Geology, Tephrochronology, Radiometric Ages, and Cross Sections of the Mark West Springs 7.5' Quadrangle, Sonoma and Napa Counties, California

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INTRODUCTION

The purpose of this geologic map is to provide a context within which to interpret the Neogene evolution of the active strike-slip fault system traversing the Mark West Springs 7.5' quadrangle and adjacent areas (fig. 1, sheet 1). Based on this geologic framework, the timing and total amounts of displacement and the Neogene rates of slip for faults of the right-stepover area between the Healdsburg and Maacama Faults are addressed.

The Mark West Springs quadrangle is located in the northern California Coast Ranges north of San Francisco Bay (fig 1, sheet 1). It is underlain by Mesozoic rocks of the Franciscan Complex, the Coast Range ophiolite, and the Great Valley sequence, considered here to be the pre-Tertiary basement of the northern Coast Ranges. These rocks are overlain by a complexly interstratified and mildly to moderately deformed sequence of Pleistocene to late Miocene marine and nonmarine sedimentary and largely subaerial volcanic rocks. These rocks and unconformably overlying, less-deformed Holocene and Pleistocene strata are cut by the active right-lateral Healdsburg and Maacama Fault Zones.

Mapping of the Mark West Springs quadrangle began in 1996 and was completed in October 2002 (fig. 2, sheet 1). Most of the mapping presented here is original, although a few other sources of existing geologic mapping were also utilized (fig. 2, sheet 1). Funding for the project was provided by the National Cooperative Geologic Mapping and Earthquake Hazards Reduction programs of the U.S. Geological Survey, in cooperation with geologic hazards mapping investigations of the California Geological Survey.

STRATIGRAPHIC OVERVIEW

PRE-TERTIARY UNITS

The pre-Tertiary bedrock units of the Mark West Springs quadrangle are the Franciscan Complex, the Great Valley sequence, and the Coast Range ophiolite, all of which overlap in age and were tectonically juxtaposed in the latest Cretaceous to early Tertiary. The oldest and the youngest of these rocks are part of the Franciscan Complex, which represents a subduction complex accreted to the continental margin of California and Oregon between Miocene and Middle Cretaceous time (McLaughlin and Ohlin, 1984). The Great Valley sequence rocks, which project into the subsurface of the map area from the northwest, are largely of Early Cretaceous and Late Jurassic age and represent sedimentary rocks deposited in a forearc setting structurally above the subduction setting represented by coeval Franciscan Complex rocks. The Coast Range ophiolite is Middle Jurassic in age where dated in adjacent quadrangles, but only undated, serpentinized ultramafic rocks (Jos) are exposed in the Mark West Springs quadrangle. These ophiolitic rocks are considered to be the primitive forearc basement on which Great Valley sequence strata were deposited. Recent interpretations of the setting in which the Coast Range ophiolite formed (Coleman, 2000) suggest a back arc, supra-subduction, or mantle wedge tectonic setting in the hanging wall of the Franciscan Complex subduction zone. Hopson and others (1981) suggest that the ophiolite formed during interaction of a mid-ocean ridge spreading center with the fringes of a volcanic arc rooted along the Jurassic continental margin. Serpentinized ultramafic rocks exposed in the Mark West Springs quadrangle are complexly interleaved with melange of the Franciscan Complex as elsewhere in the northern California Coast Ranges (McLaughlin and others, 1988).

Franciscan Complex

Central belt

The Franciscan Complex consists of the Central belt, which is largely a tectonic melange enclosing coherent blocks and slabs from <1 m to several kilometers in maximum dimension. Some of the large slabs and lithologically distinct melange blocks have been divided into tectonostratigraphic terranes in previous work (McLaughlin and Ohlin, 1984; Blake and others, 1984; Blake and others, 2000). Assignment of the Franciscan Complex rocks to specific tectonostratigraphic terranes in this report (for example, the Marin Headlands-Geysers terrane) is based largely on data and criteria developed by McLaughlin and Ohlin (1984) and Blake and others (1984).

Imbrication of the Franciscan Complex Central belt with ophiolitic and Great Valley sequence rocks is interpreted to have occurred in the latest Cretaceous and earliest Tertiary and to have resulted from oblique translation and underthrusting of the Central belt melange as a tectonic wedge. This melange wedge emplacement post-dated deep subduction of Franciscan Complex rocks (the Eastern belt) in the Late to Middle Cretaceous beneath the Coast Range ophiolite and depositionally overlying Great Valley sequence (McLaughlin and Ohlin, 1984).

During latest Cretaceous to earliest Tertiary time, the Central belt was emplaced and translated along low-angle faults toward the northeast, and previously accreted parts of the Franciscan Complex Eastern belt, Great Valley sequence, and Coast Range ophiolite were imbricated with the Franciscan Complex Central belt along the low-angle faults (thrusts).

Regional stratigraphic relationships (McLaughlin and Ohlin, 1984) indicate that deeply subducted, high-pressure Franciscan rocks were first unroofed in the earliest Tertiary (late Paleocene to early Eocene time). Considerable regional uplift and erosion of the unroofed rocks occurred between the Eocene and late Miocene, but these events are obscured in the map area by an unconformity beneath 5 Ma and younger volcanic rocks. This Miocene unconformity in the Mark West Springs quadrangle largely obliterates the rock record from about 5 Ma (early Pliocene) to 90 Ma (Turonian).

Coast Range ophiolite

Rocks of the Coast Range ophiolite that are exposed at the surface in the Mark West Springs quadrangle consist largely of serpentinized ultramafic rocks (unit Jos) and associated minor cumulate ultramafic rocks, gabbro, and diabase. In most places this unit is intimately interleaved and imbricated with the Central belt of the Franciscan Complex along folded, west-northwest-trending faults and shears, which form the structural grain of melange of the Central belt of the Franciscan Complex (McLaughlin and others, 1988).

Great Valley sequence

The Great Valley sequence rocks are not present at the surface in the Mark West Springs quadrangle but are present in the core of an anticline near the east boundary of the adjoining Healdsburg quadrangle. These Lower Cretaceous and Jurassic Great Valley sequence strata project into Mark West Springs quadrangle beneath Pleistocene-Pliocene fluvial gravel and Tertiary volcanic rocks between the west boundary of the Mark West Springs quadrangle and the Leslie Road Fault (cross sections A-A’ and B-B’, sheet 2). The Great Valley sequence strata probably are structurally underlain at an unknown depth by rocks of the Coast Range ophiolite and (or) the Franciscan Complex.

EARLY QUATERNARY AND LATE TERTIARY UNITS

Sonoma Volcanics

The oldest Tertiary rocks exposed in the area of the Mark West Springs quadrangle are 5.0-m.y.-old basalt, basaltic andesite, and andesitic to basaltic flow breccia (Tsb) of the Sonoma Volcanics. The basalt is dark gray to black where fresh but weathers to reddish brown, typically with a thick, red-brown, Fe-rich soil. Based on a few major oxide analyses ($Si0_2$ = 53-56 percent; K_20 = 0.55-1.1 percent), these rocks are basaltic andesites (Whitlock, 2002), although some true basalts may be present where there are no wall-rock inclusions.

Southwest of the Maacama Fault, the basaltic and andesitic rocks locally overlie the Franciscan Complex. The basaltic rocks are aphyric to porphyritic, with locally prominent olivine, clinopyroxene, and plagioclase phenocrysts. These rocks, especially the andesites, commonly contain conspicuous wall-rock xenoliths and xenocrysts of reacted felsic and (or) mafic pyroxene and olivine-bearing rock. Southwest of the Maacama Fault, a brown, fine-grained andesitic tuff (Tstb) is interbedded in the upper part of the basalt and andesite. Eruptive centers for these mafic rocks are poorly known. No vent areas are specifically identified in the map area, although local vents probably are present and some are possibly associated with west-northwest-trending faults.

The oldest basalt and andesite (Tsb) in the quadrangle is radiometrically dated ($^{40}Ar/^{39}Ar$) at 5.4 Ma near Telegraph Hill (fig. 3*A*, table 1, sheet 2), where the flows and flow breccias are tilted westward along the Maacama Fault Zone and are in normal and fault contact with the Franciscan Complex. To the west of this area, stratigraphically higher basalt (Tsb) is dated at 4.6±0.05 Ma near Larkfield and 4.8±0.03 Ma at Leslie Road. The basalt at Larkfield, southwest of the Larkfield Fault Zone and northeast of the Healdsburg Fault (fig. 3*A*, loc. 63, and table 1), stratigraphically underlies the ash flow tuff of Riebli Road, dated at 3.12±0.03 Ma (fig. 3*A*, loc. 62, and table 1). The basalt of Leslie Road (Tsb) northeast of the Mark West Fault Zone (fig. 3*A*, loc. 45, and table 1) overlies the silicic Lawlor Tuff (fig. 3*B*, loc. 47, and table 1), which was dated elsewhere at 4.83 Ma (Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1984; Reheis and others, 1991; Reheis and others, 2002).

Northeast of the Maacama Fault Zone, younger basalt and basaltic andesite (Tsb) having a conspicuous flaggy, closely-spaced flow parting is intercalated in siliceous ash flow tuff younger than 2.85±0.02 m.y.B.P.

The mafic rocks of the Sonoma Volcanics are typically overlain by white to gray, buff- to yellow-weathering units of rhyolitic to dacitic tuff. The silicic Sonoma Volcanics tuffs (Tst) consist predominantly of fine to coarse pumice shards and clasts (from <1mm to as much as 24 cm diam) that contain plagioclase phenocrysts and varying amounts of lithic and xenolithic fragments. Based on silica (~78-72 percent) and K_20 (5.7-2.95 percent) content, these tuffs are clearly transitional from rhyolite to dacite in composition (table 3, sheet 2). The general absence of modal quartz and K-feldspar (except as xenoliths or xenocrysts) and the presence of conspicuous plagioclase phenocrysts are the primary field criteria for mapping the Sonoma Volcanics tuffs as rhyodacitic.

The tuffs (Tst) are largely ash flows but some were deposited by air fall. The ash flows include waterlain deposits and local interbedded laharic gravel or flow breccia (Tstb where locally subdivided). Basaltic and andesitic volcanic rocks (Tsb) occur high in the tuff section in places, particularly northeast of the Maacama Fault Zone in the northeast corner of the map area. The thickness of the siliceous tuff section southwest of the Maacama Fault varies from as much as 550 ft to <100 ft. Northeast of the Maacama Fault, the siliceous tuff section is much thicker. There, it could exceed 2,300 ft along Porter Creek Road northeast of the Petrified Forest (sheet 2, cross section C-C'), but generally it is 800-1,500 ft thick (sheet 2, cross sections A-A', B-B'). Where the ash flows were covered by younger, hot basalt or other ash flows, the overridden ash flow is welded, forming locally mapped, distinct black and pink-streaked zones of fused glass that contain plagioclase phenocrysts (Tstw) and reddish-brown baked zones. In the Franz Valley area northeast of the Maacama Fault, the tops of ash flows are locally fused into black, glassy vitrophyre (Tstv) that contains plagioclase phenocrysts.

The siliceous tuffs of the Sonoma Volcanics in the map area (Tst) include numerous, geochemically distinct, widespread tephra layers that are dated radiometrically, as well as other tephra units that are newly dated and used for stratigraphic correlations herein (fig. 3*B*, tables 2, 3, sheet 2). Two regionally widespread, formally named tephra layers that are present in the map area are the Lawlor Tuff (4.83 Ma) and the Putah Tuff (3.34 Ma) (Sarna-Wojcicki, 1976). These two tuffs have been found at numerous localities throughout California and in western Nevada (Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1984; Reheis and others, 1991; Reheis and others, 2002). Other tuffs, such as the tuff of Pepperwood Ranch (3.19 Ma) and the tuff of Riebli Road (3.12 Ma), dated and informally named in this study, are important markers within the area of the Sonoma Volcanics and the general northern San Francisco Bay Area. The ages of several other informally named, geochemically distinct tephra layers within the map area are determined by their stratigraphic relations to these dated tuffs and to the lava flows dated in this report (fig. 3*A*, *B* and tables 1-3, sheet 2).

Other units mapped in the Sonoma Volcanics include coarse, angular volcanic breccia (Tstb), rhyodacitic flows and intrusives (Tsr), dacitic flow rocks (Tsd), and basaltic intrusive rocks (Tsbi).

Volcanic breccia (unit Tstb) is present at several stratigraphic levels within the ash-flow tuff section northeast of the Maacama Fault, but it is shown on the map only locally, near the east edge of the map area east of the confluence of Humbug and Deadhorse Creeks. The breccia unit is mapped in a fault block bounded to the northeast by the Petrified Forest Thrust and to the southwest by the Gates Canyon Thrust. The breccia consists of angular, ≤1.5-m- to boulder-scale blocks of basalt, andesite, and vitric, porphyritic rhyodacite in a lithic rhyodacitic tuff matrix. It appears to be within the lower part of the ash flow tuff sequence in the Petrified Forest and Franz Valley, although its precise stratigraphic position cannot be determined due to the bounding thrust faults. The breccia deposits are probably largely laharic in the map area but could also include vent breccias, as suggested by the coarseness and angularity of clasts, the general lack of evidence for water transport, and the vitric, fused character of the outer parts of included volcanic clasts.

Hard gray porphyritic rhyodacite (Tsr) occurs discontinuously at the base of the volcanic section in Franz Valley on the Pepperwood Ranch Natural Preserve and also as erosional remnants along the east side of the Maacama Fault Zone at the base of a thin, petrified-wood-bearing ash-flow tuff. The porphyritic rhyodacite may actually represent the welded base of the overlying ash-flow unit (ash-flow tuff of Pepperwood Ranch). A plagioclase separate from the rhyodacite is dated by $^{40}Ar/^{39}Ar$ techniques at 3.19±0.02 Ma. This age is identical to the 3.19±0.04 Ma $^{40}Ar/^{39}Ar$ age (plagioclase) obtained from black vitric tuff (vitric tuff of High Ridge Ranch) at the base of the Sonoma Volcanics along the axis of Franz Valley Anticline (sheets 1 and 2, fig. 3*A*, and table 1).

In the northeast corner of the map area, undated, coarsely granular and porphyritic plagioclase- and quartz-bearing rhyodacitic rocks (Tsr) may intrude ash flows in upper Bidwell Creek. In the same area, a small, circular body of undated, dense, aphanitic, black basalt (Tsbi) intrudes ash-flow tuff along the ridge northwest of Bidwell Creek.

Sandstone

Un-named, friable, lithic, gravelly nonmarine sandstone (Tss) is locally mapped beneath or interbedded in the lower part of the Sonoma Volcanics along the east side of the Maacama Fault Zone west of Franz Valley. Framework clasts and pebbles in the lower part of the sandstone and gravelly sandstone are largely derived from the underlying Franciscan Complex. These lower gravelly sandstone beds are overlain by tuffaceous gravel derived from Tertiary volcanic sources.

At the south edge of Knights Valley, on the west side of Franz Valley Road, the sandstone is overlain by early Pleistocene to Pliocene terrace deposits (QTg) that, based on geochemical data, contain obsidian clasts derived from the Glass Mountain area of Napa Valley southeast of the map area and also from local sources of obsidian in the Franz Valley area. The sandstone south of Knights Valley may interfinger with or underlie fluvial and lacustrine deposits of Humbug Creek (Tgp), which are exposed to the northwest and southeast.

South of Devils Kitchen on the northeast side of the Maacama Fault Zone, Franciscan Complex-derived gravelly sandstone of the sandstone unit is in fault contact with silica carbonate rock and serpentinite to the west and with undated basalt to the north. To the east, the sandstone is overlain by a thin bed of tuffaceous gravel and by the 3.22-3.34-Ma ash flow tuff (Tst) of the Devils Kitchen area (fig. 3, sheet 2). The age of this unit is, therefore, ≥3.22-3.34 Ma and probably overlaps the age of the fluvial and lacustrine deposits of Humbug Creek (Tgp).

Fluvial and Lacustrine Deposits of Humbug Creek

Northeast of the Maacama Fault Zone, gravel, sandstone, siltstone, mudstone, and nonmarine diatomite (unit Tgp) underlie and interfinger with the lower part of the Sonoma Volcanics. In its lower part, this fluvial unit exhibits north-northwest-directed paleoflow and is predominantly derived from pre-Tertiary basement, including rare obsidian clasts. Higher in the fluvial section, the unit includes coarse, Tertiary volcanics-derived gravel and tuffaceous sandstone and siltstone. In places, the fluvial and lacustrine deposits of Humbug Creek are intercalated with the lower part of the Sonoma Volcanics section east of the Maacama Fault, or the gravel may include thin intercalations of basaltic andesite, silty rhyodacitic tuff, and laharic gravel. The base of the fluvial and lacustrine deposits is not exposed, but it may grade downward into or interfinger with the lithic gravelly sandstone (unit Tss).

The age of the fluvial and lacustrine deposits of Humbug Creek is not well established due in part to no exposure or faulting along its basal contact. Southwest of the Petrified Forest, the fluvial and lacustrine deposits of Humbug Creek are overlain by Sonoma Volcanics that include the Putah Tuff, and, therefore, the gravels are older than 3.34 Ma (fig. 3, tables 2, 3, sheet 2). Rare, centimeter-sized pebbles of obsidian collected from gravel exposed on Calistoga Road along Humbug Creek, about 1 km northeast of the intersection with Mark West Creek and Alpine Road, are geochemically distinct from any of the known in-place obsidian sources. The obsidian clasts from the Humbug Creek gravel unit are distinctly less hydrated than obsidian from in-place sources in Annadel State Park southeast of the map area (Santa Rosa and Kenwood 7.5' quadrangles) that we have dated at 4.5 Ma by $^{40}Ar/^{39}Ar$ techniques. We interpret this as indicative of an age for the Humbug Creek obsidian clasts that is younger than the Annadel obsidian source area. The age of the fluvial and lacustrine deposits of Humbug Creek, thus, are interpreted as ≥3.34 but ≤4.5Ma.

Fluvial and Lacustrine Deposits

Fluvial and minor lacustrine deposits (QTg) of gravel, sandstone, siltstone, mudstone, and diatomite overlie and are, in places, interbedded with silicic tuff of the uppermost Sonoma Volcanics. Together with the Sonoma Volcanics, these sedimentary deposits formed a complex west-sloping alluvial fan system deposited in the early Pleistocene and late Pliocene. The sedimentary deposits of this unit previously were assigned to the Glen Ellen and Huichica Formations, which are largely coeval with the fluvial and lacustrine deposits described here. The previous nomenclature is not used here, however, because lithologic and stratigraphic criteria for distinguishing the Glen Ellen Formation from the Huichica Formation is inconsistent. It is not clear that both formations were continuous from their type areas to the map area, and new stratigraphic data from this study seem to warrant a somewhat different stratigraphic framework tied more closely with the volcanic stratigraphy and chronology.

Southwest of the Maacama Fault, the fluvial and lacustrine deposits of unit QTg unconformably overlie or are interbedded with siliceous tuff of the Sonoma Volcanics. Northeast of the Maacama Fault, the gravels unconformably overlie pre-Tertiary basement, the Sonoma Volcanics, and older fluvial and lacustrine deposits of Humbug Creek (Tgp).

The gravel of unit QTg is pebbly to bouldery and derived both from Tertiary volcanic rocks and from pre-Tertiary basement rocks to the north, east, and southeast. Gravels dominated by clasts derived from pre-Tertiary basement sources (greywacke, chert, blueschist, and metavolcanic clasts of the Franciscan Complex; distinctive rounded silicic volcanic porphyry clasts from Lower Cretaceous conglomerates in the Great Valley sequence; and gabbro, diabase, and ultramafic rocks from the Coast Range ophiolite) indicate paleoflow toward the west, southwest, and south from the Dry Creek and Alexander Valleys and from the Mayacmas Mountains. Tertiary volcanic clasts in the gravels were derived from sources in the Sonoma Volcanics to the east and southeast.

A thin marine diatomite interbed (QTgd) occurs near the base of the fluvial and lacustrine strata northeast of the Healdsburg Fault, in the southwestern corner of the map area. According to S.W. Starratt (written commun., 2003), this diatomite (fossil loc. F-1) contains a diverse diatom flora and sponge spicules indicative of mixed, fresh, and brackish water. The diatom flora is also identical to that found in the present San Francisco Bay and surrounding marshes. Though not age diagnostic, the diatoms and sponge spicules suggest an estuarine setting. Based on its stratigraphic position above 5.0-3.1 Ma basaltic andesites and silicic tuffs, the diatomite may correlate with marine strata in the Wilson Grove Formation of Fox (1983), which crops out southwest of the Mark West Springs quadrangle. The presence of a marine diatomite interbed within the fluvial and lacustrine deposits documents eastward encroachment of the late Pliocene marine margin into the map area and suggests that fluvial and lacustrine gravel of unit QTg interfingers with the late Pliocene marine Wilson Grove Formation of Fox (1983) beneath the Santa Rosa plain, southwest of the Mark West Springs quadrangle.

Other interbeds in unit QTg were locally mapped as stratigraphic markers southwest of the Maacama Fault. They include a few siltstone (QTgs) interbeds and several thin, waterlain siliceous tuffs (QTgt) that notably occur stratigraphically above the marine diatomite (Qtgd) in the southwest corner of the map area.

Near the west boundary of the map area, a boulder within a thin erosional outlier of the fluvial gravel overlying basaltic andesite contains fresh-water mollusks cemented by a siliceous sinter of quartz and chalcedony (fossil loc. F-2). The boulder may have been eroded from a subaqueous, fresh-water, hot-spring deposit. According to C.L. Powell, II (written commun., 1999), the molluskan fauna includes indeterminate small Bivalvia and *Physa* sp., a cosmopolitan gastropod that lived in Quaternary to Paleocene fresh-water environments. The unusual silicic matrix of the boulder, the westward paleoflow measured in the gravels, and the co-occurrence of the sinter clast with abundant Tertiary volcanic detritus suggest derivation from a setting closely associated in time with Sonoma-age volcanism.

Most of the early Pleistocene and Pliocene fluvial gravel (QTg) includes very rare to common clasts of obsidian ranging from <1 cm to >10 cm in diameter. Geochemical fingerprinting of the obsidian clasts indicate that they are predominantly derived from two sources: Napa Valley (Glass Mountain area), dated radiometrically at 2.78 Ma, and from a separate source in the Franz Valley area. Obsidian clast-bearing gravels of this unit overlie 2.85 Ma and older tuffs of the Sonoma Volcanics northeast of the Maacama Fault and the 3.12 Ma ash flow tuff of Riebli Road southwest of the Maacama Fault. The gravels are unconformably overlain by Pleistocene terrace gravels. The age of these fluvial and lacustrine deposits is, therefore, younger than 2.78 Ma. The upper age limit is poorly constrained but is considered to be early Pleistocene, because, in the Healdsburg quadrangle to the west of Mark West Springs quadrangle, correlative obsidian-bearing gravels are mapped stratigraphically above marine upper Pliocene strata of the Wilson Grove Formation of Fox (1983).

Silica Carbonate

Silica carbonate rock in the map area consists of hydrothermally altered ultramafic rocks associated with the Franciscan Complex and the Coast Range ophiolite. The silica carbonate is composed of quartz and magnesium carbonate mineral assemblages. This type of alteration is commonly associated with mercury and other epithermal, base-metal, sulfide occurrences (Ag, Au, Pb, Zn, Cu). The age of the silica carbonate generally corresponds with the associated epithermal mineralization ages, which correspond with, but are somewhat younger than, the ages of associated Pleistocene and Pliocene volcanic rocks that provided hydrothermal heat sources in this area (McLaughlin and others, 1996).

SURFICIAL UNITS

Surficial deposits in the map area consist of alluvial fan and terrace deposits, colluvium, and landslides.

The most extensive of these deposits are alluvial fan and terrace deposits that range from Holocene to Pleistocene in age and consist of bouldery to pebbly gravel, sand, and silt derived primarily from older sedimentary and igneous units. These deposits generally are little deformed and exhibit geomorphology and sedimentary facies typical of alluvial fans and terraces, and the geomorphic form of the deposits can generally be related to the canyons, channels, and valleys that contain them.

The stratigraphic succession of the surficial deposits was mapped by relating the morphology of fan deposits to distributary channels and drainages that incise successively older fans and their respective sediment distribution systems. The Pleistocene alluvial fan and terrace deposits (Qoa) generally are more dissected than younger Holocene and Pleistocene fans and terraces (Qal, Qt, $Qhpf_2$, $Qhpf_1$, and Qhpf), and the least dissected deposits are generally the youngest (Qal, Qhf_2, and Qhf). Some deposits inferred to include sediment of Holocene and Pleistocene age (Qhpf) are locally subdivided into older ($Qhpf_2$) and younger ($Qhpf_1$) deposits.

In addition, the Holocene alluvial fan and fluvial terrace deposits (Qhf) are locally divided into an older Holocene fan subunit (Qhf_2). The older Holocene fan and fluvial terrace subunit is the intermediate of three subunits of Qhf that are mapped in adjacent areas (R.J. McLaughlin, unpub. mapping).

Landslide deposits of Holocene and Pleistocene age are present throughout the area. These deposits vary in character from extensive intact slabs that form deep-seated, rotational, block-style landslides to shallow, slow-moving earth flows to shallow, fast-moving debris flows. No attempt was made to systematically map all the landslides in the map area or to subdivide the landslides into various categories by mode of movement or depth of deposit. The landslides depicted on this map are generally the larger slides; numerous shallow slides and large rotational block slides have not been mapped. No attempt was made to systematically delineate the active from dormant landslides.

Colluvium, consisting of regolith, soil, and slope talus, is mapped in only a few areas where these deposits are locally thick and extensive enough to show at the map scale. Colluvium of Holocene to Pleistocene age occurs in varying thickness and areal extent on all rock units, slopes, and surfaces throughout the map area and formed in a variety of climatic, slope, and hydrologic conditions.

STRUCTURAL OVERVIEW

Rocks in the Mark West Springs 7.5' quadrangle are divided into three principal structural blocks (Windsor, Mark West, and Franz Valley) by the northwest-striking Healdsburg and Maacama Fault Zones (fig. 4, sheet 2). The Healdsburg and Maacama Faults are major right-lateral strike-slip faults of the San Andreas transform system. To the southeast, they connect in en-echelon right-fault steps with the Rodgers Creek and then with the Hayward-Calaveras Fault system of the eastern San Francisco Bay region (fig. 1, sheet 1). Each of the principal fault blocks are also deformed internally by numerous north-northwest- to west-northwest-oriented subsidiary faults and folds that accommodated late Cenozoic contractional and extensional deformation.

Within the fault block bounded by the Healdsburg and Maacama Faults (the Mark West block) right-lateral slip is partitioned northward and eastward in a right-stepping extensional sense from the Rodgers Creek Fault (southeast of the map area) to the Healdsburg Fault and to the Maacama Fault (fig. 1, sheet 1). Since 2.8-3.1 Ma, as much as 6 km (herein reduced from an earlier estimate) of right slip occurred across the Healdsburg Fault and about 24±2 km of slip occurred across the Maacama Fault (McLaughlin and others, 2000).

West-northwest-trending thrust faults and folds that deform ≤2.8-3.1 Ma volcanic rocks and fluvial deposits are widespread within both the Mark West and Franz Valley fault blocks and the valley and ridge topography of this region is largely parallel to the west-northwest-oriented contractional deformation features. In detail, the northwest-trending Maacama Fault Zone, which forms the Mark West-Franz Valley block boundary, clearly truncates and is younger than the west-northwest-trending faults, folds, and associated west-northwest-oriented valley and ridge topography. The Maacama Fault Zone also is largely in an upland area, suggesting that extensional deformation associated with the active strike-slip fault system has had little control on regional topography, probably due to the youthfulness of strike slip faulting.

WINDSOR BLOCK

Rocks of the Windsor Fault block (fig. 4, sheet 2) are present only in the southwestern part of the map area, where pre-late Pliocene rocks are covered largely by Holocene and Pleistocene alluvium and by tilted and folded early Pleistocene to Pliocene gravel deposits

(QTg). South of the map area in the northwestern Santa Rosa quadrangle, the fluvial and lacustrine gravel of early Pleistocene to Pliocene age (QTg) is underlain and in fault contact with the Petaluma Formation of Miocene and Pliocene age along the northeast side of the Windsor block. In that area, the Petaluma Formation contains the 6.26±0.4 Ma (K-Ar) Roblar tuff. In the Mark West Springs quadrangle, both the Petaluma Formation and the early Pleistocene to Pliocene fluvial and lacustrine deposits (QTg) may be present beneath Quaternary cover southwest of the Healdsburg Fault Zone.

MARK WEST BLOCK

The Mark West block (fig. 4, sheet 2), bounded by the Healdsburg and Maacama Fault Zones, is broken internally by numerous subsidiary faults that trend northwest, generally at somewhat more westerly orientations than the block-bounding fault zones. These subsidiary faults include the Larkfield, Rincon Creek, Mark West, and Leslie Road Faults. They display kinematic evidence of dip-slip and strike-slip deformation that accommodated internal deformation within the Mark West block.

The Larkfield Fault dips steeply to the southwest and, locally, is upthrown both on the southwest and northeast. Slickensides rake at low angles (6-10˚) to the southeast or northwest and indicate sinistral strike slip. Based on the age of the offset tuff of Riebli Road (fig. 3, sheet 2), displacements along the Larkfield Fault are younger than 3.12 Ma.

The Rincon Creek Fault consists of two left-stepping, en echelon fault strands that partly bound the northeast side of Pleistocene-Pliocene gravel deposits (QTg) in the Riebli Road syncline. The faults are mapped mainly on the basis of straight alignment and oblique truncations along strike of contacts between andesite and basalt of the Sonoma Volcanics (Tsb), andesitic tuff (Tsta), silicic ash-flow tuff (Tst), and Pleistocene-Pliocene gravels (QTg). At Redwood Hill and west of Mark West Springs Road, the northwestern segment of the Rincon Creek Fault bends north, away from the gravel-volcanic contact. Nevertheless, the gravel-volcanic contact has strong linear topographic expression northwest of Mark West Springs Road (fig. 3, sheet 2), although volcanic units and gravels appear to be in depositional contact in that area.

The Mark West Fault Zone is a diffuse zone of west-northwest-trending faults that bound the northeast side of the Mark West Antiform. Relative motion of the Mark West Fault Zone appears to be largely up on the southwest and faults of the zone dip moderately to steeply to the northeast locally. Faults of this zone appear to merge with the Maacama Fault Zone to the southeast.

The Leslie Road Fault splays north-northwest from the Mark West Fault Zone at Mark West Springs and aligns with a part of Mark West Creek to the southeast and with the headwaters of Barnes Creek to the northwest. The fault dips steeply 50-70˚ NE., and motion along the fault is up to the southwest. Lineations on the fault surface rake 45˚ SE. and indicate dextral extension. The fault juxtaposes basaltic andesite and ash-flow tuff of the Sonoma Volcanics against Pleistocene and Pliocene gravels (QTg). Based on the ages of the offset volcanic rocks (fig. 3, sheet 2), the faulting is younger than 4.83 Ma. The Leslie Road Fault Zone can be traced northwestward into the easternmost part of the Healdsburg quadrangle, where it continues to follow the trend of Barnes Creek.

FRANZ VALLEY BLOCK

Northeast of the Maacama Fault Zone, the Franz Valley block (fig. 4, sheet 2) is deformed by numerous west-northwest-trending, steeply dipping, southwest-verging subsidiary reverse and thrust faults. Folds of similar trend are interspersed between the contractional faults. Many of the faults are truncated by the Maacama Fault. One narrow, north-trending zone of steep extensional strike-slip faults (Bidwell Creek Fault Zone) traverses the east side of the Franz Valley block. Most of the contractional structures are interpreted as part of a fold and thrust belt that formed prior to the right-lateral Healdsburg-Maacama stepover fault system. The Bidwell Creek Fault Zone may be related to the younger strike-slip system. Based on the ages of offset rocks and the regional distribution of scattered small magnitude ($M \leq 2.4$) earthquakes with thrust focal mechanisms, the transpressional faults of the Franz Valley block have been active since 2.8 Ma and still may be accommodating regional deformation.

The Petrified Forest Thrust Zone and Gates Canyon Thrust Fault in the southeast part of the map area form an imbricate zone of south-southwest-vergent reverse faults. These thrust and reverse faults locally dip from 50˚ to nearly vertical at the surface and exhibit rakes on fault surfaces indicating local components of dextral strike-slip. In the footwall blocks of the Petrified Forest Thrust Zone and Gates Canyon Thrust, 3.2-3.4-Ma ash-flow tuff, basaltic andesite, and Pliocene fluvial gravel (Tgp) are folded into three unnamed discontinuous synclines, which are locally overturned toward the southwest.

The hanging wall block of the Petrified Forest Thrust Zone is an antiformal structure (Petrified Forest Antiform) cored by rocks of the Franciscan Complex. The axis of the antiform and its bounding faults appear to truncate abruptly at the Maacama Fault Zone. The north flank of the Petrified Forest Antiform is bounded by northeast-dipping normal faults that accommodated unroofing of metabasaltic and metasedimentary Franciscan rocks in the core of the antiform.

Kinematic measurements from fault surfaces indicate that, north of the Petrified Forest Antiform, the east-west-trending Mountain Home Fault Zone accommodates dextral and normal slip. The normal slip may be associated with detachment in the hanging-wall block of the Petrified Forest Thrust Zone.

Franz Valley is an isolated alluviated valley that drains northwestward through a narrow canyon into Knights Valley. It is bounded to the southwest by the Devils Kitchen Fault Zone, a right-lateral splay from the Maacama Fault, and to the northeast by the Franz Valley Thrust Zone, which dips 45-50˚ NE. and locally subparallels the trend of the Devils Kitchen Fault Zone. Along Franz Valley School Road, the Franz Valley Thrust Zone includes sheared and crushed volcanic rocks with slickensided surfaces that exhibit complex reverse- and strike-slip displacement. The faulting here must be younger than the 2.8 Ma age of the ash flows in this area (fig. 3, sheet 2). The hanging-wall block of the Franz Valley Thrust Zone consists of a thick sequence of 3.2-2.8 Ma and younger ash flows, welded tuff, vitric tuff, and andesite folded into an anticline (the Franz Valley Anticline) around a core of Franciscan Complex melange. This anticline is interpreted to be a hanging-wall anticline associated with movement on the Franz Valley Thrust Zone. It is flanked to the northeast by several subparallel synclinal folds disrupted by faults of the Knights Valley and Bidwell Creek Fault Zones.

The Knights Valley Fault Zone is mapped along the south side of Knights Valley as a wide zone of faults that cut rocks of the Franciscan Complex, Pliocene gravel, and Sonoma Volcanics. The fault zone provided a passageway for hydrothermal fluids that locally altered Franciscan Complex metasandstones (fcs_2). At least one prominent east-west-trending, south-dipping fault of this zone tilts Pliocene gravels (Tgp) steeply against Franciscan Complex rocks along a south-flowing tributary to Franz Creek. Kinematic evidence of fault displacement is lacking along the trend of the fault zone, although its parallelism with the Franz Valley Thrust Zone suggests that it may also be a thrust fault. The Knights Valley Fault Zone appears to extend southeastward into the Calistoga 7.5' quadrangle and may be continuous with faults and air photo lineaments along the southwest side of Calistoga Valley (R.J. McLaughlin, unpub. field work and air photo reconnaissance mapping, 2000-2003).

The Bidwell Creek Fault Zone is a north-trending zone of discontinuous faults inferred from the alignment of straight drainage segments, saddles in ridges, deflection of drainages transverse to the aligned features, and local disruption of the northwest trends of other faults, folds, and bedding in the Sonoma Volcanics. Faults identified as part of this fault zone have relatively minor dip-slip and strike-slip displacements and dip steeply to the west and east. In the headwaters of Bidwell Creek near the north boundary of the map area, numerous springs occur along the fault zone.

^{40}Ar/^{39}Ar DATING OF LATE TERTIARY VOLCANIC ROCKS

Ages were determined in this study using the ^{40}Ar/^{39}Ar dating technique, first utilized by Merrihue and Turner (1966), which increases the precision of K-Ar dating. Samples are irradiated with fast neutrons, converting ^{39}K to ^{39}Ar in potassium-bearing materials. Heating of the sample then releases the ^{39}Ar together with the radiogenic ^{40}Ar, permitting simultaneous measurement of potassium and argon by mass spectrometry. Ar was released from whole-rock samples and mineral separates of volcanic rocks from the Mark West Springs quadrangle by the incremental-heating (or age spectrum) method, involving step-wise heating of the material, evolving the ^{39}Ar gas together with the radiogenic ^{40}Ar, atmospheric ^{40}Ar, and any extraneous ^{40}Ar in sequential steps or increments. Ages were calculated using ^{40}Ar/^{39}Ar laser-fusion analyses (York and others, 1981) of monitor minerals of known age to determine the neutron-flux (for example, Dalrymple and Duffield, 1988).

Incremental-heating analyses utilized a low-blank, tantalum and molybdenum, resistance-heated furnace, commonly releasing all Ar from each sample in 8 to 15 heating increments. Samples used in this study were irradiated for 2 to16 hours in the U.S. Geological Survey TRIGA Reactor Facility in Denver, Colorado. The neutron flux standard (monitor mineral) used in all irradiations was Taylor Creek Rhyolite sanidine, 85G003, with an age of 27.92 Ma as reported by Duffield and Dalrymple (1990). This age is standardized to an average age of 513.9 Ma for inter-laboratory standard hornblende, MMhb1 (Samson and Alexander, 1987) and the Menlo Park laboratory biotite standard, SB-3. Decay and abundance constants used in all calculations are those recommended by Steiger and Jager (1977). Ages reported in table 1 (sheet 2) represent the weighted means and uncertainties (Taylor, 1982), calculated from individual heating steps that define a statistically uniform value or “plateau” for a majority of the gas released. Plateau ages of ^{40}Ar/^{39}Ar age spectra are defined as the weighted mean ages of contiguous gas fractions representing more than 50 percent of the ^{39}Ar released for which no difference can be detected between the ages of any two fractions at the 95 percent level of confidence (Fleck and others, 1977).

TEPHROCHRONOLOGY OF LATE TERTIARY VOLCANIC ROCKS

Vitric pyroclastic volcanic rocks in the study area were sampled and analyzed, and selected samples were isotopically dated (fig. 3*A*, table 1, sheet 2) to provide a chronostratigraphic framework for the geologic units in the study area. This aspect of the work was undertaken to facilitate stratigraphic correlation within the mapped area and to determine the numerical ages of the geologic units being mapped. The strategy was to correlate the studied pyroclastic units, by means of chemical characterization (chemical fingerprinting), to each other and to units that had been dated previously at other localities in the study area or elsewhere in the region. In several instances when we were not able to assign a locality to a dated correlative unit by this technique, pyroclastic units were dated directly by the incremental heating $^{40}Ar/^{39}Ar$ technique. We sampled tephra layers (ash-falls, pumice-falls, ash-flows, and water-reworked tephra layers), near-source pyroclastic breccias, and obsidian from sites where the correlation of these units would assist stratigraphic mapping and structural interpretation.

Samples of these sediments and rocks were disaggregated or crushed and sieved using plastic sieves with nylon screen (the latter to prevent contamination with metals), to retain the ~80-150 µm fraction, and the components of the tephra samples were then separated and chemically cleaned to facilitate petrographic description and to prepare the materials for analysis (Sarna-Wojcicki and others, 1984). We separated isotropic volcanic glass from the samples for chemical analysis and, where necessary, plagioclase feldspar for radiometric dating. Samples of near-source obsidian were also analyzed to provide a means by which the sources and ages of obsidian clasts found in alluvial deposits could be determined. The obsidian clasts were also analyzed in order to trace their distribution away from their sources, particularly across the active faults in the study area, and thus to determine the amounts and rates of displacement on active faults. The latter study is part of a broader ongoing regional analysis, and specific analytic results are not present here.

Separates of clean, pure, isotropic glass shards were mounted in holes on copper-styrofoam wafer slides, cemented with epoxy, and polished with several progressively finer grades of diamond paste to provide a microscopically uniform, flat surface for analysis. The shards were then analyzed by means of a 5-channel JEOL 8900 Superprobe[1] electron microprobe for major and minor elements: SiO_2, Al_2O_3, FeO, MgO, MnO, CaO, TiO_2, Na_2O, and K_2O. Analytical settings were a beam diameter of 10 µm, a beam current of 10.05 νA, and 15 kV excitation potential. Element peak intensities were acquired for 20 s except for sodium, which was acquired for 10 s only to minimize migration of the ions away from the beam impact area and consequent reduction of counts with time. Standards used in analysis were GSC glass, An_{40}, and other U.S. Geological Survey analytical standards, as well as RLS-132, a homogenous obsidian that we use as an internal standard to test for reproducibility and for instrument drift. About 20 shards were analyzed for each sample. In some cases, additional shards were analyzed when multiple modes were found to be present.

Data were reduced with the ZAF data reduction package. Data reduction involved elimination of outliers or identification of multiple compositional modes, averaging of the major mode(s), and normalization of the average(s) to a 100 percent fluid-free base to reduce compositional scatter in the samples. FeO was converted to Fe_2O_3 for compatibility with our reference database of previously analyzed samples. The database of the Tephrochronology Laboratory, U.S. Geological Survey, Menlo Park, Calif., now contains ~5000 analyzed samples, mostly from the western conterminous U.S., that can be used for comparison. Many of the units analyzed are dated and their chemical composition is well determined. New analyses were compared with the database using the similarity coefficient (Borchardt and others, 1972; Sarna-Wojcicki and others, 1984). Several combinations of oxides were used in the comparisons to maximize the statistical advantage of the more abundant oxides. For example, elements present in concentrations lower than ~0.15 weight percent were generally not used. Comparisons were run with and without the alkalies, Na_2O and K_2O, to evaluate the possible effects of post-depositional alkali mobility of the volcanic glass. The alkalies often tend to become depleted or

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[1] Use of trade names is for informational purposes only and does not represent endorsement of the product by the U.S. Geological Survey.

enriched with time in natural glass for tephra layers older than a few thousand years, and alkali concentrations may vary with depositional and natural storage environment.

Names, locations, and ages of tephra and other pyroclastic units analyzed in this study are given in table 2 (sheet 2). Chemical analyses of the pyroclastic units sampled within the Mark West Springs 7.5' quadrangle are presented in table 3 (sheet 2).

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