equivalents) over much of the East Bay region around 15 Ma suggests significant pre-15 Ma subsidence, while eruption of the Page Mill Basalt at ~15 Ma is generally taken to signal initial rupture along the peninsular San Andreas trend. We suggest that "Claremont" subsidence may have represented a precursory strike-slip effect. Between 15 and 10 Ma, the Bay area structural and stratigraphic record is characterized by a pattern of block segmentation (localized uplift and subsidence) which is similar in scale and style to classic southern California borderland examples. Regional geometries at 10 Ma continue to suggest landscape evolution and sedimentation dominated by dextral strike-slip effects. Using the approximate or averaged strike of the San Andreas and Hayward faults as the orientation of the main strike-slip rupture, the trend of the elongate San Pablo shallow-marine embayment at 10 Ma coincides with the predicted orientation of extensional faulting driven by a dextral master wrench, suggesting that the San Pablo embayment occupied an extensional low associated with the transform plate boundary system. Similarly, the orientation of the nascent Diablo Range at 10 Ma (roughly normal to the trend of the San Pablo embayment, and at about 30° to the main strike-slip rupture trend) is consistent with an origin by wrench-driven contraction. By contrast, the 5 Ma map shows wholesale uplift in the Bay area, along a trend no longer at an angle to the plate boundary, but essentially parallel to it. We interpret this shift in uplift style (from localized to widespread) and orientation (from boundary-oblique to boundary-parallel) as signalling the onset of significant plate-boundary-normal compression and associated contractile deformation, some time between 10 and 5 Ma. Further, our reconstructions suggest that the Mendocino triple junction (MTJ) may have been located as far north as the southern Peninsula at 15 Ma; it was probably near the latitude of modern San Pablo Bay at 10 Ma, and near the latitude of the Sonoma volcanic field by 5-8 Ma. This suggests rough constraints on northwestward (plate-boundary-parallel) migration rates for the MTJ: ~2.1 cm/yr between 15 and 10 Ma, ~1.1 cm/yr between 10 and 5 Ma, and ~5.3 cm/yr after ~5 Ma.

INTRODUCTION

In this paper we present paleogeographic reconstructions for the greater San Francisco Bay area at intervals during mid-Miocene through Pliocene time; our reconstructions differ from previous Bay area paleogeographic maps (e.g., Graham and others, 1984) in being palinspastic. We initially constructed these maps as a conceptual tool for the East Bay Miocene-Quaternary tectonics and sedimentation working group at CSU Hayward. We regard the versions presented in this paper as work in progress; we present them in the hope that they will be useful to others with related interests, and in the hope of stimulating discussion and garnering additional feedback on the maps. We anticipate that our reconstructions will continue to evolve, resolve, and improve as work on Miocene and post-Miocene tectonics and sedimentation in the Bay area proceeds.

A primary goal in constructing these maps was to address the structural (i.e., tectonic) controls on mid-Miocene through Pliocene landscape evolution and sedimentation in the Bay area. We have been particularly interested in differentiating the relative roles of strike-slip effects (including transtension-transpression) and contraction in controlling Bay area Neogene basin evolution. Although the geologic record in the Bay area, and the California Coast Range as a whole, contains abundant, well-documented evidence for both strike-slip and contractile deformation (e.g., Aydin and Page, 1984; Namson and Davis, 1988; Unruh and others, 1992), the geometric and genetic relationship between the two structural styles is commonly unclear; resolving this issue in the Bay area has a broader application to addressing the history and significance of compression/contraction along the full length of the Pacific-North American plate boundary. One fundamental step in evaluating the relationship (or relationships?) between strike slip and contraction is to establish their relative timing in various regions. Reconstructions like those presented in this paper can assist in this task by delineating changes in landscape geometry over time.

BACKGROUND

Tectonic setting and Mesozoic-Cenozoic geologic history of the San Francisco Bay region

The modern San Francisco Bay area straddles the transform boundary between the Pacific and North American plates (Fig. 1). Modern landscapes in the Bay area are largely controlled by motion along strands of the plate-boundary fault system and associated structures, which divide the region into a series of roughly parallel, generally northwesterly-trending ridges and depressions.

The plate-boundary fault system comprises three main strands, all characterized by a dominant right-lateral sense of separation. The westernmost of the three strands is the San Andreas fault (~15 Ma at the latitude of the Bay area; e.g., Fox and others, 1985), which bisects the peninsula on the west side of the modern Bay (Fig. 1). The central and eastern strands are the Hayward fault (~10 Ma; Graham and others, 1984) and the Calaveras fault (~4 Ma; Page, 1982), which together define the steep ridge of hills east of the modern Bay (Fig. 1).

During Mesozoic time, the region now occupied by San Francisco Bay and the surrounding hills (Fig. 1) lay at the convergent boundary between the oceanic Farallon and continental North American plates. Mesozoic subduction is recorded in the San Francisco Bay area by exposures of Franciscan accretionary prism rocks and by forearc basin sediments of the Great Valley Group (Radbruch, 1969); farther east, the Sierra Nevada represents the exhume plutonic root of the Mesozoic-early Cenozoic arc system (Dickinson, 1981).

The Farallon-North American trench consumed oceanic lithosphere faster than it was produced at the spreading center; thus, as subduction proceeded, the East Pacific Rise and Pacific Plate came into contact with North America, initiating the Pacific-North American transform boundary at about 30 Ma. The young transform was bounded to the north by the Mendocino triple junction (ridge-transform-transform), and to the south by the Rivera triple junction (ridge-trench-transform). Over the next ~25 m.y., the Farallon plate was progressively consumed at the active arc segments north and south of the transform, and the transform boundary lengthened. Thus, the Mendocino triple junction migrated northward, and the Rivera triple junction southward, to their modern positions off Cape Mendocino and at the mouth of the Gulf of California respectively (Atwater, 1970; Dickinson and Snyder, 1979; Sevinghaus and Atwater, 1990).

As the Mendocino triple junction migrated northward, central California underwent a progressive
Figure 1. Location map. SAF = San Andreas Fault; HF = Hayward Fault; RCF = Rodgers Creek Fault; Calif = Calaveras Fault; ConF = Concord Fault; GF = Greenville Fault. BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block. Highways and freeways shown are those used as piercing points in restoring strike slip along block-bounding faults.

Table 1. Net slip, timing of slip onset, derived constant (average) slip rate, and Holocene movement rate for major "block-bounding" fault strands in the greater San Francisco Bay Area. SAF = San Andreas Fault; H-RCF = Hayward-Rodgers Creek fault trend; Cal-Car = Calaveras-Carneros fault trend; Gr-D-C-GVF = Greenville-Diablo-Concord-Green Valley fault trend. Net slip, slip onset, and Holocene rate figures rounded off from data in Graham and others (1984), Page (1990) and Sarna-Wojcicki (1992).

<table>
<thead>
<tr>
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<th>Holocene Rate</th>
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<td>Grnvile-0.1-0.7 cm/yr</td>
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transition from subduction to transform tectonics. This is documented regionally by the northward-younging shut-off of Sierran arc volcanism (e.g., Dickinson and Snyder, 1979). In the Bay area, as throughout the Coast Range, local Neogene volcanic suites have been interpreted as marking the northward passage of the Mendocino triple junction, and the onset of motion along strands of the transform boundary (Fox and others, 1985; Graham and others, 1984). One such assemblage is the ~15-Ma Page Mill Basalt, which was erupted during the early phases of motion on the San Andreas fault south of San Francisco (Fox and others, 1985; Fig. 1). In the East Bay, the ~10-Ma Grizzly Peak volcanics are associated with the initiation of motion on the Hayward fault, and unannealed ~3.6-Ma basalts near Gilroy may signal the onset of Calaveras fault slip (Page, 1982; Graham and others, 1984).

Tentative correlation of several volcanic units suggests constraints on total slip along the Hayward fault and its presumed northerly continuation (see Fox, 1983; Youngman, 1989), the Rodgers Creek fault (Fig. 1). For instance, Louderback (1951) and later Fox and others (1985) proposed a correlation between the Tolay Volcanics of Sonoma County, and the lithologically similar Grizzly Peak Formation in the Berkeley Hills (Fig. 1); this implies post-Tolay slip of about 43 km along the Hayward-Rodgers Creek trend (cf. the 38 km figure derived from correlation of sedimentary units by Liniecki-Laporte and Andersen, 1988). Youngman (1989) echoed this estimate by correlating what she renamed the Donnell Ranch Volcanics (the Neogene volcanics exposed between the Tolay and Rodgers Creek faults, previously considered to belong to the Tolay; Fig. 1) with the Berkeley Hills volcanic units. Alternatively, however, she pointed out lithologic similarities between the Donnell Ranch Volcanics and the Quien Sabe Volcanics, exposed about 180 km to the southeast along the Rodgers Creek-Hayward fault trend; this raises the possibility of much greater slip along the Hayward and related East Bay faults (Youngman, 1989; see also McLaughlin and others, 1990).

**Significance of Miocene-Quaternary contractile structures in the Bay area**

In the hills surrounding San Francisco Bay, as in other parts of the California Coast Ranges, Miocene and younger units are tightly folded and locally reverse-faulted. Fault strikes and fold trends range from nearly parallel to slightly oblique to the dominant orientation of the major strike-separation faults of the plate boundary system (e.g., Aydin and Page, 1984), suggesting an important component of compression roughly normal to the plate boundary.

The significance of compression in the Bay area, and the Coast Ranges as a whole, remains controversial. Various workers suggest that Coast Ranges compression reflects a component of convergence in Plio-Quaternary Pacific-North American relative plate motion vectors (e.g., Cox and Engebretson, 1985; Harbert and Cox, 1989; see also Wentworth and Zoback, 1989). Aydin and Page (1984) have attributed compressional deformation in the eastern San Francisco Bay area to the left step-over between the right-lateral Hayward and Calaveras faults; they view it as localized transpression due to the configuration of the strike-slip strands of the plate boundary. Jones and others (1994) also address late Neogene shortening associated with the plate boundary; they interpret the major strike-slip faults of the East Bay as steeply eastward-dipping structures soling at depth into a near-horizontal ductile shear zone. They suggest further that this shear zone is probably coincident with the brittle-ductile transition, and functions as a decollement which should be regarded as the actual Pacific-North American plate boundary (Jones and others, 1994). Furlong (1992; see also Zandt and Furlong, 1982, and Furlong and others, 1989) presents an alternative model for a geometrically and kinematically complex plate boundary with sub-horizontal components. He interprets the Hayward and Calaveras faults as the fundamental lithospheric boundary between the Pacific and North American plates, with crust of the "Bay area block" (the region between the San Andreas and Hayward-Calaveras faults) decoupled from the underlying mantle lithosphere such that the decollement functions as part of the plate boundary system.

**METHODS**

In order to construct these maps, we assembled and correlated available sedimentologic, stratigraphic, and geochronologic literature for the Miocene and early Pliocene record in the greater Bay area east of the San Andreas fault zone. Our data set is summarized and referenced in Figure 2. We have also integrated results from ongoing California State University, Hayward mapping and field studies where appropriate. Information on outcrop distribution was taken from Wagner and others (1981), Wagner and Bortugno (1982), and Wagner and others (1990).
**Figure 2.** Generalized correlation chart for the greater Bay area, used as the basis for constructing maps in Figs. 3-6. Sources include Huey (1948), Weaver (1949), Ham (1952), Wagner (1978), Hill (1979), Graham and others (1984), Davies (1986), Youngman (1989), Crane and Lyon (1994), Sullivan and others (1994), and unpublished mapping by A. Buising, K. Vollbrecht, and J. Walker.

<table>
<thead>
<tr>
<th></th>
<th>BB</th>
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<th>ECRB</th>
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**Legend:**
- Continental
- Estuarine
- Shallow Marine
- Deep Marine
- Volcanic

BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block.
NoSPB = north of modern San Pablo Bay; SoSPB = south of modern San Pablo Bay; PenN = peninsula north of ~Palo Alto; PenS = peninsula south of ~Palo Alto. SAF = San Andreas fault; HF = Hayward-Rodgers Creek fault trend; CF = Calaveras-Carneros fault trend; GF = Greenville-Diablo-Concord-Green Valley fault trend.
Following are the conventions we adopted in constructing the maps.

(1) We selected an arbitrary 5-m.y. time interval for our basic maps (15 Ma, 10 Ma, and 5 Ma). This was done in order to avoid the bias inherent in choosing times "when we thought something interesting was happening" for map reconstructions.

(2) The versions of our 15-, 10-, and 5-Ma palinspastic reconstructions presented in this paper restore both strike-slip and contraction (folding and reverse faulting). Strike separation along the major faults of the Bay area is fairly well constrained (see for example Page, 1990); thus we felt that we could restore slip along at least the major strike-slip fault strands with some confidence. By contrast, estimates of net plate-boundary-normal shortening, and boundary-normal shortening rates, (e.g., Wakabayashi and others, 1992; Jones and others, 1994) remain highly speculative.

Work by Unruh and others (1992) suggests a late Neogene Coast Range shortening rate of 1 mm/yr; we use this rate, with a 5-Ma start date for contraction (see for example Cox and Engebretson, 1985; Harbert, 1991) in our basic "contraction-corrected" map set. In the basic "contraction-corrected" map set, we model contraction as evenly distributed over the region between the San Gregorio fault and the eastern margin of the Coast Range at the latitude of Livermore.

Other studies imply more extreme rates of shortening in at least parts of the Coast Range (e.g., Jones and others, 1994; Crane, this volume), and we felt that it was important to test the effect of more significant regional contraction on the geometries depicted on our maps. Thus, we constructed a second set of maps using a 20 mm/yr shortening rate (derived from data of Jones and others, 1994) and a 5-Ma contraction onset date, with contraction evenly distributed over the region between the San Gregorio fault and the eastern margin of the Coast Range at the latitude of Livermore. Interestingly, even the more significant regional shortening modeled on this "paleogeographic worst-case scenario" version of the maps has surprisingly little effect on the general regional geometries (sediment transport directions, orientations of topographic highs and lows) shown by the maps. Hence, of the 20 mm/yr map set, we reproduce only the 10 Ma map.

(3) In order to simplify and systematize strike-slip restorations, we treat the Bay area as composed of several large lithospheric blocks bounded by major strike-slip fault strands. Our usage is similar but not identical to that of previous workers, including Graham and others (1984), Jones and others (1994), and Graymer and others (1994). From the palinspastic standpoint, this approach should be valid regardless of whether the major strike-slip faults are viewed as near-vertical, deep-rooted structures or as shallow structures rooting into a sub-horizontal mid-crustal decollement (see for example Furlong, 1992; Jones and others, 1994). From west to east, we refer to the blocks as: Salinia, the Bay block, the East Bay Hills block, the Livermore block, and the Eastern Coast Ranges block (see Fig. 1). Our reconstructions address aggregate slip on major "block-bounding" faults or fault systems only; we have not restored slip on lesser faults within individual lithospheric blocks. Ignoring slip on subsidiary intra-block faults of course introduces some uncertainty into our reconstructions; we hope to address this in future versions of the maps. Similarly, our reconstructions do not address rotation of blocks bounded by strike-slip faults; it may be possible to do so in future, if we are able to improve constraints on block rotation.

(4) In order to restore movement on block-bounding strike-slip fault strands, we assume a constant slip rate equal to (net slip)/(duration of fault movement). We derived values for net slip and duration of fault movement from various sources in the literature; net slip, duration of fault movement, and our reconstructed constant (average) slip rate values are summarized and referenced in Table 1, along with Holocene slip rates. Notice that the reconstructed average slip rates are not necessarily equal to Holocene or present-day slip rates, although they are generally in close agreement.

(5) Our basic palinspastic reconstructions use the more conservative estimate of ~60 km net slip on the Hayward-Rodgers Creek + Calaveras trend (Page, 1990; Sarna-Wojcicki, 1992); additional versions of these maps will incorporate the alternative slip estimate of ~190 km proposed by McLaughlin and others (1990).

DISCUSSION OF THE MAPS

15 Ma

At 15 Ma, much of the Bay area was below sea level, with an inferred west-northwesterly-trending shoreline located somewhere east of the modern
Concord and Greenville faults (Fig. 3). The sandy shoreface facies belt of the Monterey Formation, extending from what is now the Diablo foothills (Oursan Sandstone; Crane and Lyon, 1994) west toward Dublin Canyon (coeval parts of the Sobrante Sandstone; Hill, 1979), received a mixture of Franciscan and Sierran detritus (Hill, 1979). The basin deepened to the west, reaching upper bathyal depths (~500 m) from the latitude of modern San Pablo Bay south almost as far as modern Gilroy. In this deep, largely starved, portion of the basin, siliceous chemical sediments and mudrocks (Claremont Shale and equivalents) accumulated under intermittently reducing conditions (Hill, 1979; Graham and others, 1984).

The North Bay east of the modern Rodgers Creek fault trend was likely a topographic high at 15 Ma; mid-Miocene sedimentary rocks are absent from the record in this region, where younger Miocene sedimentary and volcanic rocks (Sonoma volcanics and associated sedimentary strata; see below) directly overlie basement rocks of Mesozoic–early Tertiary age (Davies, 1986; Youngman 1989; Wagner and others, 1990). This North Bay high may have represented—at least in part—inherited topography; work of Sucheccki (1984) suggests significant relief in the Coast Range at the latitude of the northern Sacramento Valley beginning in Mesozoic time and continuing through the mid-Tertiary. In any event, the North Bay high was probably the source for Franciscan detritus described by Hill (1979) in the sandy units of the 15-Ma Monterey: a southerly grain-size fining trend and southwesterly transport indicators described by Hill (1979) are consistent with derivation of sediment from a North Bay Franciscan uplift, and other potential Franciscan source terranes—the Bay block and the future Diablo Range—can be shown to have been submerged at this time (see below and Fig. 3). Outcrop distribution suggests that the northern margin of the 15-Ma Monterey basin was somewhat to the north of, or roughly coincident with, modern San Pablo Bay; minor Monterey outcrops exist along the Carneros fault in southern Sonoma County (Wagner and Bortugno, 1982), but the age of these rocks is rather ill-constrained.

Two lines of evidence suggest that the Bay block (including the modern Peninsula east of the San Andreas trend) may also have been slightly higher than the East Bay Hills block at 15 Ma. First, the sedimentary record on the Peninsula north of Palo Alto lacks Miocene strata; on the northern Peninsula, Plio-Pleistocene marine and marginal-marine deposits (Merced Formation) directly overlie basement units of Mesozoic and early Tertiary age (Wagner and others, 1990; see also Clifton and Hunter, 1987; Clifton, 1988). Second, on the Peninsula south of Palo Alto, the ~15-Ma Page Mill Basalt is overlain by shallow-marine Ladera sandstone (Fox and others, 1985; M. Angell, pers. comm., 1995).

Interestingly, however, coarse detritus is absent from the western portion of the 15-Ma Monterey Group outcrop belt (Fig. 3), which seems to preclude the presence of significant Bay block uplift at 15 Ma. On the other hand, if the Bay block were at bathyal depths around 15 Ma, it should have accumulated a thick cover of Claremont Shale-equivalent sediments; we would expect these sediments to appear recycled as clasts in the overlying Bay block-derived Orinda Formation (basal Contra Costa Group between the Hayward and Moraga faults; see usage of Wagner, 1978 and Graham and others, 1984). However, the basal Contra Costa near Berkeley (Fig. 1) is overwhelmingly dominated by Franciscan material in both sand and coarse-clast fractions (Graham and others, 1984; Busing, unpublished data). Elsewhere, Claremont detritus is present in the lower part of the Contra Costa section (e.g., at Upper San Leandro Reservoir; Busing, unpublished mapping; see also Wagner, 1978); however, it is nowhere volumetrically important compared to material of Franciscan and probable Sierran derivation (Busing, 1995 and unpublished data). Thus, it seems unlikely that the Bay block was accumulating much sediment at 15 Ma; we postulate that the northern Bay block (north of ~Palo Alto) formed a subaqueous sill to the "Claremont" basin, while the southern Bay block probably sat at or near sea level.

Changes between 15 and 10 Ma

Two principal changes took place in the period between 15 Ma and 10 Ma. First, the portion of the Bay block between about modern Palo Alto and modern San Jose began to subside, accumulating first shallow marine sands directly overlying the Page Mill Basalt (Ladera Sandstone) and then deeper marine siliceous rocks ("Monterey" in the broad sense; M. Angell, pers. comm., 1995). Second, at least the northern (and/or eastern?) portion of the Bay block was significantly uplifted by 12-13 Ma, based on the presence of abundant Franciscan detritus in the westward-thinning, eastward-transported Orinda Formation (usage as above; see Wagner, 1978 and Graham and others, 1984). Thus, the Bay "block"
15 Ma
Contraction-corrected
(1 mm/yr, onset at 5 Ma)

Figure 3. Palinspastic paleogeographic map for the greater San Francisco Bay area at 15 Ma. BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block. Dashed line represents approximate position of sea level (Monterey Group shoreline). Heavy dotted line shows approximate latitude of Mendocino Triple Junction. Large arrows represent transport directions inferred from clast compositions and paleocurrent indicators. Small arrows show positions of 0-Ma piercing points (freeways and highways shown in Figure 1). Only San Andreas fault is active.
appears to have been structurally dissected or segmented in the period immediately following 15 Ma, rather than behaving as a single entity. The simplest interpretation would divide the Bay "block" roughly in half along an E-W trending axis at about the latitude of Palo Alto. However, the block may also have been segmented along one or more north-south or northwesterly-oriented structures; Angell and Hall (1995) have shown that at least one such structure existed on the southern Bay block during the 15-10 Ma time frame.

10 Ma

The 10 Ma map shows an elongate shallow-marine embayment developed across the East Bay Hills, Livermore, and eastern Coast Ranges blocks (Figs. 4, 5); we refer to this body of water as the San Pablo embayment after sediments of the shallow-marine and estuarine San Pablo Group. The Tolay-Grizzly Peak volcanic field was active at 10 Ma, and appears to have occupied a roughly linear trend at an angle of 20-30° to the orientation of the Hayward fault. Graham and others (1984) have linked Grizzly Peak volcanism with the inception of slip along the Hayward fault proper.

The San Pablo embayment appears to have received both westerly-derived (Coast Range) and easterly-derived (Sierran) sediment (Graham and others, 1984; Buisin, 1995). The Bay block continued as a significant uplift at 10 Ma, shedding predominantly Franciscan detritus via the Contra Costa alluvial/fluvial plain into the San Pablo embayment. San Pablo outcrops in the foothills southwest of Mt. Diablo record fluvial and shallow marine deposition; coarse-clast compositions suggest mixing of Sierran- and Coast Range-derived material (Walker, unpublished mapping). Based on the presence of what we tentatively identify as the ~9.7-Ma Black Diamond Park tuff (see Graymer and others, 1994) near the middle of the Diablo foothills section, these strata are probably correlative with Sierran-derived and/or mixed-source fluvial San Pablo outcrops south of Altamont Pass (Figs. 4, 5; see Huey, 1948); this tract likely records a major westward-flowing fluvial system carrying Sierran (± more locally-derived) detritus into the San Pablo embayment.

To the southeast, the Diablo Range began to rise by 10 Ma or very shortly thereafter (see Bartow, 1992; Unruh and others, 1992), forming a drainage divide between fanglomerates shed to the east from the young Diablo rangefront (Carbona unit of Raymond, 1969) and westward-transported San Pablo fluvial sediments. This reconstruction depends critically on the observation that while the Carbona fanglomerates overlie pre-9.5 Ma strata (Neroly Formation) east of Livermore (Bartow, 1992), the Carbona is coeval with slightly younger (~9-Ma) Neroly north of modern-day Mt. Hamilton (D. W. Andersen, pers. comm., 1995; see also discussion in Barlow, 1988). The trend of the nascent Diablo Range uplift (based on the contraction-corrected trend of the Carbona outcrop belt) appears to have been roughly normal to the northern portion of the San Pablo shoreline and at an angle of about 30° to the plate boundary trend.

Based on the absence of 10-Ma sediments in the region between the present-day Carneros and Green Valley faults (Figs. 1, 4, 5) we infer that this region continued as high ground through at least 10 Ma; as before, this may have represented inherited topography rather than uplift due to Miocene tectonism. West of the modern Carneros fault trend, sediments of the Petaluma Formation record fluvial-acustrine and estuarine conditions (Davies, 1986) in a system believed to have drained southward into the San Pablo embayment. Davies (1986) has suggested that Monterey detritus in the Petaluma Formation was derived from a western (Salinian) uplift; however, this requires it to have crossed not one but two major fault trends active by this time (San Andreas and Hayward-Rodgers Creek). We suggest an alternative (lateral) source within the northern East Bay Hills block, where small outcrops of (post-15 Ma?) Monterey Formation occur along the Carneros fault.

Changes between 10 and 5 Ma

The most significant change between the 10 and 5 Ma maps is in the location and geometry of uplifted terrain in the greater Bay area. At 10 Ma, uplifts were comparatively localized, and, in at least the Diablo Range case, were oriented oblique to the throughgoing strike-slip trend; the general impression is of blocky, borderland-style topography. By 5 Ma, uplift became much more widespread; more of the Bay area stood relatively higher. Emergence is documented by the increasing dominance of continental sediments in the stratigraphic record of the East Bay Hills, Livermore, and Eastern Coast Ranges blocks, where marine
10 Ma
Contraction-corrected
(1 mm/yr, onset at 5 Ma)

Figure 4. Palinspastic paleogeographic map for the greater San Francisco Bay area at 10 Ma, restored using 1 mm/yr contraction rate (see discussion in text). BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block. Dashed line represents approximate position of sea level (San Pablo embayment shoreline). Heavy dotted line shows approximate latitude of Mendocino Triple Junction. Large arrows represent transport directions inferred from clast compositions and paleocurrent indicators. Small arrows show positions of 0-Ma piercing points (freeways and highways shown in Figure 1). San Andreas and Hayward-Rodgers Creek faults are active.

Figure 5 (below). Palinspastic paleogeographic map for the greater San Francisco Bay area at 10 Ma, restored using 20 mm/yr Coast Range contraction rate (see discussion in text). BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block. Dashed line represents approximate position of sea level (San Pablo embayment shoreline). Heavy dotted line shows approximate latitude of Mendocino Triple Junction. Large arrows represent transport directions inferred from clast compositions and paleocurrent indicators. Small arrows show positions of 0-Ma piercing points (freeways and highways shown in Figure 1). San Andreas and Hayward-Rodgers Creek faults are active.
10 Ma
Contraction-corrected
(20 mm/yr, onset at 5 Ma)
deposition in the San Pablo embayment probably ceased by ~8 Ma (Graham and others, 1984). We ascribe the emergence of the East Bay to tectonic uplift (perhaps exacerbated by rapid sedimentation rates) rather than eustatics, since sea level underwent a net rise through latest Miocene-earliest Pliocene time (Haq and others, 1987).

Thick sedimentary sections on the East Bay Hills and Livermore blocks attest to the existence of significant topographic relief in the period between 10 and 15 Ma (Fig. 2). Fluvial, lacustrine and lacustrine-deluvial sediments of the Contra Costa Group continued to accumulate on the East Bay Hills block, receiving sediment derived both from the still-uplifted Bay block, and from the Sierra (Buisng, 1995). 6- to 8-Ma strata of the Contra Costa Group show intercalation between Coast Range-derived sediment packets and packets dominated by Sierran sediment, suggesting that a conduit carrying Sierran sediment was at least intermittently open as far west as Contra Costa depocenter(s) on the East Bay Hills (+ Livermore) blocks (Buisng, 1995). Subsidence in the Livermore basin, recorded in continental sediments of the Sycamore Formation, appears to have begun at ~8 Ma, concomitant with the rise of the Altamont Hills and continued uplift in the Diablo Range proper (Isaacson and Andersen, 1992).

Volcanic activity began in the North Bay (Sonoma volcanic field) by ~8 Ma (Youngman, 1989); near Berkeley, volcanism shifted inland slightly from the Tolay-Grizzly Peak center to the Bald Peak vent.

5 Ma

By 5 Ma, much of the area east of the Hayward fault was above sea level and undergoing alluvial and fluviatile sedimentation (Wagner, 1978; Graham and others, 1984; Isaacson and Andersen, 1992) on a broadly westward- or northward-draining system (Fig. 6). Coarse-clast compositions in the Sycamore Formation of the Livermore block suggest continued uplift in the Diablo Range, including the Mt. Hamilton area (Isaacson and Andersen, 1992). Similarly, the Altamont Hills probably continued high, depriving the Bay area system of Sierran detritus, which was shunted southward to the Etchegoin depocenter (east of the San Andreas trend between the latitudes of Hollister and Bakersfield; see Perkins, 1987). The Livermore basin, surrounded by these highs, appears to have been a well-developed low at 5 Ma (Isaacson and Andersen, 1992).

Much if not all of the Bay block appears to have been high ground at 5 Ma. There is a gap in the peninsular sedimentary record at this time—shallow-marine sediments of the Plio-Pleistocene Merced Formation overlie Mesozoic-lower Tertiary basement rocks—suggesting uplift and erosion prior to the onset of Merced deposition in latest Pliocene or early Pleistocene time (Clifton and Hunter, 1987; Wagner and others, 1990).

By 5 Ma, the locus of active volcanism in the Bay area had migrated to the region north of modern San Pablo Bay (Sonoma volcanic field; see Youngman, 1989). Petaluma fluvial deposition continued west of the Rodgers Creek trend. The Petaluma has been interpreted as the northwestward continuation of the East Bay "Contra Costa" belt (Liniecik-Laporte and Andersen, 1988); the Contra Costa-Petaluma fluvial system probably drained, via the shallow Wilson Grove marine shelf, into the Delgada submarine fan (see Davies, 1986; Sarna-Wojcicki, 1992).

SYNTHESIS ANDTECTONIC INTERPRETATION

Our paleogeographic reconstructions suggest that dextral strike-slip effects (in the broad sense) were the primary control on landscape evolution and sedimentation in the San Francisco Bay area from ~15 Ma to at least 10 Ma and probably as late as 5-7 Ma; there is no evidence in the stratigraphic record requiring significant plate-boundary-normal contraction (contraction driven by Pacific-North American convergence, as distinct from local contraction driven by wrench faulting) prior to 5-7 Ma.

Deposition of bathyal sediments over much of the East Bay Hills block at 15 Ma suggests significant pre-15 Ma subsidence. Graham and others (1984) interpret this mid-Miocene bathyal trend as recording the last stages of deposition in the Great Valley forearc. We suggest as an alternative possibility that the "Claremont" basin may have formed in response to early strike-slip effects, perhaps as a precursory sag developed in advance of strike-slip rupture. Eruption of the Page Mill Basalt at ~15 Ma probably records initial rupture along the peninsular San Andreas system (Graham and others, 1984); Claremont subsidence could be thus be viewed as an early strike-slip effect. More convincingly, the pattern of block segmentation and localized uplift/subsidence which
Figure 6. Palinspastic paleogeographic map for the greater San Francisco Bay area at 5 Ma. BB = Bay block; EBHB = East Bay Hills block; LB = Livermore block; ECRB = Eastern Coast Ranges block. Heavy dotted line shows approximate latitude of Mendocino Triple Junction. Large arrows represent transport directions inferred from clast compositions and paleocurrent indicators. Small arrows show positions of 0-Ma piercing points (freeways and highways shown in Figure 1). San Andreas and Hayward-Rodgers Creek faults are active.
Figure 7. Idealized strain ellipse for right-lateral simple shear, based on experimental and field studies at a variety of scales. Compare orientations of transtensional and transpressional features with orientations of San Pablo embayment and Diablo Range uplift on 10 Ma maps (Figs. 4-5). Redrawn based on Wilcox and others (1973), Crowell (1974), and Christie-Blick and Biddle (1985).

characterizes the Bay area structural and stratigraphic record between 15 and 10 Ma is similar in scale and style to southern California borderland examples (e.g. Crowell, 1974) and can probably be best interpreted in terms of strike-slip tectonics.

Geometries evident on the 10 Ma maps reflect the continued primacy of the regional strike-slip regime. If the approximate strike of the San Andreas and Hayward faults is taken as the orientation of the main strike-slip rupture or master wrench, the trend of the elongate San Pablo embayment coincides with the orientation of extensional faulting driven by the master wrench system (Figs. 4, 5, 7; Wilcox and others, 1973; Christie-Blick and Biddle, 1985). This suggests that the San Pablo embayment may have occupied an extensional low associated with the dextral transform plate boundary fault system. Notice that, although the restored trend of the San Pablo embayment varies between the 1 mm/yr contraction rate and the 20 mm/yr contraction rate versions of the 10 Ma map (Figs. 4, 5), the embayment trend on both maps is within the observed range for extensional (transtensional) faulting driven by a master wrench system (e.g., Wilcox and others, 1973); thus, we infer that the transtensional model for San Pablo subsidence is reasonable regardless of which estimate of post-San Pablo contraction is closer to the truth. Interestingly, the orientation of the San Pablo shoreline, and presumably any bounding normal faults responsible for San Pablo subsidence, is similar to the orientation of northeasterly-striking faults interpreted as "tear" faults associated with regional contraction (Crane and Lyon, 1994; also unpublished mapping by Buisin and by former CSU Hayward undergraduate Kurt Vollbrecht); perhaps some or all of these "tear" faults are actually reactivated features.

Similarly, the orientation of the nascent Diablo Range at 10 Ma (at about 30° to the main strike-slip rupture, based on the contraction-corrected trend of the Carbona outcrop belt; Figs. 4, 5) is consistent with an origin by transpression.

By 5 Ma, the picture is slightly different. The 5 Ma map shows wholesale uplift of the East Bay Hills and Livermore blocks, and perhaps the Bay block as well, along a trend no longer at an angle to the plate boundary, but essentially parallel to it. We interpret this shift in uplift style (from localized to widespread)
and orientation (from boundary-oblique, at least in part, to boundary-parallel) as signalling the onset of significant plate-boundary-normal compression and associated contractile deformation.

**IMPLICATIONS FOR LOCATION AND MIGRATION RATE OF THE MENOCINO TRIPLE JUNCTION**

Our reconstructions permit the Mendocino triple junction (MTJ) to be located significantly farther north at 15 Ma than previous studies would suggest (e.g., Severinghaus and Atwater, 1990); we tentatively place it at the latitude of the southern peninsula at 15 Ma. MTJ locations suggested by our 10 and 5 Ma maps coincide fairly closely with those suggested by other workers (e.g., Fox and others, 1985; Severinghaus and Atwater, 1990); we locate the MTJ at the approximate latitude of modern San Pablo Bay at 10 Ma, and at the latitude of the Sonoma volcanic field by 5 Ma.

This in turn suggests rough constraints on the rates of northward migration of the MTJ since ~15 Ma; if the assumption of constant (average) slip rates on the various strands of the plate-boundary fault system which underpins our palinspastic reconstructions is even close to realistic, then it becomes clear that the MTJ has not migrated at a constant rate since 15 Ma. Our 15 and 10 Ma locations for the MTJ suggest an approximate north-westward (plate-boundary-parallel) migration rate of 2.1 cm/yr for the MTJ between 15 and 10 Ma. Between 10 and 5 Ma, our locations suggest a 1.1 cm/yr MTJ migration rate; this requires a post-5 Ma migration rate of 5.3 cm/yr in order for the MTJ to arrive at its present position at 0 Ma. Interestingly, this dramatic increase in MTJ migration rates appears to have coincided roughly in time with the 3-5 Ma reorganization in plate motion vectors discussed by previous workers (e.g., Harbert and Cox, 1989; Harbert, 1990).

**CONCLUSIONS**

Based on the current versions of our palinspastic paleogeographic reconstructions for the greater San Francisco Bay area, we infer that the primary control on basin evolution and landscape development in the Bay area between ~15 Ma and ~6 Ma was dextral strike slip; contraction driven by relative Pacific-North American plate convergence probably became important after ~6 Ma. Deposition of bathyal sediments (Claremont Shale and equivalents) over much of the East Bay region around 15 Ma indicates that significant subsidence took place prior to 15 Ma; we interpret this "Claremont" subsidence as a precursory strike-slip effect. Eruption of the ~15 Ma Page Mill Basalt was probably related to early rupturing along the peninsular San Andreas trend. Between 15 and 10 Ma, the Bay area structural and stratigraphic record is characterized by a pattern of localized uplift and subsidence suggesting strike slip-controlled borderland topography, and strongly resembling southern California borderland examples in both scale and style. Regional geometries at 10 Ma continue to suggest landscape evolution and sedimentation dominated by dextral strike-slip effects. The trend of the elongate San Pablo shallow-marine embayment at 10 Ma parallels the strike of extensional faults driven by a dextral master wrench with the orientation of the San Andreas and Hayward faults; we suggest that the San Pablo embayment occupied an extensional low controlled by the transform plate-boundary system. Similarly, the orientation of the nascent Diablo Range at 10 Ma (roughly normal to the trend of the San Pablo embayment, and at about 30° to the main strike-slip rupture trend) is consistent with an origin by wrench-driven contraction. By contrast, the 5 Ma map shows wholesale uplift in the Bay area, along a trend no longer at an angle to the plate boundary, but essentially parallel to it. We interpret this shift in uplift style (from localized to widespread) and orientation (from boundary-oblique to boundary-parallel) as signalling the onset of significant plate-boundary-normal compression and associated contractile deformation, some time between 10 and 5 Ma.

Our palinspastic reconstructions suggest that the Mendocino triple junction (MTJ) may have been located as far north as the southern Peninsula at 15 Ma; it was probably near the latitude of modern San Pablo Bay at 10 Ma, and near that of the Sonoma volcanic field by 5-8 Ma. This suggests a rough estimate of northwestward (plate-boundary-parallel) migration rates for the MTJ during late Neogene time: ~2.1 cm/yr between 15 and 10 Ma, ~1.1 cm/yr between 10 and 5 Ma, and ~5.3 cm/yr after ~5 Ma.

We are encouraged that these maps have proved to be useful in recognizing different structural styles controlling landscape evolution and sedimentation in the greater San Francisco Bay area since ~15 Ma. While the reconstructions presented here are still in a fairly embryonic state, we anticipate that they will
become even more informative as they are refined with continuing work.

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