Tectonic Setting of Late Miocene, Pliocene, and Pleistocene Rocks in Part of the Coast Ranges North of San Francisco, California

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By KENNETH F. FOX, JR.

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A study of the structural contrast between the little-deformed rocks of the Sebastopol block and the highly deformed rocks of the Santa Rosa block

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TECTONIC SETTING OF LATE MIOCENE, PLIOCENE, AND PLEISTOCENE ROCKS IN PART OF THE COAST RANGES NORTH OF SAN FRANCISCO, CALIFORNIA

By KENNETH F. FOX, JR.

ABSTRACT

Late Miocene, Pliocene, and Pleistocene strata in Marin, Sonoma, and Napa Counties, Calif., near the west edge of the North American plate, are much more intensely folded in one area than in another. The average dip of that part of these deposits west of the north-south-trending valley between Healdsburg and Petaluma, Calif., is 5.8°, whereas east of this valley the average dip is 34.5°. This difference in deformational intensity defines two structural blocks—the Sebastopol block on the west and the Santa Rosa block on the east.

The relatively flat lying deposits of the Sebastopol block are late Miocene and Pliocene marine sandstone, with minor intercalated conglomerate and one widespread layer of pumice lapilli tuff dated at about 6 m.y. old. These beds nearly abut the N. 40° W.-trending San Andreas fault on the west and are cut by several N. 60° W.-trending dip-slip faults. The relative undeformity of the late Miocene rocks in this area suggests that they were deposited after northwestward transit of the triple junction between the Pacific, Juan de Fuca, and North American plates, now at Cape Mendocino. This hypothesis is based on the premise that the extreme deformation of Miocene and Pliocene rocks in the vicinity of Cape Mendocino was caused by northwestward movement of the triple junction relative to the continental plate and that a wake of similarly deformed rocks should lie along the path of the triple junction to the southeast of Cape Mendocino.

The relatively intensely deformed rocks of the Santa Rosa block include the Sonoma Volcanics and the Petaluma Formation and the unconformably overlying Glen Ellen Formation. These strata range in age from about 12 m.y. to late Pleistocene, but even the younger deposits are intensely deformed locally.

The structural contrast between the Sebastopol block and the Santa Rosa block is paralleled by a geomorphologic contrast. The Sebastopol block is beveled by a now uplifted and dissected but little-deformed surface known as the Mendocino plateau, whereas the surface of the Santa Rosa block is broken and folded into a series of active structural basins and ranges. This structural configuration implies that the mechanism responsible for the late Miocene to Pliocene or Pleistocene deformational contrast is still functioning. The distribution of basement rock types shows no correlation with these structural domains; therefore, the contrasting deformational intensities probably stem from peculiarities in the pattern of regional stress distribution and not from a difference in the identity of the basement rocks.

The Santa Rosa block is cut by eight major north-northwest-trending right-lateral faults or fault systems: the Tolay, Rodgers Creek, Healdsburg, Maacama, Bennett Valley, Carneros, West Napa and Green Valley faults. The Rodgers Creek, Maacama, West Napa (in part), and Green Valley faults are currently active. Offsets on the faults and the trends of faults, folds, and dikes indicate that a major N. 30° W.-trending wrench system transects the Santa Rosa block. Right-lateral displacement across this wrench zone aggregates 85±25 km since about 8 m.y. B.P.

The faults within the wrench zone characteristically consist of short echelon right-stepping segments, trending somewhat more westerly than the wrench zone as a whole. Bends in the fracture surfaces that would be required to link major echelon segments of the Rodgers Creek and Maacama faults at Santa Rosa, Calif., as well as patterns of nearby folds and thrust faults, indicate that shear stress is locally concentrated in the vicinity of Santa Rosa.

Viewed more broadly, the deformational contrast probably reflects a difference in the intensity of horizontal compressive stress on a regional scale. Stress concentration in the Santa Rosa block relative to the Sebastopol block could be due to either, or possibly both, of two causes: (1) local thinning of the upper elastic part of the lithosphere because of an elevated geothermal gradient in the Santa Rosa block, or (2) the unique position of the Sebastopol and Santa Rosa blocks with respect to the dynamically interacting Pacific, North America, and Juan de Fuca plates. The widespread presence within the Santa Rosa block of late Miocene to Pleistocene volcanic rocks, as well as the presence of the Geysers steam field, suggests that the geothermal gradient there is indeed higher than in the adjacent Sebastopol block.

A regional compressional-stress field with principal horizontal axis oriented roughly north-south is assumed to be present in the western part of the North American plate. A component of the horizontal compressive stress along the coast may be intercepted by the northeasterly subducting Juan de Fuca plate, leaving a zone of reduced stress along the plate margin beginning near the triple junction at Cape Mendocino and extending southward to the vicinity of San Francisco, Calif. Thus, the Sebastopol block may represent this zone of reduced stress, and the Santa Rosa block the adjacent area of higher compressive stress.

The region of generally higher compressive stress, containing local areas of more extreme stress concentration (as at Santa Rosa), presumably intersects the San Andreas fault south of San Francisco. Locking of the San Francisco segment of the San Andreas at this intersection may be caused by the braking effect of this regional stress concentration. Therefore, it is probable that earthquakes at Santa Rosa, and on the locked segment of the San Andreas fault near San Francisco, could be triggered by stress changes in the vicinity of the triple junction.

INTRODUCTION

Late Miocene, Pliocene, and Pleistocene sedimentary and volcanic rocks in the study area north of San Francisco, Calif. (fig. 1), show a puzzling regional contrast in intensity of folding. In general, the deposits in this area that are east of Santa Rosa and Petaluma (fig. 2) are much folded, whereas those to the west are scarcely folded at all. This difference in deformational intensity defines two structural blocks—the Sebastopol block on the west and the Santa Rosa block on the east. The objectives of this report are to document this structural contrast and to explore the tectonic mechanisms that may have created it.

The geology of much of the study area was outlined in a pioneering study by Weaver (1949). His work, along with later contributions by Gealey (1951), Travis (1952), Cardwell (1958), Kunkel and Upson (1960), and numerous other investigators, has been synthesized in the map compilations by Blake and others (1971, 1974), Fox and others (1973), and Sims and others (1973). The structural data in these compilations form the observational basis for the present study.

Acknowledgments.—I am grateful to the many individuals who permitted access to their property during this investigation. Technical advice and help from J. O. Berkland, now Santa Clara County Geologist; Daniel T. Cardwell, Office of the Public Works Director, Napa, Calif.; and E. H. Boudreau, consulting geologist, Sebastopol, Calif., are greatly appreciated. I also thank U.S. Geological Survey geologists F. K. Miller and C. E. Meyer for providing K-Ar and fission-track ages, E. C. Schwarzman for help in petrography and geologic mapping, J. M. Donnelly, B. C. Hearn, Jr., and F. E. Goff for providing data on the geology of the Clear Lake area, and R. J. McLaughlin for freely sharing his insights into the stratigraphic and structural problems of western California.

PLATE-TECTONIC SETTING

In view of the strategic location of the Coast Ranges at the west edge of the North American plate, tectonism in this region is probably in part a response to interaction between this plate and adjoining plates to the west. According to plate-tectonic theory, the North American, Pacific, and Juan de Fuca plates meet at a triple junction at Cape Mendocino (fig. 1) (McKenzie and Morgan, 1969; Atwater, 1970). Throughout late Miocene, Pliocene, and Pleistocene time, the Pacific plate has apparently moved north-northwestward relative to the North American plate along their mutual boundary, a boundary that ultimately evolved into the present-day San Andreas fault system. The Juan de Fuca plate has accreted along the Gorda and Juan de Fuca ridges and moved eastward relative to the Pacific

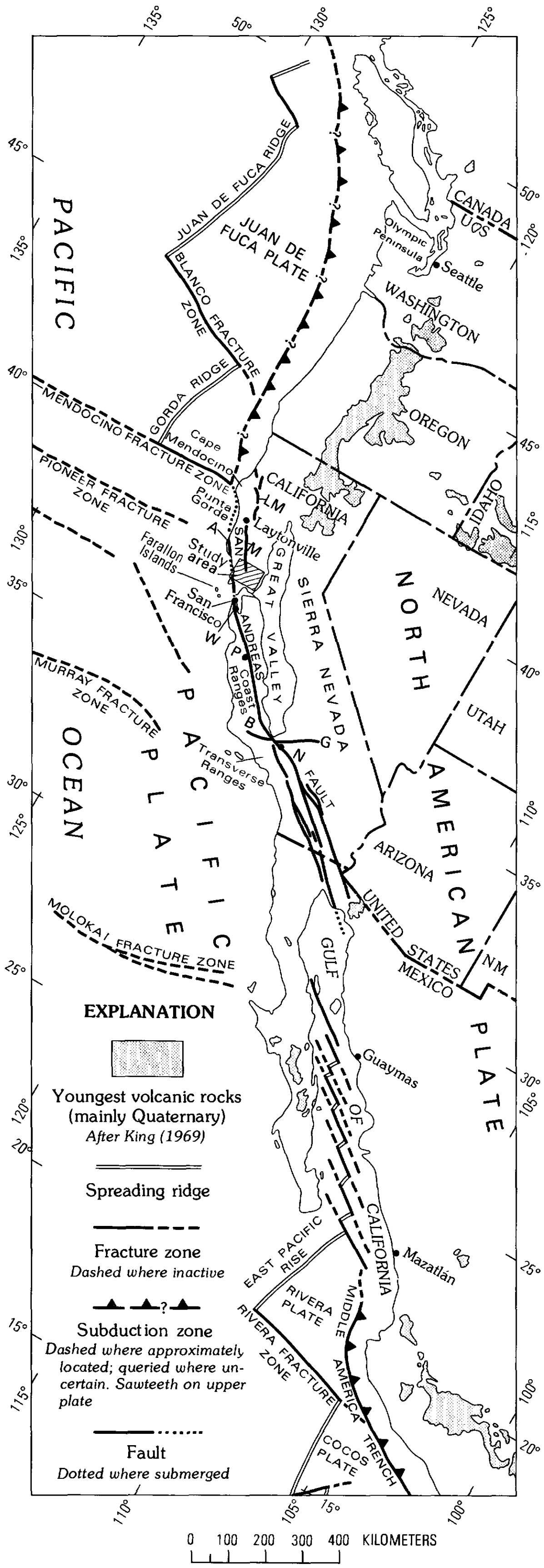

FIGURE 1.—Location of study area with respect to regional plate-tectonic features along Pacific coast of North America. A, Point Arena; B, Big Pine fault; G, Garlock fault; LM, Lake Mountain fault; M, Maacama fault; P, the Pinnacles Volcanic Formation of Matthews (1967); N, the Neenach Volcanic Formation of Dibblee (1967); W, Woodside.

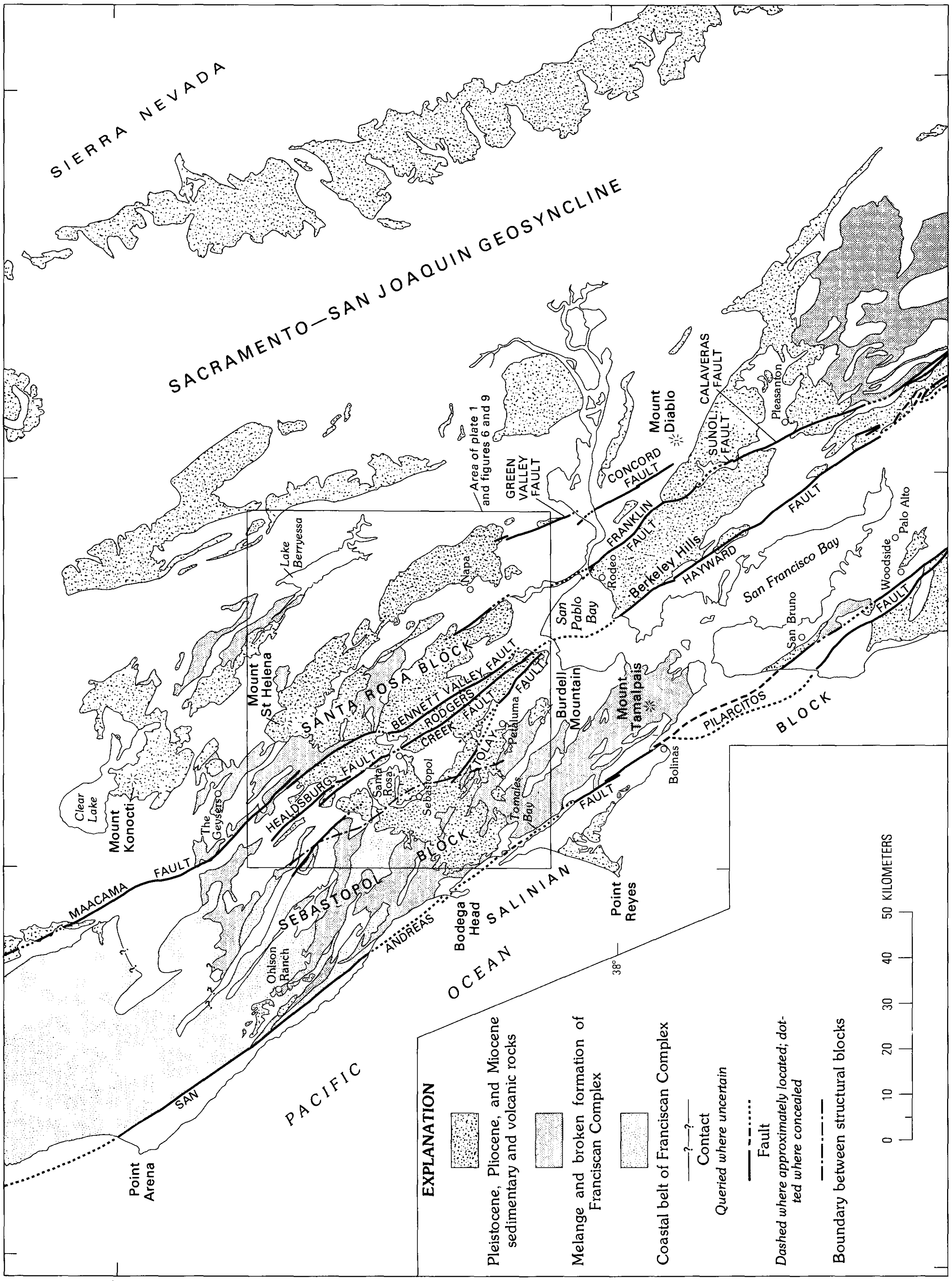

FIGURE 2.—Distribution of late Miocene, Pliocene, and Pleistocene rocks and other geologic features in central Coast Ranges, Calif. (modified from Jennings, 1973, 1977).

plate along the Mendocino fracture zone, underthrusting the North American plate along an ill-defined subduction zone seaward of and parallel to the coast of Oregon and Washington.

According to Atwater's (1970, p. 3516) reconstruction, that part of the Pacific plate between the Murray and Pioneer Fracture Zones contacted the North American plate shortly after formation of anomaly 10, that is, about 30 m.y. B.P. (on the basis of the time scale of LaBrecque and others, 1977). After formation of anomaly 8, about 3 to 4 m.y. later, the Pacific plate between the Pioneer and Mendocino Fracture Zones contacted the North American plate, forming the triple junction now at Cape Mendocino (see Atwater, 1970, p. 3523, fig. 12). Thus, the maximum age of the triple junction and the beginning of strike-slip movement on the newly formed transform fault between the Pacific and North American plates is about 27 m.y. Since the formation of this transform fault whose modern successor is the San Andreas fault, right-lateral movement along it has caused a corresponding right-lateral shift of the Mendocino triple junction to the north-northwest, relative to an arbitrary reference point on the North American plate.

Assuming that the sea-floor magnetic anomalies are dated and correlated approximately correctly, no radical departure from the late Miocene to Holocene part of the geologic history implicit in this model seems defensible. However, the rate and continuity of movement between the Pacific and North American plates since formation of the triple junction are still in doubt.

The average spreading rate on the East Pacific Rise in the Gulf of California of about 6 cm/yr for the past 2 m.y. (Larson and others, 1968; Larson, 1972, p. 3354) probably approximates the rate of right-lateral offset between the Pacific and North American plates during this period. This rate was amended slightly by Minster and others (1974, p. 559), who calculated a somewhat more precise slip rate of 5.5 cm/yr at the plate boundary in central California, on the basis of a simultaneous solution of rotation vectors between 11 major lithospheric plates. This result was not changed by omitting the spreading rate in the Gulf of California from the calculation.

Atwater (1970) predicated her popular constant-motion model on the assumption that Larson and others' (1968) estimated rate of 6 cm/yr for the past 2 m.y. could be extrapolated back to the Cretaceous. Subsequently, however, Atwater and Molnar (1973) calculated quite different rates of offset between the North American and Pacific plates for the Neogene by chaining spreading rates in the North Atlantic, Indian, and South Pacific oceans. On this basis, they suggested that the rate averaged about 5 cm/yr between 29 and 21 m.y. B.P., 1.3 cm/yr between 21 and 10 m.y. B.P., 4 cm/yr between 10 and 4.5 m.y. B.P., and 5.5 cm/yr since 4.5 m.y. B.P.

However, direct correlation of petrotectonic assemblages—groups of rocks formed in an identifiable plate-tectonic setting—with the causal plate-tectonic feature seems to confirm the constant-motion premise, at least for the Neogene. Specifically, correlation of the melange of the Olympic Peninsula of Washington with the transit of a Humboldt-type triple junction (Fox, 1976) that formed at the intersection of the Pacific, Juan de Fuca, and North American plates when the transform fault marked by the Aja Fracture Zone (Naugler and Wageman, 1973) intersected the west edge of the North American plate requires a rate of offset between the North American and Pacific plates of roughly 6 cm/yr for at least the past 16 m.y. (Fox, 1983).

Central California (fig. 1) presently lies immediately east of the Pacific plate and is transected by the San Andreas fault; tectonism in this area is now dominated by the effects of right-lateral wrenching along this fault. If the 5.5-cm/yr rate of offset is approximately valid for the entire Neogene, as suggested above, this area lay inland from the Juan de Fuca plate until the triple junction marking the northwest end of the San Andreas fault crept past during late Miocene and early Pliocene time. Tectonism in the study area before that time was probably dominated by processes that develop over or immediately inland from subduction zones.

In addition, a third tectonic regime, related to passage of the triple junction itself, might be recognizable. An insight into the tectonics of this triple junction can be gained from study of the rocks in its present vicinity. North of Point Arena the San Andreas fault bends slightly eastward and, skirting the coast, curves smoothly to an apparent junction with the Mendocino Fracture Zone at Punta Gorda (fig. 1) (Curray, 1966; Curray and Nason, 1967). Ogle (1953) showed that in the area to the north of the Mendocino triple junction, Neogene rocks designated by him the "Wildcat Group" consist of a sequence of marine and nonmarine conglomerate, sandstone, claystone, and siltstone more than 3,500 m thick. This sequence, dated by Nelson (1978) as early Pliocene to early Pleistocene, is folded and locally overturned along west-northwest-trending axes. Reverse and thrust faults parallel the axial traces of the folds and offset these beds possibly as much as 3,000 m (Ogle, 1953, p. 65).

Post-Pliocene orogeny in the Cape Mendocino area thus encompasses both strong folding and faulting. Deformation seemingly reflects north-northeastward-directed compression and is more extreme in the southern part of the area, toward Cape Mendocino and Punta Gorda, where isoclinal folding and shearing probably culminated in the generation of melange (Fox, 1976).

The path of the triple junction is probably marked by a deformational trail of structural features similar to those in the Cape Mendocino area. If this trail can be recognized and dated, it would afford an additional method of calibrating the rate of drift of the Pacific plate with regard to the North American plate.

The average post-Oligocene right-lateral offset on the San Andreas fault has, in fact, been only about 1.3 cm/yr, on the basis of correlation of the 23.5-m.y.-old Pinnacles Volcanic Formation of Matthews (1973) with the Neenach Volcanic Formation of Dibblee (1967) (fig. 1), now 314 km apart and adjacent to, but on opposite sides of, the San Andreas fault (Turner and others, 1970; Matthews, 1973). Offset of this approximate magnitude has been confirmed by discovery of another field, 22 m.y. old, that is bisected by the fault and offset 295 km (Huffman and others, 1973, p. 370).

The substantial discrepancy between these rates—1.3 and 6 cm/yr—must mean that most post-Oligocene offset between the Pacific and North American plates has been distributed across faults outside the San Andreas fault zone. In fact, the transform boundary between the Pacific and North American plates probably could not jump inland to the present trace of the San Andreas fault until the triple junctions now at Cape Mendocino and at the east terminus of the East Pacific Rise had separated a distance nearly equivalent to the present length of the San Andreas. Thus, the San Andreas fault probably did not assume its role as the transform fault separating the North American and Pacific plates until late in the Miocene, in which case the rate of movement on it since then has probably been substantially greater than 1.3 cm/yr.

STRATIGRAPHY

The central part of the Sebastopol block is occupied in part by erosional remnants of a former blanket of marine sand of late Miocene and Pliocene age, mapped as the Wilson Grove Formation (pl. 1). This deposit unconformably overlies typically weakly metamorphosed but much-deformed rocks of the Franciscan Complex of Berkland and others (1972).

The Santa Rosa block consists chiefly of late Miocene to Pleistocene rocks infolded with a pre-Miocene basement composed chiefly of the Franciscan Complex on the west and the Great Valley sequence on the east. The block includes the Petaluma, Glen Ellen, and Huichica Formations, the Sonoma Volcanics, and the Clear Lake Volcanics. Their aggregate maximum thickness locally exceeds 1,500 m, on the basis of drill-hole data, but throughout most of the study area probably does not exceed 3,000 m.

Also present are isolated erosional remnants of various Eocene formations. These units are not sufficiently extensive significantly to influence rheologic properties of the pre-late Miocene basement and thus are not considered further here.

BASEMENT ROCKS

The basement rocks consist chiefly of tectonically as well as depositionally juxtaposed bodies of graywacke, shale, and sandstone, mafic volcanic rocks (greenstone), melange, broken formation, and ultramafic rocks, all part of the Franciscan Complex (Berkland and others, 1972; Fox, 1983). The coherent depositional sequences of shale, sandstone, and conglomerate referred to as the Great Valley sequence, and the subjacent quasi-stratiform masses of serpentine and serpentinized ultramafic rock, are also part of the basement rocks.

As defined by Berkland and others (1972), the Franciscan is a structural complex. As such, it forms a rock-stratigraphic unit that includes rock types that previously were informally assigned to the Franciscan assemblage of Bailey and others (1964). The age of the complex is that of its structural aggregation and resulting structural fabric. This age necessarily postdates that of the youngest fossils found locally within the complex, which are Late Cretaceous (Campanian) throughout much of its central and eastern parts (Irwin, 1957, p. 2289-2294; Bailey and others, 1964, p. 115) and Paleocene and Eocene in its western part (O'Day and Kramer, 1972; Blake and Jones, 1974, p. 351; Kleist, 1975).

The complex may be the product of several episodes of structural aggregation, each of different areal extent, and so the age of the complex as a whole may vary from place to place. Within the map area (pl. 1) the complex is assigned a Paleocene and (or) Eocene age on the basis of proximity of this area to parts of the complex to the northwest containing fossils of this age. However, further study may reveal that parts of the complex within the map area are pre-Tertiary.

Rocks included within the Great Valley sequence range in age from late Jurassic (Tithonian) to Late Cretaceous and thus are equivalent in age to some of the lithologic elements that were incorporated within the Franciscan Complex (Irwin, 1957; Bailey and others, 1964, p. 123-139; Berkland, 1973, p. 2396-2399). The Franciscan Complex and the Great Valley sequence are not found in depositional contact with each other; instead, the two units are faulted together or faulted against folded sheetlike bodies of serpentine and varyingly serpentinized ultramafic rocks that intervene between the two units (Irwin, 1964; Blake and others, 1967).

Plate 1 shows the distribution of the Great Valley sequence and the Franciscan Complex within the study area. Melange and broken formation, which form the lithologically weaker elements of the Franciscan, are about as abundant in the western part of the Santa Rosa block as in the Sebastopol block (fig. 2).

SANDSTONE, SILTSTONE, SHALE, AND CONGLOMERATE

Miocene or Miocene(?) marine sedimentary rocks older than the lower member of the Sonoma Volcanics are exposed within three small areas in the southeastern part of the study area (pl. 1). These sedimentary rocks represent the northwest fringe of a thick depositional wedge of lower and middle Miocene rocks and subjacent Miocene(?) strata centered southeast of San Pablo Bay (fig. 3). This depositional wedge is transected and offset by the Franklin-Sunol-Calaveras fault system. Thus, the distribution of the three small remnants of this wedge that are present in the study area (pl. 1) bears on the position of the northwestward extension of this fault system—believed to be the Carneros fault—and on offset on it.

The stratigraphic sequence within the depositional wedge south of San Pablo Bay includes three major units: the San Ramon Sandstone at the base, the Monterey Group (as used by Lawson, 1914) and its correlatives in the middle, and the San Pablo Group at the top. The upper two of these units appear to be transgressive toward the north and east edges of the depositional wedge and to lap over the distal part of the subjacent unit onto the basement rocks.

SAN RAMON SANDSTONE

The San Ramon Sandstone (Clark, 1918, p. 78-81), 160 m thick at the type section southwest of Walnut Creek (fig. 3), consists there of fine-grained bluish-gray tuffaceous sandstone. In the study area (pl. 1) the San Ramon consists of medium-grained bluish-gray to light-brown sandstone, with an exposed thickness of about 90 m, cut off at the base by the Carneros fault (Weaver, 1949, p. 65).

Weaver (1949, p. 65) concluded that the San Ramon was Oligocene, on the basis of its marine-invertebrate fauna, but more recently the age of the San Ramon was revised upward to Miocene(?) by Addicott (1970, p. 40).

MONTEREY GROUP OF LAWSON (1914)

Because of rather abrupt changes in facies and thickness, the stratigraphy of the Monterey group is somewhat complex. As originally defined by Lawson (1914), the Monterey immediately south of San Pablo Bay in the Concord, Calif., area (fig. 3) consisted of seven formations, which in ascending order included the Sobrante Sandstone, the Claremont Shale, the Oursan Sandstone, the Tice Shale, the Hambre Sandstone, the Rodeo Shale, and the Briones Sandstone. Trask (1922) later showed that the fauna of the Briones more closely resembled that of the overlying San Pablo Group (which then included only the Neroly and Cierbo Sandstones) and, on that basis, transferred the Briones Sandstone from the Monterey to the San Pablo Group.

Weaver (1949) was able to follow the interlayered sandstone and shale beds of the Monterey Group from Lawson's (1914) map area northward into the southern limb of the San Pablo syncline, but not from the southern limb to the northern limb. On the northern limb he found a sequence of thinly interlayered shale, shaly sandstone, and sandstone that he believed to be the equivalent of the Briones Sandstone plus all of the Monterey Group, although individual beds within the sequence could not be distinguished, owing, he speculated, to rapid lateral change in their lithology. Weaver (1949, p. 71) termed this sequence the "Monterey Shale." West of the Carneros fault, 7 km east of Sonoma, Calif. (pl. 1), the Monterey Shale consists of a 150-m-thick sequence of fine- to medium-grained light-gray to white sandstone, shaly sandstone, and sandy shale and overlies the San Ramon Sandstone with apparent conformity (Weaver, 1949, p. 74).

A further complication in terminology was formalized by Lutz (1951). In the Concord area, Lawson (1914) had applied the term "Sobrante Sandstone" to the basal sandstone of his Monterey Group. Lutz retained this usage for that area but named the 200-m-thick sequence of sandstone and shale representing the entire Monterey Group in the Pacheco syncline area (fig. 3) the "Sobrante Formation." Like the Monterey Shale of Weaver (1949), individual formations of the Monterey Group are indistinguishable within the Sobrante Formation of Lutz (1951).

SAN PABLO GROUP

The San Pablo Group (Clark, 1915, 1930; Trask, 1922) as presently defined consists of three formations: the Briones Sandstone at the base, the Cierbo Sandstone in the middle, and the Neroly Sandstone at the top. The Neroly Sandstone is exposed in a small window eroded through the overlying lower member of the Sonoma Volcanics, 13 km north of Sonoma (pl. 1), and also west of the Carneros fault, 7 km east of Sonoma. West of the Carneros fault, the Neroly consists of bluish-gray coarse-grained sandstone with subordinate tuff, shale, and pebbly layers, aggregating at least 225 m in thickness (Weaver, 1949, p. 85).

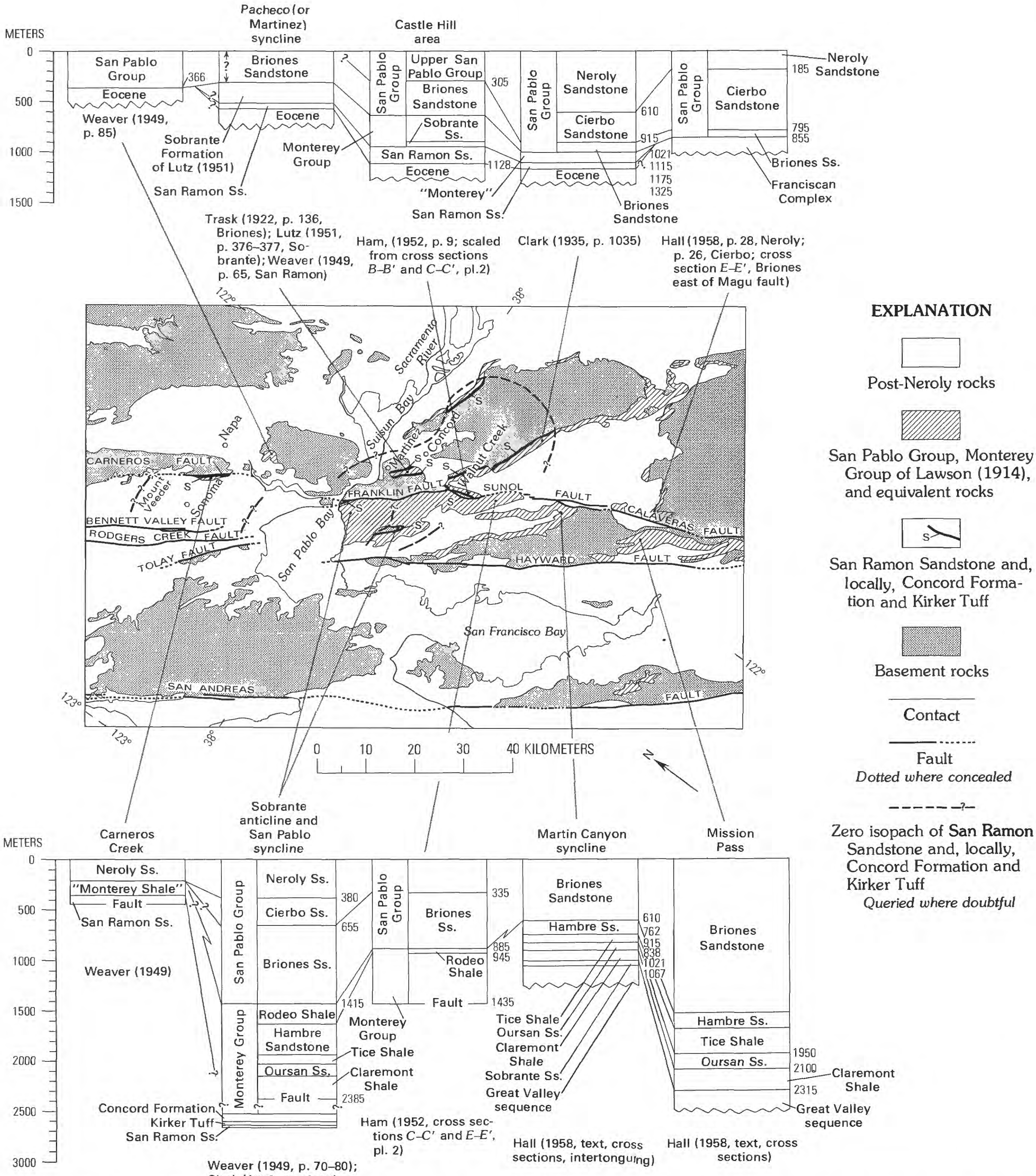

FIGURE 3.—Relation of Carneros-Franklin-Sunol-Calaveras fault system to distribution of the San Ramon Sandstone, the Monterey Group of Lawson (1914), and the San Pablo Group. Stratigraphic nomenclature is that of authors cited.

The rocks of the San Pablo Group generally are abundantly fossiliferous and contain a late Miocene marine fauna (Hall, 1958, p. 23-28); intercalated beds at several horizons show features indicative of deposition in estuarine or brackish water (Clark, 1915, p. 396). In some areas, however, the Neroly grades laterally or upward into marine and (or) continental deposits containing fossil leaves and fossil vertebrates, including horse teeth of Clarendonian age (Stirton, 1939, p. 341-342, 363-365; Kilmer, 1953, p. 40).

TOLAY VOLCANICS OF MORSE AND BAILEY (1935)

The Tolay Volcanics consists of basaltic to andesitic lava flows, with interlayered tuff, breccia, and agglomerate, overlying dacite and dacite porphyry (Morse and Bailey, 1935, p. 1442-1443). These rocks were penetrated at depth below the Petaluma Formation in several oil test holes, including the Murphy No. 1 about 6 km east-northeast of Petaluma (pl. 1). The deepest well bottomed in the Tolay after penetrating more than 1,200 m of these volcanic rocks (Morse and Bailey, 1935, p. 1441).

Basalt flows capping Burdell Mountain, 9 km south of Petaluma (pl. 1), were assigned to the Tolay Volcanics by Mankinen (1972). A sample of the basalt at Burdell Mountain yielded a K-Ar age of 11.8±0.8 m.y. (Mankinen, 1972, p. 2065). Volcanic rocks cropping out east of Petaluma that were believed to be the Tolay by Morse and Bailey (1935, pl. 127) were reassigned to the Sonoma Volcanics by Weaver (1949, pl. 10). Weaver thus designated as the Tolay only those strata encountered at depth in the oil test wells, although he accepted the legitimacy of the Tolay Volcanics as a formational unit distinct from the Sonoma Volcanics.

Morse and Bailey (1935, p. 1441) suggested that the thick section of the Petaluma Formation between the Tolay Volcanics and the Sonoma Volcanics in the Petaluma-Sonoma Mountains area thins toward the east flank of the Sonoma Mountains and might wedge out farther to the northeast. If the Petaluma does wedge out to the northeast, they postulated that two distinct and extensive, though undifferentiated, volcanic members may be present within the mountainous region east of the Sonoma Valley. The volcanic rocks in that area (near Mount Veeder, pl. 1) are presently all assigned to the lower member of the Sonoma Volcanics. Whether a significant unconformity exists within the volcanic rocks in this area and whether any of them correlate with the Tolay Volcanics of Morse and Bailey (1935) are not known. Pending further definition of the Tolay Volcanics and study of its possible correlatives, all the late Miocene volcanic rocks exposed at the surface within the map area (pl. 1), except for those at Burdell Mountain, are here assigned to the Sonoma Volcanics.

PETALUMA FORMATION

The Petaluma Formation (Dickerson, 1922, p. 540-543) comprises interfingering beds and lenses of poorly consolidated clay, shale, silt, sand, and gravel, and local interbeds of tuff and diatomite (Cardwell, 1958, p. 32-35). Clay or clay-shale is the most common rock type; the gravel within the Petaluma is composed chiefly of Franciscan detritus, along with minor amounts of volcanic detritus. Pebbles of laminated siliceous shale resembling the Monterey Shale of Miocene (and possibly Oligocene) age are also present.

On the basis of well data, the Petaluma Formation is at least 1,200 m thick southeast of Petaluma, Calif., (Morse and Bailey, 1935, p. 1444). Deep drill holes, including the Murphy No. 1, that penetrated the Petaluma in this area have bottomed in the underlying Tolay Volcanics. According to Morse and Bailey (1935, p. 1445), the contact with the underlying Tolay is transitional, in that the volcanic rocks are interlayered with ostracode-bearing shale of the Petaluma through a well thickness of 37-51 m.

The nature of the contact of the Petaluma Formation with the Sonoma Volcanics is controversial. Morse and Bailey (1935, p. 1450) contended that the gently dipping Sonoma overlies the truncated steeply dipping Petaluma with pronounced angular unconformity; this view was echoed by both Cardwell (1958) and Weaver (1949). However, mapping of the west margin of the Sonoma Volcanics in the Sonoma Mountains reveals that the lower member of the Sonoma contains numerous interlayers of clay, clay shale, diatomite, sandstone, and gravel that resemble the Petaluma. Weaver (1949) had previously recognized that the Sonoma Volcanics was interlayered with sedimentary rocks about 10 km northwest of Petaluma (pl. 1) but had assigned these sedimentary rocks to the Merced Formation. However, these beds consist of interlayered shale, clay shale, sandstone, and gravel that lithologically resemble the Petaluma and hence were reassigned to the Petaluma by Blake and others (1971) and Fox and others (1973). Thus, as presently defined and mapped, the Petaluma interfingers with the lower member of the Sonoma Volcanics. This relation implies that unconformities comparable to that observed by Morse and Bailey (1935) between elements of the Sonoma Volcanics and elements of the Petaluma Formation could be present, though not recognized, within the Petaluma itself.

In some places the Petaluma Formation contains elements of a freshwater and, in other places, a brackish-water fauna (Dickerson, 1922, p. 542). Mammalian fossils are rare: horse teeth from two localities were considered early Upper or late Middle Pliocene (Stirton, 1939, p. 389, 393) (probably late

Miocene—that is, 5 m.y. or older—by modern correlations; C. A. Repenning, written commun., 1978). A bison from sediment correlated with the Petaluma was considered later Pleistocene (Rancholabrean) by Savage (1951, p. 283); this age is much younger than any other part of the Petaluma. It is doubtful that the Petaluma could be younger than the upper member of the Sonoma Volcanics and the Glen Ellen Formation, and so this age is here disregarded. Probably the bison came from unmapped alluvial deposits locally overlying the Petaluma.

A tuff bed intercalated with the Petaluma Formation along the east side of the Sonoma Mountains (about 6 km west of Sonoma, pl. 1) yielded plagioclase crystals dated by K-Ar methods at 11.0±0.6 m.y. (K. F. Fox, Jr., unpub. data, 1977). The Tolay Volcanics transitionally underlying the Petaluma has not been dated directly, although basalt flows capping Burdell Mountain (pl. 1) that yielded a K-Ar age of 11.8±0.8 m.y. were assigned to the Tolay by Mankinen (1972, p. 2065, 2068). A layer of vitric tuff exposed with the Petaluma Formation (Morse and Bailey, 1935, p. 1445) west of the Sonoma Mountains and about 9 km east-southeast of Petaluma was correlated with the tuff in the Wilson Grove Formation by Sarna-Wojcicki (1976), which has been dated at 5.7 and 6.1 m.y. by K-Ar methods. The lava flows and pyroclastic deposits of the Sonoma Volcanics within the Sonoma Mountains area that are interlayered with sediment similar to the Petaluma have been dated at 5.5 to 7.1 m.y. by K-Ar methods (K. F. Fox, Jr., and C. E. Meyer, unpub. data, 1977).

Although the Petaluma Formation has traditionally been regarded as Pliocene, the evidence outlined above suggests that it is wholly late Miocene. The Petaluma probably represents fluviatile, lacustrine, and brackish-water marine deposits that accumulated during the late Miocene within an elongate trough that subsided along the west margin of the Santa Rosa block. The present distribution of the Petaluma Formation, flanking both sides of the Sonoma Mountains, suggests that the axis of this late Miocene downwarp coincided roughly with the present trend of the range.

WILSON GROVE FORMATION

A blanket deposit of fine-grained unconsolidated sand mantling parts of the Sebastopol block is here named the "Wilson Grove Formation"; this deposit was formerly assigned to the Merced(?) Formation. The area between Wilson Grove (pl. 1) and Mark West Creek, $2^1/_2$ km due south, is designated the type locality. This locality, in T. 8 N., R. 9 W., is 11 km north of Sebastopol, Sonoma County, Calif.

The Wilson Grove Formation consists chiefly of massive sand and minor amounts of gravel and tuff. According to Travis (1952, p. 18), the formation reaches as much as 150 m in thickness and was deposited under beach and shallow-marine conditions on a surface of low to moderate relief beveled across Franciscan and Great Valley basement rocks. Locally, deposits of gravel and sand of probable alluvial origin overlie the marine beds. These freshwater sedimentary rocks were included with the older marine beds assigned to the Merced(?) Formation by previous workers but are here treated as a separate unit, informally designated the "sand and gravel of Cotati." The contact of the Wilson Grove Formation with the Petaluma Formation to the east is concealed by these younger deposits and by alluvium.

In its lower and middle parts, the Wilson Grove Formation contains a conspicuous but discontinuous interbed of pumice lapilli tuff, well exposed at and near the type locality. Trace-element concentrations indicate that this tuff was erupted from the Sonoma Volcanics and is a probable correlative of a tuff in the Petaluma Formation (Sarna-Wojcicki, 1976). The tuff is present 15 to 75 m above the base of the Wilson Grove Formation (Travis, 1952, p. 20) and has yielded K-Ar ages of 5.7±0.5 m.y. (Sarna-Wojcicki, 1976) and 6.1±0.1 m.y. (Bartow and others, 1973); thus the tuff and, by implication, the beds below it, are late Miocene. This conclusion is at variance with that of Bartow and others (1973), who considered molluscan faunas from localities stratigraphically below the tuff to be early Pliocene and those from localities above to be late Pliocene. This contradiction has not yet been resolved. However, placing greater reliance on the K-Ar ages, the Wilson Grove Formation is here considered late Miocene and Pliocene, spanning the revised boundary between the Miocene and Pliocene of about 5 m.y. B. P.

Early workers (Lawson, 1893, p. 142; Osmont, 1905, p. 69) correlated Wilson Grove strata with the type Merced Formation of the San Francisco peninsula on the basis of a marine megafauna, which was considered Pliocene by Dickerson (1922, p. 543-550). This correlation was later questioned by Higgins (1960, p. 203) on the basis of faunal and lithologic differences between the type Merced and the Wilson Grove Formation. According to Weaver (1949, p. 92), the type Merced "* * * probably represents a longer interval of deposition, possibly extending into the Pleistocene * * *," and the strata herein designated the "Wilson Grove Formation" are "* * * probably equivalent to the lower Merced of the type section."

The type section of the Merced Formation, as defined by Glen (1959), is a 1,500-m-thick sequence of sedimentary strata exposed on the seacliff southwest of San Francisco. The section is transected by the San

Andreas fault; a 185-m-thick sequence of shallow-dipping poorly exposed argillaceous sandstone and sandy siltstone unconformably overlying Franciscan basement lies south of the fault, and a 1,300-m-thick sequence of steeply northeast dipping siltstone, sandstone, and conglomerate lies north of the fault (Glen, 1959, p. 154-155).

Glen (1959) referred to that part south of the San Andreas fault as the "lowermost Merced" and informally divided the sequence north of the fault into the "lower Merced" (1,200 m thick) and the "upper Merced" (125 m thick). Glen believed the upper Merced to be separated from the lower Merced by a fault or unconformity, although this relation was obscured by a large landslide (Glen, 1959, p. 151). On the basis of megafossils, the lowermost Merced is middle Pliocene, the lower Merced probably late Pliocene, and the upper Merced Pleistocene (Glen, 1959; Hall, 1966). The Merced south of the San Andreas fault is apparently older than anywhere north of the fault (Glen, 1959, p. 151). The lower Merced is chiefly shallow-water marine, whereas the upper Merced is chiefly nonmarine (progressively estuarine, littoral, and continental) (Hall, 1966). A thin tuff bed in the upper part of the upper Merced has been dated by fission-track methods at 0.45 ± 0.08 m.y. (weighted average of 15 samples; Meyer and others, 1980).

The Wilson Grove Formation is lithologically similar to parts of the lower Merced of Glen (1959), but whether it is of the same age is uncertain. The upper Merced of Glen (1959) has no lithologic or age counterpart in the Wilson Grove Formation. However, the alluvial deposits overlying the Wilson Grove and here referred to the sand and gravel of Cotati could be a chronologic equivalent of the nonmarine strata of the upper Merced.

SONOMA VOLCANICS

The Sonoma Volcanics was named by Weaver (1949, p. 122) who described it as " * * * a complex series of lava flows and tuff beds that in certain areas are interbedded with sandstone, gravel, and conglomerate." This series had previously been broken into three units by Osmont (1905), in ascending order: the Mark West Andesite, the Sonoma Tuff, and the St. Helena Rhyolite. Weaver was impressed by the heterogeneity and lateral variation of the Mark West Andesite and the Sonoma Tuff and stated that both units contained andesitic and basaltic flows which vary areally in the same manner; he concluded that they, along with the St. Helena Rhyolite, should be regarded as a single geologic unit, the Sonoma Volcanics. Nevertheless, in his text and on his maps, Weaver distinguished the St. Helena Rhyolite Member from other parts of the Sonoma Volcanics. More recent mapping (Fox and others, 1973; Sims and others, 1973) indicates that the St. Helena Rhyolite Member as mapped by Weaver (1949) is interlayered with older as well as younger parts of the Sonoma Volcanics and shows a comparable age range, although it is true that most of the rhyolite and rhyolitelike lithoidal welded tuff occur in the upper part of the Sonoma Volcanics.

In this report, the Sonoma Volcanics is informally divided into a lower and an upper member. These units correspond roughly to Osmont's (1905) Mark West Andesite and Sonoma Tuff, except that the St. Helena Rhyolite Member as mapped by Weaver (1949), which includes numerous discrete bodies of various age, is here lumped with the lower or upper members as appropriate.

The Sonoma Volcanics formed a volcanic field whose erosional remnants now span a northwest-trending area 90 km long by 30 km wide (pl. 1). The lower member occupies most of the southern part of the volcanic field as it is exposed today. This member consists chiefly of silicic basalt, andesite, and dacite flows, with subordinate interlayered ash flows and rhyolite flows, and thus contrasts with the predominantly tuffaceous rocks of the younger part of the field to the north. In the southern part of the field, the lower member forms the erosionally resistant shields of three northwest-trending mountainous ridges; these include the Sonoma Mountains on the west, the Mount Veeder area in the middle, and the Mount George area on the east (pl. 1). Correlation of the volcanic rocks across the intervening valleys—which are floored with younger deposits—has not been successful; in fact, some lithologic contrasts are apparent. In the Sonoma Mountains, the most prevalent lithology is silicic basalt or basaltic andesite containing both augite and olivine. In the Mount Veeder area, augite andesite and augite-hypersthene dacite are most abundant. In the Mount George area, augite-hypersthene dacite is abundant low in the section; this rock, along with subordinate interlayered agglomerate and tuff, is disconformably overlain, in ascending order, by ash flows, welded tuff, and rhyolite. Rocks above the disconformity are provisionally assigned to the lower member. Rhyolite is present mainly as domes or crosscutting intrusive plugs in the Sonoma Mountains, whereas it is clearly interlayered with andesitic and dacitic lavas in the Mount Veeder area. As noted in the section on the Tolay Volcanics, Morse and Bailey (1935, p. 1441) suggested that the lower part of the volcanic sequence in the Mount Veeder area might correlate with their Tolay Volcanics.

The upper member of the Sonoma occupies much of the north-central part of the study area. This member consists of a thick sequence of ash flows, of which many are welded or partially welded, as well as tuff, tuff breccia, agglomerate, and rhyolite that are locally capped by basalt flows. Ash flows and bedded tuff at the base of the upper member interfinger with fluviatile and lacustrine conglomerate, sandstone, siltstone, claystone, and diatomite of the upper part of the Huichica Formation along Mark West Creek, 9 km northeast of Santa Rosa (pl. 1). To the north and east the upper member unconformably laps onto both the basement rocks and isolated patches of the lower member of the Sonoma Volcanics.

The Sonoma Volcanics has been regarded as Pliocene or younger on the basis of its presumed unconformable basal contact with the Petaluma Formation, which was previously believed to be Pliocene (Weaver, 1949, p. 128). Reported K-Ar ages of rocks here assigned to the lower member, but exclusive of those in the Sonoma Mountains area, range from 8.9±4.5 m.y. at a locality about 6 km north of Santa Rosa (sample loc. S20, Mankinen, 1972, p. 2065) to 3.8±0.1 m.y. near Mount George (rhyolite dated by G. H. Curtis, 1971, in Sarna-Wojcicki, 1976, p. 4-5). The K-Ar age of the lower member within the Sonoma Mountains ranges from about 5.5 to at least 7.1 m.y. (K. F. Fox, Jr., unpub. data, 1977).

The rocks in the Sonoma Mountains appear to be decidedly older than those in the Mount George area. Volcanic rocks in stratigraphic sequence below the 3.8-m.y.-old rhyolite at Mount George have been dated by K-Ar methods at 4.2±0.1 m.y., 4.7±0.2 m.y. (Mankinen, 1972), and 5.4 m.y. (G. H. Curtis, unpub. data, cited by Sarna-Wojcicki, 1976, p. 4-5). On the basis of these ages, the lower member of the Sonoma Volcanics is late Miocene and early Pliocene.

A rhyolitelike lithoidal welded tuff capping Mount St. Helena (pl. 1), believed to be near the top of the stratigraphic sequence of volcanic rocks included in the upper member of the Sonoma Volcanics, has been dated at 2.9±0.2 m.y. (Mankinen, 1972, p. 2065). A layer of tuff at the base of this sequence has also been dated; this tuff, along with remnants of the redwood forests that grew on it, is exposed at the locally famous Petrified Forest (pl. 1). The K-Ar age of the tuff at this locality is 3.4 m.y. (Evernden and James, 1964, p. 971). On the basis of these ages, the upper member of the Sonoma Volcanics is Pliocene.

Dikes, pipes, and plugs cutting the Sonoma Volcanics are not abundant except in the northeastern part of the volcanic field (see fig. 6). These intrusive rocks range in composition from basalt to rhyolite and thus have a compositional spectrum similar to that of the Sonoma Volcanics as a whole. Probably they were feeders to extrusive rocks of the Sonoma Volcanics that locally have been eroded away. The dikes, of which 28 are known, dip steeply and, along with one clastic dike and two veins, show a preferred northeasterly orientation (fig. 4).

HUICHICA FORMATION

The type locality of the Huichica Formation (Weaver, 1949, p. 98) lies about 10 km southeast of Sonoma (pl. 1). In that area, according to Weaver, the formation consists of stratified gravel, sand, reworked tuff, clay, and conglomerate containing clasts derived from both volcanic and sedimentary rocks. A tuff bed interlayered with these rocks yielded a K-Ar age of 3.94±0.18 m.y. (A. M. Sarna-Wojcicki, oral commun., 1977). Sand and gravel deposits in Napa Valley included by Weaver in the Huichica Formation are similar, except that there diatomite is interbedded with the rock types noted above.

In Bennett Valley, 10 km southeast of Santa Rosa (pl. 1), a thick sequence of clay shale, gravel, and minor tuff and diatomite, previously included in the Petaluma Formation by Weaver (1949, p. 86), is here assigned to the Huichica Formation. A tuff from this sequence gave a K-Ar age of 3.81±0.31 m.y. (J. A. Bartow, oral commun., 1977) and has a minor-element chemistry similar to that of the tuff in the Huichica at the type locality (A. M. Sarna-Wojcicki, oral commun., 1977).

In the upper reaches of Mark West Creek, 8 km northeast of Santa Rosa (pl. 1), a sequence of gravel, sand, and reworked tuff correlated with the Huichica Formation unconformably overlies the lower member of the Sonoma Volcanics. There, the Huichica Formation in its upper part interfingers with the lower part of the upper member of the Sonoma Volcanics. These age and contact relations suggest that the Huichica Formation is early Pliocene.

GLEN ELLEN FORMATION

The Glen Ellen Formation (Weaver, 1949, p. 98) consists of interstratified gravel, sand, tuffaceous sand and silt, and reworked tuff. These beds contain detritus from both the Franciscan Complex and the Sonoma Volcanics. As J. O. Berkland pointed out to the author (oral commun., 1970), beds mapped as the Glen Ellen Formation by Weaver in its type locality near Glen Ellen (pl. 1), contain very sparse but ubiquitous pebbles of black obsidian. This obsidian was apparently derived through erosion of obsidian in the upper member of the Sonoma Volcanics, and not from superficially similar obsidian in the Clear Lake Volcanics (K. F. Fox, Jr., and M. B. Norman, unpub. data, 1977). Obsidian pebbles have not been observed in the otherwise similar but older gravel of the Petaluma and Huichica Formations, and so their presence in gravel

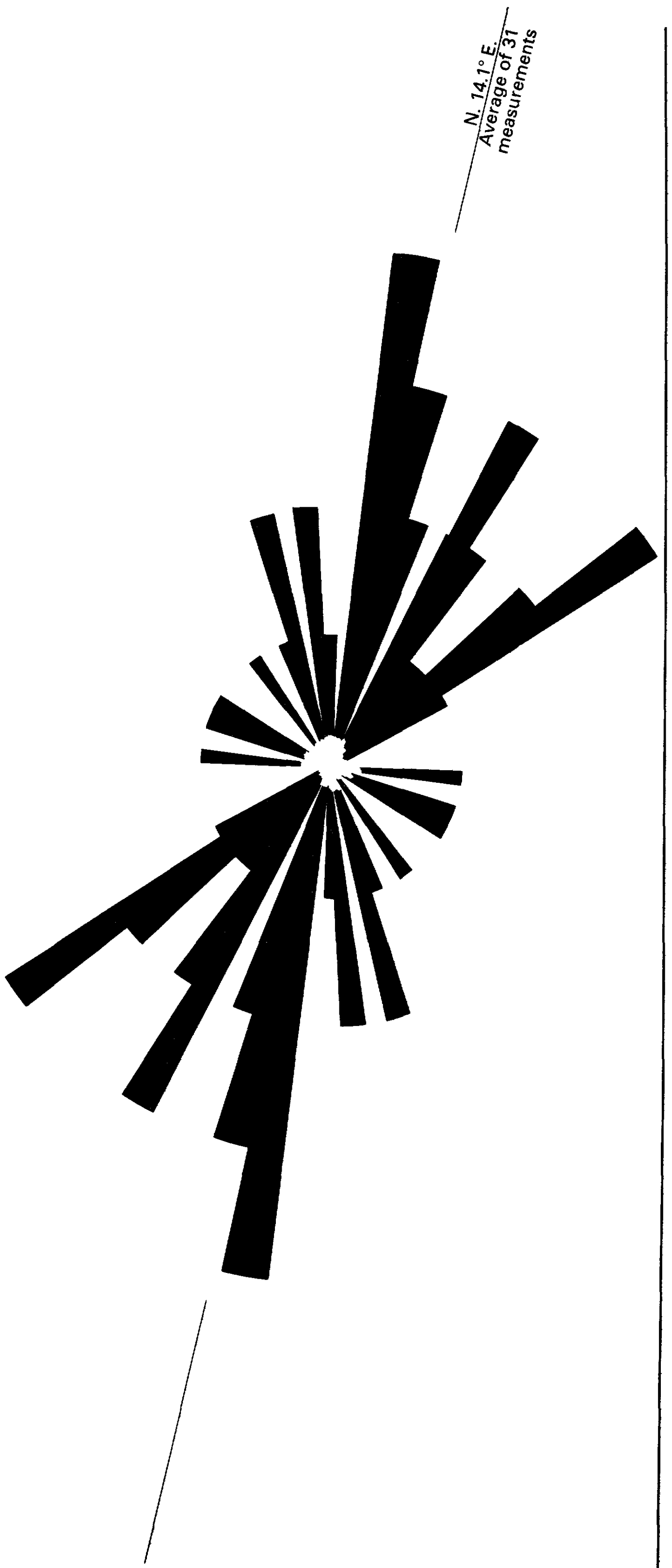

FIGURE 4.—Rose diagram showing orientation of 28 volcanic dikes, 2 veins, and 1 clastic dike that cut the Sonoma Volcanics (see fig. 6).

and sand deposits in this region is here considered definitive of the Glen Ellen Formation. Because the obsidian pebbles are sparse, their apparent absence at any one outcrop must be evaluated cautiously.

As redefined above, the Glen Ellen Formation unconformably overlies the upper and lower members of the Sonoma Volcanics and also the Huichica Formation. The relation of the Glen Ellen to the Clear Lake Volcanics is uncertain, although in one locality, basalt flows in the older part of the Clear Lake Volcanics overlie obsidian-bearing gravel that may be part of the Glen Ellen (B. C. Hearn, oral commun., 1977). On the basis of the contact relations noted above, the Glen Ellen Formation is late Pliocene and (or) Pleistocene.

SAND AND GRAVEL OF COTATI

West and south of Cotati, Calif. (pl. 1), the Petaluma and Wilson Grove Formations are unconformably overlain by stratified sand and gravel of continental origin. These rocks were referred to as "fresh-water Merced" by Johnson (1943, p. 626), but because no correlation with the type Merced Formation on the San Francisco peninsula has been established, an informal local name is probably more appropriate.

The sand and gravel of Cotati is composed chiefly of detritus derived from the Franciscan Complex and probably from the Monterey Group of Lawson (1914) or its equivalents. Obsidian pebbles and other clasts of volcanic origin that could have been derived from the Sonoma or Clear Lake Volcanics have not been observed. The contact of this sand and gravel with the obsidian-bearing Glen Ellen Formation immediately to the north is concealed by alluvium. Judging from its composition, the sand and gravel of Cotati was probably eroded from a source terrane to the west or south. These strata may have been deposited contemporaneously with the Glen Ellen Formation immediately to the north, or conceivably they could be a western facies of the Huichica Formation. Though younger than the Wilson Grove Formation, the Cotati strata have been moderately folded and in places are inclined 25° to 30°. On the basis of their contact relations and considering their deformation, the sand and gravel of Cotati is here considered Pliocene and (or) Pleistocene.

CLEAR LAKE VOLCANICS

Within the map area (pl. 1), the Clear Lake Volcanics consists of a basalt flow 9 km east of Mount St. Helena and, farther east, more extensive flows of quartz-bearing olivine basalt. The K-Ar age of the basalt is 1.94±0.4 m.y., and the quartz-bearing olivine basalt flows are 1.3 to 1.6 m.y. old (Donnelly and others, 1977, p. 30). To the north the field includes complexly interleaved domes, flows, and pyroclastic deposits of basaltic, andesitic, dacitic, and rhyolitic composition, ranging in age from 2.04±0.4 m.y. to less than 44,500±800 years (Donnelly and others, 1977, p. 30-31). Quartz-bearing olivine basalt is the oldest unit.

FAULTS

Faults that cut Miocene or younger strata within the study area (pl. 1; figs. 5, 6) include the San Andreas fault, a group of faults cutting the Sebastopol block, and eight major faults cutting the Santa Rosa block; these eight include the Tolay, Healdsburg, Rodgers Creek, Maacama, Bennett Valley, Carneros, West Napa, and Green Valley faults. Offset on most of these faults is believed to be predominantly strike-slip and right lateral, although some, such as the faults cutting the Sebastopol block, the Tolay fault, and the Carneros fault, show substantial dip-slip or reverse dip-slip. Two thrust faults are also known within the study area, and although the mapped length of their surface trace is short, they are discussed below because of their possible significance in interpreting the regional stress distribution.

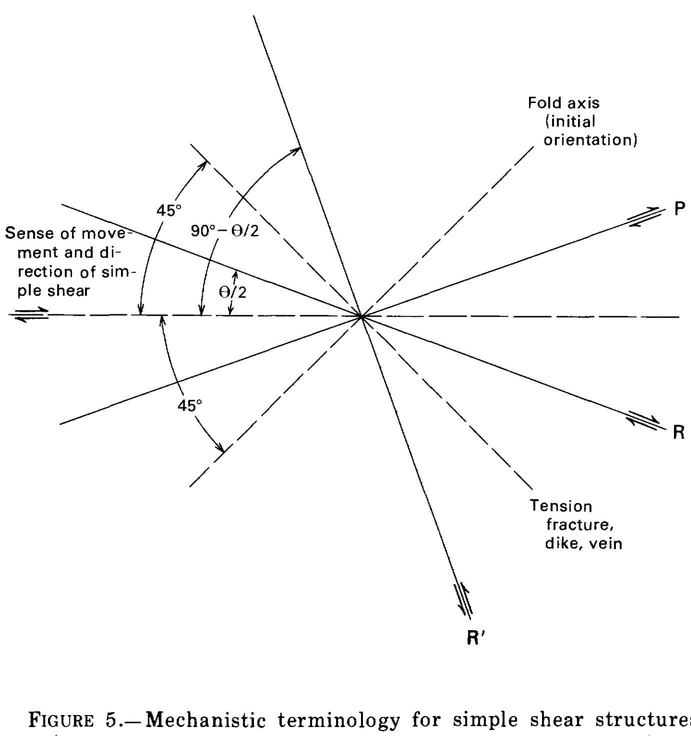

FIGURE 5.—Mechanistic terminology for simple shear structures (modified from Tchalenko and Ambraseys, 1970, p. 43). θ, maximum angle of shearing resistance within material undergoing shear; R, Riedel shear (angle $\theta/2$); R′, conjugate Riedel shear (angle $90°-(\theta/2)$); P, echelon fractures forming when deformation is large, with individual fractures inclined at an angle $\theta/2$ to general direction of movement (arrows).

SAN ANDREAS FAULT

The San Andreas fault is still one of the most enigmatic structural features in the California Coast Ranges, despite the intensive study it has received since it was first recognized by Lawson (1893, p. 151). The geology of the San Andreas fault zone north of San Francisco was reviewed by Oakeshott (1966, 1972); only details pertinent to the present study need be recited here.

Northwest of San Francisco (fig. 1), the San Andreas fault forms a wide linear zone of brecciated to broken strata trending N. 35°-40° W. Right-lateral offset of bedrock along the 1906 fault trace within this zone probably reached a maximum of 4.9 m near Point Arena and approached this amount between Tomales Bay and Bolinas, Calif. (Brown and Wolfe, 1972). Past displacement has been chiefly right lateral at a rate estimated from offset of various features of about 1.3 cm/yr averaged over the past 25 m.y. (Grantz and Dickinson, 1968). This average rate over this period has been confirmed by correlation and dating of volcanic features transected and offset by the fault (for example, Turner and others, 1970; Huffman and others, 1973; Matthews, 1973). However, one or more significant changes in the rate also have probably occurred within this period (Huffman, 1972, p. 2939). In fact, as discussed in the introductory section of this report, it is likely that post-Oligocene movement on the San Andreas fault began only 8-5 m.y. B.P. and that the rate of offset during this period approached 4 to 5 cm/yr.

Since the 1906 earthquake, the San Francisco segment of the fault (from Point Arena to Woodside, Calif.) has been inactive; it exhibits no surface slippage (Nason, 1971, p. 9-10, 89-94) and little seismicity except for small earthquakes in the Palo Alto and San Bruno-Bolinas, Calif., areas (Tocher, 1959a, p. 48).

The epicenter of the 1957 San Francisco earthquake was in the San Bruno area. This earthquake had a magnitude of 5.3 and was on a fault plane that dips steeply east. Surprisingly, first-motion studies revealed that the movement was vertical, east side up, and not right lateral (Tocher, 1959b, p. 71).

FAULTS WITHIN THE SEBASTOPOL BLOCK

The late Miocene and Pliocene Wilson Grove Formation of the Sebastopol block is cut by steeply dipping echelon faults that trend about N. 60° W., oblique to the trace of the San Andreas fault to the west. With a few exceptions, these faults form a stairstepping set with northeast side elevated 30 to 180 m (Travis, 1952, p. 24-25). None of these faults is known to be currently active. Other faults with this same general trend and marked by impressive shear zones cut the Franciscan

Complex but not the overlying Wilson Grove Formation. Therefore, the N. 60° W.-trending faults of the Sebastopol block probably originated before Wilson Grove time, and some continued to be active or were later reactivated during and after Wilson Grove deposition.

TOLAY FAULT

The Tolay fault forms the northeast boundary of a 15-km-long wedge of the Franciscan Complex (pl. 1); this wedge forms the core of the asymmetric Sears Point anticline (Weaver, 1949, p. 151). The fault

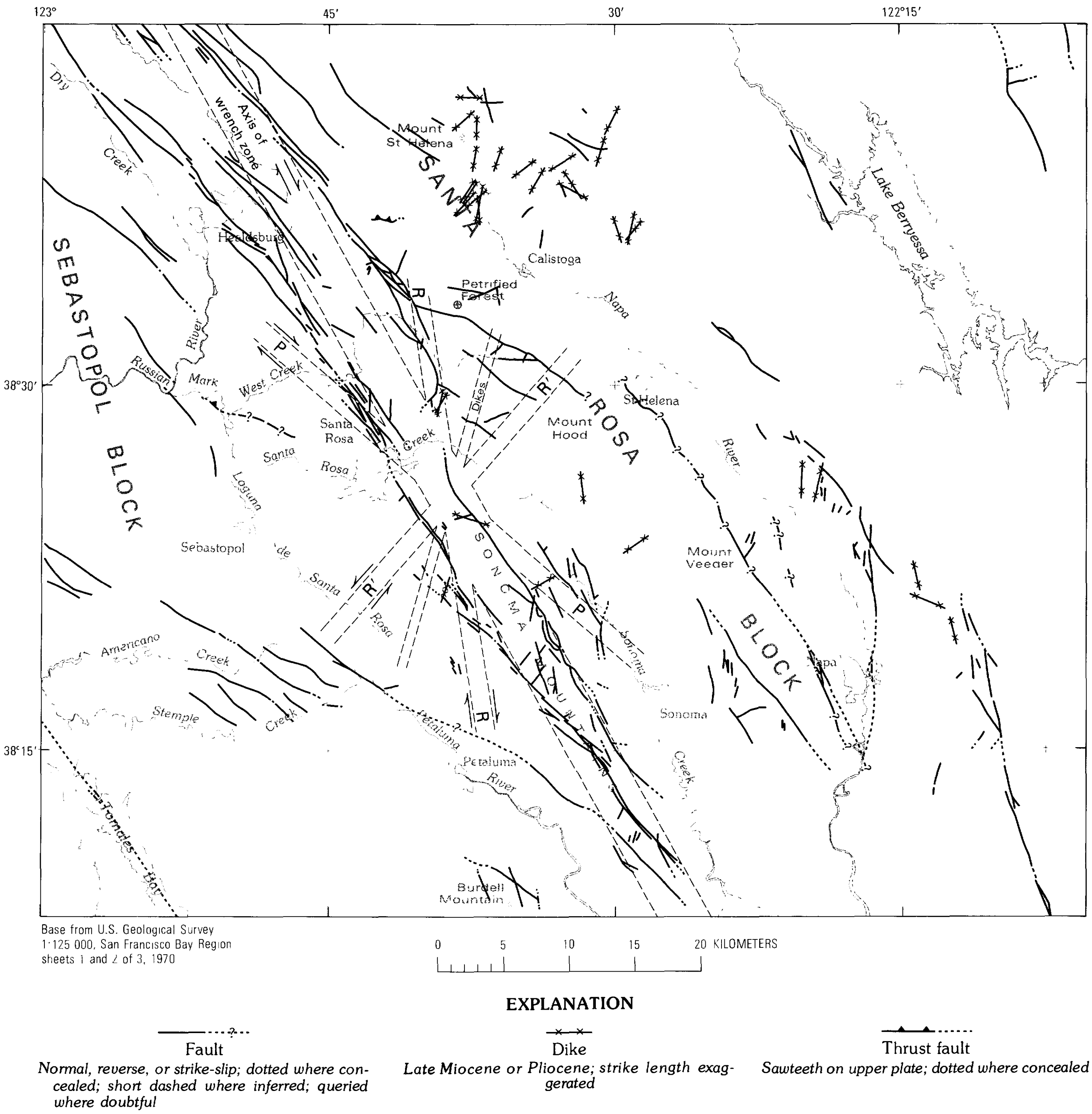

FIGURE 6.—Distribution of faults and dikes within study area (see fig. 2 for location), showing expected orientation of P, R, and R' faults (see fig. 5 for explanation) and of dikes and veins in wrench system with axis oriented N. 29° W. and maximum angle of shearing resistance 40°.

trends N. 50° W., dips 60° SW., and brings the Franciscan into contact with much-folded beds of the Petaluma Formation on the north; total offset must have a reverse dip-slip component of at least 1,400 m (Morse and Bailey, 1935, p. 1451-1452). The Franciscan rocks are scabbed with the Sonoma Volcanics and also are apparently unconformably overlain by strata of the Petaluma Formation on the southwest. The Tolay fault disappears beneath alluvial cover both to the northwest and southeast. A rather doubtful or obscure fault on strike to the northwest that could have a similar sense of displacement has been considered an extension of the Tolay fault (Travis, 1952, p. 24); alternatively, the Wallace Creek fault zone (Gealey, 1951, p. 36) could be the northwestward continuation of the Tolay fault (pl. 1). Similarly, the Hayward fault (fig. 2), though not precisely alined with the Tolay, has been considered the southward continuation of the Tolay fault because the Hayward also shows substantial dip-slip and Franciscan rocks are exposed in the upfaulted block west of the fault (Weaver, 1949, p. 134). Unlike the Hayward fault, however, the Tolay fault is not known to be active. Because the Petaluma overlies a thickness of volcanic rocks in excess of 1,200 m west of the Sonoma Mountains near the Murphy No. 1 well (pl. 1), the absence of these volcanic rocks at the supposedly depositional contacts between the Petaluma and Franciscan just 8 km along the general strike of the depositional basin to the southeast must mean that the Tolay fault and its complementary structure, the Sears Point anticline, were active during or after Tolay volcanism and before deposition of the upper part of the Petaluma.

Louderback (1951), p. 79) suggested that the Tolay Volcanics correlates with volcanic rocks in the Berkeley Hills. If the Tolay was also originally coextensive with these volcanic rocks, as such a correlation implies, strike-slip displacement on the Tolay-Hayward or Rodgers Creek-Hayward fault system after extrusion of the volcanic rocks may be about 45±15 km. G. H. Curtis (unpub. data, 1974, in Prowell, 1974, p. 1, 152, 171, 173) provided a more precise estimate of this displacement; he correlated an 8-m.y.-old titanaugite basalt flow in the Berkeley Hills with a rock of similar petrography and age 45 km to the northwest. Displacement of similar magnitude was suggested by A. M. Sarna-Wojcicki (oral commun., 1973) on the basis of the chemical similarities between tuff beds offset by this fault system.

HEALDSBURG AND RODGERS CREEK FAULTS

The Rodgers Creek and Healdsburg faults form an echelon system trending N. 35° W. (fig. 2), approximately parallel to the San Andreas fault. Judging from the linearity of their fault traces over uneven terrain, they dip vertically or nearly so.

The Healdsburg fault was first mapped and described by Gealey (1951), who concluded that the Healdsburg fault had been recently active, from the presence along its trace of perched alluvial valleys and of geomorphic features similar to those along the San Andreas fault. Brown (1970) and Blake and others (1971) also considered most of the numerous individual fault traces of the Healdsburg fault zone to be active faults. However, except for a kilometer-long fault segment 4 km north of Healdsburg (pl. 1) and the numerous fault traces within the 11-km-long segment of the fault zone extending north-northwestward from Santa Rosa, Herd and Helley (1977) found the Healdsburg fault zone to be devoid of geomorphic evidence of recent faulting.

The Rodgers Creek fault (Weaver, 1949, p. 135) was recognized and mapped by Dickerson (1922, p. 581-584), who described it as the northward extension of the Hayward rift. The trace of the Rodgers Creek fault is marked by sag ponds, stream offsets, spring zones, hillside benches, and small linear rift valleys—features that mark it as an active fault (fig. 7).

Where it crosses the Sonoma Mountains, the Rodgers Creek fault zone nearly coincides with a line of rhyolitic masses within the Sonoma Volcanics, some intrusive, and some intrusive into the fault zone itself. Emplacement of the rhyolite, believed to have been about 7 m.y. B.P.—that is, late Miocene (K. F. Fox, Jr., unpub. data, 1977)—was probably controlled by the Rodgers Creek fault, and so this part of the fault is at least as old as late Miocene.

Gealey (1951, p. 36-37) suggested that the Rodgers Creek fault connects to the northwest with the Wallace Creek fault (pl. 1) and that the Healdsburg fault zone connects to the southeast with a fault here described as the "Bennett Valley fault." Brown (1970) was the first to recognize that the northern section of the active trace of the Rodgers Creek fault diverges toward the north from its general N. 35° W. trend in the Sonoma Mountains and, diverging also from the line of rhyolite intrusive rocks, intersects the Healdsburg fault zone at Santa Rosa. This intersection is concealed by alluvium and urban development.

The epicenters of the destructive 1969 Santa Rosa, Calif., earthquakes were apparently located on the northeastern outskirts of Santa Rosa, at the south end of the Healdsburg fault zone (Steinbrugge, 1970). Both earthquakes occurred the evening of October 1, the first with a magnitude of 5.6 at 9:57 p.m. P.d.t. and the second with a magnitude of 5.7 at 11:20 p.m. First-motion studies of subsequent aftershocks in this area indicated that "* * * right-lateral strike-slip motion occurred on a fault plane striking about N. 30° W. and dipping steeply to the southwest" (J. D. Unger and

J. P. Eaton, in Steinbrugge, 1970, p. 45). However, the spatial distribution of 115 aftershocks recorded by a temporary network of 19 portable seismographs from October 3 to 10 forms a diffuse northwest-trending pattern not clearly associated with any one of the several mapped fault traces in the area (pl. 1). This record contrasts with a map showing damage to sidewalks, curbs, and pavement in Santa Rosa compiled by Bigglestone (1970, fig. 57). According to Bigglestone (1970, p. 39), sidewalks and curbs buckled and cracked owing to compressional effects from large horizontal movements in structurally weak alluvium. The zone of maximum damage as shown by his map coincides with the concealed (dotted line, pl. 1) connecting trace of the Rodgers Creek and Healdsburg faults.

The concentration of damage to paving, sidewalks, and curbing along the concealed intersection of the Rodgers Creek and Healdsburg faults implies foreshortening across this trace during one or both of the 1969 Santa Rosa earthquakes. The distribution of epicenters of aftershocks indicates stress release at this intersection and on several nearby faults. These nearby faults may include one or more that could be part of the southward extension of the Healdsburg fault zone and one that could be a southward extension of the Maacama fault.

The Rodgers Creek and Healdsburg faults are both right-lateral strike-slip faults. The Healdsburg fault shows at least 5 km of right-lateral offset (Gealey, 1951, p. 36). The amount of offset on the Rodgers Creek is not known; however, the Sonoma Volcanics on either side of the Rodgers Creek fault appears to be lithologically similar and of about the same age—roughly between 5 and 7 m.y. (K. F. Fox, Jr. and J. A. Bartow, unpub. data, 1977)—and probably is not offset right laterally more than 10 km at most.

Active right-lateral creep on the Hayward fault (Radbruch-Hall, 1974) may presently be accommodated by offset on the Rodgers Creek fault. As originally recognized by Dickerson (1922, p. 581), the Hayward fault may be functioning as a southeastward echelon continuation of the Rodgers Creek fault, because they are both active, have about the same strike, and are nearly in line (fig. 2).

MAACAMA AND BENNETT VALLEY FAULTS

The Maacama fault zone comprises several parallel fault strands across which rocks in the upper part of the Sonoma Volcanics on the west are downfaulted against Franciscan rocks on the east. The fault zone, locally as wide as 800 m, is quite linear and has excellent topographic expression, marked by a succession of small rift valleys, hillside benches, springs, wind gaps, and eroded scarps—all features indicating that the Maacama is an active fault. Gealey (1951, p. 35) estimated that the minimum post-Sonoma Volcanics dip-slip component of displacement is more than 150 to 650 m in various places along the fault.

At its southeast end (northeast of Santa Rosa, Calif.) the Maacama fault zone is obscured by landslides and alluvial deposits; possibly it bends westward to link up

FIGURE 7.—Curvilinear rift valley (F-F') developed along trace of Rodgers Creek fault where it cuts west slopes of Sonoma Mountains. View north-northwestward.

with the highly sinuous Bennett Valley fault. Although the Bennett Valley fault has very poor physiographic expression—much poorer than that of the Maacama fault—it cuts gravel of the Huichica Formation and thus has been active during or since the late Pliocene. According to Herd and Helley (1977), east of Santa Rosa the fault cuts a terrace inferred to be latest Pleistocene.

The drillers log of the William Jacobs No. 1 well, located west of the Bennett Valley fault and approximately 15 km northwest of Sonoma (pl. 1), indicates that the drill penetrated 310 m of the Huichica Formation before entering the lower member of the Sonoma Volcanics. The lower member of the Sonoma Volcanics is exposed at the surface of the upfaulted block east of this fault, and so in this area the vertical component of movement on the fault is probably at least 300 m.

The sinuosity of the fault trace in plan view may be a result of intersection of the plane of a low-angle fault with the rugged topography it crosses. Whether the Bennett Valley fault is currently active is unknown. The difference in physiographic expression of the Maacama and Bennett Valley faults, if not due to a difference in attitude, may imply that part of the recent movement on the Maacama has in some way been transferred from movement on the Rodgers Creek, rather than the Bennett Valley, fault.

Recent mapping (U.S. Army Corps of Engineers, 1978; E. H. Pampeyan, oral commun., 1979) demonstrates that the Maacama fault continues north-northwestward to Laytonville, Calif. (fig. 1); active movement is then transferred about 20 km eastward to the Lake Mountain fault zone (Herd, 1978).

WEST NAPA FAULT ZONE

A north-northwest-trending system of anastomosing fault strands mapped by Fox and others (1973) west of Napa (pl. 1) was named the "West Napa fault zone" by Helley and Herd (1977). Though not demonstrable because of the absence of suitable markers, the major component of offset on the West Napa fault zone is probably right lateral, in view of its parallelism with right-lateral faults of the San Andreas system to the west. However, measured offset on the faults in this zone indicates dip-slip. The westernmost strand drops the Sonoma Volcanics on the east down against basement rocks on the west. A water well east of the fault (loc. A, pl. 1) penetrated 78.6 m of alluvial deposits. Rocks in this area that are west of the fault are part of the Sonoma Volcanics; this relation implies that the vertical component in this locality approaches and perhaps exceeds 78.6 m, with the east side down.

The existence and position of the fault zone in the sector west of Napa are fairly well established where it cuts bedrock units; the northward extension of the zone is more conjectural. On the basis of lineaments visible on aerial photographs, Fox and others (1973) and Helley and Herd (1977) portrayed the fault as extending northward through the alluvial deposits flooring Napa Valley to Yountville, Calif. At Yountville, later geologic and geophysical studies revealed linear magnetic and resistivity anomalies whose position approximately coincides with this segment of the lineament (loc. F, pl. 1). However, reconnaissance by the author there and elsewhere along the northern part of the suspected fault failed to reveal any geologic or geomorphic features at all comparable to those related to the fault west of Napa.

Subsequently, consulting geologist E. H. Boudreau (oral commun., 1976) called the author's attention to a water well being drilled 6 km northwest of Napa (loc. E, pl. 1). Inspection of the cuttings and log, made available through the courtesy of the landowner, indicated that the well penetrated 27 m of gravel (probably alluvial), then 120 m of volcanic rock (augite andesite and vitric tuff), and reached a total depth of 147 m. The volcanic rocks are part of the Sonoma Volcanics; strata cropping out uphill to the southwest in this area, however, are part of the much older basement rocks. To account for juxtaposition of these rocks requires a major fault between them, the trace of which, concealed by alluvium and slope wash, probably passes within 100 m and to the southwest of the well. E. H. Boudreau suggested that this is the main trace of the West Napa fault zone. From there, the fault probably extends northwestward at least as far as St. Helena, Calif., and forms the contact between basement rocks on the west and the Sonoma Volcanics on the east. The fault was not recognized in outcrop along this span, although rocks cropping out near the suspected trace are sheared at the several localities examined by the author.

E. J. Helley (in Fox and others, 1973) originally proposed that certain segments of the fault zone west of Napa were active, on the basis of geomorphic evidence (see Helley and Herd, 1977). Trenching by consulting firms revealed that soil zones are indeed offset by the main traces of the fault (locs. B, C, pl. 1). However, no indication of faulting was observed by the author in another trench (loc. D, pl. 1) crossing a short subsidiary segment shown as active by Fox and others (1973) and Helley and Herd (1977) (not shown on pl. 1). The trench did not extend far enough to the west or east to cross the fault traces shown near this locality on the map (pl. 1).

The evidence now available indicates that although some photolineaments in this area do not represent active faults, several strands of the West Napa fault zone are active.

GREEN VALLEY FAULT

The Green Valley fault is a linear N. 15° W.-trending fault whose trace is marked by topographic features and displaced cultural features indicating very recent, even historical, activity—a conclusion verified by a concentration of epicenters of minor earthquakes along the fault (Frizzell and Brown, 1976). The fault is believed to be a steeply dipping right-lateral fault. The offset on it clearly has a vertical component, with the east side down an amount not exceeding 150 m (Weaver, 1949, p. 142). The strike-slip component of offset since the early Pliocene is insufficient measurably to offset distinctive units of the Sonoma Volcanics cut by the fault. This offset is not so sensitive a gage, however, because these units are nearly flat lying west of the fault and undoubtedly had much greater lateral extent originally. It is probably safe to say that right-lateral offset on the Green Valley fault since the early Pliocene does not exceed a few kilometers at most.

The Green Valley fault is now apparently taking up the right-lateral creep measured along the Concord fault (Sharp, 1973) to the south, although the mapped trace of the Green Valley fault is discontinuous with that of the Concord fault at the surface. Instead, the Green Valley fault trace is offset in echelon about 1½ km to the east.

CARNEROS FAULT

The Carneros fault juxtaposes a thick section of the lower member of the Sonoma Volcanics and underlying sedimentary rocks as old as Miocene(?) against basement rocks on the east. Although this fault cuts andesite forming the lower part of the lower member of the Sonoma Volcanics, rhyolite and tuff tentatively assigned to the upper part of this lower member overlap the Carneros fault without apparent offset. These relations indicate that the Carneros fault became inactive during the time in which the lower member of the Sonoma Volcanics was accumulating.

Weaver (1949, p. 136) suggested that the absence of rocks here referred to as the andesitic lower part of the lower member east of the fault is due to abrupt primary depositional thinning rather than local erosion before extrusion of the overlying rhyolite and tuff. On the other hand, Weaver noted that the exposed parts of the underlying 460-m-thick section of sedimentary rocks are not characteristic of an original shoreline, and so these rocks must have had a lateral continuation to the east that was faulted out before outpouring of the upper part of the lower member of the Sonoma Volcanics. According to Weaver (1949, p. 135), the fault plane is nearly vertical; on the basis of the stratigraphic relations noted above, he postulated dip-slip of at least 460 m, with the downdropped block on the west.

Displacement of the Carneros fault may also have a substantial component of right-lateral strike-slip. Correlation of the San Ramon-Neroly sequence west of the fault in the Mount Veeder area with the same sequence east of the fault could provide a basis for estimating the magnitude of strike-slip displacement along this fault. The nearest occurrence of a similar sequence on the east side of the projected southeastward continuation of the Carneros fault is south of Suisun Bay in the Martinez, Calif., area, about 35 km south-southeast of the Mount Veeder locality (fig. 3). This correlation implies that the Carneros fault is the northwestward continuation of the Franklin-Sunol-Calaveras fault system (fig. 3) and that right-lateral offset on the system is substantial, perhaps as much as 35 km. Vickery (1925, p. 612-613) postulated 20 km of right-lateral displacement on the Sunol fault after deposition of certain distinctive units at or near the lower contact of the Briones Sandstone.

The original configuration of the depositional basin in which these rocks accumulated has not been established, and so estimates of the displacement on transecting faults must be viewed with caution. In fact, the facies relations between the Monterey Shale of Weaver (1949), the Monterey Group of Lawson (1914), the Sobrante Formation of Lutz (1951), and correlative strata nearby (fig. 3) could be due in part to control of the configuration of the basin by bounding north-northwest-trending faults. The original shorelines of this basin were probably subparallel to these faults and thus provide poor markers of strike-slip.

The present distribution of the San Ramon Sandstone (fig. 3) does not seem to reflect structural control of its depositional basin by the northwest-trending faults. Offset of the distal edges of this unit, were they accurately located, could provide a reliable measure of the offset on transecting faults.

In spite of the uncertainties mentioned above, it seems likely that the Carneros fault was at one time the northwestward continuation of the Franklin-Sunol-Calaveras fault system and that post-San Ramon offset must include a substantial component of right-lateral slip.

TRENTON AND FRANZ VALLEY FAULTS

Two thrust faults of latest Miocene age or younger are known within the map area (pl. 1): one, herein called the "Trenton fault," is about 10 km north of Sebastopol, Calif.; the other, called the "Franz Valley fault," is about 10 km west-northwest of Calistoga (pl. 1).

The Trenton fault strikes about N. 70°-75° W. and dips about 17° NNE. where it is exposed at the east end of a kilometer-long roadcut (fig. 8). In this locality, graywacke and crumpled ribbon chert of the Franciscan Complex are thrust over massive sand of the Wilson Grove Formation. The fault plane is marked by a 2- to 5-cm-thick fault gouge. At the west end of the roadcut, Franciscan rocks on the north are faulted against tuff intercalated in the Wilson Grove Formation, but the fault plane itself is covered.

The extension of the fault to the west-northwest is concealed beneath alluvium in the valley of Mark West Creek. To the east-southeast, the fault trace probably is marked by a rounded, incised, and subdued south-facing scarp, about 12 m high, in gravel and tuffaceous sand of the Glen Ellen Formation. This material is very poorly exposed, but in one drainage crossing the scarp, exposed beds strike nearly parallel to the scarp and dip 26° SW.

The Franz Valley fault, first discovered by Hurlbut (1948), strikes N. 70° E. and dips 40° N. where it is exposed in a shallow roadcut. In that locality, brecciated to closely fractured graywacke of the Franciscan Complex is thrust over poorly lithified gravel that in this area forms the basal part of the upper member of the Sonoma Volcanics.

FOLDS

Attitudes of late Miocene, Pliocene, and Pleistocene deposits shown on the map compilations by Blake and others (1971, 1974), Fox and others (1973), and Sims and others (1973) were contoured according to the following procedure: (1) the map area was arbitrarily gridded into cells 2 km on a side; (2) an average dip per cell was obtained by arithmetically averaging the dip shown by dip and strike symbols (several steep dips immediately adjacent to faults were omitted on the supposition that the dip was oversteepened by drag folding); and (3) the average dip per cell was contoured. The resulting map (fig. 9), simplified slightly for legibility at publication scale, shows that these deposits are significantly less deformed within the Sebastopol block than within the Santa Rosa block: their average dip in the Sebastopol block is 5.8°, in comparison with 34.5° in the Santa Rosa block.

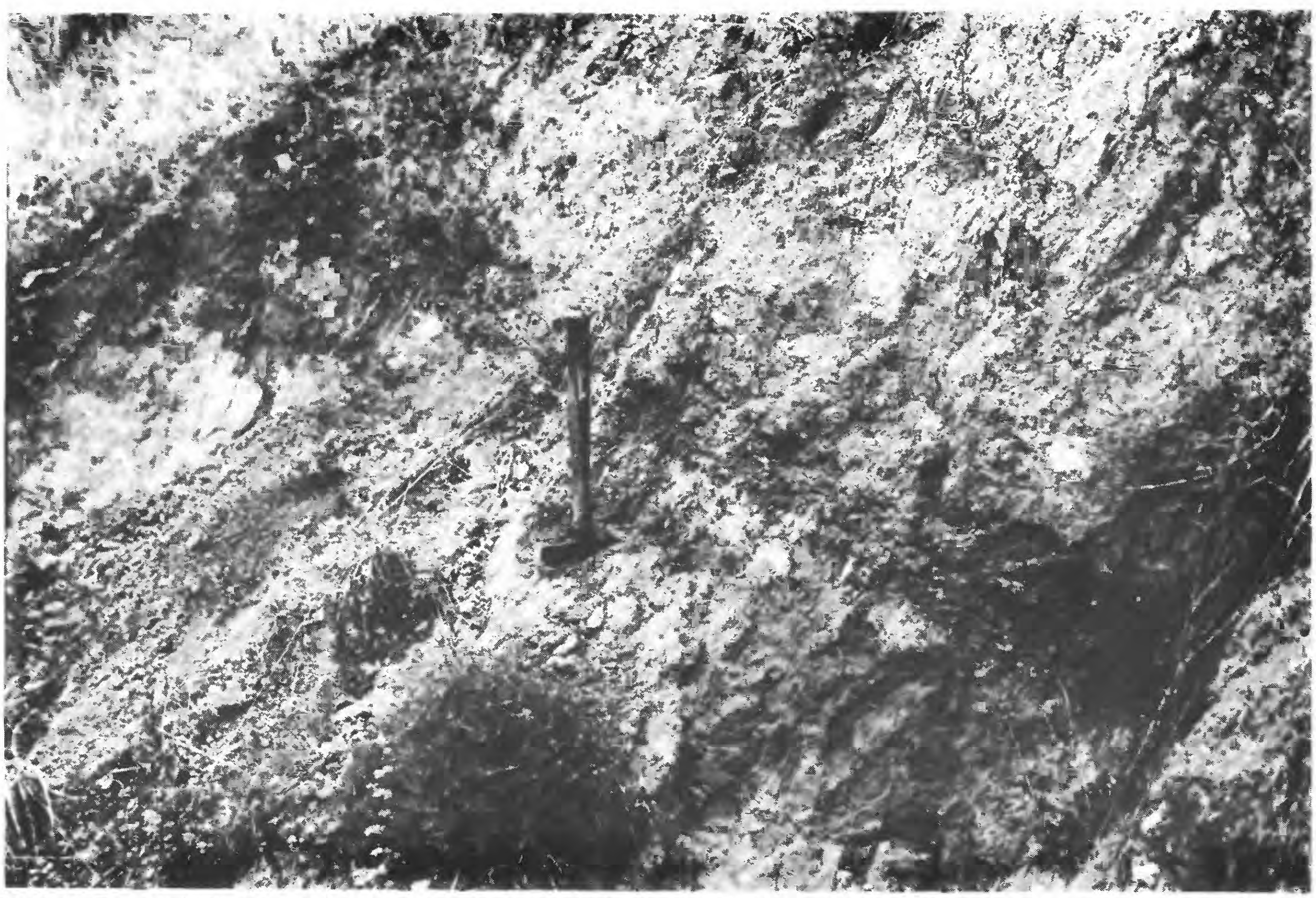

FIGURE 8.—Trenton fault about 10 km north of Sebastopol, Calif., showing the Franciscan Complex thrust over massive sandstone of the Wilson Grove Formation on fault plane (above hammer) dipping about 17° NNE. View northwestward.

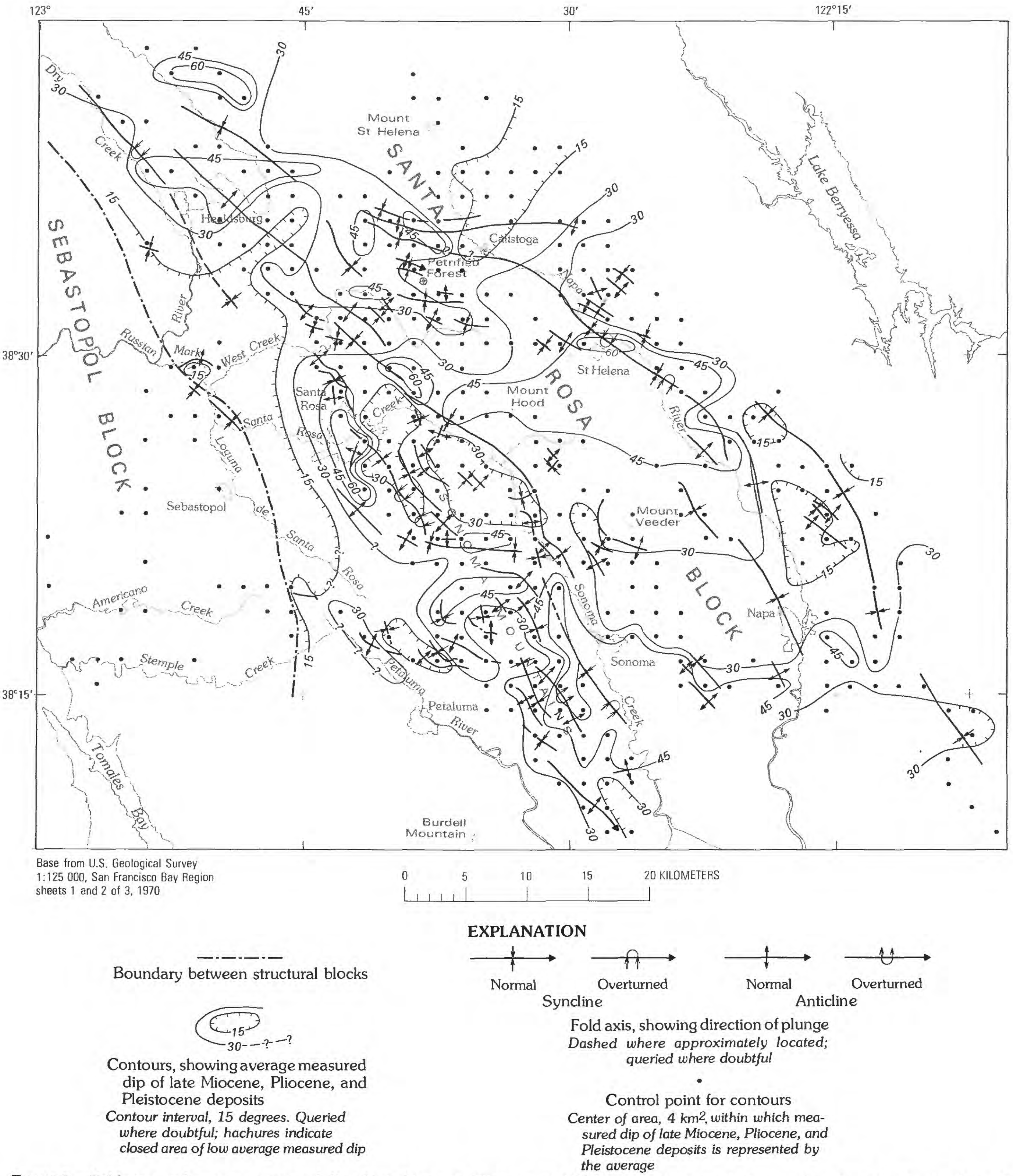

FIGURE 9.—Fold axes and average measured dip of late Miocene, Pliocene, and Pleistocene strata in study area (see fig. 2 for location), on the basis of maps by Blake and others (1971, 1974), Fox and others (1973), and Sims and others (1973).

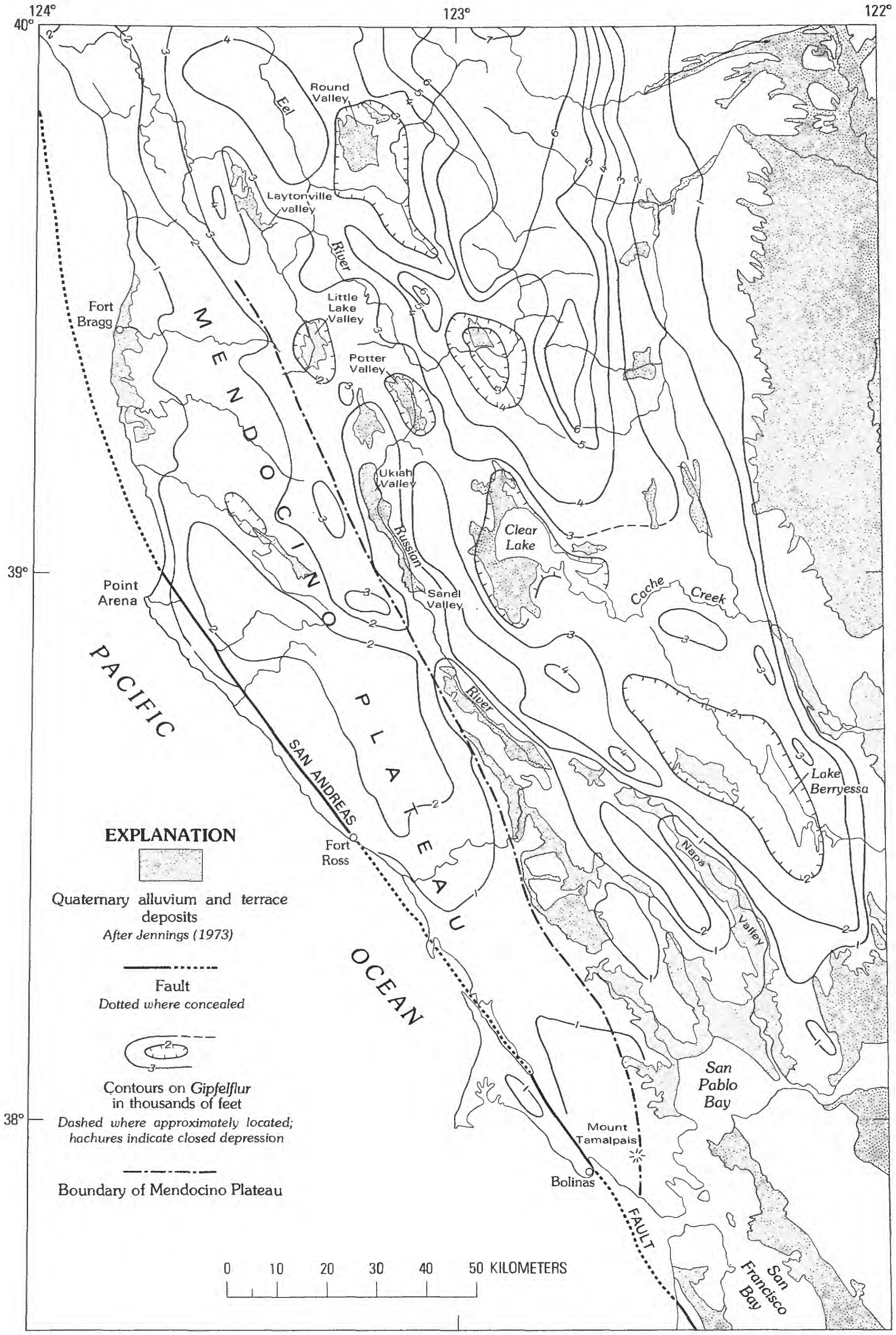

FIGURE 10.—Generalized physiographic diagram of part of Coast Ranges north of San Francisco Bay as expressed by contours on *Gipfelflur* (generalized surface of summit altitudes). Modified slightly from Wahrhaftig and Birman (1965, p. 322).

In interpreting these data, the reader should recall that the ages of the strata within these two contrasting domains are not comparable. For the Sebastopol block, the dips were measured almost exclusively on the Wilson Grove Formation, which for present purposes can be regarded as a datum approximately 6 m.y. old. In the Santa Rosa block, on the other hand, the dips reflect the attitude of the Petaluma Formation, the Sonoma Volcanics, the Huichica Formation, and the Glen Ellen Formation, a sequence ranging in age from late Miocene to probably Pleistocene. Until the stratigraphy within the Sonoma Volcanics is better understood, quantitative comparison of deformational intensity cannot be made according to the age of the strata.

A few qualitative observations, however, are possible. Overturned folds within the upper member of the Sonoma Volcanics—that is, the part 2.9 to 3.4 m.y. old—indicate that deformation is locally as severe there as it is in the lower member. Fold axes within the Sonoma terrane (fig. 9) show a general N. 35° W. trend subparallel to the San Andreas fault, except in the north-central part of the study area, where they swing to east-west.

GEOMORPHOLOGY AND RECENT DEFORMATION

The accordant rounded to tabletopped summits of the low hills and ridges in the central part of the Sebastopol block define an undulating to subplanar erosional surface known as the Mendocino plateau (fig. 10) (Lawson, 1894, p. 242-243; Gealey, 1951, p. 41) that extends to both the northwest and the southeast. Northwest of the meandering, deeply incised, and superposed lower course of the Russian River (Higgins, 1952), the subdued terrain that is typical of the central part of the plateau merges with a rugged, intricately dissected upland. Here, the plateau is represented only by the roughly accordant summits of scattered peaks and prevailingly knifelike interstream divides. To the southeast, erosional remnants of the plateau climb gradually to the summit of Mount Tamalpais, but there the terrain breaks sharply away, and the plateau has no definition farther to the south (fig. 11).

The Mendocino plateau, though much dissected by a youthful closely spaced drainage network, probably extends northwestward at least as far as Fort Bragg, Calif., (fig. 10). The plateau is cut across Franciscan basement or the Wilson Grove Formation except for an area north of Fort Ross, where it is in part developed on the Ohlson Ranch Formation of Higgins (1960), a blanket deposit of marine sand presumably of Pliocene age (Peck, 1960). This formation, like the Wilson Grove, is relatively flat lying and unfolded, and so this area has been only slightly deformed during post-Pliocene time (Wahrhaftig and Birman, 1965, p. 323).

Near Fort Bragg, where the plateau dips beneath the sea, Franciscan basement in the coastal area is mantled by a succession of flat-lying marine-terrace deposits of

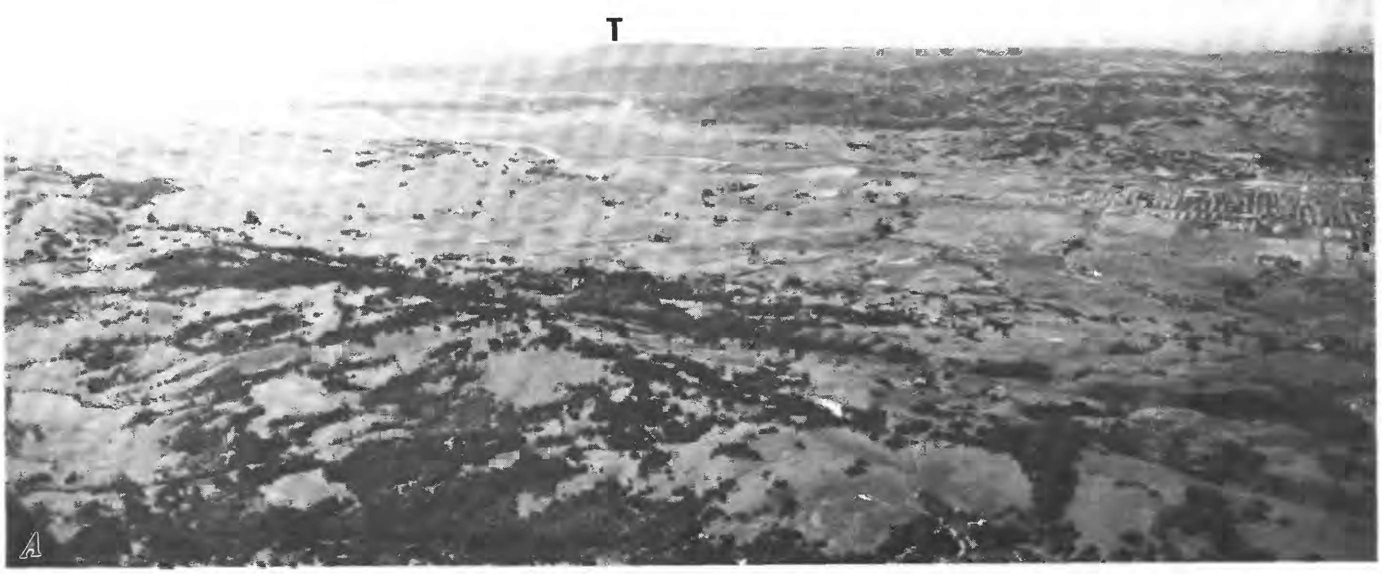

FIGURE 11.—Terrain of Mendocino plateau (see fig. 10 for location). *A*, Accordant ridge summits (in distance on right) and eroded remnants of southern part of Mendocino plateau, sloping gradually upward to summit of Mount Tamalpais (T). South and east of Mount Tamalpais, topography slopes steeply downward into valleys occupied by San Pablo Bay (on left) and San Francisco Bay (far distance on left). View southwestward. *B*, Dissected surface of Mendocino plateau in foregound, with ridge-and-valley terrain of Santa Rosa block beyond. Boundary between Sebastopol block (near) and Santa Rosa block (distant) coincides approximately with a line drawn between segment of Russian River (R) and Petaluma (P). SM, Sonoma Mountain; S, Santa Rosa; H, Mount St. Helena; N, Napa; B, Lake Berryessa. View eastward. Photograph by U.S. Air Force, 1967.

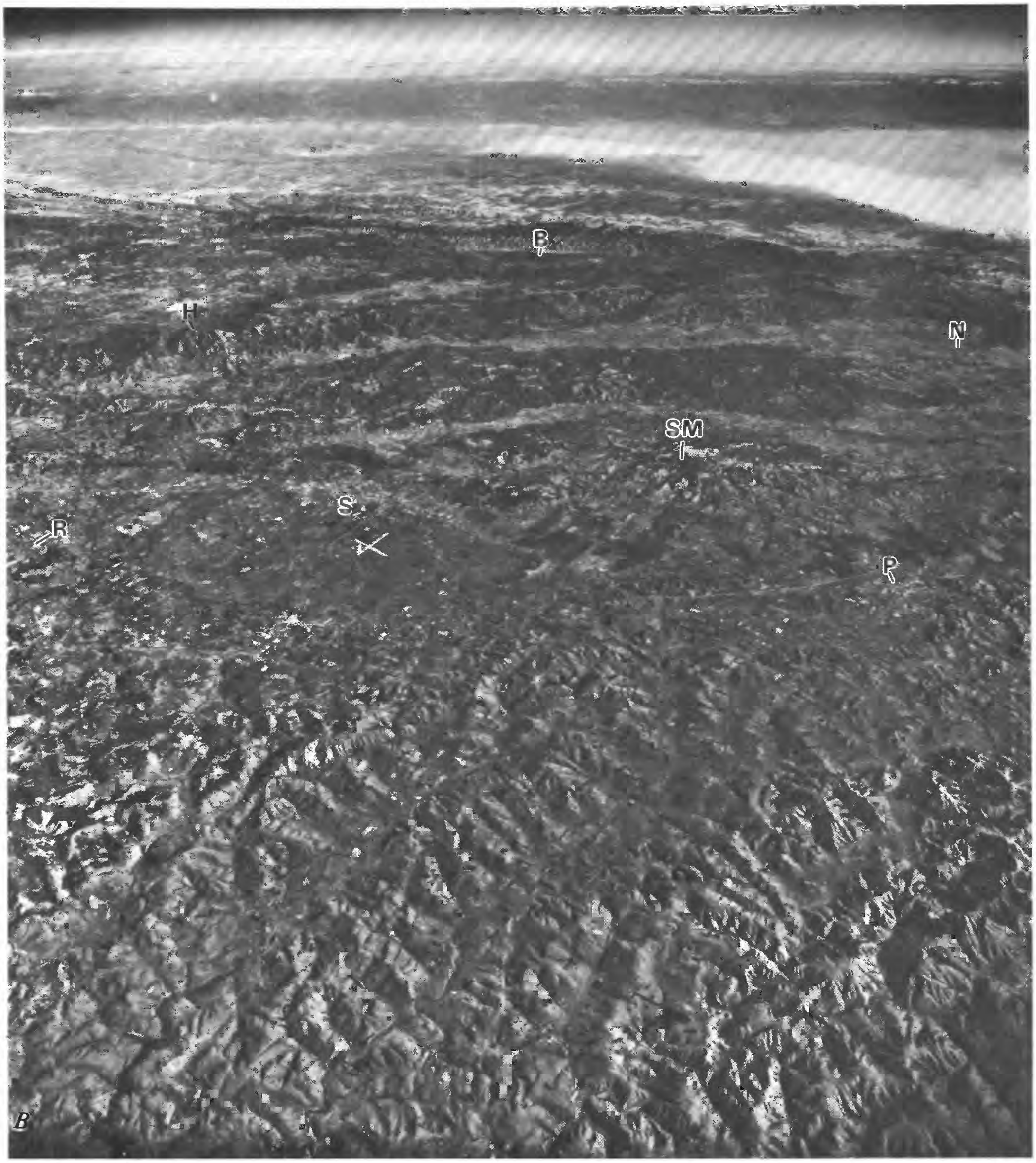

FIGURE 11.— Continued

probable Pleistocene age. These deposits consist of unconsolidated and poorly consolidated sand, gravel, and clay, aggregating 18 m in thickness, and form a succession of terraces stepping up eastward to 500-ft elevation (California Division of Water Resources, 1958). This part of the plateau, though uplifted, has not been markedly deformed, at least in geologically recent time.

On the northeast, the Mendocino plateau is bounded by the valley between Healdsburg and Petaluma, Calif., the westernmost of the alluvium-filled intermontane valleys of the Santa Rosa block (fig. 11*B*).

Many of the major physiographic features (fig. 12) of the Santa Rosa block have originated through Quaternary folding and faulting. For example, the Napa Valley (fig. 11) "* * * appears to have been formed by folding into a northwest-trending shallow synclinal trough complicated by sharp marginal folding and faulting" (Weaver, 1949, p. 167). Near St. Helena (pl. 1), the Napa Valley follows the axis of an appressed locally overturned syncline formed by folding of the younger part of the Sonoma Volcanics.

Rugged terrain, characterized by wide tectonic basins surrounded by ridges and mountains, extends to the north beyond the north limit of the deformed coextensive Miocene, Pliocene, and probable Pleistocene strata partly covering the Santa Rosa block. These structural basins include Laytonville valley, Little Lake Valley, Round Valley (fig. 10) (California Division of Water Resources, 1958, p. 52, 59, 70), and the Clear Lake basin, which is a particularly noteworthy example.

Clear Lake (fig. 10) has an area of about 150 km^2 and a maximum depth of about 16 m (Brice, 1953, p. 54). The lake now drains eastward by way of Cache Creek to the Sacramento River; previously it may have drained westward to the Pacific by way of the Russian River (Davis, 1933, p. 197-200) and, before that, by way of the Eel River (Berkland, 1972, p. 16-17). The lake occupies a topographic basin bounded on the east by uplifted Pliocene and Pleistocene continental deposits of the Cache Formation of Rymer (1981). These deposits, 4 to 15 km east of Clear Lake, consist of interbedded conglomerate and sandstone, perhaps aggregating as much as 1,500 m in thickness (Rymer, 1981), most of which predates the Clear Lake Volcanics (Donnelly and others, 1977, p. 27). The Cache Formation marks the site of a deep tectonic trough—now uplifted and deformed—ancestral to the present Clear Lake basin. A substantial part of the subsidence recorded by the Cache beds occurred before extrusion of the Clear Lake Volcanics (see Hodges, 1966, and Hearn and others, 1975). The deep sinking of the Cache basin, its subsequent deformation and uplift, and, still later, the downwarping or foundering of the Clear Lake basin, as well as its attendant drainage instability, indicate that this area has been a region of great crustal mobility during Pleistocene and probably Holocene time.

FIGURE 12.—West-dipping strata (part of upper member of the Sonoma Volcanics) forming homoclinal eastern limb of syncline. Napa Valley (on left) follows axis of syncline. Mount St. Helena (H) is visible on skyline in center. Area is typical of structurally controlled ridge-and-valley terrain of Santa Rosa block. View northwestward.

San Pablo Bay, San Francisco Bay, the Berkeley Hills, and the Coast Ranges southeast of San Francisco also represent a system of rising ranges and subsiding basins, formed by Quaternary flexing around the flanks of the basins and ranges and by warping within them; local movement continues (Christensen, 1965, p. 1116). Pliocene and Pleistocene rocks within and marginal to the basins and ranges are commonly folded and, in places, strongly folded, even overturned. The similarity of this physiographic and deformational style to that characteristic of the Santa Rosa block indicates that this structural province extends southward to these areas and wraps around the southeast termination of the Mendocino plateau and the Sebastopol block (fig. 10).

INTERPRETATION

ORIGIN OF FAULT, DIKE, AND FOLD PATTERN

North of San Pablo Bay, echelon sets of strike-slip faults, including the Rodgers Creek, Healdsburg, Maacama, and Bennett Valley faults, are associated with echelon folds. On the basis of known fault displacements, these faults and folds probably originated within a right-lateral wrench system. The general direction of movement along this system is roughly parallel to a line connecting the midpoints of individual segments of the echelon faults—that is, about N. 30° W., trending somewhat more northerly than the general N. 35° W. strike of the San Andreas fault west of the study area (fig. 6).

Wrench faults and their associated features, such as folds and tension fractures, resemble the fracture patterns formed experimentally in clay models subjected to simple shear (shear caused by differential movement on parallel planes) (Tchalenko and Ambraseys, 1970). In these clay models, studied experimentally by Cloos (1928), Riedel (1929), Wilcox and others (1973), and Freund (1974), sets of two echelon fractures form, with individual fractures of one set inclined at an angle $\theta/2$ and of the other set at $90°-(\theta/2)$ to the general direction of movement, where θ is the maximum angle of shearing resistance within the material undergoing shear. Following Tchalenko and Ambraseys (1970, p. 43), these shears are here call "Riedel" (R) and "conjugate Riedel" (R′) shears (fig. 5). Note that movement on R′ shears is opposite to that of the shear system as a whole—that is, in the right-lateral shear system of figure 5, movement on R′ shears is left lateral.

Where the deformation is large, a third set of echelon fractures, termed P faults, form, with individual fractures inclined at an angle $\theta/2$ to the general direction of movement (Tchalenko and Ambraseys, 1970, p. 43). In addition, tension fractures may form parallel to the direction of maximum compression, which is inclined 45° to the general direction of movement and bisects the angle subtended by the R and R′ shears (Tchalenko and Ambraseys, 1970, p. 44; Wilcox and others, 1973, p. 79).

Echelon folds have also been formed in the experiments. According to Wilcox and others (1973), for true simple shear, fold axes are always inclined less than 45° to the general direction of movement, and in most wrenching experiments with clay, about 30° to the general direction of movement.

Individual segments of the Maacama, Bennett Valley, Healdsburg, and Rodgers Creek fault systems have a somewhat more westerly orientation than the N. 30° W. trend of these systems as a whole and so, in the terminology of figure 5, are probably P faults. This deduction leads to the interpretation suggested in figure 6, which implies that most of the major fault segments are P faults and that R and R′ shears are also present, though subordinate to these P faults.

The average trend of dikes (fig. 4), though admittedly poorly defined both because of the paucity of the data and their scatter, is about N. 15° E. The trend of tension fractures and the direction of maximum compression expected in a simple shear system with a general direction of movement of N. 30° W. are also N. 15° E.

Freund (1974, p. 126) noted that in models the P faults appear at advanced stages of deformation, after earlier faults have been folded; he proposed that "* * * the stresses responsible for the initiation of the P-faults emerge from the resistance of the curved fault to any further movement." The results of his exploration of this possibility by photoelastic modeling reveal interesting parallels with fault patterns in the study area. In his experiments, a curved fault was simulated by machining two pieces of Perspex glass to the shape shown in figure 13*A*. When the pieces were pressed together and pulled in the direction indicated by the arrows, the stress pattern shown in fugure 13*B* developed. Freund (1974, p. 126) noted that the stress difference near T-T (fig. 13*B*) is 5 times the difference between the applied stresses, and he concluded that these places would be the most probable sites of any secondary structure. Folds and thrusts, according to Freund (1974, p. 126), should parallel the principal tensile-stress trajectories (dashed lines, fig. 13*B*) near T-T.

Figure 13*C* shows the trajectories of maximum effective shear stress. The solid lines, according to Freund (1974, p. 127), show the expected orientation of secondary strike-slip faults with the same sense of displacement (here, right lateral) as the major fault, and the dashed lines those with the opposite sense of displacement.

Freund (1974, p. 127) noted that the faults most likely to form have the exact shape and orientation of P faults, and he concluded that P faults should be expected along curved strike-slip faults regardless of the origin of the curve. This conclusion has an important bearing on the origin of the echelon offsets in the trace of active faults at Santa Rosa, Calif.

The chief features of the deformational pattern in the vicinity of Santa Rosa are: (1) the intersection or near-intersection of four major faults, including the Healdsburg, Rodgers Creek, Maacama, and Bennett Valley faults; (2) the transfer of active movement from the Rodgers Creek to the Maacama fault through this zone of intersection; (3) the inverted-S shape (in plan view) of the Rodgers Creek and Maacama fault zones where they arc into this zone of intersection; (4) the thrust or reverse faults both northeast and west of this intersection; and (5) the change in strike of fold axes from the customary northeastward trend in the study area as a whole to an eastward trend north of this intersection.

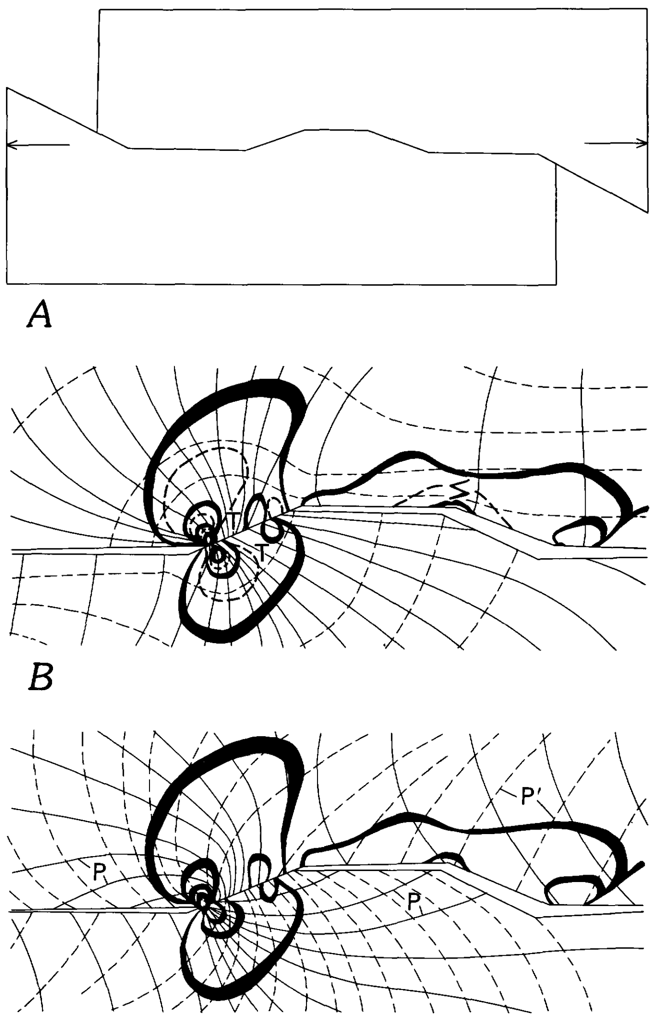

FIGURE 13.—Photoelastic model of stress along a curved fault, modified from Freund (1974, p. 127). *A*, Shape of model; arrows indicate direction of pull. *B*, Orientation of principal-stress trajectories: solid line, compressive; dashed line, tensile. Dark bands (solid and dashed) indicate stress difference. T, expected location of folds and thrust faults (parallel to dashed stress trajectories). *C*, Direction of maximum effective shear stresses (internal friction, 30°. P, expected orientation of faults with right-lateral displacement; P′, expected orientation of faults with left-lateral displacement.

The inverted-S shape of the active faults (Rodgers Creek and Maacama) near Santa Rosa resembles the trajectories of maximum shear stress developed in the photoelastic model in the area where the opposing sides of the bent fault impinge on each other (fig. 13C). The trends and positions of thrust faults and folds near Santa Rosa correspond roughly to those predicted by Freund (1974) near the stress concentration at T-T in his photoelastic experiments. If this analogy is valid, the Rodgers Creek and Maacama faults represent a set of P faults joining at an area of stress concentration centered near Santa Rosa. This stress concentration is apparently similar to that which might develop through folding of, and continued wrenching along, a deep-seated master fault older than the Rodgers Creek and Maacama faults. The Healdsburg and Bennett Valley faults could be disjoined and now-inactive segments of that earlier fault.

In summary, it is hypothesized that the right-lateral wrench system through the Santa Rosa block was deflected near Santa Rosa. A formerly active fault within the zone—a continuous Healdsburg-Bennett Valley fault—was locked by this deflection, so that movement was transferred to a different set of strike-slip faults within the wrench zone. This different set, which includes the northern section of the Rodgers Creek fault and the southern section of the Maacama fault zone, formed along trajectories of maximum shear stress that curve through the zone of deflection. However, a shear or system of shears connecting the active sections of the Rodgers Creek and Maacama fault zones has not as yet completely broken through—at least, none has been mapped.

This hypothesis provides some insight into the development of the wrench zone as a whole. Differential crustal contraction in response to regional compression has probably caused repeated bending or warping of active fault surfaces elsewhere within the wrench zone, as it apparently did at Santa Rosa. Thus, active movement has shifted from fault to fault across the width of the wrench zone, in some places renewing older faults and in other places breaking new faults, but always seeking the path of least resistance. The numerous inactive faults and fault segments within or near the wrench zone are relics of this process.

Continued movement along a right-stepping connection between echelon faults could ultimately create—within a right-lateral wrench system—a pullapart basin centered at the point of inflection of the echelon strands. The downwarp now inundated by the waters of San Pablo Bay may be a pullapart basin developed at the right-stepping intersection of the Hayward and Rodgers Creek faults.

Despite a long history of wrench faulting probably spanning at least 7 m.y., the Sonoma Volcanic field has not been totally dismembered by strike-slip displacement along the wrench system. The major part of right-lateral displacement between the Pacific and North American plates since the late Miocene has probably been concentrated west of the Sonoma Volcanics at the plate boundary (the San Andreas fault) and on faults near the boundary between the Sebastopol and Santa Rosa blocks.

The Sebastopol block has been right laterally displaced from the Sonoma terrane along the Tolay-Wallace Creek(?), Hayward-Rodgers Creek-Maacama, and Healdsburg-Bennett Valley fault systems. Correlation of the Tolay Volcanics with volcanic rocks in the Berkeley Hills implies a right-lateral offset of 45±15 km on the Hayward fault and its extension to the north, either the Rodgers Creek or the Tolay fault, since 8 m.y. B.P.

Right-lateral shear within the Santa Rosa block has probably been considerable, notwithstanding the apparent integrity of the Sonoma Volcanics. Except for these volcanic rocks, geologic markers from which the actual amount of displacement can be precisely estimated are not available. However, some idea of the magnitude of this displacement can be gained from the relations outlined below.

As previously noted, the lower member of the Sonoma Volcanics consists chiefly of volcanic rocks exposed in three discrete areas: the Sonoma Mountains area, the Mount Veeder area, and the Mount George area. These three areas could have been telescoped by right-lateral movement on intervening faults, now concealed except for the Carneros fault (pl. 1).

Presuming the Carneros fault to be the now-inactive northward extension of the Franklin-Sunol-Calaveras fault system, right-lateral offset on it probably aggregates at least 20 and perhaps 35 km, or roughly 28±8 km. Almost all differential right-lateral movement of the Sonoma Mountains, Mount Veeder, and Mount George areas had occurred before eruption of most of the younger members of the Sonoma Volcanics, which, after eruption of the ash flows and tuff at the Petrified Forest about 3.4 m.y. B.P., overlapped the projected extensions to the north of these earlier faults.

Total right-lateral offset on the known major wrench systems—the Hayward-Rodgers Creek (or Tolay)-Maacama and the Carneros-Franklin-Sunol-Calaveras—could aggregate 73±23 km. To this amount should be added a few kilometers for offset on the Green Valley fault, and possibly 5 to 10 km to account for offset on minor faults and the component in the direction of shear of crustal shortening through folding. In summary, 85±25 km seems to be a reasonable estimate of right-lateral offset across a zone encompassing the entire width of the Santa Rosa block since about 8 m.y. B.P.

One restriction on movement on the San Andreas fault should also be noted. Because the Wilson Grove Formation capping the Sebastopol block is relatively undeformed, it must have been deposited after passage of the triple junction now at Cape Mendocino. Therefore, about 6 m.y. B.P., during deposition of the tuff in the Wilson Grove near what is now Sebastopol, that area must have been south-southeast of the zone of active tectonism around the triple junction. In other words, the Wilson Grove Formation was deposited on part of the North American plate already bypassed by the triple junction. That triple junction is now situated about 270 km from the nearest outcrop of the Wilson Grove Formation. Therefore, the average rate of right-lateral movement of the triple junction (and the Pacific plate) relative to the Sebastopol block could not exceed roughly 4½ cm/yr for the past 6 m.y.

Although the details of late Neogene faulting are still hazy, the overall picture of movement in the study area and vicinity seems fairly well established. After transit of the triple junction now at Cape Mendocino past the western part of the study area, a substantial part—perhaps about one-fifth—of the presumed 5½-cm/yr offset between the North American and Pacific plates was accommodated by means of offset on a N. 30° W.-trending right-lateral wrench system passing through the study area. Deformation related to that wrench system distinguishes the Santa Rosa block from the less deformed terrane of the Sebastopol block to the west. The fault system within this wrench zone has apparently evolved into echelon sets of P faults as a consequence of folding and refolding of earlier faults. Before and during passage of the triple junction, quite different tectonic regimes probably existed, but the features consequently formed are not now recognizable.

The volcanic rocks, including those in the Berkeley Hills, the Sonoma Volcanics, and the Clear Lake Volcanics, presumably formed through partial melting of mantle material welling up behind the northerly moving trailing edge of the subducted Juan de Fuca plate; this process created a chain of volcanoes that were progressively younger to the north and northwest. This mechanism, first proposed by Dickinson and Snyder (1975), is not readily testable. However, the proximity of the Sonoma Volcanics and the Clear Lake Volcanics to the plate boundary makes it doubtful that these youthful volcanic rocks formed through melting of the subducted slab itself.

Subsequent offset of parts of the volcanic fields by right-lateral faults has telescoped them, translated the lower member of the Sonoma Volcanics clockwise, and possibly slipped rocks correlative with volcanic rocks in the Berkeley Hills into the western part of the study area (the Burdell Mountain area and the vicinity of the Murphy No. 1 well, pl. 1).

ORIGIN, EXTENT, AND AGE OF DEFORMATIONAL PROVINCES (SEBASTOPOL AND SANTA ROSA BLOCKS)

The Santa Rosa block seems to represent a zone of deformation developed along a right-lateral wrench system, whose principal zone of movement is now along the Rodgers Creek-Healdsburg-Maacama fault system. The wrenching forces necessary to generate the couple implied by the presence of this wrench system are probably being transferred across the San Andreas fault from the northwesterly moving Pacific plate (considering the North American plate as fixed). Transfer of these forces across the San Andreas fault requires substantial friction and perhaps locking of a segment of this fault northwest of its intersection with the principal displacement zone of the Rodgers Creek fault system. However, the undeformity of the Neogene rocks capping the Sebastopol block implies that the forces transferred from the Pacific plate through this block contribute only in a minor way to the forces generating the wrenching couple within the Santa Rosa block. Frictional forces between the Sebastopol block and the Pacific plate need not be so large as those farther to the southeast.

The wrench zone through the Santa Rosa block has apparently prevailed from pre-Sonoma or at least early Sonoma time. This conclusion is based on the existence of such known faults as the Carneros that offset the lower part of the Sonoma Volcanics but are covered in places by younger units of the Sonoma Volcanics. That the wrench zone is as old as the lower member of the Sonoma Volcanics is confirmed by the presence of a roughly 7 m.y. old rhyolite emplaced along the Rodgers Creek fault zone and, to some extent, is reinforced by the agreement of trends of dikes of the Sonoma Volcanics with the expected direction of maximum compression in a wrench system with an orientation comparable to that of the Rodgers Creek-Maacama fault.

Considering the relative incompetency of the late Miocene rocks capping the Mendocino plateau and their susceptibility to erosion, their preservation and the correlation between geomorphologic and deformational provinces must mean that the mechanism responsible for the contrast in late Miocene to Pleistocene deformation of the Sebastopol and Santa Rosa blocks has continued to function into the recent past and, in fact, may be functioning now.

It might be suspected that the deformational and geomorphic contrast between the Santa Rosa and Sebastopol blocks implies only that the basement rock of the Sebastopol block is relatively strong and rigid in comparison with that of the Santa Rosa block. However, the distribution of basement rock types—melange, broken formation, serpentine, Franciscan rocks, and the Great Valley sequence—shows no obvious correlation with the pattern of late Miocene and younger deformation. Thus, there is little direct evidence that the bedrock of the Sebastopol block inherently differs rheologically from that of the Santa Rosa block.

Irwin and Barnes (1975) evaluated the possibility that shearing stresses along faults in parts of the San Andreas system are materially reduced where the faults are somehow lubricated. Judging from their map, the known and inferred distribution of serpentine is such that this mineral could indeed act as a lubricant in other parts of the fault system, though not in the segment west of the Sebastopol block.

Kusznir and Bott (1977, p. 247) adopted a model in which the lithosphere consists "* * * of an elastic layer about 10-30 km thick (depending on geothermal gradient) above a ductile layer forming the underlying part of the lithosphere * * *." They showed that horizontal stress in this elastic layer is inversely proportional to its thickness; thus, this stress is amplified in areas where the elastic layer is thin because of a high geothermal gradient.

The presence of the Sonoma Volcanics, the Clear Lake Volcanics, and the Geysers steam field (fig. 2) suggests that since late Miocene time the geothermal gradient within parts, and possibly much, of the Santa Rosa block has been elevated relative to surrounding areas without similar volcanic manifestations, such as the Sebastopol block. Stress amplification caused by consequent thinning of the upper elastic layer within the Santa Rosa block may be sufficient to explain the observed deformational contrast between the Santa Rosa and Sebastopol blocks. However, this hypothesis provides little insight into the origin of the Maacama-Hayward wrench system, nor does it reconcile the pattern of the zone of deformation through the Santa Rosa block with the regional plate-tectonic geography.

Finally, shearing stresses within the Sebastopol block could be smaller than elsewhere along the San Andreas because of marked local reduction of the regional forces holding together this part of the North American plate and the opposing Pacific plate. This reduction in compressive force could be due to some singularity in the position of the Sebastopol block with respect to the North American, Juan de Fuca, and Pacific plates. Each of these three plates applies a traction against the other two along their mutual boundaries; it follows that the differing directions of transport and the differing attitudes of contacts of the Pacific and Juan de Fuca plates with regard to the North American plate must generate some eccentricity in the regional stress pattern within the North American plate. This eccentricity would be situated near the mutual point of contact of the three plates—the Mendocino triple junction.

It is assumed that the western part of the North American plate has been subjected to regional horizontal compression since late Miocene time and that in central California the principal axis of compressive stress has been oriented roughly north-south during this time (Stone, 1970). This axis must be in the northern sector to neutralize the rotational effect of northwesterly directed shear stress at the plate boundary, and to account for left-lateral displacement on the Garlock-Big Pine fault systems and right-lateral displacement on the San Andreas fault (fig. 1) and allied faults in the Transverse Ranges (Jahns, 1973, p. 154, 161). The directon of this principal axis of compressive stress need not, of course, coincide with the direction of relative movement of any of the three lithospheric plates here discussed. In their experiments in photoelastic modeling of the San Andreas fault, Nikonov and others (1975, p. 154) justified similar assumptions about the present-day stress field—namely, existence of a stress field of active regional compression and submeridional direction of the axis of greatest compression—on the basis of seismologic and deformational (measured strain) data. However, because of the irregular geometry of the contacts between the Pacific, Juan de Fuca, and North American plates and the differing directions of movement of these plates, it is unlikely that the regional stress pattern could be so simple as the preceding discussion seems to imply.

North of the Mendocino triple junction, the orientation of the principal axis of compressive stress within the continental plate probably veers from northward inland to northeastward along the coast. This shift seems necessary to balance tractions applied by the northeasterly underthrusting Juan de Fuca plate at its sloping interface—presumably a subduction zone—with the North American plate. Some part of the regional horizontal compressive stress within the North Ameri-

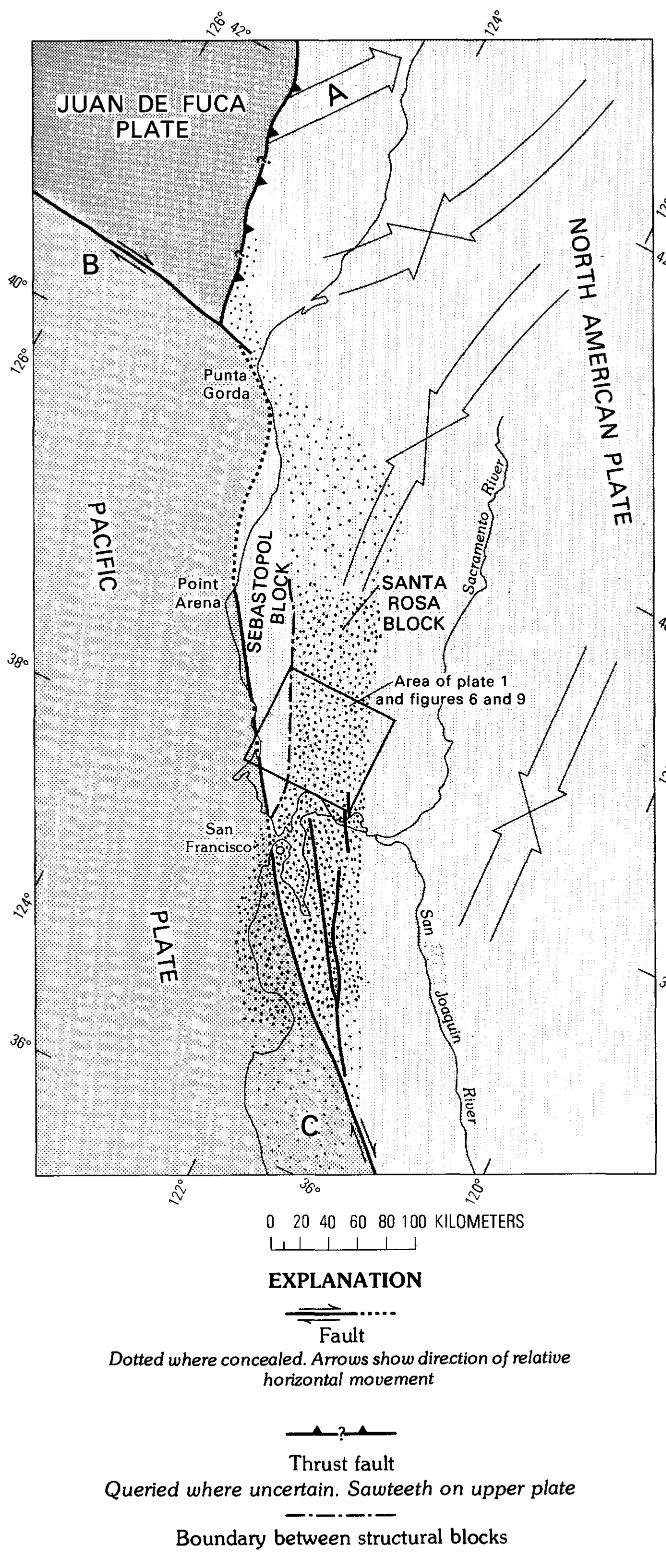

FIGURE 14.—Hypothetical directions of principal horizontal component of compressive stress (large arrows) and zone of maximum shear stress (stippled) in North American plate between San Francisco and Punta Gorda. Lightly stippled area represents possible extension of zone of maximum shear stress beyond area of figure 10. Arrow at A shows direction of underthrusting of Juan de Fuca plate relative to North American plate. Arrows at B and C show right-lateral offset on Mendocino Fracture Zone and San Andreas fault, respectively. Influences of body forces (gravity, magnetic field, inertia) and of tractions at base of lithospheric plates due to convection currents and drag are ignored.

can plate is thus intercepted, and a zone of reduced compressive stress is left along the plate boundary, beginning near the Mendocino triple junction and extending an unknown distance to the south. The little-deformed Sebastopol block may represent that zone, and the Santa Rosa block the adjacent area of easterly increasing horizontal compressive stress (fig. 14).

In a sense, the Sebastopol block lies within the stress shadow of the Mendocino triple junction. Thus, some part of the compressive force applied along the boundary between the Pacific and North American plates is bridged: the north abutment is the subducted lip of the Juan de Fuca plate, and the the south abutment is simply an area of stress concentration along a section of the San Andreas fault southeast of San Francisco (Fox, 1979). Stress concentration in the Santa Rosa block could thus be due to either or both of two possible causes: (1) local thinning of the elastic layer of the lithosphere because of elevated geothermal gradient, or (2) the unique position of the block with respect to the dynamically interacting Pacific, North American, and Juan de Fuca plates.

CONCLUSIONS

Presumably, the zone of stress concentration responsible for deformation of the Santa Rosa block extends southward and intersects the San Francisco section of the San Andreas fault. Locking of this section of the fault may be caused by the braking effect of the increased horizontal compressional stress postulated in the preceding section. This braking effect could doubtlessly be overcome by long-term buildup of regional stresses. More importantly, from the point of view of earthquake prediction, short-term perturbations in the regional stress pattern east of the Mendocino triple junction might affect the magnitude of compressional and shear stresses in the area of locking and thus could trigger earthquakes on the San Andreas fault. Stress concentrations at the intersections of the Rodgers Creek and Maacama faults near Santa Rosa might also be so affected. Such perturbations could result from stress buildup (possibly associated with slippage along the Mendocino Fracture Zone) along the contact between the Juan de Fuca and North American plates. The possibility that stress levels in the hypothesized area of stress concentration at Santa Rosa may be several times greater than the generally prevailing levels of shear stress should be evaluated in the context of seismic risk and earthquake prediction through monitoring of onsite stress.

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