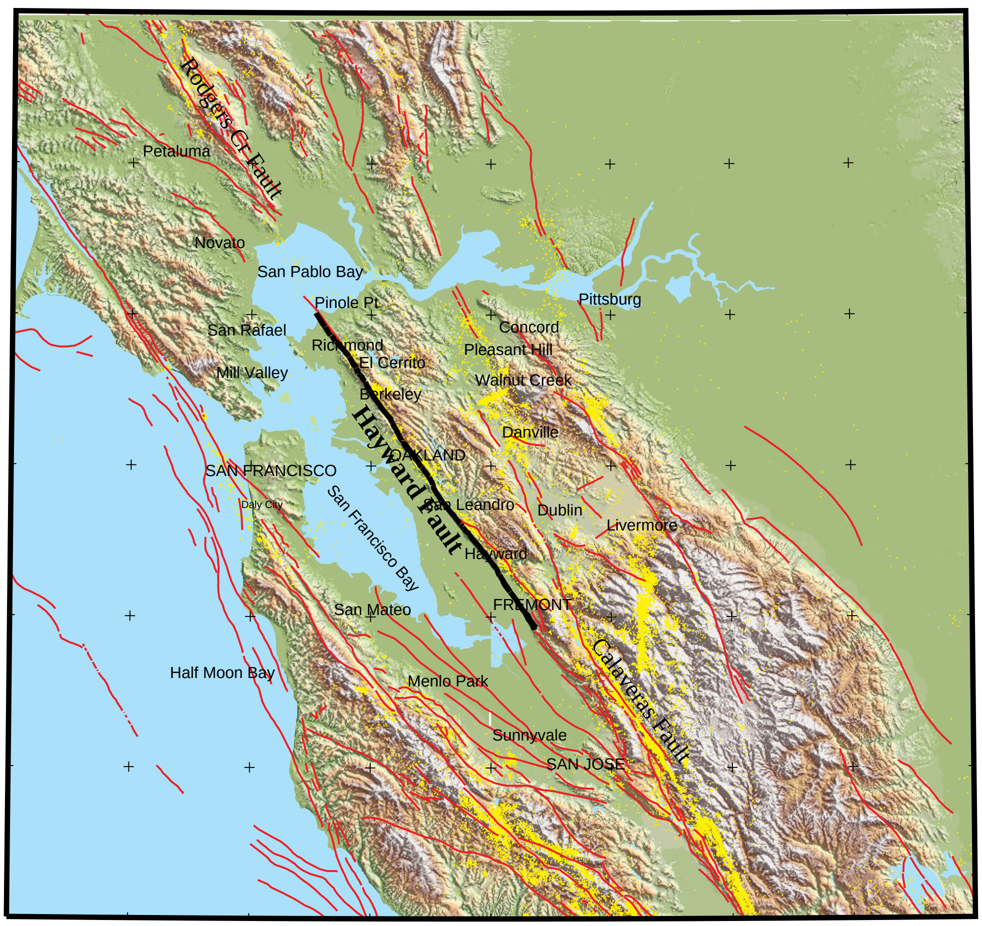
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Proceedings of the Hayward Fault Workshop, Eastern San Francisco Bay Area, California, September 19-20, 2003

Edited By David A. Ponce[1], Roland Bürgmann[2], Russell W. Graymer[1], James J. Lienkaemper[1], Diane E. Moore[1], and David P. Schwartz[1]

Open-File Report 03-485



2003

U.S. DEPARTMENT OF THE INTERIOR
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INTRODUCTION

The technical abstracts presented at this workshop, convened in Sunol, California, on September 19, 2003 and associated field trip the following day, summarize some of the recent scientific knowledge gained along the Hayward Fault (e.g. Hart and others, 1982; Borchardt and others, 1992). The Hayward Fault and its northern extension, the Rodgers Creek Fault, are regarded as one of the most hazardous fault systems in the San Francisco Bay Area with a probability of about 27% for a ≥**M**6.7 earthquake over the next thirty years (Working Group on California Earthquake Probabilities, 1999; 2003).

Recent studies, some of which are described in the abstracts contained herein and summarized below, include advancements in creep measurements and geodesy, paleoseismology, relocation of the 1836 earthquake away from the Hayward Fault, modeling of the epicenter of the 1868 earthquake, geologic maps, modeling the depth of creep, double-difference relocated hypocenters, geometry and segmentation, understanding the relationship between the Hayward and Calaveras Faults, and estimates of earthquake probabilities.

Historical seismicity data indicate that seismic activity along the Hayward Fault was much greater in the 19^{th} century than in recent years (Bakun, this volume). An analysis of intensity data for the **M**6.8 21 October 1868 earthquake suggests that most of the damaging ground motions were generated by slip located in the vicinity of San Leandro, possibly near a 1-km right step in the recent trace of the Hayward Fault (Bakun, this volume). A re-evaluation of the location of the 1836 earthquake, originally thought to be associated with the northern Hayward Fault, suggests that it occurred south of San Francisco Bay (Toppozada and Borchardt, 1998).

Advances in the collection and analysis of instrumental seismicity data have greatly increased their resolution (Nadeau, this volume) yielding important new information on earthquake behavior. A high-precision double-difference seismicity-relocation procedure (Waldhauser, 2001; Waldhauser and Ellsworth, 2000; 2002) has greatly improved the precision of relative earthquake locations to 10's of meters, and a regional double-difference procedure has improved the precision of relative locations to 100's of meters (Ellsworth and others, 2000) for the entire San Francisco Bay Area.

Ongoing paleoseismic studies along the Hayward Fault, particularly at Tyson's Lagoon (Lienkaemper and others, this volume), indicate a mean recurrence interval for large earthquakes of 195 ± 15 yr for ten events, including the 1868 earthquake, during the past 1750 yr. This is longer than a previously determined interval of 130 ± 40 yr for four events during the past 400 yr, suggesting variability in earthquake repeat times. Paleoseismic studies along the northern part of the Rodgers Creek—Healdsburg segment, north of Santa Rosa indicate at least three and possibly four surface-rupturing events (Swan and others, this volume). Textural characteristics of sand deposits from active fault zones show differences between deformation fabrics produced by aseismic creep and those produced by coseismic rupture (Cashman and others, this volume). For example, differences in the orientation of elongate grains relative to the fault suggest that grains are oriented parallel to the fault for creeping faults, and oblique to the fault for active faults with a coseismic history.

Recent studies modeling fault creep along the Hayward Fault as changes in locking depth using a screw dislocation boundary element model, reveal locked and retarded patches along the central part of the Hayward Fault (Bürgmann and others, 2000; Simpson and others, 2001; Wyss, 2001). On the basis of interferometric synthetic aperture radar (InSAR), GPS (Global Positioning System), and repeating earthquake data, Bürgmann and others (2000) suggest that the northern part of the Hayward Fault may be creeping throughout its seismogenic zone (to a depth of about 12 km), and thus is not likely to independently produce a large earthquake. GPS data for the entire San Francisco Bay Area have been reprocessed using a uniform methodology in an attempt to generate a comprehensive model of crustal deformation (d'Alessio and others, this volume). These data, including 88 stations in the eastern San Francisco Bay Area, serve as a basis for monitoring fault slip and strain accumulation throughout the region. Furlong and others (this volume), analyze the slip deficit that can be accumulated on the Hayward Fault. They indicate that a smooth transition occurs in the creep rate from locked to fully creeping areas and that a significant slip deficit accumulation is implied not only in fully locked zones but also in adjacent low friction areas. Repeat subsurface creep measurements in Fremont in two adjacent 30-m boreholes, reveal that fault slip at 10-20 m depth occurs at a rate of 5.6 mm/yr; and since 1997, surface creep has lagged behind the long-term rate by about 5 mm/yr. (Bilham, this volume).

Both the peak (failure) and frictional strengths of gabbro, keratophyre, basalt, sandstone, and serpentinite samples collected along the Hayward Fault increase systematically with increasing effective pressure. All of the samples tested are velocity-strengthening—that is, frictional strength increases with increasing sliding velocity—which is associated with stable slip (creep) (Morrow and Lockner, this volume). The frictional behavior of the serpentinite mineral chrysotile is characterized by strength minimum corresponding to about 3-km depth in a fault zone, where slip is also likely to be stable, followed by a rapid increase in strength and a possible shift to unstable (seismic) slip at greater depths. This variation in frictional behavior is consistent with those models of the Hayward Fault that propose that fault creep extends to about 5-km depth, with a locked zone beneath (Moore and others, this volume).

Regional magnetic, gravity, and geologic information, combined with seismic reflection, seismic refraction data, and drill-hole logs provide a regional tectonic framework and long-term historical perspective of the Hayward Fault Zone (Jachens and others, this volume; Graymer, this volume). The analysis of magnetic and gravity data along the Hayward Fault, in particular near a gabbroic body near San Leandro, indicate that the fault dips about 75^0 NE and reactivated or preferentially followed a pre-existing feature (Ponce and others, 2003). Inter-relationships between gravity and magnetic anomalies, mafic and ultramafic rocks, structural trends, creep rates, and clusters of seismicity suggest that the Hayward Fault may consist of numerous fault-zone discontinuities, some of which may play a role in defining fault segments (Ponce and others, this volume).

An analysis of high-precision, relocated, double-difference seismicity data, combined with geologic and geophysical information, indicate that the Hayward Fault dips become much shallower to the SE, at least in the upper 6 km, and that it may ultimately connect with the Calaveras Fault in a complex way. These data were used to define a three-dimensional active fault surface at depth that connects with the creeping fault traces mapped at the Earth's surface. In contrast, below about 6 km the Hayward and Calaveras Fault may connect in a simple way along several linear, near-vertical segments. (See Simpson and others, this volume).

Finite-element and crustal-structure models of the Hayward fault (Parsons and others, this volume) suggest that the Hayward Fault is strongly influenced by its neighbors. The models indicate an increase in extensional stress in the step-over region between the Hayward and Rodgers Creek Faults. This, combined with long-term interaction with the San Andreas Fault, leads to a reduction in normal stress along the northern Hayward Fault that may influence the distribution of creep.

A three-dimensional geologic map of the Hayward Fault Zone (Jachens and others, this volume) reveals possible correlations between rock type and seismicity. For example, fewer earthquakes occur along the northern part of the fault where sheared Franciscan melange abuts the fault face, than the region to the south where more coherent rocks of other Franciscan terranes or Coast Range ophiolite are present. Clusters of earthquakes also correlate spatially with some of the contacts between Franciscan terranes (Jachens and others, this volume) and Coast Range Ophiolite (Ponce and others, 2003).

The coordinators and participants of this workshop hope that these proceedings, highlighting recent work along the Hayward Fault, spawn a renewed interest in scientific studies, promote a better understanding of earthquake mechanics and hazards, and ultimately result in improved earthquake hazard preparedness and response.

ACKNOWLEDGMENTS

We would like to thank all the participants and organizations for their contributions to this volume and conference. Special thanks to Diane Moore for organizing and presiding over the workshop, to David Schwartz for leading the introduction and closing discussion, and to the San Francisco Bay Area Earthquake Project for providing funding for this workshop.

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PROGRAM

Creeping Toward the Big One: What's New on the Hayward Fault

FRIDAY, SEPTEMBER 19, 2003

7:45 – 8:30 AM Poster set-up, coffee and pastries

Observations I

8:30 – 8:45 Introductions (David Schwartz)

8:45 – 9:30 Seismicity: Historical (Bill Bakun)
Instrumental (Bob Nadeau)

9:30 – 10:15 Strain Measurements: GPS/InSAR (Roland Bürgmann)
Creep (Jim Lienkaemper)

10:15 – 10:30 Coffee break

Observations II

10:30 – 11:00 A Regional Geophysical Perspective (Bob Jachens)

11:00 – 11:30 Long-Term Fault History (Russ Graymer)

11:30 – 12:00 Paleoseismology (Jim Lienkaemper)

Brunch – Posters – Geowall

12:00 – 2:15 PM Brunch and Poster Session

Interpretations

2:15 – 2:40 Hayward Fault Models (Kevin Furlong)

2:40 – 3:05 Geometry and Segmentation (Dave Ponce)

3:05 – 3:30 Hayward Fault Geometry (Bob Simpson)

3:30 – 4:00 Geowall Presentation–3D Structural Visualization (Bob Jachens and others)

4:00 – 5: 00 Discussion: Implications for earthquake hazard and future directions

SATURDAY, SEPTEMBER 20, 2003

9:30 AM– 5:30? PM Hayward Fault Field Trip.

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CONCLUSIONS

The Hayward Fault is regarded as one of the most hazardous faults in California, and perhaps the world, because it traverses the highly urbanized zone between the San Francisco Bay and the East Bay Hills. Hospitals, police and fire departments, universities, and a major international airport are also located in this potentially hazardous seismic corridor. Thus, studies related to understanding and mitigating earthquake hazards associated with the Hayward Fault are important to the safety and economy of northern California, and are applicable to earthquake hazards worldwide.

As a result of this Workshop, we recognize a number of unanswered questions and unresolved issues, and recommend a number of scientific studies that might address them. Some of the more important issues include the extent of the 1868 earthquake, whether or not the fault is segmented, the rate and depth extent of creep, and the nature of the connections between the Hayward Fault and the Rodgers Creek Fault to the north and the Calaveras Fault to the south.

Issues

What effect do large post-seismic transients from the 1868 earthquake along the Hayward Fault and the 1906 earthquake on the San Andreas Fault have on creep? Is the rate of creep now the same as in the past (pre-1868)?

Is the Hayward Fault segmented (individual north and south, or other segments)?

How can we model/explain the fast creep on the southern end of the surface trace of the Hayward Fault?

Is Oakland the nucleation area for large events? Where did the 1868 earthquake nucleate?

What is the recurrence interval on the northern Hayward Fault?

How can we better quantify the rate and extent of creep at depth on the northern Hayward Fault? How does this affect the occurrence of large earthquakes?

What is the nature of the connection between the southern Hayward and Calaveras Faults? Can the southern Hayward and Calaveras Faults link in a rupture? If so, what are the geometry, kinematics, and slip behavior of the linking faults?

What is the nature of the connection between the northern Hayward and Rodgers Creek Faults?

Recommendations for future studies

High-precision tomography.

Establish a large dense array to detect small magnitude events (**M**≤0.5) to better illuminate the fault zone structure and to allow detection of significantly more repeating events for subsurface creep rate measurement.

Northern Hayward paleoseismology, including earthquake dates and slip rate.

Measure frictional strength, physical properties, and wave speed of fault zone materials and adjacent rock types.

Model ruptures along the fault with large creeping (velocity strengthening) patches.

Evaluate the effect of stress changes from a range of Bay Area earthquake scenarios on the triggering of a large Hayward Fault event.

Model stress concentrations associated with the San Leandro gabbro body.

ABSTRACTS

Historical Seismicity on the Hayward Fault

William H. Bakun
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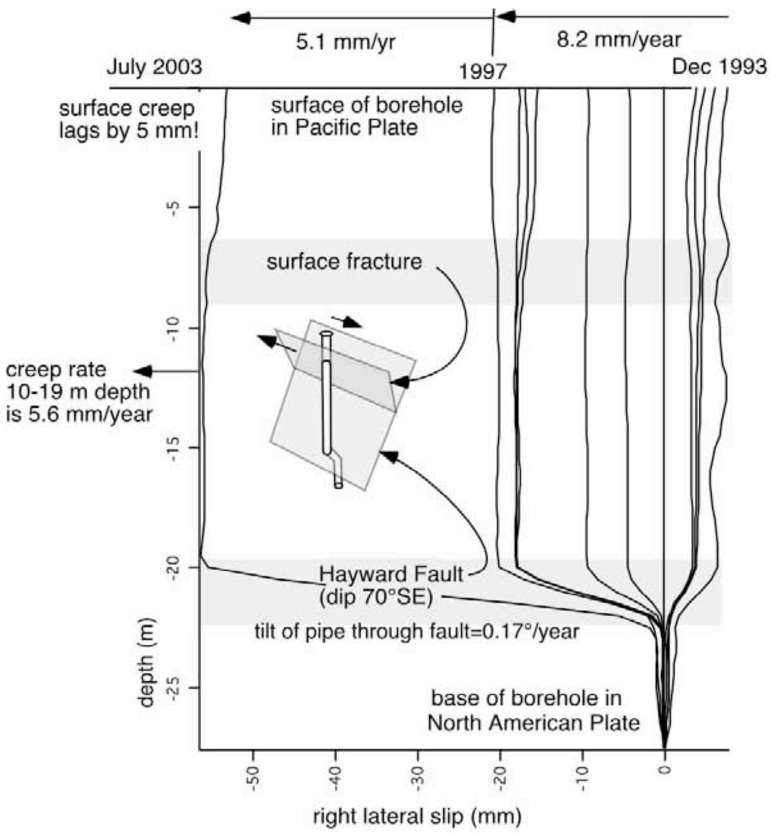
Seismic activity along the Hayward fault in the 19th century was more than twenty times that in recent years. The outstanding historical Hayward fault event was the **M**6.8 earthquake that occurred on 21 October 1868; the **M**6.5 earthquake that occurred on 10 June 1836 probably occurred on a south bay fault, not on the north section of the Hayward fault. The **M**6.8 1868 source can be modelled as a 45-km-long, 10-km-deep rupture from Warm Springs to just north of Montclair with $<u> = 1.5$m. The location of the intensity center suggests that most of the damaging ground motions were generated by slip at or near the 1-km right step in the fault near San Leandro.

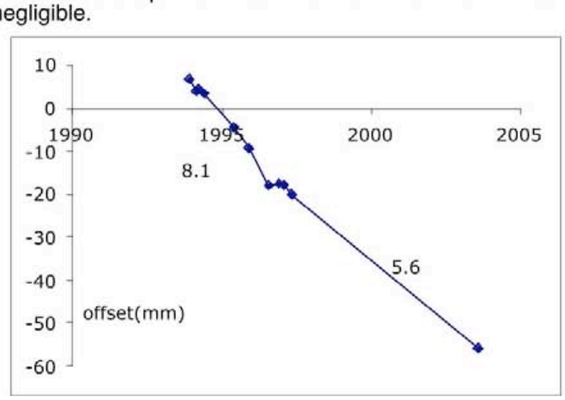
Subsurface Creep Fremont

Roger Bilham, University of Colorado, Boulder CO 80309-0399

Prior to 1986 the Osgood Road creepmeter in the Gallagos Winery in Fremont was creeping close to the long term rate of 8.5 mm/year, a rate established since 1890. Since then the creep rate has reduced to 5.1 mm/year, a rate similar to that of the central and northern part of the Hayward fault. The Fremont instrument is unique in that the two end mounts are 30 m deep columns within which an inclinometer lining permits lateral displacements to be detected every 50 cm to the base of each hole. Serendipidously the eastern borehole pierced the 75° SE-dipping Hayward fault at a depth of 20 m leaving the hanging wall and passing into the footwall of the creeping fault. Repeated measurements reveal the slip of the fault at depth. Twelve measurements have been made since installation in 1993 (see Figure in which the measurements are all referred to 1994). Irregular slip of a minor fracture near the surface (7 m depth) adds noise to the surface creep measurements. The slip at 10-20 m depth occurs monolithically at a rate of 5.6 mm/yr. Since 1997 the creep *displacement* at the surface in Fremont has lagged 5 mm behind the creep at 10 m depth. The creep *rate* at Fremont has been retarded by almost 3 mm/year for the past five years, compared to the century-long rate. The rotation rate of the 2 m section of the borehole where it crosses the main fault is 0.25 degrees/year.



Progressive offset of Hayward fault as a function of depth revealed by borehole inclinometer measurements 1993-2003. Differences are plotted relative to 1994. Fault-normal deformation is negligible.



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Investigation of Microscale Fault Textures Associated with Aseismic Creep and Coseismic Rupture in Active Fault Zones

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Micro-scale textures in poorly consolidated sand collected from active fault zones show differences between deformation fabrics produced by aseismic creep and those produced by coseismic rupture. Oriented samples of late Pleistocene to Holocene sand were collected from creeping sections of the Green Valley, Southern Calaveras, and San Andreas Faults, all parts of the San Andreas Fault system in north-central CA. Samples were also collected from two structures thought to record coseismic rupture: the McKinleyville Fault, CA, an active thrust fault in the forearc of the Cascadia Subduction Zone, and the hypothesized New Madrid North fault, MO, a possible active strike-slip fault in the New Madrid Seismic Zone. Samples were cemented with low-viscosity epoxy and examined using image analysis of photomicrographs and SEM images.

Fault zone sediment samples from the active faults studied share several textural characteristics at the microscopic scale. Fault zone samples from both coseismic slip and creeping faults have finer grain size and less pore space than sediments outside of (>10 cm from) the fault zone, as well as some degree of preferred grain orientation. These textures record a combination of fault zone kinematics (translation, rotation, strain history of sediments) and authigenic processes.

Of particular interest to paleoseismologists are textural characteristics that differ between fault zones with histories of coseismic slip and those experiencing fault creep. One such texture in the coseismic slip examples studied is a pronounced anastomosing shear zone structure consisting of relatively undeformed sand lenses surrounded by fine-grained shear zones. Grains within lenses in the McKinleyville fault deformation band appear undamaged, while those in the New Madrid North fault show some grain size reduction relative to sand several meters from the fault zone. Abrupt decrease in grain size at the boundaries of these lenses suggests that grain size reduction accompanied concentration of shear in localized shear zones. This texture may be an indicator of velocity weakening, potentially unstable stick-slip behavior.

Another textural characteristic that differs between the samples studied is the orientation of elongate grains relative to the fault. In the McKinleyville and New Madrid North fault samples, preferred grain orientation is oblique to the fault. In contrast, in samples from creeping segments of the Southern Calaveras Fault at Costa Ranch, and San Andreas Fault at Flook Ranch, the highest concentration of elongate grains is oriented parallel to the fault. Factors other than the creep vs. stick-slip history of these faults may influence preferred grain orientation in fault zone sand. Possible factors include differences in sense of motion, mechanics of fracture initiation, interplay between fault strands, etc. We plan to extend our studies to additional sites in order to investigate further the relationships between fault texture and slip history.

The Bay Area Velocity Unification (BAVU); Bringing Together Crustal Deformation Observations from throughout the San Francisco Bay Area

Matthew A. d'Alessio, Ingrid A. Johanson, Roland Bürgmann, and the UC Berkeley Active Tectonics Group

In an effort to put together the most comprehensive picture of crustal deformation in the San Francisco Bay Area, the UC Berkeley Active Tectonics Group has begun work on the Bay Area Velocity Unification (BAVU, pronounced "Bay-View"). This dataset unites campaign GPS data for nearly 180 GPS stations throughout the greater San Francisco Bay Area from Sacramento to San Luis Obispo. The BAVU dataset includes data collected from 1991 to 2003 by U.C. Berkeley, the U.S. Geological Survey, the California Department of Transportation, Stanford University, U.C. Davis and the Geophysical Institute in Fairbanks, AK, combined with continuous GPS data from the Bay Area Regional Deformation (BARD) network and the global IGS network. We have reprocessed and combined all of these data using a uniform methodology with the GAMIT/GLOBK software package. BAVU has 88 GPS stations in the eastern San Francisco Bay Area with 64 of those within 15 km of the Hayward fault. GPS data are complemented by InSAR range-change rates estimated from a stack of > 20 interferograms spanning 1992-2002. The BAVU dataset comprises a consistent velocity field that will serve as the basis for monitoring fault slip and strain accumulation throughout the greater San Francisco Bay region.

Modeling Fault Creep on the Hayward Fault and Implications of Seismicity for Defining Patterns of Fault Creep

Kevin P. Furlong (1), Christine Gans (1), Rocco Malservisi (1,2)
(1) Geodynamics Research Group, Penn State University
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The Hayward fault is considered to be one of the primary hazards in the San Francisco Bay region. Although it is documented to undergo significant creep, with some creeping patches accommodating 50% or more of the long-term fault displacement, the fault also experiences moderate to large earthquakes (most recent M ~6.8 in 1868). Under the assumption that the seismic hazard associated with a fault is related to the distribution and amount of slip deficit accumulated during interseismic periods. Therefore mapping creep patterns on a fault plane is an important component in the assessment of the seismic hazard. Combining observations of surface creep rate and the distribution of micro-seismicity, with modeling results derived from a visco-elastic finite-element model driven by far field plate motions, we have analyzed the slip deficit that can be accumulated on the Hayward Fault. Our results show that the interaction of the fault with the surrounding lithosphere leads to a smooth transition of the creep rate from locked to fully creeping areas and implies significant slip deficit accumulation not only in fully locked zones but also in adjacent low friction areas.

In order to link seismic potential to the rate at which moment accumulates on the fault plane, we need to understand the patterns and distribution of creep over time. As might be expected, the microseismicity observed on the fault produces only a negligible percentage of the seismic moment dissipated on the Hayward fault, whereas aseismic creep releases about 25% of the moment accumulating on the fault. The distribution of creep on the fault can change throughout the earthquake cycle, in particular after major seismic events. Although at present the post-seismic transients have mostly decayed, the pattern of accumulated moment is significantly different when these transients are included.

Long-term history of the Hayward Fault Zone

R.W. Graymer, U.S. Geological Survey

The Calaveras-Hayward-Rodgers Creek-Healdsburg Fault Zones form the boundary between two major structural blocks in the San Francisco Bay area. On the southwest of the Hayward Fault Zone, the San Francisco Bay block is made up of interleaved Franciscan terranes, Coast Range Ophiolite, and Jurassic to Early Cretaceous Great Valley Sequence strata of the Healdsburg terrane, locally overlain by relatively small areas of Miocene and younger strata, and more generally overlain by a veneer of Quaternary sediments. By contrast, the East Bay Hills block on the northeast is made up of a thick sequence of late Cretaceous Great Valley Sequence strata and Paleocene through Pliocene units, and Quaternary sediments are largely limited to valley fill. Presumably the lower Great Valley Sequence, Coast Range Ophiolite, and Franciscan rocks are present in the deep subsurface of the East Bay Hills block. The fault zone itself is mostly made up of slivers of Franciscan, Coast Range Ophiolite, and lower Great Valley Sequence rocks.

The Hayward Fault currently joins southward with the central Calaveras Fault through a left step/bend, and northward with the Rodgers Creek Fault through a right step. However, correlation of five rock units offset by the fault indicate that for some time in the past the Hayward Fault joined northward to the Petaluma Valley Fault, which is a relatively straight extension of the Hayward Fault. The total post-12 Ma offset on the Hayward Fault has been about 100 km: 20 km between 12-10 Ma, 20 km between 10-6 Ma, 35 km between 6-3.5 Ma, and 25 km since 3.5 Ma. The 6-3.5 Ma offset was taken up by the Petaluma Valley Fault, whereas the 10-6 Ma and post-3.5 Ma offset was taken up by the Rodgers Creek Fault. It is presently not possible to determine which northern fault took up the 12-10 Ma offset, although geometric considerations in the palinspastic reconstruction favor the Rodgers Creek Fault.

In many places the mapped active strands of the Hayward Fault have accumulated substantially less offset. In at least three locations distinctive rock bodies are offset 5 km or less by the mapped active strands, so other nearby strands now considered inactive must have been the locus for Hayward Fault offset for the bulk of its history. However, in at least one place (Montclair), the active strands do appear to have accumulated the total offset.

In addition to right-lateral offset, the distribution of Pleistocene gravels and the areal topography demonstrate that rocks on the northeast side of much of the Hayward Fault Zone have been uplifted. Comparison of gravel deposit elevation across the fault zone suggests that long-term vertical offset has accumulated at about 1 mm/yr since early Pleistocene time. The lack of comparable pre-Pleistocene strata across much of the fault, and the folding and right-offset of the few correlative units, precludes the calculation of earlier uplift rates. However, clast content and imbrication in the late Miocene Orinda Formation in the Berkeley Hills shows that prior to Hayward Fault offset, the San Francisco Bay block was, at least locally, topographically higher than the now-higher East Bay Hills Block.

Preliminary Insights on Hayward Fault Seismicity and Geology: Results from Analyzing a 3-Dimensional Geologic Map of the Hayward Fault and Vicinity, San Francisco Bay Region, California

Jachens, R.C., Graymer, R.W., Simpson, R.W., Phelps, G.A., Ponce, D.A., and Wentworth, C.M.[1]
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New relationships between seismicity and geology along the 3-dimensional surface of the Hayward Fault were discovered using a 3-dimensional geologic map of the fault and surrounding regions. The 3-dimensional geologic map allowed for the construction of 'geologic maps' of the fault surface, maps that show geologic units on either side of the fault that truncate against the fault surface. The two resulting 'geologic maps' of the fault surface, one for the east side and one for the west side, were compared with the Hayward Fault seismicity using flexible 3-dimensional visualization software that permitted free exploration of the 3-dimensional relationships. A first-order correlation of seismicity to rock type is apparent from viewing the seismicity relative to the 'geologic map' of the western face of the fault. Far fewer earthquakes occur along the northern part of the fault where an intensely sheared Franciscan melange abuts the fault face, compared to the region to the south where more coherent rocks of other Franciscan terranes or of the Coast Range ophiolite are present. More locally, clusters of earthquakes appear to correlate spatially with some of the contacts between Franciscan terranes. However, these correlations are critically dependent on the ability to reliably project the surface geologic contacts into the subsurface. Simple tests suggest that these correlations are somewhat robust and thus are worth analyzing more fully.

The three-dimensional geologic map of the Hayward Fault encompasses a volume 90 km long, 20 km wide, and 14 km deep roughly centered on the active trace and extends southeastward from the north side of San Pablo Bay to Mission San Jose. The primary structural element in the map, the Hayward Fault, is far from simple. A 3-dimensional fault surface based on mapped surface traces, seismicity located with the double-difference algorithm, and geophysical modeling shows that the fault varies in dip along strike: near vertical at the north end; about 75° NE along the central part of the Hayward Fault near San Leandro; to about 55° NE near the southern part of the creeping section of the fault near Fremont. The fault surface also contains local topography that must hinder smooth slip. The proposed surface connects the Mission seismicity trend between the southern Hayward Fault and the central Calaveras Fault with the creeping trace of the Hayward Fault to the west with a 3D surface that dips progressively more shallowly to the northeast as one moves to the south along the Hayward Fault trace.

Building out from this fault surface, the geology in the surrounding volume was assembled in the following way. The distribution and thickness of Cenozoic deposits west of the fault were defined by an inversion of gravity data, which generated a surface representing the top of the Mesozoic basement. The Franciscan terranes beneath the young Cenozoic deposits west of the fault were defined at the Mesozoic basement surface by combining sparse outcrop shown on the geologic map and geophysical expression in the gravity and magnetic maps. The terranes were projected into the subsurface using a constant dip that reflects the structural relationships within the Franciscan terranes observed northwest of the study volume, where the Mesozoic rocks are better exposed. The subsurface relations east of the fault were mapped by manually contouring the projection of surface geology along stacked cross-sections, with the addition of a significant volcanic unit in the north part of the map that lacks surface exposure (although it is present in one petroleum exploration well), but possesses a prominent magnetic expression.

The 3-dimensional geologic map of the Hayward Fault and vicinity was assembled using EarthVision (TM, Dynamic Graphics, Inc.; www.dgi.com), a geologic modeling software package that includes three-dimensional rendering and model manipulation capabilities. The 3-dimensional map was interactively explored and analyzed using Geowall (www.geowall.org; Electronic

Visualization Laboratory associated with the University of Illinois), a stereo projection system to visualize three-dimensional models. Geowall uses dual polarized images projected onto a polarization-preserving screen to create the illusion of three dimensions when viewed through polarized glasses and permits large groups to explore, analyze, and interpret 3-dimensional maps interactively.

Although preliminary in nature, the results of comparing seismicity along the Hayward Fault with the inferred 3-dimensional geology suggest that any attempt to understand the detailed distribution of earthquakes should include consideration of the rock types that interact across the fault surface. Such consideration would benefit greatly from incorporating into the 3D database the extensive laboratory results on properties and behavior of the rock types likely to exist at depth along the fault.

The Hayward Fault in the East San Francisco Bay Region, California: A Regional Geophysical and Geological Perspective

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Regional gravity, magnetic, and geologic data, together with sparse seismic reflection and refraction data, and drill hole logs, provide a regional tectonic perspective and context of the Hayward fault. The fault is at least 85 km long and terminates at both ends at pull-apart basins. The southeastern terminus falls near the northeastern tip of the NW-SE Evergreen basin, which likely formed in the wake of a right step between the Silver Creek and Hayward Faults as a result of large right slip. The northwestern terminus lies along the southwestern edge of the deep basin that lies beneath eastern San Pablo Bay and extends, as the East Bay Trough, both southeast and northwest. Here, a structural manifestation of the Hayward Fault (the southwestern edge of the deep basin) steps right to about trace of the Tolay thrust Fault, whereas seismicity and recent movement step farther right to the Rodgers Creek Fault. The deep basin under San Pablo Bay is three times wider than the right step from the Hayward fault to the Rodgers Creek fault, suggesting that if this basin is a strike-slip pull-apart basin, then faults farther east of the Rodgers Creek fault must have been involved in its formation. The local basin that formed during the past few million years in the wake of the Hayward-Rodgers Creek right step probably is no more than 500 m deep, according to a seismic reflection profile. A continuous magnetic anomaly probably reflecting a buried volcanic body lies between the Rodgers Creek Fault and the western deep basin margin north of San Pablo Bay, continues southward to truncate against the Hayward fault beneath most of San Pablo Bay. This body is not dismembered, precluding a simple strike-slip connection between the Rodgers Creek and Hayward Faults with more than about 10 km of offset (compared to the estimated roughly 100 km of total offset across the Hayward fault).

The Hayward fault separates two distinctly different crustal blocks. The Bay block to the southwest generally consists of a basement of Franciscan terranes mantled by a veneer of Plio-Quaternary deposits generally <400 m thick. One exception is the San Leandro synform west of the central reach of the Hayward fault, which contains about 800 m of folded, probably Tertiary, strata overlain by about 300 m of flat-lying younger deposits. Northeast of the Hayward Fault Franciscan terranes lie beneath Mesozoic Coast Range Ophiolite, Cretaceous Great Valley Sequence, and overlying Cenozoic deposits exposed at the surface. The Great Valley Sequence and younger sedimentary deposits probably reach a thickness in excess of 8 km beneath Livermore Valley and San Pablo Bay, suggesting structural relief on the Franciscan basement of more than 9 km (bottom of Livermore basin to top of the Diablo Range to the south).

The central reach of the Hayward Fault lies at the western base of a steeply east-dipping slab of Coast Range ophiolite, indicating that the present-day Hayward Fault is here controlled by the older Coast Range Fault, a wedge fault that regionally separates subduction-related Franciscan rocks from overlying forearc Coast Range ophiolite and Great Valley Sequence strata.

A 2000-Year Preliminary Record of Large Earthquakes on the Southern Hayward Fault

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The Hayward fault, a major branch of the right-lateral San Andreas fault system, traverses the densely populated eastern San Francisco Bay region, California. We are conducting a multiyear paleoseismic investigation to better understand the Hayward fault's past earthquake behavior. Our site is near the south end of Tyson's Lagoon, a sag pond formed in a right step of the fault in Fremont. Because the Hayward fault creeps at the surface, we identified paleoearthquakes primarily using features which we judge to be unique to ground ruptures or the result of strong-ground motion, such as the presence of fault-scarp colluvial deposits and liquefaction. We correlate the most recent event evidence to the historical 1868 **M** 6.9 earthquake, which caused liquefaction in the pond. We recognize nine additional paleoruptures since about AD 115 (± 135 yr) and two earlier events as yet undated. Event ages were estimated by chronological modeling, which incorporates historical and stratigraphic information as well as radiocarbon and pollen data. The preliminary mean recurrence interval (RI) for these ten events is 195 ± 15 yr. This long-term (AD 115-1868) RI is somewhat greater than a previously determined RI of 130 ± 40 yr for the period AD 1470-1868. Our event sequence includes event evidence from fault traces on both sides of the pond by tracing key stratigraphic units across. Our continuing work at this site focuses on carefully examining the possibility of missing events due to a hiatus in sedimentation to verify that the current record of paleoearthquakes is complete over the 2000-yr period. More age data is still needed to refine and complete the chronologic model to characterize the aperiodicity of the recurrence interval for the southern Hayward fault.

Frictional Behavior of Chrysotile Gouge at Seismogenic Depths and its Application to the Hayward Fault Zone

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Frictional strength of the serpentine mineral chrysotile has been measured in triaxial tests at effective normal stresses between 40 and 200 MPa in the temperature range 25° to 280°C. Overall, the coefficient of friction, μ of water-saturated chrysotile gouge increases both with increasing temperature and effective normal stress, but the rates vary and the temperature-related increases begin at ≈100°C. For heated chrysotile, the rate of increase of μ with increasing effective normal stress is 3-4 times higher below 100 MPa than above. As a result, a frictional strength minimum ($\mu \leq 0.1$) occurs at normal stresses below 50 MPa at about 100°C. Maximum strength ($\mu \geq 0.55$) results from a combination of effective normal stresses of 150 MPa or greater and temperatures above 250°C. The low-strength region is characterized by velocity-strengthening and the high-strength region by velocity-weakening behavior. Thoroughly dried chrysotile has $\mu \geq 0.7$ and is velocity weakening. The wide range in the frictional strength of chrysotile can be explained by its tendency to adsorb large amounts of water, which acts as a lubricant during shear. The adsorbed water is progressively driven off the crystal surfaces with increasing temperature and pressure, causing chrysotile to approach its dry strength.

The chrysotile content of California serpentinites has been shown to increase with shearing, and the concentration of chrysotile along the principal shear surfaces of serpentinite-filled fault zones potentially could strongly influence fault behavior. Rock units of the Coast Range ophiolite, including serpentinite and serpentinite mélange, are exposed along much of the length of the Hayward fault zone, and chrysotile is an important constituent of serpentinite gouge collected from the fault. A depth profile constructed from the laboratory data for chrysotile in a fault zone is characterized by a strength minimum at about 3-km depth, where slip is also likely to be stable, followed by a rapid increase in strength and a possible shift to unstable (seismic) slip at greater depths. Such a profile would be consistent with those models of the Hayward fault which propose that fault creep extends to about 5-km depth, with a locked zone beneath.

Hayward Fault Rocks: Porosity, Density, Strength and Wave Speed Measurements

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Porosity, density, strength, and wave speed measurements were conducted on rock samples collected from the Hayward Fault region in Northern California as part of the Hayward Fault Working Group's efforts to create a working model of the Hayward Fault. The rocks included in this study were both fine- and coarse-grained gabbros, altered keratophyre, basalt, sandstone, and serpentinite from various rock formations adjacent to the Hayward Fault. The densities of these rocks ranged from a low of 2.25 g/cm^3 (altered keratophyre) to 3.05 g/cm^3 (fine-grained gabbro), with an average of 2.6 g/cm^3, typical of many other rocks. Porosities were generally around 1% or less, with the exception of the sandstone (7.6%) and altered keratophyre (13.5%).

Failure and frictional sliding tests were conducted on intact rock cylinders at room temperature under effective pressure conditions of up to 192 MPa, simulating depths of burial to 12 km. Both peak strength (usually failure strength) and frictional strength, determined at 8 mm of displacement, increased systematically with effective pressure. Coefficients of friction, based on the observed fracture angles, ranged from 0.6 to 0.85, consistent with Byerlee's Law. All samples showed velocity strengthening, that is, the samples became slightly stronger at a faster sliding rate. Velocity strengthening behavior is associated with stable sliding (creep), as observed in the shallow portions of the Hayward Fault. Possible secondary influences on the strength of the Hayward rock samples may be surface weathering, or the presence of pre-existing fault-related fractures. Shear and P-wave velocities were also measured at effective pressures up to 230 MPa on a separate suite of intact cores. Velocities ranged from 2.4 to 3.7 km/sec (S-wave) and 4.2 to 7.0 km/s (P-wave), and correlated with rock porosity and density. In all, the physical properties measurements showed a wide range of values, but were consistent with the characteristics of the diverse rock types.

Instrumental Hayward Fault Seismicity

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Analyses of instrumentally recorded seismograms provide relatively precise estimates of earthquake location, time, magnitude and focal mechanism. After nearly a century of instrumental recording, thousands of Hayward Fault earthquakes have been analyzed. Collectively, their space, time, size and mechanism distributions provide important information for hazard related issues such as fault zone structure, deformation style, segmentation, moment release, and evolution. With time, advances in the collection and analyses of instrumental data have also significantly increased the resolution of the seismic observables. Most recently this has led to the discovery and use of previously unrecognized earthquake systematics (e.g. tight spatial clustering and lineations of similar small earthquakes and the characteristically repeating microearthquake phenomena) for extraction of additional hazard related information. These advances are significantly improving our ability to integrate the seismic observables with geologic, geodetic and other geophysical information and are helping to improve the accuracy of fault and earthquake forecast models for the Hayward Fault. In this talk, results of instrumentally recorded Hayward Fault seismicity (1910-) are presented, the improving picture of seismicity with time is discussed, and recent results using modern high-resolution data and analyses are shown.

Effects of Hayward Fault Interactions with the Rodgers Creek and San Andreas Faults

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Finite-element and crustal-structure models of the Hayward fault emphasize its position within a network of interacting faults, and indicate a number of expected influences from other faults. For example, a new structural cross section across San Pablo Bay in association with potential field maps allows us to map and model detailed interactions between the Hayward and Rodgers Creek faults. The two faults do not appear to connect at depth, and finite-element models indicate growing extensional stress in the stepover between the two faults. A model consequence of extensional stress in the stepover, combined with long-term interaction with the San Andreas fault, is normal-stress reduction (unclamping) of the north Hayward fault. If this occurs in the real Earth, then substantial reduction in frictional resistance on the north Hayward fault is expected, which might in turn be expected to influence the distribution of creep. Interaction effects on a shorter time scale are also evident. The 1906 San Francisco, and 1989 Loma Prieta earthquakes are calculated to have reduced stress on the Hayward fault at seismogenic depths. Models of the 1906 earthquake show complex interactions; coseismic static-stress changes drop stress on the north Hayward fault while upper mantle viscoelastic relaxation slightly raises the stressing rate. Stress recovery is calculated to have occurred by ~1980, though earthquake probability is still affected by the delay induced by stress reduction. We conclude that the model Hayward fault is strongly influenced by its neighbors, and it is worth considering these effects when studying and attempting to understand the real fault.

Geometry and Segmentation of the Hayward Fault, Northern California

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The Hayward Fault, one of the most hazardous faults in northern California, trends NNW and extends for about 90 km along the eastern margin of the San Francisco Bay region. At numerous locations along its length, distinct and elongate gravity and magnetic anomalies correlate with mapped mafic and ultramafic rocks. The most prominent of these anomalies reflects a 16-km long gabbro body, hereafter referred to as the San Leandro gabbroic block. Inversion of magnetic and gravity data constrained with physical property measurements is used to define the subsurface extent of the San Leandro gabbro body and to speculate on its origin and relationship to the Hayward Fault Zone.

Gravity and magnetic modeling indicates that the San Leandro gabbro body is about 3 km wide, dips about 75° northeast, and extends to a depth of at least 6 km. One of the most striking results of the modeling, which was performed independently of seismicity data, is that accurately relocated seismicity, that extends to a depth of about 12 km, is concentrated along the western edge or stratigraphically lower bounding surface of the San Leandro gabbro. The western boundary of the San Leandro gabbro block is the base of an incomplete ophiolite sequence and probably represented by Late Cretaceous to early Tertiary, a low-angle roof thrust related to the tectonic wedging of the Franciscan Complex. After repeated episodes of extension and attenuation, the strike-slip Hayward Fault probably reactivated or preferentially followed this pre-existing feature in the late Tertiary.

Because earthquakes concentrate near the edge of the San Leandro gabbro but tend to avoid its interior, this massive igneous block may influence the distribution of stress. The microseismicity cluster along the western flank of the San Leandro gabbro leads us to suggest that this stressed volume may be the site of future moderate to large earthquakes.

Historically, the Hayward Fault has been partitioned into two fault segments on the basis of an 1868 and an 1836 earthquake. However, because the 1868 earthquake ruptured beyond the segment boundary and the 1836 earthquake is no longer associated with the Hayward Fault, this necessitates a re-evaluation of the two-segment model of the Hayward Fault.

The inter-relationships between gravity and magnetic anomalies, mafic and ultramafic rocks, structural trends, creep rates, and clusters of seismicity suggest that the Hayward Fault consists of numerous fault-zone discontinuities that may define several fault segments. Fault segment boundaries can be defined by various fault-zone discontinuities based on geometric, structural, geophysical, and geologic information. Segment boundaries or asperities are locations where seismic ruptures may tend to nucleate or terminate. We suggest that the Hayward Fault may be partitioned into several segments based on geological and geophysical evidence. While some of these may be rupture bounding segments, the ability of an earthquake to propagate across segment boundaries may, in part, be related to the location, magnitude, and rupture propagation velocity of the earthquake. The approximate location and rupture length of the great M6.7 1868 earthquake combined with geophysical evidence suggests that it may have been located at or near a segment boundary and propagated bilaterally to both the northwest and southeast. In addition, geological and geophysical data suggest that the rupture associated with the 1868 earthquake may have terminated at a segment boundary near Berkeley.

Geometry of the Hayward Fault and its Connection to the Calaveras Fault Inferred from Relocated Seismicity

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Sixteen years of earthquakes recorded by the Northern California Seismic Net (NCSN) between 1984-2000 and relocated using the Double-Difference technique (Ellsworth and others, Eos, 2000) reveal a number of intriguing structures within the Hayward and Calaveras fault zones and a complex relationship between the main fault surfaces and secondary oblique or reverse faults. As suggested by Waldhauser and Ellsworth (2002) and Manaker and Michael (2003), the central Calaveras fault appears to connect to the Hayward fault through a volume bounded on the north by the Mission seismicity trend. As defined by seismicity below 6 km depth, the connection appears quite simple, involving several straight, near-vertical segments forming a restraining bend along the Mission seismicity trend. Above 6 km the connection is complex and not well-defined by seismicity. At the Earth's surface, the mapped creeping trace of the southern Hayward fault deviates from the eastward diverging seismicity along the Mission trend, suggesting that the fault dips to the east in this vicinity to connect with the deeper seismicity. The mapped surface traces of the two faults do not connect, but run subparallel about 5 km apart for 25 km. The area of overlap is characterized by mapped reverse and oblique faults. At one location in the overlap region, seismicity suggests a dipping fault that appears to cut and offset horizontally a near-vertical Calaveras fault plane, raising the interesting possibility that seismogenic asperities are being created as the strike-slip and reverse/oblique systems interact. Intersections of this sort between two active fault systems might explain the linear streaks of repeating microearthquakes that have been noted in a number of studies.

By plotting the relocated seismicity in a series of cross-sections spaced at 2.5 km intervals along the Hayward-Calaveras faults and digitizing the inferred (sometimes interpolated or extrapolated) fault surface from each of the sections, we have attempted to define an active fault surface at depth that connects with the creeping fault traces mapped at the Earth's surface. Our inferred surface has a scoop-like geometry in the upper several kilometers at its southern end. Slip on the inferred surface, because it is non-planar, must be accompanied by local deformation or slip on secondary faults. A simple dislocation model in which the surface is made to slip by imposing plausible long-term slip rates on vertical dislocations under the model yields a deformation pattern consistent with the "snow plow" effect described by Manaker and Michael (2003) and also suggests that the low elevation triangle in the Niles-Mission district area of Fremont may be explained by the proposed dipping geometry of the Hayward fault in this region.

Paleoseismic Investigation of the Rodgers Creek/Healdsburg Fault at Shiloh Regional Park, Sonoma County, California

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Determining the timing of paleoearthquakes and refining the slip-rate and recurrence estimates on the Hayward-Rodgers Creek fault system are important for assessing the seismic hazards and probabilities of potentially damaging earthquakes in the San Francisco Bay region. The most recent ground rupturing event on the Rodgers Creek fault south of Santa Rosa is believed to have occurred between about 1670 and 1776 (Schwartz, et al., 2001; Randolf-Loar, 2002; Working Group on California Earthquake Probabilities, 2003); however the timing of the most recent event on the northern part of the Rodgers Creek-Healdsburg segment north of Santa Rosa is not well constrained. As part of the USGS Bay Area Paleoseismic Experiment (BAPEX), preliminary investigations were conducted during 2002 at two sites at Shiloh Regional Park. At the northern site, a trench was excavated across a small sag on a 5-m-high terrace that is aligned along the southward projection of a right-lateral stream offset. The stratigraphic and structural relations exposed in the trench provide evidence for at least three and possibly four surface-faulting earthquakes. Twenty-one samples of detrital charcoal were collected from four separate stratigraphic layers within the late Quaternary alluvial and colluvial deposits exposed in the trench. Radiocarbon analyses of these samples will enable us to constrain the timing of events 1, 2 and 3. At the southern site, a detailed survey of an offset terrace was made to document the 13.5 ±0.5 m of right-lateral offset of the valley margin. Three charcoal samples were collected from the offset alluvium at the Southern Site; one of which has a measured radiocarbon age of 680 ± 40 BP indicating that faulting has occurred within about the past 700 years along this segment of the fault. Additional geologic data are needed at the Southern Site to determine the relation between the dated alluvium and the cumulative 13.5 ±0.5-meter lateral offset of the valley margin.

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AUTHOR INDEX

A geologic and geophysical tour of the Hayward Fault Zone

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for the 2003 Hayward Fault Workshop

Introduction

The Hayward Fault is extremely well studied, and has been the subject of a number of excellent fieldtrips. The purpose of this fieldtrip guide is not to repeat what has already been written elsewhere, but to take a look at some of the less familiar aspects of the fault and results of recent research. To that end we will be visiting many localities familiar to those who have gone on a Hayward Fault fieldtrip (Tule Pond, Downtown Hayward, Point Pinole), but we will look largely at aspects of the fault other than its recent strike-slip offset. These aspects include:

- Recent research on recurrence interval
- 100 km long term offset
- Little long term offset on the mapped active strand in at least three areas, suggesting other faults represent one or more long term “Hayward Faults”
- Quaternary east-up vertical offset
- Active and possibly active traces in addition to the mapped active trace
- 3-dimensional character of the fault zone
- Complexities in connection to the Calaveras and Rodgers Creek Faults at the south and north ends

Throughout this guidebook we refer to the “mapped active strand(s) of the Hayward Fault.” In all cases that phrase refers to the surface traces mapped in Lienkaemper (1992), though in some cases that map has been generalized for scale or to create a through-going feature. The location of other faults mentioned is from Graymer and others (1996) or Graymer (2000).

The guidebook is organized in the following manner: directional maps (Figures 1A-C), roadlog, stop descriptions, figures. The figures numbers are subdivided by the fieldtrip stop they are associated with, so Figure 2-3 is the third figure for the second stop. Figures associated with features we will see while driving but won’t stop to see are numbered with the preceding stop. The features we will see while driving are described briefly in the roadlog.

Figure 1A. Maps showing the location of the initial meeting point for the fieldtrip. Park in the lot at the southeast end of the BART Station (near Walnut Way).

Key

Fieldtrip route, described in the following Roadlog. Dots mark main fieldtrip stops, diamonds mark points of interest for viewing along the route, as described in the Roadlog.

Generalized trace of the mapped active strand of the Hayward Fault (generalized from Lienkaemper, 1992)

Generalized trace of other faults mentioned in the text (generalized from Graymer and others, 1996)

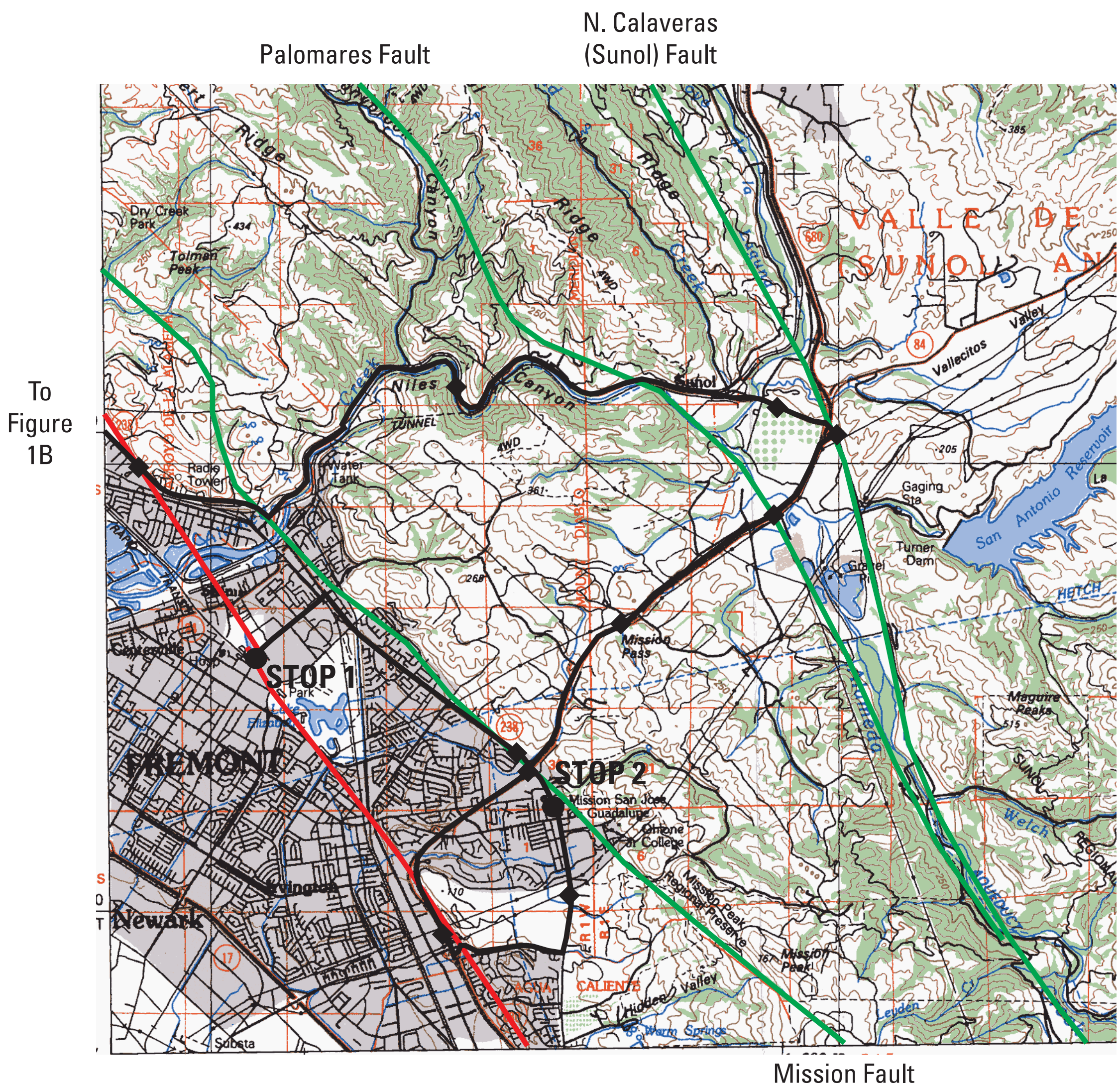

Figure 1B. Fieldtrip route map

Figure 1C. Fieldtrip route map, continued

Roadlog

Approx. miles	Driving directions	Description
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0.0	**Stop 1**	**Tule Pond trench site**
	East on Walnut	Note ahead the ridge underlain by Miocene Briones Formation bounded on the west by the Mission Fault.
0.8	Right onto Mission Blvd	Driving south on Mission, you are looking up at Mission Peak.
3.5		Mission Blvd crosses the Mission Fault here.
4.0	**Stop 2 – Lunch**	**Mission San Jose**
5.0		Continuing south on Mission, the large Mission Peak landslide is visible on the left
5.4	Right onto Durham	
6.4	Left onto freeway I-680 North	As you go onto the freeway proper, note the west facing Hayward Fault scarp underlain by early Pleistocene Irvington gravels. The scarp has been much modified by gravel quarries and freeway construction, but is still evident on the 7.5’ quadrangle topographic maps (Figure 2-6).
8.9		The freeway crosses the Mission Fault here.
		Mission Pass, note the folded and faulted Miocene Briones Formation, Claremont Shale, and Tice Shale. Also note that, although Mission Pass is the lowest part of the ridge, Alameda Creek, which drains all of the northern Diablo Range, does not pass through here, but has carved a deep canyon farther north.
12.5		The freeway crosses the Palomares Fault here. A now-dormant fault, palinspastic reconstruction of the East Bay Fault System suggests that the Palomares (and it’s along-strike continuations, Miller Creek-Moraga-Pinole-Carneros Faults) accumulated 50 km of right-lateral offset between 10-3.5 Ma.
13.6	Take the Calaveras Road/ Sunol exit	

13.7	Left onto Calaveras Road	We are on the mapped trace of the northern Calaveras (Sunol) Fault here
		After we pass under the freeway, notice the high terrace underlain by Livermore gravels to the left (Figure 2-7). The small hills to the right are also underlain by Livermore gravels. These gravels are equivalent in age, clast content, heavy mineral content, and lithology to the Irvington gravels, suggesting that these two now-separated gravel bodies were once part of a contiguous alluvial system, and that they have been separated by uplift of the intervening ridge since alluvial deposition about 1.5 Ma.
14.4	Veer left onto Niles Canyon Road – Hwy 84	
		Alameda Creek passes through the deeply incised Niles Canyon. As we drive down, note how the canyon meanders (Figure 2-3), unlike the relatively straight northwest trending canyons common in the East Bay hills. Also look for the almost vertical beds of the Cretaceous Great Valley Sequence. Why does the Creek pass through here instead of the softer rocks of the lower part of the ridge at Mission Pass? Because the meandering Alameda Creek predates the uplift of the ridge, and the drainage was superposed on the ridge that has been lifted up in the last 1.5 million years.
21.0	Right onto Mission Blvd	
21.6		The road crosses the mapped active strand of the Hayward Fault here. The mapped active strand runs parallel on the right for many miles.
29.7	Straight on Mission Blvd	You'll need to be in the left lane to avoid going right onto Foothill. Note that the mapped active strand of the Hayward Fault passes through the structures on the right.
30.2	**Stop 3**	**Creeping mapped active strand of the Hayward Fault, downtown Hayward**
30.4		Note the scarp of the large shutter ridge to the right.
31.4		The road crosses San Lorenzo Creek here. This creek takes a prominent right step along the mapped active strand just southeast of here, and another upstream in the valley east of the shutter ridge (Figure 3-2). This suggests that there may be another active strand of the Hayward Fault in that valley, although there is no documented creep evidence or trench evidence along it.

32.6	Right onto 162nd	
32.9	Left onto Marcella	
33.0	**Stop 4**	**Trench site, active strand in addition to the mapped active strand**
33.1	Right onto 159th	
33.4	Right onto Manchester, then immediately right onto Foothill	
33.8		Note the gabbro outcrop in the roadcut northeast of the Fairmont/Foohill intersection
33.9	Onto I-580 toward Oakland	
37.0		The freeway crosses the mapped active strand here.
39.4		The large quarry face to the right exposes the Jurassic Leona rhyolite, the silicic upper part of the Coast Range ophiolite here. This altered rhyolite (keratophyre) is host rock to a massive chalcopyrite deposit that was mined for many years as a source of sulphur.
40.0	Exit onto Hwy 13 north toward Berkeley	
43.5		The freeway crosses the mapped active strand here. The Montclair district is to the right. Juxtaposition of elongate bands of Franciscan and Great Valley complex rocks on either side of the fault here suggest that the total 100 km long-term offset on the Hayward Fault Zone is accumulated on or very close to the mapped active strand here, unlike at Stop 4 and elsewhere.
45.0		The freeway crosses the mapped active strand here, and runs through Lake Temescal (a Regional Park) on the left. There is modest evidence of creep there.
45.6	Go straight toward Berkeley	
46.0	Go straight onto Tunnel	
46.6		The large white building to the right is the historic Claremont Hotel. The mapped active strand runs right along the back of the building.
46.9	Right onto Claremont Ave, then immediately left onto Claremont Blvd.	

47.2	Left onto Derby	
47.4	Right onto Warring	
47.6	Curve left onto Piedmont	
48.0		Memorial Stadium is on the right. The mapped active strand passes through the structure, and evidence of creep is obvious in the south end.
48.4	Left onto Hearst	The mapped active strand passes under the new dorms on your right as you turn.
48.9	Right onto Spruce	
49.1	Go straight, don't turn onto Virginia	
50.2	Left onto Marin	The mapped active strand passes under the school grounds on the right as you turn. The school buildings have been relocated and totally rebuilt in the past several years.
50.4	Right onto Shattuck	
50.6	Right onto Indian Rock **Stop 5**	 **Indian Rock Park, Northbrae rhyolite**
50.8	Right onto Santa Barbara	
50.9	Right onto Marin	
51.1	Right onto Arlington, curve immediately left, don't get back onto Indian Rock	
52.0		The mapped active strand passes under the road here.
53.0		The mapped active strand passes under the road here.
54.4		The golf course to the right was host to the recent trench study on the northern Hayward Fault (Hayward Fault Paleoseismic Group, 1997).
57.0	Left onto McBryde	
57.1	Left onto Park	Multiple active strands mapped in Alvarado Park to the right
57.6	Right onto San Pablo	
59.8		The mapped active strand passes under the road here

60.7	Left onto Hilltop
60.9	Left onto Richmond Parkway
61.4	Exit at Giant Highway exit
61.7	Right onto Giant Highway
61.9	Right onto Giant Highway
62.1	Right onto Giant Highway. Yes, that's three consecutive right turns onto Giant Highway
62.6	Left into the Regional Park
62.8	**Stop 6** **Point Pinole, San Pablo Bay**

Stop 1 – Tule Pond (aka Tyson's Lagoon)

At this stop we can see evidence of the Hayward fault in the three forms: (**1**) *creep evidence* (a right-lateral curb offset and left-stepping en echelon shears in Walnut Avenue), (**2**) *geomorphic evidence* (linear fault scarps bound a classic sag pond formed by a right step in a right lateral fault), and (**3**) *trenching evidence* (offset Holocene sag pond units and Pleistocene gravels are juxtaposed in trench "03A", which is only the latest of many exposures made at this site in over three decades.

Park in the BART parking lot. On the weekend the lot is usually not crowded, but may be full during the week, and then you may need to park nearby and walk back. Look for creep evidence where the Hayward Fault main trace (Figure 1-1) runs under the parking lot. CAREFULLY cross Walnut Avenue to the southeast side. In 2003, the effect of creep on the sidewalk southeast of Walnut Avenue at the Hayward Fault main trace was pronounced. Broken pavement is routinely replaced along the Hayward Fault, however, so be aware of the larger-scale deflection of the street as well as looking for cracks in the pavement.

The low-lying area ahead of you is all that remains of a once-larger sag pond. You can still see the scarps along both strands of the fault (Figure 1-1). The continually down dropping base of the small basin here is caused by northwest-southeast directed extension associated with the small right step in the largely right-lateral Hayward Fault. The basin creates the perfect conditions for recording earthquakes in the layered deposits revealed by trenching (Figure 1-2), including swampy ground providing a good source for carbon-rich plant materials that can be used for radiometric dating of the layers. Multiple radio-carbon dates are needed to accurately determine the age of any given layer.

The trenches here have revealed a history of at least 12 large earthquakes resulting in surface rupture at this location over the past 2000 years (Figure 1-3). See the abstract by Lienkaemper and others, this volume, for details

Stop 2 – Mission San Jose

Established in 1797, by the early 1800's this was one of the wealthiest missions in California. The large, adobe church was dedicated in 1809. However, in 1868, a large earthquake on the Hayward Fault destroyed the church and many of the surrounding adobe structures. The present church and mission museums are the result of almost 90 years of restoration efforts, culminating in the construction of a replica church beginning in 1982 (Figure 2-1).

As you eat your lunch, note the broken adobe walls still visible.

In 1868, a length of the Hayward fault zone stretching from Oakland to Fremont broke, and the rocks west of the fault suddenly jumped several feet to the northwest with respect to those east of the fault. The energy released by this sudden motion produced a major earthquake, causing destruction throughout the San Francisco Bay region (Figure 2-2). Until 1906, the Hayward fault zone quake was known as the Great San Francisco Earthquake. Although the effects of this earthquake were well studied at the time, the work was for the most part lost, thought to have been suppressed by local government officials concerned that scientific studies of earthquakes could dampen growth and development in the region! Since 1868, however, the Hayward fault zone has been relatively quiet, and has not generated a large earthquake.

The prominent mountain above the mission is Mission Peak. The uppermost (eastern) portion of the mountain is underlain by Miocene Briones Formation, mostly quartz-rich sandstone and siltstone with many erosion-resistant shell-rich layers. The lower (western) part of the mountain is underlain by younger late Miocene Orinda Formation, made up of non-marine conglomerate, lithic sandstone, and mudstone (Figures 2-3 and 2-4). The contact between the two is the steeply east dipping reverse (oblique?) Mission Fault. In map view, a distinct narrow band of historic seismicity runs roughly along the surface trace of the Mission Fault (Figure 2-5) leading to earlier speculation that the Mission Fault might be active, forming the connection between the Hayward and Calaveras Faults. However, because the Mission Fault dips to the east, and the seismicity is several kilometers deep, the projected fault misses the seismicity by at least a kilometer. More recent analysis suggests that the seismicity is a manifestation at depth of an east-dipping Hayward Fault, and that at seismogenic depth the Hayward Fault connects directly with the Calaveras Fault. In the upper crust the connection is much more complicated. The surface traces of the mapped active Hayward and central Calaveras Faults run roughly parallel for about 25 km, separated by a zone about 3 km wide characterized by imbricate reverse (oblique?) faults.

As we leave Mission Peak behind and merge onto the freeway, note the, much modified by construction of the freeway, west-facing scarp of the Hayward Fault (Figure 2-6). On the east, early Pleistocene Irvington gravels have been lifted up and tilted. Along most of its length, the Hayward Fault has an east-up component (though not everywhere, the area near Stop One is the primary exception). Detailed studies of the microseismicity along the fault show that it is dipping steeply east at depth, and level-line surveys suggest that the fault is accommodating about 1 mm/yr vertical movement along most of its length (in addition to the 9 mm/yr of right-lateral movement).

QTi Irvington Gravels of Savage (1951) (Pleistocene and Pliocene?)--Poorly to well consolidated, distinctly bedded pebbles and cobbles, gray pebbly sand, and gray, coarse-grained, cross-bedded sand. Cobbles and pebbles are well- to sub-rounded, and as much as 25 cm in diameter, and consist of about 60 percent micaceous sandstone, 35 percent metamorphic and volcanic rocks and chert probably derived from the Franciscan complex,

> and 5 percent black laminated chert and cherty shale derived from the Claremont Formation. A large suite of early Pleistocene vertebrate fossils from this unit in quarries in Fremont was described by Savage (1951). [From Graymer, 2000]

In fact, the fossils found near here enabled Savage to recognize a North American mammal stage between the Blancan and Rancholabrean. That stage, which represents the latest Pliocene and much of the Pleistocene (from about 2 to 1 Ma), is called Irvingtonian.

Stop 3 – Downtown Hayward

This is one of the classic areas to view the effects of a creeping fault. The mapped active strand of the Hayward Fault is here actively deforming the manmade structures that lie on it (Figure 3-1), including the old Hayward City Hall (now a park, the building is empty). It won't take long for you to find evidence for right lateral offset here.

Notice as well the east-up nature of deformation along the fault. Although not as pronounced here as near Stop 2, there is a well-developed, west-facing scarp here. The scarp is underlain by late Pleistocene and Holocene alluvium (which may be why it is less pronounced).

Stop 4 – Marcella Street Trench Site

We are outside the area designated for special studies on the California Geological Survey Alquist-Priolo fault rupture hazard maps for Hayward Fault, but we are still in the active Hayward Fault Zone. Two trench studies here have documented fault activity that has juxtaposed Mesozoic basalt (Coast Range ophiolite) on the east against and over the youngest colluvial and alluvial deposits on the west.

The multiple active strands here (Figure 4-1) show that the active Hayward Fault Zone occupies several strands in a zone as much as a kilometer broad. This pattern of multiple potentially active strands is repeated in several places along its length and is very similar to the fault rupture mapped after the 1992 Landers earthquake (Hart and others, 1993). As much as 58 cm of offset from the Landers event (about 6 m total offset) was measured on these subsidiary faults, and even larger offsets were distributed on multiple strands in the area where surface rupture took a 2 km right step (Figure 4-2). This complexity of multiple active strands is probably confined to the upper 6 km, as deep microseismicity on the Hayward Fault defines a relatively simple fault plane.

Although the Mesozoic rock found in the trench here is basalt, the hills above us are underlain by a large Mesozoic gabbro body (the San Leandro gabbro). The mapped active of the Hayward Fault bisects the gabbro body, but only offsets its edge by about 5 km (Figure 4-3). The total post-12 Ma offset on the Hayward Fault zone is about 100 km (Graymer and others, 2002), so the remaining 95 km must have been taken up on fault strands east or west of the gabbro body, including the Chabot Fault to the east and the fault in the trench here.

The most prominent geophysical anomaly (gravity and magnetic) along the Hayward Fault occurs near San Leandro and reflects the 16-km long gabbro body (Figure 4-4). Inversion of gravity and magnetic data, constrained by surface geology and physical property measurements, indicates that the San Leandro gabbro is much more extensive in the subsurface than previously thought and is about 3 km wide, dips about 75° northeast, and extends to a depth of at least 6 km (Figure 4-5).

Accurately relocated seismicity, that extends to a depth of about 12 km, is concentrated along the western edge or stratigraphically lower bounding surface of the modeled San Leandro gabbro (Figure 4-5). Because the western boundary of the San Leandro gabbro probably represented by Late Cretaceous to early Tertiary time a low-angle roof thrust related to the tectonic wedging of the Franciscan Complex, the Hayward Fault at depth may have locally reactivated or preferentially followed this pre-existing feature. In addition, because seismicity concentrates near the edge of the San Leandro gabbro but tends to avoid its interior, this massive igneous block appears to influence the distribution of stress and may be the site of a future moderate to large earthquake.

Stop 5 – Indian Rock Park

The rocks here are the distinctively flow-banded Northbrae rhyolite. Until recently, these were considered part of the Jurassic silicic volcanics that make up the upper part of the Coast Range ophiolite in many areas (the Leona rhyolite that we passed by in the Oakland Hills, for example). However, very careful study of the Northbrae rhyolite by Lin Murphy of California State Univ., Hayward, has revealed that they are instead much deformed Miocene volcanics. Ar/Ar dates obtained by Robert Fleck (U.S. Geological Survey, Menlo Park) on samples collected by her are about 11 Ma, which suggest that these rocks are a fragment of Quien Sabe – Burdell Mountain Volcanics left behind in the Hayward Fault Zone.

These flow banded rocks crop out on both sides of the mapped active Hayward Fault in the Berkeley Hills (Figures 5-1 and 5-2), and like the gabbro at the previous stop show little sign of offset (about 5 km or less). Burdell Mountain is about 45 km to the northwest, suggesting that about that much offset has been accommodated by faults west of the Northbrae rhyolite, which would leave about 50 km accumulated on faults east of the rhyolite.

The mapped active fault here also has little relation to the topography, running roughly halfway up the elongate ridge of the Berkeley Hills. It is tempting to ascribe the topography to an active strand of the fault zone at the base of the steep ridge, but no such active fault has been documented, and the Berkeley Hills lack the uplifted and deformed Pleistocene gravels that are found in the Oakland Hills and farther south.

Stop 6 – Point Pinole

The final stop is at the former dynamite factory and company town of Giant, now just called Point Pinole and most famous (among geologists, anyway) as the place where the Hayward Fault runs off into the unknown. Walk north from the parking lot and turn west to cross the bridge over the railroad tracks (Figure 6-1). Go left (southwest) on first trail, the Bay View Trail, until you emerge from the trees and have a clear view of the Bay. The active strand, probably actually several closely spaced strands, have fairly well developed geomorphic expression in places here.

After inspecting the active fault, continue northwest on the Bay View Trail for about .35 miles to a beach access path on the left. The rocks here (again on both sides of the mapped active strand) are Orinda Formation, late Miocene fluvial deposits (Figure 6-2). The rocks are visible here in the wave cuts, peaking out from below very thick colluvial cover. Again, here the active strand has accommodated very little of the long term offset.

Return to the Bay View Trail and continue north for about .86 miles to another beach access. Here the mapped active strand passes out into the Bay and extends NW across roughly the center of San Pablo Bay. Although concealed from direct view by water, the fault is strongly expressed in the gravity and magnetic fields over the bay. A linear magnetic boundary likely reflecting the southwest edge of a body of Tertiary volcanic material coincides with the active strand at Point Pinole and continues on line nearly the entire distance across the bay. The magnetic anomaly indicates that the volcanic body extends northward from its truncation against the Hayward Fault more than 15 km and that its northeast boundary lies against the Rodgers Creek Fault where mapped north of the Bay. A strong linear gravity gradient parallels the linear magnetic anomaly across the bay, and separates high gravity values over near surface Franciscan rocks southwest of the Hayward Fault from a 12 km wide deep gravity low northeast of the fault that reflects a thick section (as much as 8 km) of Cretaceous and younger sedimentary and volcanic deposits. This gradient delineates a steeply-dipping density boundary parallel to, but about 1 km northeast of the inferred Hayward Fault beneath the bay.

Slip on the Hayward Fault is transferred to the Rodgers Creek Fault across a 5 km wide right step beneath San Pablo Bay. This step is much too narrow for the large gravity low over the east half of the bay to reflect a pull-apart basin formed in the wake of the current right step. In fact, seismic reflection data and detailed analysis of the gravity data suggest that only about 500 m of subsidence has take place during the past few million years as a result of movement across the Hayward-Rodgers Creek right step. We interpret the magnetic, gravity, and seismic reflection data to indicate a volcanic body beneath the bay that is tabular, about 1 km thick, and has the shape of a synform with its southwest limb lying against the Hayward Fault. This volcanic body forms a continuous connection between the northern Hayward Fault and the southern Rodgers Creek Fault according to the magnetic data (Figure 6-3). The apparent continuity of this body precludes a simple strike-slip connection between the Rodgers Creek and Hayward Faults with more than about 10 km of offset (compared to the estimated roughly 100 km of total offset across the Hayward fault).

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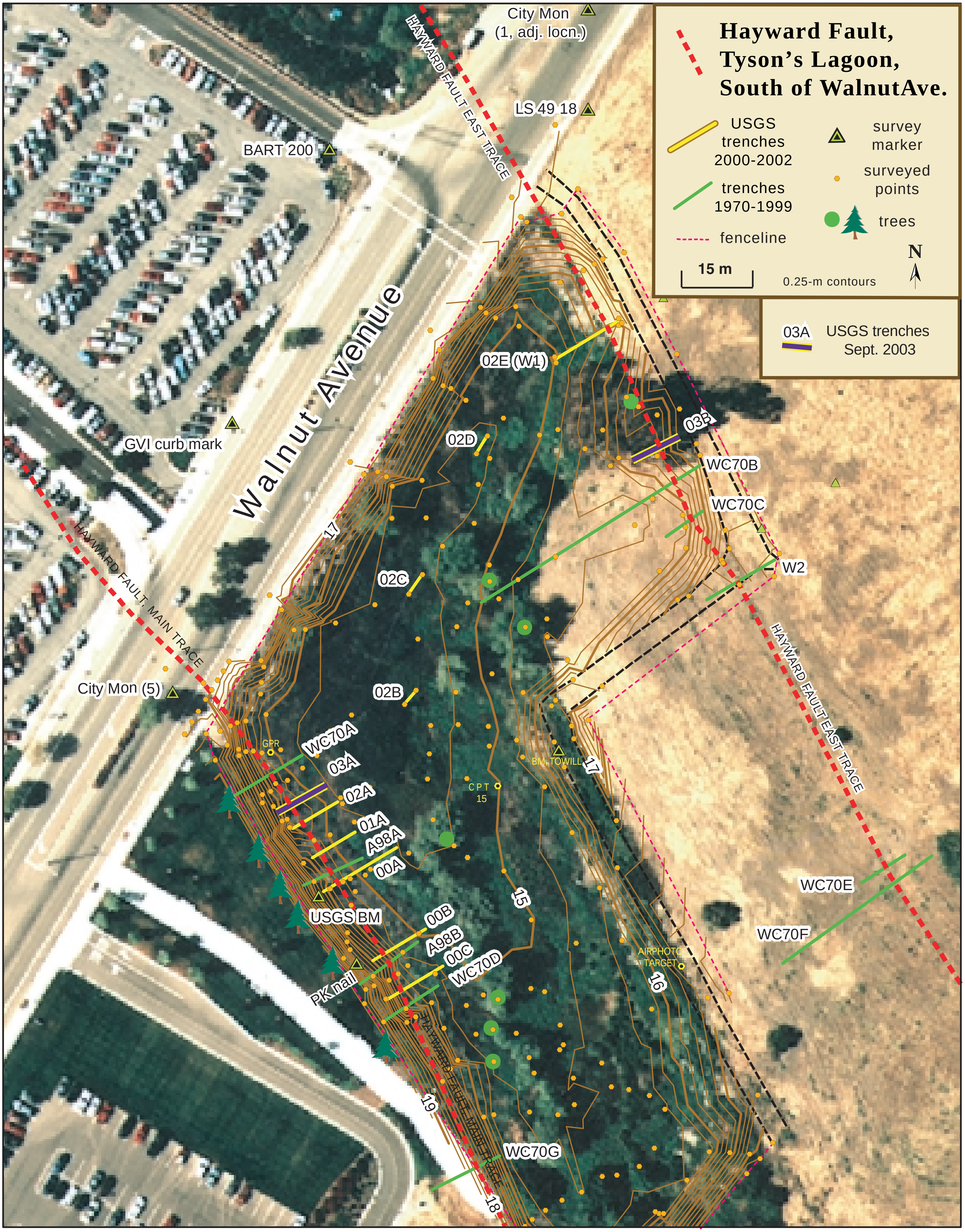


Figure 1-1. Location of trenches

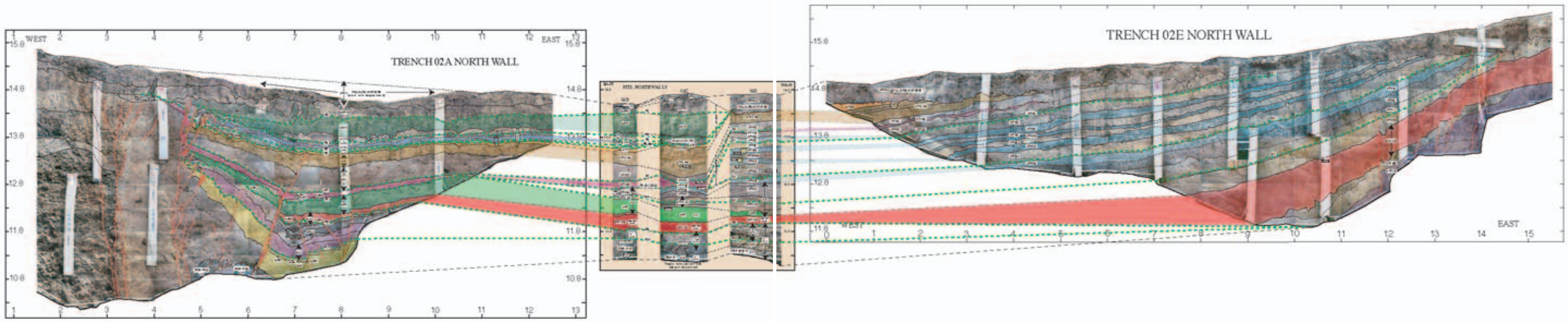


Figure 1-2. Logs of trenches in 2002 (see Figure 1-1 for locations). Trench 02A crossed the western or main trace of the Hayward Fault, trench 02E crossed the eastern trace, and pits 02B, C, and D were located between 02A and 02E at approximately 25 m spacing. Grid is in meters, west is to the left. The most prominent marker layer, shown in red, is a pond unit unusually rich in shells, mostly gastropods. The approximate age of this unit is between 1800-2000 yr BP (uncalibrated radiocarbon ages). The approximate ground surface at the time of each paleoearthquake or "event horizon" is shown as a dashed green line. Evidence for ten paleoearthquakes has been recognized in several trenches across the western trace and evidence for two additional events was found only in trenches across the eastern trace, because a major erosional unconformity exists on the western half of the pond. Multiple pond units on the eastern trace, shown in blue, do not reach the western fault trace. This ~500 year interval includes 3 events on the eastern trace, which appear as only one event on the western trace. Thus, there are a total of 12 events in evidence over the last 2000-2400 yr BP. The four youngest events are not well expressed in the 2002 trenches (only two event horizons for this interval are shown above, the youngest horizon associated with the historic earthquake in 1868 has been eroded away and the third event horizon back is obscured by bioturbation). These four events are described in Lienkaemper and others (2002).

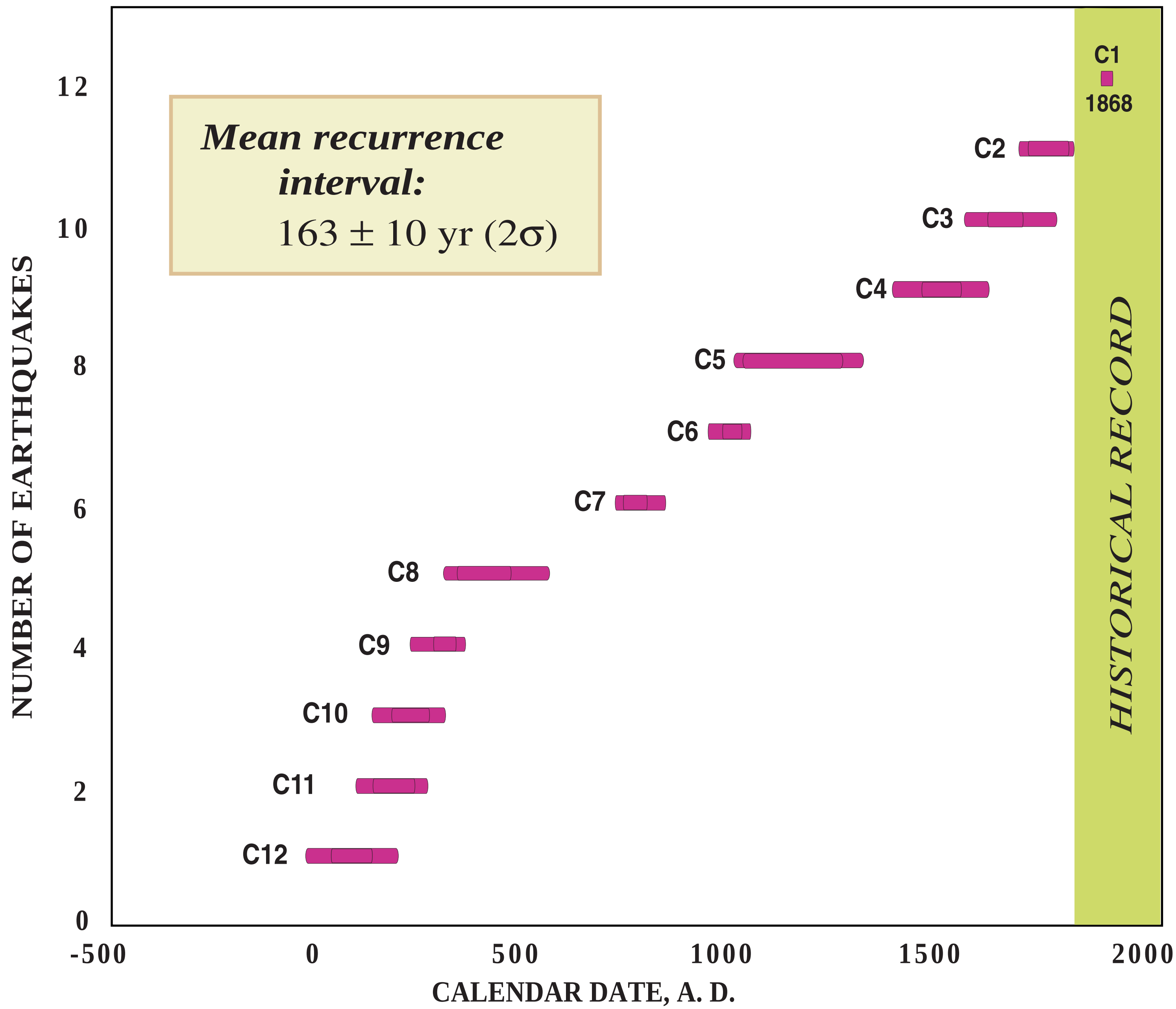
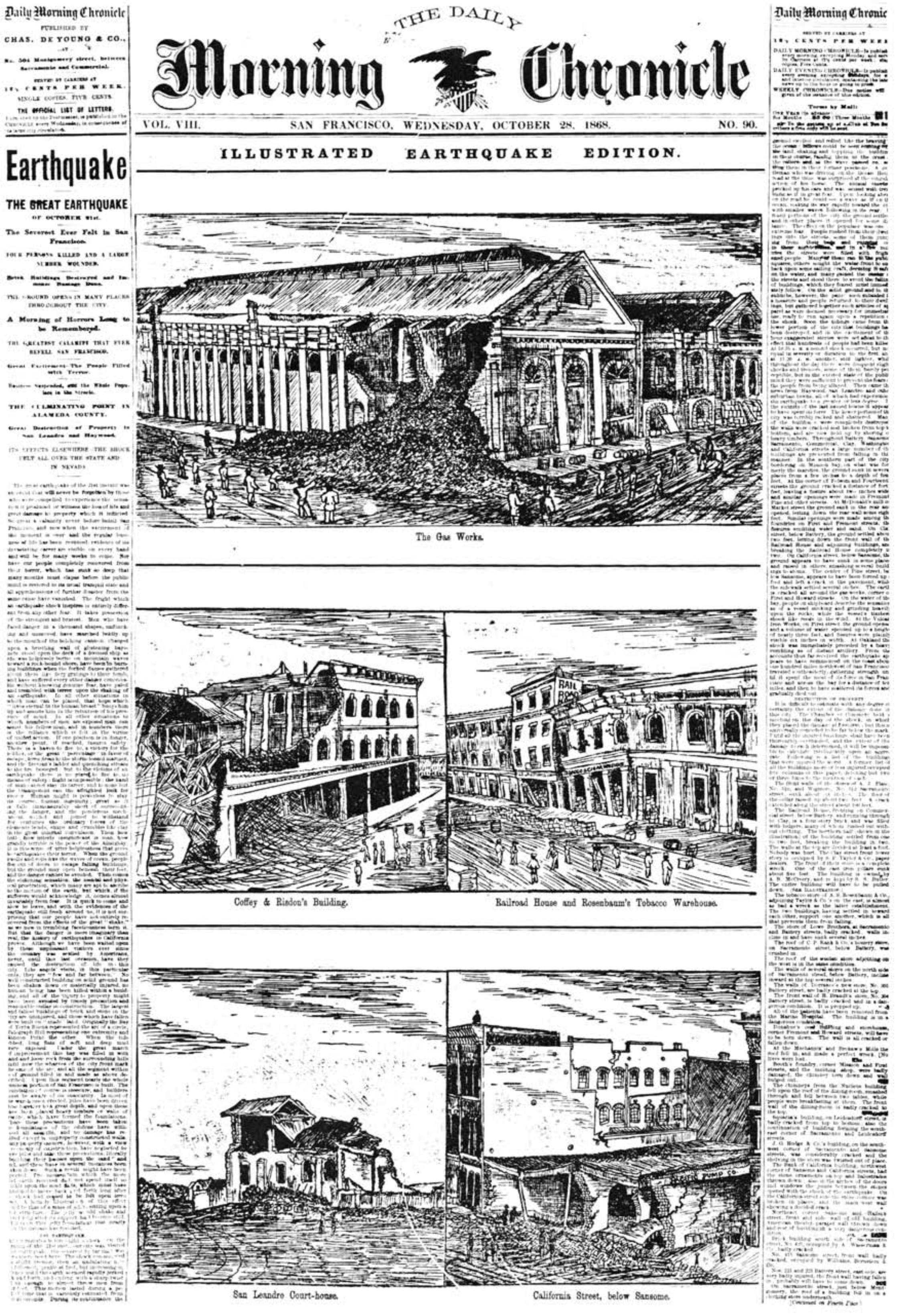


Figure 1-3. Preliminary 2000-year earthquake history on the southern Hayward Fault. The age of paleoearthquakes is shown as rounded pink rectangles (events C1 through C12) at 95-percentile uncertainty; darker pink shows 68-percentile confidence range. The age of the unit underlying event C12 is currently subject to ambiguity; an alternative age value gives mean recurrence of 173 ± 10 yr for events C1 through C11. Thus the mean recurrence interval for the last 2000 years can be stated as 168 ± 15 yr (2s) while encompassing both interpretations. The plot above seems suggestive of periods of frequent earthquakes separated by quiescence, however, several more radiocarbon dates are needed to constrain actual variability within this sequence. Also, periods of slow sedimentation rate may allow 1-2 events to escape documentation, thus the mean recurrence interval discussed above may represent a minimum estimate.

Figure 2-1. Restored Mission San Jose.



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ILLUSTRATED EARTHQUAKE EDITION.

Earthquake

THE GREAT EARTHQUAKE

The Severest Ever Felt in San Francisco.

A Morning of Horrors Long to be Remembered.

The Gas Works.

Coffey & Risdon's Building.

Railroad House and Rosenbaum's Tobacco Warehouse.

San Leandro Court-house.

California Street, below Sansome.

Figure 2-2. The front page of the San Francisco Morning Chronicle following the 1868 Hayward Fault earthquake.

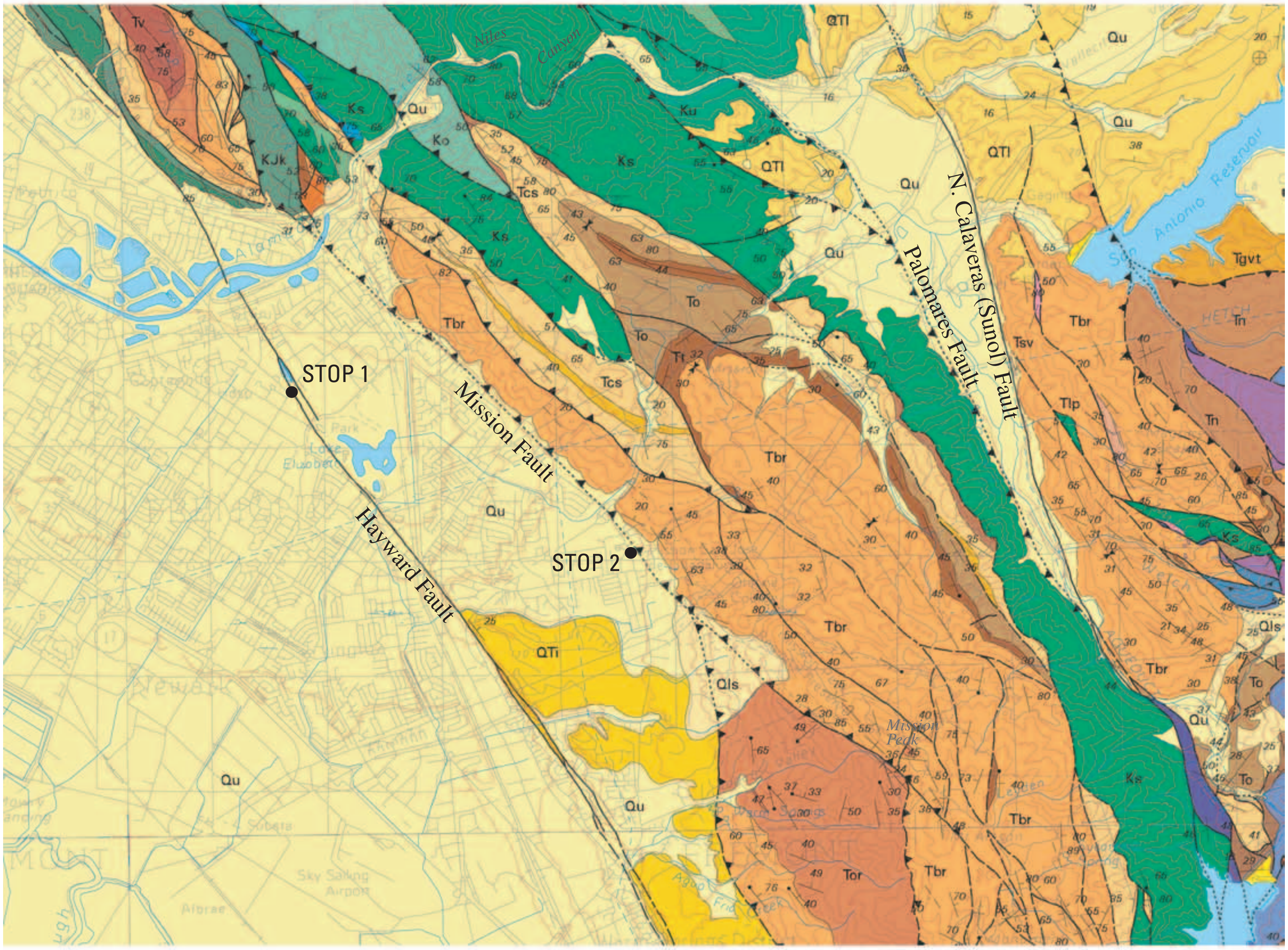

Figure 2-3. Geologic map of the area around Mission Peak and Niles Canyon (from Graymer and others, 1996). Fieldtrip stops 1 and 2 are shown. Faults with teeth are reverse (oblique?) faults, including the Mission Fault. Units mentioned in the text are labeled (Qls - landslide deposits, QTi - Irvington gravels, QTl - Livermore gravels, Tor - Orinda Formation, Tbr - Briones Formation, Tt - Tice Shale, Tcs - Claremont Shale).

Figure 2-4. Photograph of Mission Peak from Mission Blvd in Fremont, south of fieldtrip stop 2. The Mission Fault is shown. Note the cliff-forming Briones Formation above the fault and the rounded ridges of the younger Orinda Formation below.

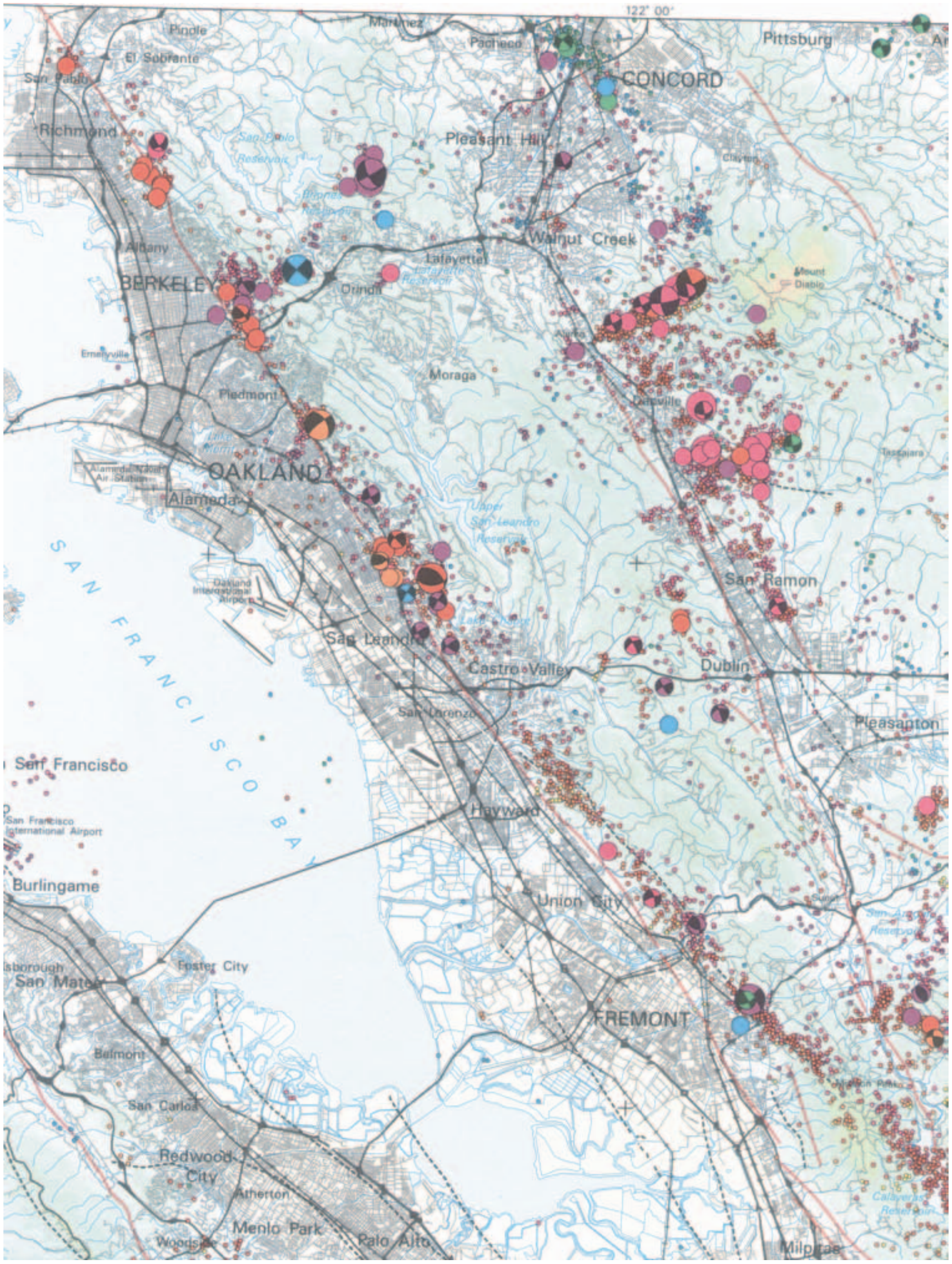

Figure 2-5. Seismicity in the east San Francisco Bay area (from Walter and others, 1998). Note the divergence of seismicity from the mapped active trace of the Hayward Fault southeast of Hayward, roughly along the trend of the Mission Fault. We now believe that this apparent divergence is related to hypocenters being deeper to the south along an east-dipping Hayward Fault, as well as shallower fault-plane dip in the left-step region of connection to the central Calaveras Fault.

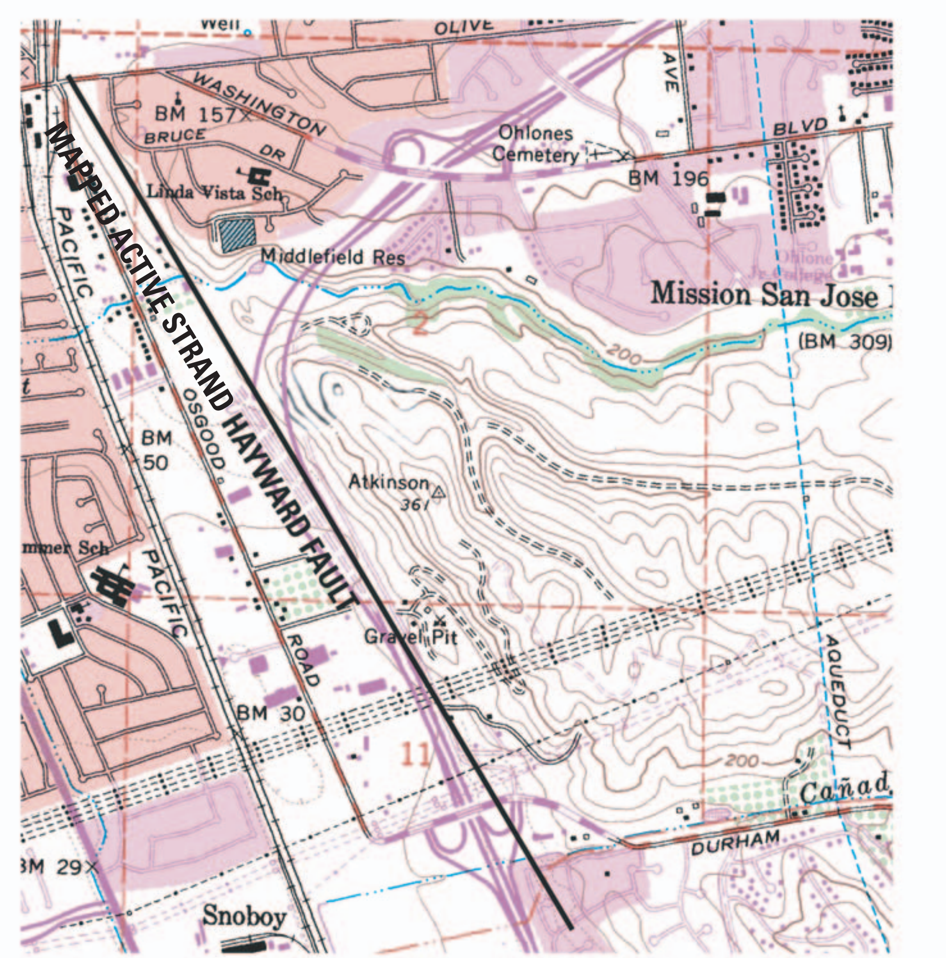

Figure 2-6. Above, topographic map showing the west facing scarp at the mapped active trace of the Hayward Fault. The ridge east of the fault is underlain by Irvington gravels. Below, photograph of Irvington gravels. Maximum clast length is about 5 cm. Clasts are largely composed of Franciscan and Great Valley complex graywacke, with subsidiary varicolored Franciscan complex chert and metamorphic rocks and laminated siliceous shale and chert of the Miocene Claremont Shale.

Figure 2-7. Above, photograph of a high terrace underlain by Livermore gravels in the Sunol area. Below, photograph of Livermore gravels at Sunol. Maximum clast length about 20 cm. Age and clast composition are the same as the Irvington gravels shown in Figure 2-6.

Figure 3-1. Photograph of evidence of right lateral creep on the mapped active strand of the Hayward Fault. This offset curb is in the parking lot between A and B streets in downtown Hayward.

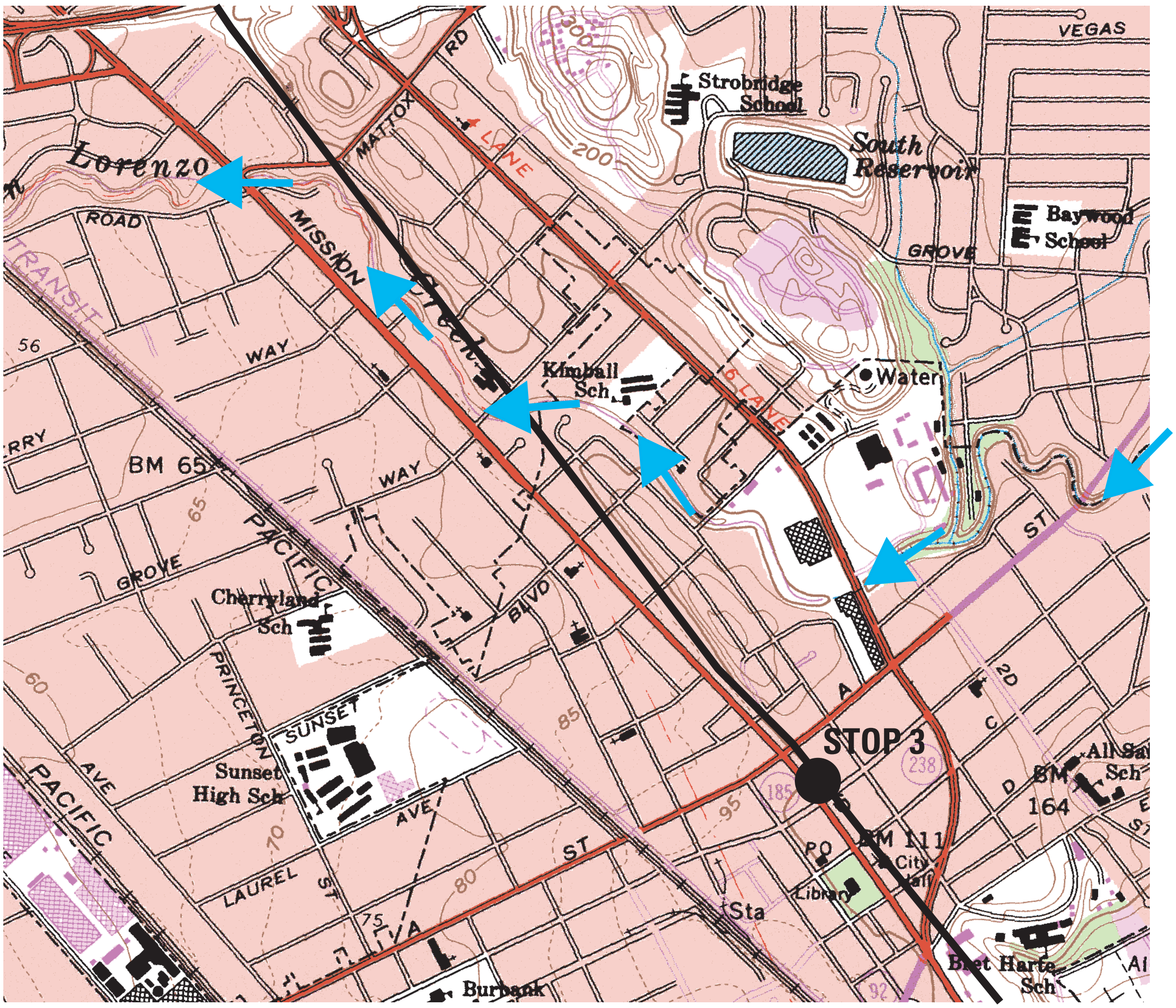

Figure 3-2. Topographic map of the area north of downtown Hayward, with fieldtrip stop labeled. The mapped active trace of the Hayward Fault is shown as a thick black line, and the double right-step in San Lorenzo Creek is illustrated by the blue arrows.

Mapped active
strands of the
Hayward Fault

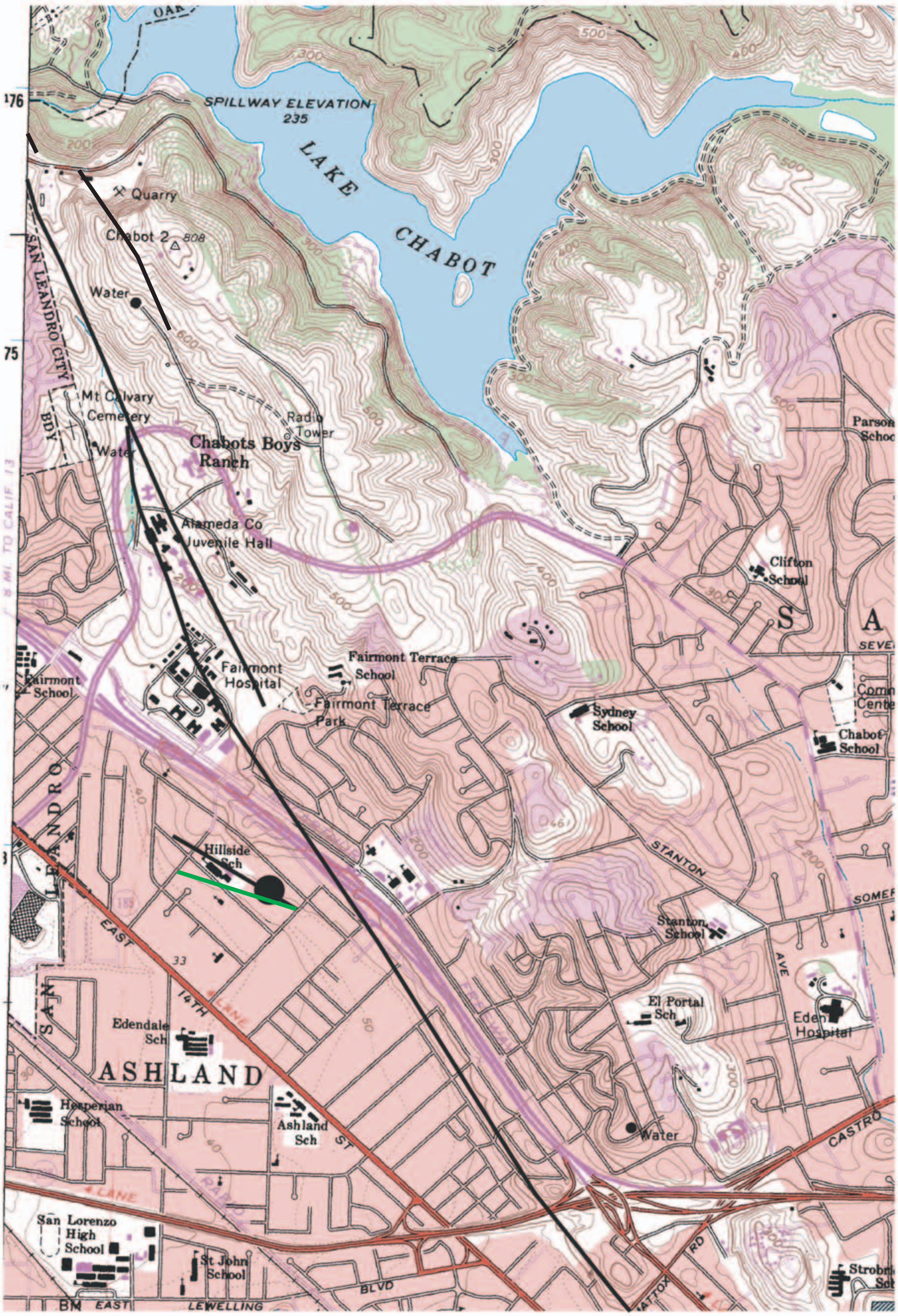

Figure 4-1. Topographic map the Ashland district of San Leandro. The mapped active strands of the Hayward Fault are shown as thick black lines, the active trace at fieldtrip stop 4 is shown as a thick green line, and the rough position of the trench site is shown as a black dot.

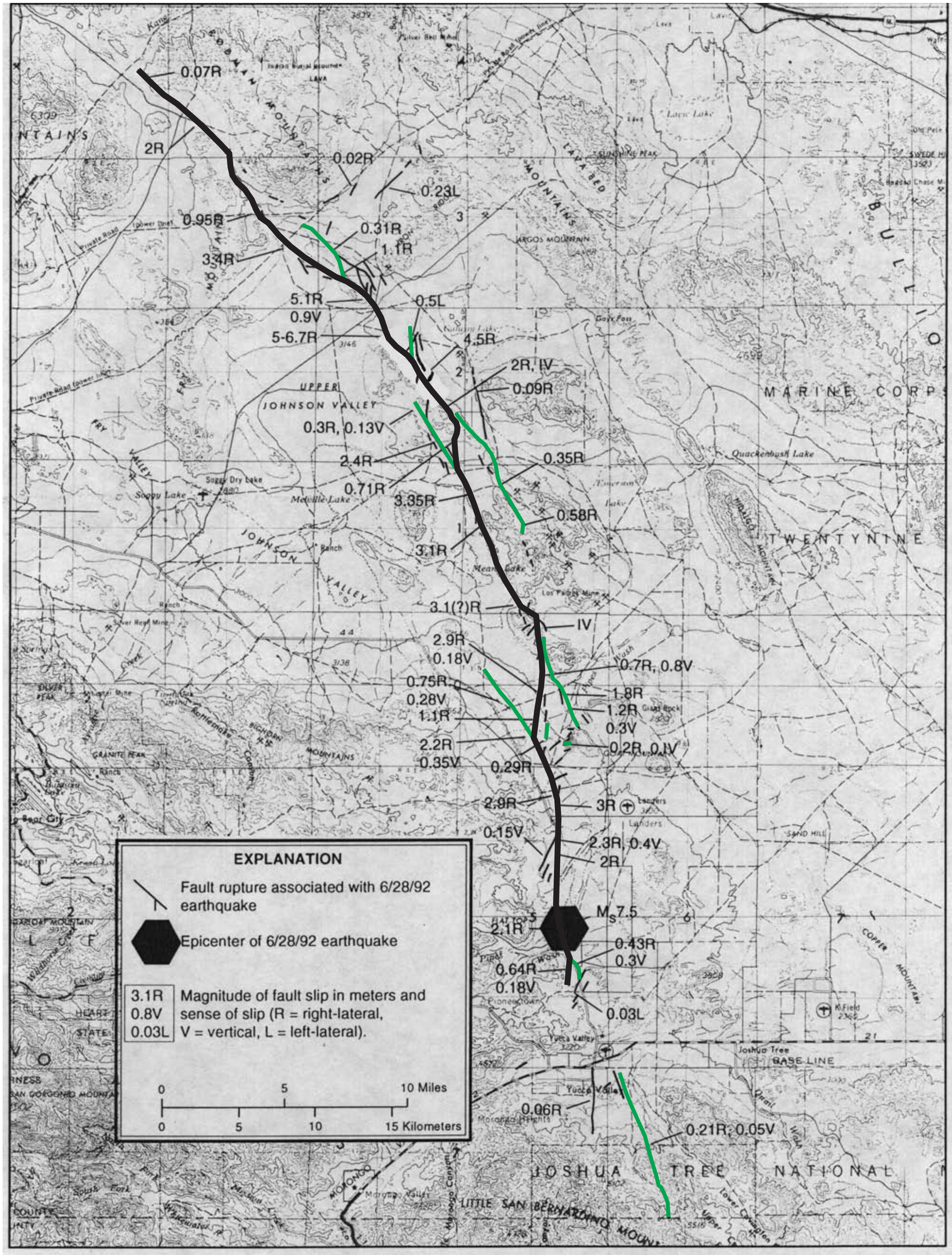

Figure 4-2. Surface rupture map of the 1992 Landers earthquake (from Hart, 1993). The main, through-going trace is shown by the thick black line, subsidiary traces with more than 10 cm documented right-lateral offset are shown as green. Compare the pattern of fault rupture with the pattern of Hayward Fault traces (mapped active traces, the trenched trace at fieldtrip stop 4, and the suspect trace associated with the double right step of San Lorenzo Creek, Figures 3-2 and 4-1).

Figure 4-3. Geologic map of the Hayward - San Leandro area (from Graymer, 2000). The through-going mapped active strand of the Hayward Fault is shown as a thick black line. Offset on the south edge of the San Leandro gabbro along the active strand is denoted by the black arrows, about 5 km which is much less than the total long-term offset of 100 km.

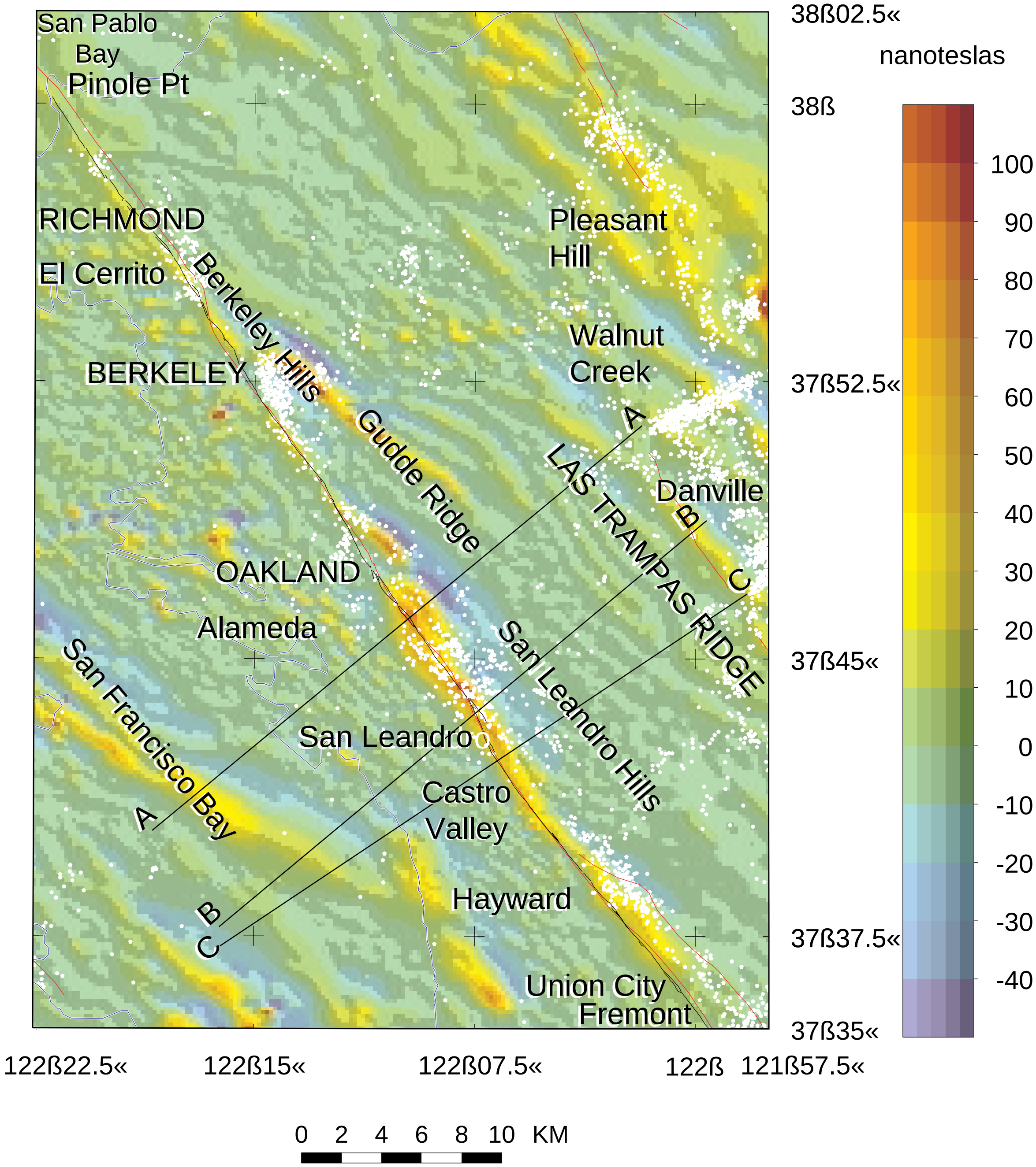

Figure 4-4. Magnetic map enhancing shallow magnetic sources along the Hayward Fault Zone. Shallow magnetic sources were enhanced by upward continuing the magnetic data a small distance (250 m) and then subtracting this field from the unfiltered data set to derive a residual field. The resulting map highlights magnetic sources within about 2.5 km of the surface. Red lines, faults from Jennings and others (1977); black line, recent trace of the Hayward fault from Lienkaemper (1992), white circles, seismicity data from the USGS's Northern California Seismic Net from September 1969 through September 1999, M greater than or equal to 1.0.

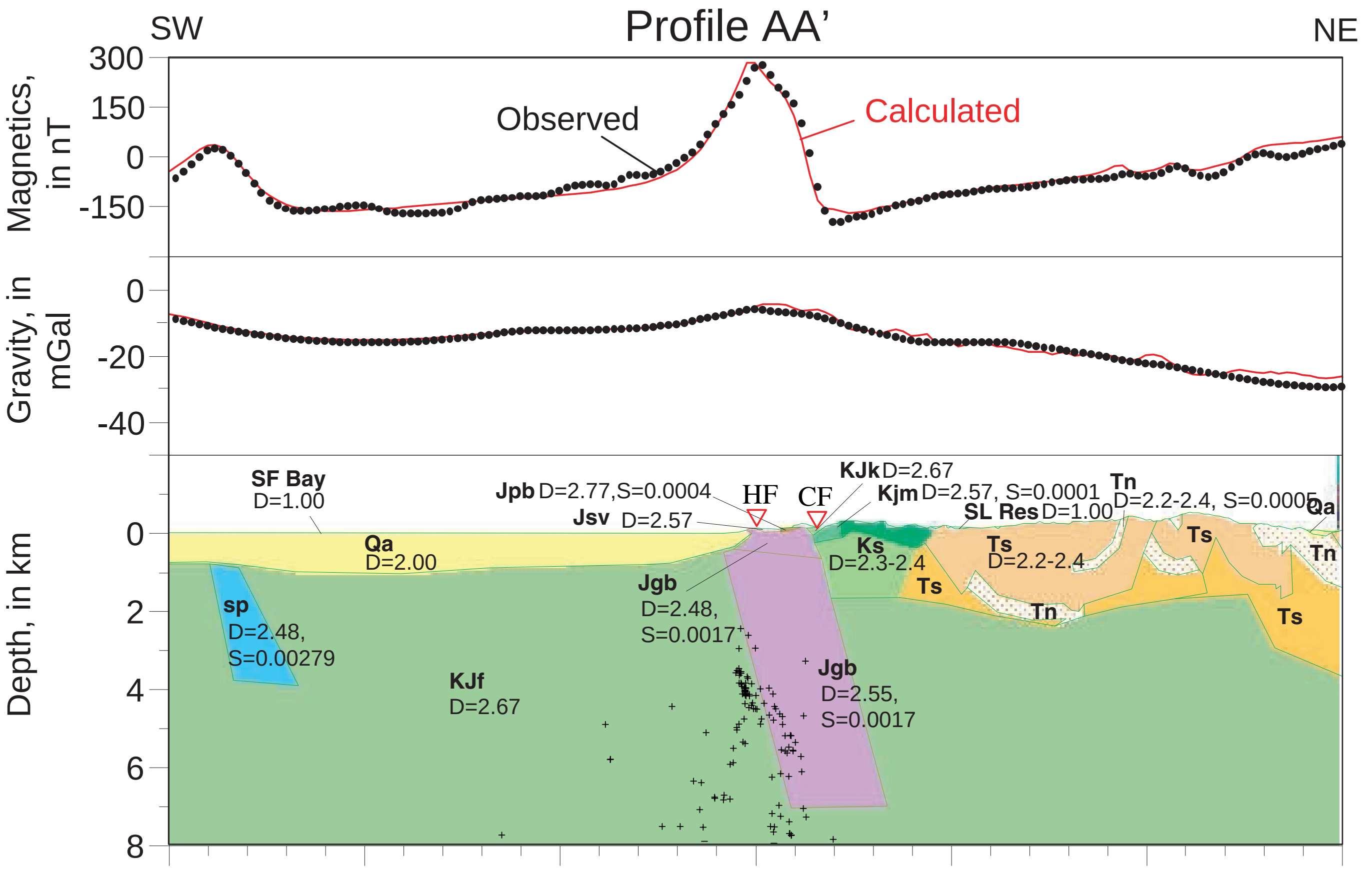

Figure 4-5. Gravity and magnetic model across the San Leandro gabbro. Physical properties are based on measurements on rocks and core samples. Profile AA' is along and partly based on a geologic cross-section by Graymer (2000). Geologic symbols: Qa, Quaternary alluvium and related low-density materials; Tn, Neroly Sandstone; Ts, undifferentiated Tertiary sedimentary rocks; KJf, Franciscan Complex; Kjm, Joaquin Miller Formation; KJk, Knoxville Formation; Ko, Oakland Conglomerate; Ks, undifferentiated Cretaceous sedimentary rocks; Jb, basalt; Jgb, gabbro; Jpb, pillow basalt; Jsv, quartz keratophyre; sp, serpentinite; sp-px, pyoxenite. Geographic and other symbols: SF Bay, San Francisco Bay; SL Res, San Leandro Reservoir; Inverted red triangles, recent trace of Hayward Fault (HF) and Chabot Fault (CF); D, density in g/cm3; S, susceptibility in CGS units; Drill-hole symbol, thickness of offshore sedimentary basin from seismic and gravity data (Marlow et al., 1999); +, seismicity from relocated hypocenters using a high-resolution double difference relocation procedure within 5 km of the profile (Waldhauser and Ellsworth, 2000;2002). No vertical exaggeration.

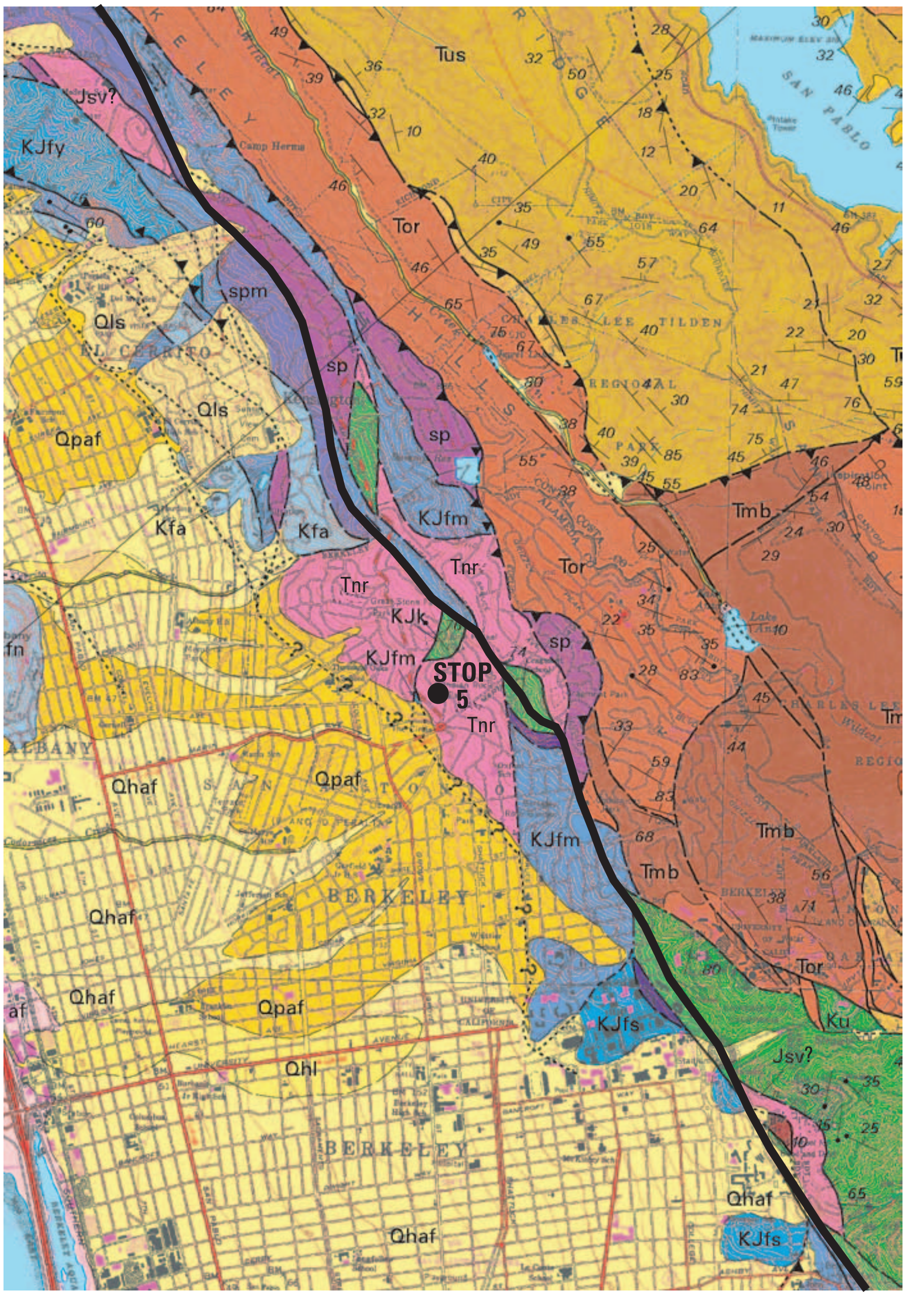

Figure 5-1. Geologic map of the Berkeley area (modified from Graymer, 2000) showing the distribution of the Northbrae rhyolite (Tnr). The through-going mapped active strand of the Hayward Fault is shown as a thick black line, fieldtrip stop location is shown as a black dot. Note that the Northbrae rhyolite has no apparent offset along the mapped active strand of the Hayward Fault, although the outcrops of questionably identified silicic volcanics of the Coast Range ophiolite (Jsv?) could be correlative with the Northbrae rhyolite, which would indicate an about 4 km offset.

Figure 5-2. Photographs of flow-banded Northbrae rhyolite from Indian Rock Park (fieldtrip stop 5) west of the mapped active strand of the Hayward fault (above) and from Cragmont Park east of the mapped active strand.

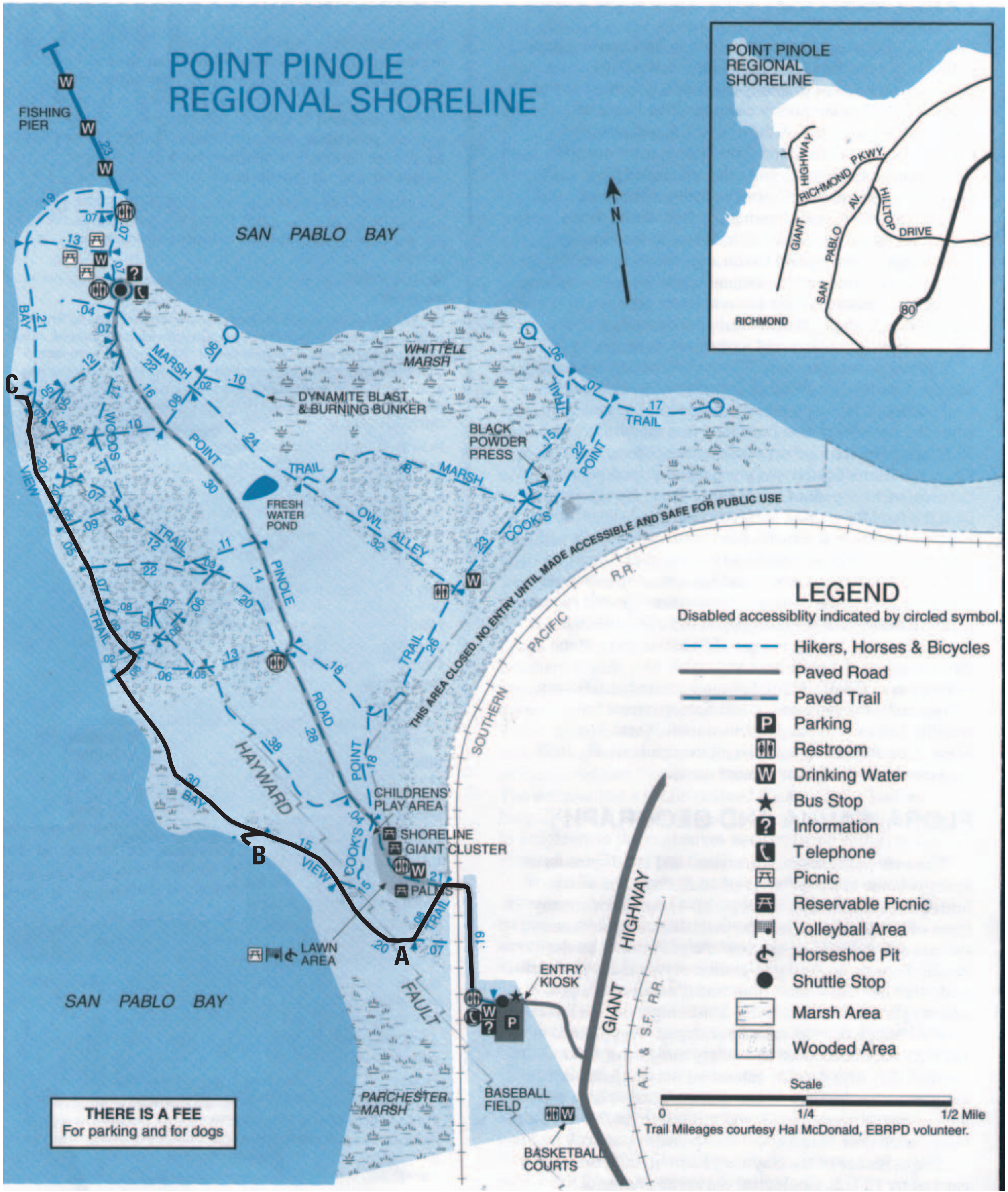

Figure 6-1. Map of Point Pinole Regional Shoreline showing our walking route as a thick blsck line. Stops described in the text are labeled: **A** - The trail crosses the mapped active strand of the Hayward Fault here, look for geomorphic expression of fault activity; **B** - Orinda Formation is exposed west of the mapped active trace in the wave-cuts here; **C** - The mapped active trace runs into San Pablo Bay here. (Map from East Bay Regional Park District)

Figure 6-2. Geologic map of the San Pablo area (modified from Graymer, 2000). Fieldtrip stop 6 is shown as a large black dot and our walking route is shown as a green line. Stops described in the text are labeled as on Figure 6-1: **A** - The trail crosses the mapped active strand of the Hayward Fault here, look for geomorphic expression of fault activity; **B** - Orinda Formation is exposed west of the mapped active trace in the wave-cuts here. Maximum offset of the Orinda Formation along the mapped active strand of the Hayward Fault, marked by the black arrows, is about 2 km.

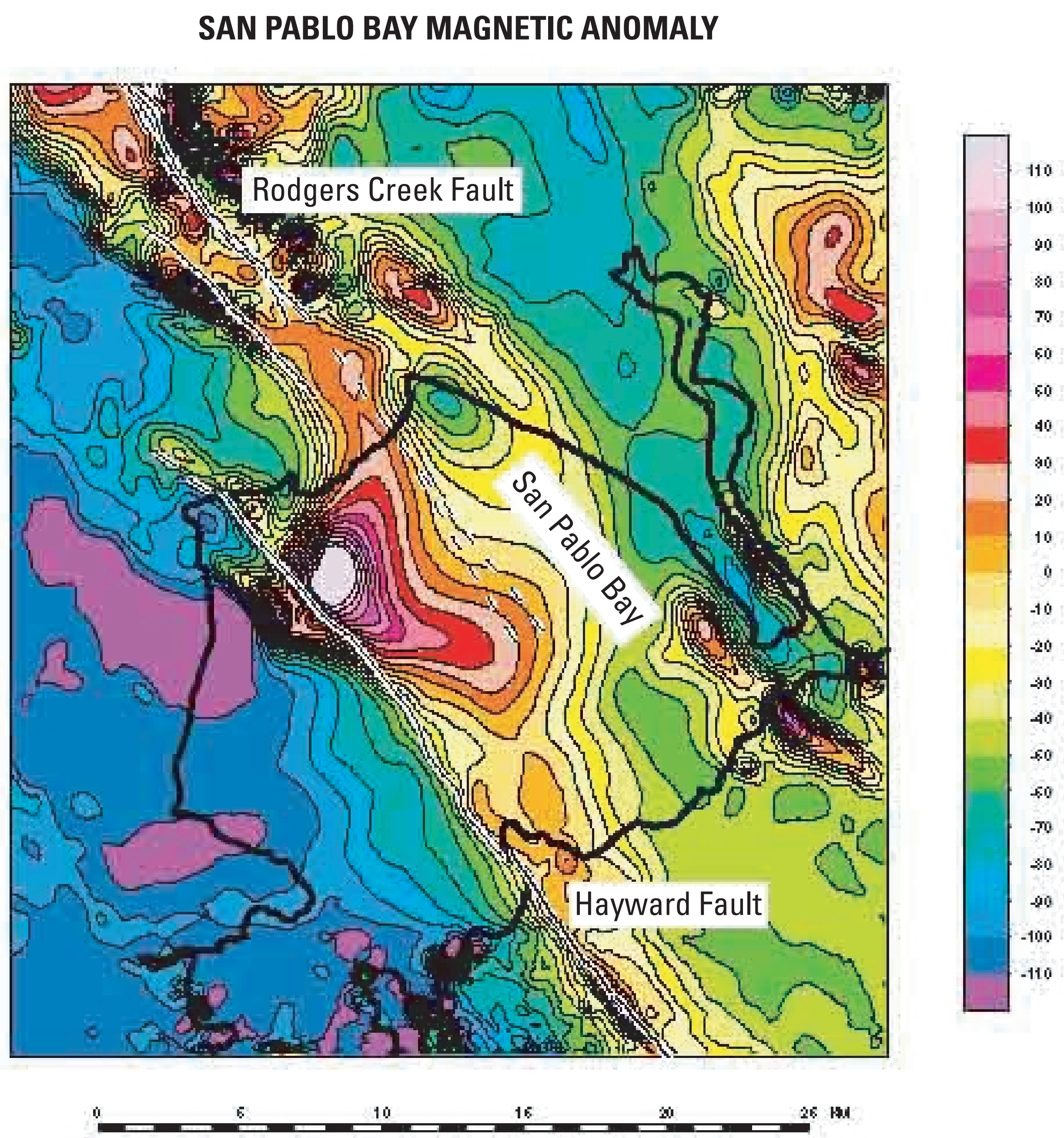

Figure 6-3. Map showing San Pablo Bay magnetic anomaly, reflecting an inferred buried Tertiary volcanic mass. Note that the volcanic mass lies between the Rodgers Creek and Hayward Faults but shows no indication of being dismembered by a through-going fault connecting the Hayward Fault to the Rodgers Creek Fault. A simple through-going fault with more than about 10 km of offset seems to be precluded by the continuity of this magnetic anomaly.