NORTHERN CALIFORNIA
GEOLOGICAL SOCIETY

FIELD TRIP GUIDE
TO
LATE CENOZOIC GEOLOGY
IN THE
NORTH BAY REGION

MAY 16, 1992
NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

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TO

LATE CENOZOIC GEOLOGY

IN THE NORTH BAY REGION

MAY 16, 1992

T. L. WRIGHT
Editor

Guidebook distributed by:

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Earth scientists in the San Francisco Bay region have a remarkable opportunity to conduct research that in most areas would be deemed purely academic but here can be applied directly to earthquake hazards. Studies of stratigraphy and paleogeography, volcanism, paleotectonics, and potential-field geophysics lead us to recognize the major zones of weakness in the brittle crust, reconstruct their histories, and assess the probability and severity of future earthquakes along these zones. The third-dimensional velocity models that tomographic inversions can provide will allow us to locate with precision the planes of active faulting. They may also permit us to define at depths of many kilometers the crustal blocks suggested by paleotectonic and potential-field studies. Investigations of plate motions and crust/mantle kinematics and dynamics provide insights on the driving mechanisms that are the ultimate cause of earthquakes.

The ongoing BASIX (Bay Area Seismic Imaging Experiment) project is serving as a catalyst for a surge of new research. And of course, all of these more theoretical studies must be integrated into the continuing studies of active fault zones, seismotectonics, and regional deformation from triangulation or GPS (global positioning satellites) that provide the direct linkage to improved estimates of earthquake probabilities and magnitudes and fault rupture hazards. Only as we come to understand how mantle processes drive earthquakes and how the brittle crust reacts to these processes can we hope to employ measurements of creep and regional deformation, and especially patterns of minor seismicity, to derive useful near-term predictions of major earthquakes.

Today's field trip is but a minor one of the many iterations of these regional studies that will be required to reach a new understanding of earthquakes in the Bay area. The Northern California Geological Society has tentative plans for a major symposium on the geology and tectonics of the North Bay region, as a part of the Pacific Section AAPG/SEPM/SEG annual meeting in the spring of 1995. It is our hope that this trip and its guidebook will stimulate several years of focused research yielding answers to many of the questions raised today.

Our 1992 North Bay field trip will look at one of the Bay area's three main geographic subdivisions. Each has its own geologic character and challenges. The Peninsula/Santa Cruz Mountains is now receiving intensive study as a result of the 1989 Loma Prieta earthquake and has little detailed relationship to problems of North Bay geology. The East Bay region, however, has many geologic connections to the North Bay. Active faults and other major structural features extend from the East Bay region into the North Bay, though commonly with puzzling anomalies beneath the Delta or Bay waters. Late Neogene depositional and volcanic patterns have been translocated by right-slip faulting, requiring the most careful integration of studies in both areas if we are to reconstruct the

← Figure 1. Geologic features in the central Coast Ranges, California (after Fox, 1983, USGS PP 1239).
Figure 2. Geologic sketch map of the North Bay region, showing route of 1992 NCGS field trip (arrows) and stops (circled). Abbreviations are: RMF=Burdell Mountain fault, BVF=Bennett Valley fault, C=Calistoga, Cf=Carneros fault, Cdf=Cordelia fault, Pf=Franklin fault, Hf=Healdsburg fault, LB=Lake Berryessa, M=Martinez, Mf=Maacama fault, N=Napa, O=Oakland, P=Petaluma, Pf=Pinole fault, R=Richmond, Sb=Sebastopol, Sbf=San Bruno fault, SC-SGF=Seal Cove-San Gregorio fault, Sf=Southampton fault, SF=San Francisco, So=Sonoma, SRA=San Rafael, SRO=Santa Rosa, Tf=Tolay fault, WNfz=West Napa fault zone.
tectonic evolution of the central Coast Ranges. In the past we have used the waters of San Francisco and San Pablo Bays and the lower Delta as convenient boundaries that would limit the scope of our researches to a manageable size. Now we must reach across these waters to relate North Bay to East Bay, and East Bay to the San Francisco Peninsula.

Today's trip will focus on rocks and tectonics of the past 15 million years. Because of time constraints we must exclude the entire scope of subduction tectonics -- while recognizing that relict features of that era may now be reactivated by young thrusting and folding in the eastern part of the North Bay region. We will, however, look south across San Pablo Bay and consider evidence for connecting the Tolay fault to the Hayward fault, the Rodgers Creek fault to the Pinole (or related) fault, the Petaluma trough with the Contra Costa basin, and the volcanic rocks of Sonoma County with volcanics in the Berkeley Hills and still farther south.

Figure 1 depicts the major faults and areas of Neogene basinal deposition and volcanism in the San Francisco Bay area. Figure 2 shows additional detail in the area of today's field trip and the trip route (arrows). Most of the northwest-striking faults show evidence of right-lateral separation and are active elements of the broad San Andreas transform zone (Figure 3) that forms the boundary between the Pacific and North American plates. This transform zone has developed behind the Mendocino Fracture Zone, an ancient and primary feature within the northwestward-migrating system of oceanic plates of the Pacific. North of the Mendocino FZ, oceanic crust of the Gorda and Juan de Fuca plates forms the slab within the Cascadia subduction zone. As the Mendocino FZ moved northward past the North American plate (and beneath its westernmost edge), subduction was replaced by interplate shear across a zone as much as 80 km wide.

Figure 3. Tectonic plates and the San Andreas transform zone in northern California (after Atwater, 1989, DNAG v. N)
The Coast Ranges in the region of San Francisco Bay have been affected by at least five distinct modes of deformation during the Cenozoic Era:

- Early Cenozoic subduction that created the melanges of the coastal belt of the Franciscan Complex. The Franciscan and its deformation will not be examined on this field trip.

- Mid-Neogene block faulting that uplifted the basement block west of the Hayward and Tolay faults and the block between the Carneros and Green Valley. These basement blocks are clearly defined on Bouguer gravity maps of the region (Smith, this volume). Stratigraphic evidence (Graham, et al, 1984) dates the initiation of major uplift west of the Hayward fault at about 13 Ma. That block boundary was an important control on deposition until about 6 Ma, when it was overlapped by fluvial sediments in the vicinity of Petaluma.

- Mid-Miocene and early Pliocene transtension that was accompanied by widespread volcanism, especially north of San Pablo Bay. This volcanism has been ascribed (e.g., Furlong, this volume) to upwelling of asthenospheric mantle in the slab window that follows in the wake of the Mendocino FZ during its northward passage.

- From late Pliocene time to the present, right slip on faults of the San Andreas system has been the most notable mode of deformation. Localized transtension is recorded by thick sedimentary accumulations in small basins (Figure 1) near Pleasanton (Livermore basin), at San Pablo Bay, east of Clear Lake (Cache Creek basin), and perhaps elsewhere in the region.

- Concurrent with latest Cenozoic right slip on faults of the San Andreas system, fault-normal contraction has produced reverse faulting and thrusting on many faults within the Coast Ranges and on blind thrusts beneath active folds along the west side of the Great Valley. This mode of deformation, though subordinate to transform motion across the San Andreas system, is a significant element in local seismicity, as witnessed by the 1989 Loma Prieta earthquake.

Perhaps our most useful local information about active processes of deformation within the lithosphere comes from the earthquakes themselves, and especially the constant small events recorded by the extensive net of seismograph stations in the Bay area. Figure 4 shows two transverse depth sections across the San Andreas fault system in the Napa-Sonoma region (F-F') and the Bay-Delta region (G-G'). Patterns of hypocenters from small events clearly show that the base of the seismogenic zone increases in depth eastward, from depths of 11 to 13 km beneath the Hayward and San Andreas faults to as much as 23 km beneath the Greenville fault and the Great Valley. The base of the seismogenic zone is commonly taken as representing the brittle/ductile (or brittle/plastic) transition within the crust. This transition is primarily temperature-dependent and in the San Andreas zone of the Coast Ranges occurs at about 300°C (Hill et al, 1990, USGS PP 1515). In regions of high heat flow, such as near The Geysers (F-F'), the base of seismicity is not as deep as in adjacent areas.

The cross-sections of Figure 4 convey the impression that faults of the San Andreas transform system are narrow, near-vertical zones of shear. This is somewhat illusory. On these cross-sections the vertical scale has been
exaggerated by a factor of 2 and vertical linearity is consequently enhanced. Other analyses (e.g., Wong, this volume) provide an unexaggerated depth scale and may give a more ambiguous view of these faults. Wong's Figure 4d and e, for example, suggest that the Healdsburg fault north of Santa Rosa dips about 70° to the east and might best be considered a reverse-oblique right-slip fault.

![Graphical representation of depth sections](image)

Figure 4. Transverse depth sections across the San Andreas fault system in the northern Coast Ranges. Faults: BS=Bartlett Springs, C=Calaveras, GV=Greenville, H=Hayward, M=Maacama, SA=San Andreas. Circles show hypocenters projected into plane of section; size of circle is proportional to magnitude (from Hill, et al, 1990, USGS FP 1515).

Two more serious problems detract from the use of microseismicity patterns to map active faults at depth within the upper crust. One of these, the inadquacy of the present seismograph network especially in the North Bay region, could be alleviated with increased funding and/or improved technology. The other source of location error is the present inability to correct for lateral velocity variations in the crust when determining hypocentral locations and focal mechanisms. Any significant progress toward understanding local earthquake processes will require that these two problem areas be addressed.

Micro-earthquake depth sections such as those in Figure 4 have stimulated a new view of the plate boundary at the San Andreas transform zone. By this
view, the plate boundary beneath the Coast Ranges is seen as sub-horizontal and perhaps coincident with the brittle/ductile transition. Two variants, by Furlong and Jones, are presented in this volume. Jones' model (Figure 5) extends the Pacific plate eastward beneath the Coast Ranges, beneath the western part of the Great Valley, and beneath the westernmost edge of Sierran basement.

Figure 5. Schematic structure section through the East Bay Hills. (From Jones, this volume)

Furlong's interpretation shows the upper crust west of the San Andreas fault (to the continental slope) partially coupled to the Pacific plate. Between the San Andreas and Hayward-Calaveras faults he shows the upper crust as uncoupled and has drawn a horizontal plate boundary (this volume, his figures 6 and 9). Farther to the east he shows the upper crust as fully coupled to the North American plate. In Figure 7 (below) I have modified Furlong's earlier sketch, extending the sub-horizontal plate boundary to encompass the entire San Andreas transform zone.

As envisaged by Furlong, the crust in each plate is dragged along by motion of the underlying lithospheric mantle. The upper mantle, ductile yet stiff, deforms "dominantly via temperature dependent creep processes". In my own view this property of the upper mantle promotes distributive shear adjacent to plate boundaries that is reflected in the progressive eastward decrease in right slip across the San Andreas system in the North Bay area, from the San Andreas fault east to (and beyond?) the Green Valley fault.

Volcanic rocks are an important element in the Late Cenozoic geology of the North Bay region and the absence of a paper on the subject represents a serious omission from this guidebook. Figure 7 outlines the major volcanic centers in

![Map showing volcanic centers and age ranges](image)

**Figure 7.** Locations and age ranges of Neogene volcanic centers and subjacent strata in coastal California. (from Johnson and O'Neil, 1984).
in the Coast Ranges. In the area north of San Francisco Bay, Neogene volcanic rocks record semi-continuous eruptive activity from nearly 14 Ma to 0.3 Ma or less. Their composition varies from basalt and andesite to dacite and rhyolite. The volcanic rocks are grouped into three sequences, from south to north the Tolay Volcanics (13 to 9 Ma, or mid- to late-Miocene), the Sonoma Volcanics (8 to 2.6 Ma, or late Miocene to late Pliocene), and the Clear Lake Volcanics (2.24 to 0.04 Ma, or late Pliocene to late Pleistocene). Youngman (this volume) has proposed a fourth sequence that he mapped in southern Sonoma County and has called the Donnell Ranch Volcanics. It ranges in age from 10.6 Ma to 8.2 (or perhaps 7.4) Ma. Those three (or four) sequences are progressively younger from south to north. All four sequences include similar rock types and their differentiation is based primarily on radiometric dating and on their geographic location, although trace element geochemistry has also been used as a criterion.

The northward-younging of volcanic rocks in the Coast Ranges is commonly linked to migration of the Mendocino triple junction. Figure 7 shows that relationship and Figure 8 shows the volumes and types of magmas produced. Continuing investigations into the composition and rate of Neogene volcanism at

![Diagram](image)

**Figure 8.** Magma production rates for Cenozoic volcanic rocks in the Coast Ranges. The histogram shows basaltic magma production (dark area) and silicic magma production (light area). Arrows indicate approximate location of the Mendocino triple junction at various times. (Liu and Furlong, 1992, JGR)
various locations are providing important clues to mantle processes associated with the evolution of the San Andreas transform zone.

Within the Bay region, Neogene volcanic rocks also offer evidence for right-lateral separation across major faults. Right-lateral strike slip faulting may have moved the Tolay Volcanics northward into close juxtaposition with Sonoma Volcanics on the opposite (east) side of the Rodgers Creek fault zone (Figure 9). A possible correlation with volcanic rocks in the Berkeley Hills, about 40 km (25 mi) to the south, has been postulated by Fox et al (1985). Youngman (1989) has suggested that the Tolay may represent the displaced western part of the Quien Sabe Volcanics east of the Hayward-Calaveras fault zone near Hollister, 180 km (112 mi) to the south.

Figure 9. Palinspastic reconstruction of Sonoma, Tolay, Berkeley Hills, and Quien Sabe volcanic centers. Present outcrop pattern on left, reconstructed pattern on right (with present coastline). (after Johnson and O’Neil, 1984)

A subject of major interest in the North Bay region has been the postulated continuity between the Hayward and Rodgers Creek faults, both seismically active. Smith (this volume) presents the results of geophysical surveys and exploratory drilling conducted during the 1960’s. These data illuminate the relationships among the Hayward, Tolay, and Rodgers Creek faults beneath and north of San Pablo Bay. A 1967 proprietary gravity survey with 568 bay-bottom stations and more than 2000 onshore stations shows that the Hayward fault is paralleled by a steep gravity gradient of more than 30 milligals, which extends north into the Tolay fault after being deflected around the southeast plunge of the basement-cored Sears Point anticline. This gradient reflects the density contrast between shallow Franciscan basement west of the fault and a deep section of late Neogene and Holocene sediments and volcanics east of the fault. Gravity profiling suggests a total post-Franciscan sedimentary/volcanic fill approximately 8 km thick beneath San Pablo Bay.

Exploratory wells drilled on the north shore of San Pablo Bay near Sears
Point constrain the locations of the Tolay and Rodgers Creek faults southeast of their mapped surface traces. The faults are separated by a block down-dropped at least 1300 m (at the top of the Sonoma Volcanics) that is the northern continuation of the San Pablo trough.

High-resolution marine profiling across southern San Pablo Bay conducted as part of the Bay Area Seismic Experiment (BASIX) survey found the only clear displacement of shallow sediments offshore from the Pinole fault. The zone of the Hayward fault shows no evidence of active shallow deformation. Relocations of 1969-1989 seismic events show a series along the Hayward-Tolay alignment extending at least 8 km north of San Pablo Bay, at depths of 3 to 11 km. A sparse alignment of events at depths of 5 to 13 km is associated with the Pinole fault.

These data suggest that the Hayward-Tolay and Rodgers Creek faults are two separate active features converging beneath the northern part of San Pablo Bay and only 1.7 km apart at Sears Point. Active right-slip on the Hayward fault appears to decrease to the northwest; the Tolay fault is judged to be inactive. The Rodgers Creek fault may terminate southward beneath San Pablo Bay and the Pinole-El Sobrante area in a complex of tensional fault blocks associated with the Pinole fault. Transfer of motion between the Hayward and Rodgers Creek faults might well have produced those structures within the thick sedimentary sequence beneath and adjacent to the bay. Segmentation of the fault zone by this transtensional right step would appear to limit the maximum size of a possible earthquake along this fault system.

Korbay (this volume) documents a gravity gradient beneath the city of Petaluma that is co-linear with the gradient along the Hayward fault and appears to reflect the same boundary between uplifted Franciscan rocks on the west and a trough filled with late Neogene sedimentary and volcanic rocks on the east. The alignment is interrupted by the Sears Point anticline, which might represent either a relatively shallow east-vergent thrust of Franciscan rocks or a deep-seated asperity along the fault that could have forced the right-step to the Rodgers Creek fault. Collins (this volume) has described features in the Petaluma Marsh that may reflect recent deformation in the gap between the Hayward and northern Tolay faults; her suggestions warrant further investigation. Additional gravity modeling in this area, using the data provided by Smith plus new surveys in the marsh, could clarify the relationship between the Hayward and Tolay faults.

The material in this guidebook suggests numerous lines of investigation that could greatly advance our understanding of earthquake processes and hazards locally and in the greater San Francisco Bay area. If the guidebook serves to spur such research it will have served its purpose.

Summary

During the evolution of the San Andreas fault system in the San Francisco Bay region, a volcanic "rift" existed along the Hayward-Tolay-Rodgers Creek fault zone from about 12 Ma to 3 Ma. North of San Pablo Bay the Tolay fault forms the western edge of this rift zone. The combined Hayward-Tolay fault alignment is a major boundary between a western block -- the Sebastopol block of Fox (1983) and its southeastern extension -- of uplifted Franciscan rocks and a downfaulted eastern block that preserves Great Valley, Paleogene and Neogene strata. Within
this eastern block, deep local depocenters formed at San Pablo Bay and the Livermore Valley during latest Neogene time. Between those two areas the Berkeley Hills have been uplifted as a result of basin inversion [apparently caused by fault-normal compression and the buttressing effect of the Mount Diablo uplift].

Initiation of the rift at about 12 Ma is marked by the Tolay-Quien Sabe (TQS) volcanic field, now separated by about 170 km due to right slip on the Hayward-Calaveras fault system. The Tolay near Petaluma and volcanic rocks in the Berkeley Hills are very similar in age and composition (Fox, et al, 1985) and an offset of about 42 km has been suggested. The Quien Sabe east of Hollister is less well studied and total separation along the fault system cannot yet be quantified.

The Sonoma Volcanics represent the peak period of rift volcanism, from about 8 Ma to 3 Ma. Basalt, andesite, dacite and rhyolite erupted within a northwest-trending zone 90 km long and 30 km wide (Fox, 1983). Flows and tuffs interfingered westward into lacustrine and estuarine beds of the Petaluma Formation that filled the low area east of the Tolay fault. The Siesta Formation in the Berkeley Hills is believed to represent the southeastern portion of this late Miocene basin (Linieke-Laporte and Andersen, 1988).

During latest Pliocene and Quaternary time the locus of right slip north of San Pablo Bay has shifted to the Rodgers Creek fault, which now serves as the active northwest extension of the Hayward fault. That shift accompanied renewed fault-normal compression in the Coast Ranges that may be related to a change in plate motion at about 3.5 Ma (Harbert and Cox, 1989). Volcanism has continued, with its locus now in the Clear Lake area. The northward younging of volcanism in the central California Coast Ranges has been ascribed to migration of the Mendocino triple junction and the plate window that trails it beneath the western margin of the North American plate (Zandt and Furlong, 1982). The Hayward-Tolay-Rodgers Creek fault system is an important tectonic feature that penetrates the crust and has localized that volcanism.
INTRODUCTION

The Loma Prieta earthquake of October 17, 1989, drew attention in a very dramatic way to the power and consequences of plate tectonic processes. The earthquake clearly demonstrated the inherent complexity in tectonic processes along the boundary of lithospheric plates, and reminded us of the need to improve our understanding of these complexities if we hope to improve our abilities to assess future hazards from earthquakes along the San Andreas fault system. In particular it is becoming clear as a result of both the faulting characteristics of the Loma Prieta earthquake and other studies that the three-dimensional (3-D) geometry of the plate boundary separating the Pacific and North American plates is not nearly as simple as that typically shown for transform plate boundaries. The 3-D complexity of the plate boundary in the San Francisco Bay region is not a consequence of local crustal structure, but rather is the expected result of the thermal-mechanical evolution of this plate boundary. One key ingredient in understanding the underlying causes and resulting consequences of earthquakes in the Bay area is knowledge of the plate boundary structure, its evolution, the consequences of this structure for crustal and lithospheric kinematics, and the connections between plate kinematics and the earthquake cycle.

Most studies of the kinematics of the San Andreas fault system have used either predictions of regional relative plate motions given by global models (e.g. Minster and Jordan, 1978; DeMets et al., 1990), or have focused on the kinematic information contained in regional seismicity. The former provides information on the large scale components of relative plate motions, but does not attempt to be directly applicable to investigations on the length scale appropriate for the Bay area. Studies based on seismicity patterns and associated kinematic indicators provide detailed information on deformation behavior in the upper seismogenic crust, but unfortunately provide little information on the coupling between upper crustal deformation and large scale plate tectonic processes. In this study we have focused on the link between seismogenic processes in the upper crust and the deeper and larger scale deformation associated with plate tectonics.

The applicability of earthquake hazard evaluations for the San Francisco Bay region will depend on the completeness of the earthquake cycle models used. The degree to which seismic activity along one segment of the San Andreas system in the San Francisco Bay region affects the earthquake cycle on other segments is at present not clear. Historical
patterns of the occurrence of large earthquakes in the region (Figure 1) appear to support
the concept of earthquake pairing between San Andreas and East Bay faults (Ellsworth,
1990). Unfortunately the historical record is far too short to be rigorously tested, but
modeling studies of the role plate boundary structures may play in producing particular
patterns of earthquake occurrence can provide needed constraints in estimating the possible
consequences of Loma Prieta for other fault segments in the region.

LITHOSPHERIC EVOLUTION

Most studies of the evolution and behavior of the San Andreas fault system have
focused on the stress and deformation regime in the middle to upper crust. This is a
reasonable region to investigate as it encompasses the seismogenic component of the plate
boundary. We have taken a somewhat different approach, focusing rather on the behavior
of the lithosphere below the seismogenic layer. The deformation and stress regime within
the non-seismogenic lithosphere plays an important role in the earthquake cycle along the
San Andreas system, and we believe this approach serves a complementary role with
studies of the seismogenic layer in unraveling the processes which drive the earthquake
cycle along the San Andreas.

PLATE TECTONICS OF SAN FRANCISCO BAY REGION

As described by a variety of investigators (e.g. Atwater, 1970, Dickinson and
Snyder, 1979; Zandt and Furlong, 1982) the formation of the San Andreas plate boundary
is a consequence of the northward migration of the Mendocino Triple Junction. The
development of a transform boundary in lieu of a convergent boundary is fundamental to
the rest of its evolutionary history. A 3-D schematic view of the plate tectonic cause of this
lithospheric evolution is shown in Figure 2.

This 3-D view of lithospheric structure in the vicinity of the Mendocino Triple
Junction (MTJ) shows the typical subduction configuration north of the MTJ where the
Gorda plate subducts beneath the North American plate. The specifics of the relative plate
motions at this fault-trench triple junction require that the motion of the Gorda plate
relative to North America must have a component of motion comparable to the motion
between the Pacific and North American plates. This leads not only to the cessation of
subduction with the passage of the MTJ but also the concurrent removal of the subducted
Gorda slab. These events produce a region of thin North American lithosphere, the base of
which is exposed to relatively hot mantle. This region of the upper mantle beneath the
western edge of the North American plate has been variously called the slabless window or
asthenospheric window. The emplaced asthenospheric mantle will cool over time,
becoming part of either the Pacific or North American lithosphere with the Pacific-North
American plate boundary developing as the locus of deformation in this region of accreted
lithosphere (Furlong et al., 1989).
Paired Bay Area Earthquakes?

Figure 1. Map view showing possible linkage among historical earthquakes in the San Francisco Bay area. Short duration of the historical record precludes placing substantial significance to apparent coupling, however patterns suggest investigation of potential stress communication between fault strands is merited.
Figure 2. Schematic view of the three-dimensional lithospheric structure in the vicinity of the Mendocino triple junction. Plate boundary structure develops in region of emplaced asthenospheric mantle.
Schematic cross-sectional views of this evolution are shown in Figure 3, which also indicates several details of the plate boundary evolution which play important roles in the plate kinematics in the Loma Prieta region. The newly developing boundary between the Pacific and North American plates will develop where deformation is concentrated. Since this is a plate boundary structure, the overall Pacific-North American relative velocities must be accommodated within the plate boundary region. The specifics of the location of the center of deformation and the width of high strain region will depend primarily of the temperature structure of the slab window. The thermal regime controls the initial location of the plate boundary (Furlong et al., 1989), but mineralogic conditions (most likely regions of strain induced reduced grain size) may serve to further localize and maintain the position of the plate boundary within the mantle lithosphere.

Deformation within the lithospheric mantle occurs dominantly via temperature dependent creep processes. The non-linear relation between strain rate and temperature for the appropriate deformation mechanisms leads to a localization of strain to the sites of highest temperature (at any given depth). As a result, strain will localize and the associated plate boundary will form within the slabless window as shown in Figure 3. The exact position of this boundary will depend on both the cross-sectional geometry of the slabless window and details of the kinematics of Pacific plate mantle. Geodetic data (e.g. Lisowski et al. 1991) can also provide an estimate of the location of the plate boundary within the lithospheric mantle, specifically it can locate the position of the center of deformation of the plate boundary deformation zone. Both thermal-mechanical modeling (Furlong et al., 1989) and geodetic data (Lisowski et al., 1991) point to a plate boundary forming within the slab window substantially east of the western edge of the thinned North American lithosphere, in a position which approximately corresponds (on the surface) to the Hayward Fault in the San Francisco Bay region.

The offset in northern California between the surface trace of the San Andreas fault, which during recent geologic time has served as the primary crustal component of the plate boundary, and the deeper plate boundary structure lies at the heart of our model for plate boundary evolution in the vicinity of the San Francisco Bay. An elusive but necessary component of the plate boundary is a connection between the base of the San Andreas fault and the plate boundary which has developed within the slabless window. Although precise details of this structure cannot be determined at present, rheologic considerations and the rupture behavior of the Loma Prieta earthquake (Furlong and Langston, 1990; Langston et al., 1990) lead us to tentatively place this structure within the lower crust at approximately 18 km depth. We also cannot place tight limits on the depth extent of this connecting structure, but it should be contained within the lower crust, and thus its maximum extent would be from approximately 18 km to the local position of the Moho. We would expect strain localization processes to further limit this structure to less than 5 km in thickness, with our preferred model a 2-3 km thick detachment structure.

The combination of plate tectonic events with the thermal and rheologic evolution of the lithosphere leads to a plate boundary configuration in the Loma Prieta region similar to that shown in Figure 4. The plate boundary within the crust includes both the San Andreas and East Bay faults (Hayward, Calaveras, etc.), which connect via a lower crustal structure.
Figure 3. Cross sectional views of plate boundary structure south of the Mendocino triple junction (39° N), and configuration of the plate boundary in the San Francisco Bay area (37° - 38° N).
Figure 4. Schematic 3-D view of plate boundary structure in the San Francisco Bay region. Vertical cut is approximately at the latitude of Loma Prieta. Shading indicates plate affinity of the various crustal and mantle components of the plate boundary.
to the plate boundary within the mantle which lies approximately below the East Bay faults. This complex 3-D plate boundary structure is ephemeral, with the faults which sit above the deeper extent of the plate boundary eventually becoming the dominant component of the plate boundary within the crust. Such a developmental step has occurred in central California, where the plate boundary structure within the crust (the San Andreas) lies above the plate boundary within the lithospheric mantle. The Loma Prieta earthquake occurred along a section of the San Andreas which links these two styles of crustal plate boundary, a region in which the lower crustal detachment structure begins to play a critical part in the overall behavior of the stress and strain regime.

KINEMATICS OF THE LITHOSPHERE

The evolutionary model for the San Andreas system leads to several very important complications to the kinematics of what is often considered a simple strike-slip plate boundary. The position and orientation of the plate boundary within the lithospheric mantle reflects both the nature of its formation (cooling of the mantle material within the asthenospheric window) and the directions of relative motion between the North American and Pacific plates. Geodetic observations and our previous modeling studies (Furlong et al., 1989) indicate this boundary is located approximately as shown in Figure 5. This boundary will be essentially entirely right lateral shear, which we believe, based on rheologic modeling, to be a relatively narrow deformation zone (< 10-20 km) within the lithospheric mantle. Relative to the North American reference frame, the sub-crustal Pacific lithosphere extends to this boundary. The kinematics of the crustal components of this plate boundary system differ from this configuration, and play an important part in the earthquake cycle in the San Francisco Bay region.

Crustal kinematics lead us to consider the crust along the San Andreas in the Bay area in terms of the four blocks shown in Figure 6. East of the lithospheric plate boundary (east of the Hayward-Calaveras fault systems) the North American crust overlies and is coupled to the North American lithosphere. Similarly, offshore to the west, oceanic crust of the Pacific plate is well coupled to its lithospheric mantle. The kinematics of these crustal blocks mimic that of the underlying lithosphere. Between these regions of strong crust-mantle coupling lie two crustal blocks of uncertain affinity. Between the San Andreas and the various East Bay faults lies what we have termed the Bay Area block. This is to some degree equivalent to the Sebastopol block of (Fox, 1983). In the vicinity of the San Francisco Bay this block is likely uncoupled from the underlying lithosphere (which is Pacific plate lithosphere - see Figure 4). The kinematics of this block are complex since it is partly linked to the North American crust to its east (while the East Bay faults are locked), and drag along its base from the motion of the underlying mantle of the Pacific plate may affect internal deformation and motion.

To the west of the San Andreas fault is a region we have termed the Santa Cruz block. This crustal block is normally thought of as behaving as Pacific crust, and no obvious active fault boundary separates it on the west from the adjacent crust. The eastern margin of this block is well defined (the San Andreas) and thus its motions are prescribed
Figure 5. View of location and kinematics of the Pacific - North America plate boundary within the lithospheric mantle.
Figure 6. View of location and kinematics of crustal blocks in the plate boundary region. The Bay Area Block is effectively decoupled from underlying Pacific plate, while the Santa Cruz Block appears to be partly coupled to the underlying Pacific plate.
by the geometry of the San Andreas. The kinematics of the Santa Cruz block are shown in Figure 6. The discrepancies between the kinematics of this crustal block and the underlying pacific mantle lead to partial coupling, the possibility of substantial internal strain, and the likely westward partial obduction of this block over oceanic crust of the Pacific plate.

These differences between the kinematics of the crustal and mantle components of the San Andreas plate boundary played an important part in the generation of the Loma Prieta earthquake. Loma Prieta is located where the motions of the Santa Cruz block differ most greatly from those of the Pacific plate. It is also in this region where the decoupling of the Santa Cruz block from the underlying Pacific mantle must occur (Furlong and Langston, 1990). Thus the generation of the Loma Prieta earthquake reflects two types of processes (1) decoupling of Santa Cruz block crust from its underlying mantle; and (2) interactions between the largely uncoupled Bay Area block and the Santa Cruz block. Because of these complications, it is important to consider both the crustal and mantle kinematics in the investigation of the Loma Prieta event. In the numerical modeling which follows, the consequences of this interaction of crustal blocks and mantle kinematics are investigated.

The kinematic model described above provides a framework in which to evaluate through quantitative modeling the events which led up to the Loma Prieta earthquake and the consequences post-Loma Prieta for the crust and lithospheric stress regime throughout the Bay area. The response of the regional stress field to Loma Prieta is not static, but rather varies in time and space. In the finite element modeling briefly described below we have investigated the first order effects of the Loma Prieta event on patterns of deformation and stress in the San Francisco Bay region. These model results provide additional insight into the possible consequences of the Loma Prieta earthquake on the seismic potential of other faults of the San Andreas system, and also provide a means to relate observations of crustal deformation to the underlying plate tectonic framework of the region.

MODELING PLATE BOUNDARY DEFORMATION DURING THE EARTHQUAKE CYCLE

We have tested several different scenarios of plate boundary structure and rheology in evaluating the plate boundary deformation leading up to the Loma Prieta earthquake and the subsequent consequences for the stress regime on adjacent segments of the San Andreas fault system. In all cases we have placed the primary plate boundary through the mantle lithosphere as shown in Figure 4 and focused on the consequences of different types of coupling between the crust and underlying mantle. The modeling described here refers to our preferred model (Detachment Model), in which a mid-crustal shear zone connects the base of the San Andreas through the Santa Cruz Mountain and Peninsula segments to the East Bay faults and the plate boundary in the lower crust and upper mantle (lithospheric shear zone).
THE FINITE ELEMENT MODEL

The finite element code TECTON (Melosh and Raefsky, 1980, 1981) was used for the modeling. The faults are held locked except during 'earthquakes'. These faults were represented using the split node technique of Melosh and Raefsky (1981). Earthquakes are simulated in the modeling in a very simple manner, specified displacements are applied to the faults (which are unlocked) during the time step of the earthquake. The 1906 earthquake is simulated by 4 meters of slip on the entire length (in the model) of the San Andreas fault (Thatcher, 1975). The 1989 Loma Prieta earthquake was simulated by 2.25 meters of strike slip motion and 2 meters of dip slip motion on a 60 km long section of the Santa Cruz Mountain segment of the San Andreas. The slip at Loma Prieta did not include the surface node in the finite element model to be consistent with observations of little or no rupture at shallow levels (e.g. Langston et al., 1990; Wald et al, 1991). This simple implementation of earthquakes does not provide information on the instantaneous response of the stress regime during the earthquake, but is a reasonable means to evaluate the deformational behavior on the time scale of crust and mantle relaxation.

Results of the modeling are shown in two forms. In these 3-D time dependent models, values for both stress and strain are available at all locations for all time steps. Interpreting such results can be a daunting task. We have tried to distill these results to a set of figures which contain the fundamental aspects and implications of the modeling, particularly as they apply to the stress conditions on the East Bay fault system. The stress field is presented in two ways. Along the faults, the fault parallel shear stress is shown at specific times through the earthquake cycle (pre-1906 to post Loma Prieta). This provides insight into the interaction of the stress field among the fault segments and the spatial variability of the stress regime. It is important to realize that the faults are not necessarily the sites of maximum shear stress, but are reasonable locations to consider in this modeling as they represent the regions which have failed repeatedly in earthquakes. In addition the stress histories for specific locations along the faults are shown as a function of time through the model history. Such stress histories provide a means to investigate both the relaxation phase of crustal deformation and the co-seismic and post-seismic interaction of the various fault strands.

STRESS HISTORY

The model results shown here encompass the effects of both the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake. Results are shown in each case for the time period beginning ~10 years prior to the 1906 event until ~20 years after the Loma Prieta. [Note the model 'runs' for approximately 500 years prior to the 1906 event in order to appropriately pre-stress the regime so the co-seismic and post seismic strain relaxation acts on an appropriate stress field]. Results for the fault parallel shear stress are shown in Figure 7 (Detachment Model). The fault parallel shear stress is shown at the base of the seismogenic layer (i.e. depth level of fault locking). Figure 8 shows the results for stress history at the specific locations.
Detachment Model
Fault Parallel Shear Stress
Base of Seismogenic Layer

Pre 1906

Pre Loma Prieta

Coseismic 1906

Coseismic Loma Prieta

Post 1906 (20 y)

Post Loma Prieta (20 y)

Figure 7. Stress regime produced by the Detachment Model. Fault parallel shear stress at the base of seismogenic layer (18 km) plotted along the traces of the major faults in region during the earthquake cycle simulated in this modeling. Height and shading represent magnitude of shear stress.
Figure 8. Stress history at base of seismogenic layer for the Detachment Model. Curves correspond to specified sites. Intervals of 'earthquake' slip are indicated by shaded bars. Values change on 5 year increments which was the time step used in the modeling.
With the inclusion of a detachment surface within the middle-lower crust connecting the Peninsula and East Bay fault segments, the stress levels acting on the Peninsula segment of the San Andreas are elevated as compared with a model with no direct linkage between the faults. In all cases shear stress levels on the Peninsula segment are lower than the East Bay segment. A first order result of this and previous modeling (Verdonek and Furlong, 1992) is that the role played by the Peninsula segment as the major plate bounding fault in this region implies that this segment must in some sense be weaker than the East Bay segment, since it must fail at lower values of fault parallel shear stress.

In comparing the results shown in Figures 7 and 8 with other models we have investigated, we see that the Detachment Model produces a stress field that differs from the other model scenarios in several important ways. First, as mentioned above the Detachment Model produces the highest levels of stress on the base of the locked faults along the Santa Cruz Mountain and Peninsula segments. Second, the detachment model configuration allows stress (on the Peninsula segment) which is transferred into the lower crust during the 1906 event to relax post-seismically, while such stress cannot relax in models where the lower crust deforms purely by elastic means or the lower crust in general is weak as compared to the seismogenic upper crust.

The stress histories during the earthquake cycle shown in Figure 8 provide insight into the consequences of the 1906 event on the other fault segments and the possible stress loading which the 1989 Loma Prieta event may have caused. In all models the 1906 event causes a decrease in stress level at all locations. The stress drop is largest along the fault segments which ruptured in 1906, but is also seen at the East Bay sites (Morgan Hill, Oakland). In both the elastic and weak crust models the stress increase at Loma Prieta during the post 1906 period is minimal, and relative stress levels at the time of the Loma Prieta event are quite low. The detachment model shows a somewhat greater stress increase and higher stress levels at Loma Prieta.

The Loma Prieta event is significantly smaller than the 1906 earthquake, so its effects on the regional stress field are reduced over the 1906 effects. However the pattern of stress response from Loma Prieta is more complex than that following 1906. The Loma Prieta event produces a stress drop at Morgan Hill, but has a neutral effect or produces a stress increase at all other locations. The effect on the Peninsula segment is relatively minor, but is a slight increase in the case of the detachment model. What may be more important than the actual stress drop or increase associated with Loma Prieta (since the magnitudes are small) is the change in stress patterns caused by the Loma Prieta event. Although the effects are quite small and must be validated by more complete modeling studies, the Loma Prieta event changed the relative stress levels along both the East Bay system and the Santa Cruz Mountain/Peninsula fault system. Just prior to the event, the Oakland location has the minimum level of stress with Pinnacles National Monument and Morgan Hill showing slightly higher values. After Loma Prieta, Morgan Hill becomes the location of minimum stress with an increase at Pinnacles and effectively no change at Oakland. How this may relate to future earthquakes is not entirely clear, since earthquakes are not simply a consequence of stress level. However it is tempting to speculate that
changes in the relative patterns of stress may play an important part in the patterns of earthquakes along the San Andreas in the S.F. Bay region.

BASIX - BAY AREA SEISMIC IMAGING EXPERIMENT

BASIX, conducted in September 1991, was designed to use a combination of vertical-incidence and wide-angle seismic data to image the San Andreas and associated faults. The results of this experiment will provide, for the first time, a detailed image of the plate boundary between the Pacific and North American plates. A particular target of BASIX is the identification and delineation of the lower crustal connection (described above) between the San Andreas and East Bay faults. The deep structure of these faults has been difficult to determine since seismicity along the faults is restricted to the upper crust (depths < 12-15 km) and thus illuminates only the shallow fault structure.

BASIX is being conducted by a consortium of academic and government institutions including the U.S. Geological Survey, University of California at Berkeley, Lawrence Berkeley Laboratories, Stanford University, Pennsylvania State University and Woods Hole Oceanographic Institution. The USGS research vessel, the S.P. Lee provided the seismic source, a 12 gun, 5850 in³ airgun array, and served as the platform for data recording and seismic receiver deployment. The multi-channel profile extended from east of Antioch, California, west to San Pablo Bay, south in the San Francisco Bay, and west under the Golden Gate Bridge (Figure 9). One hundred and twenty seismic receivers, tethered to buoys along the shipping channel were deployed each day. In addition to the multi-channel marine seismic investigation of the San Francisco Bay area, the USGS Calnet Array, consisting of more than 200 permanent stations, recorded the airgun source at wide-angles. Wide-angle coverage was further augmented by the temporary deployment of 22 USGS 5-day recorders, 30 PASSCAL instruments and 5 USGS Ocean bottom seismometers. Offsets of greater than 160 km were achieved. Locations of instrument deployments are shown in Figure 9.

An additional component of BASIX is the detailed, high-resolution imaging of shallow structure. A combination of profiling during the primary experiment and subsequent detailed 3-D studies of target areas will provide detailed information for the delineation of fault traces and structure within the shallow sedimentary sequence.

BASIX represents an active experiment to develop a critical data set which will allow a fundamentally new framework for geologic investigations of the San Francisco Bay area. At present only preliminary results are available, but over the next 6-12 months the wealth of information obtained via BASIX should begin to be available.

DISCUSSION

Coupling our understanding of the 3-D plate boundary structure and kinematics with numerical modeling of the stress and deformational response of the lithosphere to
Figure 9. Schematic view of BASIX experiment and its association with the proposed Pacific North American plate boundary in the San Francisco Bay region. Reflection line indicates path taken by the *S.P. Lee* (airgun source). In addition to the locations of instruments shown on the figure, data were collected at more than 200 of the U.S. Geological Survey's Calnet stations distributed throughout the study area.
earthquakes along the San Andreas system provides insight into the causes and consequences of earthquakes in the San Francisco Bay Area. First, when seen in the perspective of 3-D plate kinematics, the occurrence of the Loma Prieta earthquake should be considered to be associated more with the necessary decoupling of the crust of the Santa Cruz block from the underlying Pacific plate, rather than simply a smaller version of the 1906 earthquake. Second, it is important to evaluate the deformational consequences of the Loma Prieta event in concert with the deformation associated with the 1906 event and with the larger scale plate motions as seen in lithospheric scale deformation. Third, during the first 10-20 years after the Loma Prieta earthquake, observations of crustal deformation should provide important constraints on the details of the 3-D structure and rheology of the plate boundary in the San Francisco Bay region.

The occurrence of the Loma Prieta earthquake along a segment of the San Andreas fault system which also ruptured in 1906 makes it natural to relate processes associated with Loma Prieta to those associated with the San Andreas earthquake of 1906. The initiation of rupture in the Santa Cruz Mountains segment at the base of the seismogenic layer however is compatible with considering the Loma Prieta event to be associated with the decoupling of the crust from the underlying Pacific plate (which continues along the path shown in Figure 5). The increase in stress (shear stress in the horizontal plane) in the vicinity of the Loma Prieta rupture during the interval between 1906 and the Loma Prieta earthquake provides the mechanism for such a style of rupture. This horizontal shear stress increases with each 1906 type event leading eventually to the less frequent (but quasi-periodic) Loma Prieta events. The longer recurrence time for Loma Prieta type events (events with a significant vertical component) as compared with 1906 type events (Anderson, 1990; Valensise and Ward, 1991) may reflect the need for several strike slip events to increase stress to the point of generating the decoupling event. The existence of the easily deforming detachment surface on the 'North American' side of the fault through the Santa Cruz Mountains and S.F. Bay area allows the dissipation of any similar horizontal stresses in that region.

Considering the series of events that led up to the Loma Prieta earthquake is an important element in evaluating the consequences of the event. Although much of the post-seismic relaxation following the 1906 earthquake has occurred, the stress regime in the S.F. Bay area prior to the Loma Prieta event evolves in response to both the 1906 relaxation and post-1906 plate motions. This 'pre-loading' of the system plays an important part in the post-Loma Prieta events. This is partly a consequence of our assumptions of visco-elastic rheologies for the plate boundary area. We feel they more closely represent the deformational behavior of the crust, lithospheric mantle, and plate boundary zone than simple elastic models. Much of the co-seismic deformation, and even some of the long term deformation field, can be adequately simulated by elastic dislocation models. However, the evaluation of crustal deformation on the time scale of the earthquake cycle in the San Francisco Bay area which for large events in the overall region is ≤ 100-200 years, requires the incorporation of viscous rheologies and the inclusion of the series of events which precede the earthquake of interest.
Although the Loma Prieta event does not rank with the great earthquakes which have occurred along the San Andreas fault system in northern California, it does provide an important tool for improving our understanding of lithospheric behavior. The deformation regime prior to the Loma Prieta event, although well documented in the S.F. Bay area, cannot conclusively differentiate among the models. The various models have quite different implications for the overall stress regime in the Bay area, and thus consequences for the earthquake potential of the fault segments differ from model to model. The early stages of lower crustal and plate boundary relaxation after Loma Prieta may provide the key to making that differentiation.

It is important to remember that 3-D modeling of the deformation field associated with a complex plate boundary is still in its infancy. These models serve as important extensions of models of the co-seismic response of the region and regional deformation. We have found that coupling this modeling with improved kinematic models of plate boundary behavior allows us to begin to focus on details of plate boundary deformation which play important roles in the earthquake cycle. It is premature to use these results directly to answer questions of earthquake potential on specific fault segments. Although it is tempting to cite the results shown in Figure 8 as providing the information needed to evaluate the concept of paired earthquakes, we do not feel that our model results, at present, argue conclusively for or against that model. We do however believe that the style of modeling we have undertaken has the potential to improve our understanding of the spatial and temporal variability in stress and deformation associated with the earthquake cycle. This improved understanding of the underlying physics of plate boundary deformation in the San Francisco Bay area is key to an improved assessment of earthquake risk and potential in the area. The Loma Prieta earthquake of 1989 has focused attention on these processes and has served as an important tool which will allow improved observations of the post-seismic response of the plate boundary.

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TECTONICS OF A TRANSPRESSIVE PLATE BOUNDARY: A NEW PARADIGM FOR THE CENTRAL CALIFORNIA COAST RANGES

David L. Jones

Tectonic models of the Neogene evolution of the California Coast Ranges have concentrated on the importance of strike-slip faulting, with the San Andreas fault being viewed as a vertical structure that separates the Pacific plate from the North American plate. The presence of large-amplitude folds and related thrust faults that deform young rocks throughout the central Coast Ranges, however, shows that an important component of contraction has existed since Pliocene time, and continues today. Each major splay of the San Andreas fault system has an attendant parallel thrust belt that roots within the strike-slip fault zone and dips either to the east or west. West-verging thrusts are blind; east-verging thrusts break to the surface and define pop-up blocks. Vergence of these subsidiary thrust belts, viewed as long-term strain indicators, suggests that the San Andreas fault north of Gilroy dips to the west, and the Hayward, Calaveras, and Greenville faults dip to the east. Replotting of earthquake hypocenter data confirms this geometry, which suggests that these faults are listric splays from a subhorizontal mid-crustal decollement (shear zone) that marks the transition from brittle upper crust to ductile lower crust. Retrodeformational analysis indicates that the San Andreas fault and its splays also have been displaced eastward through time and do not continue as vertical structures below the decollement.

These geometrical relations impose important constraints on the kinematics of the San Andreas fault system and the mechanism for transfer of stress through the crust. One obvious conclusion is that the present plate boundary between the Pacific plate and the North American plate is the mid-crustal decollement, not the San Andreas fault. If so, this has important ramifications for geodynamic models and for assessment of risks in seismically active regions such as the central California Coast Ranges. In particular, this model suggests that thrust faults are still active within the Bay Area, but little consideration has been given to assessing the risks posed by major vertical displacements.


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SCHEMATIC STRUCTURE SECTION THROUGH EAST BAY HILLS

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W       BERKELEY HILLS       E

NORTH AMERICAN PLATE

DUCTILE SHEAR ZONE

PACIFIC PLATE

5 km.

5 km.
Contemporary Seismicity, Active Faulting and Seismic Hazards of the Coast Ranges Between San Francisco Bay and Healdsburg, California

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Contemporary seismicity in the northern California Coast Ranges from San Francisco Bay to the town of Healdsburg and east of the seismically quiescent North Coast segment of the San Andreas fault is generally confined to the intensely deformed Santa Rosa block relative to the adjacent Sebastopol block. Much of this activity is concentrated along the Rodgers Creek, Healdsburg, Bennett Valley, and Maacama faults. A prominent gap in microseismicity exists along much of the 43- km-long Rodgers Creek fault, although paleoseismological evidence suggests that the fault has generated at least three paleoearthquakes of moment magnitude (Mw) 7 or greater during the late Holocene (Budding et al., 1991). Earthquakes in the region are generally confined to upper crustal depths of less than 10-12 km. Right-lateral strike-slip faulting on both northwest and north striking faults is currently the primary mode of regional crustal deformation based on observed focal mechanisms, although both reverse faulting, especially in the vicinity of the major Quaternary faults, and normal faulting occur within the region. The tectonic stress field in the region is dominated by north-northeast to northeast directed compressive stresses. Although the Rodgers Creek fault may pose the highest known level of seismic hazard in the region in the next few decades, abundant geological evidence and the contemporary seismicity suggest that faults such as the Healdsburg, Bennett Valley, and Maacama faults also pose significant hazards because of their potential to generate Mw 6-7+ earthquakes.

INTRODUCTION

The portion of the California Coast Ranges north of San Francisco Bay to the town of Healdsburg (hereafter referred to as the study region) (Figure 1) is very tectonically active. The region is bordered on the west by a portion of the North Coast segment of the San Andreas fault and traversed by several faults that form the San Andreas fault system. Although this segment of the San Andreas fault has been seismically quiescent since the cessation of aftershocks of the 1906 San Francisco moment magnitude (Mw) 8 earthquake, the region to the east has been characterized by a relatively high level of seismicity. Several investigators have recognized that the contemporary seismicity between the San Andreas fault and the western margin of the Great Valley north of San Francisco Bay has been concentrated along two major trends: the Healdsburg–Rodgers Creek–Maacama faults and the Green Valley–Bartlett Springs faults [Bufe et al., 1981; Cockerham, 1986; Eberhart-Phillips, 1988; Wong, 1990]. The dominant fault within the study region, the Rodgers Creek fault, however, has been essentially aseismic along most of its length. This observation, together with recent paleoseismological investigations [Budding et al., 1991], suggests that the Rodgers Creek fault is a seismic gap and capable of generating a Mw 7 or larger earthquake.

From October 1970, when adequate microearthquake monitoring by the U.S. Geological Survey (USGS) came into existence, through August 1989, approximately 1000 earthquakes generally greater than Richter magnitude (Ml) 1.0 reportedly occurred within the study region. The specific objectives of this study were to refine the hypocentral locations of these events, based on a more appropriate region-specific crustal velocity model (with station delays), and to determine focal mechanisms for all well-recorded earthquakes. From these analyses and a review of the available geologic data on Quaternary faulting, more accurate assessments were made regarding (1) the spatial distribution of earthquakes in the study region; (2) the style and orientation of seismogenic faulting; (3) the possible association of earthquakes with specific structures, in particular the Rodgers Creek, Healdsburg, Bennett Valley, Maacama, and Tolay faults; and (4) the nature and orientation of tectonic stresses active in the region. The study described herein represents the first comprehensive and detailed analysis of the contemporary seismicity and active faulting in this portion of the northern Coast Ranges. On the basis of this evaluation an improved understanding of the level of seismic hazard in the region has resulted and is discussed below.

GEOL O GICAL AND TECTONIC SETTING

The study region is located in the Coast Ranges, which are composed of rocks of the Franciscan Complex that were severely deformed during unthrusting of oceanic plate(s) beneath the western margin of North America from Late Jurassic to early Tertiary times [Page, 1981] (Figure 1). Other assemblages within the Coast Ranges include the forearc-basin sediments of the late Mesozoic Great Valley sequence and plutonic and metamorphic rocks of the Salinian Block [Page, 1981].

The Coast Ranges tectonic province is bounded on the west by the northwest trending San Andreas fault, the principal element of the plate boundary (Figure 1). A 100 to 200-km-wide region centered on the plate boundary, which includes much of the Coast Ranges, is tectonically dominated at present by the dextral shear resulting from the relative motion of the Pacific and North American plates. During the Neogene, en echelon compressional basins of
deposition, en echelon folds, northwest trending strike-slip faults, and lesser east-west trending thrust faults were formed [Page, 1981].

The San Andreas fault was formed by the northward migration of the Mendocino triple junction. Furlong et al. [1989] have proposed that the evolution of the San Andreas fault system is largely controlled by the thermal-mechanical behavior of the Pacific and North American lithosphere in the vicinity of the fault system and the development of a "slabless" window beneath the western edge of the North American plate. The window was formed by the northerly movement and removal of the subducting Juan de Fuca (Gorda) plate from beneath North America. Furlong et al. [1989] also suggest that between the approximate latitudes of 37° and 39°N, the plate boundary within the mantle has developed approximately 40–60 km east of the surface trace of the San Andreas fault and lies beneath the Hayward-Calaveras faults and associated faults (including the Rodgers Creek and Healdsburg faults). These latter faults, which have developed relatively recently (since 2–4 Ma), appear to have accommodated only a fraction of the plate motion where the San Andreas fault has served as the principal source of long-term strain release since the latter was formed 7–10 m.y. ago [Furlong et al., 1989]. Eventually, the faults east of the San Andreas fault will evolve into the new plate boundary in the brittle upper crust.

On the basis of a contrast in deformation, Fox [1983] has defined two structural blocks in the Coast Ranges north of San Francisco Bay: the Sebastopol block on the west and the relatively intensely deformed (faulted and folded) Santa Rosa block to the east (Figure 1). The average dip of late Miocene, Pliocene, and Pleistocene strata within the Sebas-
Wong: Coast Ranges Seismicity, Faulting, and Seismic Hazards

Fig. 2. Historical seismicity ($M_L \geq 2.5$) in the study region from 1855 to 1969 and significant Quaternary faults. Epicentral data sources are Toppozada et al. [1981], Real et al. [1978], and the University of California earthquake catalogs.

The Santa Rosa block is cut by eight major north-northwest trending, right-lateral, strike-slip faults or fault zones including the Tolay, Rodgers Creek, Healdsburg, Maacama, Bennett Valley, Carneros, West Napa, and Green Valley faults (Figure 1). These faults appear to constitute a N30°W trending wrench system that has been displaced by an aggregate of 85 ± 25 km in a right-lateral sense since about 8 Ma [Fox, 1983]. The first five listed faults are the subject of this paper. The seismicity and faulting characteristics of the Green Valley fault have been evaluated previously by Wong [1990].

No major faults occur within the Sebastopol block. Possible Quaternary faults include the Burdell Mountain, Americano Creek, Dunham, Bloomfield, and Wallace Creek faults, and a possible northern extension of the Tolay fault [Wagner and Bertugno, 1982] (Figures 2 and 3). These faults all appear to be generally less than 20 km in length.

HISTORICAL SEISMICITY

The historical earthquake record for California dates back only to the late 1700s (primarily from the initial establishment of Franciscan Missions along the coast) and is probably only complete for very large earthquakes. The first earthquake documented in the study region occurred in 1855 (Figure 2). Although the first seismographic stations in central coastal California were established by the University of California at Berkeley (UCB) and atop Mount Hamilton in 1887, earthquakes were not instrumentally located until additional UCB stations were installed in Palo Alto in 1927, San Francisco in 1931, Ferndale in 1933, and Fresno in 1935. Prior to the 1930s, earthquake locations were based principally on felt reports. After 1930, seismographic coverage, though still quite regional in extent, improved sufficiently for UCB to locate earthquakes instrumentally.

Only two UCB stations, however, have operated in the study region: in Calistoga and Point Reyes from 1961 to 1964. After the occurrences of the October 1, 1969, Santa Rosa earthquakes, seismographic coverage improved significantly when the USGS expanded their central California network north of San Francisco in 1970. Thus adequate seismographic coverage of the region for the detection and location of earthquakes smaller than $M_L \geq 3$ came into existence between 1970 and 1973. The current epicentral location accuracy is estimated to be of the order of 2 km or possibly better and the level of detection is approximately $M_L \geq 1.5$.

A total of 126 earthquakes of approximate $M_L \geq 2.5$ and
greater are thought to have occurred in the study region from 1855 to 1969. Only one earthquake is thought to have exceeded \( M_L \) 6, and four additional earthquakes have exceeded \( M_L \) 5 in the region (Figure 2). The March 31, 1988, earthquake of \( M_L \) 6.5 [Ellsworth, 1991] partially or totally collapsed several buildings (modified Mercalli (MM) VIII) on Mare and Tubb islands [Topozada et al., 1981]. Houses were knocked from their foundations in neighboring towns, and extensive ground cracking was observed. Although this earthquake has been assigned a location just east of the southern end of the Rodgers Creek fault based on its isoseismal pattern (Figure 2), the epicentral uncertainty does not permit an association with a specific fault.

The four \( M_L \) 5 earthquakes include events on October 12, 1891, of estimated \( M_L \) 5.5, August 9, 1893 (\( M_L \) 5.1), and the two largest events of the 1969 Santa Rosa sequence (\( M_L \) 5.6 and 5.7) (Figure 2). In the 1891 earthquake, several brick buildings were cracked and moved off their foundations in Napa and Sonoma. This ground shaking corresponds to a maximum MM intensity of VIII [Topozada et al., 1981]. In the somewhat slightly smaller 1893 event, chimneys were knocked down and plaster fell in Santa Rosa (MM VII).

Recent seismicity in the region has been dominated by the 1969 sequence. At 2156 LT on October 1, the \( M_L \) 5.6 earthquake struck near Santa Rosa, followed by the \( M_L \) 5.7 event at 2320 LT. Fifteen injuries were reported and no deaths [Steinbrugge et al., 1970]. Structural damage including damage to building contents exceeded $7 million. At least 200 aftershocks were recorded in the sequence, with the largest a \( M_L \) 4.3 event on October 2. Aftershock recordings by a temporary network operated by the USGS suggest that this sequence occurred principally on a southern extension of the Healdsburg fault (J. D. Unger and J. P. Eaton, unpublished manuscript, 1970). However, the source of the two principal events has not been well determined due to location uncertainties and the geological complexity of what appears to be a right step from the Rodgers Creek fault to the Healdsburg and Maacama faults (I. G. Wong et al., manuscript in preparation, 1991).

**DATA ANALYSIS**

The approximately 1000 earthquakes which occurred from October 1970 to August 1989 in the study region were relocated using the computer program HYPOELIPSE [Lahr, 1984]. Only events which were recorded by seven or more seismographic stations (generally \( M_L \) > 1) were analyzed using the velocity model in Table 1.

This velocity model is based on (1) an upper crustal model developed by Eberhart-Phillips [1988] for the Clear Lake region and modified by Merriam [1986] for the area between Clear Lake and Lake Berryessa and (2) a lower crustal and upper mantle model appropriate for the Coast Ranges in central California from Wesson et al. [1973]. The depths to the layer boundaries were systematically varied for a set of 31 well-recorded and well-distributed calibration earthquakes (\( M_L \) > 2.5) to find the best model which minimized the root-mean-square (rms) errors in the travel time residuals. This final velocity model was tested against the model used by the USGS in routine locations of central California earthquakes [Wesson et al., 1973] and proved superior based on the smaller rms errors of the calibration events. A model similar to the final model was used by Wong [1990] in a study of seismicity near Lake Berryessa.

**TABLE 1. P Wave Velocity Model Used in This Study**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity, km/s</th>
<th>Depth to Top of Layer, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.45</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>5.10</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>5.50</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>5.60</td>
<td>4.25</td>
</tr>
<tr>
<td>5</td>
<td>5.90</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>6.80</td>
<td>14.0</td>
</tr>
<tr>
<td>7</td>
<td>8.00</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Station delays based on the 31 calibration events were determined by iteratively incorporating the average station residuals. A final set of station delays was obtained when the changes in rms errors became minimal. (The use of station delays improves the relative locations of the earthquakes but may not remove absolute location errors.)

All P wave arrival times from the USGS stations within an epicentral distance 100 km were used in the earthquake locations. Stations beyond this distance were disregarded in order to minimize departures from the crustal velocity model. The first motion data from all stations recording the event were used in focal mechanisms which were generated using the computer program FFFIT [Reasenberg and Oppenheimer, 1985]. Arrival times as originally read by the USGS were used, and no rereading was performed except for first motions. S waves for the majority of events were seldom read by the USGS due to, the difficulty in reading such arrivals on devolocorder film; thus no S waves were used in the relocations. Station elevation corrections were calculated assuming a velocity equal to the velocity of the top layer of the model.

A total of 930 earthquakes (including the 31 calibration events) that occurred from October 1970 to August 1989 in the study region were relocated. After unreliable arrival times were deleted from the location solutions, any event with fewer than generally seven recording stations was removed from the data set. A few events with rms errors greater than 0.25 s were also deleted. The average rms error of the relocated earthquakes was 0.07 s compared to an error of 0.13 s for the original USGS locations. The HYPOELIPSE epicentral standard errors (ERHs) of the relocated events were 1.0 km or less for 73% of the events.

An attempt was made to evaluate the validity of the velocity model and station delays and hence the absolute epicentral accuracy of the relocated events; however, no known large explosions occurred within the study region. Fifteen blasts at two quarries near the town of Napa and at the Warm Springs Dam located just outside the study region were relocated generally within 1 km of the actual quarry locations and at depths of 1 km or less. Thus based on the low rms errors and ERHs and the relocations of quarry blasts, the majority of relocated epicenters are believed to have an accuracy of ±1 km or better. Because of the 10–20 km average spacing between USGS stations in this portion of the central California network (and hence few close-in stations) (Figure 3) and the absence of S waves in the hypocentral determinations, computed focal depths have an estimated accuracy of ±2 km. Equivalent Richter magnitudes quoted in this study have been determined by the USGS, Menlo Park, generally based on coda durations.
RESULTS AND GEOLOGIC IMPLICATIONS

Data from the relocated earthquakes indicate that the vast majority of events were concentrated in the vicinity of the Rodgers Creek, Healdsburg, Bennett Valley, and Maacama faults (Figure 3). With the exception of the Bennett Valley fault, this seismicity is consistent with the geological evidence of these faults being active in Holocene and/or late Quaternary times. (It should be noted that seismicity alone is not always sufficient for, or in some cases capable of, delineating or completely characterizing all active faults in a region.) Diffuse but significant seismicity also appears to be occurring outside this principal zone of faulting and deformation (Figures 3 and 4). A few scattered microearthquakes were located in the vicinity of the seismically quiescent North Coast segment of the San Andreas fault in Tomales Bay. The following is a discussion of the geological implications of these results as they pertain to the significant Quaternary faults within the study region.

San Andreas Fault

From October 1970 to August 1989, only 10 well-recorded microearthquakes occurred in the vicinity of the 37-km-long portion of the North Coast segment of the San Andreas fault within the study region (Figure 3). Of these, possibly only half actually occurred along the principal traces of the fault. None of the microearthquakes near Tomales Bay exceeded $M_I$ 3.0 (Figure 3). All events were confined to upper crustal depths of 8 km and less (Figure 4h). Three microearthquakes were located near the surface probably as a result of inadequate coverage by the USGS network near the coast.
Fig. 4. Locations of cross sections and views of the relocated seismicity: (a) Healdsburg–Rodgers Creek faults, longitudinal; (b) Bennett Valley fault, longitudinal; (c) Rodgers Creek and Bennett Valley faults, transverse; (d) and (e) Healdsburg fault, transverse; (f) and (g) Maacama fault, longitudinal and transverse; (h) San Andreas fault near Tomales Bay, longitudinal; and (i) Rodgers Creek fault to Hayward fault right bend, longitudinal.
Fig. 4. (continued)
Rodgers Creek Fault

The Rodgers Creek fault as mapped extends for a distance of at least 43 km from near Sears Point near San Pablo Bay northwestward across the Sonoma Mountains to a location 4 km north of Santa Rosa [Wagner and Bortugno, 1982] (Figure 2). Uncertainty regarding the location and character of large portions of the fault is due to burial by landslides. Although some investigators consider the Rodgers Creek fault to be the southern extension of the Healdsburg fault, Herd and Helley [1977] suggest that the Maacama fault zone has apparently acted as the northward continuation of the Rodgers Creek fault zone during the Quaternary. In contrast, the seismicity (as will be discussed later) suggests that the Rodgers Creek, Healdsburg, Maacama, and Bennett Valley faults are probably all part of the same broad zone of deformation.

Of the faults located within the study region the Rodgers Creek fault exhibits geologically the greatest degree of recent activity as manifested by geomorphic features such as sag ponds, stream offsets, and small linear rift valleys [Pampeyan, 1979]. The fault zone appears to consist of at least four geometric segments (not rupture segments) with each segment showing evidence of recent and systematic right-lateral slip [Hart, 1982a]. The segments are well defined by major right step-overs with the longest segment extending approximately 12 km.

Recent significant paleoseismological trenching studies by Budding et al. [1991], 18.5 km northwest of San Pablo Bay, have revealed possibly three to four paleoearthquakes on the Rodgers Creek fault. They also estimated a minimum late Holocene slip rate of 2.1-5.8 mm/yr for the past 1300 years and a maximum recurrence interval of 248-679 years for surface-faulting events (M ~ 7). Budding et al. [1991] further suggest, based on the absence of fault creep and seismicity, that the fault is locked and, given the uncertainties of their recurrence and slip rate estimates, the elapsed time since the last major earthquake on the Rodgers Creek fault (minimum of 182 years) may be approaching the average recurrence interval.

The relocations support earlier observations [e.g., Bufe et al., 1981] that the Rodgers Creek fault is generally seismically quiescent. A dramatic absence of microearthquakes characterizes the southern 22 km of the fault south of Sonoma Mountain (Figures 3 and 4a). In the mapped northern 21 km, only a few microearthquakes occur in the vicinity of the fault except for a concentration of events at a depth of about 8 km near the junction of Taylor Mountain and a northwest striking splay of the fault considered to have been active in the late Quaternary by Wagner and Bortugno [1982] (Figures 3 and 4a). A cross-sectional view through the Taylor Mountain activity suggests that the Rodgers Creek fault is a near-vertical fault to a depth of about 14 km (Figure 4c). Given the absence of additional observations, however, this dip may vary slightly along the length of the fault.

In the northernmost portion of the fault east and north of Santa Rosa (although there is some question whether the latter is part of the Rodgers Creek fault or the Healdsburg fault), no microearthquakes have been observed to date (Figure 3). A concentration of activity does occur on the parallel, southernmost traces of the Healdsburg fault (see following section). No earthquakes larger than M_3 have been observed along the fault since adequate seismographic coverage came into existence in 1970 through August 1989; hence no focal mechanisms have been determined for the Rodgers Creek fault (Figure 6).

The fault has also been apparently devoid of significant seismicity in historical times dating back to the mid-1800s (or 1808 as suggested by Budding et al. [1991]), which supports the observation that the fault is presently a seismic gap. Empirical relationships based on fault rupture length indicate that if the mapped 43-km or longer fault ruptured in a single event, the fault could generate a M_6 or M_7 or larger earthquake. This value is consistent with the estimate by Budding et al. [1991], based on an estimated average slip per event observed in their paleoseismological trenches. The Working Group on California Earthquake Probabilities [1990] has estimated a 22% probability for a M_7.0 or larger earthquake occurring on the Rodgers Creek fault in the next 30 years based primarily on the findings of Budding et al. [1991].

Etisworth et al. [1982] suggested, on the basis of microseismicity, that the Healdsburg-Rodgers Creek fault is continuous with the Hayward fault to the south, although Wagner and Bortugno [1982] show the Rodgers Creek fault unmapped 3 km from San Pablo Bay (Figure 3). The projections of the mapped faults indicate the two are separated by a 6-km right step-over or fault bend. Aydin [1982] has suggested that a pull-apart basin may exist beneath San Pablo Bay as a result of extension across a right step-over. Budding et al. [1991] note that the step-over or bend is associated with a 35-mGal negative gravity anomaly in San Pablo Bay and that such areas are often associated with rupture termination points. On the basis of the broad north trending zone of epicenters (Figure 3), a bend between the two faults appears more likely. The presence of both strike-slip and reverse faulting, combined with the focal mechanisms (Figure 6), suggests that the bend consists of a complex zone of deformation, possibly including multiple faults in San Pablo Bay.

Significant clusters of events have occurred off the Rodgers Creek fault: in particular, one cluster to the southwest and one along a northwest striking splay fault northwest of Sonoma Mountain (Figure 3). In the former, two focal mechanisms (events 10 and 11, Figure 5) exhibit predominantly reverse faulting along a northwest trending plane, which is consistent with a subtle northwest trending zone of epicenters (Figure 6). Such semiparallel seismogenic reverse faulting located off a major strike-slip fault has been increasingly observed along faults of the San Andreas system, including the Calaveras and Hayward faults [Oppenheimer et al., 1988; Oppenheimer, 1990; Wong et al., 1991].

Focal mechanisms 2, 4, and 22 for the cluster of events along the Sonoma Mountain splay fault (Figures 5 and 6) are nearly identical, exhibiting right-lateral strike-slip faulting on the northwest trending plane. The area also appears to have been the site of previous historical activity (Figure 2). Wagner and Bortugno [1982] show this fault to have been active in late Quaternary times. A focal mechanism for a single event (event 25, Figure 5), located between the splay and the Rodgers Creek fault, also exhibits right-lateral strike-slip faulting. Seismicity in the vicinity of the fault appears to be confined to the top 12 km of the crust, with a few events as deep as 15 km (Figures 4a and 4c).
LOCATION AND MAGNITUDE OF THE 1898 "MARE ISLAND" EARTHQUAKE

Tousson R. Toppozada

The 1898 "Mare Island" event was one of the largest earthquakes to occur in the Bay Area in the decades before the 1906 San Francisco event. It damaged buildings (intensity VII or greater) in the counties of Sonoma, Marin, San Francisco, Alameda, Contra Costa, Solano, and Napa. The strongest damage (intensity VIII or greater) occurred along the northern border of San Pablo Bay from Vallejo and Mare Island to near Sonoma and Petaluma. The name "Mare Island" earthquake results from the concentration of major structures damaged in the Navy yard on made land on that island. However, the intensity VIII isoseismal is centered approximately on the southern end of the Rodgers Creek fault, suggesting it is possibly the source of the 1898 event. Other candidates are a source in San Pablo Bay such as the northern extension of the Franklin fault, or the Tolay fault in Sonoma County. Of these three possible sources, the Rodgers Creek fault is the only one known to have been active in the Holocene. A source on the Rodgers Creek fault is also supported by the distribution of 1898 reports of aftershocks, which apparently were strongest and most numerous at Sonoma.

A M 6.2 was estimated for the 1898 event by Toppozada and others (1981) by comparing the isoseismal areas of the 1898 event to those of California earthquakes having instrumentally determined magnitudes. This M 6.2 estimate now appears to be low in light of the Bay Area earthquakes that have occurred since 1981. Comparisons of the V, VI, and VII isoseismals of the 1898 event to those of the 1984 Morgan Hill event of M 6.2 and the 1989 Loma Prieta event of M 7.0 give estimates ranging from M 6.4 to M 7.0, averaging about M 6.7. If the estimates from the VII isoseismals are excluded due to differences in building construction between 1898 and 1984-1989, the average of the remaining estimates is about M 6.6 for the 1898 event.

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Reprinted from Program and Abstracts, Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area, 1992
GEOLGY OF THE PETALUMA VALLEY AREA

ANN DAVIES HUDSON

The passage of the Mendocino Triple Junction and the resulting transition from a subduction margin to a transform margin initiated the formation of the Petaluma basin and produced the structural features observed today (Figures 1 and 2). A lack of understanding of the plate tectonic concept combined with poor exposure, inaccurate formation descriptions, complex stratigraphic relationships, and unrecognized folding and faulting of this area led to the proposal of conflicting interpretations by previous workers (e.g. Osmont, 1905; Dickerson, 1922; Morse and Bailey, 1935; Weaver, 1949; Trans, 1952; Cardwell, 1958). Re-examination of this area with an awareness of regional tectonic processes and improved dating techniques has produced a more accurate picture of the stratigraphic and structural relationships in the Petaluma Valley (Fox, 1983; Davies, 1986; Youngman, 1989). Although some issues remain unresolved, knowledge of the stratigraphic and structural relationships is crucial for interpreting the geology of the Petaluma Valley and understanding how it fits into the regional tectonic history of the San Francisco Bay area.

STRATIGRAPHY

The Miocene and Pliocene formations of the Petaluma Valley area include both sedimentary and volcanic deposits that overlie a Mesozoic basement of Franciscan and Great Valley rocks (Figure 3). The sedimentary units include the Petaluma Formation, the Wilson Grove Formation, and the Cotati member of the Wilson Grove. In the past outcrop identification has been hampered by poor exposure, lithologic similarity, inaccurate formation descriptions, incorrect correlations with nearby deposits, complex stratigraphic relationships, a paucity of datable fossils, and constant revision of the Miocene-Pliocene boundary.
Figure 3. Ages and stratigraphic relationships of a generalized southwest-northeast cross-section in the Petaluma Valley area.
The volcanics in the area were thought to be a single formation until the drilling of an oil well proved the existence of at least two formations, the Sonoma Volcanics and the Tolay Volcanics (Morse and Bailey, 1935). Geochronologic and geochemical analyses have now suggested that a third formation can be identified as the Donnell Ranch Volcanics (Youngman, 1989). All of the volcanics exhibit a wide range of compositions and textures, so identification of a sample must be done with dating and geochemical techniques.

Tolay Volcanics

The Tolay Volcanics were discovered to be underlying the Petaluma Formation when 4000 ft. of volcanics were encountered in the Murphy #1 well without ever reaching the Mesozoic basement (Morse and Bailey, 1935). The Tolay interfinger upward with the Petaluma through a 200' transition zone. They are described as flows, breccias, tuffs and agglomerates that are largely andesitic and basaltic in composition with minor acidic material. Radiometric dating has shown that some of these older rocks also occur at the surface, mostly along the west side of the Petaluma Valley (Figure 4). Tolay specimens (as currently defined by Youngman, 1989) are Middle Miocene in age and have been dated at 13.62 ± 2.39 Ma to 11.76 ± 0.44 Ma.

Petaluma Formation

The Petaluma Formation is comprised of a lower lacustrine unit and an upper fluvial unit. Well data suggests that the lower unit is 600 ft. thick and the upper unit is 3500 ft. thick with a gradational contact between the two units (Morse and Bailey, 1935).

The Upper Petaluma consists mostly of clays with lenses of sand and conglomerate; however, the sands and clays weather quickly into soils and are covered with vegetation. The conglomerates
Figure 4. Radiometric date localities, slightly modified from Fox et al. (1965b).
outcrop most often, but even these exposures are generally poor. They consist of poorly-sorted, subangular to well-rounded clasts that range from 1 cm to 20 cm in size, but are most commonly 3-6 cm. The pebbles are either clast-supported or matrix-supported in a poorly- to moderately-sorted brown or orange, lithic, silty sand matrix. The clasts consist largely of red or other-colored chert and lithic, moderately indurated, orange or brown sandstone. They also commonly include white vein quartz; older, silicified sedimentary rocks; and blueschist or very rare greenschist. Pebbles of dark, fine-grained volcanics; silicified, laminated Monterey shale; flow-banded white rhyolite; or quartz or plagioclase porphyry are locally abundant reflecting the active tectonism in the area at the time of deposition.

Rare fragments of mammalian bone, horse teeth, or leaf fossils are sometimes found in the Upper Petaluma.

The lacustrine Lower Petaluma consists of dark, wavy-laminated clays that sometimes contain fresh or brackish shells, ostracods, leaves, fish debris, or 5 mm diameter burrows that are usually oriented perpendicular to the lamination. The lower Petaluma is exposed in the cores of the Adobe and Washoe anticlines.

The age of the Petaluma has been determined through the dating of volcanic beds believed to be interbedded with the Petaluma and through mammal or leaf fossils that are rarely diagnostic of a precise time. A horse tooth found near Sears Point was identified as Equus and has been determined to be Blancon or Pliocene in age (probably ~3.5 Ma) by Don Savage (in Davies, 1986). Sycamore leaf imprints found in the core of the Adobe anticline were identified by Howard Schorn (in Davies, 1986) as Clarendonian. In the San Francisco Bay area the Clarendonian ranges from ~9 Ma to ~12 Ma and is upper Middle Miocene or lower Upper Miocene.
Radiometric dates within the Petaluma include the Sebastopol tuff at Sears Point dated at 5.77 ± 0.12 Ma (Fox et al. 1985b), a tuff near Lakeville dated at 6.8 Ma (Davies, 1986), and a lapilli tuff near Carriger Creek that is believed to be interbedded with Lower Petaluma sediments dated at 11.33±0.88 Ma (Fox et al., 1985b). In addition, the Lower Petaluma is interbedded with the Tolay Volcanics which are known to range from 13.62 ± 2.39 Ma to 11.76 ± 0.44 Ma. Thus, both fossil and radiometric evidence indicates that the Petaluma is late Middle Miocene to middle Pliocene in age.

Sonoma Volcanics

The Sonoma Volcanics include flows, tuffs, and breccias that range in composition from basaltic to rhyodacitic in composition with porphyritic andesite and basaltic andesite being the most common lithologies (Youngman, 1989). Dates of the Sonoma Volcanics range from 7.28 ± 0.16 Ma (Youngman, 1989) to 2.6 ± 0.3 Ma (Fox et al., 1985). The Sonoma Volcanics were once believed to be interbedded with and overlying the Petaluma Formation. However, recent work by Youngman (1989) has suggested that these rocks include a geochemically and geochronologically distinct group named the Donnell Ranch Volcanics.

Donnell Ranch Volcanics

The dominant lithologies of the Donnell Ranch Volcanics are olivine basalts and basaltic andesites. Dacites and rhyolites are also found. Radiometric dates within the Donnell Ranch Volcanics range from 10.64 ± 0.27 Ma to 8.24 ± 0.22 Ma and possibly as young as 7.04 ± 0.16 Ma (Youngman, 1989).

The Donnell Ranch Volcanics occur on both sides on the Rogers Creek Fault. Youngman describes these rocks as thrust sheets resulting from a flower structure along the fault. Some of these contacts had previously been described as examples of the interfingerling of
Sonoma Volcanics with the Petaluma Formation. The ages of the Sonoma and Donnell Ranch Volcanics and of the Petaluma Formation indicate contemporaneous deposition. The stratigraphic and structural relationships of the formations need to be re-examined in the context of Youngman’s new ideas.

Wilson Grove Formation

The Wilson Grove Formation is a shallow marine sandstone that overlies the Mesozoic basement on the west side of the Petaluma Valley and extends westward to the coast. It was previously correlated with the Merced Formation, but now it is known not to be correlative (Fox, 1983). The Wilson Grove is usually a massive, well-sorted, fine-grained, buff-colored sand. Color varies from orange to brown to gray. The texture ranges to coarse-grained and is sometimes only moderately sorted. Rarely do the sands contain pebbles. Uncommon beds of pelecypods, gastropods, and other shallow marine fossils are quite distinctive (Bedrossian, 1971, 1974, 1982). The Sebastopol tuff near the base of the Wilson Grove has been dated at 5.9 Ma or uppermost Miocene (Fox et al., 1985). The tuff is believed to be correlative with the tuff overlain by Petaluma sediments at Sears Point (Fox et al., 1985; Sarna-Wojcicki, 1976, 1979). The uppermost part of the Wilson Grove Formation is an estuarine to fresh water facies now referred to as the Cotati member.

Cotati Member of the Wilson Grove

The Cotati member of the Wilson Grove Formation consists largely of fluvial sands and conglomerates with some outcrops of estuarine sand and clay. The fluvial deposits of the Cotati are white, buff, or light gray, fine sands and silts that may or may not be moderately indurated and easily weather into soil. Sorting ranges from very poor to moderate.

The conglomerates contain pebbles that are usually 1-2 cm in length and are very well-rounded and well-sorted. The pebbles
range from 0.5 cm - 5 cm and are rarely subrounded or moderately sorted. Pebbles of white vein quartz and older, silicified metasedimentary and metavolcanic rocks are most abundant with chert and sandstone pebbles being common. The sandstone pebbles in the Cotati are different from those in the Petaluma. They are usually very well-indurated and often have a white or gray, speckled, "salt-and-pepper" appearance. Pebbles of Monterey shale, flow-banded white rhyolite, quartz or plagioclase porphyries, and dark, fine-grained volcanics are locally abundant. Blueschist or sandstone pebbles similar to those found in the Petaluma are very rare and are probably reworked.

Outcrops of the estuarine facies of the Cotati are rare. They consist of massive or crossbedded tidal channel sands with rare clay intraclasts overlain by laminated or bioturbated clays and sands that are interpreted as tidal flat deposits. The clays are white or light gray. The sands are moderately to well-sorted and fine- to medium-grained and are usually light in color, although ironstaining may delineate laminations or burrows. Estuarine outcrops along the Old Redwood Highway are overlain by fluvial Cotati deposits on the hill above the highway, (Davies, 1986).

No identifiable fossils or volcanics that can be dated radiometrically have been found within the Cotati. The Cotati seems to be locally unconformable on older, deformed Petaluma beds found at the Meacham Hill, Washoe, and Llano anticlines. Deposition seems to have continued during deformation as the Cotati member itself is disturbed, particularly near the Penngrove, Meacham Hill, and Cinnabar School Faults. Tenuous relationships at the Washoe anticline suggest that the Cotati was being deposited no more than ~4 Ma (Davies, 1986). Thus the Wilson Grove Formation ranges from more than 6 Ma to possibly less that 4 Ma or Late Miocene to Early Pliocene. The Wilson Grove Formation was deposited contemporaneously with the Petaluma to the east, and it is possible that the two interfinger beneath the Petaluma Valley.
STRUCTURE

The Miocene and Pliocene deposits of the Petaluma Valley have been greatly affected by folding and faulting due to passage of the Mendocino Triple Junction and the transition to a strike-slip margin (Figures 1 and 5). The Petaluma-Santa Rosa Valley is a large syncline. Major folds in the area include the Sears Point, Adobe, Meacham Hill, Washoe, and Llano anticlines. The cores of these anticlines expose progressively older rocks at the surface in a southeasterly direction (except for the Adobe anticline which is northeast of the others).

The dominant fault in the area is the right-lateral Rogers Creek Fault which accommodates some of the motion of the San Andreas fault zone. Youngman (1989) has proposed flower structure thrust faults along the Rogers Creek Fault as discussed previously.

The Tolay Fault and the Meacham Hill Fault are major reverse faults that bring Mesozoic basement and Tolay Volcanics to the surface. Other significant faults in the Petaluma Valley area are the Penngrove Fault, the Cinnabar School Fault, and the Sebastopol Fault. There are many other minor faults that exist in this area as well.

PETALUMA OIL FIELD

The Petaluma oil and gas field is located along the faulted Adobe anticline. The smaller Cotati gas field was drilled on the Llano anticline. The source of the hydrocarbons is still quite controversial. The lacustrine sediments of the Lower Petaluma seem to contain organic matter, but there may not have been enough heat in the interfingered volcanics to bring the sediments into the oil maturation window in a relatively short time. It is possible that the Monterey formation, now exposed only in a fault sliver along Carneros Creek east of the Petaluma Valley, may underlie part of the area and provide the source. The Franciscan Formation has also been suggested as a possible source (Schlax in Davies, 1986).
REGIONAL TECTONICS AND CORRELATIONS

The Petaluma Valley was formed because of subsidence related to the passage of the Mendocino Triple Junction, which allowed the deposition and preservation of Miocene and Pliocene sediments and volcanics. These deposits were then deformed in a right-lateral wrench system that developed within the pre-existing Mesozoic basement as the area became dominated by transform faults. Some of these faults or splays seem to parallel the N50-55W strike of structural contacts formed within the Franciscan-Great Valley basement during the prior period of subduction rather than the N35W trend of the present San Andreas Fault. The strong reverse motion along the Meacham Hill and Tolay faults may result from a period of convergence along the San Andreas system during the last 5 Ma that is due to plate interactions in the Pacific (Davies, 1986; Engebratson, 1984; Engebratson et al., 1985). Deposition of the Petaluma Formation and the Cotati member of the Wilson Grove seems to have continued during deformation (Davies, 1986).

The outcrop pattern of Franciscan and Great Valley rocks north of San Francisco Bay suggests that the curvature of the west side of the Petaluma-Santa Rosa Valley may be inherited from the now-covered trace of the Coast Range Thrust (Figure 6; Davies, 1986). East of San Francisco Bay the Hayward Fault of the strike-slip San Andreas system has occupied the zone of weakness created by the previous trace of the Coast Range Thrust. This fault is in fair alignment with the western margin of the Petaluma Valley. Most of the transform motion of the Hayward Fault is taken up along the Rogers Creek Fault. Recent evidence suggests that San Pablo Bay is a pull-apart basin formed at the junction between these two faults (Youngman, 1989). If right-lateral motion occurred along the former Coast Range Thrust along the curved western margin of the Petaluma-Santa Rosa Valley, it would account for some of the compression that produced the Tolay and Meacham Hill reverse faults in the south and the subsidence of the Santa Rosa Valley in the north.
Figure 6. The Mesozoic basement and the Coast Range Thrust.
Legend on following page.
Legend for Figure 6

The Mesozoic basement and the Coast Range Thrust.

Franciscan Complex

Great Valley Sequence

Other areas covered by Cenozoic deposits.

Exposed trace of the Coast Range Thrust. Teeth are on the upper plate.

Proposed trace of covered Coast Range Thrust. Teeth are on the upper plate.

Several researchers have proposed that the Miocene and Pliocene deposits of the Petaluma Valley correlate with those of the Contra Costa basin east of San Francisco Bay and the Hayward Fault (e.g. Fox et al., 1985, Liniecki-Laporte and Andersen, 1988, and Youngman, 1989). The Contra Costa Group includes the sedimentary Orinda, Siesta, and Mulholland Formations and the Grizzly Peak Basalt and the Bald Peak Basalt. The lower Contra Costa Group interfingers with the marine San Pablo Group to the east (Graham et al., 1984). The Contra Costa Group and the Petaluma Valley formations are lithologically similar and they were deposited contemporaneously. However, it has not been shown conclusively whether or not the two basins were geographically juxtaposed and if the formations were interfingered during deposition.
REFERENCES


CORRELATION OF ROCK UNITS

Approximate Age (myr)

4.0 —

2.0 —

1.5 —

UNCONFORMITY

2906

Lower part of Carelia Volcanics

2015

Older part of Carelia Volcanics

3.5 —

Sand and gravel of Glacial

3.0 —

UNCONFORMITY

2015

Lower part of Carelia Volcanics

2906

Older part of Carelia Volcanics

3.5 —

Sand and gravel of Glacial

4.0 —

5.0 —

Bivins Cave Formation

5.5 —

UNCONFORMITY

6.0 —

GHC-650

6.5 —

GHC-650

7.0 —

SP-1

7.5 —

GHC-650

8.0 —

8.5 —

9.0 —

9.5 —

10.0 —

10.5 —

11.0 —

11.5 —

12.0 —

12.5 —

13.0 —

13.5 —

14.0 —

Age scale not extended to older rocks

LOWER TERTIARY

Miocene

Tertiary

Cretaceous

Jurassic

Quaternary
Gravity Interpretation of San Pablo Bay and Vicinity

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Introduction

As a follow-up to Standard Oil Company's Bethlehem #1 (sec. 19, T2N, R4W), oil discovery in early 1969, a semi-detailed analysis of existing high quality gravity and aeromagnetic data was undertaken. Surface geology, well data, and seismic information -- both onshore and offshore -- were incorporated to produce a reasonable and compatible interpretation of Tertiary regional structural-stratigraphic relationships in San Pablo Bay and to the north and northwest (Figure 1). With minor local revisions and additions, this article is condensed from that study (Smith, 1969), and may stimulate new ideas for the major structural architecture of the region.

Figure 1. Index map, showing area studied (outlined). Abbreviations: BMF=Burdell Mountain fault, BVF= Bennett Valley fault, C=Calistoga, Cf=Carneros fault, Cdf=Cordelia fault, Ff= Franklin fault, Hf= Healdsburg fault, LB=Lake Berryessa, M=Martinez, Mf=Maeacama fault, N=Napa, O=Oakland, P=Petaluma, Pf= Pinole fault, R= Richmond, Sb= Sebastopol, Sbf=San Bruno fault, SC= Sgf=Seal Cove-San Gregorio fault, Sf=Southampton fault, SF=San Francisco, So=Sonoma, SRa=San Rafael, SRo=Santa Rosa, TF=Tolay fault, WNfz= West Napa fault zone.

Gravity and Aeromagnetic Interpretation

The 1960's were the "golden age" of potential geophysical methods at Chevron. Shipboard, bottom meter, and conventional onshore gravity metering, along with both airborne and occasional ground magnetometer surveys, were often conducted concurrently. Rigid procedures for collection and reduction of data were conscientiously monitored.
At the same time research was being pursued within the company via computer modeling in large part, to recognize and isolate on Bouguer and gamma contour maps significant measurable parameters directly related to "geologic" events. Such information as section thickness; fault trace, dip, and throw; as well as the location of subsurface sedimentary truncations and overlaps, was thus obtainable from high quality surveys in many cases.

Although many earth scientists contributed to these advances, most notable were R. R. Clawson and R. D. Hovey. Geologists with past experience in regional stratigraphic projects were found to make the best interpreters after several months of formal and "workshop" training.

In areas where abundant surface folds and faults are encountered, gravity mapping can be particularly helpful to sort out minor and surficial structures from the major ones, perhaps basement controlled. This is because of the gravity meter's penchant for "smoothing" shallower geologic events --- a benefit in this area, the writer believes.

Gravity Control: Sonoma - San Pablo Bay

The 1967 San Pablo Bay gravity data (Plate I, Bouguer gravity map) consists of 568 bottom-meter stations and bases at 1/4-mile intervals along NE-SW lines spaced 1/2-mile apart. A Model H underwater gravity meter and positioning from fixed onshore triangulation stations were used. PhotoGravity Company, Inc., the contractor, also surveyed nearly 2400 onshore stations. Mudflat and shallow-water readings were obtained by conventional meters in small motorboats or by helicopter. All data were tied and reduced to a sea-level datum. This detailed coverage extended both north and south of the bay, beyond the cities of Sonoma and Napa to the north, but not reaching the city of Petaluma in a northwest direction. Beyond these limits, published State of California gravity control was utilized (but was not converted to the PhotoGravity base value). To eliminate negatives, all final values have had a +1000 milligal figure algebraically applied.

Aeromagnetic Control

In 1966, contractor Lockwood Kessler and Bartlett flew an airborne magnetometer survey of the entire study area at an elevation of 2,000 ft ASL with northeast-southwest cross-lines spaced one mile apart and northwest-southeast tie-lines spaced at six miles. The flight lines traversed the entire length of the San Pablo trough, tying to Franciscan basement both to the northeast and southwest and seven miles below Pinole Point to the southeast.

Within the study area only the Tertiary volcanic series and ultramafic units within the Mesozoic basement have adequate magnetic susceptibility to be recognized on the gamma contour map (not included with this report). Rock sampling of cores and outcrop verifies that metasedimentary units of Franciscan basement consistently have little to no magnetic signature here and generally throughout western California. The magnetic control here has been of some assistance in tracing volcanic distribution and locating possible faulting. Almost certainly, further study of the magnetic data could yield useful geologic information.
Rock Column Density

Since most quantitative depth, throw, or thickness information obtained from gravity surveys is only as good as known density values of, and significant density contrasts within, the local rock column, compilation of these data from surface samples, well cores, and formation density logs must precede any geologic interpretation. Representative values for the San Pablo are shown in the accompanying density chart (Figure 2).

<table>
<thead>
<tr>
<th>GEOLOGIC UNIT</th>
<th>DENSITY IN g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.90</td>
</tr>
<tr>
<td>PLIOcene &amp; RECENT</td>
<td></td>
</tr>
<tr>
<td>PLEISTOCENE</td>
<td></td>
</tr>
<tr>
<td>VOLCANIC SERIES</td>
<td></td>
</tr>
<tr>
<td>EOCENE - PALEOCENE</td>
<td></td>
</tr>
<tr>
<td>UPPER CRETACEOUS</td>
<td></td>
</tr>
<tr>
<td>LOWER CRETACEOUS</td>
<td></td>
</tr>
<tr>
<td>FRANCISAN BASEMENT</td>
<td></td>
</tr>
</tbody>
</table>

* Based on 5 Formation Density Logs
** Based on 2 and 6 Well Cores
*** Based on 6 and 16 Well Cores

Figure 2. Density Chart

Noteworthy is the average density for the Tertiary volcanic series, whose high percentage of pyroclastics and interbedded sediments produce a density not too different from other Tertiary beds.

A study of the more than 6,000 ft of so-called "Sonoma Volcanics" from the Tidewater (now Texaco) Noble #1 well, by Craig Lyon (Chevron) in 1966, shows 54% agglomerate, 24% basalt flows, and 22% siltstone. Agglomerate constituents are 70% volcanic, 20% Franciscan basement, and 10% matrix. By applying known density numbers to these constituents, a density for the entire series was calculated to be 2.46 g/cc. This figure is consistent with that for the volcanic interval in the accompanying Formation Density Log for the Chevron Bethlehem #1 well (Figure 3).
Density contrasts of 0.20 g/cc or more are most desirable for mapping geologic trends and permitting mathematical analysis. The chart shows these are common between Franciscan basement and younger Tertiary section.

By a technique called Equigradient Zone Analysis, major geological features (fault zones and stratigraphic cut-outs) that produce horizontal density contrasts were mapped within the San Pablo sedimentary basin. For the sake of clarity these Equigradient Zones have been omitted from the accompanying Bouguer gravity map.
Regional Structure

San Pablo Bay overlies the deepest portion of a linear Tertiary basin extending at least as far north as Santa Rosa and referred to in this report as the San Pablo trough. This feature is bounded on the southwest by the continuous Hayward-Tolay fault zone and on the northeast by the continuous Franklin-Carneros fault zone. These correlations are excellently demonstrated by tracing unbroken Equigradient Zones on the Bouguer gravity map. This trough resembles a sinuous graben (refer to Figure 4, Regional Structural Sketch Map), narrower and more tightly compressed at its south end at San Pablo Bay than at its north end in the Santa Rosa-Sebastopol area. High-angle faults on accompanying structural sections AA' and BB' (Plate II) show the effects of this compression.

A semi-continuous major anticline or anticlinorium centrally located within the "graben" is expressed by the Matanzas gravity high, the Wildcat Mountain anticline, and the Wildcat Mountain gravity high. Regional synclinal trends flank this mid-basin up-folding: the Sonoma syncline and gravity minimum extension on the northeast and the Santa Rosa gravity low - Tubbs syncline trend on the southwest. It is noteworthy that the three most prominent fold structures along the south shore of San Pablo Bay are the Rodeo syncline, the Pinole anticline, and the Sobrante syncline.

Gravity profile analysis across the Tolay fault 2-1/2 miles southwest of the city of Sebastopol (Figure 5) suggests that with basement rocks (2.65 g/cc) on the "upside" and only Pliocene Wilson Grove sediments on the "downside", fault throw may be on the order of 1900 ft here. The fault plane is probably vertical here and along most of its strike into the Sears Point area. There, however, its lobate trace suggests a low angle of dip for the fault plane, this being further indicated by reported Pliocene sediments at total depth beneath Franciscan rocks in the Chamberlain Cardoza #1 well (Sec. 16, T4N, R5W) which spudded on the west side of the Tolay fault. [FIG 5- FULL PAGE]

Immediately east of the General Crude Fillippini #1 well (Sec. 2, T4N, R5W) gravity calculations on the Carneros fault here suggest 2900 ft of vertical throw. From examination of its gravity character along the entire length of the fault, this may be the maximum throw that occurs.

The Matanzas gravity high (Figure 6) is a positive anomaly of 13.5 milligals amplitude, believed to be caused by a large anticline or anticlinorium. Supporting this interpretation is the presence, over the gravity maximum, of an aeromagnetic minimum anomaly. Such gravity-maximum/magnetic-minimum association commonly results over a shallow uplift of non-magnetic but high-density basement rock.

Along a structure section (not included) striking N50E through the Santa Rosa Exploration Company's Stevens-Rohnert #11 (Sec. 26, T6N, R8W) and crossing the Matanzas gravity high, gravity calculations suggest Franciscan basement to be at 8,200 ft subsea beneath this well and at 3,800 ft subsea on the crest of the anticline causing the Matanzas high. Additional gravity calculations of depth to "density basement" within the San Pablo trough are compatible with a regional southeast basin plunge into San Pablo Bay. In the vicinity of the city of Sonoma, basement may be at 13,000 ft, at the location of the Fillippini well at 16,000 ft, and in the San Pablo Bay deep possibly as much as 25,000 ft. Because of the density assumptions accuracy can easily vary by 10% plus or minus.
Regional structural sketch map. Abbreviations as in Figure 1 plus: Hf=Hayward fault, Kfu=outcrop of Cretaceous undifferentiated, KJf=outcrop of Franciscan basement, MGH=Matanzas gravity high, PA=Pinole anticline, RCF=Rodgers Creek fault, RS=Rodeo syncline, SRL=Santa Rosa gravity low, SB=Soberanes syncline, SS=Sonoma syncline, TS=Tubbs syncline, WMA=Wildcat Mountain anticline, WMH=Wildcat Mountain gravity high.

\[ g_z = 11 \text{ mgals} \]

**Formulas:**

\[ G = 12.77 \sigma t \], where \( G \) = gravity relief, \( \sigma \) = density contrast across fault, \( t \) = throw

**CASE I:** Section on downside of fault is only Qs and Tps (1.80 and 2.20 g/cc)

Then  \( \sigma = KJF \ 2.65 - TQs \ 2.00 \) or 0.85

\[ t = \frac{11}{12.77 \times 0.65} = 1.3 \text{ kilofeet or 1300 feet} \]

**CASE II:** Section on downside of fault is Tps only (2.20 g/cc).

Then  \( \sigma = KJF \ 2.65 - 2.20 \) or 0.45

\[ t = \frac{11}{12.77 \times 0.45} = 1.9 \text{ kilofeet or 1900 feet} \]

**Conclusion:** Additional geologic field evidence could indicate which of these figures is more compatible. The writer favors CASE II.

Figure 5. Analysis of gravity profile 2.5 miles southwest of Sebastopol.
Figure 6. Geologic model, Matanzas high, San Pablo trough

A northeast-southwest-striking lineament or interruption is discernable on both the Bouguer and gamma contour maps crossing the north end of the San Pablo trough just north of Sebastopol and Santa Rosa. Since it apparently does not affect Tertiary outcrop, it may represent an old inactive basement break.

The Rodgers Creek fault has no obvious or persistent expression on the gravity and aeromagnetic contour maps examined by the writer. If identical lithologies occur on either side of the fault zone, little if any lateral density and magnetic susceptibility contrast would be expected. Surface geology and well data seem most dependable for tracing this fault, but detailed gravity metering might be helpful over its northern extension.

Stratigraphic Distributions

The gravity relief within the regional San Pablo trough minimum is caused by Cretaceous sedimentary section as well as Cenozoic rocks, since they too have density contrast with Franciscan basement (refer to density chart, Figure 2). Lower Cretaceous strata may be as thick as 10,000 ft beneath Tertiary section in the Sonoma syncline. The approximate regional subsurface distribution of Upper
Cretaceous rocks appears to be fairly well recorded by the upper limit of a 10-to-12-milligal equipotential zone traceable from the actual outcropping of the Upper and Lower Cretaceous contact near Vallejo, northwestward through the Filippini well (Figure 7), southwestward across Sears Point, and southeastward along the west side of the Hayward fault in San Pablo Bay. Earlier gravity modeling by R. B. Kraetsch showed that Upper Cretaceous beds could thicken 6,500 ft southward between the Haire and Cullinan wells and produce this equipotential zone.

![Diagram](image)

Figure 7. Structural model through General Crude wells, San Pablo Sloughs.
(Note: Total Cretaceous thickness from outcrop, gravity calculations, and seismic data)

From their outcrop along the west side of the Carneros fault east and north of Sonoma, and their occurrence in the Cullinan, Haire, and Filippini wells in the Sonoma low, lower Miocene rocks are believed to extend westward to underlie the volcanic rocks on the Matanzas and Wildcat Mountain structural high trends.

The middle Tertiary volcanic series and equivalents have blanket distribution within the study area except where truncated and overlapped by late Pliocene to Recent deposits both north and west of General Crude’s Cullinan #1 well (sec 5, T3N, R4W) in the south end of the Sonoma low. A narrow gravity equipotential zone extending 8 miles southeast from the well location to volcanic outcrop on the north flank of the Rodeo syncline seems to record the volcanic cut-out there. Well data shows that the volcanic rocks vary in thickness from approximately 1500 ft to nearly 6000 ft. These greater thicknesses seem to be preserved in the synclinal trends or "lows" where high-amplitude aeromagnetic maximum anomalies occur as a result.
Recommendations For Further Gravity Study

1. Subject all cross-basin structure sections (tied to basement outcrop at both ends) to two-dimensional modeling.

2. Extend the detailed gravity surveying northwestward to include the Healdsburg area, with adequate tie-lines to Franciscan basement outcrop.

Acknowledgments

Appreciation is due to Chevron U.S.A., Inc., for release of geophysical and well data utilized in this study.

Reference Cited

High resolution geophysical profiling in San Pablo Bay: Visualization of young faulting and structure

P.L. Williams, R. J. Anima

Introduction. The bay and river waters of the Bay Area provide a unique marine path across the primary faults of the region along which shipboard geophysical surveys can be conducted. As part of BASIX (the Bay Area Seismic Imaging eXperiment) high resolution marine seismic reflection profiles were acquired across the Hayward fault and the major gravity low in San Pablo Bay Bay. The high-resolution data have allowed us to construct new maps of remarkable deformation features within the upper 5 to 150 meters of sedimentary material. Geological structure imaged in the high-resolution exercise includes folds and faults that heretofore were unknown. This is a cooperative effort. The principal cooperating institutions are: the Seismographic Station at the University of California, Berkeley, the Lawrence Berkeley Laboratory (UCB/LBL), the U.S. Geological Survey (USGS), and Stanford University. The project is funded by the USGS, the National Science Foundation, and the California Department of Transportation (CALTRANS). The experiment addresses important societal concerns in the understanding and mitigation of seismic hazard in the Bay Area, and it was possible because of special congressional appropriations following the Loma Prieta earthquake of 1989.

High resolution field methods. The initial BASIX high resolution data were "piggy-backed" on the USGS-funded portion of the BASIX program. The S.P. Lee deployed a four-plate Uniboom system. Those data were recorded on graphic recorders and analog tape. A second high resolution BASIX cruise, funded by NSF and CALTRANS, was conducted by the USGS research vessel David Johnston (DJ). Use of the DJ provided access to shallower water (3' draft), allowing us to substantially increase the area of high resolution track coverage. A single plate Geopulse system and a 5 cubic inch air gun were alternately deployed on the second cruise. Single channel reflection data from both of these sources were recorded digitally.

Investigation of the San Pablo Bay area. High-resolution tracklines in San Pablo Bay crossed the entire width of the bay in order to investigate all major fault-projections into the bay (Figure 1). The BASIX surveys imaged west-dipping Plio-Pleistocene (?) strata (Figure 2) beneath the eastern half of San Pablo Bay. Gravity mapping shows a dramatic low density zone bounded on the west by the Hayward fault (Roberts et al. 1991, Wright and Smith, 1992). The east side of the low density zone extends to the eastern edge of San Pablo Bay and well to the north. The anomaly appears to be fault bounded at its northeastern extent by the
West Napa fault. The west-dipping Plio-Pleistocene (?) strata coincide with gravity contours along the eastern side of the anomaly (Figure 3). We interpret the west-dipping beds to be the eastern limb of a large basinal feature, the San Pablo basin. The eastern hinge of the basin is well resolved by transition from relatively steep west-dipping to relatively flat bedding at the southeastern corner of San Pablo Bay. We interpret the west-dipping beds to be the east limb of a large pull-apart complex associated with right-stepping transfer of strike-slip deformation from the Hayward fault to the Rogers Creek and West Napa faults. Wright and Smith (1992) show that San Pablo Basin is a Tertiary compressional feature. We suggest on the basis of fault geometry, and the subsidence of Plio-Pleistocene (?) strata, that the modern San Pablo Basin is an extensional feature.

A prominent north-trending fault is imaged on BASIX track line 108W ("major growth faulting," Figure 2). This fault lies near the intersection of projections of the Rogers Creek and Pinole faults and thus suggests a fault connection between these structures. Is the Pinole fault active? These new data do suggest the Pinole, or a fault closely associated with it, is involved in the evolution of the San Pablo basin. Growth features of the newly imaged fault extend upward to Holocene (?) strata (Figure 2). Active faulting in this location was not anticipated, and the fault’s presence merits a rethinking of the mechanisms by which slip is transferred between the Hayward and Rogers Creek faults.

On the basis of the evidence of young faulting presented here, and the gravity data of Roberts et al. (1991) and Wright and Smith (1992), we suggest that there is not a simple fault connection between the Hayward and Rogers Creek faults, but rather a wide and complex right-stepping zone of dextral slip that includes the Pinole and West Napa faults. The well-defined gravity inflection that passes between the Pinole fault and the West Napa fault indicates that a fault connection between these faults is likely. If verified, this complex right-stepping fault system presents a broader zone of tectonic hazard than previously appreciated.

To date, we have not been able to associate a particular zone of faulting or any other deformation to the projected Hayward fault crossing. A broad zone of small fractures or "blocky structure" surrounds the Hayward and some of these features may be primary faults; others may result from a combination of primary tectonic faulting and lateral spreading associated with strong ground motion in previous large earthquakes.

Summary of high resolution fault studies. The goals of the high resolution studies in BASIX included investigation of the pattern of deformation around the Hayward - Rogers Creek fault step. Initial interpretations of the high resolution data indicate the presence of active faulting in eastern San Pablo Bay, possibly linking the Rogers Creek and Pinole faults, but on the basis of high quality gravity data, the newly resolved faulting may link the Pinole
with the West Napa fault. The fault is located on the western portion of a broad west-dipping Plio-Pleistocene (?) monocline.

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Figures

Figure 1. Figure 3. High resolution track lines in San Pablo Bay with interpreted structures. The region of west facing monoclines are interpreted to be the east limb of a large pull-apart complex created by distributed strike-slip faulting. A possibly active fault was imaged at the location of the projected intersection of the Rogers Creek and Pinole faults. No distinct break was imaged in the region of the Hayward Fault, but rather a region of blocky structure which may be due to a combination of faulting and lateral spreading.

Figure 2. BASIX High Resolution profile across eastern San Pablo Bay. To the east are west-dipping Plio-Pleistocene (?) strata coincident with westward decrease of isostatic residual gravity towards the middle of San Pablo Bay. The west-dipping beds appear to be the east limb of a large pull-apart complex associated with distributed strike-slip faulting. A prominent fault is also imaged on the west edge of the Figure. Subsequent profiling of this fault indicates offset of Holocene beds. This fault lies near the intersection of projections of the Rogers Creek and Pinole faults and thus suggests a structural connection between these faults.

Figure 3. Gravity mapping across the East Bay fault zone by Roberts et al. (1991). Note the dramatic low gravity region bounded on the west by the Hayward fault and on the east by a hypothetical connection between the Pinole and West Napa faults.
Figure 1. High resolution track lines in San Pablo Bay with interpreted structures. The region of west facing monoclines coincides with a decrease of isostatic residual gravity toward the center of San Pablo Bay. The west facing monoclines are interpreted to be the east limb of a large pull-apart complex created by distributed strike-slip faulting. A possibly active fault was imaged at the location of the projected intersection of the Rogers Creek and Pinole faults. No distinct break was imaged in the region of the Hayward Fault, but rather a region of blocky structure which may be due to a combination of faulting and lateral spreading.
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Figure 3. Gravity mapping across the East Bay fault zone by Roberts et al. (1991). Note the dramatic low gravity region bounded on the west by the Hayward fault and on the east by a hypothetical connection between the Pinole and West Napa faults.
STRATIGRAPHY AND STRUCTURE
OF THE SOUTHERN SONOMA VOLCANIC FIELD,
SONOMA COUNTY, CALIFORNIA

by

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ABSTRACT

Previous attempts to determine the stratigraphic and structural relationships in the southern Sonoma volcanic field, north of San Pablo Bay in southern Sonoma County, were hampered by a poor understanding of the ages of the rock units and by mistaken interpretations of map patterns. A revised structural interpretation of this area has been made based on detailed mapping combined with lithologic, petrographic, and radiometric analyses.

The formations within the study area include the Donnell Ranch Volcanics, the sedimentary Petaluma Formation, and the Sonoma Volcanics. The right-lateral strike-slip Rodgers Creek fault bisects the study area. Several previously unrecognized thrust faults, interpreted as flower structures, occur on both sides of the Rodgers Creek fault, and may be near-surface low-angle segments of the Rodgers Creek fault. These tectonic contacts were previously interpreted as depositional unconformities, and the Donnell Ranch Volcanics west of the Rodgers Creek fault were identified as Sonoma Volcanics by earlier investigators.

The reinterpreted stratigraphic and structural relationships in the study area suggest that the Late Cenozoic tectonic history of this area has involved transpressional deformation along the Rodgers Creek fault zone.

INTRODUCTION

Late Miocene and Pliocene sedimentary and volcanic rocks in the central and northern Coastal Ranges of California occur in a structurally complex region influenced by numerous strands of the San Andreas fault system. The San Andreas system includes the Hayward fault east of San Francisco Bay and the Rodgers Creek, Tolay, and Healdsburg faults north of San Pablo Bay. Structural analyses of the Late Tertiary formations in the Coast Ranges allow an assessment of the various modes of deformation associated with the evolution of the San Andreas system.

The Sonoma volcanic field, cut by the Rodgers Creek fault in the study area, has been studied by numerous investigators (e.g., Osmont, 1905; Dickerson, 1922; Morse and Bailey, 1935; Weaver, 1949; Cardwell, 1958; Cebull, 1958; Mankinen, 1972; Fox, 1983). However, due to the presence of lithologically similar Late Miocene volcanics on opposite sides of the Rodgers Creek fault, a paucity of radiometric dates, and previous misinterpretations of structural and stratigraphic relationships, the detailed structure of the southern Sonoma volcanic field remained unresolved. Such knowledge is critical to understanding the structural evolution of the region.

In order to determine more accurately the stratigraphic and structural relationships present in the southern Sonoma volcanic field, detailed field mapping was undertaken and supplemented with lithologic, petrographic, and radiometric analyses (Youngman, 1989). The new radiometric data are consistent with the age-data of Fox et al. (1985), which show a significant difference in the ages of compositionally similar volcanic rocks across the Rodgers Creek fault. A revised structural interpretation suggest a more
complex tectonic regime exists in this region than was previously recognized (Youngman, 1989) (see Geologic map)

STUDY AREA

The Sonoma volcanic field occupies an area 70 km long and 35 km wide northeast of San Francisco Bay. Three large northwest-trending ridges occur in the southern portion of this field; the western Sonoma Mountains, the central Mount Veeder area, and the eastern Mount Georges area. Broad alluvial valleys separate these ridges.

A 32 square km area of the southern Sonoma volcanic field in the Coast Ranges of Sonoma County was selected for detailed study (Figure 1). The study area includes part of the Sears Point and Petaluma 7.5' quadrangles.

Late Tertiary units outcropping in the study area include the sedimentary Petaluma Formation, the Sonoma Volcanics, and the Donnell Ranch Volcanics (regarded as Tolay Volcanics by Fox et al., 1985). Although the underlying basement rocks do not outcrop in the mapped area, they are presumed to be the Mesozoic Franciscan Complex inasmuch as this unit is exposed nearby, west of the Tolay fault. The Rodgers Creek fault, a major strand of the San Andreas fault system, cuts through the study area.

VOLCANIC ROCK UNIT NOMENCLATURE

Earlier workers mapped all of the volcanics exposed in the region northeast of San Francisco Bay as belonging to the Sonoma group, and they considered these volcanics to be younger than the Petaluma Formation (Osmont, 1905; Dickerson, 1922). Subsequently, Morse and Bailey (1935) discovered a thick sequence of volcanics overlain by Petaluma sediments in a well core and named them the Tolay volcanics. Although Morse and Bailey (1935) mapped outcrops occurring west of Tolay Creek as Tolay volcanics, Weaver (1949) kept the earlier designation of Sonoma Volcanics for all volcanics in the area, and described the Tolay volcanics as "subsurface volcanics". This usage was continued by other workers until Mankinen (1972) demonstrated that volcanics in the Burdell Mountain area are much older than those to the northeast and designated the older rocks as Tolay Volcanics. Fox et al. (1985) followed this precedent and, on the basis of age differences which appeared to coincide with the southern Rodgers Creek fault trace, assigned older volcanics outcropping west of the fault to the Tolay Volcanics.

The volcanics outcropping between the Rodgers Creek and Tolay faults were redesignated as the Donnell Ranch Volcanics by Youngman (1989) because of age differences distinguishing them from the Tolay volcanics of Fox et al. (1985) that occur west of the Tolay fault. In addition, a different name was warranted because these volcanics do not meet the stratigraphic criteria for the Tolay Volcanics established by Fox et al. (1985), and they probably have a different source or a different mode of emplacement than the Tolay Volcanics west of the Tolay fault (Youngman, 1989).

Volcanic rocks outcropping east of the Rodgers Creek fault were mapped as Sonoma Volcanics by Youngman (1989). Although distinguishing between the Sonoma and Donnell Ranch Volcanics in the field is difficult, the Sonoma Volcanics are generally younger than the Donnell Ranch Volcanics. The two units differ geochemically, as well (Youngman, 1989).

TOLAY VOLCANICS

The Tolay Volcanics were first described and defined by Morse and Bailey (1935), who recognized this unit in well cores from the Petaluma Valley region. They stated that these volcanics consist of basalts, andesites, dacites, breccias, tufts, and agglomerates, and reach thicknesses of more than 1220 m in some places. Well core data indicate that the Tolay Volcanics grade upward, through a transition zone of interbedded volcanics and olistostromal shales, into the Petaluma Formation. Although the base of the volcanics was never reached during drilling, Morse and Bailey (1935) assumed that the Tolay Volcanics rest on Franciscan basement. Fox et al. (1985) assigned volcanic rocks that are "directly
overlying the Franciscan Complex or Great Valley sequence and that are overlain by the Wilson Grove or the Petaluma Formations* to the Tolay Volcanics.

West of the Tolay fault, dates from the Tolay Volcanics range from 13.62 to 11.75 Ma (Fox et al., 1985), and are Middle Miocene in age. Although volcanics outcropping between the Rodgers Creek and Tolay faults are younger, with dates ranging from 10.64 to 8.52 Ma, Fox et al. (1985) designated them as Tolay volcanics as well. Dates obtained by Youngman (1989) on rocks outcropping between the Tolay and Rodgers Creek faults are consistent with those compiled by Fox et al. (1985)

DONELL RANCH VOLCANICS

The volcanics outcropping between the Tolay and Rodgers Creek faults are younger than the Tolay Volcanics west of the Tolay fault. In addition, Youngman (1989) determined that the relationship of the volcanics and the Petaluma Formation between the Tolay and Rodgers Creek faults differs from the stratigraphic criteria proposed by Fox et al. (1985) for their Tolay Volcanics. Due to the variance in age and stratigraphic relationship, the volcanics between these two faults have been renamed as the Donnell Ranch Volcanics (Youngman, 1989).

In the study area, olivine basalts and basaltic andesites are the predominant lithologies of the Donnell Ranch Volcanics. Lesser amounts of dacitic to rhyolitic flow material of the Donnell Ranch Volcanics occur on both sides of the Rodgers Creek fault. These exposures outcrop as crudely shaped masses with poorly defined surfaces between individual flows. Generally, they are blocky, with boulders up to 2 m across, although often they appear to consist of breccias with angular fragments averaging 2 to 5 cm in diameter. A small outcrop of rhyolitic tuff also occurs within the Donnell Ranch Volcanics west of the Rodgers Creek fault in the study area.

Radiometric dates obtained by Youngman (1989) from the Donnell Ranch Volcanics between the Rodgers Creek and Tolay faults in the study area generally range from 10.64 to 8.24 Ma, and include a younger age of 7.37 Ma (Figure 2). These age-data are in good agreement with those of Fox et al. (1985) for their "Tolay Volcanics" outcropping between the Rodgers Creek and Tolay faults. They presented ages from volcanics exposed between the southern traces of the two faults that range from 10.64 to 8.52 Ma (Figure 2). East of the Rodgers Creek fault, the Donnell Ranch Volcanics are dated as young as 7.04 Ma. All are Late Miocene in age. In contrast, west of the Tolay fault, radiometric dates for the Tolay Volcanics range from 13.62 to 11.75 Ma, and are Middle Miocene in age (Fox et al., 1985).

The stratigraphic relationship of the Donnell Ranch Volcanics with the Petaluma Formation in the study area is complex. Weaver (1949) mapped all surface volcanics as Sonoma Volcanics, and interpreted them as depositionally unconformable over the Petaluma Formation. Cebull (1958) agreed with Weaver's (1949) interpretation. Subsequently, Youngman (1989) determined that the contact of the Donnell Ranch Volcanics with the underlying sediments is tectonic rather than depositional. Evidence for this interpretation is presented later in this paper.

PETALUMA FORMATION

The Petaluma Formation is a sedimentary unit of continental origin and includes clays, clay shales, sands, sandstones, and conglomerates. Dickerson (1922) first used the name in describing an outcrop near Petaluma Creek. Although the clay-rich portion of this formation is quite erodable, most outcrops consist of somewhat resistant, discontinuous beds of sandstone and coarse gravels. Previous investigators have estimated the total thickness of the Petaluma at between 915 and 1220 m (Morse and Bailey, 1935; Weaver, 1949).

The Petaluma Formation in the study area outcrops west of the Rodgers Creek fault. The sediments are predominantly clays and clay shales with subordinate amounts of sand, sandstone, and conglomerate. The shales occasionally contain ostracods. Limestone beds and lenses occur locally. Exposures of this unit are poor, and soil characteristics (e.g., color, clay content, clast composition) were thus relied upon in mapping much of the Petaluma Formation (Youngman, 1989).
In the study area, sands and conglomerates of the Petaluma Formation were observed west of Wildcat Mountain as well as just west of the contact between the Petaluma and the volcanics in the northernmost map region. Continuous sandstone beds are rare; this facies usually occurs as lenses within the clays and clay shales. Conglomerates are the least abundant of the clastic sediments in the study area. Like the sandstone facies, the conglomerates occur mostly as lenses within the Petaluma clays and clay shales, and are often poorly-consolidated. Clasts, often well-rounded, are generally 2 to 5 cm in diameter but may be as large as 12 cm. They vary in lithology and include siliceous shale, red chert, graywacke sandstone, and occasional blueschist; lithics of mafic volcanics are locally abundant.

Beds of limestone, which vary from less than 2 to nearly 30 cm thick, are commonly interbedded with the clays and clay shales. Some of the limestone contains abundant ostracods. Near the western contact of the Donnell Ranch Volcanics and the Petaluma Formation in the southwestern part of the study area, tectonically disrupted limestone beds appear to be highly siliceous. Where observed in stream cuts and gullies, the interbedded limestone and clay shale are complexly folded and faulted.

Morse and Bailey (1935) divided the Petaluma Formation into upper and lower units. They stated that the Lower Petaluma consists of laminated dark clay shales, thin sands, and thin beds of gray limestone, with the Upper Petaluma composed chiefly of indistinctly bedded clays with thick lenses of poorly-sorted fluvial sands and gravels. In the study area, exposures containing intercalated limestone and clay shale are common in the region west of the Donnell Ranch Volcanics in the southern half of the map area, and may correspond to the Lower Petaluma unit of Morse and Bailey (1935). Sandstones and conglomerates, which most commonly outcrop in windows of the Petaluma Formation as well as west of the Rodgers Creek fault near hill 434 in the northern study area, may represent Morse and Bailey's Upper Petaluma.

The presence of abundant ostracods, dark colored shales, and limestone beds suggested to many workers that depositional environments of the Lower Petaluma included freshwater lacustrine, fluviatile, estuarine, and lagoonal conditions (Osmont, 1905; Morse and Bailey, 1935; Weaver, 1949; Cebull, 1958; Axelrod, 1971; Berkland, 1971; Davies, 1986; Liniecki-Laporte and Andersen, 1988). Many of these investigators surmised that the depositional basin was either indirectly open to the sea or, perhaps, closed and occasionally inundated by brackish waters. It appears that the basin in which the lower and upper units of the Petaluma Formation accumulated had subsided to near sea level and was occasionally penetrated by brackish water. Over time, this basin gradually filled in and progressed to a more fluvial environment.

The age of the Petaluma Formation, as constrained by radiometric dates and fossil evidence, extends from the late Middle Miocene to the mid-Pliocene. Potassium-argon and fission-track dates on tuffs from three locations within the Petaluma Formation surrounding the study area range from 11.33 to 5.77 Ma (Fox et al. 1985). The presence of Neohipparion gidleyi (Hemphillian) and of Equus (early Blancan) horse teeth indicate a Late Miocene to Early Pliocene age (Davies, 1986). Fossil flora collected by Davies (1986) were identified as "probably Clarendonian" and are upper Middle Miocene or lower Upper Miocene in age.

SONOMA VOLCANICS

The Sonoma Volcanics consist of a highly complex group of lava flows and flow breccias, agglomerates, tuffs and tuff breccias, and tuffaceous continental sediments. The name was taken from the Sonoma Mountains where exposures of this unit are abundant. The name "Sonoma volcanics" was first published by Morse and Bailey (1935), and has been retained by subsequent workers (e.g., Weaver, 1949; Cardwell, 1958; Cebull, 1958; Fox, 1983; Davies, 1986).

The lithology of the Sonoma Volcanics varies quite markedly. In the study area, this formation includes flows, tuffs, and breccias that range from basaltic to rhyodacitic in composition. Pyroxene andesite is the predominant lithology of the Sonoma Volcanics in the map area, and basaltic andesites are subordinate. Dacitic to rhyolitic tuffs are the least abundant volcanic rock type in the study area.

In the past, the age of the Sonoma Volcanics in the study area was considered as Pliocene or younger (Weaver, 1949; Cebull, 1958). This age assignment was based on the following: 1) all of the volcanics in the study area were regarded as Sonoma Volcanics; and 2) the contact of the "Sonoma"
volcanics, west of the Rodgers Creek fault, with the underlying Petaluma Formation, of presumed Late Miocene to Early Pliocene age, was interpreted as a depositional unconformity. However, it is now recognized that the volcanics west of the southern Rodgers Creek fault represent a different volcanic unit (Fox et al., 1985; Youngman, 1989). In addition, the contact of the volcanics and the Petaluma sediments just west of the Rodgers Creek fault is probably tectonic rather than depositional unconformable, and it is not known what lies below the Sonoma Volcanics east of the Rodgers Creek fault in the study area (Youngman, 1989). K-Ar and fission-track radiometric dates from the Sonoma Volcanics in the study area, which occur east of the Rodgers Creek fault, range from 7.28 to 5.81 Ma, or Late Miocene in age (Fox et al., 1985; Youngman, 1989) (Figure 2). A single K-Ar date of 3.80 Ma may extend the age of the Sonoma Volcanics in this area to Early Pliocene. Beyond the study area, radiometric dates indicate that the Sonoma Volcanics are Late Miocene to Late Pliocene in age (Fox et al., 1985; Youngman, 1989).

Comparison with the Donnell Ranch Volcanics

Although the Donnell Ranch and Sonoma Volcanics are not easily distinguishable in outcrop, general lithologic differences are recognized between the two units within the study area (Youngman, 1989). The Sonoma Volcanics east of the Rodgers Creek fault consist mostly of hypersthene-augite andesite and lesser basaltic andesite. Mafic and silicic tuffs and tuff breccias and mafic flow breccias are present as well. West of the fault, basaltic andesite and olivine basalt are the predominant lithologies of the Donnell Ranch Volcanics. Dacitic tuffs interbedded with mafic flows are common, and rhyolite tuff is subordinate. Large masses of rhyolite flow material, regarded here as a member of the Donnell Ranch Volcanics, occur on both sides of the Rodgers Creek fault. Exposures of silicic flow material within the Sonoma Volcanics are rare in the study area.

The Donnell Ranch Volcanics and the Sonoma volcanics in the study area overlap slightly in age, although there is an age distinction between similar lithologies in the two units (Youngman, 1989). East of the Rodgers Creek fault, the oldest mafic sample of the Sonoma volcanics was dated at 7.28 Ma (Youngman, 1989), and the youngest mafic flow yielded a K-Ar date of 5.81 Ma (Curtis, unpublished data). West of the Rodgers Creek fault, the oldest date from mafic rocks in the Donnell Ranch Volcanics is 10.64 Ma (Fox et al., 1985), and the youngest dated mafic flow assigned confidently to this unit is 8.24 Ma. In the northernmost study area, mafic volcanics occurring west of the fault have yielded dates of 7.37 and 7.05 Ma (Fox et al., 1985; Youngman, 1989). These outcrops were mapped as Donnell Ranch Volcanics, but available data are not sufficient to assign them conclusively to this unit (Youngman, 1989).

STRUCTURE AND TECTONICS

The Coast Ranges in the San Francisco Bay region are characterized by complex folding and faulting. West of San Francisco Bay lies the San Andreas fault, which is believed to mark the boundary between the North American and Pacific plates. Major right-lateral strike-slip faults in this area associated with the San Andreas fault system include the Hayward, Calaveras, Franklin, and Concord faults east of San Francisco Bay, and the Rodgers Creek, Healdsburg, Bennett Valley, and Maacama faults north of San Pablo Bay. The Tolay reverse fault is located west of the Rodgers Creek fault. Late Cenozoic deposits throughout this region have been intensely folded, producing numerous synclines and anticlines.

FOLDS

Evidence of folding in the study area is present in the Tertiary volcanic and sedimentary units. Deformation has occurred since the late Miocene, as indicated by folding of the Late Miocene Donnell Ranch Volcanics and the Late Tertiary Petaluma Formation and Sonoma Volcanics in and beyond the study area (Youngman, 1989). Beyond the study area, deformed sediments are as young as Pleistocene, and it is believed that similar deformation probably continues today (Fox, 1983).

Folds in and near the study area include the Adobe Creek (A-A', B-B'), Donnell Ranch (F-F', G-G'), Lee Lake (D-D'), and Sears Point anticlines and the Tolay Creek syncline (Figure 3). Weaver (1949)
named the structure in the northwesternmost portion of the study area the Adobe Creek anticline, and Davies (1986) determined that the axis of the anticline generally strikes N 45 W, although it is often offset by faulting. The eastern limb was observed to dip from 43 to 46 degrees NE (Youngman, 1989). The Donnell Ranch anticline has an axial strike which bends from nearly east-west near Highway 121 to approximately N 45 W just east of Wildcat Mountain. The crest of the Donnell Ranch anticline near Wildcat Mountain is indicated by several horizontal beds, and alternating beds of tuffs, flows, and flow breccias in the eastern limb were observed to dip between 24 and 54 degrees NE (Youngman, 1989). A small anticline located east of the Rodgers Creek fault and north-northeast of Lee Lake in the northern study area is named the Lee Lake anticline (Youngman, 1989). The axis of this structure strikes approximately N 20 W, and the western limb appears to dip at slightly greater angles than the eastern limb. The Sears Point anticline is located just south of the study area. Weaver (1949) determined that the axis of this structure plunges to the southeast, south of Sears Point, and undulates in its northwest extension. West of the Adobe Creek anticline, and extending beyond the study area, is the Tolay Creek syncline of Weaver (1949). He stated that numerous small faults and folds, largely obscured by soil, complicate this structure. In the study area, the Tolay Creek syncline may extend southward into the window of Petaluma sediments just west of Wildcat Mountain (Youngman, 1989).

FAULTS

Numerous faults are present in and near the study area. The right-lateral strike-slip Rodgers Creek fault, locally trending N 35-40 W, is the major fault structure in the study area. To the southwest, the Tolay reverse fault roughly parallels the southern Rodgers Creek fault for a short distance; however, the northern trace of the Tolay fault diverges slightly westward (Huffman and Armstrong, 1980). In addition, several previously unrecognized thrust faults and normal faults were mapped by Youngman (1989).

Strike-Slip and Normal Faults

Late Cenozoic translational deformation along the western margin of North America resulted from the collision of the Pacific-Farallon sea floor spreading center and an Early Tertiary oceanic trench. As a consequence of this oblique convergence, two triple junctions formed. The Mendocino Triple Junction subsequently migrated northward and the Rivera Triple Junction migrated southward. The San Andreas transform connects these two triple junctions. Numerous strike-slip faults related to the San Andreas fault system have displaced late Tertiary formations right-laterally along the western continental margin.

The Rodgers Creek fault is part of the San Andreas fault system, and consists of a zone of braided fault splays (Figure 3). In the study area and elsewhere, this zone is marked by topographic features indicative of active faulting, including sag ponds, scarps, and linear ridges and troughs (Huffman and Armstrong, 1980; Fox, 1983). Fox (1983) proposed that the fault was active during the Late Miocene since he found intrusive rhyolites, about 7 Ma old, nearly coinciding with the fault zone.

The Rodgers Creek fault trends approximately N 40-45 W in the southern study area. Near Gravelly Lake and to the north-northwest, this fault diverges and forms two separate strands trending N 30-35 W and N 40-45 W. Since the trace of the Rodgers Creek fault is fairly linear and cuts uneven topography, it probably has a nearly vertical dip. Within the study area, it generally separates the Sonoma Volcanics to the east from the Petaluma Formation and Donnell Ranch Volcanics to the west (Youngman, 1989). (Cross-Sections A-A' through G-G')

A previously unrecognized normal fault, the Roche-Cardoza fault, occurs between the Rodgers Creek and Tolay faults in the southern study area (Youngman, 1989) (Figure 3) (E-E' & F-F'). The southern trace of this N 65-70 W trending fault joins the Rodgers Creek fault at a prominent bend or asperity in the latter. To the northwest, the Roche-Cardoza fault appears to join the Tolay fault, and may be a high-angle branch or strike-slip splay of the Tolay fault. The linear trace of the Roche-Cardoza fault cuts uneven topography and it is thus probably a high-angle fault. The south side of this fault appears to have been displaced relatively downward. Complexly folded and faulted interbedded clay shale and limestone beds are abruptly terminated in a gully at the contact between the sediments and the volcanics.
along the fault. The Roche-Cardeza fault truncates the Wildcat Mountain thrust fault (F-F''), discussed below, in several locations and the Roche-Cardeza normal fault is thus younger than the Wildcat Mountain thrust fault.

Just north of the Roche-Cardeza fault trace is another linear, apparently high-angle fault which trends N 60 W (Youngman, 1989) and is probably a splay of the Roche-Cardeza fault. The southwest side appears to be displaced relatively downward.

Several other right-lateral or tear faults occur in the study region. Tear faults, commonly marked by transverse strike-slip faults, form as large rock masses are broken into smaller structural units during transport.

West of the Rodgers Creek fault in the southwest study area, the westernmost contact of the Wildcat Mountain thrust fault appears to be offset in two places by the Goose Lake fault (Youngman, 1989). This right-lateral tear fault, trending N 20 E, may best explain the southern offset along the trace of the thrust fault (Figure 3). In addition, the Goose Lake fault separates rocks with markedly different attitudes in the Petaluma Formation. Another tear fault is present northwest of the Goose Lake fault. In this region, an abrupt change in direction of the Wildcat Mountain thrust fault occurs. A tear fault, trending N 55-60 E, may account for the offset and change in direction of the Wildcat Mountain thrust fault in this region (Youngman, 1989).

Two additional faults occur east of the Rodgers Creek fault (Youngman, 1989). The Stefansky fault is located southeast of Goose Lake and trends N 20-25 E (Figure 3). The Stefansky fault separates a bed of dactitic tuff to the northwest from bedded mafic flows, tuffs, and flow breccias to the southeast and is probably nearly vertical. The second fault, the Yenni fault, is located east-northeast of the Stefansky fault (Youngman, 1989). This structure trends approximately N 15 E, and has displaced beds of mafic flows, tuffs, and breccias right-laterally (Figure 3).

**Thrust Faults**

Detailed field mapping in the southern Sonoma volcanic field has led to the recognition of several previously unrecognized thrust faults (Youngman, 1989). These faults display sinuous map patterns, generally have shallow dips, and commonly have structurally juxtaposed older units over younger units. Complex outcrop patterns in places, including klippen and windows, have resulted from the erosion of these thrust sheets. Most of these faults are interpreted as flower structures that were thrust up and out of the Rodgers Creek fault deformation zone. Although the faults are termed thrust faults in this section, most are regarded as low-angle segments of the Rodgers Creek strike-slip fault.

The thrust and reverse faults in the study area include the Wildcat Mountain (A-A' to F-F'), Lee Lake (D-D'), Donnell Ranch (G-G'), Gravelly Lake (D-D'), Gilardi (B-B' & C-C'), and Martinelli (A-A') faults (Youngman, 1989) (Figure 3). West of the Rodgers Creek fault, the Wildcat Mountain thrust fault has emplaced older Donnell Ranch Volcanics over the younger Petaluma Formation. An abrupt change in the direction of the western Wildcat Mountain thrust fault trace is probably the result of tear faulting. Two other thrust faults west of the Rodgers Creek fault in the northwestern study area, the Gilardi and Martinelli thrust faults, have emplaced older rhyolitic masses of the Donnell Ranch Volcanics over younger mafic flows. Three faults occur east of the Rodgers Creek fault. The Donnell Ranch and Gravelly Lake thrust faults, located in the southeast and central study area, respectively, juxtapose rhyolites of the Donnell Ranch Volcanics over younger mafic Sonoma Volcanics. Just north of the Gravelly Lake thrust fault, the steeply-dipping Lee Lake reverse fault is marked by fault breccia.

Cross-cutting relationships in the study area record a complex history of folding and faulting possibly extending over a considerable period of time. The Wildcat Mountain thrust fault is truncated in several places by the Roche-Cardeza normal fault and its northern splay, indicating that the latter faults are younger. The western extent of the Lee Lake fault is truncated by the Rodgers Creek fault, and indicates that the Rodgers Creek fault is the most recently active of the two. The Gravelly Lake thrust fault is truncated to the north by the Lee Lake reverse fault and to the west by the Rodgers Creek fault, which implies that the latter two are younger. To the east, the Gilardi thrust fault is truncated by the Rodgers Creek fault and, to the west, by the Wildcat Mountain thrust fault; therefore, the Gilardi thrust fault is older.
STRUCTURAL REINTERPRETATION

Compressional deformation along the western margin of North America during the Late Cenozoic resulted from the interaction of convergent plates. This deformation is expressed by thrust faulting and associated folding of Late Tertiary and Quaternary rocks in western California.

In zones of convergent strike-slip faulting, Sylvester (1988) has shown that elongate uplifts form as a result of crustal shortening. These uplifts include pressure ridges, long low hills, and small mountain ranges. Laboratory modeling studies of transpressive regimes demonstrate that "an elongate, fault-bounded welt forms above the zone of principal displacement" (Sylvester, 1988). The welt is described by Sylvester (1988) as "bounded by sinuous faults". In addition, he states that the faults "are nearly vertical at depth and flatten upward, carrying parts of the welt short distances outward upon the adjacent, stable blocks". A block diagram (Figure 4) depicts the arrangement of upward and outward branching faults, termed "flower structures" or "palm tree structures", that may result in convergent strike-slip zones (Sylvester, 1988). Surficial traces of faults in convergent strike-slip or transpressive regimes are often sinuous in map view; hence, they are commonly interpreted as thrust faults. However, many of these thrust faults are now recognized as near-surface, low-angle segments of strike-slip faults (Sylvester, 1988).

A similar style of deformation appears to be preserved in the study area. The Wildcat Mountain, Donnell Ranch, Gravelly Lake, Gilardi, and Martinelli thrust faults are interpreted as flower structures or palm tree structures that have resulted from convergent strike-slip motion (Youngman, 1989). In most cases in the study area, the rock units in the upper plates are bounded by sinuous faults, and the fault planes apparently flatten upward.

These tectonic contacts were misinterpreted by earlier workers. Weaver (1949) and Cebull (1958) believed that the contact of the volcanics and the Petaluma Formation in the study area, west of the Rodgers Creek fault, represented a depositional unconformity since the Petaluma sediments are more highly folded than the volcanics and structural relations are discordant. Field and map evidence, supported by radiometric data, indicate that the unconformable contacts of Weaver (1949) and Cebull (1958) are instead tectonic (Youngman, 1989).

The recognition of these thrust faults, which probably represent near-surface low-angle segments of the Rodgers Creek strike-slip fault, is important. The reinterpretation of the stratigraphic and structural relationships in the southern Sonoma volcanic field suggests that transpressional deformation has occurred in the region. Since most of the thrust faults in the study area are apparently the result of compressional strike-slip along the Rodgers Creek right-lateral fault, it is believed that compressional and translational deformation in this region are contemporaneous.

ACKNOWLEDGMENTS

I would like to thank my adviser, Garniss Curtis, and my thesis committee members, Davey Jones and Ted Oberlander, for their contributions to the original research project. The generous permission for access to private land, provided by the landowners and caretakers, was greatly appreciated. The crew at the Berkeley Geochronology Center and personnel in the U.C. Berkeley Geology Department were helpful with laboratory analyses and in providing answers to numerous questions. Discussions with David Kraig, Claudia Lewis, Scot Krueger, Andrei Sarna-Wojcicki, and Fraser Goff were most helpful. Thanks also go to Sharie Shute, my "research assistant", and to Kim Liptak-German and Dean Eppler, who assisted me in the field. Moral support provided by my friends and family was especially important during the trials and tribulations of my masters research while at Berkeley. Special kudos go to Steven Reneau for his constructive review of this paper.
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Figure 1. Location map of study area.

Figure 2. Location map of radiometric dates in the study area. Ages in Ma. Dated samples designated by "PY" presented in Youngman (1989). Remaining samples compiled from Fox et al. (1985) and Curtis (personal communication, 1988)

Figure 3. Locations of geologic structures in and near the study area.

Figure 4. Block diagram depicting upward and outward branching of "flower" or "palm tree structures" (from Sylvester, 1988).

Cross-Sections A-A', B-B', C-C', D-D', E-E', F-F', G-G'
FIGURE 1
QUATERNARY
PETALUMA FORMATION
SONOMA VOLCANICS
DONELLY RANCH VOLCANICS
MAFIC FLOWS AND DACITIC TUFFS
RHYOLITE FLOWS
FRANCISCAN COMPLEX
(INCLUDES COAST RANGE OPHIOLITE)

SOUTHERN RODGERS CREEK FAULT
AND VICINITY

After Youngman (1989) and
Armstrong (1980)
Figure 4. Block diagram depicting upward and outward branching of "flower" or "palm tree" structures. (from Sylvester, 1988)
Possible Evidence for Faulting at the Petaluma Marsh

Laurel M. Collins

Historic margins of the Petaluma Salt Marsh and fluvial design of the Petaluma River have intriguing characteristics that may signify Holocene tectonic influences. A small body of evidence supports the notion that faulting may occur along the eastern portion of the Petaluma Marsh in the vicinity of Hog Island, south of Lakeville. These indicia are offered and discussed herein with the objective of encouraging further research and field investigation.

The possible location of the Hayward fault north of Point Pinole and through San Pablo Bay has interested many scientists concerned with the study of active faulting in the Bay Area. Some early geologists, for example G. K. Gilbert in his writings on the Hydraulic-mining Debris in the Sierra Nevada (1917), depicted the Hayward fault to trend northwestward, just east of the Petaluma River. Because of the present day unresolved disputes over whether the Hayward fault merges or steps right to the Tolay or Rogers Creek faults, more recent geologic maps do not depict the Hayward fault north of Point Pinole. If the Hayward fault is projected as a straight line from Point Pinole northward, it intersects the Petaluma trough and enters the Petaluma Marsh near Hog Island, about km north of the San Pablo Bay (Figure 1).

Geomorphologic study of the Petaluma Marsh combined with geophysical exploration might reveal the nature of secondary faulting near the northern terminus of the Hayward fault. This remnant tidal wetland is about 60% of its former size, due to the extensive diking and reclamation of the land which has altered the extent and pattern of the marsh margins and sloughs, as well as the configuration of the Petaluma River. Detailed maps of the historic marshland must be obtained to effectively evaluate geomorphic features. Comparisons between the 1860 Coast Survey Map of Petaluma Creek and recent aerial photography indicate that the earlier mapping was extremely accurate for all tidal marsh features (Leopold et al., in press; Collins et al., 1987). Nichols and Wright (1971) projected historic tidal margins onto recent cartography. Figure 2 is a modified version of their map. Yet for examination of local geomorphic features, the original maps of the Coast Survey are most useful due to for their high level of detail, Figure 3.

The 1860 Coast Survey maps of Petaluma Creek show an unusual drainage pattern in the vicinity of Hog Island. Clearly evident are the sharply defined angular bend of the river toward the west, a subsiding island tilting downward toward the east with a false bay, and an abandoned reach of the Petaluma River to the south that is filling with sediment and vegetation. These features, in combination, suggest localized effects of regional tectonic activity.
Since the time of the 1860's mapping the angular bend in the river has become much more rounded, suggesting that the angularity depicted in the earlier map may be a relatively fresh feature of that time. The narrowing of the abandoned channel also appears to be a recent phenomena, given the similarity in width between the extant and abandoned channel reaches. One plausible explanation for this configuration of the marsh is that subsidence affected the area following the 1836 quake on the northern segment of the Hayward fault. Another plausible explanation is that a graben type structure exists in this particular area. According to Pat Williams (1992, personal communication) secondary fault features of this sort could result from extensional deformation associated with a right step occurring between the Hayward and Rogers Creek faults.

Two gravity surveys performed in the region by Chevron and the Calif. Division of Mines and Geology (Neal Smith, 1992) suggest that a north-south fault may extend from lakeville south into the Petaluma Marsh but this anomaly of three milligals occurs at the edge of the survey and it is not well controlled for this marshland (Tom Wright, personal communication). An east-west trending fault may also be indicated south of the gravity high that occurs southeast of Lakeville. The complexity of the region is obvious.

Interpretation of infrared photography taken different years by NASA and by the author indicates a single lineation occurring through Hog Island, Figure 1. This lineation corresponds to the former eastern margin of the island and points toward other topographic features and lineations to the north of the marsh. The lineation corresponds to the western headward extent of all but one of the eastward draining channels and to a linear northwest trending trough on the historic 1860 map of Hog Island, figure 2. Interestingly, the intersection between this lineation and the TOLAY fault is another area that has been subject to various interpretations. For example, Garniss Curtis (1981, personal communication) has suggested that the TOLAY fault does not extend northwest of a small reservoir located north of the Lakeville School on Stage Gulch Road, Highway 116. Thomas Wright (1992, written communication) indicates a northward bend of the TOLAY fault where it intercepts the Hog Island lineation, while many other published maps show the TOLAY fault to continue as a straight line.

The epicenter of a 3.6 magnitude earthquake, dated April 1948, plots on the southeast corner of the marsh. The accuracy of the epicenter location is questionable, however, given the information that was available at that time. The epicenter of a 2km deep microseismic quake plots on the east side of the abandoned reach of the Petaluma River (Tom Wright, written communication). Both these events, shown on Figure 2, plot very close to the straight projection of the Hayward fault from Point Pinole.

These various bits of data do not yield a decisive pattern of faulting in the Petaluma Marsh, yet they do add to the image of
complex deformation associated with the major active fault traces of the region. To better define the seismotectonic environment of the northern Bay Area the need exists to draw upon various data to establish a line of research that includes the geophysical investigation of the many diked and remaining tidal marshlands of the northern estuary.

References Cited


Curtis, Garniss, 1981, Personal communication.


U. S. Coast Survey, 1860, Petaluma Creek California, plane table sheet no. 5, surveyed by D. Kerr. A. D. Bache superintendent, scale 1:10,000.

Williams, P., 1992, Personal communication.

Wright, T., 1992, Personal and written communication.
Figure 1. The Petaluma Marsh is about 10 km north of the San Pablo Bay. Hog Island is located in the lower central portion of the map. Lakeville is near the center of the map. The dashed line represents a lineation interpreted from aerial infrared photography and a possible gravity anomaly. The dotted line represents an east-west trending gravity anomaly.
Figure 2. The Petaluma Marsh is located in the upper left corner of this modified map of the Historic Margins of Marshlands, San Francisco Bay (Nichols and Wright, 1971). Two earthquake epicenters are plotted just north and southeast of Hog Island.
Figure 3. Hog Island, located in the center of this map, is a detail from the Coast Survey of Petaluma Creek (1860). Note the angular bend of Petaluma Creek north of the false bay, the abandoned channel in the lower right, and the subsiding eastern edge of Hog Island.
investigation of the many diked and remaining tidal marshlands of the northern estuary.

References Cited


Curtis, Garniss, 1981, Personal communication.


U. S. Coast Survey, 1860, Petaluma Creek California, plane table sheet no. 5, surveyed by D. Kerr. A. D. Bache superintendent, scale 1:10,000.

Williams, P., 1992, Personal communication.

Wright, T., 1992, Personal and written communication.
Late Holocene Behavior and Seismogenic Potential of the Rodgers Creek Fault Zone, Sonoma County, California

David P. Schwartz, USGS, Menlo Park, CA 94025

The Rodgers Creek Fault Zone (RCFZ) is a major fault segment within the San Francisco Bay Area strike-slip system and is a potential source of the next M7 Bay Area earthquake. The surface expression of the fault extends from just north of Highway 37 on the south to approximately 6 km southeast of Healdsburg on the north, a total distance of about 60 km. Along much of its length the RCFZ is in bedrock, but where it occurs in alluvium it displays classical strike-slip geomorphology. The field trip provides the opportunity to walk along a section of the main trace of the RCFZ that contains some of the best preserved microgeomorphic expression of recent surface faulting. These features include offset and beheaded streams, shutter ridges, pressure ridges, sag ponds, and fault scarps, all of which are developed in late Holocene alluvial deposits. This section of the fault also contains the two trench sites that have been the focus of USGS efforts to develop information on the recent behavior of this major Bay Area earthquake source.

In 1988 the Working Group on California earthquake probabilities issued its first report on the probability of a M7 earthquake in the San Francisco Bay Area during the next 30 years (Working Group, 1988). The probability was 50 percent. This value was based on the then-current understanding of the behavior of the north and south segments of the Hayward fault, and of the North Coast (1906 rupture zone), Peninsula, and Santa Cruz Mountains segments of the San Andreas fault zone. The Rodgers Creek fault zone, which had long been recognized as a major Holocene fault and was designated as a Special Study zone by the California Division of Mines and Geology, was discussed during meetings of the Working Group. However, the decision was made to exclude the RCFZ from the probabilistic estimate because of a complete absence of information on earthquake recurrence intervals, slip rate, slip per event, and the elapsed time since the most recent M7 earthquake.

Beebe Ranch Site

In May 1989, prior to the Loma Prieta earthquake, we initiated a study of the Rodgers Creek fault zone for the specific purpose of obtaining information on its Late Holocene behavior. The first site was on the Beebe Ranch. (Figure 1) At this location we used offset channels exposed in trenches across alluvial fan and debris flow deposits to measure a minimum slip rate of 2.1 to 5.8 mm/yr for the past 1300 years, calculate a preferred range for the maximum recurrence interval of 248 to 679 years, and measure a surface offset of 2 +0.3, -0.2 m during the most recent event. These initial results were reported in Budding et al (1991) (see attached reprint) and led directly to inclusion of the RCFZ in the Working Group's 1990 revised 30-year probabilities for the Bay Area (Working Group, 1990). The probability estimated for the RCFZ was ≥22 percent and the addition of the fault was the primary factor in increasing the Bay Area probability to 67 percent. Continuing investigations at the Beebe Ranch site, particularly new radiocarbon dates obtained in the Spring of 1991, have allowed us to: a) increase the slip rate estimate to 6.4 to 10.4 mm/yr for the past 750 years, which is a rate comparable to the Hayward fault zone; and b) revise the calculated recurrence interval to 131 to 370 years with a best estimate of 230 years.

Triangle G Ranch Site

In the Summer of 1991 seven trenches were excavated parallel to and across the RCFZ (Figure 2, Figure 3) in fluvial deposits on the Triangle G Ranch, 0.7 km to the north of the Beebe Ranch site (Figure 1). At this location the fault is expressed as a 3- to 8-m-wide, 1-m-high pressure ridge.
The southwest edge of the pressure ridge is a scarplet formed by slip along subvertical faults; the northeast edge is a scarplet formed by slip along low angle reverse oblique-slip faults. The trenches exposed evidence of the past three surface faulting earthquakes on the RCFZ. Each paleoearthquake is identified on the basis of the upward termination of faults by unfaulted deposits and by other stratigraphic indicators such as fissure infills. Initial accelerator mass spectrometer radiocarbon dating of detrital charcoal indicates the three events occurred during approximately the past 1000 years. Our preliminary earthquake chronology based on dendro-corrected ages is:

**Event Y.** This paleoearthquake occurred after 1438-1654 AD but prior to 1808 AD and is the most recent event on the RCFZ. It is observed along both traces of the fault in trench 3 where the vertical trace offsets deposits dated at 1438-1654 AD (Figure 4). It is also observed in correlative units in trench 5 (Figure 5).

**Event S** occurred after 993-1193 AD but before 1275-1413 AD. This paleoearthquake is identified in the lower part of trench 5 by a faulted fissure infill and by upward termination of shears along the dipping trace (Figure 5).

**Event D** occurred shortly before 993-1193 AD. The event is defined by upward termination of a dipping fault trace in trench 4 (Figure 6). The unfaulted unit that directly overlies this fault trace is the same unit that defined the ground surface in trench 5 at the time of event S.

Radiocarbon dating of an additional 20 charcoal samples from the Triangle G site is in progress and results will be available in the Fall of 1992. These new dates should place tighter constraints on the timing of the three paleoevents. Additional trenching is planned at this site for late Summer 1992 to trace a distinct channel that may provide information on the amount of offset during the most recent event. The present fault behavior information from both sites is summarized on Figure 7. Results are encouragingly consistent. Actual intervals are within the range of calculated values, which gives hope that, for the Bay Area strike-slip fault segments, our approach to defining recurrence for hazard estimates is not entirely unreasonable.

**The Future**

The elapsed time on the RCFZ is the longest of any major Bay Area fault segment (at least 184 years) and is near, at, or possibly beyond the average repeat time. A two meter slip event, even as we walk along the fault trace, would not be unexpected!

**References**


Figure 1. Location of Trench Sites

Brown, R.D., Jr., 1970, Recently active traces of...
View SW of Rodgers Creek Fault at Triangle G Site

Figure 3.
<table>
<thead>
<tr>
<th></th>
<th>BEEBE RANCH</th>
<th>TRIANGLE G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slip Rate</strong></td>
<td>6.4-10.4 mm/yr (775 yr)</td>
<td>----</td>
</tr>
<tr>
<td><strong>Slip/Event</strong></td>
<td>1.8-2.3 m</td>
<td>----</td>
</tr>
<tr>
<td><strong>Recurrence</strong></td>
<td>3 events (≤ 925 yr)</td>
<td>3 events (≤1000 yr)</td>
</tr>
<tr>
<td><strong>Interval</strong></td>
<td>131-370 yr</td>
<td>Y&gt;1438-1654 AD</td>
</tr>
<tr>
<td></td>
<td>230 yr</td>
<td>S&gt;993/1193&lt;1275/1413 AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D&lt;993-1193 AD</td>
</tr>
<tr>
<td><strong>Elapsed Time</strong></td>
<td>184 yr (min)</td>
<td>184 yr (min)</td>
</tr>
<tr>
<td></td>
<td>472-602 yr (max)</td>
<td>338-554 yr (max)</td>
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</tbody>
</table>

Figure 7
SLIP RATE, EARTHQUAKE RECURRENCE, AND SEISMOGENIC POTENTIAL OF THE RODGERS CREEK FAULT ZONE, NORTHERN CALIFORNIA: INITIAL RESULTS

Karin E. Budding1, David F. Schwartz2, and David H. Oppenheimer2

Abstract. Instrumental seismicity defines a seismic gap along the Rodgers Creek fault zone (RCFZ) between Santa Rosa and San Pablo Bay. Results of a paleoseismicity study within the gap, using offset channels in late Holocene alluvial deposits as piercing points, indicate a minimum slip rate of 2.1 to 5.8 mm/yr for the past 1300 years, a preferred range for the maximum recurrence interval of 248 to 679 years, and a surface offset of 2 ±0.3,-0.2 m during the most recent event. The RCFZ has produced past M7 earthquakes, and historical seismicity data indicate a minimum elapsed time of 182 years since the most recent earthquake of this size.

Introduction

The Rodgers Creek fault zone (RCFZ) is a major northwest-trending segment of the Hayward fault zone. It extends at least 50 km from San Pablo Bay to northwest of Santa Rosa and includes the Healdsburg fault (Helley and Herd, 1977; Herd and Helley, 1977) (Figure 1). In contrast to the Hayward fault zone, parts of the RCFZ lack microearthquake activity and there is no known surface creep. The RCFZ has long been recognized as a Holocene fault (Fox et al., 1973; Huffman, 1971) and is designated as a Special Studies Zone (Hart, 1982), but little has been known about its past behavior. Based on seismicity and geodetic data and the initial results of an ongoing paleoseismicity study, this paper presents the first quantification of slip rate, recurrence interval, slip per event, and elapsed time for the RCFZ and an evaluation of its seismogenic potential.

Seismicity


The U.S. Geological Survey began recording earthquakes in the vicinity of the RCFZ in 1969 (Figure 2). A pronounced feature of the RCFZ is the aseismic region between San Pablo Bay and Sonoma Mountain. This is one of the best defined gaps in microearthquake activity on faults in the Bay Area. Much of the seismicity between Sonoma Mountain and Santa Rosa also appears to be off-fault. Such aseismic regions likely represent fault segments that are locked except during mainshock rupture (Oppenheimer et al., 1990). In contrast, microearthquakes from Santa Rosa northward occur on a steep northeast-dipping fault plane to a depth of approximately 12 km (Figure 2). Significant off-fault seismicity also occurs to the east of the RCFZ along this northern reach.

Hypocenters of the 1969 M 5.6 and 5.7 Santa Rosa earthquakes were about 3 km northwest of Santa Rosa (Figure 2) at depths of 9.5 and 10.5 km, respectively (Steinbrugge et al., 1970). Aftershocks extended from Santa Rosa northwestward for about 9.5 km along trend of the RCFZ. However, it is uncertain whether the 1969 earthquake sequence occurred on the RCFZ or on a subparallel structure to the east (Wong et al., 1990).

Historical Seismicity.

Records of historical seismicity in the San Francisco Bay area, while limited for older events, extend back to 1800 (Townley and Allen, 1939). An earthquake in 1808 caused damage at the Presidio in San Francisco. This is the oldest event in the catalogue that could have occurred on the RCFZ although its actual source is unknown.

An earthquake in 1836 having an estimated magnitude of 6.8 (Toppozada et al., 1981) may have ruptured the northern segment of the Hayward fault zone (Louderback, 1947) (Figure 1). A chronicle of the Sonoma Mission (Smilie, 1975) makes no mention of this or other earthquakes between 1824, when the mission was built, and 1868, when damage resulted from a magnitude 6.8 (Toppozada et al., 1981) earthquake on the southern Hayward fault (Figure 1). The apparent lack of damage to the Sonoma Mission, located only 7 km east of the RCFZ, and lack of reports of other earthquake effects in the region in 1836, suggest that the 1836 event was not on the RCFZ. The 1898 Mare Island earthquake, which damaged the Mare Island Naval Yard (Townley and Allen, 1939), had an estimated magnitude of 6.2 and appears to have been centered east of the south end of the RCFZ (Toppozada et al., 1986) (Figure 1). Although there are limitations, the historical record suggests that at least 182 years have elapsed since the most recent surface-faulting earthquake on the RCFZ.

Fig. 1. Location map showing major active faults in the San Francisco Bay area. Trench site indicated by dot. Epicenters of 1969 Santa Rosa earthquakes and 1898 Mare Island earthquake shown by stars. Approximate extent of 1836 rupture of Hayward fault delineated by hachured line; approximate extent of 1868 rupture of Hayward fault delineated by bold solid line.

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Paper number 91GL00465
Paleoseismological Observations

For most of its length the RCFZ lies within late Tertiary andesitic to basaltic flows of the Sonoma Volcanics (Fox et al., 1973). Consequently, there are only a few locations along the fault trace where Holocene deposits capable of recording information on recent displacement history occur. The paleoseismicity site is one of these, an alluviated flat adjacent to Rodgers Creek about 25 km southeast of Santa Rosa (Figure 1). Here the fault is geomorphically expressed as a linear, 1/2-m-high, southwest-facing scarp in a late Holocene alluvial fan, and by a right-lateral offset of a surface debris flow and the gully incised into it (Figure 3). Measurement of the gully thalweg and debris flow margin across the fault gives an offset of 2.0 +0.3,−0.2 m. The debris flow is the youngest stratigraphic unit at the site. The youthful, well-preserved geomorphic expression of the debris flow and the gully walls suggest the offset occurred during the most recent event.

Two fault-parallel trenches on each side of the scarp and one cross-fault trench (Figure 4) exposed a sequence of fine-to coarse-grained debris flow and alluvial fan deposits. The fault is a well-defined wedge-shaped vertical zone distinguished by fissure infill and pervasive secondary organic coating. Fault planes extend up to but not through a 10 to 15 cm-thick bioturbated horizon at the surface, supporting an absence of surface creep. The apparent vertical separation of 0.4 m up to the northeast of units OAL and UDF coincides with the scarp height and indicates that both units record the same displacement history.

Preliminary Slip Rate

Filled channels in the upper two units (Figure 5) provide piercing points to measure offset. Although they branch and

Geodetic and Creep Rates

Repeated measurement of a trilateration network spanning the northern San Francisco Bay region indicates strain is accumulating across the RCFZ. Although ambiguities in fault models make it difficult to determine how the slip is partitioned among the San Andreas, Rodgers Creek, West Napa, and Green Valley faults, fault-parallel (N340W) relative motion across the network totals 29 ± 3 mm/yr, with 9 ± 1 mm/yr of the relative motion distributed across a 35-km-wide zone centered on the RCFZ (Lisowski et al., in press).

The RCFZ south of Santa Rosa exhibits no observable surface creep where it crosses roads, fences, and other cultural features, particularly in the microearthquake gap. This is consistent with observations from two theodolite measurement sites located on the RCFZ north of the paleoseismicity site. One was measured from 1980–1986 and the other from 1986–1989; neither has shown any net slip movement (Galehouse et al., 1989). Prescott and Yu (1986) concluded that for the period 1972–1983 there was no surface creep on the RCFZ. In contrast, the Hayward fault zone creeps at rates of 5 to 10 mm/yr at sites along 60 km of the fault southeast of San Pablo Bay (Lienkaemper et al., 1989).
vary somewhat in width and depth, the same channels can be identified on both sides of the fault. Channels B, D, and the southeast margin of Channel A are the best piercing points. Figure 6 is the interpreted best-fit channel geometry prior to faulting. If this reconstruction is correct, the southeast margin of Channel A is offset 5.6 m; the northwest and southeast margins of Channel B are offset 5.8 and 5.7 m, respectively; and both margins of Channel D are offset 5.7 m. Alternatively, channels A, B, and D can be projected to the fault using their orientations in the trenches closest to the fault (Figure 6). In this case, the southeast margin of Channel A is offset 5.1 m; the northwest margin, thalweg, and southeast margin of Channel B are offset 6.2, 5.4, and 5.4 m, respectively; and the northwest margin, thalweg, and southeast margin of Channel D are offset 5.2, 7.2, and 6.9 m, respectively. The variability in channel geometry over short distances results in some uncertainty in establishing the matches. This is reflected in the range of offset values. Channel C is excluded from the present slip rate calculations. If projected along known trends, its apparent offset is significantly greater than the range established by the other three channels. To fall within the range, Channel C would be required to meander sharply across the fault. With existing trench exposures, constraints cannot be placed on its geometry at the fault crossing.

The paleochannels contain small amounts of detrital charcoal that have been dated using conventional and accelerator mass spectrometer techniques. The radiocarbon ages and their dendrochronological corrections are listed in Table 1. Because the charcoal is detrital, the deposits are younger than the radiocarbon age by an unknown amount. The range in ages of the six charcoal samples from unit UDF indicates that older charcoal was reworked into younger deposits.

Slip rate is the amount of net tectonic slip during a specific time interval. The rate at the site is derived from the youngest age of unit UDF (1440 ± 60 years) minus the time since the most recent event (1950 A.D. - 1808 A.D.). This gives an interval of 1298 ± 60 years. Because the deposits are younger and the elapsed time is longer, this is a maximum interval. The amount of offset recorded by units UDF and OAL during this interval is 5.1 to 7.2 m. Because the offset is relatively small and the deposits are young, the timing of channel formation relative to the occurrence of an event within the earthquake cycle affects the rate calculation. If the channels formed just after an earthquake, then the offset of 5.1 to 7.2 m represents the net slip accumulated and released in the 1298 ± 60-year period. This gives rates of 3.8 to 5.8 mm/yr. However, if the channels formed immediately prior to an event, then part of the offset represents slip accumulated over a period longer than the interval. To use the interval in this case, the amount of slip from the oldest event is subtracted. If the 2 ±0.3-0.2 m offset of the gulley represents slip during a characteristic earthquake, then offsets of 2.8 to 5.4 m in 1298 ± 60 years give rates of 2.1 to 4.4 mm/yr. Taking into account the uncertainties in both measurement and dating, the minimum slip rate for the RCWZ is in the range of 2.1 to 5.8 mm/yr.

Earthquake Recurrence.

The site has not yielded actual dates of paleoearthquakes; however, recurrence intervals can be estimated by two methods. The first is to divide the slip per event (2 ±0.3-0.2 m) by the minimum slip rate (2.1 - 5.8 mm/yr). This gives a range of recurrence intervals of 310 to 1095 years. The second involves dividing the interval over which the slip rate is calculated, 1298 ± 60 years, by the number of paleoearthquakes during that time interval. If the offset of the gulley and surficial debris flow is a characteristic amount, then the offset displayed by the paleochannels of 5.1 to 7.2 m represents at least two, and at most four paleoearthquakes. Recurrence calculations depend on assumptions of when the oldest and most recent events occurred relative to the age of the displaced datum. If the oldest event occurred immediately after deposition of the datum, there will be one less interval than the number of events. If a period equal to

![Fig. 6. Plan view of best-fit reconstruction of channel geometry prior to faulting. Thalwegs located by X.](image)

![Fig. 5. Schematic logs showing channels in unit OAL (clear) and UDF (stippled) used as piercing points in four fault-parallel trench walls. Channel thalwegs and margins designated by letters A through D are described in text. Gap in logs at 0 m is location of cross-fault trench A.](image)

### Table 1. Radiocarbon Analyses

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lab</th>
<th>Field</th>
<th>Strat.</th>
<th>14C Age (years B.P.)</th>
<th>cal B.P.*</th>
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<td>UDF</td>
<td>1,545 ± 50</td>
<td>1,440 ± 60</td>
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<td>RC1-8</td>
<td>UDF</td>
<td>1,780 ± 110</td>
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<td>AA-4526</td>
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<td>TO-1799</td>
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<td>RC3-19</td>
<td>RC3-19</td>
<td>LDF</td>
<td>4,900 ± 70</td>
<td>5,650 ± 80</td>
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</table>

*Number of years before 1950 A.D.; based on Stuiver and Reimer (1986).
about half the recurrence interval elapsed before the oldest event, the number of intervals will equal the number of events. If an event occurred immediately prior to deposition of the datum and a period equal to the recurrence interval elapsed before the oldest event, there will be one more interval than the number of events. Using this approach, the recurrence is 413 to 1358 years for two events, 310 to 679 years for three events, and 248 to 453 years for four events. Because three or four events are more likely, 248 to 679 years is considered a better estimate of a maximum recurrence interval.

Seismogenic Potential

The potential size of an earthquake on the RCFZ is a function of fault rupture length, average slip per event, and fault width. The potential rupture length is estimated at about 50 km from the fault geometry and the pattern of microseismicity. The south end of the rupture segment is likely to be in the vicinity of San Pablo Bay where there is a 6 km right-step, or structurally complex bend, between the surface traces of the RCFZ and Hayward fault (Figures 1 and 2). This stepover is associated with a 35-mg negative gravity anomaly in San Pablo Bay (Chapman and Bishop, 1988). Large releasing steps or bends, such as this, are often associated with rupture termination points (Sibson, 1985). The possible north end of the rupture segment is in the vicinity of Santa Rosa. Here the RCFZ is characterized by complex faulting, which includes a small right step, and by a change to on-fault microseismicity north of Santa Rosa. It is also the location of the 1969 earthquakes.

The slip during the most recent event at the paleoseismicity site is 2.03−0.2 m. This value is used as an average slip per event although it is unclear where it lies in the slip distribution curve for the event. The fault width is estimated at 12 km (Figure 2). Using these parameters, the expected magnitude for a future event on the RCFZ is $M_{w}7$.

The absence of microearthquakes activity, which defines a seismic gap along at least the south half of the fault, and the lack of recognizable surface creep indicate that the RCFZ is locked and accumulating stress. Historical seismicity data suggest a minimum elapsed time of 182 years and the geomorphic expression of faulting suggests the most recent event probably did not occur more that several hundred years ago. Given the uncertainties discussed, the actual elapsed time may be approaching the average recurrence interval.

Acknowledgments. We thank Mike Lisowski, Carol Prentice, John Sims, and an anonymous reviewer for insightful comments on the manuscript. David Browne, John Hamilton, Don Hoirup, Dan Meier, and Carol Ostergren provided valuable field assistance. We are especially grateful to Mrs. Lilian Beebe for the generous use of her land.

References


(Rceived: August 24, 1990; accepted: November 1, 1990)
PETALUMA OIL AND GAS FIELD

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The Petaluma oil field is located about 4 miles east of the city of Petaluma in southern Sonoma County, California. It is situated in moderately hilly pasture land at the southwest edge of the Sonoma Mountains at an elevation of approximately 200 ft. At present (1990) the field is marked by 4 oil tanks (2 silver and 2 red-brown) on a hilltop 0.2 miles north of Adobe Road and 2.2 miles west of Highway 116.

Stratigraphy

The Petaluma field produces from thin fluvial sands within the lower lacustrine unit of the Petaluma Formation (see Hudson, this volume), of late middle to late Miocene age. Subsurface stratigraphic data are summarized on the following page (location of the type electric log is indicated by T on the map). The uppermost interval on the electric log, described variously as Sonoma Volcanics or Quaternary, probably represents sandstones and conglomerates of the upper fluvial unit of the Petaluma Formation. Producing zones include:

- Upper gas zone- average depth 670 ft average thickness 20 ft
- Oil zone- average depth 920 ft average thickness 25 ft
- Lower gas zone- average depth 1,240 ft average thickness 20 ft

The Petaluma Formation is underlain by the middle Miocene Tolay Volcanics. In the Shell Murphy No. 1 well, interbedded volcanics and shale in the interval 2,055-2,235 ft mark a transition zone. That well was still in volcanic rock at total depth of 6,385 ft, indicating a thickness greater than 4,150 ft for the Tolay Volcanics in this area. In the Cotati area 10 miles to the northwest, the Santa Rosa Exploration Co. Stephens-Rohnert No. 1 well reported Eocene shale beneath a Tolay Volcanics interval 3,255 ft in thickness (California Division of Oil and Gas, 1964, and public files).

Structure

The Petaluma oil field is localized on the central part of the Adobe Creek anticline, a northwest-trending surface feature at least 6 miles in length (Armstrong, 1980; Youngman, 1989; Hudson, this volume). The accompanying map shows the subsurface structure as mapped by the field's recent operator. Although at least 12 wells within the contoured area have useable electric logs, they are limited to a narrow band in the axial portion of the field and provide very little control on the flanks or on fault trends. The map indicates that most of the productive wells are on a small subsidiary anticline (defined by the -1,000-ft contour) south of the main fold. Cross faults mapped in the subsurface are primarily those mapped at the surface by Morse and Bailey (1935).

The Adobe Creek anticline is in a structural block 2 to 3 miles wide between the Tolay and Rodgers Creek faults. It is essentially parallel to those faults and does not display the angular divergence that might be expected if it were caused by right-lateral faulting on the Rodgers Creek
SUBSURFACE STRATIGRAPHY
PETALUMA OIL FIELD

ELECTRIC LOG FROM PETALUMA OIL & GAS DEVELOPMENT
CO. PETALUMA COMM. 5 NO. 7A; CORE DESCRIPTIONS BY

(ALTHOUGH DIV OF O&G CALLS THIS INTERVAL "SONOMA
VOLCANICS", WELL FILE REPORTS IT AS QUATERNARY,
NO WELLS IN VICINITY REPORT SHALLOW VOLCANICS,
AND GEOLOGIC MAP DOES NOT SHOW SURFACE VOLCANICS)

MUDSTONE/SILTSTONE, MASSIVE, LT GRAY
AS ABOVE + SANDSTONE, FINE-MED-GRAIN, MODERATE
POROSITY
SANDSTONE, FINE-MED-GRAIN W/ OCCASIONAL PEBBLES,
POROUS, OIL-STAINED. STREAKS CARBONACEOUS
SLTSTN

MUDSTONE, MASSIVE, GRAY, OCCASIONAL SAND GRAINS
-COURED HORIZON (TOP 5-1 ZONE)

(ALTERNATING BASALT, TUFF, SEDIMENTS; FROM OTHER
DESCRIPTIONS)
fault. More probably it is the result of late Neogene compressive folding of the Petaluma section against the buttress of Franciscan basement uplifted on the southwest side of the Tolay fault (see Hudson, this volume, Figure 1).

Source Rocks

The source of the oil in the Petaluma oil field is perhaps its most interesting aspect. The gas is reported as a dry gas (essentially methane) and was most probably generated at shallow depths from organic matter in the lower lacustrine unit of the Petaluma Formation, in source rocks closely associated with the productive sands. Maturation of oil, however, requires higher temperatures than are normally found at the maximum burial depths (less than 4,500 ft) postulated for the lower Petaluma Formation. Three alternative hypotheses might be considered for the source of this oil:

- generation in lower Petaluma lacustrine shales and related to high heat flow associated with local extrusion of the Sonoma Volcanics during Pliocene time.
- generation in a concealed remnant of Monterey Shale beneath the Tolay Volcanics (Morse and Bailey, 1935) and migration upwards through fractures and faults in the volcanic series. Twelve miles east of the Petaluma oil field, an interval mapped as Monterey Shale dips west beneath the Sonoma Volcanics in the valley of Carneros Creek (see colored route map and cross section in this volume). The presence of Monterey Shale beneath the Petaluma Valley is highly problematical.
- generation from shales within the Franciscan Formation. Although the Franciscan is a very unlikely source rock, "high-grade oil shows" were reported from Franciscan rocks in the Sonoma Oil Co. No. 1 well drilled 9 miles west of the Petaluma oil field, and oil shows in the Franciscan were also reported in the Thompson Occidental No. 1 well, 22 miles northwest of the field.

Other than the gravity of the oil — 20°API — no analyses are available that might suggest which of these alternative sources is most likely.

History

Discovery of the Petaluma oil field is credited to the H. N. Witt & Associates No. 2 well drilled in 1926 to a total depth of 1,420 ft and completed for 12 bopd of 19° oil from the interval 950 to 1,022 ft. Earlier that year the Witt No. 1 well blew out while drilling with cable tools at a depth of 1,303 ft and flowed an estimated 100 Mcf gas before being abandoned with junk in the hole (California Division of Oil and Gas, 1960, 1982, public files). Seven more wells were drilled during 1926-28 but none of them established commercial production. Four of those wells were drilled by Shell, including the Murphy No. 1 which reached a total depth of 6,385 ft and remains the deepest well in the field. Most of the oil produced during that period by the Witt No. 2 well, which totaled about 5,000 bbl (Stalder, 1943), was sold to Shell for use in drilling.

The lower gas zone was discovered in August 1941, by the Petaluma Oil & Gas Development Co. Petaluma Community 5 No. 1 (ex Trico Miller No. 1) well, completed for an initial production of 3,030 Mcf/day of dry gas. Commercial
gas deliveries began in August 1942. In 1948 the Petaluma Community 5 No.2 well (ex Trico) was completed for 32 bbl/day of 20⁰ oil, stimulating a minor boom that saw 6 more wells drilled through 1950, and 4 more by 1957. One of those wells, the Petaluma Community 5–4, also produced oil at a 6 b/d rate. Peak oil production was in 1951 when 1,508 barrels was produced, and peak gas production of 136,004 Mcf came in 1956. The upper gas zone was first developed in 1958, for an initial production of 1,000 Mcf/day, and 5 more wells were drilled through 1962. Only 3 wells have been drilled in the last 28 years. The last year of production was 1985 when 12 barrels of oil and 18,239 Mcf of gas were produced.

Field Statistics

Cumulative production: Oil – 14,000 bbl; Gas – 1,291 MMcf
Estimated reserves: 229 MMcf gas
Maximum proved area: 135 acres
Number of Wells: 36 total (in and near field), 12 completed, 10 wells currently (1/90) shut in

References Cited


_____ , 1982, California oil and gas fields — volume 3, northern California: California Division of Oil and Gas, Sacramento, California, unpagedinated.

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THE TOLAY FAULT:
GEOPHYSICAL EVIDENCE IN THE CITY OF PETALUMA,
AND UPDATE

Stephen R. Korbay, CEG

[Note: The geophysical investigation described below was conducted by Harding-Lawson Associates for the Hillcrest Hospital in Petaluma in 1976 and is in open file at the Division of Mines and Geology.]

ABSTRACT

Gravity and seismic refraction measurements were used to determine pre-Tertiary bedrock and basement configurations and to delineate fault patterns in the Petaluma Valley, Sonoma County, California. One reversed seismic refraction profile with a length of 1400 meters was resolved into four seismic layers. Velocities in the Quaternary valley fill and Tertiary sediments range from 0.51 to 3.12 km/sec. Sediments of the Franciscan Complex have a velocity of 6.10 km/sec. The indicated depth to volcanic or pre-Tertiary bedrock varies from 370 to 590 meters. Gravity data from 95 field stations indicate that the general trend of isogonal contours is northwesterly. Computed basement configuration is regular and generally horizontal except where faulted by the northern extension of the Tolay fault which is defined by a long, linear although somewhat irregular, steep-sided gravity anomaly which transects the Petaluma Valley in a northwest to southeast direction. The anomaly represents a rather steep decline in gravity, on the order of 4 to 8 mgal per kilometer, from east to west. The trace of the Tolay fault as defined by the anomaly enters the east side of the valley south of the City of Petaluma and crosses the valley passing through the city and closely following the trend of the Petaluma River from that point north.

GRAVIMETRIC INVESTIGATION

Gravity stations were established at 82 locations in the Petaluma Valley area of Sonoma County, California. Of these stations, 16 had previously been occupied by Clement (1965) and 2 by Chapman, et al (1974). These and the data from 13 additional gravity stations (Clement, 1965) in the area of investigation were made available by Rodger B. Chapman, California Division of Mines and Geology (CDMG). Gravity measurements were made using a La Coste Romberg, Model G, Geodetic Gravity Meter. Where possible, gravity stations were established on a one kilometer grid. Geodetic control was provided by locating stations at established survey monuments such as benchmarks and triangulation stations. Many of the readings were taken at road intersections, well locations and other points where elevations were known or could be derived from 1:24,000 scale topographic maps. The base station for the survey was established at a CDMG gravity base station. This station, which is on the datum of Behrendt and Wollard (1961) and Wollard and Rose (1963), is located at USGS benchmark J-107 in Walnut Park, Petaluma, California. Gravity observations were made at each station through a series of three readings of which the average was used for the observed value.

Data Reduction

In order to isolate gravity anomalies which result solely from variations in the subsurface geology it is necessary to refine the raw field data through a series of calculations and corrections. Most of the data reduction was done
with the help of computers, the advantage being not only a great increase in the speed of reduction but a similar increase in precision and therefore data reliability.

The following is a discussion of the corrections made to the field data.

Instrument Calibration Instrument readings were converted to observed gravity in milligals by multiplying by a calibration constant. The calibration constant for the instrument used (No. G-358) is 1.05849.

Drift Correction Observed gravity values were corrected for earth tides by computer. Program input consisted of time of observation, day of the year, station latitude and longitude and observed gravity. Instrumental drift for the gravimeter used is less than 0.1 milligal per month.

Latitude Correction Theoretical gravity values \( TG \) were calculated by computer by correcting for latitude variations using the international reference spheroid formula:

\[
TG = 978.049 \left(1 + 0.0052884 \sin^2 \theta - 0.0000059 \sin^2 \theta \right)
\]

where \( \theta \) is the station latitude and \( TG \) is the theoretical gravity in gals.

Free Air Correction Variations in station elevation were corrected by use of the formula for the normal vertical gradient:

\[
FA = \frac{2gh}{R_0} \left(1 - \frac{3H + \ldots}{2R_0} \right)
\]

where \( g \) is the average gravity value, \( R_0 \) is the average curvature radius and \( h \) is the height above the geoid. For practical use this reduces to:

\[
FA = 0.30860 \ h \text{ milligals}
\]

where \( h \) is in meters and \( FA \) is the free air anomaly. This value is added to or subtracted from \( TG \) as the station lies above or below the reference datum level.

Bouguer Mass Correction A correction that accounts for the amount of material that lies between station levels is added to or subtracted from \( TG \) as the station is situated below or above the reference datum, which for the purposes of this study is sea level. The Bouguer mass correction \( \Delta G \) is based on the equation:

\[
\Delta G = 2\pi \rho \gamma
\]

where \( \rho = 2.67 \ \text{gm/cm}^3 \) is the density of a semi-infinite slab of thickness \( t \) and \( \gamma \) is the universal gravitational constant. This equation reduces to:

\[
\Delta G = \text{SELEV} \ (0.041896)
\]

where \( \text{SELEV} \) is the station elevation (above sea level) in meters.

Terrain Correction Of the 82 gravity stations occupied during this investigation, only those located on the flanks of the Petaluma Valley in or near
areas of topographic relief had terrain corrections applied to them. Where
terrain corrections were applied they were calculated to a radius of 2.6 km
surrounding the station. Those stations occupied by Clement (1965) and Chapman
(1974) were corrected for terrain to a radius of 22.5 and 166.7 km, respectively.

Reduction Accuracy The average repeatability of the observed gravity obtained
at stations that were occupied more than once is on the order of 0.25 mgals. It
is estimated that most of the Bouguer values are accurate to ±0.5 mgals.

DISCUSSION

The Bouguer anomaly map of the Petaluma Valley is presented on Figure 1.
The general trend of isogal contours is northwesterly. A long, linear, although
somewhat meandering gravity anomaly is believed to be associated with the Tolay
fault. This feature, which will hereafter be described as the Tolay anomaly,
represents a west to east decline in Bouguer gravity on the order of 4 to 8
mgals/km. At the south end of the valley the anomaly is relatively narrow, but
it becomes increasingly broad in a northerly direction. The location of the
anomaly correlates well with the previously mapped locations of the fault at the
north and south ends of the valley. In the valley itself, the fault shows no
surface expression.

Two profiles have been constructed perpendicular to the alignment of the
Tolay anomaly. Profile A-A' (Figure 2) shows the variation in Bouguer gravity
in an area where the location of the fault is based on surface exposures. Profile B-B' (Figure 3) crosses the Tolay anomaly in the vicinity of the proposed
Hillcrest Hospital site. This profile shows that east and west of the anomaly
the gravitational field is flat, suggesting there is no regional trend along an
east-west alignment. For that reason no attempt has been made to calculate a
regional effect or to separate the regional and residual anomalies. Both
profiles have been interpreted with the aid of computer according to the method
of Talwani, et al (1959). The two-dimensional density models that provide the
best fit of calculated gravity to observed gravity are illustrated with the
profiles on Figures 2 and 3. Both models indicate a step fault structure with
the west side of the fault displaced vertically upwards. The fault plane dips
westward at an angle of 50 to 60 degrees from the horizontal, being more shallow
along Profile A-A'. This is consistent with the meandering trend of the Tolay
anomaly and the increasing width of the anomaly from south to north. Both models
indicate an anomalous block of relatively low density material on the east side
of the fault. This 1 to 2 km thick section represents a mass deficiency of 0.35
to 0.40 gm/cm3 relative to the underlying material and the adjoining material on
the west side of the fault. It should be pointed out that these models are not
unique. There may be other interpretations that may fit the observed gravity
equally well. The models presented on Figures 2 and 3 represent simplified
approximations of the geology and structure based on the available geology,
seismic, and gravimetric data. Although other interpretations may be possible,
it is doubtful that given the available data the location of the Tolay fault
could be much removed from the location described herein.

By using the known location of the Tolay fault trace at the north and south
ends of the Petaluma Valley and the estimated fault location based on the seismic
profile (Figure 4) and and gravity profiles A-A' and B-B', and by following
the trend of the isogal contours between these points, it is possible to trace the
approximate location of the Tolay fault the length of the Petaluma Valley. The
fault enters the area of investigation from the south and first disappears beneath Petaluma Valley sediments approximately 4 km east-southeast of Petaluma. From there the trace bends westward, passing directly beneath the city and from there northwest closely following the trend of the Petaluma River until it is again exposed at the north end of the valley just west of U.S. Highway 101 near Meacham Hill.

**SEISMIC INVESTIGATION**

One seismic refraction profile was obtained in the northern portion of the Petaluma Valley (Figure 1), near the site of the proposed Hillcrest Hospital just north of Petaluma. Data from this profile provides information on the depth to Franciscan bedrock and possibly the location of the Tolay fault.

Seismic data were recorded using a 12-channel SIE portable seismograph. Linear arrays of 12 geophones spaced 8 to 30 meters apart were located along most of the length of the profile. Shot points were located on both ends of the profile to provide reversal information on possible dipping layers. Energy coupling was fair in shot holes which averaged about 1 meter in depth.

The data obtained with the seismic profile are presented on the Time vs. Distance graph shown on Figure 4a. Due to the close proximity of the profile to U.S. Highway 101 and North McDowell Avenue, the background noise level was high. Since the shot size was limited, this resulted in a low signal to noise ratio and questionable first-break picks near either end of the spread. However, the process of determining first-break times was facilitated through the use of second arrival information and reversal times. The reduced seismic data were interpreted with the aid of a computer program developed by Scott, et al (1972). Part of the computer routine is an iterative ray-tracing procedure that provides depth information beneath each geophone location given as input data. The result is the detailed seismic profile shown on Figure 4b.

The subsurface beneath the Petaluma Valley seismic profile has been resolved into four seismic layers. Velocities range from 0.51 km/sec for the upper layer of Quaternary alluvium and colluvium to 6.10 km/sec for Franciscan bedrock. The intermediate layers (the Merced [Wilson Grove] and Petaluma Formations) have velocities of 1.74 and 3.12 km/sec, respectively.

The near-surface alluvial layer is quite thin with a maximum thickness of 8 meters near the Petaluma River. The layer decreases in thickness to the east and either lenses out or becomes too thin to define as a separate unit east of the mid-point of the profile. Underlying Layer 1 is a seismic layer with a velocity of 1.74 km/sec. This unit, which possibly represents saturated Quaternary valley fill and Tertiary sediments of the Merced [Wilson Grove] Formation, is 47 meters thick beneath the west shot point and thickens to 152 meters at the east end of the profile. The third layer in the section has a seismic velocity of 3.12 km/sec. This layer represents a rather thick sequence of Tertiary Petaluma Formation sediments. As with Layer 2, this unit thickens eastward: from 317 meters beneath the west end of the profile to 430 meters at the east end. Finally, underlying the Quaternary valley fill and Tertiary sediments, Layer 4 has a velocity of 6.10 km/sec. This unit undoubtedly represents Franciscan bedrock [and/or perhaps Tolay Volcanics of Miocene age]. The bedrock surface generally is regular and dips gently to the east, varying in depth along the profile from 372 to 582 meters west to east.

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A rather abrupt change in elevation of the top of Layer 3, on the order of +30 meters east to west, occurs near the west end of the profile and possibly marks the trace of the Tolay fault. Petaluma Formation rocks west of the fault are displaced upward relative to those on the east side. This location for the fault trace is in good agreement with the gravity data interpretation.

The topography of the seismic layers underlying the hospital site appears smooth and regular with no obvious indication of faulting.

REFERENCES CITED


Chapman, R. H., and Bishop, C. C., 1974, Bouguer gravity map of California, Santa Rosa Sheet: California Division of Mines and Geology, 7 p. and map, scale 1:250,000.


*****

DETAILED GEOLOGY

Recent field work by the writer in 1991 in the vicinity of the west side of Tolay Lake (Figure 5) and southeast of Stage Gulch Road (Highway 116) revealed the presence of several traces of the Tolay fault along the northwest-southeast-trending ridge line. At this location, several small hills underlain by both the Sonoma Volcanics and the Petaluma Formation are in fault contact with serpentinite and meta-sediments of the Franciscan Complex. Although there is no evidence of displacement of Quaternary deposits, subtle breaks-in-slope are indicative of differential erosion between the resistant serpentinite, the Sonoma volcanic flow-rock, and the weaker claystone, siltstone, and sandstone of the Petaluma Formation.

THE TOLAY FAULT - AN UPDATE

According to Huffman and Armstrong in Special Report 120, Geology for Planning in Sonoma County (CDMG, 1980), the Tolay fault was considered potentially or possibly active based on several right-laterally offset streams, a large playa lake (Tolay Lake), close proximity to the Rodgers Creek fault and
a zone of fractures to the southeast, and field observations by Armstrong in 1974.

However, Fault Evaluation Report 140 by the CDMG (Hart, 1982) indicated that the fault is a zone of indistinct traces, partly inferred, and offsets units no younger than late Pliocene or early Pleistocene. Previous workers are not consistent on the location of fault traces nor its existence in some places. There is no surface evidence either from topographic irregularities or from photo lineations or tonal anomalies to suggest displacement of late Pleistocene deposits. Furthermore, there is no compelling evidence that the northwest segment and the southeast segment are connected beneath Petaluma Valley. The fault is believed to be a right lateral strike-slip fault with some reverse movement along planes dipping steeply to the southwest.

As a result of the work by Armstrong (1974) and Huffman and Armstrong (1980), the fault was placed in a Special Studies Zone in 1976. However, evaluation of their work by Hart (1982) including re-checking air photos and performing field work failed to confirm the early interpretation that the fault had evidence of potential activity or Holocene displacement. In fact, Hart concluded that displacement is pre-Holocene and surface anomalies are from differential erosion and landsliding. Hart also concluded that if there is Holocene activity, such activity is disruptive, minor, and restricted to the southeast end of the fault where it is in close proximity to the active Rodgers Creek fault. The fault is well defined at the surface only in the southeast segment, southeast of the quarry located north of the intersection of Highway 116 and Lakeville Road. As a result of Hart's evaluation, the Tolay fault was judged not to exhibit sufficient evidence to justify placing it into a Special Studies Zone and therefore it has been removed from the Alquist-Priolo Act requirements.

According to Fox (1983, USGS Professional Paper 1239), the Tolay fault forms the northeast boundary of a 15-km-long wedge of the Franciscan Complex where it contacts the Petaluma Formation and occasional volcanics of the Sonoma Group. Although the Tolay had been thought to be the northwest extension of the Hayward fault, Fox considers the Tolay to have been active prior to deposition of the upper Petaluma Formation because of the Petaluma overlying a significant thickness of volcanic rocks in the basin east of the fault that are absent at the supposedly depositional contacts between Petaluma and Franciscan west of the fault.
FIGURE 1
BOUGUER GRAVITY MAP
PETALUMA VALLEY

Data from Harding-Lawson Associates, 1976

KEY

Gravity station showing Bouguer value

Approximate location of Talay Fault (dashed where based on geological data, dotted only where based on gravity and seismic data).

Gravity profile

Seismic profile

* All values are -978000 m. gals.
Figure 2

KEY:
- Observed gravity
- Calculated gravity
- Density contrast

$\rho' = 0.30 \text{ gm/cm}^3$
FIGURE 3

KEY:
- Observed gravity
- Calculated gravity
- Density contrast

\[ \delta = 0.35 \text{ g/cm}^3 \]

HARDING-LAWSON ASSOCIATES
Consulting Engineers and Geologists

PROFILE B-B'
Hillcrest Hospital
Petaluma, California

Job No. 9130, 001.01  Apr. 11/9/76
FIGURE 4a

TIME VS. DISTANCE GRAPH
LONG-TERM DISPLACEMENT RATES OF THE SAN ANDREAS FAULT SYSTEM IN NORTHERN CALIFORNIA FROM THE 6-Ma ROBLAR TUFF

A.M. Sarna-Wojcicki

The informally named, approximately 6-Ma Roblar tuff is identified at several sites in northern California and the northeastern Pacific Ocean: 1) in Deep-Sea Drilling Hole 34, at the distal edge of the Delgada submarine fan, west of the main strand of the San Andreas fault; 2) in the Wilson Grove Formation east of the main strand, west of the Tolay fault; 3) in the Petaluma Formation east of the Tolay fault, west of the Hayward-Rodgers Creek fault; 4) in the Contra Costa Group east of the Hayward-Rodgers Creek fault, northwest of the Sunol-Calaveras fault; and 5) near the base of the Tassajara Formation or top of the Green Valley Formation east of the Sunol-Calaveras fault. Thus, the tuff is present in each of the major blocks displaced by the northern San Andreas fault system (SAFS).

The tuff is water laid, reworked, and from east to west, present in progressively finer sediments: generally fluvial sands and gravels in the Tassajara and Green Valley formations, fresh-to-brackish-water sands and silts in the Contra Costa Group, estuarine brackish water sands and silts in the Petaluma Formation, shallow-water marine sands and silts in the Wilson Grove Formation, and deep-water silts and clays of the Delgada fan. Thus, the sites at which this tuff is found may have once been part of a single, west- to northwest-flowing drainage system.

The fault-bounded blocks of the SAFS can be restored palinspastically so that all these tuff sites and areas of coeval sediments form a narrow, west- to northwest-trending band. This suggests that the tuff and enclosing sediments were originally small in areal extent, and were displaced by right slip along the SAFS. If these assumptions are correct, displacements of the SAFS during the last six million years are:

<table>
<thead>
<tr>
<th>Fault</th>
<th>Displacement (km)</th>
<th>Rate (cm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern San Andreas (main trace)</td>
<td>228 ± 13</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>Hayward-Rodgers Creek + Tolay</td>
<td>68 ± 13</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>Tolay (inactive)</td>
<td>(40 ± 10)</td>
<td>(0.7 ± 0.2)</td>
</tr>
<tr>
<td>Hayward-Rodgers Creek (active)</td>
<td>(28 ± 3)</td>
<td>(0.5 ± 0.04)</td>
</tr>
<tr>
<td>Concord-Sunol-Calaveras</td>
<td>13 ± 7</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Northern San Andreas Fault System</td>
<td>308 ± 18</td>
<td>5.1 ± 0.3</td>
</tr>
</tbody>
</table>

Displacement errors are determined from the probable errors in palinspastic reconstruction of the faulted blocks. Previous studies of the magnetic orientation of the Roblar tuff indicate that there has been little or no rotation of the blocks within the northern SAFS; consequently, most of the displacement must be accomplished by movement on the fault strands. The close agreement between total rate of displacement on the SAFS obtained from displacement of the Roblar tuff (5.1 cm/yr), and from several independent calculations based on other offsets, plate motions, and hot spot positions (4.8-5.6 cm/yr) suggest that the assumption of initial proximity of the tuff sites, and thus of their displacements, may be correct.

1U.S. Geological Survey, MS 977, 345 Middlefield Road, Menlo Park, CA 94025

Reprinted from Program and Abstracts, Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area, 1992
GEOLOGY OF THE CALISTOGA AREA

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Calistoga is a hot springs resort town located in the northwest end of the Napa Valley. In the late 1800s and early 1900s, there were many hot springs resorts in Lake, Napa and Sonoma Counties. Calistoga is nearly the only survivor. There are a number of spas in and around Calistoga where one can "take the waters" as it was called at one time. Mud baths, mineral baths, hot swimming pools and massages are offered. Most of the resorts obtain their mineral waters from shallow wells, 20 to 200 feet deep. Several wells have been drilled to depths of approximately 2,000 feet. One, located near the north end of Tubbs Lane, sampled a reservoir with a temperature of 167°C (333°F). Hot Springs and hot wells are found for a strike length of at least six miles in the northwestern most part of Napa Valley.

Figure 1 is a geologic map of Calistoga and the northwest end of the Napa Valley (Fox and others, 1973). The northwest portion of the Napa Valley and surrounding ranges consist of a southeast plunging syncline that lies on the upper plate of the Maacama thrust fault, which is a portion of the Coast Ranges fold and thrust belt described by Phipps and Unruh, 1992. The Valley is surrounded by Late Pliocene Sonoma Volcanics. To the southwest of the Napa Valley, the Sonoma Volcanics dip mainly to the northeast 20° to 40° with some local complexities. To the northeast, the Sonoma Volcanics generally dip to the southwest; however, these dips are complicated by land slides and complex structure. South and west of Calistoga the splays of the Maacama thrust fault place Franciscan rocks on Pliocene sedimentary and volcanic rocks of the Sonoma Volcanics. Earthquake hypocenter locations plotted on a plan map and on sections by Wong, 1991, (Figure 2) suggest that the Maacama fault dips under Calistoga at a depth of about 5.5 kilometers (18,000 feet).

The heat for the geothermal system that outcrops in the northwestern Napa Valley may be related to the same heat source as The Geysers geothermal field which is located about 25 kilometers (15 miles) to the northwest of Calistoga. If so, the hydrologic system must be interesting. There is no local evidence for a heat source. The Sonoma Volcanics are 3.7 ma to 2.0 ma in this area, which is probably too old to maintain the present day geothermal system. Northwest striking bands of silica carbonate rocks, indicators of past hydrothermal activity, outcrop abundantly along with serpentinite near tectonic contacts with Franciscan rocks. Small, high-grade mercury deposits are found in association with the silica carbonate rocks. In this area the mercury deposits often contain hydrocarbon minerals.
References Cited


WONG: COAST RANGES SEISMICITY, FAULTING, AND SEismic HAZARDS

Figure 2. Earthquake hypocenters on the Maacama Fault. (From Wong, 1991)