

UPPER CRETACEOUS STRATIGRAPHY OF WESTERN SOLANO COUNTY, CALIFORNIA

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ABSTRACT

A thick section of Upper Cretaceous strata of the Great Valley sequence crops out in western Solano County. The section represents part of the fill of the Late Jurassic to Tertiary Great Valley forearc basin and forms the upper part of the Upper Jurassic to Upper Cretaceous Great Valley sequence. The Great Valley sequence rests conformably on Jurassic oceanic crust of the Coast Range ophiolite and dips eastward beneath the adjacent southern Sacramento Valley. The Santonian, Campanian and Maestrichtian units of the Upper Cretaceous part of the Great Valley sequence produce large amounts of gas in the southern Sacramento basin, principally from submarine-fan, submarine-canyon and deltaic facies. In outcrop, the Upper Cretaceous units consist entirely of submarine-canyon and submarine-fan sandstone bodies and intervening basin-plain and slope shale units.

The Upper Cretaceous units in ascending order consist of (1) the Venado Formation, (2) the Volo Formation, (3) the Sites Formation, (4) the Punks Formation, (5) the Guinda Formation, (6) the Forbes Formation, (7) the Sacramento Shale, and (8) the Winters Formation. Lower Tertiary shallow-marine strata rest with angular unconformity on the lower Winters Formation; Maestrichtian units, which include the upper Winters Formation, H&T Shale, and Mokelumne River Formation, do not crop out but are present in subsurface within most of the southern Sacramento basin.

INTRODUCTION

Upper Cretaceous strata of the Great Valley sequence crop out in western Solano County north of Vacaville as the north-striking west limb of an asymmetrical syncline that underlies the Sacramento basin to the east (Figure 1). The strata extended north to the county border along Putah Creek to the west of Winters and south to the Fairfield area (Figure 2). Upper Cretaceous strata also crop out northward from Putah Creek along the western flank of the Sacramento basin, in the Redding area at the northern end of the basin, north and east of Chico in the foothills of the Sierra Nevada, and around the flanks of Sutter Buttes, a Pliocene volcanic extrusive complex in the central part of the basin (Figures 1, 2). To the south, Upper Cretaceous strata crop out along the western flank of the San Joaquin basin; the nearest outcrops are in the northeastern Diablo Range.

The Santonian to Maestrichtian units of the Upper Cretaceous sequence produce large amounts of gas in the Sacramento basin; as a result, the stratigraphy, structure, sedimentology, subsurface and outcrop extent are better known for these units than for older

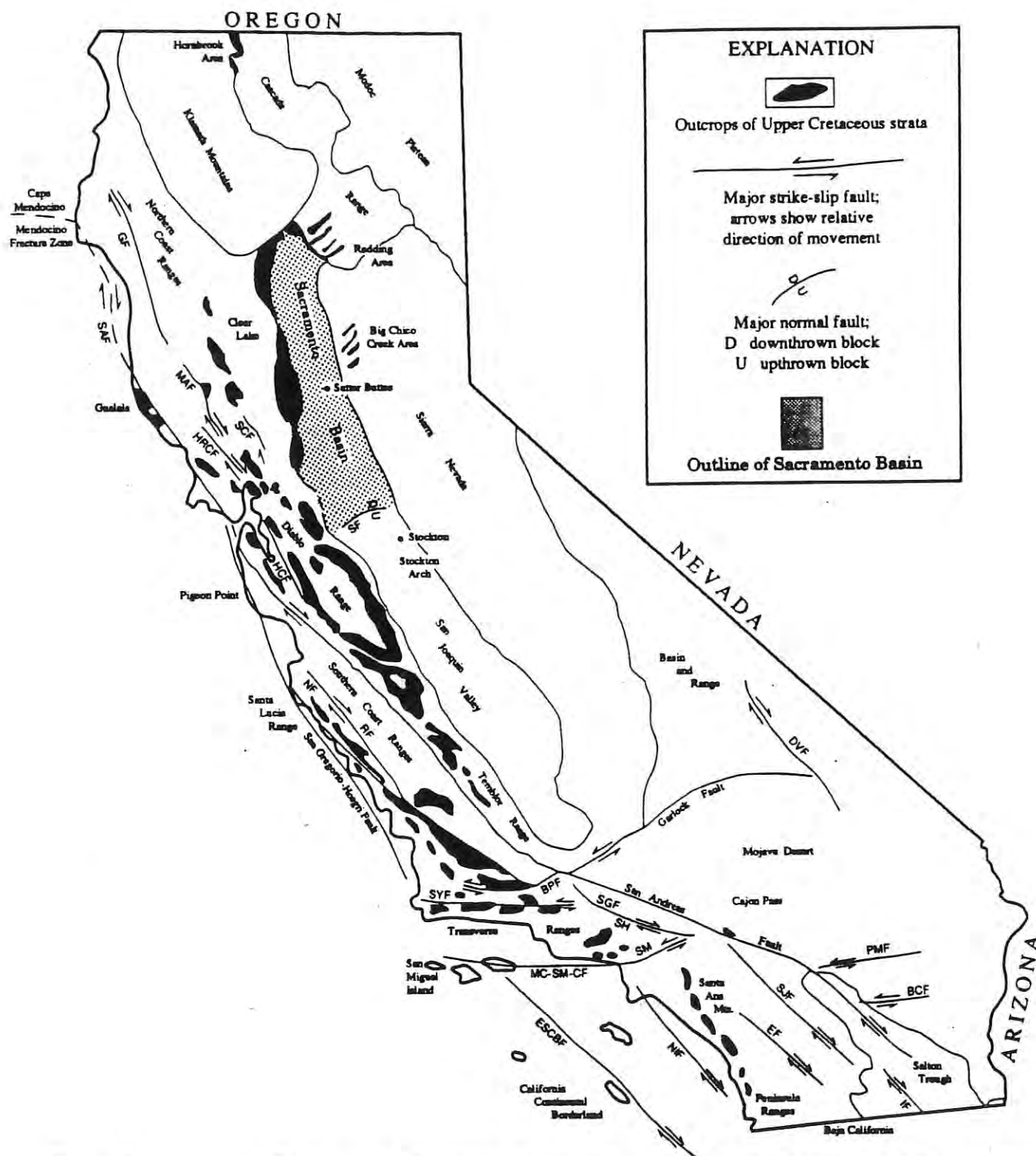


FIGURE 1. INDEX MAP OF CALIFORNIA SHOWING THE LOCATION OF THE SACRAMENTO BASIN, MAJOR FAULTS, OUTCROPS OF CRETACEOUS STRATA, MAJOR FAULTS, AND PRINCIPAL GEOLOGIC PROVINCES (FROM NILSEN, 1986, FIG. 18). ABBREVIATIONS: BCF, BLUE CUT FAULT; BPF, BIG PINE FAULT; DVF, DEATH VALLEY FAULT; EF, ELSINORE FAULT; ESCBF, EAST SANTA CRUZ BASIN FAULT; HRCF, HEALDSBURG-ROGERS CREEK FAULT; IF, IMPERIAL FAULT; MAF, MAACAMA FAULT; MC-SM-CF, MALIBU COAST-SANTA MONICA-CUCAMONGA FAULT; MF, MIDLAND FAULT; NF, NACIMINENTO FAULT; NIF, NEWPORT-INGLEWOOD FAULT; PMF, PINTO MOUNTAIN FAULT; RF, RINCONADA FAULT; SAF, SAN ANDREAS FAULT; SCF, SUND-CALAVERAS FAULT; SF, STOCKTON FAULT; SGF, SAN GABRIEL FAULT; SH, SIMI HILLS; SM, SANTA MONICA MOUNTAINS; SJF, SAN JACINTO FAULT; AND SYF, SANTA YNEZ FAULT.

and more deeply buried units of the Great Valley sequence (Figure 3). Data from subsurface wells, cores, and seismic-reflection profiles, combined with outcrop data, provide a wealth of information about the Santonian to Maestrichtian sequences, and these units will be discussed in greatest detail in this paper (see also Nilsen, 1990). The purpose of this paper is to summarize the stratigraphy of the outcropping Upper Cretaceous deposits of western Solano County, emphasizing the Santonian to Maestrichtian units. Upper Cretaceous units that are present only in the subsurface to the east will not be discussed in detail.

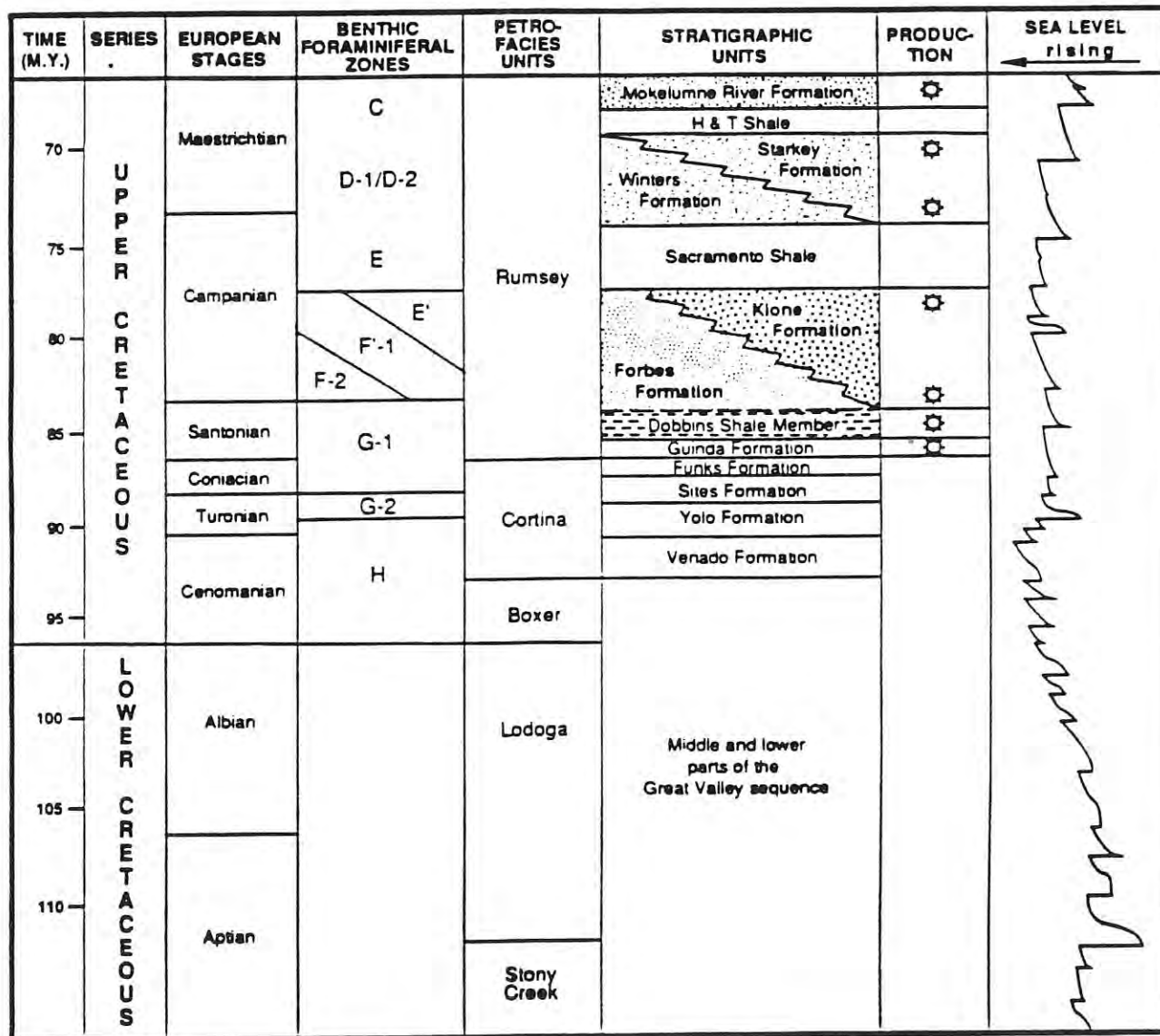


Figure 3. Chart showing Late Cretaceous European stages and associated time divisions (modified from Palmer, 1983), general stratigraphy of the Sacramento basin (modified from Kirby, 1943b), Late Cretaceous benthic foraminiferal zones (modified from Goudkoff, 1945), petrofacies units (from Ingersoll, 1983), producing intervals, and eustatic relative changes in sea level (modified from Haq and others, 1987).

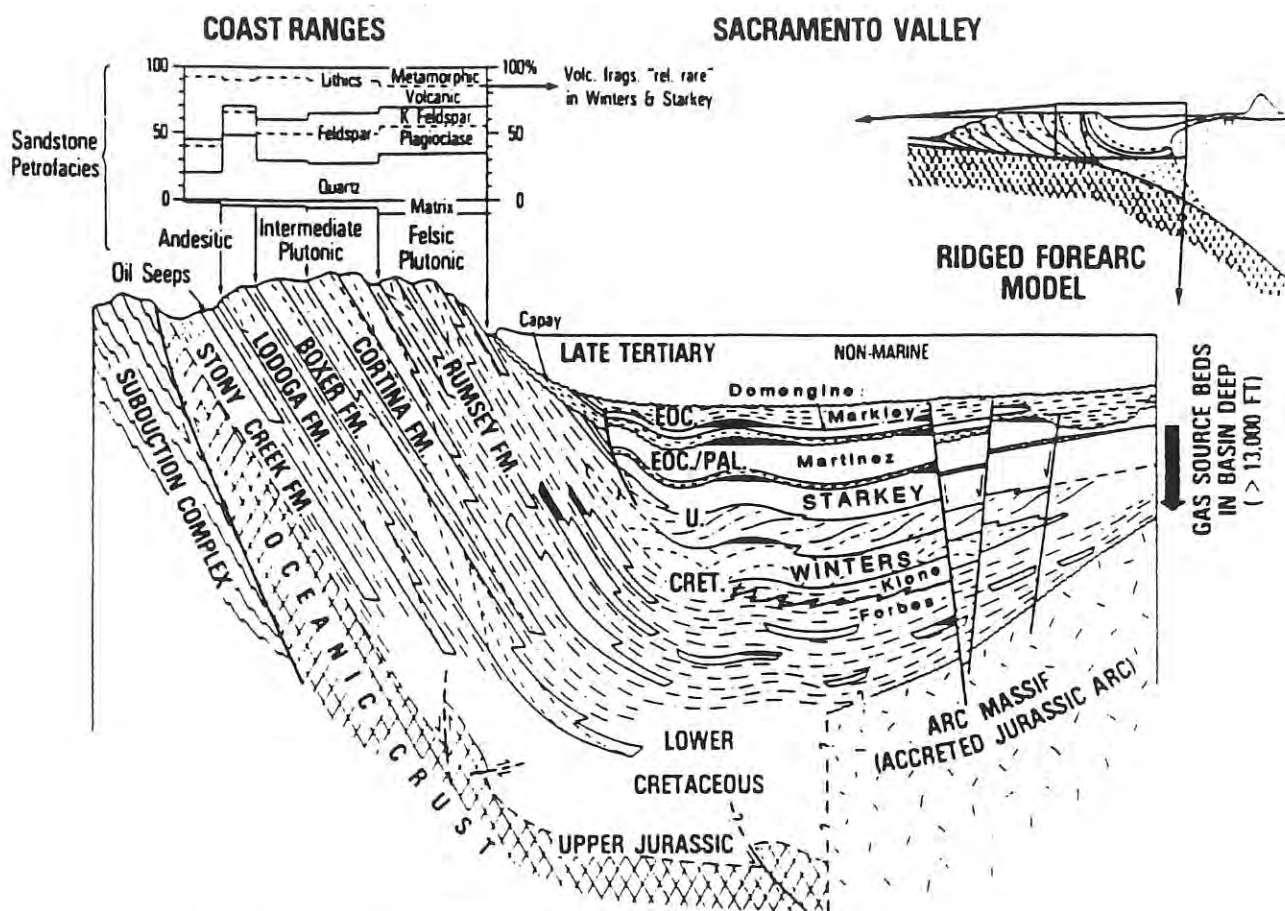


Figure 4. Schematic cross-section showing structure and stratigraphy of the Sacramento basin (from Graham, 1981, Fig. 2, modified from Dickinson and Seely, 1979). Outcrop sandstone petrofacies are from Ingersoll and others (1977). Volcanic content of Winters and Starkey and progradation between them are from Drummond and others (1976). Interpretation of Upper Cretaceous source beds is from Ziegler and Spotts (1978). Generalized gas occurrences are shown as blackened areas. Stratigraphic and structural relations are not to scale. Thrusting of oceanic crust on subduction complex (left side of diagram) occurred after deposition in the Cretaceous forearc basin.

sandstone and shale with local conglomerate (Figures 3, 4). Most of the Upper Cretaceous units, where exposed on the western flank of the basin in the eastern Coast Ranges, consist of turbidites and deep-marine shale. However, on the eastern flank of the basin, Upper Cretaceous units consist largely of shallow-marine and nonmarine deposits where exposed on the gently west-sloping flank of the Sierra Nevada foothills (Figure 1). The upper Cretaceous part of the Great Valley sequence is also generally thinner, less complete, and less deformed on the east side of the basin. Upper Cretaceous strata along the northern margin of the basin in the Redding area are also generally of shallow-marine origin.

Regional benthic foraminiferal zones defined by Goudkoff

(1945) and modified by Almgren (1986) for the Upper Cretaceous of the Sacramento basin range from H (Cenomanian and Turonian) to C (Late Maestrichtian), a time span of about 31 m.y. Figure 3). Regional petrographic studies of the Great Valley sequence by numerous workers (see references cited by Ingersoll, 1983) have permitted the sequence to be subdivided into petrofacies units (Figures 3, 4). Ingersoll and Dickinson (1981) and Ingersoll (1982) suggested redefining the Great Valley sequence as the Great Valley Group, with each of the regionally defined petrofacies units attaining the status of formations (Ingersoll, 1990). In this paper, however, I retain use of the term Great Valley sequence, because of its precedence and the regional applicability of Upper Cretaceous stratigraphic names proposed by Kirby (1943a) to the subsurface in the Sacramento basin.

The petrofacies units of the Great Valley sequence are thought by Ingersoll (1982, 1983) to record progressive unroofing of a magmatic-arc source area from the Late Jurassic to Tertiary (Figure 4). As a result of unroofing, the Upper Jurassic sandstones contain abundant andesitic detritus and the Upper Cretaceous sandstones contain abundant plutonic detritus. The Sierra Nevada and, to a lesser degree, the Klamath Mountains, have been considered to be the major source areas (Ingersoll, 1983).

The Great Valley forearc basin resembles many other modern and ancient forearc basins (Dickerson and Seely, 1979). Strata within the basin generally form a broad asymmetric south-southeast-plunging syncline that is steeply dipping on the west and gently dipping on the east (Figure 4). To the west, the Great Valley sequence rests nonconformably on Jurassic oceanic crust of the Coast Range Ophiolite. To the east, the Great Valley sequence rests nonconformably on granitic and metamorphic basement rocks of the Sierra Nevada (Figure 4). To the north, the Great Valley sequence rests nonconformably on granitic and metamorphic basement rocks of the Klamath Mountains.

A subduction complex to the west structurally underlies the Coast Range Ophiolite (Figure 4). This subduction complex has been assigned to the Franciscan assemblage or Franciscan Complex (Berkland and others, 1972). The Franciscan assemblage ranges in age from Late Jurassic to Miocene (McLaughlin and others, 1982) and records accretion through most of the late Mesozoic and Cenozoic.

The Late Cretaceous was primarily a time of worldwide relative sea-level rise (Figure 3). However, numerous relative lowerings of sea level occurred from the early Aptian to the late Maestrichtian (Hag and others, 1987).

STRATIGRAPHIC FRAMEWORK

Early studies of the Upper Cretaceous strata around the margins of the Sacramento basin resulted from various mapping surveys and fossil-collecting expeditions. As a result of these early studies in California (summarized in Matsumoto, 1959, and

Popenoe and others, 1960), Upper Jurassic strata were referred to the "Knoxville", Lower Cretaceous to the "Shasta", Upper Cretaceous to the "Chico", and Paleocene to the "Martinez" series. Lithologically and structurally more complex Upper Mesozoic strata in the Coast Ranges west of the Sacramento basin were assigned to the "Franciscan" series.

Upper Cretaceous strata previously assigned to the "Chico series" crop out extensively around the margins of the Sacramento basin (Figures 1, 2). The type area of the "Chico series" is located in and adjacent to Big Chico Creek on the western flank of the Sierra Nevada. In the Coast Ranges to the west, Kirby (1943a) mapped and stratigraphically subdivided the Upper Cretaceous sequence, dividing it into a number of formations (Figures 3, 4).

Stratigraphic nomenclature for the "Chico series" in the Sacramento basin quickly became very complex as a result of great differences in lithology, thickness, and facies between the various outcrops and subsurface, and the presence of different workers with varying interests in each area (Jenkins, 1943; Goudkoff, 1945; Anderson, 1958; Popenoe and others, 1960; Bailey and others, 1964). In order to aid regional subsurface and outcrop correlations, Goudkoff (1945) proposed a zonation for the Upper Cretaceous and lower Tertiary of the Great Valley region that was based on detailed studies of benthic foraminifers (Figure 3).

The subsurface stratigraphy of the Upper Cretaceous strata of the Sacramento basin gradually became better defined in the 1950s with the discovery of many new gas fields and pools. Edmondson (1962) defined a number of Santonian to Maestrichtian subsurface stratigraphic units within Goudkoff's (1945) G-1 to C zones. However, he concluded that the benthic foraminifers used by Goudkoff (1945) to zone the Upper Cretaceous were controlled chiefly by water depth; as a result, he considered the Kione Formation, which contained a shallow-marine fauna, to be in part laterally equivalent to the upper part of the Forbes Formation, which contained a deep-marine fauna (Figure 3). He thus placed the Kione Formation in the F-zone of Goudkoff (1945) rather than in the E-zone, as previous workers had done.

Edmondson (1962) outlined the subsurface distribution, stratigraphy, and depositional environments of the Forbes Formation, Kione Formation, Sacramento Shale, Winters Formation, and Starkey Formation (Figure 3). He demonstrated that these Upper Cretaceous units generally thickened westward but were truncated in many areas by an erosional unconformity at the base of the Paleogene, which he referred to as the Capay gorge. These units were also found to be regionally truncated along the western margin of the basin by an erosional unconformity at the base of the Neogene Tehama Formation.

Edmondson (1962) thought that most stratigraphic variations in the Upper Cretaceous resulted from minor transgressions and regressions, coupled with southwestward tilting of the basin floor. However, he recognized that sandstone bodies in the western part of the Forbes Formation might have been deposited by turbidity currents. The Kione Formation was inferred to record southward

progradation of a delta that had its source to the north and east (Thomson, 1962). Edmondson (1962) concluded that five factors were important in controlling the distribution of sandstone bodies and gas accumulation: (1) distance from the zero line of sedimentation, (2) depth of deposition, (3) location of tributary rivers, (4) basin relief, and (5) initial folding.

Following the definitions by Edmondson (1962) of the Campanian and Maestrichtian lithostratigraphy of the Sacramento basin, numerous subsequent workers proposed additional stratigraphic subdivisions and correlations. Callaway (1964) described the distribution and character of uppermost Cretaceous sandstone and shale units in the northern San Joaquin basin between T 16 N and T 10 S. He classified all of the sandstone units as regressive, transgressive, bar, channel, or deltaic sands.

Callaway (1964) concluded that the Winters "Sand" had been derived from erosion of the northern Diablo Range to the west. The unconformably overlying Starkey "Sands" of Callaway (1964) were considered in general to be regressive sands derived from Sierran sources. Other sandstone and shale units in the southernmost Sacramento and northern San Joaquin basins of upper Campanian and Maestrichtian are were thought to have been derived largely from western source areas. These units generally thicken southward into the San Joaquin basin, whereas the Winters Formation generally thins and pinches out southward into the San Joaquin basin.

Additional surface and subsurface geological mapping, some associated with published field-trip guidebooks, greatly advanced understanding of the Upper Cretaceous units. Field-trip guidebooks and/or published maps and cross sections clarified outcrop relations for the entire basin (Olmsted and Davis, 1961, 1962; Lachenbruch and others, 1962), for the western (Lachenbruch, 1962) flanks of the basin, for the Rumsey-Capay Hills area (Mee, 1954; Brooks, 1962a; Brooks and others, 1962), for the Putah Creek area along the southwestern flank of the Sacramento basin (Brooks, 1962b; Emerson and Roberts, 1962), and for the Sutter Buttes area (Thamer, 1961; Garrison, 1962a, b). Exploration-related subsurface cross-sections by Cross (1954), Harding and others, (1960), Corvalan and Harbaugh (1962), and Edmondson (1967a, b) clarified regional subsurface relations.

Detailed studies of the framework mineralogy led to the subdivision of the Great Valley sequence into five petrofacies units that were mapped along the western margin of the Sacramento basin. Ingersoll (1976, 1983) integrated these studies by dividing the entire Great Valley sequence into eight petrofacies intervals, six of which are present in the Sacramento basin (Figures 3, 4).

Sedimentological studies of outcrops of the Great Valley sequence along the western flanks of both the Sacramento and the San Joaquin basins demonstrated that deposition had been chiefly by south-flowing turbidity currents. Ojakangas (1968) provided three possible models for this depositional pattern: (1) southward plunge of the basin axis, (2) left-hooking of prograding deep-sea fans, and (3) south-flowing slope-parallel currents. Tamesis (1966) and Shawa (1970, 1971) inferred that parts of the Great

Valley sequence cropping out west of the San Joaquin basin had been deposited by slope-parallel contour currents; however, Colburn (1971) concluded that evidence for currents of this type was lacking in these rocks, and no subsequent studies, except in part of the Hornbrook Formation to the north (Nilsen, 1984), have substantiated this idea.

Some studies of the Great Valley sequence have suggested that land masses to the west that included Franciscan rocks may have supplied sediment to the Great Valley forearc basin. However, framework-mineralogy studies have not supported this concept. Minor amounts of glaucophane and chert may have source areas in the ophiolites of the western Sierra Nevada. The Franciscan assemblage was not uplifted sufficiently to form a major source until the middle Eocene, when shallow-marine and deep-marine units of the central Coast Ranges were deposited in small basins (Nilsen, 1987).

Regional tectonic, petrologic, sedimentologic, and radiometric studies in the 1970s clarified the nature of the Great Valley sequence (Figure 3). These studies interpreted the Great Valley sequence as the fill of a late Mesozoic ridged forearc basin (Dickerson, 1971, 1974, 1976; Dickinson and Seely, 1979) that developed in the arc-trench gap between the Franciscan assemblage subduction complex to the west (Blake, 1984) and the Sierran magmatic arc to the east (Bateman, 1981, 1983).

Ingersoll (1978a, b, 1979, 1982, 1983) developed a comprehensive model for deposition of the Great Valley sequence based chiefly on sedimentologic and petrographic studies of outcrops on the western flank of the Great Valley. Ingersoll concluded that the forearc basin widened through time as the locus of subduction migrated westward toward the down going oceanic slab and the locus of magmatism migrated eastward through time. For most of the Upper Cretaceous part of the Great Valley sequence, he mapped sequences of slope channels, inner-fan channels, middle-fan channels, outer-fan lobes, and basin-plain turbidites. The slope deposits had been previously recognized by the mapping of large re-transported blocks of Lower Cretaceous strata within Upper Cretaceous slope and submarine-canyon deposits (Brown and Rich, 1960, 1967; Lowe, 1972).

Detailed biostratigraphic and magnetostratigraphic studies of the Santonian, Campanian and Maestrichtian strata of the Sacramento basin over the past 20 years have helped to refine the benthic foraminiferal zones developed by Goudkoff (1945). Almgren (1986) modified some of Goudkoff's zones on the basis of new benthic foraminiferal studies. Zonations based on planktic foraminifers, radiolarians, ammonites, and nannofossils have helped refine regional and local correlations. Magnetostratigraphic studies by Ward and others (1983) and Verosub and others (1989) resulted in the recognition of a magnetic reversal directly above the Santonian-Campanian boundary in both the Big Chico Creek area on the east flank and the Rumsey-Capay Hills areas on the west flank of the basin, providing a new framework for cross-basin correlations.

Moxon and Graham (1987) and Moxon (1988) outlined the

subsidence history and the various controls on subsidence patterns in the Great Valley forearc basin. Dumitru (1988) used backstripping analyses to reconstruct the burial histories of outcropping strata of the Great Valley sequence and fission-track analyses of apatite grains to determine the maximum burial temperatures; the analyses indicate that subnormal geothermal gradients characterized the forearc basin and that subduction was essentially continuous through the late Mesozoic and most of the Cenozoic.

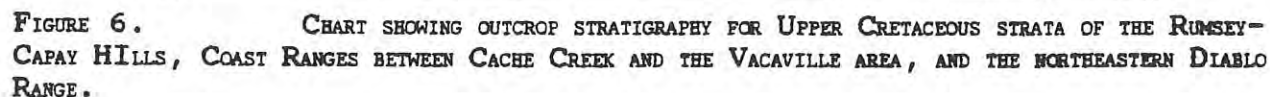
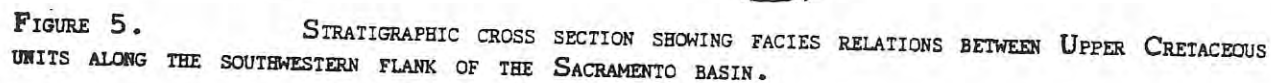
OUTCROP AND SUBSURFACE STRATIGRAPHY

Guinda Formation

The Santonian Guinda Formation of Kirby (1943a, b) crops out in the eastern Coast Ranges as far south as Mix Canyon, where it pinches out between underlying and overlying shale units (Figures 2, 5, 6). It represents an extensive submarine-fan deposit that locally has either a sand-rich or mixed-sediment character. Its subsurface extent remains uncertain because of the lack of abundant and widespread well penetrations; however, it has produced minor amounts of gas in a number of different fields.

In the Coast Ranges south of Cache Creek and the Rumsey-Capay Hills, the Guinda Formation consists of sand-rich submarine-fan deposits with southward-directed paleocurrents. However, to the south of Cache Creek (T 10 N), considerable disagreement has developed regarding which mappable units are of Campanian age and which units should be mapped as the Forbes Formation (Figure 7). Kirby (1943a) did not extend his units directly south of Cache Creek. Brooks (1962a) mapped strata directly south of Cache Creek as the Forbes Formation and showed the Guinda Formation as a very thin unit. Sonneman and Switzer (1962) mapped the units south of Cache Creek as upper and lower members of the Forbes Formation, with no Guinda present; Sims and others (1973), whose mapping was based largely on that of Sonneman and Switzer (1962), showed the same outcrops to be Guinda and Forbes Formation, with the upper member of the Forbes Formation of Sonneman and Switzer (1962) equivalent to their Forbes Formation and the lower member of the Forbes Formation of Sonneman and Switzer (1962) equivalent to their Guinda Formation.

These stratigraphic differences were compounded by additional interpretations in the Putah Creek area (T 7 N and T 8 N) to the south. Kirby (1943a) mapped the Guinda and Forbes Formations at Putah Creek and adjacent areas to the north and south. Subsequent workers concluded that Kirby's (1943a) Guinda Formation at Putah Creek was in fact roughly equivalent in age to the lower and middle parts of the Forbes Formation farther north, and that Kirby's Forbes Formation at Putah Creek was equivalent to the upper part of the Forbes Formation in subsurface to the north (Goudkoff, 1945;



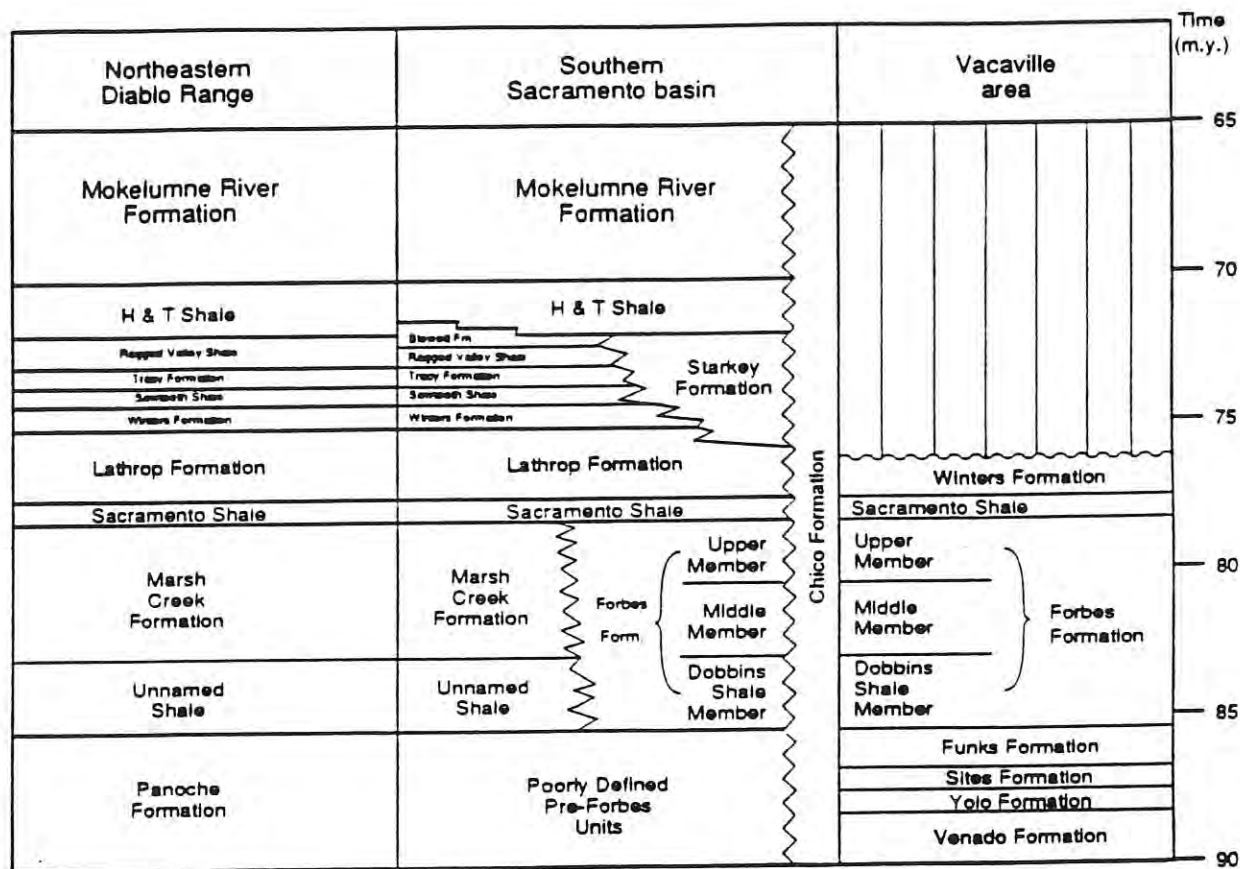


FIGURE 7. CHART SHOWING STRATIGRAPHIC NOMENCLATURE USED FOR UPPER CRETACEOUS STRATA IN THE SOUTHERN SACRAMENTO BASIN AND THE ADJACENT OUTCROP AREAS.

Lachenbruch, 1962, p. 61). Emerson and Roberts (1962) remapped the Putah Creek area and showed the presence of the Guinda Formation below the Dobbins shale member and overlying middle and upper members of the Forbes Formation. Emerson and Roberts (1962) also mapped a shale unite, their Pleasant Valley Shale, above the Forbes Formation.

Sonneman and Switzer (1962) mapped the Forbes Formation as a lower member and upper claystone member, without any Guinda Formation being present in the Putah Creek area and southward to the Vacaville area. Sims and others (1971), however, mapped these lower and upper members as Guinda Formation and Forbes Formation, respectively. Emerson and Roberts (1962) extended the Forbes Formation southward into the Vacaville area, and mapped the Guinda Formation as a thin unit that pinches out southward in outcrop between Putah Creek and Vacaville.

The confusion in mapping and formational assignments in this area has partly been resolved by subsequent micropaleontological studies. On the basis of ammonites and magnetostratigraphy (Haggart and Ward, 1984), planktic foraminifers (Trosper, 1985), and calcareous nannofossils (Filewiz, 1986), the Forbes Formation exposed in the Rumsey-Capay Hills is clearly the lower Dobbins Shale Member and the middle member, the sandier and productive part

of the Forbes, equivalent to the F-2 zone of Goudkoff (1945). Southward, however, in the Putah Creek area, the upper and middle members of the Forbes Formation are exposed (F-1 zone), as well as the Dobbins Shale Member (G-1 zone); some thin outcrops of the Guinda Formation are also present, as mapped by Emerson and Roberts (1962). Foraminiferal studies by Almgren (1986) and calcareous nannofossils by Filewicz (1986) confirm these relationships. The Forbes Formation continues in outcrop southward to the Vacaville area, but the Guinda Formation thins and pinches out completely between Putah Creek and Vacaville (Figures 5, 6, 7).

The Guinda Formation thus pinches out near Mix Canyon between the underlying shale deposits of the Funks Formation and the overlying Dobbins Shale Member of the Forbes Formation (Emerson and Roberts, 1962). The Guinda Formation also appears to pinch out southward into shale units in the subsurface beneath the southern Sacramento basin.

Forbes Formation

Background

The Forbes Formation can be divided into three members, in ascending order (Imperato and others, 1990):

1. The Dobbins Shale Member, late Santonian (G-1 zone of Goudkoff, 1945), as thick as 115 m (375 ft), basin-plain and slope mudstone and shale;
2. The unnamed middle member, early Campanian (F-2 zone of Goudkoff, 1945), as thick as 1,402 m (4,600 ft), deep-sea-fan deposits; and
3. The unnamed upper member, early to middle Campanian (F-1 zone of Goudkoff, 1945), as thick as 808 m (2,650 ft), slope mudstone and sandstone-filled gully deposits (Figures 5, 6, 7).

The Dobbins Shale Member and most of the middle member of the Forbes Formation are exposed in the Rumsey-Capay Hills along the western margin of the central Sacramento basin (Wagner and Saucedo, 1984). South of the Rumsey-Capay Hills, all of the members of the Forbes Formation are exposed as far south as the Vacaville area (Figures 5, 6, 7).

Early workers considered the Forbes Formation to be of marine origin, citing as evidence the discontinuous nature of the sandstone bodies and the presence of scattered megafossils. Edmondson (1962) concluded that it had been deposited mainly by west-flowing shelf currents generated from west-flowing rivers that drained the Sierra Nevada; southerly longshore drift and turbidite sedimentation to the west were thought to have possibly

redistributed some sediment. He inferred that the partly coeval Kione Formation consisted dominantly of southward-transported deltaic deposits.

Ingersoll (1976, 1979) concluded that outcrops of the Forbes Formation along the west side of the Sacramento Valley were basin-plain deposits; he thought that basin-plain deposition would have characterized turbidite sedimentation during Campanian eustatic sea-level rise (Figure 2). Graham (1981) suggested that the Forbes Formation in the subsurface probably consisted of middle-fan turbidites, deposited between Ingersoll's outcropping basin-plain deposits to the west and the feeding Kione delta system to the north and east (Figure 3).

Ward (1985) concluded that the middle member of the Forbes Formation consisted of thick channel sandstone with minor shale, and that the upper member consisted chiefly of nonfossiliferous shale with an increasing abundance of turbidite sandstone near the top. He contended that the youngest part of the Forbes Formation, near the town of Winters, consisted of shallow-marine Maestrichtian sandstone that recorded westward migration of the shoreline.

Trosper (1985) and Trosper and Douglas (1985, 1986) proposed that the middle and upper members of the Forbes Formation consisted of lower-slope, fan-fringe, and middle-fan turbidites deposited at lower bathyal to upper abyssal water depths with minor upward shoaling. These members were thought to have been characterized by high rates of sedimentation, with upward increases in the number and thickness of beds of sandstone and also in the amount of bioturbation.

Fischer and others (1986) concludes that cores from the Forbes Formation in the northern Sacramento basin contained thin beds of sandstone and siltstone as well as mudstone that is characterized by partial Bouma sequences, micro-ripple cross-lamination, and finely laminated cyclic sequences of mudstone turbidites. Rider (1986), on the basis of subsurface log correlations and radiolarian assemblages, concluded that the Dobbins Shale Member of the Forbes Formation in the southern Sacramento basin was deposited at or near the shelf-slope break. He concluded that the local absence of the Dobbins might have resulted from scour associated with the formation of submarine canyons. He thought that overlying parts of the Forbes Formation in this area formed apronlike drapes or overlaps on these canyons.

Moser and others (1986) examined the subsurface stratigraphy of the Forbes Formation and determined that it consists of middle- to outer-fan turbidites overlain successively by slope deposits and shelf deposits of the Kione Formation. Fining-upward sequences, pebbles or lenses of sandstone, and possible local unconformities associated with narrow, discontinuous, southeast-trending channels and fan lobes characterize the middle member of the Forbes Formation. Crevasse-splay, overbank, and possibly submarine-canyon deposits were also noted.

Morgan and Campion (1987) reinterpreted the Forbes/Kione depositional system within the framework of Exxon's global onlap curves and seismic stratigraphic concepts. They concluded that the

middle member of the Forbes Formation represented deposition of sand-prone, sharp-based, fining-upward units, with an aggradational or retrogradational stacking of fan lobes; they indicated that this member consists of massive sandstone, pebbly sandstone, conglomerate, pebbly mudstone, turbidites, and lenticular turbidites referred to by most workers as inner-fan-channel or middle-fan-lobe deposits. They concluded that the overlying upper member represented deposition of a younger shale-rich fan described by other workers as basin-plain, outer-fan, inner-fan levee, and slope deposits. Finally, Morgan and Campion (1987) concluded that rapid eustatic falls in sea level controlled deposition of the Forbes fan complex.

The Forbes Formation was deposited as a mud-rich, basin-plain, deep-sea-fan and slope turbidite system which prograded southward down the axis of the Cretaceous forearc basin (Imperato and Nilsen, 1990; Imperato and others, 1990). The source of sediment for this system was probably north of the present-day basin margin.

Dobbins Shale Member

The Dobbins Shale Member of the Forbes Formation (Kirby, 1943a, b) is a black shale to mudstone that contains abundant limestone concretions that weather to a gray color in outcrop. Trosper (1985) and Trosper and Douglas (1985, 1986) concluded that the Dobbins Shale Member had been deposited above the carbonate compensation depth but below the foraminiferal lysocline. In this setting, bottom waters that contained low amounts of oxygen but which were not continuously dysaerobic permitted intermittent bioturbation and ultimately preservation of a somewhat different foraminiferal assemblage than that of the overlying parts of the Forbes Formation.

The Dobbins Shale Member in the subsurface is characteristically a low-resistivity shale unit that has an average thickness of 60 m (200 ft). In the central and western parts of the basin, it consists of pelagic or hemipelagic basin-plain shale deposits that drape older strata and conformably underlie the middle member. The Dobbins Shale Member or its equivalent extends southward beneath the Marsh Creek Formation into the northern San Joaquin basin (Figure 5).

Unnamed Middle Member

Deep-sea-fan deposits of the middle member of the Forbes Formation consist of stacked sequences of genetically related channel-levee-complexes (Imperato and Nilsen, 1990; Imperato and others, 1990). The member has an average thickness of 900 m (3,000 ft) and a maximum thickness of about 1,200 m (4,000 ft) in the central and northern parts of the basin (Imperato and others, 1990). The channel-levee complexes typically consist of levee deposits intercalated with interchannel deposits that are overlain by sandstone-rich channel-margin and channel deposits.

Unnamed Upper Member

The shale-rich upper member of the Forbes Formation consists dominantly of slope shale deposits that prograded southward down the basin axis; it also contains gully-fill sandstones and shelf deposits of the eastern Sierra basin margin. This member has an average thickness of 300-450 m (1,000-1,500 ft) and a maximum thickness of 750 m (2,500 ft) in the central and northern parts of the Sacramento basin (Imperato and others, 1990). Complex thickness variations within this interval are related to progradational deltaic lobes of the Kione Formation. Gully-fill sandstone bodies may exceed 150 m (500 ft) in thickness. Gullies are generally oriented north-south and are generally less than 1.6 km (1 mi) wide.

Sacramento Shale

The Sacramento Shale is a basin wide fine-grained unit that was probably deposited during an interval of rapidly rising sea level or during a highstand (Figures 3, 5, 6, 7). It is of lower E zone age (Almgren, 1986) and is generally easily correlatable throughout the basin. It is more than 105 m (350 ft) thick and forms a shale drape that overlies the Kione Formation in parts of the central Sacramento basin, the upper member of the Forbes Formation in the southern Sacramento basin, and the Marsh Creek Formation in the southernmost Sacramento basin. It also extends southward into the northern San Joaquin basin.

The Sacramento Shale crops out in the southern Coast Ranges south of the Rumsey-Capay Hills and in the northeastern Diablo Range (Figure 2). In the southern Coast Ranges, it was mapped by Emerson and Roberts (1962) as the Pleasant Valley Shale. This unit extends southward from about 0.6 km (1 mi) north of Putah Creek to the Vacaville area. The unit has also been mapped by Sonneman and Switzer (1962) as the Sacramento Shale and by Sims and others (1971) as an undifferentiated Cretaceous unit. Almgren (1986) confirmed the stratigraphic equivalence of the subsurface Sacramento Shale and the Pleasant Valley Shale, assigning both to the lower E zone of Goudkoff (1945).

The thickness of the Sacramento Shale in the subsurface is highly variable, and it locally contains interbedded sandstone and siltstone. It was deposited as a basin-plain shale in the southern and western parts of the Sacramento basin, as slope shale in the central and eastern parts of the basin, and as shallow-marine shale in the north-central and easternmost parts of the basin.

WINTERS FORMATION AND RELATED UNITS

Background

Upper Campanian and lower Maestrichtian strata of the central

and southern Sacramento basin form a thick and stratigraphically complex assemblage of varied siliciclastic lithofacies deposited conformably on the underlying middle Campanian Sacramento Shale. The Starkey Formation consists chiefly of fluvio-deltaic deposits derived from the Sierra Nevada and can be divided into six separate deltaic sandstone bodies that prograded southwestward into the deeper part of the forearc basin. The Starkey Formation delta systems prograde southwestward over slope shale units and, farther to the southwest, at the base of slope, a series of deep-sea-fan sandstone bodies that include, in ascending order, the Lathrop Formation, the Winters Formation, the Tracey Formation, and the Blewett Formation (Figure 7). The submarine-fan bodies are separated by a series of shale units that include the Sawtooth Shale and Ragged Valley Shale (Figure 7). Only the Winters Formation crops out in western Solano County in the Vacaville area (Figures 5, 6, 7).

Winters Formation

The Winters Formation consists of slope and submarine-fan deposits. Drummond and others (1976) introduced a lithofacies model for the Starkey and Winters Formations of the Sacramento basin that emphasized their facies relations. These workers interpreted the units to be a time-transgressive prograding sequence that consisted in ascending stratigraphic order of basinal turbidite sands of the Winters Formation, slope shales defined as the "Delta Shale," and shelf sands of the Starkey Formation. Large-scale foresets or clinoforms were recognized in seismic lines to connect the Starkey shale sands with the Winters basinal sands. Foraminiferal faunas indicated inner-bathyal to outer-neritic water depths during deposition of the lower to upper Winters sandstone and nonmarine to inner-neritic water depths during deposition of the Starkey sandstone.

Garcia (1980, 1981) discussed the stratigraphic relations and facies associated between the Starkey and Winters Formations in the Sacramento basin, concluding that the Starkey Formation was a high-constructive delta that prograded westward from Sierran source areas to feed slope deposits of the Lathrop, Winters, and Tracy Formations. Garcia (1980, 1981) considered the Winters Formation to be a deep-sea-fan system fed by the outbuilding Starkey deltaic system through a series of submarine canyons. The Lathrop, Tracey, and Blewett fan systems were thought to be older and younger sequences deposited to the south in the same manner.

Tillman and others (1981) and Williamson and Hill (1981) concluded that the Winters Formation was deposited as a deep-sea-fan that was supplied with sediment from shelf deposits of the Starkey Formation. Cherven (1983a, b) concluded that the Starkey Formation was deposited initially as lobate wave-dominated deltas and subsequently as lobate fluvial-dominated deltas that supplied sediment to a variety of different deep-sea-fan and slope systems.

The offlapping relationship between the Starkey Formation

deltaic sequence and the deep-marine Winters slope and submarine-fan sequence is evident in seismic data, where clinoforms can be traced basinward from the base of the deltaic sequence into slope and fan deposits. The sand-rich submarine fans of the Winters Formation are similar in character to the modern suprafan-dominated types of Normark (1978) and many ancient sand-rich submarine-fan deposits.

The Winters Formation submarine fans were fed by a series of gully/submarine-canyon systems along which sediment was transported from the shelf to the basin floor. Coarser grained sediment was deposited at the base of the slope within inner-fan channels; the majority of the remaining coarse-grained sediment was spread out on the basin floor to form a partly channelized middle-fan sequence, equivalent to the topographic bulges on modern fans referred to by Normark (1970) as suprafans. The submarine-canyon systems transported sediment from the north, northeast, and east and fed a number of coalescing sand-rich fans which generally trend northeast-southwest. Different episodes of submarine-fan deposition are separated by relatively continuous shale breaks probably caused by sea-level highstands.

The Winters Formation crops out in the southern Coast Ranges between Putah Creek and the Fairfield area (Figures 2, 5, 6, 7). It was mapped as an undifferentiated Upper Cretaceous unit of upper E-zone age (Emerson and Roberts, 1962; Sonneman and Switzer, 1962; Sims and others, 1971) that conformably overlies the Pleasant Valley Shale. This unit consists of thin, distal Facies C and D turbidites of the outer-fan or basin-plain facies associated in the north and channelized middle-fan facies to the south.

SUMMARY AND CONCLUSIONS

Upper cretaceous strata of western Solano County were deposited in a large forearc basin. The basin deepened southward and was bordered on the east and north by granitic and metamorphic highland source areas of the northern Sierra Nevada and Klamath Mountains, respectively. The principal, Santonian to Maestrichtian, coarse-grained depositional systems, in ascending stratigraphic order, appear to have been the following:

1.

A Santonian submarine-fan complex consisting of the Guinda Formation, deposited in the deeper parts of the Sacramento basin. The fan complex was deposited conformably on the basin-plain shale facies association of the Funks Formation and is overlain by the basin-plain facies association of the Dobbins Shale Member of the Forbes Formation. The submarine-fan deposits of the Guinda Formation have sedimentary and stratigraphic features characteristic of sand-rich and mixed-sediment

types of fans at different localities. The Guinda Formation pinches out southward between the bounding shale units in norther Solano County.

2.

A lower Campanian southward-prograding delta, slope, and fan complex consisting of the Kione Formation, upper member of the Forbes Formation, and the middle member of the Forbes Formation, respectively. This complex was deposited on underlying basin-plain deposits of the upper Santonian Dobbins Shale Member of the Forbes Formation and is overlain by shallow-marine, slope, and basin-plain deposits of the middle Campanian Sacramento Shale.

3.

A complex upper Campanian and lower Maestrichtian system of submarine-fan, submarine-canyon, and deltaic deposits that prograded southwestward into the central and southern parts of the Sacramento basin. This system includes submarine-fan deposits of the Lathrop, Winters, Tracy, and Blewett Formations, which were fed by various deltaic units of the Starkey Formation. The entire sequence was derived from erosion of the Sierran magmatic arc to the east of the basin. Various shale units provide the means to correlate between the fans and deltas and to subdivide the system into mappable facies associations.

4.

An upper Maestrichtian to lower Paleocene deltaic complex consisting of the Mokelumne River Formation and its stratigraphic equivalent in the northern San Joaquin basin, the Garzas Formation. This deltaic complex prograded westward across the entire southern Sacramento basin, recording the filling of the Great Valley forearc basin, which by this time had existed for about 100 m.y., to sea level. The deltaic complex does not crop out in western Solano County, although it is widespread in the subsurface.

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INTRODUCTION

The Franciscan Complex of the California Coast Ranges is an assemblage of variably deformed and metamorphosed rock units that formed as a subduction complex associated with east-dipping subduction at the western North American plate margin from the late Jurassic through the Tertiary, a period of over 140 million years (e.g. Hamilton 1969; Page 1981). Franciscan lithologies are predominantly detrital sedimentary rocks with subordinate basaltic volcanic rocks and chert, and minor limestone. The Franciscan is well-known for the occurrence of high P/T metamorphic rocks (Ernst, 1970; 1971). The Coast Range ophiolite structurally overlies the Franciscan and is depositionally overlain by well-bedded sandstones and shales of the Great Valley sequence that are coeval with the Franciscan (e.g. Dickinson 1970). The Coast Range ophiolite and Great Valley sequence lack high P/T metamorphism. From west to east, the three sub-parallel geologic provinces of the Franciscan, Great Valley sequence and Sierra Nevada batholith (see Fig. 1) may represent respectively the subduction complex, forearc basin deposits and arc of an ancient arc-trench system (e.g. Dickinson 1970; Ingersoll 1978).

Much has been written about the regional tectonics of the Franciscan Complex. This short paper will not attempt to present a review of Franciscan tectonics (for a recent paper on this subject see Wakabayashi (in press)) but will instead focus on field characteristics of Franciscan rocks. A regional overview of Franciscan field relations is presented first, followed by a discussion of distinguishing field characteristics of Franciscan rocks and, finally, a brief summary of Franciscan field relations in northern Sonoma County.

THE FRANCISCAN COMPLEX: REGIONAL OVERVIEW

Within the Franciscan Complex are numerous fault-bounded units, each with distinctive lithology, age, metamorphism and structure, that have been termed 'tectonostratigraphic terranes' (e. g. Blake et al. 1982). Names of units discussed in this paper follow Franciscan terrane nomenclature of Blake et al. (1982) except where previously unnamed. The Franciscan can be divided into four regions (fig. 1) that differ in structural and lithologic character: (1) the northern Coast Ranges; (2) the region between the San Andreas and Hayward/Healdsburg-Rodgers Creek faults; (3) the Diablo Range and (4) the Nacimiento block (Sur terrane of McWilliams and Howell 1982).

(1) Northern Coast Ranges: In this region, the Franciscan has traditionally been subdivided into three northwest-southeast trending lithologic belts: the Eastern, Central and Coastal Belts (Berkland et al. 1972). Easternmost and structurally highest, the blueschist grade Eastern Belt consists of thrust sheets of metaclastic and metavolcanic rocks, with fine-grained metamorphic minerals generally less than 0.2 mm in size (Worrall 1981; Blake et al. 1988). The belt has been divided into the structurally highest and highest metamorphic grade Pickett Peak terrane, schistose rocks commonly with complete textural reconstitution, and the structurally lower Yolla Bolly terrane, unfoliated to foliated rocks with variable preservation of protolith textures (Blake et al. 1982). The Yolla Bolly terrane also includes a subunit of shale matrix melange (Worrall 1981; Jayko and Blake 1989). Yolla Bolly terrane metaclastic rocks have yielded Tithonian to Cenomanian fossils (Blake et al. 1988). Eastern Belt and similar rocks are referred to as 'regional metamorphic rocks' in this paper. Among coherent (non-melange) Franciscan rock units, only the regional metamorphic rocks exhibit penetrative fabrics, with the exception of local weakly-developed foliation in some sandstones.

The Central Belt lies west of and structurally below the Eastern Belt and contains a large proportion of shale matrix melange that includes blocks of varying lithologies and metamorphic grades (Hsü 1968; Gucwa 1974; Cloos 1982; Blake et al. 1988). The boundary between the Eastern and Central belts is somewhat ill-defined and Seiders (1991) has mapped conglomerate units that strike across the previously-defined boundary without apparent offset. The Central Belt includes units of largely coherent internal structure ranging up to tens of kilometers in size. Detrital rocks of these coherent units have yielded fossils ranging from Tithonian to Campanian in age (Blake et al. 1984; 1988). Franciscan melange matrix displays a strong shear fabric and most Franciscan melanges, including those present in the Eastern and Coastal Belts, appear to have functioned as shear zones during part of their history (e.g. Cloos 1982). Some Franciscan melanges may have originated as olistostromes that were subsequently subducted (e.g. Aalto 1984 and Murphy; Cowan 1985; MacPherson et al. 1990). Most coherent units within the Central Belt are of prehnite-pumpellyite grade (Blake et al. 1984; 1988).

The Coastal Belt (including the Yager terrane of Underwood and Bachman 1985), the westernmost of these three Franciscan belts, structurally underlies the Central Belt (Bachman 1978; Blake et al. 1988). The Coastal Belt is composed of variably deformed sandstone and shale, including melange units, with minor basalt, limestone and chert, and is of mostly zeolite grade (Bachman 1978; Blake et al. 1988). Excluding pelagic rocks, the Coastal Belt contains fossils ranging in age from Paleocene to Miocene (Blake et al. 1988).

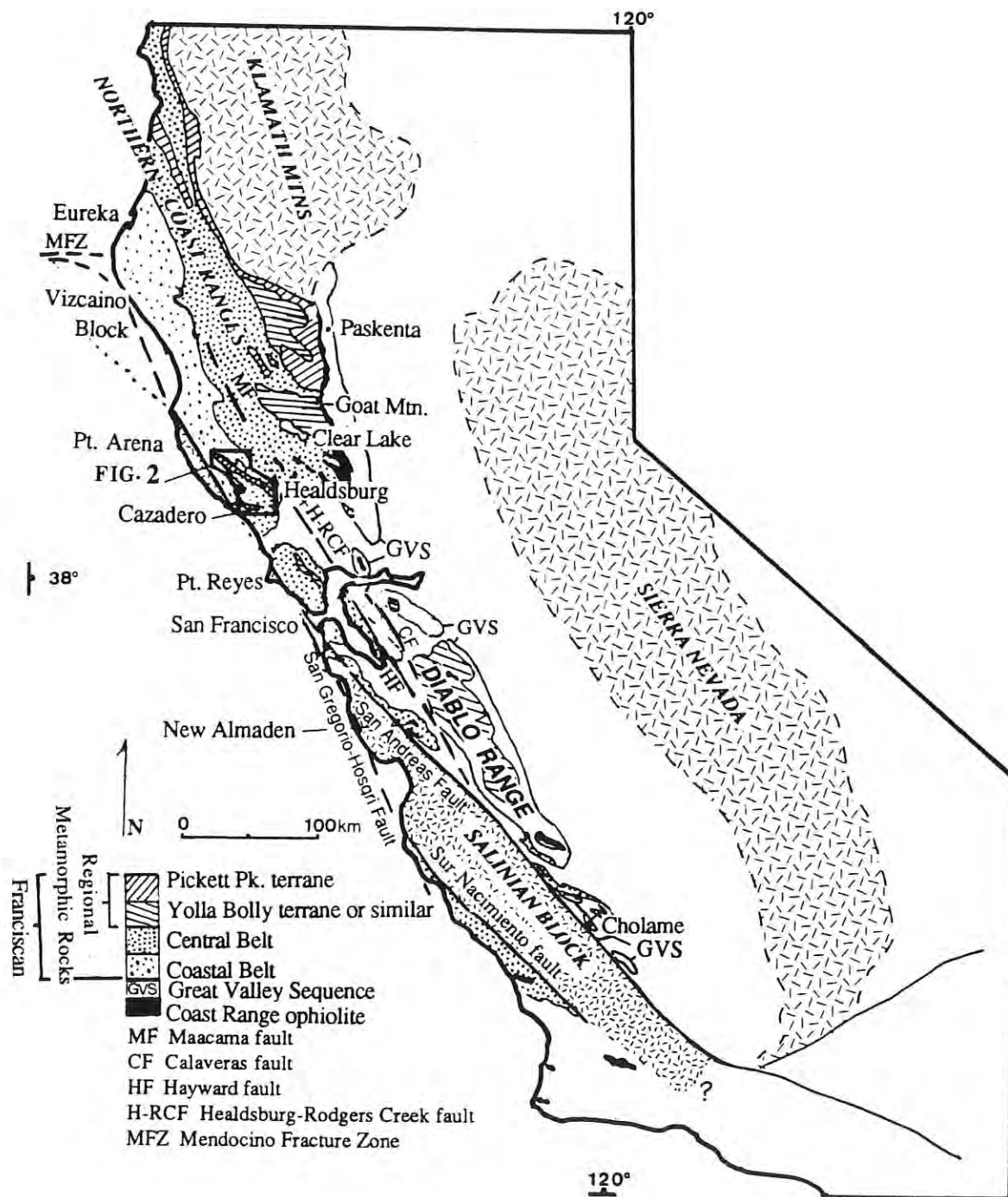


Figure 1: Distribution of Franciscan rocks in California. Adapted from Wakabayashi (in press).

(2) The region bounded roughly by the San Andreas, Hayward, and Healdsburg-Rodgers Creek faults, herein called the San Francisco block: In this region, the Franciscan comprises a stack of nappes composed of coherent terranes of varying lithology and metamorphic grade, separated by low-angle melange zones (Blake et al. 1984; Wakabayashi in press). Melange is subordinate to coherent units in much of this area. With the exception of locally severe deformation near the San Andreas fault (Page 1981), this domain may be the least affected by Neogene deformation of any region in the Coast Ranges (Herd 1978; Fox 1983), and as such provides a good field area to examine Franciscan field relations that may have resulted from subduction. The nappes of this region have been gently folded about NW-SE subhorizontal axes. Erosion has produced the present-day map pattern of belt-like rock units with their long axes oriented parallel to these fold axes. This region includes most Franciscan exposures in Sonoma County.

(3) Diablo Range: In the Diablo Range, slabs of metagreywacke, mostly of blueschist grade, are separated by melange zones that commonly contain high-grade blocks (Raymond 1973; Cotton 1972; Cowan 1974; Crawford 1975; Page 1981; Blake et al. 1984). Some of the coherent slabs (the Eylar Mtn. terrane) have been correlated with the Yolla Bolly terrane of the Eastern Belt of the northern Coast Ranges (Blake et al. 1982), although these slabs exhibit more widespread crystallization of jadeitic pyroxene. South of the Diablo Range and east of the San Andreas fault, the Franciscan crops out in limited exposures consisting mainly of melange that locally contains high-grade blocks and serpentinite. The Diablo Range domain is bounded on the west by the San Andreas and Hayward faults. West of the San Andreas fault is the Salinian block, a 700 km x 70 km allochthonous slice of continental crust with granitic and high T/P metamorphic basement.

(4) Nacimiento Block or Sur terrane: West of the Salinian block across the Sur-Nacimiento fault zone is a belt of Franciscan exposures composed primarily of melange (e.g. Hsü 1968; Page 1981; the Sur terrane of McWilliams and Howell 1982).

DISTINGUISHING FIELD CHARACTERISTICS

How can Franciscan Complex rocks be readily distinguished in outcrop from other rock units? The ease of outcrop identification of Franciscan rocks depends on the type of Franciscan rock. The most easily identified Franciscan rocks are the metamorphic rocks. 'Metamorphic' is defined here as rocks that are of blueschist grade or higher. Such rocks generally possess some type of metamorphic fabric. Lower grade rocks in the Franciscan almost never have a planar fabric and metamorphic minerals so fine-grained and/or poorly developed that the rock appears 'unmetamorphosed' in a hand specimen. By the preceding definition no non-Franciscan rock units in the northern Coast Ranges are metamorphic. Franciscan 'high-grade' tectonic blocks or "knockers", the most eye-catching of Franciscan metamorphic rocks, occur as blocks (generally tens of meters in size or less) in the shale or serpentinite matrix melanges of the Franciscan (As a cautionary note it should be noted that high-grade blocks have also been found as olistostrome blocks in the basal Great Valley sequence (Phipps 1984a, Carlson 1983)). These blocks exhibit gneissose or schistose textures with metamorphic minerals such as amphibole, omphacite, garnet and white mica up to 1 cm or more in size. These blocks include amphibolites, eclogites and coarse grained blueschists. At some localities the crystallization order of amphibolite to eclogite to blueschist can be observed in the form of cross-cutting or overprinting assemblages (Moore and Blake 1989, Oh and Liou 1990, Wakabayashi 1990). Because of their physical attractiveness and variety of sometimes unusual mineral assemblages the high-grade blocks have attracted a disproportionate amount of attention from geologists, considering they represent much less than 1% of the Franciscan. Franciscan regional metamorphic rocks are present as relatively intact continuous units (thrust sheets as opposed to tectonic blocks in melange) and make up much greater proportion of the Franciscan than the high-grade blocks. In contrast to the high-grade blocks, metamorphic minerals in the regional metamorphic rocks range seldom exceeds 0.2 mm in grain size and are often not even obvious under inspection with a hand lens. Although these rocks have been referred to as 'coherent blueschists' by several authors (including this one), most of these rocks lack obvious blue amphibole in hand specimen and most are not schistose. As noted earlier, Franciscan regional metamorphic rocks have been divided into two types: rocks that are mostly schistose, the Pickett Peak terrane (Blake et al. 1982) and rocks with preserved protolith textures, the Yolla Bolly terrane (Blake et al. 1982). Most of the Yolla Bolly terrane rocks are metagreywackes. Pickett Peak terrane rocks consist both of fine-grained quartz mica schist and lawsonite, pumpellyite or epidote-bearing blueschists.

In Sonoma County there are correlatives to both types of regional metamorphic rocks. Rocks similar to Yolla Bolly terrane rocks are present as greenstones with incipient growth of blueschist minerals (usually much too fine to be recognized in hand specimen). These rocks hardly appear 'metamorphic' and cannot be readily distinguished from prehnite pumpellyite grade Franciscan greenstones or basalts of the Coast Range ophiolite. Somewhat more obvious regional metamorphic rocks are present in the form of schists near Cazadero (the famous Ward Creek locality of Coleman and Lee 1963; see also Maruyama and Liou 1988) comprising a relatively continuous 4 x 17 km exposure

(Coleman and Lee 1963; Erickson 1991) and a 70 x 3 km belt of schist (Wakabayashi in press) that trends northwest from the vicinity of Healdsburg (fig. 2). These rocks have collectively been called the Skaggs Springs schist (Wakabayashi in press). These metamorphic rocks have been correlated to the Pickett Peak terrane (Blake et al. 1984) but are somewhat coarser grained, with metamorphic minerals up to 1 mm in size. The rocks of the long schist belt are mostly quartz-rich schists probably derived from sandstones with visible blades of glaucophane, white mica and tablets of lawsonite. Rocks of the Cazadero consist of both quartz rich schists and metabasaltic rocks that contain large proportions of blue amphibole.

Most of the Franciscan is made up of sandstone or shale varying from sequences with well-preserved bedding to block-in-matrix fabrics of melanges. Sandstones and shales of the Franciscan can be distinguished from their Great Valley sequence counterparts if the outcrop consists of melange, broken formation or similar amounts of major stratal disruption (Although it should also be noted that the Great Valley sequence includes a basal olistostromal unit (Phipps 1984a)). This description applies to much of Franciscan low-grade clastic rocks. However, there are Franciscan units that are comparatively little deformed and maintain good stratal continuity. Such units must be distinguished on the basis on supplemental information such as age or metamorphism (as noted petrographically)...

Having accomplished the task of identifying which exposures are Franciscan and which are not, a question may well be asked: How does one map structures in a terrane that includes a large proportion of melange? Because of the lack of stratal continuity the location of faults and the identification of folds can be very difficult. However, research in the Franciscan has revealed that there are some structural/stratigraphic markers that one can use to make sense out of apparent chaos.

Following the introduction of the melange concept to the Franciscan (Hsü 1968) it became popular to characterize much of the Franciscan as melange and assume that this region had little structural coherence (a view expressed verbally by many field geologists, but not necessarily explicitly stated in the published literature, with the possible exception of works by Cloos (e.g. 1982)). Within the past decade or so the terrane concept (e.g. Blake et al. 1982, 1984, 1988) has been used to identify a number of distinctive rock units with fairly unique characteristics within the Franciscan. Blake et al. (1984) related the Franciscan terranes of the San Francisco Bay region to a stack of nappes hypothesized to have formed during subduction/accretion. Wakabayashi (in press) extended the nappe concept and suggested that all Franciscan terranes including melanges correspond to a discrete structural horizons that are related to the original geometry in the accretionary wedge. As such Franciscan terranes themselves can be used as regional-scale structural markers. John Maxwell and his graduate students at the University of Texas at Austin (Maxwell 1974; Gucwa 1975; Jordan 1978; Kleist 1974), identified distinct melanges that represented different structural/stratigraphic horizons. Seiders (1991) proposed an innovative method of discerning regional scale structure in the Franciscan through use of conglomerate horizons. When mapped these conglomerate horizons define a pattern suggestive of a sequentially accreted stack of thrust sheets that has since been refolded (Seiders 1991, fig. 2).

A significant amount of deformation has taken place in Franciscan and much younger rocks during the Neogene. In addition to the easily-recognized strike-slip faulting thrust faulting is common (e.g. Suppe 1978; Phipps 1984b, Phipps et al. 1991; Aydin and Page 1984). The Neogene compressional tectonics (that accomodate the component of compression normal to the San Andreas dextral strike-slip system) has formed fold and thrust systems (Suppe 1978; Phipps 1984b; Phipps et al. 1991) that can be difficult to distinguish from earlier structures in Franciscan units. Given the widespread fold and thrust structures in Neogene rocks the question may well be asked: is it possible to identify earlier (subduction age) structures at all? Structures such as foliations and lineations can be related to subduction age events because of the growth of blueschist metamorphic minerals associated with them (although because of the fine grain size in regional metamorphic rocks, this cannot generally be seen in hand specimen). Age determination of folding and faulting is much more difficult however. This is due in part to the general lack of overlapping and/or intrusive relationships in the Franciscan. This problem is especially acute in distinguishing between subduction-related nappe structures and Cenozoic thrust systems. The only evidence bearing on this problem is somewhat circumstantial and involves paleontologic and/or isotopic metamorphic age determination of the units involved. If the units in a nappe stack display decreasing 'accretionary' age with structural depth (upside-down age progression), then it is likely that the nappe stack formed during subduction accretion by sequential offscraping or underplating. For such a sequence to form in the Neogene would require too much of a coincidence. 'Accretionary age' however itself is subject to interpretation. Generally this emplacement age can be approximated by the youngest clastic rocks in each thrust packet (when the unit in question was near the trench immediately before offscraping or underplating) or in the case of regional metamorphic rocks, the isotopic metamorphic age (approximating the time of deep underplating or underthrusting during subduction/accretion (for a discussion of accretionary age constraints see Wakabayashi (in press)). Accretionary age nappe stacks have been recognized as a characteristic of the Franciscan (Wakabayashi in press), but are more apparent in regions that have largely escaped

HEALDSBURG-CAZADERO AREA GEOLOGY

Franciscan rock units:
 Tfc: Coastal Belt: variably deformed sandstone and shale; prehnite pumpellyite grade and lower
 Kfr: Rio Nido terrane: variably deformed sandstone and shale; prehnite pumpellyite grade and lower, shown in light stipple

Non-Franciscan rock units:
 KJfu: shale matrix melange; shown in dense stipple
 KJfg: greenstone; lacks fabric; incipient blueschist metamorphism
 KJms: Skaggs Springs schist; fine-grained blue amphibole-bearing schist.
 KJmv: blueschist grade metabasals of the Ward Creek area.
 sp: serpentinite

Sequence:
 KJogv: Coast Range ophiolite and/or Great Valley Sequence.

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severe Neogene deformation.

THE FRANCISCAN IN NORTHERN SONOMA COUNTY

As noted earlier, much of the Franciscan of Sonoma County is part of a large domain of Franciscan (between the San Andreas and Healdsburg-Rodgers Creek strike-slip faults) that has been affected less by Neogene deformation than most other regions in the Franciscan (Herd 1978, Fox 1983). Figure 2 is a map and cross section of Franciscan and related rocks in northern Sonoma County (for other maps of the area see Blake et al. 1971, Gealey 1951). The regional low-angle nature of the contacts can be inferred on the basis of the sinuous trace of the contacts and repeated units in map view. Bedding and foliation attitudes define NW-SE trending subhorizontal fold axes. Erosion of these folds produced a series of subparallel belt-like rock units that characterize the Franciscan of this region. Based on cross-cutting relationships, different generations of low-angle faults are present, some of which may post-date the accretion of the units (see fig. 2, one of these younger faults is marked with "2" as an example on the cross section). The younger faults may be similar to Cenozoic thrusts identified by Suppe (1978), Phipps (1983; 1984a,b) and Phipps et al. (1991) elsewhere in the northern Coast Ranges. If the younger faults are removed, the older low-angle fault contacts (several of them marked with "1" as examples on fig. 2 cross section) of the Cazadero region appear to form an accretionary age nappe stack, 5 km thick (excluding the thickness of the Coastal Belt), with larger nappe sheet dimensions of 45 km across and 70 km along strike. Some interesting features of the nappe stack are: (1) The Skaggs Springs schist forms the structurally highest Franciscan horizon. (2) Most high grade blocks are found either in narrow shear zones cutting the Skaggs Springs schist or in melanges structurally above and adjacent to the upper Coastal Belt tectonic contact. (3) Most of the melange in the region constitutes a single, discrete structural horizon (KJfu in fig. 2). Probable nappe emplacement ages decrease structurally downward, with the following sequence: (1) Skaggs Springs schist: ~145 Ma based on metamorphic age (Wakabayashi and Deino 1989); (2) Greenstone with incipient blueschist metamorphism of uncertain age; (3) Melange of uncertain age; (4) The Rio Nido terrane: 90 Ma based on Turonian fossils (Blake et al. 1984); (5) The (structurally highest part of the) Coastal Belt: <60 Ma based on fossils in detrital rocks (Blake et al. 1988).

As previously noted previously, this area contains a distinctive unit of regional metamorphic rocks, the Skaggs Springs schist. Excellent exposures of this unit are found along the Skaggs Springs road a little over five miles west of the intersection with Rockpile road. One of the striking characteristics of these rocks is the strong stretching lineation expressed as parallel quartz-rich streaks and parallel alignment of glaucophane blades. Another interesting field relationship associated with these rocks are the occurrence of high-grade blocks associated with narrow (less than 50 m wide) shear zones that cut the foliation of the schist. The matrix of these shear zones appears to be serpentinite or ultramafic schist (tremolite and/or chlorite-bearing).

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**STRATIGRAPHY AND STRUCTURE
OF THE SOUTHERN SONOMA VOLCANIC FIELD,
SONOMA COUNTY, CALIFORNIA**

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ABSTRACT

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

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

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

INTRODUCTION

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

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

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

STUDY AREA

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

A 32 km² area of the southern Sonoma volcanic field in the Coast Ranges of Sonoma County was selected for detailed study (Figure 1). The study area includes part of the Sears Point and Petaluma River 7.5' quadrangles.

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

VOLCANIC ROCK UNIT NOMENCLATURE

Earlier workers mapped all of the volcanics exposed in the region northeast of San Francisco Bay as belonging to the Sonoma group, and they considered these volcanics to be younger than the Petaluma Formation (Osmont, 1905; Dickerson, 1922). Subsequently, Morse and Bailey (1935) discovered a thick sequence of volcanics overlain by Petaluma sediments in a well core and named them the Tolay Volcanics. Although Morse and Bailey (1935) mapped outcrops occurring west of Tolay Creek as Tolay Volcanics, Weaver (1949) kept the earlier designation of Sonoma Volcanics for all volcanics in the area, and described the Tolay Volcanics as "subsurface volcanics". This usage was continued by other workers until Mankinen (1972) demonstrated that volcanics in the Burdell Mountain area are much older than those to the northeast and designated the older rocks as Tolay Volcanics. Fox et al. (1985) followed this precedent and, on the basis of age differences which appeared to coincide with the southern Rodgers Creek fault trace, assigned older volcanics outcropping west of the fault to the Tolay Volcanics. The volcanics outcropping between the Rodgers Creek and Tolay faults were redesignated as the Donnell Ranch Volcanics by Youngman (1989) because of age differences distinguishing them from the Tolay Volcanics of Fox et al. (1985) that occur west of the Tolay fault. In addition, a different name was warranted because these volcanics do not meet the stratigraphic criteria for the Tolay Volcanics established by Fox et al. (1985), and they probably have a different source or a different mode of emplacement than the Tolay Volcanics west of the Tolay fault (Youngman, 1989). Volcanic rocks outcropping east of the Rodgers Creek fault were mapped as Sonoma Volcanics by Youngman (1989). Although distinguishing between the Sonoma and Donnell Ranch Volcanics in the field is difficult, the Sonoma Volcanics are generally younger than the Donnell Ranch Volcanics. The two units differ geochemically, as well (Youngman, 1989).

TOLAY VOLCANICS

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

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

DONNELL RANCH VOLCANICS

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

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

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

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

PETALUMA FORMATION

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

The Petaluma Formation in the study area outcrops west of the Rodgers Creek fault. The sediments are predominantly clays and clay shales with subordinate

amounts of sand, sandstone, and conglomerate. The shales occasionally contain ostracods. Limestone beds and lenses occur locally. Exposures of this unit are poor, and soil characteristics (e.g., color, clay content, clast composition) were thus relied upon in mapping much of the Petaluma Formation (Youngman, 1989).

In the study area, sands and conglomerates of the Petaluma Formation were observed west of Wildcat Mountain as well as just west of the contact between the Petaluma and the volcanics in the northernmost map region. Continuous sandstone beds are rare; this facies usually occurs as lenses within the clays and clay shales. Conglomerates are the least abundant of the clastic sediments in the study area. Like the sandstone facies, the conglomerates occur mostly as lenses within the Petaluma clays and clay shales, and are often poorly-consolidated. Clasts, often well-rounded, are generally 2 to 5 cm in diameter but may be as large as 12 cm. They vary in lithology and include siliceous shale, red chert, graywacke sandstone, and occasional blueschist; lithics of mafic volcanics are locally abundant.

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

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

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

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

SONOMA VOLCANICS

The Sonoma Volcanics consist of a highly complex group of lava flows and flow breccias, agglomerates, tuffs and tuff breccias, and tuffaceous continental sediments. The name was taken from the Sonoma Mountains where exposures of this unit are abundant. The name "Sonoma volcanics" was first published by Morse and

Bailey (1935), and has been retained by subsequent workers (e.g., Weaver, 1949; Cardwell, 1958; Cebull, 1958; Fox, 1983; Davies, 1986).

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

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

Comparison with the Donnell Ranch Volcanics

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

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

STRUCTURE AND TECTONICS

The Coast Ranges in the San Francisco Bay region are characterized by complex folding and faulting. West of San Francisco Bay lies the San Andreas fault, which is believed to mark the boundary between the North American and Pacific plates. Major right-lateral strike-slip faults in this area associated

with the San Andreas fault system include the Hayward, Calaveras, Franklin, and Concord faults east of San Francisco Bay, and the Rodgers Creek, Healdsburg, Bennett Valley, and Maacama faults north of San Pablo Bay. The Tolay reverse fault is located west of the Rodgers Creek fault. Late Cenozoic deposits throughout this region have been intensely folded, producing numerous synclines and anticlines.

FOLDS

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

Folds in and near the study area include the Adobe Creek, Donnell Ranch, Lee Lake, and Sears Point anticlines and the Tolay Creek syncline (Figure 3). Weaver (1949) named the structure in the northwesternmost portion of the study area the Adobe Creek anticline, and Davies (1986) determined that the axis of the this anticline generally strikes N45W, although it is often offset by faulting. The eastern limb was observed to dip from 43° to 46° NE (Youngman, 1989). The Donnell Ranch anticline has an axial strike which bends from nearly east-west near Highway 121 to approximately N45W just east of Wildcat Mountain. The crest of the Donnell Ranch anticline near Wildcat Mountain is indicated by several horizontal beds, and alternating beds of tuffs, flows, and flow breccias in the eastern limb were observed to dip between 24° and 54° NE (Youngman, 1989). A small anticline located east of the Rodgers Creek fault and north-northeast of Lee Lake in the northern study area is named the Lee Lake anticline (Youngman, 1989). The axis of this structure strikes approximately N20W, and the western limb appears to dip at slightly greater angles than the eastern limb. The Sears Point anticline is located just south of the study area. Weaver (1949) determined that the axis of this structure plunges to the southeast, south of Sears Point, and undulates in its northwest extension. West of the Adobe Creek anticline, and extending beyond the study area, is the Tolay Creek syncline of Weaver (1949). He stated that numerous small faults and folds, largely obscured by soil, complicate this structure. In the study area, the Tolay Creek syncline may extend southward into the window of Petaluma sediments just west of Wildcat Mountain (Youngman, 1989).

FAULTS

Numerous faults are present in and near the study area. The right-lateral strike-slip Rodgers Creek fault, locally trending N35-40W, is the major fault structure in the study area. To the southwest, the Tolay reverse fault roughly parallels the southern Rodgers Creek fault for a short distance; however, the northern trace of the Tolay fault diverges slightly westward (Huffman and Armstrong, 1980). In addition, several previously unrecognized thrust faults and normal faults were mapped by Youngman (1989).

Strike-Slip and Normal Faults

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

margin.

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

The Rodgers Creek fault trends approximately N40-45W in the southern study area. Near Gravelly Lake and to the north-northwest, this fault diverges and forms two separate strands trending N30-35W and N40-45W. Since the trace of the Rodgers Creek fault is fairly linear and cuts uneven topography, it probably has a nearly vertical dip. Within the study area, it generally separates the Sonoma Volcanics to the east from the Petaluma Formation and Donnell Ranch Volcanics to the west (Youngman, 1989).

A previously unrecognized normal fault, the Roche-Cardoza fault, occurs between the Rodgers Creek and Tolay faults in the southern study area (Youngman, 1989) (Figure 3). The southern trace of this N65-70W-trending fault joins the Rodgers Creek fault at a prominent bend or asperity in the latter. To the northwest, the Roche-Cardoza fault appears to join the Tolay fault, and may be a high-angle branch or strike-slip splay of the Tolay fault. The linear trace of the Roche-Cardoza fault cuts uneven topography and it is thus probably a high-angle fault. The south side of this fault appears to have been displaced relatively downward. Complexly folded and faulted interbedded clay shale and limestone beds are abruptly terminated in a gully at the contact between the sediments and the volcanics along the fault. The Roche-Cardoza fault truncates the Wildcat Mountain thrust fault, discussed below, in several locations and the Roche-Cardoza normal fault is thus younger than the Wildcat Mountain thrust fault.

Just north of the Roche-Cardoza fault trace is another linear, apparently high-angle fault which trends N60W (Youngman, 1989) and is probably a splay of the Roche-Cardoza fault. The southwest side appears to be displaced relatively downward.

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

West of the Rodgers Creek fault in the southwest study area, the westernmost contact of the Wildcat Mountain thrust fault appears to be offset in two places by the Goose Lake fault (Youngman, 1989). This right-lateral tear fault, trending N20E, may best explain the southern offset along the trace of the thrust fault (Figure 3). In addition, the Goose Lake fault separates rocks with markedly different attitudes in the Petaluma Formation. Another tear fault is present northwest of the Goose Lake fault. In this region, an abrupt change in direction of the Wildcat Mountain thrust fault occurs. A tear fault, trending N55-60E, may account for the offset and change in direction of the Wildcat Mountain thrust fault in this region (Youngman, 1989).

Two additional faults occur east of the Rodgers Creek fault (Youngman, 1989). The Stefansky fault is located southeast of Goose Lake and trends N20-25E (Figure 3). The Stefansky fault separates a bed of dacitic tuff to the northwest from bedded mafic flows, tuffs, and flow breccias to the southeast and is probably nearly vertical. The second fault, the Yenni fault, is located east-northeast of the Stefansky fault (Youngman, 1989). This structure trends approximately N15E, and has displaced beds of mafic flows, tuffs, and breccias right-laterally (Figure 3).

Thrust Faults

Detailed field mapping in the southern Sonoma volcanic field has led to the recognition of several previously unrecognized thrust faults (Youngman, 1989). These faults display sinuous map patterns, generally have shallow dips, and commonly have structurally juxtaposed older units over younger units. Complex

outcrop patterns in places, including klippen and windows, have resulted from the erosion of these thrust sheets. Most of these faults are interpreted as flower structures that were thrust up and out of the Rodgers Creek fault deformation zone. Although the faults are termed thrust faults in this section, most are regarded as low-angle segments of the Rodgers Creek strike-slip fault.

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

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

STRUCTURAL REINTERPRETATION

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

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

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

These tectonic contacts were misinterpreted by earlier workers. Weaver

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

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

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Figure 1. Location map of study area.

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

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

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

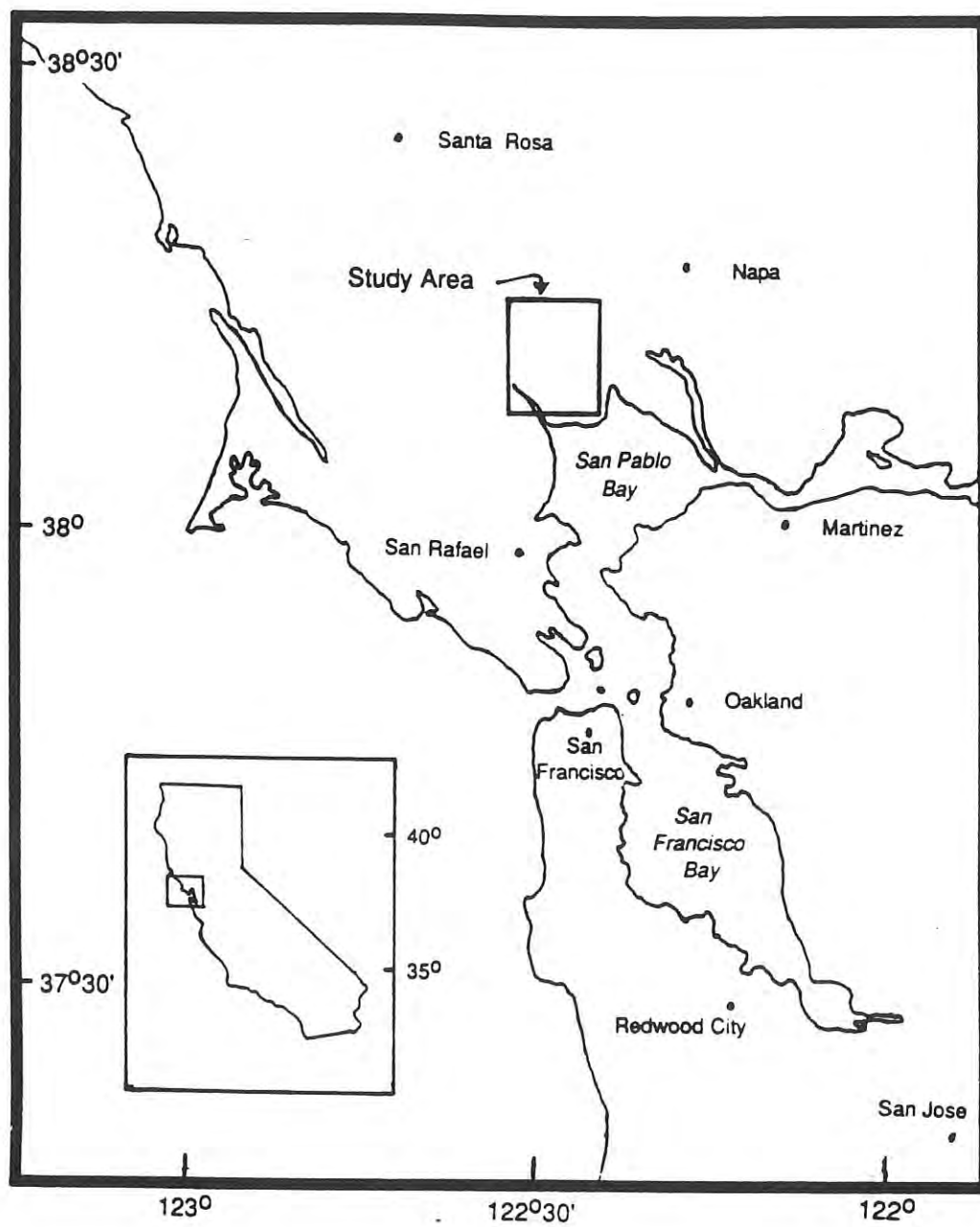


FIGURE 1

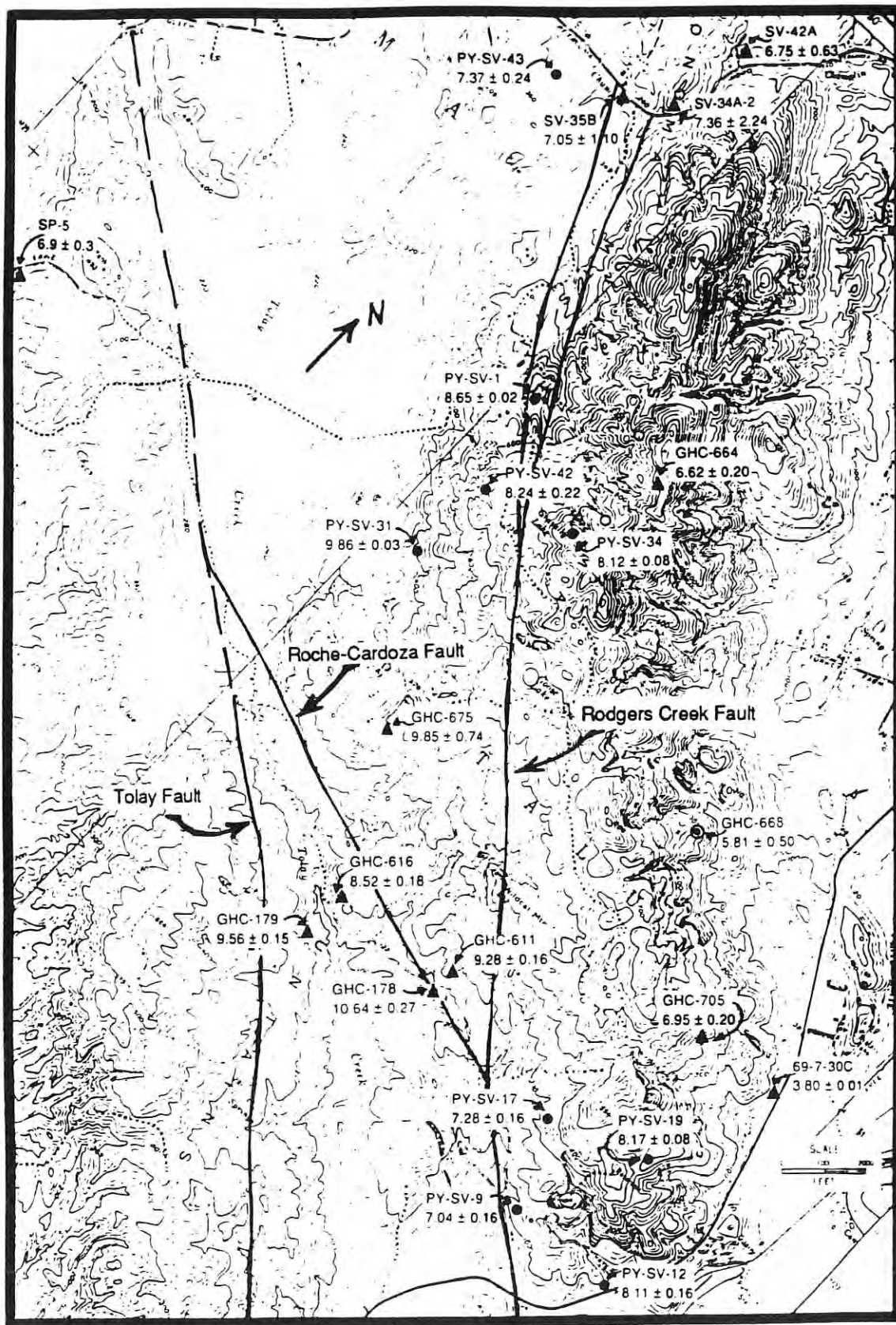


FIGURE 2



FIGURE 3

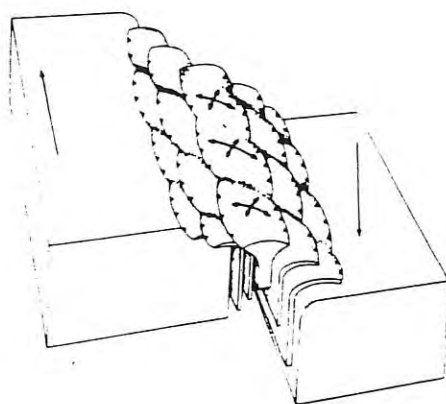


FIGURE 4

LANDSLIDING IN SKY VALLEY, SOLANO COUNTY, CALIFORNIA

E. C. Winterhalder*
James M. Joyce**

ABSTRACT

Sky Valley is the site of widespread landsliding in moderate to steep terrain underlain by strongly folded sedimentary rocks of Cretaceous through Eocene age. Mapping of surface features and subsurface exploration in portions of Sky Valley reveal a wide range of landslide types and depths of debris. Notable are very large, deep-seated translational landslides which are common in dip slopes along the west side of the valley. Regional geologic mapping (Sims et al., 1973) indicates a north trending asymmetric syncline coincident with the east slopes of Sky Valley. Low angle dips in Cretaceous marine mudstones on the west limb of the syncline appear to be responsible for landslides ranging up to approximately 1/2 mile in larger dimension. Smaller wedge-type or rotational slumps occur on both limbs. Steep slopes on the east limb along the east side of Sky Valley are the site of shallow debris flow type landslides.

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INTRODUCTION

Sky Valley is in southwestern Solano County east of Vallejo and north of Benicia. It is drained by the southward flowing Sulphur Springs Creek into Lake Herman and Suisun Bay. The extreme northward portion is currently being developed for residential and recreational usage. Similar developments are contemplated in other portions of the valley.

Previous geologic studies include those of Weaver (1949) and Sims et al. (1973). Weaver's work was stimulated to some degree by mercury deposits in the Sulphur Springs Mountain area west of the valley. Sims work was a part of geologic studies conducted by the U.S. Geological Survey throughout the San Francisco Bay Region. More recently the authors have conducted more intensive studies in Sky Valley including an approximate 2-mile-square area owned by PG&E. Figure 1 presents a simplified version of the mapping performed by the authors in those studies. The bedrock formations indicated are modified after Sims et al., 1973.

GEOLOGY

Bedrock Stratigraphy

As indicated on Figure 1, the study area within Sky Valley is underlain by four formations consisting, from oldest to youngest, of the Franciscan Formation (map symbol KJfs), an unnamed formation of Jurassic-Cretaceous age generally referred to as the Great Valley Sequence (KJgvm), the Eocene Domengine Sandstone Formation (Ted), and the Kreyenhagen Formation which is further divided into the Nortonville Shale member (Ten) and the Markley Sandstone member (Tem).

The Great Valley Sequence rocks consist predominantly of clay shales or mudstones together with much thinner beds of arkosic sandstone. Generally, the sandstone beds are 1 to 5 feet in thickness and are highly discontinuous along strike. The mudstone is thin bedded to massive and generally is closely fractured. Within the near surface weathered zone, the mudstone has been decomposed to plastic adobe type clays which are expansive and highly susceptible to landslide movement on steep slopes. As a consequence, the large areas underlain by the Great Valley Sequence mudstone are blanketed by a thick layer of surface soils or landslide debris. Natural exposures of the mudstone are rare and generally limited to recently eroded stream banks. The widely spaced interbedded sandstones also weather to sandy clays and are rarely exposed.

Because of the paucity of exposures of the Great Valley Sequence rocks, the structure of this formation and details of its stratigraphy are limited almost entirely to information that has been obtained through scattered backhoe pit exposures. The common lack of visible bedding in the massive mudstone also limits structural information.

The Domengine Sandstone Formation, as revealed in outcrops along the east ridge is predominantly coarse-grained sandstone that is commonly cross bedded and locally interbedded with clay shale. The sandstone crops out prominently in the steeper slopes east of Sky Valley where it forms numerous knolls and small north trending ridges. The overlying Kreyenhagen Formation consists of clay shales of the Nortonville Shale member and arkosic and micaceous sandstone of the Markley Sandstone member. The latter forms the higher north trending ridges east of Sky Valley.

Bedrock Structure

In the slopes west of Sulphur Springs Creek, observed bedding within the Great Valley Sequence rocks generally strikes north to northwest with dips towards the north and east. However, numerous backhoe pits encountered contorted bedding and local flexures indicated by dips to the south or west. East of Sulphur Springs Creek the dips steepen toward the east in the Great Valley Sequence rocks. Near the axis of the syncline dips within the Eocene rocks are steep to near vertical and may locally be overturned. However, some of the overturned bedding viewed in outcrop may be a result of slope creep. Local variations in strike and dip occur and apparently are the result of fault drag near a series of small offsetting tear faults. However, the predominant structure is a northwest trending syncline. Faulting appears limited to a series of northwest striking tear faults that offset the Eocene rocks as indicated and probably also extend westward into the Great Valley Sequence where they are unrecognizable through lack of marker beds.

LANDSLIDES

Landslide areas, as indicated on Figure 1, have been mapped on the basis of surface irregularities that typically result from slope movements plus the results of subsurface exploration using various combinations of test borings, backhoe excavated pits, and refractive type seismic velocity measurements. The arrows indicate the general direction of landslide movement.

The landslides consist primarily of three types:

1. Very large translational, possibly block glide type landslides, with slippage on bedding planes or bedding plane faults;
2. Smaller and generally shallower complex earthflows, wedge type failures, and locally deeper rotational slides;
3. Shallow debris flow slides.

Where subsurface exploration has been performed in the larger landslides, depths on the order of 50 feet, or somewhat more, have been revealed. A very large landslide located centrally within Section 3 of the east slopes of Sulphur Springs Mountain has not been explored and may possibly reach depths on the order of 100 feet. This particular landslide showed indications of renewed movement during or shortly following the intensive Presidents Day rainstorm in February 1986. That rainstorm also triggered numerous debris flow type landslides throughout the study area. Although this type landsliding occurs throughout the study area in steep slopes underlain by both the Cretaceous and Eocene rocks, sandy surface soils developed from weathering of the Eocene sandstones appear most susceptible to debris flows. Ravines flowing westward from those outcrops contain debris from such flows as indicated by large subangular boulders of weathered Eocene sandstone. This type debris was encountered in test pits some distance west of the mouths of those steeply inclined ravines indicating relatively high flow velocities with deposition of debris well beyond the source areas.

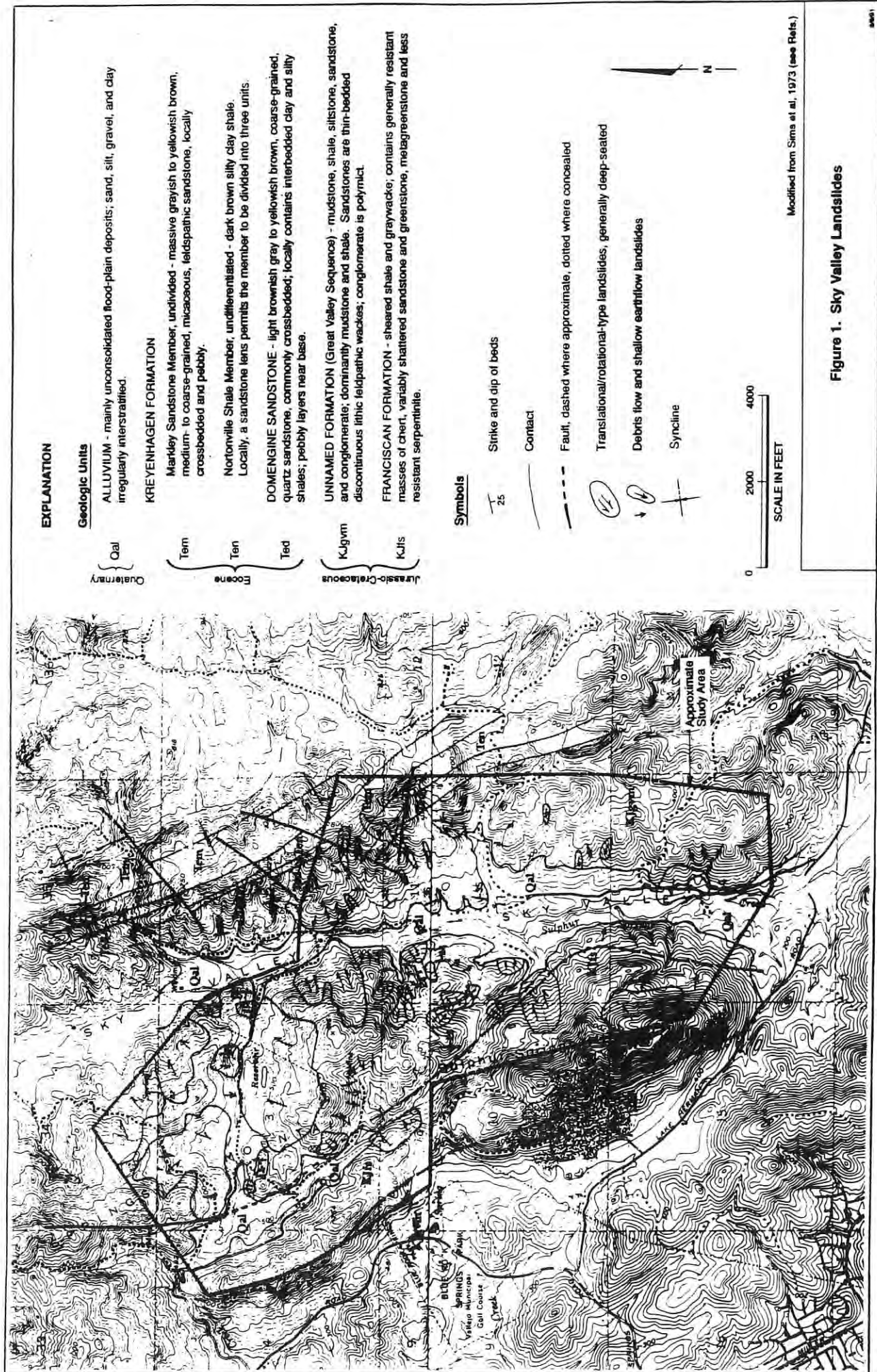
SUMMARY

A study of landslides in the Sky Valley area reveals some geologic control on the type, size, and location of landslides. Very large translational, possibly block glide type landslides in part, occur in areas of relatively flat north to east dips and involve mudstone of the Great Valley Sequence. Bedding plane faults, possibly related to thrust faulting during the activity on the Coast Range thrust belt, may also be present and may locally contribute to landsliding.

Localized adverse conditions resulting from various combinations of stratigraphy and structure have resulted in numerous but generally smaller rotational and wedge type failures but mostly involving the Great Valley Sequence rocks. Debris flow type landslides with indications of high velocity flows are also present and are more prevalent in the steeper slopes east of Sulphur Springs Creek underlain by Eocene sandstones.

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Modified from Sims et al., 1973 (see Refs.)

Figure 1. Sky Valley Landslides

4001

Sinclar Property

J. Preece

In the fall of 1989, Berlogar Geotechnical Consultants conducted a preliminary geologic investigation on the Sinclar Property located north of Benicia (Figure 1). The study was performed in order to characterize bedrock lithology and structure, investigate a fault trace mapped by Sims, et. al. (1973), and map the extent of surficial deposits including landslides, colluvium, and alluvium. The study included the excavation and logging of 210 test pits, 5 exploration trenches, as well as magnetometer and seismic refraction surveys. An evaluation of the location and activity of the fault appeared warranted, as the fault trace mapped by Sims (1973) splays off of the active Green Valley Fault,

Four bedrock units are present at the site:

1. The Markley Sandstone Member of the Kreyenhagen Formation (Eocene) which is characterized as a thinly to thickly bedded, moderately strong, micaceous sandstone, siltstone, and claystone unit with some highly sheared claystone beds;
2. The Nortonville Shale Member of the Kreyenhagen Formation (Eocene), which consists primarily of pervasively sheared, friable claystone;
3. The Domengine Sandstone Formation (Eocene), which is typically a fine-grained massive sandstone with strong characteristics except near its basal contact, where it locally becomes friable; and
4. The Jurassic/Cretaceous mudstone which Dibble (1980) maps as the Panoche Formation and Sims (1973) identifies as an unnamed unit.

In the northwest portion of the site, a northwest-trending syncline was mapped with gently dipping limbs. The fold appears to become tighter, with more steeply dipping limbs, to the south where the fold axis intersects a north-south trending fault (Figure 2). Where the syncline intersects the fault, beds of the Markley Sandstone are juxtaposed against the Domengine Sandstone.

The fault trace mapped by Sims (1973) could not be identified to the north of this location where it appeared to be entirely within the highly sheared Nortonville Shale. To the south, the fault was mapped as the contact between the Domengine Sandstone and the Nortonville Shale and appeared to be congruent with the axial plane of the syncline. Further south, vertical beds of Domengine Sandstone form prominent outcrops. At this location, it is suspected that the syncline is isoclinal and that the fault trace parallels the axial plane of the fold. It appears as though deformation caused by the folding and uplift of these bedrock units was absorbed along bedding-plane faults in the Nortonville Shale. Right-lateral, strike-slip transform movement of the San Andreas Fault system is exhibited by strain releases in the form of fault breaks that follow existing bedrock weaknesses such as bedding plane shear zones found primarily within the Nortonville Shale. Alternatively, the syncline may have locally become so tight from tectonic compression that deformation could no longer be absorbed along bedding plane faults and a break occurred across formational contacts as an oblique-slip fault.

Activity on the fault spay mapped by Sims (1973) could not be confirmed as Holocene in age since fault trenching could not be done where the fault crosses alluvial deposits. However, recommendations for setbacks were made on the basis that the fault splay exists on the site and that it is subparallel to and joins the active Green Valley Fault.

Numerous surficial and deep-seated landslides were mapped throughout the site. Deep-seated landslide features are common in the portion of the site underlain by the Nortonville Shale bedrock unit. The shale locally contains thin beds of weathered volcanic ash. Low rock strength, in part due to intense tectonic shearing, and the presence of ash beds contribute to the unit's susceptibility to slope failure. Some of the deep-seated landslides, covering as much as 30 acres, may not be economically feasible to stabilize.

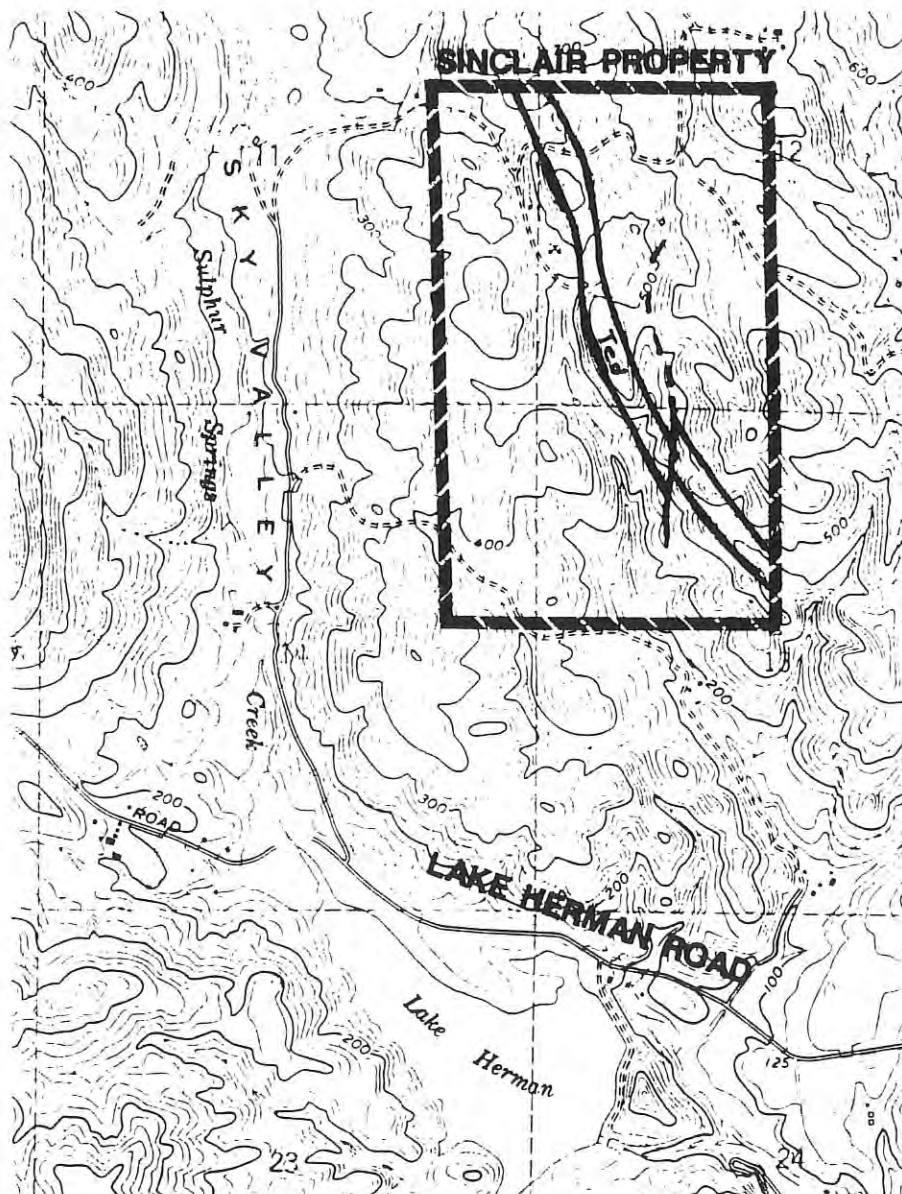


FIGURE 1

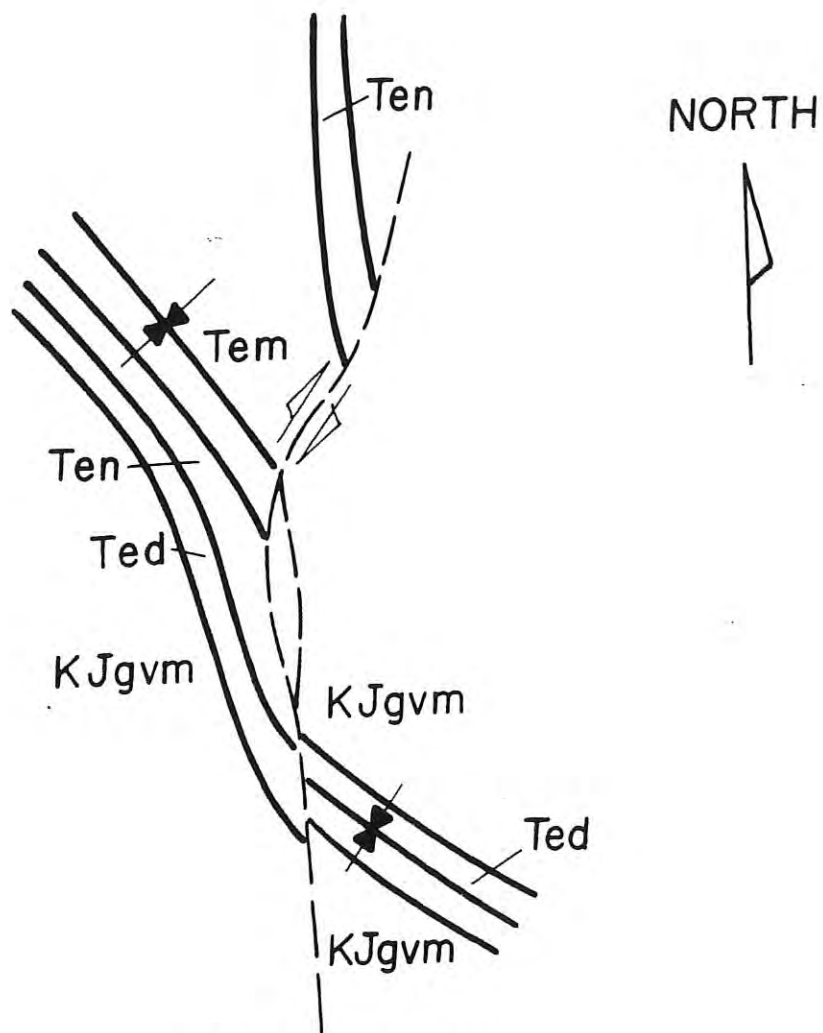


FIGURE 2

MERCURY IN SOLANO COUNTY, CALIFORNIA

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INTRODUCTION

Mercury, Hg, is the only liquid metal at ordinary temperature. Commonly, it is called quicksilver by the miner and in many geological reports. In scientific, financial and statistical reports the name mercury is preferred. Most of the mercury produced in California between 1850 and 1914 was used in the recovery of gold by amalgamation. After World War I mercury was used largely in the manufacture of chemicals and in scientific and industrial applications.

MINERALS

Over 20 minerals containing mercury are known throughout the world. Most of them are rare, however, and are not ordinarily found in producing mines in California. Cinnabar, mercury sulfide (HgS), is the principle ore mineral. Metacinnabar, the less stable form of mercury sulfide, and native mercury (Hg) occur in economic quantities in some mines. Other mercury minerals found in California mines are eglestonite (Hg₂Cl₂O), calomel (HgCl₂), montroydite (HgO), tiemannite (HgSe) and coloradoite (HgTe).

Cinnabar is recognized by its red color, red streak, high specific gravity (8.1) and adamantine luster. Metacinnabar is black and produces a black streak. Native mercury, a silver colored liquid, fills vugs in some California mines. Pyrite (FeS₂) and sometimes marcasite (FeS₂) are generally present in small quantities, and stibnite (Sb₂S₃) is found in some mines. The principle gangue minerals are: quartz, opal, chalcedony, magnesite, dolomite and calcite. Liquid or solid hydrocarbons are present in very small quantities in some deposits, and gold has been noted microscopically.

GEOLOGIC OCCURENCE

Mercury deposits are largely confined to regions of Tertiary and Quaternary volcanic activity. The deposits are classed as epithermal, being formed by the deposition of ore minerals from alkaline aqueous solutions at relatively low temperatures and shallow depth.

Slightly over 50 percent of the larger mercury deposits in California occur in serpentine which has been hydrothermally altered to silica-carbonate rock. This alteration product is composed chiefly of quartz, opal, chalcedony and various magnesium and calcium carbonates. It is frequently iron-stained owing to alteration of pyritic minerals to iron oxides. Although silica-carbonate rock is more widespread than the mercury mineralization, it can be used as a guide to prospecting.

ORE BODIES

Mercury ore bodies are irregular in size and shape and are erratically distributed. They contain cinnabar and metacinnabar that fill fractures, voids, the interstices of porous or brecciated rocks, or have replaced the host rock. Many ore bodies were formed by the concentration of primary minerals in porous rocks capped by relatively impervious rocks. Other bodies are the result of the replacement of silica-carbonate rock. Still others were formed at or near the surface by hot springs. At some mines bodies of disseminated ore occur.

The extraction of mercury from ore is basically a distillation process. Heating the ore in air oxidizes the sulfur and frees the mercury as a vapor which condenses on cooling.

LOCALITIES

The most productive mercury mines in California lie in a belt extending through the Coast Ranges from central Lake County southward through Santa Barbara County. This belt contains many of the Nation's principal mercury producers dominated by the great New Almaden Mine (Santa Clara County) with a production record of over one million flasks, and the New Idria Mine (San Benito County) which yielded over half a million flasks. A flask is the commercial unit of mercury transactions and consists of 76 pounds of mercury. It is packaged in a metal container.

SOLANO COUNTY

Geology

The following quote on the geology of the mercury mines and prospects on Sulphur Springs Mountain is taken from Weaver, 1949, (California Division of Mines Bulletin 149, p. 98).

"Sulphur Springs Mountain is a horst-like fault block composed principally of serpentine and silica-carbonate rock and extensively intruded by andesite which has been highly altered. The block trends N20°W and is in fault contact on the northwest and southeast with shales and sandstones of the Knoxville group. These sediments, which are apparently later than the serpentine, also occur within the block as slivers bounded by faults of relatively small displacement. An older series of fault zones which intersect the folded shales, the silica-carbonate rock, and the andesite dikes has resulted in shear planes and breccia zones, some of which served as channels for mineralizing solutions. The Knoxville shale, wherever it is in contact with silica-carbonate rock, is silicified and brecciated. Ore is found in fault zones between silica-carbonate rock and the Knoxville shales, as disseminations in Knoxville sandstone or altered andesite near fissures, and replacing the carbonates of shattered andesite bodies. The ore bodies are bounded, often on the hanging wall, by clay seams or gouge."

"The ore bodies commonly occur as stockworks within areas of complex faulting and are composed of irregular masses of brecciated rock cemented with cinnabar and gangue. The deposits are characteristically associated with silica-carbonate rock, an

alteration product of serpentine, and, in the Sulphur Springs Mountain area, with the Knoxville sandstone and shale which are in contact with silica-carbonate rock."

Mines (Davis and Bailey, 1966)

St. John. Mercury was produced at the St. John mine in the Sulphur Springs Mountain area beginning in 1855. This mine, located in the NE 1/4 of section 33, T4N, R3W, MD, produced 10,530 flasks by 1870 when low mercury prices forced closure. The mine produced intermittently between 1899 and 1908, and during World War I (1914 - 1918). A small production was made from reworked tailings in 1936 and some exploration was done during World War II (1941 - 1945). Total production is estimated at 20,000 flasks.

Hastings. This mine is located in the SW 1/4 of section 11, T3N, R3W, MD, and produced a small but unrecorded quantity of mercury. It was discovered in the 1870's and operated on a small scale at that time, and again in 1904-1905 and in 1917. In 1929 a new adit encountered a large quantity of water. The adit was closed and sealed in 1930.

Brownlie. This mine in the SE 1/4 of section 10, T3N, R3W, MD, produced a small quantity of mercury from shallow cuts and short adits beginning in 1870. Some prospecting was done during World War II.

White House (Napa County). During the 1960's, silica-carbonate rock containing ore was found and mercury was produced. This mine is located approximately in the NW 1/4 of section 33, T4N, R3W, MD. The ore was treated in a rotary furnace.

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Weaver, C.F., 1949, Geology and mineral resources of an area north of San Francisco Bay: Calif. Div. Mines, Bull. 149, p. 98-101.

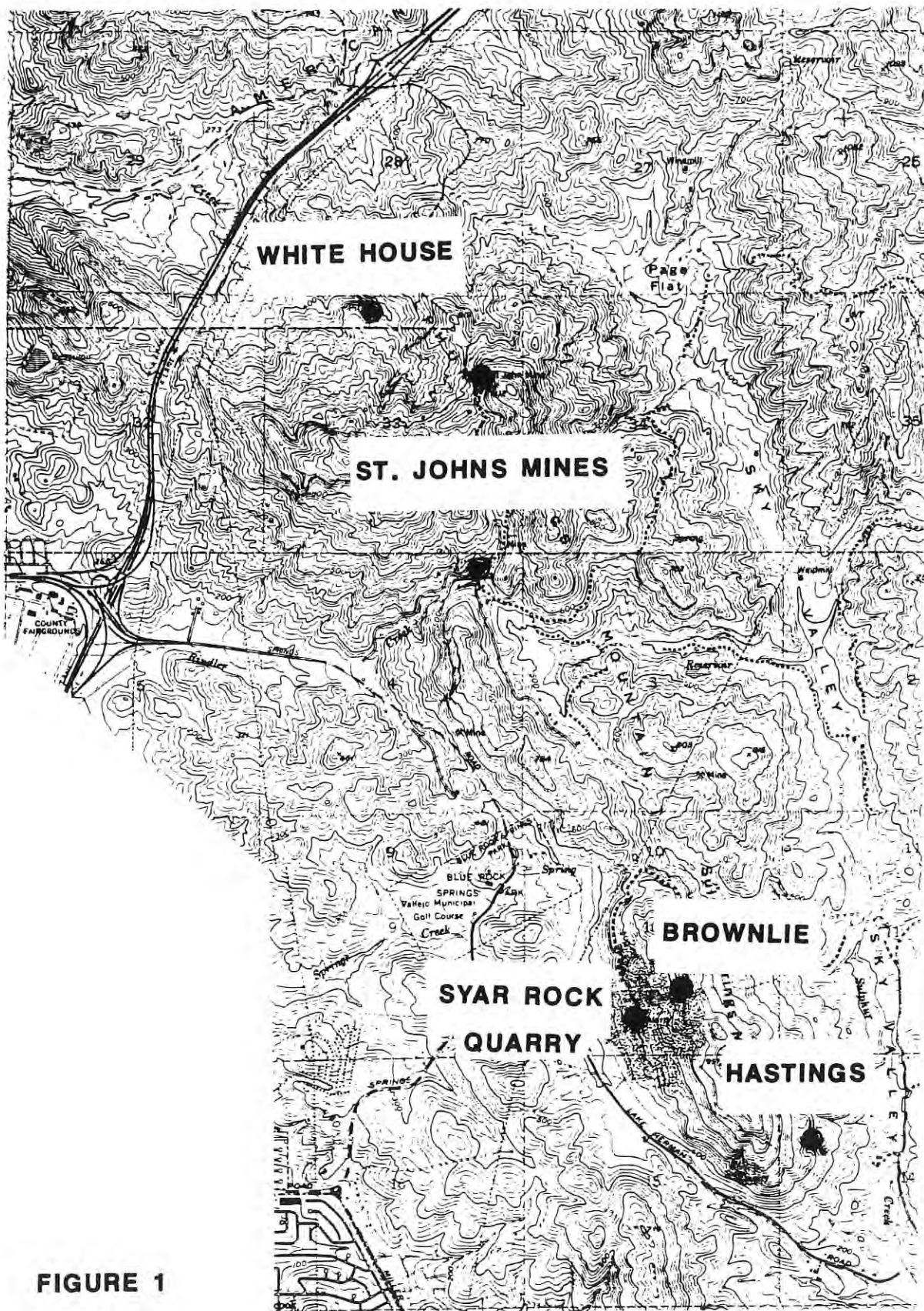


FIGURE 1

MERCURY MINES IN SOLANO COUNTY