Geology, geochronology, and paleogeography of the southern Sonoma volcanic field and adjacent areas, northern San Francisco Bay region, California

David L. Wagner¹, George J. Saucedo², Kevin B. Clahan², Robert J. Fleck³, Victoria E. Langenheim³, Robert J. McLaughlin³, Andrei M. Sarna-Wojcicki³, James R. Allen⁴, and Alan L. Deino⁵
¹California Geological Survey, 801 K Street, Sacramento, California 95814, USA
²California Geological Survey, 345 Middlefield Road, Menlo Park, California 94024, USA
³U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
⁴California State University, East Bay, 25800 Carlos Bee Boulevard, Hayward, California 94542, USA
⁵Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, California 94709, USA

ABSTRACT

Recent geologic mapping in the northern San Francisco Bay region (California, USA) supported by radiometric dating and tephrochronologic correlations, provides insights into the framework geology, stratigraphy, tectonic evolution, and geologic history of this part of the San Andreas transform plate boundary. There are 25 new and existing radiometric dates that define three temporally distinct volcanic packages along the north margin of San Pablo Bay, i.e., the Burdell Mountain Volcanics (11.1 Ma), the Tolay Volcanics (ca. 10–8 Ma), and the Sonoma Volcanics (ca. 8–2.5 Ma). The Burdell Mountain and the Tolay Volcanics are allochthonous, having been displaced from the Quen Sabe Volcanics and the Berkeley Hills Volcanics, respectively. Two samples from a core of the Tolay Volcanics taken from the Murphy #1 well in the Petaluma oilfield yielded ages of 8.99 ± 0.06 and 9.13 ± 0.06 Ma, demonstrating that volcanic rocks exposed along Tolay Creek near Sears Point previously thought to be a separate unit, the Donnell Ranch volcanics, are part of the Tolay Volcanics. Other new dates reported herein show that volcanic rocks in the Meacham Hill area and extending southwest to the Burdell Mountain fault are also part of the Tolay Volcanics. In the Sonoma volcanic field, strongly bimodal volcanic sequences are intercalated with sediments. In the Mayacamas Mountains a belt of eruptive centers youngs to the north. The youngest of these volcanic centers at Sugarloaf Ridge, which lithologically, chemically, and temporally matches the Napa Valley eruptive center, was apparently displaced 30 km to the northwest by movement along the Carneros and West Napa faults. The older parts of the Sonoma Volcanics have been displaced at least 28 km along the Rodgers Creek fault since ca. 7 Ma. The Petaluma Formation also youngs to the north along the Rodgers Creek–Hayward fault and the Bennett Valley fault. The Petaluma basin formed as part of the Contra Costa basin in the Late Miocene and was displaced to its present location along the Rodgers Creek–Hayward and older faults. The Tolay fault, previously thought to be a major dextral fault, is part of a fold-and-thrust belt that does not exhibit lateral displacement.

INTRODUCTION

The California Coast Ranges north of San Francisco Bay consist of Mesozoic and early Tertiary rocks that formed along a long-lived convergent plate boundary and overlying time-transgressive deposits of late Cenozoic volcanic and sedimentary rocks that were deposited along the rapidly evolving San Andreas transform boundary between the Pacific and North American plates (Figs. 1 and 2). Together these disparate, complexly deformed rocks present an exceptionally challenging geologic puzzle that bears on our understanding of plate boundary dynamics. This paper summarizes results to date from geologic mapping, radiometric dating, and tephrochronologic correlations of late Cenozoic rocks in the Sonoma and Mayacamas mountains of the California Coast Ranges. A major goal of this research is to document the age and distribution of the late Cenozoic volcanic rocks north of San Pablo Bay as well as associated sediments and structures to provide a better understanding of the tectonic and volcanic evolution of the North American–Pacific transform boundary north of San Francisco Bay. If these volcanic fields and sedimentary basins form in response to the passage of the Mendocino triple junction, a systematic pattern of northward younging should be observed.

The Sonoma Volcanics are part of a succession of volcanic fields aligned along the East Bay fault system (McLaughlin et al., 1996; Graymer et al., 2002b), which splays inboard of the San Andreas Fault south of San Francisco Bay (Fig. 1). Earlier workers recognized that the volcanism generally becomes younger to the northwest (Fox et al., 1985a; Dickinson, 1997). However, the temporal patterns of volcanism are complicated by large-magnitude dextral displacements along the evolving transform boundary. In the greater San Francisco Bay region, these fields include the Quen Sabe Volcanics, volcanic rocks in the Berkeley Hills, the Sonoma Volcanics, the Tolay Volcanics, the Burdell Mountain Volcanics, and the Clear Lake Volcanics (Fig. 1). All of these fields are complex, heterogeneous, strongly bimodal volcanic suites purported to be the result of mantle upwelling into a slab window or opening within the subducting Farallon plate that trails directly behind the northward-migrating Mendocino triple junction (Dickinson and Snyder, 1979; Furlong, 1984; Fox et al., 1985a; Dickinson, 1997). The Sonoma Volcanics differ from the other volcanic fields within the San Francisco Bay region in that (1) the Sonoma Volcanics are much more voluminous, (2) volcanism persisted much longer, and (3) they contain the only significant pyroclastic component. Complex stratigraphy, poor exposure, and a lack of recognized marker beds (Weaver, 1949) have long...
Geosphere, June 2011 659

Figure 1. Map modified from Langenheim et al. (2010) showing the study area, faults of the East Bay fault system, and their possible extensions north of San Pablo Bay. Also shown are northward-younging Cenozoic volcanic fields, some of which have been correlated across dextral faults of the East Bay fault system. Fault abbreviations: BF—Bloomfield; BMF—Burdell Mountain; FC—Franklin Canyon; CF—Carneros; M—Moraga; MC—Miller Creek; P—Palomares; PVF—Petaluma Valley; Pin—Pinole; Su—Sunol; TF—Tolay; WNF—West Napa.

Geologists have long speculated about large-magnitude dextral displacement along faults of the East Bay fault system (Vickery, 1925; Weaver, 1949; Louderback, 1951; Fox, 1983) that traverse the Sonoma Volcanics. New data presented in this paper show that rocks juxtaposed along these faults that appear to be lithologically similar are of different ages, and the basins in which they were deposited evolved rapidly in the wake of the northward-migrating Mendocino triple junction and are now deformed and fragmented.

METHODS

Radiometric Dating

The 25 new radiometric dates, using Ar/Ar techniques reported here, were run in the U.S. Geological Survey (USGS) Laboratory in Menlo Park, California, and at the Berkeley Geochronology Center in Berkeley, California; 22 Ar/Ar ages were measured in the USGS laboratory in Menlo Park (Table 1) utilizing either laser-fusion analysis with a CO₂ laser or incremental heating with a tantalum resistance-heated furnace and molybdenum crucible to extract argon from samples analyzed. Reactive gases were removed from gas extracted from the samples using a Zr-Al getter, and argon isotopic ratios were measured on a 15.5-cm-radius, 90° sector MAP 216 mass spectrometer. Samples were irradiated in the core of the USGS TRIGA reactor in Denver, Colorado, at ~1 MW power. The reactor neutron flux constant, J, was calculated for each sample using the Taylor Creek Rhyolite (TCR-2) sanidine

...
monitor, with an age of 27.87 Ma, but ages were also calculated to yield an age of 28.02 Ma on sanidine from the Fish Canyon Tuff (Renne et al., 1998) by adjusting the flux constant (Table 1). Potassium and argon isotopic abundances and the decay constants for 40K used are those recommended by Steiger and Jaeger (1977). Corrections for neutron-induced interferences were made using correction factors determined by analyzing argon from irradiated fluorite and potassium glass. Plateau ages of Ar/Ar age spectra are defined as the weighted mean ages of contiguous gas fractions representing >50% of the 39Ar released for which no difference can be detected between the ages of any two fractions at the 95% level of confidence (Fleck et al., 1977). The Ar/Ar plateau and isochron ages from incremental-heating experiments were calculated using the Isoplot program of Ludwig (2003).

Laser incremental-heating 40Ar/39Ar dating experiments (Table 2) were performed at the Berkeley Geochronology Center on plagioclase phenocryst separates from two tuff samples (PF-1 and Lichau Creek), and single-crystal total-fusion 40Ar/39Ar dating on single pheno-
crysts from one tuff sample bearing a compositional range from anorthoclase to plagioclase (PF-3). (For preparation and analysis techniques at the Berkeley Geochronology Center, see Best et al., 1995; Deino et al., 1990; Deino and Potts, 1990; Sharp and Deino, 1996.) Dating results are summarized in Table 2. Sample PF-1 was analyzed in 6 separate experiments, 2 aliquots of 40–60 mesh (0.42–0.25 mm) and 4 aliquots of 20–40 mesh (0.84–0.42 mm) plagioclase. Results are quite similar throughout in radiogenic 40Ar content, Ca/K ratio, and presence of apparent-age plateaus in the 5.41–5.26 Ma

Figure 2. Simplified geologic map of the northern San Francisco Bay region modified from Langenheim et al. (2010). Locations of wells discussed in the text: Bethlehem #1 near Point Pinole; Murphy #1 east of Petaluma; Texaco Nobel #1 near Sears Point. Faults in San Pablo Bay are from Wright and Smith (1992) and Parsons et al. (2003). Abbreviations: BM—Bennett Mountain; BV—Bennett Valley; CB—Cotati basin; CC—Carriger Creek; CV—Carneros Valley; DR—Donnell Ranch; JL—Jack London State Park; L—Lakeville; LV—Lovall Valley; MP—Mount Pigsah; NV—Nunns Valley; PB—Petaluma basin; SR—Steinbeck Ranch; WB—Windsor basin; WSVF—West Sonoma Valley fault.
The preferred age for this sample is taken as the inverse isochron age of the plateau steps of the best of these experiments (run 22664–02), which yielded a detailed apparent-age plateau and stable, high radiogenic yield across the entire release of $^{39}$Ar. This age, $5.37 \pm 0.11$ Ma (1σ), is concordant with measures of the central tendency of this suite, such as the weighted mean (5.31 Ma) and median (5.33 Ma) of the isochron results.

The plagioclase separate of the tuff of Lichau Creek was analyzed by $^{40}$Ar/$^{39}$Ar incremental heating, with and without a 3 min 7% HF leaching bath during the mineral preparation phase. In some cases HF leaching can improve the likelihood of obtaining a precise eruptive age from plagioclase during incremental heating, or conversely may have a detrimental effect; the...
ultimate result is difficult to predict in advance. In this case, the treatments yielded mutually concordant apparent-age plateaus encompassing 100% of the 39Ar release, but the untreated fraction retained a much higher radiogenic yield in the higher temperature range of the experiment. The isochron result from the untreated experiment, 6.71 ± 0.04 Ma, provides the preferred age for this sample.

Single-crystal laser-fusion dating was performed on sample PF-3. Ca/K ratios obtained as a byproduct of the 40Ar/39Ar age measurement range from typical plagioclase down to low-Ca plagioclase and/or anorthoclase. Both the lower and higher Ca/K components yield the same age within error. The isochron age of the entire suite gives the preferred age of 4.88 ± 0.06 Ma for this sample. Note that the combined probability distribution is skewed toward older ages, leaving open the possibility that the result is biased by anomalously old material and is slightly too old.

Tephrochronology

Tephra from 46 tuff samples collected during this investigation were analyzed chemically and petrographically in order to correlate them with tuffs of known sources and ages (Tables 3 and 4). The methods used to analyze the glass were electron microprobe analysis, X-ray fluorescence spectrometric analysis (both wavelength dispersive and energy dispersive), and instrumental neutron activation analysis. (For detailed descriptions of sample processing methods, methods of petrographic and chemical analyses of the volcanic glass, and methods of data evaluation and correlation of tephra units, see Sarna-Wojcicki, 1971, 1976, 2000; Sarna-Wojcicki and Davis, 1991; Sarna-Wojcicki et al., 1979, 1984, 1987, 1991, 2011.)

Tephra from different sources within the Sonoma Volcanics can be distinguished from each other as well as tephra from other volcanic fields (Sarna-Wojcicki et al., 2011; Tables 3 and 4). The tuffs erupted from the Sonoma volcanic field that provide significant time markers for this investigation are the tuff of Zamaroni Quarry, the tuff of Lichau Creek, the Roblar Tuff, the Lawlor Tuff, the Huichica Tuff, the tuff of Napa (Healdsburg), and the Putah Tuff (Table 4). The Carriger Creek tuff was erupted from an unknown source outside of the Sonoma volcanic field, but is a valuable marker in the Sonoma and Kenwood Valleys. Other exotic tuffs from known sources, such as the Nomlaki Tuff and Ishii tuff from Lassen Peak, as well as tuff from eastern California and Nevada, have also been identified, though they are not as useful as time markers.
TABLE 2. RADIOMETRIC AGES DETERMINED AT THE BERKELEY GEOPHYSICOLGY CENTER, BERKELEY, CALIFORNIA

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Material</th>
<th>Age (Ma ± 1σ)*</th>
<th>MSWD</th>
<th>n/n_{exp}</th>
<th>% 39Ar</th>
<th>Integrated age (Ma ± 1σ)</th>
<th>Age M.S.E.</th>
<th>Inverse isochron M.S.E.</th>
<th>MSWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>25096-01</td>
<td>Pl</td>
<td>6.69 ± 0.04</td>
<td>0.8</td>
<td>14/14</td>
<td>100.0</td>
<td>6.70 ± 0.07</td>
<td>6.64 ± 0.05</td>
<td>296 ± 1</td>
<td>0.7</td>
</tr>
<tr>
<td>25097-01</td>
<td>Pl</td>
<td>6.71 ± 0.03</td>
<td>1.6</td>
<td>16/16</td>
<td>100.0</td>
<td>6.76 ± 0.05</td>
<td>6.71 ± 0.04</td>
<td>297 ± 2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

PF-1 (Unnamed tuff in Petaluma Formation; 38.236°N, 122.487°W), coarse air-fall lapillistone 30–50 cm thick in diatomite

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Material</th>
<th>Age (Ma ± 1σ)*</th>
<th>MSWD</th>
<th>n/n_{exp}</th>
<th>% 39Ar</th>
<th>Integrated age (Ma ± 1σ)</th>
<th>Age M.S.E.</th>
<th>Inverse isochron M.S.E.</th>
<th>MSWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>22662-01</td>
<td>Pl</td>
<td>5.41 ± 0.13</td>
<td>5.06</td>
<td>10/10</td>
<td>80.9</td>
<td>5.02 ± 0.11</td>
<td>5.19 ± 0.26</td>
<td>296 ± 20</td>
<td>2.5</td>
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<tr>
<td>22662-02</td>
<td>Pl</td>
<td>5.26 ± 0.15</td>
<td>1.8</td>
<td>5/9</td>
<td>71.6</td>
<td>5.64 ± 0.13</td>
<td>5.08 ± 0.17</td>
<td>361 ± 38</td>
<td>1.0</td>
</tr>
<tr>
<td>22664-01</td>
<td>Pl</td>
<td>5.36 ± 0.09</td>
<td>0.2</td>
<td>7/7</td>
<td>100.0</td>
<td>5.33 ± 0.12</td>
<td>5.29 ± 0.09</td>
<td>297 ± 8</td>
<td>0.2</td>
</tr>
<tr>
<td>22664-02</td>
<td>Pl</td>
<td>5.36 ± 0.08</td>
<td>0.9</td>
<td>14/14</td>
<td>100.0</td>
<td>5.43 ± 0.11</td>
<td>5.37 ± 0.11</td>
<td>290 ± 26</td>
<td>1.0</td>
</tr>
<tr>
<td>22664-03</td>
<td>Pl</td>
<td>5.36 ± 0.08</td>
<td>0.3</td>
<td>12/13</td>
<td>87.9</td>
<td>5.49 ± 0.11</td>
<td>5.45 ± 0.14</td>
<td>275 ± 26</td>
<td>0.3</td>
</tr>
<tr>
<td>22664-04</td>
<td>Pl</td>
<td>5.36 ± 0.09</td>
<td>0.5</td>
<td>3/10</td>
<td>50.1</td>
<td>7.71 ± 0.10</td>
<td>7.67 ± 0.25</td>
<td>376 ± 102</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: Weighted-mean ages are shown in italics immediately beneath the experiments for each sample or mineral. Boxes indicate preferred age for a sample. Integrated age for the single-crystal total-fusion experiment refers to weighted mean age of all analyses before filtering. An—anorthoclase; Pl—plagioclase; MSWD—mean square of weighted deviations; M.S.E.—the modified standard error, calculated as the standard error multiplied by square root of MSWD if MSWD is >1.

An example of the utility of tephrochrono-
logical correlations is displayed in Figure 4, which shows stratigraphic relationships across the Rodgers Creek fault. Lithologically similar strata on both sides of the fault were mapped by Weaver (1949) and many subsequent investiga-
tors as undivided Petaluma Formation. How-
ever, the tephra assemblage interbedded with the middle part of the Petaluma Formation west of the fault consists of Zamaroni, Lichau, and Roblar tuffs, indicating an age range of 7.26–
6.26 Ma. East of the fault, however, the tephra assem-
bale consisting of the Pinole, Lawlor, Carriger, Napa (Healdsburg), and Putah tuffs indicate an age range of ca. 5.4 to ca. 3 Ma. Thus the sediment interbedded with these tuffs is the younger, upper part of the Petaluma Formation. As discussed in more detail herein, the volcanic and sedimentary units young to the north, evi-
dence that the juxtaposition of these lithologi-
cally similar strata of different ages indicates significant right-lateral displacement.

GEOLOGIC AND TECTONIC SETTING

The basement rocks of the California Coast Ranges north of San Francisco Bay consist of the Mesozoic rocks of the Franciscan Complex, the Great Valley Sequence, and the Jurassic Coast Range ophiolite (Fig. 2). The Franciscan rocks constitute a Jurassic–Tertiary subduction complex composed of highly deformed, accreted oceanic sediments and volcanic rocks interpersed with fragments of mafic oceanic crust. Blake et al. (1984) subdivided the Franciscan Complex into tectonostratigraphic terranes, regionally extensive, fault-bounded, geologic entities with geologic histories distinct from adjacent terranes. Juxtaposition of the Franciscan terranes is the result of accretionary tectonics since the Cretaceous (Dumitru et al., 2010) and later transform tectonics of the San Andreas system during the Neogene. The Great Valley Sequence is largely coeval with the Franciscan Complex and consists of forearc basin depo-
sits that overlie the Coast Range ophiolite in the western Sacramento Valley and lap onto the Klamath Mountains to the north and the Sierra Nevada to the east. In the Coast Ranges to the west, however, Great Valley strata and ophiolite tectonically overlie, or are imbricated with, the Franciscan Complex. In the eastern part of the mapped area, the Mesozoic basement is over-
lain by Paleogene marine formations such as the Eocene Domengine Sandstone, Nortonville Shale, and the Markley Formation. In the Carneros and southern Napa Valleys, Neogene marine strata of the San Pablo Group and possibly older sedi-
ments (Weaver, 1949) overlie the basement and locally underlie the Sonoma Volcanics.

Late Cenozoic volcanic rocks of the northern San Francisco Bay region are part of a linear belt of volcanic fields (Fig. 1) that are progressively younger to the northwest (Fox et al., 1985a). Several investigators (Fox, 1983, McLaughlin et al., 1996; Wakabayashi, 1999; Graymer et al., 2002b) recognized that parts of these volcanic fields are fault-bounded and have been displaced from their original depositional positions by dextral faults of the East Bay fault system (Fig. 1). The oldest field is represented by ca. 11 Ma lava flows that cap Burdell Mountain in northern Marin and southern Sonoma Counties (Ford, 2007; Figs. 1 and 3). Two lithologically similar but younger volcanic sequences are exposed in the southern Sonoma Mountains, the Donnell Ranch volcanics of Youngman (1989) and the Sonoma Volcanics (Fig. 3). Both younger sequences consist of rhyolite overlain by and interbedded with mafic breccia, lava flows, and, in contrast to the Burdell Mountain Volcanics, contain abundant tuff. The Donnell Ranch volcanics of Youngman (1989) are the older of the two, ranging from 10.6 to 8.5 Ma (Fox et al., 1985b; Youngman 1989), and are west of the Rodgers Creek fault. Rocks of the Sonoma Volcanics are found on both sides of the Rodgers Creek fault and range in age from ca. 8.2 to 2.5 Ma (Fox et al., 1985b; Youngman, 1989; Randolph-Loar, 2002, McLaughlin et al. 2005; Wagner et al., 2005; Sweetkind et al., 2005b). Rhyolite and rhyodacite yielding dates of 8.17–7.4 Ma (Fox et al., 1985b; Youngman, 1989) were interpreted by Youngman (1989) to be Donnell Ranch volcanics that were thrust over younger rocks of the Sonoma Volcanics; however, we interpret these rocks as part of the Sonoma volcanic field. New dating performed as part of this project (Table 1) as well as stratigraphic relationships indicate that the Donnell Ranch volcanics of Youngman (1989) are cor-
relative with the Tolay Volcanics described by Morse and Bailey (1935) from the Murphy #1 (Fig. 1) well in the Petaluma oil field.

Late Cenozoic sedimentary rocks of northern California were deposited in basins that formed in response to transform tectonics–associated northward migration of the Mendocino triple
<table>
<thead>
<tr>
<th>Locality #</th>
<th>Sample #</th>
<th>7.5' quadrangle</th>
<th>Tephra unit</th>
<th>UTM coordinates (NAD 27)</th>
<th>Inferred age</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW-SP-7-2001</td>
<td>Sears Point</td>
<td>Roblar tuff</td>
<td>546146* 4225125*</td>
<td>6.26 Ma</td>
<td>West of Tolay fault</td>
<td></td>
</tr>
<tr>
<td>DW-SP-8-2001</td>
<td>do</td>
<td>Roblar tuff</td>
<td>547177* 4222883*</td>
<td>do</td>
<td>Overlies Franciscan</td>
<td></td>
</tr>
<tr>
<td>DW-SP-64-2001</td>
<td>do</td>
<td>Roblar tuff</td>
<td>544285* 4226269*</td>
<td>do</td>
<td>do</td>
<td></td>
</tr>
<tr>
<td>DW-SP-65-2001</td>
<td>do</td>
<td>Roblar tuff</td>
<td>do</td>
<td>do</td>
<td>do</td>
<td></td>
</tr>
<tr>
<td>DW-69-SP-2002</td>
<td>do</td>
<td>?</td>
<td>544989* 4232173*</td>
<td>5.37 ± 0.11 Ma</td>
<td>Near PF-1, Table 5.37 ± 0.11 Ma</td>
<td></td>
</tr>
<tr>
<td>DW-35-GE 2002</td>
<td>Glen Ellen</td>
<td>Pinole Tuff</td>
<td>539707* 4240839*</td>
<td>5.2–5.4 Ma</td>
<td>Ishi Tuff ca. 2.5 Ma; closer to Nomlaki</td>
<td></td>
</tr>
<tr>
<td>DW-101-GE 2003</td>
<td>do</td>
<td>KT-35</td>
<td>543320* 4235287*</td>
<td>3.3 to ca. 2.5 Ma</td>
<td>Kettleman Hills, California; above Nomlaki Tuff 3.3 Ma and below</td>
<td></td>
</tr>
<tr>
<td>DW-119-GE 2003</td>
<td>do</td>
<td>Petrified Forest</td>
<td>542411* 4237269*</td>
<td>≥ 3.19 Ma</td>
<td>Uppermost layer at Petrified Forest</td>
<td></td>
</tr>
<tr>
<td>DW-123-GE 2003</td>
<td>do</td>
<td>?</td>
<td>538409* 4241298*</td>
<td>4.88 ± 0.06 Ma</td>
<td>Unusual composition, no close match</td>
<td></td>
</tr>
<tr>
<td>DW-127A-GE-2003</td>
<td>do</td>
<td>Carrierg Creek tuff?</td>
<td>540377* 4239168*</td>
<td>3.35–3.27 Ma</td>
<td>Closest match is KT-1 Kettleman Hills</td>
<td></td>
</tr>
<tr>
<td>DW-135-GE 2003</td>
<td>do</td>
<td>Carrierg Creek tuff</td>
<td>540277* 4239168*</td>
<td>4.88 ± 0.06 Ma</td>
<td>No reasonable match</td>
<td></td>
</tr>
<tr>
<td>DW-152-GE 2003</td>
<td>do</td>
<td>Tuff of Napa (Healdsburg)</td>
<td>538082* 4249746*</td>
<td>≤ 4.70–4.71 Ma</td>
<td>Pumice fragment in andesitic ash-flow tuff</td>
<td></td>
</tr>
<tr>
<td>DW-150-GE 2003</td>
<td>do</td>
<td>Tuff of Zamaroni Quarry</td>
<td>534557* 4241162*</td>
<td>7.26 ± 0.03 Ma</td>
<td>Matches vent breccia of Zamaroni Quarry and tephra layers in the area</td>
<td></td>
</tr>
<tr>
<td>DW-151-GE 2003</td>
<td>do</td>
<td>Roblar tuff</td>
<td>535957* 4237269*</td>
<td>6.26 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-157-GE 2003</td>
<td>do</td>
<td>Tuff of Napa (Healdsburg)</td>
<td>536260 4247021</td>
<td>≤ 4.70–4.71 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-158-GE 2003</td>
<td>do</td>
<td>Huichica Tuff</td>
<td>5373342 4246045</td>
<td>4.76 ± 0.05 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-159-GE 2003</td>
<td>do</td>
<td>Tuff of Napa (Healdsburg)</td>
<td>537975 4246584</td>
<td>≤ 4.70–4.71 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-160-GE 2003</td>
<td>do</td>
<td>Tuff of Geyser Peak Road</td>
<td>540810 4246554</td>
<td>3.35–3.27 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-164-GE 2003</td>
<td>do</td>
<td>Tuff of Geyser Peak Road</td>
<td>542032 4243845</td>
<td>3.22 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-171-GE 2006</td>
<td>do</td>
<td>Lawlor Tuff</td>
<td>532787 4246075</td>
<td>4.82 ± 0.02 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-174-GE 2006</td>
<td>do</td>
<td>do</td>
<td>533284 4245763</td>
<td>do</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-176-GE 2006</td>
<td>do</td>
<td>Mark West Springs tuff</td>
<td>532760 4246570</td>
<td>≤ 4.83 Ma</td>
<td>Close to locality dated by Fox et al. (1985b), K/Ar 3.95 Ma (BH71-2)</td>
<td></td>
</tr>
<tr>
<td>DW-172-GE 2006</td>
<td>Cotati</td>
<td>Zamaroni Quarry?</td>
<td>536510 4248574</td>
<td>7.26 ± 0.03 Ma</td>
<td>Matches matrix of rhyodacite breccia at Sears Point</td>
<td></td>
</tr>
<tr>
<td>DW-35a-Na 2004</td>
<td>Napa</td>
<td>Pinole?</td>
<td>534826 2433901</td>
<td>5.4–5.2 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-35b-Na 2004</td>
<td>do</td>
<td>Pinole?</td>
<td>do</td>
<td>do</td>
<td>do</td>
<td></td>
</tr>
<tr>
<td>DW-41-Son 2004</td>
<td>Sonoma</td>
<td>Tuff in Coller Cyn syncline</td>
<td>549107 4243649</td>
<td>ca. 7 Ma</td>
<td>Tassajara area; stratigraphically near Roblar tuff, 6.26 Ma</td>
<td></td>
</tr>
<tr>
<td>DW-40-Son-2004</td>
<td>do</td>
<td>Coal Valley tuff?</td>
<td>553033 4239475</td>
<td>11.1 Ma</td>
<td>2-m-thick tuff in San Pablo Group. Coal Valley tuff is in Nevada</td>
<td></td>
</tr>
<tr>
<td>DW-102-Son</td>
<td>do</td>
<td>Lawlor Tuff</td>
<td>550499 4246333</td>
<td>4.82 ± 0.02 Ma</td>
<td>Overlies andesite of Bismarck Knob</td>
<td></td>
</tr>
<tr>
<td>DW-01-KW 2007</td>
<td>Kenwood</td>
<td>Carrierg Creek tuff</td>
<td>538990 4250304</td>
<td>4.88 ± 0.06 Ma</td>
<td>Also close to tuff of Pepperwood Ranch, 3.22 Ma</td>
<td></td>
</tr>
<tr>
<td>DW-05-KW 2007</td>
<td>do</td>
<td>Tuff of Geyser Peak Road</td>
<td>533659 4248050</td>
<td>3.22 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-06-KW 2007</td>
<td>do</td>
<td>Tuff of Napa (Healdsburg)</td>
<td>534930 4243861</td>
<td>≤ 4.70–4.71 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-09-KW 2007</td>
<td>do</td>
<td>do</td>
<td>537654 4248146</td>
<td>do</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-10-KW 2007</td>
<td>do</td>
<td>do</td>
<td>536863 4247806</td>
<td>do</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-12-KW 2007</td>
<td>do</td>
<td>Mark West Springs Tuff</td>
<td>540566 4248829</td>
<td>≤ 5 to &gt; 4.82 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-17-KW 2007</td>
<td>do</td>
<td>do</td>
<td>538593 4251970</td>
<td>do</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-19-KW 2007</td>
<td>do</td>
<td>No match</td>
<td>542956 4253326</td>
<td>do</td>
<td>Probably exotic; does not match Sonoma Volcanics</td>
<td></td>
</tr>
<tr>
<td>DW-22-KW 2007</td>
<td>do</td>
<td>Roblar tuff</td>
<td>543359 4251281</td>
<td>6.26 Ma</td>
<td>Farthest northeast occurrence of Roblar tuff</td>
<td></td>
</tr>
<tr>
<td>DW-177-GE 2007</td>
<td>Glen Ellen</td>
<td>Tuff below Napa (Healdsburg)</td>
<td>536540 4244221</td>
<td>≤ 4.70 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-181-GE 2008</td>
<td>do</td>
<td>Huichica Tuff</td>
<td>537392 4246297</td>
<td>4.76 ± 0.05 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-182-GE 2008</td>
<td>do</td>
<td>Putah Tuff?</td>
<td>537468 4246094</td>
<td>3.35–3.27 Ma</td>
<td>Closest match is DW-137-GE</td>
<td></td>
</tr>
<tr>
<td>DW-183-GE 2008</td>
<td>do</td>
<td>Tuff of Napa (Healdsburg)</td>
<td>537908 4246094</td>
<td>≤ 4.70–4.71 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW-60-Son-2008</td>
<td>Sonoma</td>
<td>Lawlor Tuff?</td>
<td>546526 4245767</td>
<td>4.82 ± 0.02 Ma</td>
<td>Poor match</td>
<td></td>
</tr>
<tr>
<td>DW-13-KW 2008</td>
<td>do</td>
<td>Putah Tuff?</td>
<td>539632 4249977</td>
<td>do</td>
<td>Possibly a mixture of Putah Tuff and Roblar tuff?</td>
<td></td>
</tr>
</tbody>
</table>

Note: UTM—Universal Transverse Mercator; NAD—North American Datum; do—ditto; Cyn—Canyon.
Southern Sonoma volcanic field

Junction and development of the San Andreas fault system (Nilsen and Clarke, 1989). Two of these basins, as defined by Nilsen and Clarke (1989), the Santa Rosa basin north of San Pablo Bay and the Livermore basin south of the bay are discussed herein. There are three subbasins within the Santa Rosa basin (Fig. 2), the Petaluma, Cotati, and Windsor basins (McLaughlin et al., 2008; Langenheim et al., 2010). Miocene–Pliocene sedimentary formations in the Santa Rosa basin include the marine Wilson Grove Formation, the fluvial, estuarine, and lacustrine Petaluma Formation, and the littoral sand and gravel of Cotati. Unconformably overlying these units are the Pliocene–Pleistocene terrestrial deposits of the Huichica Formation, and the Glen Ellen Formation (Weaver, 1949; Fox, 1983). The Livermore basin, also referred to as the Contra Costa basin (Creely et al., 1982), includes the Miocene Contra Costa Group (Wagner, 1978; Creely et al., 1982; Graham et al., 1984). Parts of the Petaluma Formation are correlative with parts of the Contra Costa Group (Taliaferro, 1951; Graham et al., 1984; Allen, 2003). Linecki-Laporte and Andersen (1988) demonstrated that the Contra Costa basin was once continuous with the Petaluma basin, which now is 38 km to the northwest. Prior to dismemberment in the Miocene, there was a transition from a primarily alluvial environment in the eastern Contra Costa basin (Wagner, 1978; Graham et al., 1984) to a fluvial-lacustrine-estuarine environment in the western Contra Costa and Petaluma basins (Linecki-Laporte and Andersen, 1988; Allen,

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**TABLE 4. SUMMARY OF TEPHRA USED FOR CORRELATIONS IN THIS INVESTIGATION ALONG WITH THEIR AGES AND ERUPTIVE SOURCES**

<table>
<thead>
<tr>
<th>Tuff</th>
<th>Age (Ma)</th>
<th>Eruptive center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuff of Pepperwood Ranch</td>
<td>3.22 ± 0.02</td>
<td>Mount Saint Helena</td>
</tr>
<tr>
<td>Tuff of Geyser Peak Road</td>
<td>3.22</td>
<td>Mount Saint Helena</td>
</tr>
<tr>
<td>Putah Tuff</td>
<td>3.27–3.35</td>
<td>Mount Saint Helena</td>
</tr>
<tr>
<td>Tuff of Napa (Healdsburg)</td>
<td>4.70–4.71 ± 0.03</td>
<td>Napa Valley (Cup and Saucer)</td>
</tr>
<tr>
<td>Huichica Tuff</td>
<td>4.76 ± 0.05</td>
<td>Napa Valley (Cup and Saucer)</td>
</tr>
<tr>
<td>Lawlor Tuff</td>
<td>4.84 ± 0.02</td>
<td>Napa Valley (Cup and Saucer)</td>
</tr>
<tr>
<td>Tuff of Mark West Springs</td>
<td>&gt;4.84 &lt; 5</td>
<td>Napa Valley (Cup and Saucer)</td>
</tr>
<tr>
<td>Pinole Tuff</td>
<td>5.2–5.4</td>
<td>Napa Valley (Cup and Saucer)</td>
</tr>
<tr>
<td>Roblar tuff</td>
<td>6.25 ± 0.03</td>
<td>Zamaroni Quarry–San Pablo Bay</td>
</tr>
<tr>
<td>Tuff of Lichau Creek</td>
<td>6.71 ± 0.04</td>
<td>Zamaroni Quarry–San Pablo Bay</td>
</tr>
<tr>
<td>Tuff of Zamaroni Quarry</td>
<td>7.26 ± 0.03</td>
<td>Zamaroni Quarry–San Pablo Bay</td>
</tr>
</tbody>
</table>

---

**Figure 4. A chart showing generalized stratigraphic relationships of Neogene units in the Petaluma Valley, Sonoma Mountains, Sonoma Valley, and Mayacamas Mountains. West of the Rodgers Creek fault, tephra, including the tuff of Zamaroni Quarry (7.26 Ma), the Lichau Creek tuff (6.74 Ma), and the Roblar tuff (6.26 Ma), were erupted from the Zamaroni Quarry–San Pablo Bay volcanic center. East of the Rodgers Creek fault, the tephra assemblage is younger, including the Pinole Tuff (5.2–5.4 Ma), the Lawlor Tuff (4.84 Ma), the Carriger tuff (4.81 Ma), the tuff of Napa (Healdsburg) (4.76 Ma), and the Putah Tuff (3.27–3.35 Ma). The Petaluma Formation is divided in a lower unit (Tpl), a middle unit (Tpm) (after Allen, 2003), and an upper unit (Tpu) based on this investigation. Other units are the marine Neroly Formation, Tolay Volcanics (Tov), Sonoma Volcanics undivided (Tsv), lower Sonoma (Tsvl) and upper Sonoma (Tsvu) Volcanics, sand and gravel of Cotati (Tco), Wilson Grove Formation (Twg), and Glen Ellen Formation (QTge).**
show that these rocks are within the age range of the Tolay Volcanics. The largest exposure of volcanics assigned to the Burdell Mountain Volcanics is at Spring Hill, south of Petaluma. Here the volcanics are overlain by Petaluma Formation (Bezore et al., 2002) similar to the basal Petaluma Formation and/or Tolay Volcanics section on the Donnell Ranch, suggesting these are Tolay Volcanics rather than Burdell Mountain Volcanics. Although more Ar/Ar dating in the Petaluma-Cotati area is needed, we tentatively assign most of the volcanic rocks in this area to the Tolay Volcanics.

Wakabayashi (1999) reported an 40Ar/39Ar age of 12.9 ± 0.1 Ma on a body of mafic volcanic rock in western Petaluma. This date is difficult to interpret because it is significantly older than Burdell Mountain Volcanics dated at Burdell Mountain (10.59–11.18 Ma). If the rock dated by Wakabayashi (1999) is considered to belong to the Burdell Mountain Volcanics, then its age range would exceed that of the Quen Sabe Volcanics. An intriguing possibility is that the mafic volcanic rock dated by Wakabayashi (1999) is the result of volcanism related to an earlier 12.2 Ma hydrothermal system that affected this area (McLaughlin et al. 1996).

Tolay Volcanics Including the Donnell Ranch Volcanics

Morse and Bailey (1935) applied the name Tolay Volcanics to a sequence of rhyolite, andesite, and basalt at least 1220 m thick that was penetrated by the Murphy #1 well (Fig. 2) in the Petaluma oil field. They also applied the name to a small patch of mafic volcanics along the Tolay fault, near Lakeville. As discussed in the previous section, volcanic rocks in the Meacham Hill area and along the west margin of the Petaluma Valley are here considered to be part of the Tolay Volcanics. A silicic body west of Cotati, termed the Cotati rhyolite plug by Graymer et al. (2002b), was also dated in the age range of the Tolay Volcanics.

The Donnell Ranch volcanics were informally named by Youngman (1989) for surface exposures of mafic flows, tuff, breccia, and rhyolite that occur between the Rodgers Creek and Tolay faults from Sears Point northward to Lakeville. The Donnell Ranch volcanics of Youngman (1989) unconf ormably overlies rocks of the Franciscan Complex and are conformably overlain by the Petaluma Formation (Wagner et al., 2002a). Youngman (1989) interpreted the Donnell Ranch volcanics to be emplaced as thrust sheets or flower structures that extend outward for hundreds of meters on both sides of the Rogers Creek fault. Mapping by Randolph-Loar (2002) and Wagner et al. (2002a) confirms that on the west side of the Rodgers Creek fault the Donnell Ranch volcanics of Youngman (1989) are locally expressed as klippen thrust over younger Petaluma Formation strata. The thrusts are west dipping, away from the Rodgers Creek fault, but verge to the east toward the fault, as indicated by overturning of Petaluma strata to the east beneath the thrust klippen of the older Tolay Volcanics (Randolph-Loar, 2002). Youngman (1989) interpreted silicic volcanic rocks east of the Rodgers Creek fault to be thrust klippen of the Donnell Ranch volcanics of Youngman (1989) emplaced over Sonoma Volcanics. Randolph-Loar (2002) and Wagner et al. (2002a) interpreted all the rocks east of the Rodgers Creek fault as the Sonoma Volcanics with no local thrust sheet of the Donnell Ranch volcanics as mapped by Youngman (1989).

Basalt, basaltic andesite lava flows and breccia, as well as rhyolitic to dacitic lava flows and tuff, are the predominant lithologies in the Donnell Ranch volcanics of Youngman (1989). Basalt and basaltic andesite have yielded ages of 10.64–8.49 Ma (Youngman, 1989; Fox et al., 1985b). An Ar/Ar date of 8.52 Ma (Youngman, 1989) was obtained from an andesite lava flow that is interbedded with the lowermost part of the overlying Petaluma Formation northeast of Tolay Creek (Fox et al., 1985b). A depositional contact between basalt and overlying chert in the Petaluma Formation is exposed in the same area. These relationships provide evidence that the Donnell Ranch volcanics of Youngman (1989) both underlie and are interbedded with the lower Petaluma Formation.

Cebull (1958) was the first to suggest the interbedded Petaluma Formation and volcanic rocks along Tolay Creek are correlative to the so-called Transition zone between the Petaluma Formation and the Tolay Volcanics in the Murphy #1 well (Morse and Bailey, 1935). Two new 40Ar/39Ar dates (Table 1) from andesite samples from the Murphy #1 core are 8.99 ± 0.06 Ma (755 m depth) and 9.13 ± 0.06 Ma (1148 m depth). These dates indicate that the Tolay Volcanics in the Murphy well are the same age as the Donnell Ranch volcanics of Youngman (1989). Our mapping, together with the Ar/Ar dates, confirms that the Transition zone (Cebull, 1958) is exposed along Tolay Creek and that the Donnell Ranch volcanics of Youngman (1989) are a surface exposure of the Tolay Volcanics of Morse and Bailey (1935). Silicic lava flows and tuff southwest of Tolay Creek, previously mapped as the Pliocene St. Helena Rhyolite (Weaver, 1949; Cebull, 1958), are here also considered as part of the Tolay Volcanics because of a K/Ar date on plagioclase of 9.56 ± 0.15 Ma (Fox et al., 1985b).
Silicic lava flows and tuff assigned here to be Tolay Volcanics range in age from 9.86 to 9.56 Ma, while silicic rocks assigned to be Sonoma Volcanics range in age from 8.17 to 7.37 Ma. We also assign the volcanic rocks between the Petaluma Valley and Burdell Mountain faults to the Tolay Volcanics (Fig. 3), with the possible exception of the body dated by Wakabayashi (1999) discussed in the previous section.

The Tolay Volcanics are truncated by the Rodgers Creek fault in the southern Sonoma Mountains and extend southward beneath San Pablo Bay. Basalt from the Texas Noble #1 well just west of the Rodgers Creek fault in the tidelands north of San Pablo Bay (Fig. 2) yielded a K/Ar date of 9.2 ± 0.0 Ma, within the age range of the Tolay Volcanics. Volcanic rocks penetrated by the Bethlehem #1 well in San Pablo Bay near Point Pinole (Fig. 2), east of the Hayward fault, yielded a K/Ar date of 12 Ma (Wright and Smith, 1992). The 40Ar/39Ar dating has shown that many K/Ar dates on mafic rocks in the North Bay region are too old, so this date may be questionable, but we assume these are also the Tolay Volcanics. A magnetic anomaly interpreted to be due to volcanic rocks (Wright and Smith, 1992; Parsons et al., 2003) extends across San Pablo Bay nearly to Point Pinole.

Louderback (1951) and Taliaferro (1951) were the first geologists to suggest that the Tolay Volcanics beneath and interbedded with the Petaluma Formation in the Murphy #1 well are equivalent to the Berkeley Hills volcanics. Youngman (1989) later demonstrated that the trace element chemistry of the Tolay Volcanics (her Donnell volcanics) is identical with that of the Berkeley Hills volcanics and distinct from the Sonoma Volcanics.

Sonoma Volcanics

Basalt, basaltic andesite, rhyolite, rhyodacite, and dacite, and interbedded tuff of the Sonoma Volcanics crop out over an area of ~3100 km² (Mankinen, 1972). Osmont (1905) was the first to describe the volcanic field and divided these rocks into three units: the Mark West Andesite overlain by the Sonoma Tuff, and the uppermost St. Helena Rhyolite. Dickerson (1922) applied the name Sonoma Group, but Morse and Bailey (1935) informally applied the name in use today, the Sonoma Volcanics. Weaver (1949) formalized the name the Sonoma Volcanics, designating the lava flows, breccia, and tuffs on Sonoma Mountain, that locally are interbedded with sandstone, gravel, and conglomerate, as the type area. Fox (1983) divided the Sonoma Volcanics into a lower member that occupies most of the southwestern part of the field, and an upper member that occupies the eastern and northern parts of the field. Fox et al. (1985b) informally divided the lower member into five units: the andesite of Rodgers Creek, the rhyolite of Arrowhead Mountain, the rhyolite of Bismarck Knob, the andesite of Atlas Peak, and the soda rhyolite of Sugarloaf Ridge. Fox et al. (1985b) also divided the upper member of the Sonoma Volcanics into five informal units: the rhyolite of Mount George, the tuff breccia of Napa, the andesite of Tulucay Creek, the tuff of Petrified Forest, and the rhyolite of Calistoga. All of these informal units are accepted herein, except the andesite of Rodgers Creek, which is not a mappable unit and is here abandoned.

Based on existing radiometric dates from Mankinen (1972), Fox et al. (1985b), Youngman (1989), and our data (Table 1), the Sonoma volcanic field can be separated spatially and temporally into three age groups (McLaughlin et al., 1996; Wakabayashi, 1999; Fig. 3). The oldest group (WSV in Fig. 3) ranges in age from 8.17 Ma to 4 Ma, generally occurs in the southern and western part of the field, and for the most part conforms to the lower member of Fox et al. (1985b). The middle age group of ca. 5.4–3.4 Ma includes parts of both the upper and lower members of Fox et al. (1985b) and generally occupies the east-central part of the field (ESV in Fig. 3). The youngest part of the Sonoma Volcanics (NSV in Fig. 3) is in the northern part of the field, where dates range from 2.5 to ca. 3.4 Ma, and is entirely in the upper member of Fox et al. (1985b).

The western age group is the most extensive and has the widest age range (8.17–4 Ma) of the three shown in Figure 3. Within it, we recognize five volcanic-sedimentary assemblages. These assemblages have thicknesses of tens to hundreds of meters, and extend laterally from 5 km to more than 10 km. In the Sonoma Mountain area there are the Sonoma Mountain and the Sonoma Creek assemblages and in the Mayacmas Mountains there are the Arrowhead Mountain, the Bismarck Knob, and the Sugar Loaf Ridge assemblages. In the following we characterize each assemblage by describing a stratigraphic column for each one.

Sonoma Mountain Assemblage

This assemblage (Fig. 5) extends from the Sears Point area north to Bennett Valley and corresponds to the type area of the Sonoma Volcanics of Weaver (1949). The basal part of the Sonoma Mountain assemblage is a distinctive deposit of rhyolite to rhyodacite breccia, conglomerate, sand, and gravel that is exposed on the east side of the Rodgers Creek fault a few kilometers north of Sears Point. Boulders and blocks 1 m or more across are set in a tuffaceous matrix and are interbedded with sediments that are almost entirely rhyodacite detritus deposited by debris flow and fluvial processes. Occasional layers of pebbly sand identical to the Petaluma Formation are intercalated with the silicic detritus. Radiometric dates (40Ar/39Ar) on breccia clasts range from 8.17 to 7.3 Ma (Youngman, 1989; Table 1), providing maximum ages of the deposit. Tuffaceous matrix from the breccia is chemically similar to several tuffs erupted from the Zamaroni Quarry volcanic center near Santa Rosa, providing a loosely constrained depositional age of 7.26–6.26 Ma (Table 4). A similar breccia exposed along Warrington Road on the Santa Rosa quadrangle, west of the Rodgers Creek fault, 28 km to the north, yielded nearly identical ages and chemistry. McLaughlin et al. (2005, 2008) interpreted the breccia at both localities to be derived from the Cooks Peak rhyodacite on the Santa Rosa quadrangle, during initiation of slip on the Rodgers Creek fault.

The silicic breccia interfingers with and is overlain by a sequence of 7.36–5.08 Ma andesitic flows and tuffs along with minor rhyolite and basalt that compose the middle part of the section. The thickness of the sequence is variable, but reaches a maximum of ~250 m on the east slope of southern Sonoma Mountain, where it forms a northeast-dipping limb of an antcline (Fig. 6) that trends obliquely toward and is truncated by the Rodgers Creek fault. The Sonoma Mountain assemblage is truncated by east-west-trending reverse faults along the northern slope of Sonoma Mountain. Along the western slope of Sonoma Mountain, the Rodgers Creek fault separates Sonoma Volcanics from the Tolay Volcanics and the Petaluma Formation. To the north, along the east margin of Petaluma Valley, the situation is more complex, where Sonoma Volcanics occur on both sides of the fault. West of the fault, Sonoma Volcanics overlie moderately to steeply east-dipping strata of the Petaluma Formation along a nearly flat contact (Fig. 7). Youngman (1989) obtained an 40Ar/39Ar date of 7.37 Ma on an andesite outlier, which she considered to be a klippe overlying Petaluma Formation. The Petaluma Formation in this area contains the 6.26 Ma Roblar tuff, indicating that it is younger than the overlying Sonoma Volcanics. This older over younger relationship shows that the Sonoma Volcanics west of the Rodgers Creek fault are out of place due to landsliding and/or thrusting. This relationship seems to extend north to the vicinity east of Cotati. Northeast of Cotati, the Sonoma Volcanics west of the Rodgers Creek fault have dips similar to those of the Petaluma Formation and appear to be in place.

A sedimentary sequence consisting of diatomite, lignite, siltstone, sandstone, and conglomerate...
erate belonging to the upper part of the Petaluma Formation unconformably overlies the older volcanic rocks and interbedded older Petaluma Formation that make up the middle part of the Sonoma Mountain assemblage (Fig. 5). These sedimentary rocks are, in turn, conformably overlain along a gradational contact by a tuffaceous volcanic sequence that makes up the bulk of the northern part of Sonoma Mountain. (Restricted access seriously hampered mapping on the northern crest and slope of Sonoma Mountain, so the stratigraphic details of the area are not well understood.) This sequence is as much as 120 m thick, or thicker, at the north part of Sonoma Mountain and thins southward to <100 m in the Carriger Creek area. It is composed of silicic and andesitic tuffs overlain by basalt on the crest of Sonoma Mountain. These intermediate and silicic pyroclastic strata include the Huichica Tuff (4.76 Ma) and the tuff of Napa (4.71 Ma). The basalt flows that cap the section yielded an \(^{40}\text{Ar}/^{39}\text{Ar}\) date of 4.1 Ma (sample DW-124-GE, Table 1).

**Sonoma Creek Assemblage**

The Sonoma Creek assemblage (Fig. 5) overlies older Sonoma Volcanics, is mostly composed of tuff, and extends northward from the town of Glen Ellen to the south slope of Bennett Mountain. The assemblage is also found along the southwest margin of the Kenwood Valley. It is interbedded with and is essentially a tuffaceous equivalent of the upper part of the Petaluma Formation. It contains the tuff of Mark West Springs, the 4.88 Ma Carriger tuff, the 4.84 Ma Lawlor Tuff, the 4.70–4.71 Ma tuff of Napa (Healdsburg), and the 3.27–3.35 Ma Putah Tuff (Table 4). A K/Ar date of 5.66 Ma by Mankinen (1972) on a tuff from the south slope of Bennett Mountain is the oldest reported age for the section. The tuff of Mark West Springs (4.83–5.2 Ma) has been identified at two places (localities 37 and 38, Table 3) along the southwest margin of Kenwood Valley. The Carriger Creek tuff was identified at one locality southwest of Kenwood (locality 32, Table 3). The tuff of Napa (Healdsburg) is the most extensive tuff in the section. Originally identified near and named for Healdsburg, this tuff was later was renamed tuff of Napa because it erupted from the Napa Valley center (Sarna-Wojcicki et al., 2011). In most outcrops it is a distinctive brown color and contains dark pumice fragments to 2–3 cm in diameter. Locally, however, the tuff is white and cannot be identified in hand specimen. Areas underlain by the tuff have a distinctive rolling topography easily mistaken for landslides.

White, pumiceous ash-flow tuff and reworked tuff exposed in the hills around and north of Glen Ellen were included in the Glen Ellen Formation by Weaver (1949). This tuff was correlated with the Putah Tuff during this investigation, so it is here assigned to the Sonoma Volcanics. Fox et al. (1973) had considered it as part of the undivided Huichica and Glen Ellen Formations. Fox et al. (1985b) later included the tuff in the Huichica Formation because they believed it to be the same age as a tuff in the type locality of the Huichica Formation. The tuff in the type locality of the Huichica Formation, now known as the Huichica Tuff, is 4.76 Ma (Sarna-Wojcicki et al., 2011), significantly older than the Putah Tuff (3.27–3.33 Ma).

**Arrowhead Mountain Assemblage**

This assemblage (Fig. 8) extends from the southernmost part of the Mayacamas Range northward to at least Sugar Loaf Ridge. It unconformably overlies the Neroly Formation. In the southern Mayacamas Mountains the assemblage consists of a series of andesite flows and interbedded tuff, the rhyolite of Arrowhead Mountain of Fox et al. (1985b), and well-bedded lithic tuff in Lovall Valley (Fig. 8). The age of the oldest part of the assemblage is constrained by the age of the underlying Neroly Formation (ca.
10 Ma or older) and two fission track dates (Fox et al., 1985b). The older fission track date, 7.9 ± 0.8 Ma, is from a tuff interbedded with distinctive andesite flows near the town of Sonoma, informally named for Schocken Hill, which is on the north side of town. The andesite of Schocken Hill is a sequence of at least four flows of gray, aphyric andesite that are well exposed in the hills immediately north of the town of Sonoma. The other fission track date, 7.5 ± 1.8 Ma, is from the rhyolite on the north slope of Arrowhead Mountain that interferes with the andesite of Schocken Hill. Another sequence of west-dipping of andesite lava flows and tuff overlying the Neroly Formation makes up the ridge east of Lovall Valley and appears to dip beneath the rhyolite of Arrowhead Mountain, but it is not known if these flows are correlative with the andesite of Schocken Hill. Arrowhead Mountain is a rhyolite dome with lava flows and locally welded tuffs extending from it. Although the age of the rhyolite dome and the flows is similar to the age of the rhyodacite breccia in the Sears Point area, the lithology and mode of occurrence are quite different, making it unlikely that the two are the same unit.

The andesite of Schocken Hill and the rhyolite of Arrowhead Mountain extend northward along the western slope of the Mayacmas Mountains to the Kenwood Valley and dip 20°–40° toward the west. Just north of Schocken Hill, an intrusive andesite body (Wagner et al., 2004) appears to be a volcanic neck marking a strato-volcano that could be the source of the andesite of Schocken Hill and flows of gray, plagioclase-phryic, platy andesite, informally named the andesite of Mission Highlands. The andesite of Mission Highlands overlies the rhyolite of Arrowhead Mountain along the western flank of the Mayacmas Mountains and it also dips southwest toward Sonoma Valley.

Mafic to silicic magmatism was episodic during the eruption of the volcanics in the western Mayacmas Range, as evidenced by plugs and dikes throughout the sequence that were feeders for local lava flows. One of the more voluminous episodes occurred between ca. 6.5 and 7.5 Ma, when mafic flows erupted along nearly the entire length of the assemblage. Although these rocks were called basalt, as a field term based on the presence of olivine phenocrysts, chemical analyses indicate they are trachyandesite (K. Piturka, 2004, personal commun.). In the Huichica Creek drainage in the southeastern corner of the Mayacmas Mountains, these olivine-phryic mafic flows underlie dacite and trachydacite flows dated as 6.673 ± 0.35 Ma (DW-94-SON, Table 1) that are herein informally named the dacite flows of Huichica Creek. These flows are dark, glassy lava with a variable phenocryst assemblage of plagioclase, pale olivine, amphibole, and/or pyroxene.

The upper part of the Arrowhead Mountain assemblage is a well-bedded tuff containing cobble- to boulder-sized lithics that underlies Lovall Valley. Lithic clasts are often cracked and have red oxidation rinds, indicating they were hot when emplaced. This tuff breccia and similar ones farther north have been interpreted as proximal throat-clearing breccias (J. Rytuba, 2007, personal commun.).

**Bismarck Knob Assemblage**

An assemblage of diatomaceous sediment and volcanic rocks is exposed on the west slope of Bismarck Knob, ~8 km north of Arrowhead Mountain (Fig. 8). This assemblage overlies the Arrowhead Mountain assemblage and extends ~6 km north to Sugar Loaf Ridge. The basal part of the assemblage is on the andesite of Mission Highlands and is informally named the lithic tuff breccia of Mount Pisgah; it is a throat-clearing breccia that is similar to and likely correlatable with of the lithic tuff breccia in the Lovall Valley. Diatomaceous lacustrine sediments are interbedded with the lithic tuff breccia. A tuff interbedded with the diatomite contains tephra that is chemically similar to and possibly correlatable with tuffs in the Tassajara area near Mount Diablo, suggesting an age of ca. 6.2 Ma (locality 29, Table 3). Dacitic lava erupted into a lake or wetlands environment, where it interacted with water to form hyaloclastite. This dacitic volcanism is similar in age though slightly younger than the dacitic lava flows in the Huichica Creek area in the Arrowhead Mountain sequence to the south. Another tuff along strike farther north in lithic tuff breccia correlates with the 6.26 Ma Roblar tuff (locality 40, Table 3).
At Bismarck Knob on the crest of the range there is a succession of basalt, andesite, and rhyolite. The lower unit, informally named the basalt of Bismarck Knob, is a plagioclase-pyroxene-olivine-phyric flow basalt. It is the only true basalt known in the western Mayacamas Range section, based on chemical data (K. Pitoa, 2004, personal commun.). Overlying the basalt is a massive andesite flow. At the top of the sequence is the informally named rhyolite of Bismarck Knob (Fox, 1983), which is a dome with associated flows, tuffs, boulder breccia, and minor water-laid sediments. Sani-dine from a single block of vitrophyre yielded an 40Ar/39Ar age of 6.14 ± 0.061 Ma (sample DW-101a-SON, Table 1). Lobes of the rhyolite of Bismarck Knob extend as far south as Lovall Valley, where it overlaps the rhyolite of Arrowhead Mountain. In places it is a welded and lithoidal tuff. East of Bismarck Knob, this rhyolite is truncated by the Carneros fault and possibly displaced to the southeast at least 4 km where it laps onto the Great Valley Sequence. Immediately east of Bismarck Knob, across the Carneros fault, there is an ash-flow tuff that overlies the Great Valley Sequence in juxtaposition with the rhyolite. Pumice fragments collected near the base of the tuff correlate with the Lawlor Tuff (locality 31, Table 3). Basalt flows overlie both the rhyolite of Bismarck Knob and the ash-flow tuff. The basalt is in the same stratigraphic position as the basalt flows that cap Sonoma Mountain that were dated as 4.1 Ma (Table 1).

**Sugarloaf Ridge Assemblage**

The Sugarloaf Ridge assemblage, exposed ~6 km north of Bismarck Knob, is composed of silicic and mafic tuff, lava flows, and agglomerate (Fig. 8). The Sugarloaf Ridge assemblage is in fault contact with Mesozoic rocks on the east, and to the west it dips into the Kenwood area. Its northern extent is uncertain, but rocks mapped by McLaughlin et al. (2008) in the northeastern corner of the Santa Rosa quadrangle appear to be correlative. The Sugarloaf Ridge assemblage overlies rocks that are equivalent to the Arrowhead Mountain assemblage, that in turn overlie the Neroly Formation (Fig. 8). A lithic tuff breccia exposed in Nunn’s Valley contains the 6.26 Ma Roblar tuff (locality 4, Table 3). This is the northeasternmost occurrence yet known for the Roblar, and shows that the tuff breccia in Nunn’s Valley is equivalent to the lithic tuff breccia at Mount Pisgah in the Bismarck Knob assemblage and possibly to the tuff breccia in Lovall Valley. Near the top of the breccia there are interbeds of aphryic andesite that yielded 40Ar/39Ar dates of ca. 5.6 and ca. 5.7 Ma (localities 10 and 11, Table 1). A welded rhyolite tuff interbedded with the lithic breccia and the aphryic andesite yielded a date of 5.65 Ma (locality 4, Table 1). These 5–6 Ma and older flows and tuffs appear to be a continuation of the Bismarck Knob assemblage. The Sugarloaf Ridge assemblage is a volcanic edifice of rhyolite and andesite possibly as old as 5.3 Ma but mostly ca. 4.8 Ma and younger, and was built on the older substrate. The oldest exposed unit Sugarloaf Ridge assemblage is the Rhyolite of Adobe Canyon, which has a K/Ar date of 5.3 ± 0.2 Ma (Mankinen, 1972). A tuff containing tephra that correlates with the tuff of Mark West Springs (5.2–4.84 Ma) overlies the Rhyolite of Adobe Canyon. A body of sodic amphibole-bearing rhyolite, called the soda rhyolite of Sugarloaf Ridge by Fox et al. (1985b), overlies the tuff. An 40Ar/39Ar date of 4.83 Ma (locality 6, Table 1) was obtained for the soda rhyolite. Fox et al. (1985b) believed it to be extrusive and interbedded with andesite flows that overlie the Rhyolite of Adobe Canyon. The soda rhyolite is nearly the same age as the Lawlor Tuff, though their chemistry and petrography are different (Sarna-Wojcicki et al., 2011). Above the soda rhyolite is a thick, mafic, coarsely lithic tuff breccia interpreted to be a throat-clearing breccia proximal to a vent (J. Rytuba, 2007, personal commun.). At least two andesite flows are interbedded with the breccia. Intrusive basaltic andesite forms the arcuate Sugarloaf Ridge, and in places basaltic andesite ring dikes intruded and locally
overturned well-bedded lithic tuff breccia. Two associated basaltic andesite near-vent breccia deposits contain volcanic bombs, twisted spindles, and agglomerate, and are separated by an unconformity. We interpret the vent facies mafic rocks as intracaldera fill. A partially welded, crystal-vitic tuff exposed within the arcuate structure yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 4.806 Ma (locality 5, Table 1) and may also be an intracaldera tuff. Langenheim et al. (2010) interpreted the arcuate topography, as well as local gravity and magnetic anomalies, as a possible caldera.

Across the Kenwood Valley, northwest of Kenwood, basaltic andesite apparently flowed westward from the caldera down a paleochannel that contained ash-flow tuff as well as reworked tuffaceous channel deposits. The ash-flow tuff contains a tephra that correlates with the tuff of Mark West Springs (4.83–5.0 Ma.) (locality 37, Table 3) and reworked tephras that have chemical similarities to the Putah Tuff and/or Roblar tuff (locality 46, Table 3). We suggest that these flows emanated from the Sugarloaf Ridge caldera and flowed westward, prior to the opening of the Kenwood Valley.

**Volcanic Centers**

We recognize three volcanic centers in the Sonoma Volcanic field that are the eruptive sources for tephra that have proven useful for tephrochronological correlations (Table 4; Fig. 3): the Zamaroni Quarry–San Pablo Bay volcanic center (McLaughlin et al., 2005; Sarna-Wojcicki et al., 2011), the Napa Valley center (McLaughlin et al., 2005; Sweetkind et al., 2011; Sarna-Wojcicki et al., 2011), and the Mount Saint Helena caldera (Sweetkind et al., 2005a). There are other volcanic centers in and around Napa Valley, notably the andesitic stratovolcano at Stags Leap (Sweetkind et al., 2005a), but they have not been correlated with tuffs in the Sonoma Volcanic field, so they will not be discussed here. We recognize at least five smaller volcanic centers in the Mayacamas Mountains, including a rhyolite dome at Arrowhead Mountain (Fox et al., 1985b), a possible andesitic stratovolcano in the highlands near Sonoma, a rhyolite dome near Bismarck Knob, and a possible caldera and ring dike at Sugar Loaf Ridge. In addition there are small, mostly mafic intrusions, cinder cones, fissure eruptions, dikes, sills, and plugs throughout the Mayacamas Mountains and on Sonoma Mountain that are too numerous to describe individually. At Annadel State Park on Bennett Mountain, there are intrusive rhyolite, massive rhyolite flows and breccia, some of which contain obsidian, and ash-flow tuff (Higgins, 1983).

**Zamaroni Quarry–San Pablo Bay Volcanic Center**

Rhyodacitic intrusives, flows, tuff, and breccia exposed west of the Rodger Creek fault at the Zamaroni Quarry on the west margin of the Santa Rosa Plain, just south of Santa Rosa, have an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 7.26 Ma (McLaughlin et al., 2005). A southeast extension of the rhyodacite at nearby Cook Peak has an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 7.94 Ma (McLaughlin et al., 2008). A sedimentary breccia exposed in the same area was interpreted by McLaughlin et al. (2005) to be a basin-margin fault scarp breccia or a debris avalanche deposit. We interpret these rhyodacitic rocks to be part of a volcanic center that was truncated by the Rodgers Creek fault. Rhyodacite of the same age (7.84–7.96 Ma, Table 2) and identical sedimentary breccia are exposed east of the Rodgers Creek fault 28 km to the southeast. We suggest that the volcanic center at Zamaroni Quarry was displaced along the Rodgers Creek fault from the San Pablo Bay volcanic center that is now concealed beneath San Pablo Bay and/or Sonoma Valley. Wells drilled around the margin of San Pablo Bay penetrated agglomerate (Wright and Smith, 1992), which may reflect the presence of the volcanic center. Wright and Smith’s (1992, p. 416, a-a′ and b-b′) cross sections show the volcanics extending beneath San Pablo Bay.

**Napa Valley Volcanic Center**

The Napa Valley eruptive center is a caldera complex (Sweetkind et al., 2005a) marked by a physiographic feature called the Cup and Saucer on the Napa quadrangle (Fig. 2). Aeromagnetic and gravity data (Langenheim et al., 2010) suggest that the caldera complex extends from the Cup and Saucer westward beneath Napa Valley to the West Napa fault. Several of the tuffs known to have been erupted from the Napa Valley center have been identified in the upper Petaluma Formation and in the Sonoma Volcanics, notably between Bennett and Kenwood Valleys. The oldest of these is the 5.4–5.2 Ma Pinole Tuff. There has been some question as to whether the Pinole Tuff was erupted from the Napa Valley center or another volcanic center in the vicinity of San Pablo Bay (Olderback, 1951; Sarna-Wojcicki, 1976). Its chemistry is similar to intracaldera andesite breccia (Sweetkind et al., 2011), suggesting that the Napa Valley eruptive center is the source of the Pinole Tuff. Four younger tuffs also erupted from the Napa Valley volcanic center, the tuff of Mark West Springs (5–4.8 Ma), the Lawlor Tuff (4.84 Ma), the Huichica Tuff (4.71 Ma), and the tuff of Napa (Healdsburg) (≤4.70–4.71 Ma) have been found in the sediments in southwestern Bennett Valley, on Sonoma Mountain, in the Sonoma Volcanics in the Santa Rosa area (McLaughlin et al., 2008; Sarna-Wojcicki et al., 2011), and in the Mayacamas Mountains northeast of Bismarck Knob. All of the aforementioned tuffs have also been found in the Mount George area east of Napa, where they are associated with aprons of proximal vent facies flows and domes (Sweetkind et al., 2011). Proximal vent facies rocks, as well as these tuffs, have not been found in the Sonoma Volcanics exposed on the west side of the West Napa fault at the latitude of the Napa Valley volcanic center (Sarna-Wojcicki et al., 2011) where one would expect to see the western outflow facies rocks.

**Rhyolite Dome at Arrowhead Mountain**

Arrowhead Mountain in the southern Mayacamas Mountains is a dome and the source of 7.5 Ma (Fox et al., 1985b) rhyolite lava flows and tuff. Arrowhead Mountain is the oldest of several eruptive centers in the Mayacamas Mountains that young to the north. Rhyolitic lava flows and tuff were erupted from the dome at Arrowhead Mountain about the same time the San Pablo Bay center was active, but whether there is a direct relationship is unknown. Rhyolite flows emanating from the dome near Bismarck Knob to the north overlap rhyolite flows of Arrowhead Mountain.

**Stratovolcano Near Sonoma**

In the hills north of Sonoma there are near-vent breccias and at least one conical intrusive that is dacitic to andesitic. In addition to the intrusive, there are exceptionally thick andesite lava flows. We speculate that the intrusion is a volcanic neck that is a remnant of a stratovolcano that is the source for the mafic lava flow that are so prevalent in this area.

**Rhyolite Dome at Bismarck Knob**

On the northwest slope of Bismarck Knob, there are bulbous ridges of vitric rhyolite tuffs and lava flows. A sample of perlitic pitchstone (sample DW-101a-SON, Table 1) yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 6.143 ± 0.0061 Ma. Rhyolite with vertical flow banding is exposed in the deep stream canyons cut into the west slope of Bismarck Knob.
Possible Sugarloaf Ridge Caldera

Sugarloaf Ridge is an arcuate topographic high suggesting the presence of a caldera, and a localized gravity low (Langenheim et al., 2010) also suggests that there may be a small caldera there. The structure and lithology of the rocks of the Sugarloaf Ridge assemblage are similar and the age range is the same as that of the rocks at the Napa Valley eruptive center. West of Sugarloaf Ridge across Kenwood Valley, there are flows, domes, and tuffs, including the 4.51 Ma obsidian-bearing rhyolite (Higgins, 1983; McLaughlin et al., 2008; Delattre et al., 2007) at Annadel State Park on the east slope of Bennett Mountain. Its chemistry suggests that it is related to the Napa Valley volcanic center (McLaughlin et al., 2005, their Fig. 2.3b). Inasmuch as it is flow rock, it must have been proximal to a volcanic center, presumably the supposed Sugarloaf Ridge caldera. The Lawlor Tuff and the tuff of Napa are widespread between Kenwood Valley and Bennett Valley. The tuff of Napa contains pumice fragments larger than 2 cm, suggesting that it is proximal. We suggest that the basaltic andesite flows emanating from the supposed Sugarloaf Ridge caldera, the Lawlor Tuff, the tuff of Napa, and obsidian rhyolite flows at Annadel State Park make up the near-vent apron deposited on the west flank of the Napa Valley volcanic center, ~30 km to the southeast, that was subsequently displaced to its present location along the Carneros and West Napa faults.

Pliocene Basalt Flows

Basalt flows that cap Sonoma Mountain and the Mayacamas Mountains near Bismarck Knob, as well as basalt flows near Glen Ellen, provide important constraints on the opening of the Sonoma Valley. Basalt flows capping Sonoma Mountain were dated as 4.1 ± 0.1 Ma (sample DW-124 GE, Table 1), and basalt flows capping the Mayacamas Mountains between Bismarck Knob and Mount Veeder overlie tuff that contains tephra correlated with the 4.84 Ma Lawlor Tuff (locality 31, Table 3), suggesting that they could be equivalent. An undated basaltic center east of Glen Ellen (Berkland, 2001) produced basalt flows and breccia that underlie the middle to Late Oligocene fossils in the Carneros Valley. The age of the San Ramon Sandstone, based on the fossils, is uncertain (Fox, 1983; Graymer et al., 2002a), and it appears that the presence of the Kerker Tuff is crucial for age control. Although there are poor exposures of tuffaceous sediment where Weaver (1949) mapped San Ramon Sandstone, no tuff bed was found during mapping for this investigation (Wagner et al., 2004; Clahan et al., 2004). Given the importance the San Ramon Sandstone and the Kerker Tuff to paleogeographic restorations involving the Carneros Valley fault (Fox, 1983), more documentation is clearly needed. Wright and Smith (1992) reported sediments assigned to other formations of the Monterey Group in the subsurface of Sonoma Valley.

Neroly Formation

Marine sandstone and volcanioclastic sediments of the Neroly Formation underlie the Sonoma Volcanics in the Carneros Valley and in the Nunns Valley area in the Mayacamas Mountains (Weaver, 1949). In Carneros Valley the Neroly Formation dips west beneath the Sonoma Volcanics and can be traced in the subsurface southwest into the southern Sonoma Valley (Wright and Smith, 1992, p. 416; D. Ziegler, 2004, personal commun.). A tuff interbedded with the Neroly Formation in Carneros Valley contains tephra that correlates with the Coal Valley tuff in Nevada that is ca. 11.1 Ma (locality 42, Table 3). These occurrences of the Neroly Formation mark the northernmost part of an open marine basin that received detritus from the east (Buising and Walker, 1995).

SEDIMENTARY ROCKS

Mesozoic rocks and sediments of the Franciscan Complex and Great Valley Sequence, as well as Paleogene–Neogene sediments, underlie the Sonoma Volcanics (Fig. 2). The Petaluma Formation, the Glen Ellen Formation, the Huichica Formation, and various unnamed Plio–Pleistocene sediments interfinger with and overlie the Sonoma Volcanics. Detailed descriptions of the older units, mostly Eocene marine strata and the Mesozoic sediments, are beyond the scope of this report, but they are described briefly in the following. Instead we focus on Late Miocene and Pliocene units that bear directly on the Neogene paleogeography and history of faulting in the North Bay region.

Monterey Shale and San Ramon Sandstone

Weaver (1949) mapped narrow belts of Monterey Shale, a formation of the Monterey Group, and the San Ramon Sandstone and reported middle to Late Oligocene fossils in the Carneros Valley. The age of the San Ramon Sandstone, based on the fossils, is uncertain (Fox, 1983; Graymer et al., 2002a), and it appears that the presence of the Kerker Tuff is crucial for age control. Although there are poor exposures of tuffaceous sediment where Weaver (1949) mapped San Ramon Sandstone, no tuff bed was found during mapping for this investigation (Wagner et al., 2004; Clahan et al., 2004). Given the importance the San Ramon Sandstone and the Kerker Tuff to paleogeographic restorations involving the Carneros Valley fault (Fox, 1983), more documentation is clearly needed. Wright and Smith (1992) reported sediments assigned to other formations of the Monterey Group in the subsurface of Sonoma Valley.

Mount Saint Helena Volcanic Center

Mount Saint Helena is a caldera with a series of resurgent domes (Sweetkind et al., 2005a). Thick deposits of Putah Tuff (3.27–3.35 Ma) that erupted from the Mount Saint Helena caldera to the northeast (Fig. 4) are exposed along Sonoma Creek from Kenwood to Glen Ellen. Here the Putah Tuff underlies the Glen Ellen Formation and overlies the upper part of the Petaluma Formation. In addition to the Putah Tuff, a tuff that may be equivalent to the tuff of Geyser Peak (3.22 Ma) or the tuff of Pepperwood Ranch has also been identified (locality 33, Table 3).
Lower Petaluma Formation. Well-bedded lacustrine and estuarine sediments with some possible marine interbeds (Peterson and Allen, 2005) exposed along Tolay Creek make up the lower Petaluma Formation. Morse and Bailey (1935) described a gradational contact between the lowermost sediments and the underlying Tolay Volcanics in the Murphy #1 well, which they termed the Transition zone. This zone consists of massive to laminated mudstone with ostracode-rich intervals, cream-colored dolomite interbeds (Fig. 9A), and volcanic interbeds. Cebull (1958) mapped a similar section along Tolay Creek to the south and suggested it is the same Transitional zone. Wagner et al. (2002a) mapped a depositional contact between the Petaluma Formation and the Tolay Volcanics (Donnell Ranch volcanics) along Tolay Creek that were dated as 9.2 Ma, nearly the same age (Table 1) as the Tolay Volcanics in the Murphy #1 well. This supports the suggestion of Cebull (1958). A date of 8.52 Ma on an interbed of Tolay Volcanics and a date of 9.28 Ma on Tolay Volcanics below the Petaluma Formation (Youngman, 1989) constrains the age of the base of the Petaluma in this area to ca. 9 Ma.

Middle Petaluma Formation. The middle part of the Petaluma Formation consists of mudstone that grades upward into a section dominated by fluvial sandstone (Fig. 9B) and gravel containing abundant Franciscan detritus. Lacustrine and estuarine intervals persist well up into the middle Petaluma, but the upper part is mostly fluvial (Starratt et al., 2005). There are abundant megafauna, petrified and carbonized wood, lignite, and a sparse mammalian fauna (Weaver, 1949; Allen 2003). The middle Petaluma Formation is the most widespread of the three subunits, cropping out along the west slope of Sonoma Mountain west to Meacham Hill where it interfingers with the marine Wilson Grove Formation. It has been mapped along the west side of the Rodgers Creek fault from Sears Point to the Santa Rosa area, where it is interbedded with the Sonoma Volcanics (McLaughlin et al. 2008). The middle Petaluma Formation is present in the subsurface (McLaughlin et al., 2008; Sweetkind et al., 2010) and exposed along the western margin of the Santa Rosa Plain. East of the Rodgers Creek fault, on southernmost Sonoma Mountain, interbeds of gravel identical to that of the middle Petaluma of Allen (2003) are found within the Sonoma Volcanics that are from 8 to 5 Ma. A distinctive feature of the middle part of the Petaluma formation is the presence of chips of laminated siliceous shale derived from the Claremont Shale of the Monterey Group (Morse and Bailey, 1935; Allen, 2003). The tuff of Zamaroni Quarry (7.26 Ma), the tuff of Lichau Creek (6.71 Ma, Table 2), and the Roblar tuff (6.26 Ma) are interbedded with this part of the Petaluma Formation.

Upper Petaluma Formation. Tuffaceous sandstone and gravel interbedded with diatomite (Fig. 9C) and lignite belonging to the upper part of the Petaluma Formation are interbedded with the Sonoma Volcanics in the Santa Rosa area, Bennett Valley, and on the west side of Sonoma Valley. Sandstone and gravel of the upper Petaluma

Figure 9. (A) Folded dolomite in the lower Petaluma Formation in Tolay Valley. (B) Fluvial sandstone overlying lacustrine and estuarine siltstone in the middle part of the Petaluma Formation. The field of view is about 0.5 m. (C) Well-bedded sandstone, tuff and diatomite in the upper part of the Petaluma Formation exposed along Graham Creek in Jack London State Park.
Formation are lithologically indistinguishable from those of the middle Petaluma Formation. Fox (1983) and Fox et al. (1985b) considered these sediments to belong to the Huichica Formation and Grayner et al. (2007) considered them to be part of sand and gravel of Cotati. Based on the presence of sparse marine fossils, Powell et al. (2004, p. 10, 23) considered some of these sediments in Bennett Valley to be part of the Wilson Grove Formation. Apparently the Petaluma Formation sediments in Bennett Valley interfinger with the Pliocene part of the Wilson Grove Formation in Bennett Valley and possibly in the Santa Rosa area.

A distinctive tephra assemblage that is younger than tephra found in the older parts of the Petaluma strata in the Petaluma and Cotati area is characteristic upper Petaluma Formation. Thick diatomite contains several tephra layers, including Lawlor Tuff and the tuff of Mark West Springs, which together indicate an age of 4.83 Ma for this section (Tables 3 and 4). The locality of the tuff that is similar to the Mark West Springs is very close to or the same as a locality that yielded a sample dated as 3.95 ± 0.32 Ma (BH71–2 of Fox et al., 1985a) using the K/Ar method. Based on this date, Fox et al. (1985a) assigned these strata to the Huichica Formation. Given the revised age of 4.76 Ma for the Huichica Tuff in the type locality (Table 4) and differing lithologies in the two areas, the correlation of Fox et al. (1985a) does not appear to be correct. Rather, based on the revised age of the tephra this section is considered equivalent to a lithologically similar section at Carriger Creek ~10 km to the south. In the southwest part of Bennett Valley, McLaughlin et al. (2008) mapped a gently folded section of diatomaceous Petaluma Formation that is here considered to be part of the upper Petaluma Formation. McLaughlin et al. (2008) also mapped a folded section of diatomaceous Petaluma Formation west of the Rodgers Creek fault in Santa Rosa that is here suggested to be correlative with the upper Petaluma Formation in Bennett Valley. This indicates there was a connection between Bennett Valley and the Cotati basin during deposition of the upper part of the Petaluma Formation.

Although exposures are poor, upper Petaluma sediments can be traced along the east slope of Sonoma Mountain from the Donnell Ranch northwest to the Carriger Creek area and then northward to Graham Creek at the north boundary of Jack London State Park. Sparse exposures of diatomite-bearing sediments along the west slope of Sonoma Mountain suggest that the sediments of the upper Petaluma Formation extend beneath the mountain. Unfortunately the stratigraphic relations in this area are obscured by the Bennett Valley fault zone and large-scale landsliding. Near Carriger Creek, an exposure of tuff interbedded with diatomite, sand, and well-sorted pebble gravel has a K/Ar age of 11.83 Ma (Fox et al., 1985b), which was then considered the maximum age for the Petaluma Formation. However, the diatomite contains diatoms with Pliocene affinities (S. Sturatt, 2002, personal commun.). A date of 4.88 ± 0.06 Ma (Table 2) on tuff from the same locality using 40Ar/39Ar indicates that these sediments are part of the upper Petaluma Formation and are nearly coeval with the 4.84 Ma Lawlor Tuff. However, the chemistry is incompatible with an eruptive source within the Sonoma Volcanics, showing that it is not Lawlor Tuff. Nevertheless, the tuff is a good marker and has been informally referred to as the tuff of Carriger Creek in this paper. Another tephra collected along Carriger Creek (locality 12, Table 3) is possibly equivalent to the Pinole Tuff. To the south at the Donnell Ranch, a tuff interbedded with diatomite appears to be a mixture of more than one tuff based on the trace element chemistry. An 40Ar/39Ar date of 5.37 ± 0.11 Ma (PF-1, Table 2) on a sample from this locality indicates an age within the range for Pinole Tuff, so it may correlate with the Pinole Tuff (5.4–5.2 Ma). These data provide a maximum age of ca. 5.3 Ma for the upper part of the Petaluma Formation in this area.

Although there was a brief marine transgression during the latest Miocene or earliest Pliocene (Powell et al., 2004), most of the upper Petaluma sediments were deposited in freshwater lakes and or wetlands. Along Carriger Creek basalt flows interbedded with the upper Petaluma Formation overlie burned vegetation, showing that it was a volcanically active setting. Although the upper Petaluma Formation contains more freshwater diatomite, lignite, and petrified wood characteristic of lacustrine and wetland environments than the dominantly fluvial middle Petaluma Formation, the presence of the of the Pinole Tuff and younger tuffs (Table 4) is required to conclusively identify the upper Petaluma Formation.

Wilson Grove Formation

The Wilson Grove Formation was named by Fox (1983) for marine sediments formerly considered to be correlative with the Merced Formation on the San Francisco Peninsula (Weaver, 1949). The Wilson Grove Formation extends north from Petaluma to north of Santa Rosa and west to the Sonoma County coast. Powell et al. (2004) divided the Wilson Grove Formation into three marine environments: (1) a deep-marine facies along the western margin, (2) a shallow-marine facies in the central portion of the formation, and (3) a marine and estuarine environment along the eastern margin of the outcrop area where the Wilson Grove Formation is interfingered with the nonmarine Petaluma Formation. At Steinbeck Ranch northwest of Meacham Hill, the 6.26 Ma Roblar tuff is interbedded with the Wilson Grove Formation ~105 m above its base (Allen, 2003), indicating that the Wilson Grove is Late Miocene in its southwestern part. It becomes progressively younger to the northeast to the Santa Rosa area, where it is possibly as young as late Pliocene (Powell et al., 2004). It is the marine equivalent of the Petaluma Formation, spanning the same age range.

Sand and Gravel of Cotati

Fox (1983) named the sand and gravel of Cotati and considered it to be Pliocene–Pleistocene and to overlie the Wilson Grove Formation. Davies (1986) described it as a member of the Wilson Grove Formation. Allen (2003) and McLaughlin et al. (2005) considered it to be a transitional lithofacies interbedded with the marine Wilson Grove Formation and the fluvial and/ or estuarine Petaluma Formation. It is rich in laminated chert pebbles derived from the Claremont Shale of the Monterey Group. Many of the pebbles are polishes, suggesting that at least part of the gravel is a beach deposit. In agreement with Allen (2003) and McLaughlin et al. (2005), we conclude that the sand and gravel of Cotati is a littoral deposit marking the shoreline between the fluvial-estuarine-lacustrine Petaluma Formation and marine Wilson Grove Formation.

Huichica Formation

Weaver (1949) named the Huichica Formation for gravelly deposits at the south end of the Mayacamas Mountains along Huichica Creek. Pebble- to cobble-sized clasts in the Huichica Formation are derived from the Franciscan Complex, the Great Valley Sequence, Tertiary marine formations, and the Sonoma Volcanics. The abundance and size of the Franciscan-derived material are curious because there is no nearby source. Well data (Ziegler et al., 2005) show that the Huichica Formation thickens dramatically to the southwest, suggesting a possible source of Franciscan material in that direction. Fox (1983) reported a K/Ar date of 3.94 Ma for a tuff interbed along Huichica Creek. Subsequent 40Ar/39Ar analysis of the same tuff has yielded what we consider to be a more reliable age of 4.76 Ma (Sarna-Wojcicki et al., 2011). Fox (1983) extended the Huichica to the northwest, including strata in Bennett Valley previously assigned to the Petaluma Formation by Weaver (1949), on the basis of tuffs of similar age and chemistry. Although the new date on the Huichica Tuff plus new tephrochronological correlations
presented herein (Table 3) show that Huichica Tuff is present in a volcanic section on the north slope of Sonoma Mountain above Bennett Valley, and in the Huichica Creek area, the clastic sediment that makes up most of the Huichica Formation in its type area is not found in Bennett Valley. Massive tuff along Sonoma Creek shown as Huichica Formation by Fox (1983) and Fox et al. (1985b) has now been assigned to the tuff of Napa–Healdsburg or the Putah Tuff. Sediments near Glen Ellen in the Sonoma Valley considered by Fox (1983) and Fox et al. (1985b) to be Huichica are here assigned to the Glen Ellen Formation.

**Glen Ellen Formation**

Weaver (1949) assigned the name Glen Ellen Formation to tuffaceous sand and gravel around the towns of Glen Ellen and Kenwood, and north to Rincon Valley and on the Santa Rosa Plain. The thickness of the Glen Ellen is variable; it overlies the upper part of the Petaluma Formation in Bennett Valley, and the Putah Tuff along Sonoma Creek in and around Glen Ellen. A tephra correlation of a tuff from near the base of the formation along Mill Creek near Glen Ellen indicates an age range between 3.19 Ma and ca. 3.4 Ma (location 6, Table 3) and the underlying Putah Tuff is 3.27–3.35 Ma, providing a well-constrained age for the base of the Glen Ellen Formation in the type area. Some of the sediments along the east side of Sonoma Mountain, originally mapped as Petaluma Formation (Weaver, 1949; Fox et al., 1973, 1985b), contain tephra similar to a tuff from Kettleman Hills with an age range of 3.33 to ca. 2.5 Ma (locality 6, Table 3) and a second tuff that is similar to a tuff in the upper part of the tuff of Petrified Forest that is younger than 3.27–3.35 Ma (locality 7, Fig. 3). These data indicate that these sediments are the basal part of the overlying Glen Ellen Formation and not Petaluma Formation, as shown on earlier maps (Weaver, 1949; Fox et al., 1973; Huffman and Armstrong, 1980).

**Megaslides on Sonoma Mountain**

Large-scale, deep-seated landslides are conspicuous on the slopes of Sonoma Mountain, particularly on the north part of the mountain. Both rotational and translational block slides have modified bedrock structure in significant ways, so recognition of them is critical. Most of them originated in Sonoma Volcanics and displaced masses of volcanic rock downslope and, in many instances, out into the valleys, where they are now out of stratigraphic position. The largest megaslide is on the west slope of Sonoma Mountain ~5 km north of Petaluma. It is ~2.5 km wide and its length is uncertain, but ~5 km. There are closed depressions along a well-developed headwall scar that is 60–70 m high. The toe of the slide is not evident in the toposhaphy so the full extent of the megaslide is not known. Observations by Michael Dwyer (2002, personal commun.), using 1:100,000-scale air photos, suggest that it could extend beneath the alluvium of Petaluma Valley. Small thrust faults dipping 20° east displacing gravel beds in the Petaluma Formation were observed along Lynch Creek aligned with a topographic break in slope at the bedrock alluvium contact. These small thrusts are consistent with compression near the toe of the megaslide, providing evidence that the toe is beneath the alluvium of the valley. Most of this megaslide is a relatively old, possibly early Quaternary, block slide. It is mantled with active landslides. The Rodgers Creek fault traverses the megalandslide, and topographic features indicative of faulting postdate slide features except in areas where active landslides are present. The amount of downslope movement is unknown, but it is possible that blocks of Sonoma Volcanics moved out into the valley, overriding the Petaluma Formation.

**FAULTS AND LATE NEOGENE TECTONIC EVOLUTION**

In the northern San Francisco Bay region, episodes of extensional, contractional, and dextral faulting ensued rapidly or even overlapped in time as the San Andreas transform margin developed progressively northward. The juxtaposition of the Burdell Mountain, Tolay, and Sonoma volcanic packages occurred during at least two episodes of dextral faulting; an older, slower one between ca. 11 Ma and ca. 6–7 Ma, and a younger, faster episode from ca. 6–7 Ma to the present (Graymer et al., 2002b).

**Rodgers Creek Fault Zone**

The Rodgers Creek fault zone is an active dextral fault that extends from San Pablo Bay to beyond Santa Rosa (Fig. 2). It has been mapped beneath San Pablo Bay (Wright and Smith, 1992; Parsons et al., 2003) but it has not been recognized south of the bay. McLaughlin et al. (2008) considered the Healdsburg fault to be a northern segment of the Rodgers Creek fault.

Estimates of total displacement range from 45 km (Loudenback, 1951; Fox et al., 1985a; Curtis, 1989; Youngman, 1989) to 28 km (Sarna-Wojcicki, 1992) to as little as 5 km or less (Allen, 2003). The Rodgers Creek fault displays abundant geomorphic evidence of activity and, along with the Hayward fault, is considered by the Working Group on California Earthquake Probabilities 2007 (Field et al., 2007) as one of the most likely San Francisco Bay area faults to produce a major earthquake in the next 30 yr. It has been zoned as an Earthquake Hazard zone pursuant to the Alquist–Priolo Earthquake Fault Zoning Act. McLaughlin et al. (2005, 2008) discussed the evolution and displacement history of the Rodgers Creek fault in detail, so it is discussed briefly here.

In a palinspastic reconstruction of the Roblar tuff (Sarna-Wojcicki, 1992), 28 km of displacement on the Rodgers Creek fault since 6.26 Ma was suggested. As discussed earlier, rhyodacite breccia at Sears Point has been correlated to a similar breccia along Warrington Road on the Santa Rosa quadrangle, indicating ~28 km of displacement along the Rodgers Creek fault since 6.26 Ma, corroborating the reconstruction in Sarna-Wojcicki (1992). The interpretation of 5 km or less displacement along the Rodgers Creek fault (Allen, 2003) is based on radiometric dates of ca. 7.3 Ma reported by Youngman (1989) on andesite on both sides of the fault. Based on evidence presented herein, the dated andesite west of the Rodgers Creek fault is allochthonous, emplaced from the east side of the Rodgers Creek fault by thrusting, landsliding, or a combination of the two. Landsliding appears to be more likely since thrust faulting in this area has been shown to be east vergent and megalandslides are common along this segment of the Rodgers Creek fault.

Although geomorphic features indicative of Holocene activity abound along the Rodgers Creek fault (Hart, 1992; Randolph-Loar, 2002), there have been no large earthquakes documented along the fault for at least 200 yr (Wong, 1991; Budding et al., 1991; Hecker et al., 2005). Paleoseismological investigations conducted along the southern Rodgers Creek fault (Budding et al., 1991; Schwartz et al., 1992; Randolph-Loar, 2002) indicate late Holocene slip rates of 6.4–10.4 mm/yr, consistent with the geologic slip rate of ~6.3 mm/yr for the past 1.2–0.8 m.y. (McLaughlin et al., 2005). An important issue regarding the seismogenic potential of the Rodgers Creek fault is whether it connects directly with the Hayward fault.

Geophysical data suggest there is a connection between the Hayward and the Rodgers Creek faults (Langenheim et al., 2010). In contrast, interpretation of geophysical and well data by Wright and Smith (1992) suggested an ~6 km right stepover between the Hayward and the Rodgers Creek faults. Parsons et al. (2003) showed compelling evidence for an extensional basin between the Hayward and Rodgers Creek faults beneath San Pablo Bay and that the closest approach of the faults is 4 km. Geophysical data

Geosphere, June 2011

675

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Tolay Fault Zone

The Tolay fault was named by Morse and Bailey (1935), who described it as a reverse fault extending southward from near Lakeville to Sears Point. They estimated 1363 m (4500 ft in Morse and Bailey, 1935) of dip-slip displacement along the fault that dips 60° to the west. Morse and Bailey (1935) mapped the Tolay to ~1 km (1.6 km) north of Lakeville, where they indicated it is truncated by a northeast-trending fault. Weaver (1949) suggested that the Tolay fault could be an extension of the Hayward fault. However, the Hayward and Tolay faults are not aligned and display different displacement histories, so a direct connection between the faults is not well supported. Huffman and Armstrong (1980) depicted the Tolay fault as a complex fault zone in bedrock west of the alluvium along Tolay Creek. Unfortunately, landowners would not allow access to their property so we were not able to make field observations in this area. Near Lakeville, the Tolay fault changes dramatically where it appears to be a single, nearly vertical fault juxtaposing Franciscan rocks to the west with the lower Petaluma Formation to the east. Whether this fault is the high-angle fault that cuts the thrusts, a steepened thrust fault, or a high-angle reverse fault (Morse and Bailey, 1935) is unknown at this point.

Weaver (1949) extended the Tolay fault northwest to the edge of the alluviated Petaluma Valley and beyond. He incorrectly extended the Franciscan wedge to a low hill along South Ely Road in Petaluma. No Franciscan rocks are exposed along South Ely Road. Wagner examined cuttings from a water well drilled just north of the road on the crest of the hill and found them to be only Petaluma Formation sediments. In addition, Petaluma strata are continuously exposed along a creek north of South Ely Road where Weaver’s 1949 work shows the Tolay fault juxtaposing Franciscan rocks and Petaluma Formation. This error, depicted on compilations (Fox et al., 1973; Huffman and Armstrong, 1980; Wagner and Bortugno, 1982; Blake et al., 2000), since Weaver’s 1949 work, has been corrected on a more recent map of the Petaluma river quadrangle (Wagner et al., 2002a, 2002b).

Based on the suggestion of Weaver (1949) that the Tolay fault is a continuation of the Hayward fault, subsequent workers have generally assumed that the Tolay is a dextral fault that extends northwest beneath the alluvium of the Petaluma Valley and is exposed again northwest of Meacham Hill (Travis, 1952). However, Roblar tuff overlies the Franciscan wedge west of the Tolay fault zone (localities 2 and 3, Table 3) and is interbedded in the Petaluma Formation east of the Tolay fault zone (locality 1, Table 3). The occurrence of the Roblar tuff on both sides of the Tolay fault zone at Sears Point precludes major strike-slip displacement since the deposition of the Roblar tuff (6.26 Ma).

Petaluma Valley Fault

The Petaluma Valley fault was named by Graymer et al. (2002b) for a fault concealed by young deposits in Petaluma Valley but exhibiting geomorphic expression in older deposits west of Cotati (Figs. 1, 2, and 3). Interpretations by Wright and Smith (1992) suggest that the Petaluma Valley fault is an inactive northern extension of the Hayward fault. Based on offsets of the Roblar tuff, Graymer et al. (2002b) assigned 35 km of displacement on this fault between 6 and 3.5 Ma. At that time, K/Ar dates on volcanic rocks on Meacham Hill indicated to them to be the same age as the volcanics on Burdell Mountain. New *Ar/*Ar dates (Table 1) show that these rocks and rocks farther to the west are part of the Tolay Volcanics, constraining displacement along Petaluma Valley fault to 15–26 km. We suggest that the belt of the middle Petaluma Formation that is exposed along the east flank of Meacham Hill was displaced from the Sears Point–Lakeville area along the Petaluma Valley fault between 6 and 3.5 Ma. Because both the Rodgers Creek and Petaluma Valley faults offset the Roblar tuff, they must have been active after 6.26 Ma, but now the Petaluma Valley fault is inactive. There was an abrupt increase in the slip rate of the Rodgers Creek fault in the late Pliocene (McLaughlin et al., 2005), consistent with the conclusion of Graymer et al. (2002b) that the Petaluma Valley fault became inactive at 3.5 Ma with all the displacement then occurring along the Rodgers Creek fault. If there was only 15–26 km of displacement along the Petaluma Valley fault then ~10–20 km of displacement can be assigned to faults to the west.
Southern Sonoma volcanic field

Burdell Mountain Fault and Other Northwest-Trending Faults

The Burdell Mountain fault is one of several northwest-trending faults that are to the west of the Petaluma Valley fault. The Burdell Mountain fault is a nearly vertical fault that extends 18 km northwest from San Pablo Bay past the north-east flank of Burdell Mountain into the hills of western Sonoma County (Figs. 1, 2, and 3). It was investigated by Ford (2007), who demonstrated it has at least 10 km of right-lateral displacement. It has long been recognized as a Quaternary fault (Rice, 1973), and Ford (2007) presented evidence for Holocene ground rupture along the central part of the fault.

Several en echelon, northwest-trending faults, including the Bloomfield fault, occur northeast of the Burdell Mountain fault. If, as posited by McLaughlin et al. (2005, 2008), the Rodgers Creek fault was initiated at 6–7 Ma, then the northwest-trending faults may be ancestral traces of the Hayward fault or perhaps even predate the Hayward fault. This possibility gives rise to the notion of a proto-Hayward fault (McLaughlin et al., 2005) that may account for some of the 175 km of displacement assigned to the East Bay fault system (Graymer et al., 2002b).

Bennett Valley Fault Zone

The Bennett Valley fault zone branches south from the Maacama fault and trends southeast across Bennett Mountain into the southeast part of Bennett Valley (Fig. 2), where it is a range-bounding fault along Bennett Mountain. The northern part of the Bennett Valley fault is straight and seismicity associated with it suggests that it has a vertical dip (Wong, 1991). This northern segment forms the eastern structural boundary of the Santa Rosa pull-apart basin, which opened from 1.2 to 0.8 Ma (McLaughlin et al., 2005). South of Bennett Valley, on Sonoma Mountain, surface mapping (Wagner et al., 2003) and air photo interpretation indicate that the youngest lava flows (4 Ma or younger) on Sonoma Mountain are not significantly offset. This segment of the Bennett Valley fault must be older than the segment in Bennett Valley. At Carriger Creek on the southeastern slope of Sonoma Mountain, the fault is a well-defined zone of parallel faults and is easily traced south to the Donnell Ranch, where it disappears beneath alluvium in Sonoma Valley. Randolph-Loar (2002) considered the southern part of the Bennett Valley fault to be a thrust fault, but other mapping (Wagner et al., 2002a, 2003) shows it as a high-angle fault. Sediments of the upper Petaluma Formation appear to be offset a few kilometers to the southeast along the southeast slope of Sonoma Mountain. It does not appear that the northern segment in Bennett Valley fault is the same structure as the fault of the same name south of Bennett Valley. McLaughlin et al. (2005) speculated that the youthful segment of the Bennett Valley fault formed with the opening of the Santa Rosa pull-apart basin between 1.2 and 0.8 Ma and the older segments south of Bennett Valley are part of an ancestral Maacama fault that predates the Santa Rosa pull-apart basin.

Carneros Fault

The Carneros fault is a major fault that juxtaposes Tertiary marine strata including the Neroly Formation and overlying Sonoma Volcanics on the west, with Great Valley Sequence and overlying Sonoma Volcanics on the east (Figs. 1, 2, and 3). It is exposed in the Carneros Valley where it is a vertical fault (Clahan et al., 2005; Weaver, 1949). North of the Carneros Valley mapping of the Carneros fault is hampered by dense vegetation, extensive landslides, and restricted access that have resulted in differing interpretations of the extent and nature of the structure. Clahan et al. (2005) extended the fault trace a few kilometers to the north where its strike changes from N25°W to N50°W. Clahan et al. (2005) showed the change in trend as a truncation of the Carneros fault by an inferred younger fault. Graymer et al. (2007) however, showed the change in trend as a bend and extended the Carneros fault more than 15 km to the northwest, where they showed it to be truncated by younger thrust faulting. Based on the presence of a steep gravity gradient along the fault, Langenheim et al. (2010) extended the Carneros fault not only to the northwest, consistent with recent workers (Clahan et al., 2005; Delattre et al., 2007; Graymer et al., 2007), but also south to San Pablo Bay. Fox (1983) considered the Carneros fault to be an extension of the Franklin-Sunol-Calaveras fault system (Fig. 1) and suggested as much as 35 km of right-lateral displacement. Based on the aforementioned gravity gradient, Langenheim et al. (2010) suggested that the Carneros fault could be an extension of the Pinole fault and could have as much as 20 km of displacement. If there were 20 km or more of displacement along the Carneros and either the Pinole or Franklin-Sunol-Calaveras faults, it probably took place between 10 Ma and ca. 4 Ma. This follows because the Carneros fault cuts the rhyolite of Bismarck Knob (6.143 Ma, Table 1) and a tuff containing tephras correlated with the Lawlor Tuff (4.84 Ma; locality 30, Table 3), but a basalt lava flow at the top of the section shows very little if any displacement.

West Napa Fault

The West Napa fault was first mapped by Helley and Herd (1977) from north of Vallejo through west Napa northward to Yountville. The 2000 M 5.2 Yountville earthquake, which severely damaged downtown Napa, occurred along the West Napa fault (Langenheim et al., 2006). Its southern part, near Vallejo, is known to be active (in the Holocene) and has been designated as an Earthquake Hazard Zone by the California Geological Survey, but its extent north of Napa has been problematical. Fox (1983) could not find any evidence of the fault mapped by Helley and Herd (1977) through Yountville and cited evidence for its existence along the west side of Napa Valley as far north as Saint Helena. Fox (1983) speculated that the West Napa fault could be a major strike-slip fault, but noted at least 147 m of vertical displacement of the Sonoma Volcanics with the east side (valley side) down. Langenheim et al. (2010) suggested a correlation of a deep magnetic and dense source near Mount Saint Helena with a similar source on the other side of the West Napa fault ~40 km to the south near Vallejo. If this correlation is valid, then all of the displacement of the Napa Valley eruptive source can be attributed to the West Napa fault. Given its significance to the tectonic evolution of this region and its seismogenic potential, the West Napa fault clearly needs more investigation.

Fold-and-Thrust Belt at Sears Point and Meacham Hill

Along Tolay Creek between Sears Point and the Petaluma Valley, west-dipping, east-vergent thrust faults were mapped by Morse and Bailey (1935), Youngman (1989), Randolph-Loar (2002), and Wagner et al. (2002a), along with associated back thrusting (Morse and Bailey, 1935; Wagner et al., 2002a). Morse and Bailey (1935) showed a wedge of Franciscan rocks bounded by steeply dipping faults. The middle part of the Petaluma Formation is tightly folded and overturned in places along the back thrusts along the southwest side of the Franciscan...
wedge. The wedge extends southward to Sears Point and has been called the Sears Point anticline (Weaver, 1949; Cebull, 1958; Fox, 1983; Davies, 1986). The wedge appears to be a diapir-like structure with a core of Franciscan Complex that is surrounded and, in places, overlain by the Petaluma Formation. The structure has aspects of a fold, but is more accurately a piercement, in many respects similar to the much larger Mount Diablo piercement in the Diablo Range (Pampeyan, 1963). We interpret this structure as part of a fold-and-thrust belt (Fig. 3).

In the Petaluma oil field east of Petaluma, subsurface structure is the relatively simple, doubly plunging, faulted Adobe anticline (Morse and Bailey, 1935; Weaver, 1949; Wright, 1992). At the surface, however, bedding attitudes are chaotic and where the axis of the fold should be exposed there is a vertical shear zone and nearly vertical and locally overturned bedding (Wagner et al., 2003). Wright (1992) attributed the folding to late Neogene compression. We suggest that there is a detachment between the complex surface structure and the relatively simple anticlinal structure that traps the hydrocarbons at depth. Wagner (1978) came to a similar conclusion in his investigation of Tertiary formations in the Contra Costa basin south of San Pablo Bay; he noted that folds in the Cretaceous Great Valley Sequence have broader wavelengths and lower amplitudes than those in the more tightly folded, overlying Tertiary strata, suggesting that there is a detachment between the two. Whether this detachment is due entirely to thrusting or whether landsliding (see previous discussion of megalandslides) is also involved remains unresolved. In any case, the compression postdating the Roblar tuff affected the eastern side of the Petaluma Valley all the way to Sears Point.

At Meacham Hill, west-vergent thrusting has juxtaposed Tolay Volcanics over interbedded Wilson Grove and Petaluma Formations. Along strike to the northwest, in the Stony Point area, the Petaluma Formation, the sand and gravel of Cotati, and Sonoma Volcanics with K/Ar ages of 6.32–4.26 Ma (Fox et al., 1985b), and the Roblar tuff are folded. However, mapping of the Two Rock quadrangle by Bezore et al. (2003) indicates that the folding did not involve the Wilson Grove Formation. Geophysical evidence (Langenheim et al., 2010) suggests that the folded Petaluma Formation extends 7–8 km northwest beneath relatively flat lying Wilson Grove Formation. As mapped by Bezore et al. (2003), the Wilson Grove Formation appears to overlap the Petaluma Formation. This relationship presents a paradox since both the folded and unfolded strata contain the Roblar tuff (Bezore et al., 2003; Clahan et al., 2003), indicating that they are the same age. If this is true, then there must be a previously unrecognized thrust fault separating the folded strata from the unfolded strata.

It may be that the west-vergent thrust faults on Meacham Hill are back thrust faults above concealed east-vergent thrusts that are exposed at the surface in the Cooks Peak–Taylor Mountain area ~8 km to the northeast. Back thrusting and wedging have been documented in the Lakeville area to the south (Morse and Bailey, 1935). A similar situation may exist to the north in the Cotati basin, where there are west-vergent thrusts such as the Trenton fault (McLaughlin et al., 2005; Langenheim et al., 2010). Thus, we argue that the east-vergent thrusts in the Cooks Peak–Taylor Mountain area in the Santa Rosa quadrangle (McLaughlin et al., 2008) are equivalent to the east-vergent thrusts in the Sears Point–Tolay Creek area to the south.

Taken together, these contractional structures formed in a belt west of and parallel to the Rodgers Creek fault (Fig. 3). Rocks older than the Pinole Tuff (5.2–5.4 Ma) in the Sonoma Mountain area, including the Roblar tuff (6.26 Ma), were folded during this compressional episode. The folding propagated northward and persisted to at least 4 Ma or possibly later in the Cotati basin (McLaughlin et al., 2005, 2008).

**PETALUMA BASIN**

The Petaluma basin is southwest of and truncated by the Rodgers Creek fault. It is bounded on the southwest by a prominent gravity gradient previously considered to mark the northern extension of the Tolay fault (Chapman and Bishop, 1983; Wright and Smith, 1992), but it is here considered more likely that the gradient is due to a basin-bounding normal fault. Franciscan Complex rocks are exposed around its northern edge and are incorporated into the overlying Petaluma Formation. The structure has aspects that is surrounded and, in places, overlain by the Petaluma Formation. Geophysical evidence (Langenheim et al., 2010) suggests that the folding did not involve the Wilson Grove Formation. Geophysical evidence (Langenheim et al., 2010) suggests that the folded Petaluma Formation extends 7–8 km northwest beneath relatively flat lying Wilson Grove Formation. As mapped by Bezore et al. (2003), the Wilson Grove Formation appears to overlap the Petaluma Formation. This relationship presents a paradox since both the folded and unfolded strata contain the Roblar tuff (Bezore et al., 2003; Clahan et al., 2003), indicating that they are the same age. If this is true, then there must be a previously unrecognized thrust fault separating the folded strata from the unfolded strata.

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**Paleogeography and Geologic History of the Petaluma Basin**

Based on the correlation of the Tolay Volcanics with the Berkeley Hills Volcanics, we infer that the Tolay Volcanics were erupted from the Round Top and possibly other volcanoes (Edwards, 1983) in what is now the Berkeley Hills, between ca. 10 and 8 Ma. At that time, the Petaluma basin was a western extension of the Contra Costa basin (Liniecki-Laporte and Andersen, 1988; Fig. 10A). Lava from volcanoes in the Berkeley Hills flowed eastward across alluvial gravel of the Orinda Formation while lava that flowed westward flowed across Franciscan rocks. Lacustrine and estuarine sediments of the lower part of the Petaluma Formation began to accumulate in the Petaluma basin during the waning stages of volcanism in the Berkeley Hills. Although Wagner (1978) and Graham et al. (1984) argued that what is now the San Francisco Bay was a highland shed area, the presence of estuarine sediments in the Contra Costa–Petaluma basin shows that...
some of the western part of the basin was subsiding to at least sea level (Liniecki-Laporte and Andersen, 1988). The lower part of the Petaluma Formation is primarily lacustrine and to a lesser extent estuarine, but there are some marine ostracodes (Peterson and Allen, 2005) suggesting marine transgression into the Petaluma basin.

The Hayward fault became active ca. 9 Ma (Graham et al., 1984) and rifting of the Contra Costa–Petaluma basin began. The Zamaroni Quarry–San Pablo Bay eruptive center of the Sonoma volcanic field became active ca. 8 Ma, and lava and tuff along with dominantly fluvial sediments of the middle part of the Petaluma Formation (8–6 Ma) slowly replaced the older lacustrine and estuarine sediments. By the time the Roblar tuff was erupted (6.26 Ma), the Petaluma basin had been moving northward for nearly 3 m.y. and was near the latitude of Point Pinole, where sedimentary deposition was dominantly fluvial (Fig. 10B). Gravel rich in siliceous shale fragments composing the middle part of the Petaluma, the littoral sand and gravel of Cotati, and the Garrity Member of the Contra Costa Group (Allen, 2003) at Point Pinole were transitional lithofacies between a terrestrial environment to the east and open marine conditions to the west. The Roblar tuff was erupted from the Zamaroni Quarry–San Pablo eruptive center and was deposited throughout the Contra Costa–Petaluma basin as well in the marine Wilson Grove Formation to the west. It was reworked in a westward-flowing fluvial system and is present in clastic sediments within all the blocks cut by the San Andreas fault system in the San Francisco Bay area. Moreover, the clastic sediments interbedded with tuff form a westward succession: fluvial sand and gravel southeast of the Calaveras (Green Valley) fault, to finer-grained fluvial lacustrine, and estuarine deposits of the Contra Costa Group between the Calaveras and Hayward faults, to fluvial and estuarine sediments of the Petaluma Formation west of the Rodgers Creek fault, to fully marine deposits of the Wilson Grove Formation, to fine-grained, deep-ocean fan deposits on the Delgada Fan west of the San Andreas fault. These data taken together suggest that the now offset sites were aligned along a drainage through the Contra Costa–Petaluma basin to the sea that was subsequently dismembered by movement along the San Andreas, Hayward–Rodgers Creek, and Calaveras (Green Valley) faults.

After deposition of the Roblar tuff, transgression locally gave way to transpression (McLaughlin et al., 2008; Langenheim et al., 2010) and east-vergent thrusting formed the Sears Point–Meacham Hill fold-and-thrust belt that now separates the Petaluma basin from the Cotati basin to the north. During this transpressional episode, the lower and middle parts of the Petaluma Formation, the sand and gravel of Cotati, as well as the interbedded Sonoma Volcanics were folded, and the Tolay Volcanics and Franciscan basement were uplifted. Basement highs beneath the Santa Rosa Plain that now separate the Cotati and Windsor basins (the Warrington High of Langenheim et al., 2010) and Trenton Ridge of McLaughlin et al., 2008) likely formed during this thrusting. Deposition of the Petaluma Formation ceased in the Petaluma basin but continued in the Cotati basin and possibly the Windsor basins, where the lacustrine and fluvial upper part of the Petaluma Formation unconformably overlaps the middle part of the Petaluma Formation. Intraformational reworking of the middle Petaluma sediments into the upper Petaluma Formation resulted in gravelly sand that is identical and accounts for the presence of the chips of Claremont Shale in both units.

The presence of the upper Petaluma Formation and interbedded marine strata in Bennett Valley are good indications that there was a brief connection with the basins in the Santa Rosa Plain to the prior opening of the Santa Rosa pull-apart basin. Of the documented 28 km of displacement along the Rodgers Creek fault, ~6 km occurred since the opening of the Santa Rosa pull-apart basin at 0.8–1.2 Ma (McLaughlin et al., 2005). Restoration of that 6 km juxtaposes the gently folded diatomite-rich section in Bennett Valley with the similar diatomaceous strata in the Santa Rosa fairgrounds area (McLaughlin et al., 2008).

CONCLUSIONS

Geologic mapping, radiometric dating, and tephrochronologic correlations presented in this paper demonstrate that basin formation, sedimentary deposition, and volcanism have been sporadic but young to the north, consistent with the northward migration of the Mendocino triple junction. Within the Sonoma volcanic field, assemblages of volcanic rocks interbedded with sediments are overlapped to the north by younger assemblages.

Eruptive sources for the Sonoma Volcanics are numerous and varied, including calderas, stratovolcanoes, and a myriad of smaller, mostly...
Tertiary volcanics, includes Berkeley Hills volcanics and Tolay Volcanics west of Incipient Hayward Fault

Older Sonoma Volcanics

Middle Petaluma Fm. (siliceous shale frags.)

Middle Petaluma Fm.

Lower Petaluma Fm.

Wilson Grove Fm.

Sand and gravel of Cotati

Contra Costa Group

Garrity member of Contra Costa Group

Tolay Volcanics

Berkeley Hills volcanics

Monterey Fm.

Trt - Roblar tuff
rb - Rhyodacite breccia

PVF - Petaluma Valley Fault

Fluvial system transporting reworked Roblar tuff
mafic intrusions that are aligned along faults. Two of the major eruptive sources for the southern part of the Sonoma Volcanics, the Zamarone Quarry–San Pablo Bay and the Napa Valley volcanic centers, were cut by the Rodgers Creek and the Carneros and/or West Napa faults, respectively.

Although the middle and upper parts of the Petaluma Formation are coeval with the Sonoma Volcanics, its older parts were deposited in the Petaluma basin when it was 30–40 km south of its present location. Complex fault systems inboard of the San Andreas fault, responsible for its present location. Complex fault systems of the Miocene and Pliocene formations of the Petaluma Valley area [M.S. thesis]: Berkeley, California, University of California, 96 p.


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Southern Sonoma volcanic field


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