United States Department of the Interior

Geological Survey

Preliminary structure contour map of the Sacramento Valley, California showing major Late Cenozoic structural features and depth to basement

by

David S. Harwood
and
Edward J. Helley

Open-File Report
82-737

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

EXPLANATION

• Well used to contour top of Cretaceous rocks

621 □ Well to basement showing depth below sea level in meters; basement lithologic symbols:, △ granite, granodiorite; □, gabbro, norite, diorite; ■, serpentine, serpentinite; ▲, gneiss metavolcanic rocks, greenstone; ○, unspecified basement rocks.

>1542 ⊙ Deep well not to basement, depth below sea level to bottom of well in meters; used as minimum limit to basement in contouring

−300 Structure contour drawn on top of Cretaceous rocks; elevation of datum in meters above (+) or below (-) mean sea level; contour interval 150 m.

−750 Structure contour drawn on top of basement; elevations in meters, contour interval 150 m.

D/U Fault; no documented Late Cenozoic movement; D, downthrown side; U, upthrown side

D/U Fault with documented Late Cenozoic movement, dashed where approximately located, queried where uncertain; D, downthrown side; U upthrown side

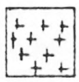
Thrust fault; teeth on upper plate

Axial trace of fold

syncline

anticline

Distribution of Lovejoy Basalt



Distribution of granitic plutons in Sierran basement

Lithologic Units

Tc	Capay Formation
Kmu	Cretaceous marine rocks, undivided
Jk	Jurassic Knoxville Formation
MzPzb	Mesozoic and Paleozoic basement rocks, undivided

Introduction

The Oroville earthquake (M 5.6, August 1, 1975) added a new dimension to geologic studies of the Sacramento Valley. For nearly a half century prior to that event, most geologic investigations focused on locating natural gas in the deeper part of the valley fill and water resources in the near-surface deposits. This work produced a wealth of structural and stratigraphic data and several regional geologic syntheses that were primarily designed to facilitate exploration for these valuable resources (Bryan, 1923; Safonov 1968; Olmsted and Davis, 1961; Redwine, 1972; Calif. Dept. of Water Resources, 1978). Regional paleogeographic and paleotectonic syntheses by Dickinson (1979) and Ingersoll (1978) interpreted the Sacramento Valley as a forearc basin and modeled its relationship to the Franciscan accretionary complex to the west and the Sierran magmatic arc complex to the east. The scope of these paleotectonic studies was too large, however, for a detailed analysis of the relatively small-scale structural features within the Valley. It took the Oroville earthquake, to awaken the geologic and engineering communities to the potential of active faulting in the Valley and Sierran foothills and that event prompted this study and several others directed toward understanding the Late Cenozoic structural history of the region (Harwood and others, 1981; Helley and others, 1981; Woodward Clyde Consultants, 1977).

The structural contour map presented here integrates subsurface data from many reports published by the California Division of Oil and Gas with our analysis of electric logs in several critical areas. Interpretation of the subsurface data was influenced, to a large degree, by new surficial mapping in the Valley by Helley (unpublished data) and by exceptionally high quality seismic reflection profiles obtained by Seisdata Services Inc. The objectives of this report are to provide an integrated picture of the structural features of the Sacramento Valley, as we now perceive them, to update information on the buried basement terranes beneath the Valley, and to focus attention on the fact that most of the folds and faults in the Valley either formed in the Late Cenozoic or are older structures that have experienced renewed movement in the past few million years.

Structure contouring procedures and philosophies

The eastern part of the structure contour map shows 150 m contours drawn on top of the metamorphic and plutonic basement rocks as defined primarily by the operator that drilled the well. Data on depth to basement and, rarely, a statement on the nature of the basement rocks are filed by the operator with the California Division of Oil and Gas. Through the years these data have been compiled and published in various formats by May and Hewitt (1948), Smith (1964), California Division of Oil and Gas (1964), and Williams and Curtis (1977). A number of discrepancies exist in the published data for specific wells and, in the few cases where disparate data significantly affected the trend of the structure contours, the depth to basement was determined from original well logs; otherwise published data were used. The published data were gathered before 1964. Well logs for a few deep wells drilled since 1964 were checked if their published location and depth (Munger, 1981), relative to already contoured data, indicated that they might reach basement.

To contour basement data, the distance between adjacent wells in a line approximately normal to the trend of the Valley was divided into segments equal to the contour interval and contour lines were drawn between fixed and interpolated points. Contours were drawn first by progressing north to south and then the contours were adjusted in a second iteration progressing south to north in an effort to minimize deflections in the contours. This contouring procedure reflects our bias that the basement surface was one of low relief with minor topographic anomalies prior to deposition of the Mesozoic Great Valley Sequence. Despite this interpretive bias, it was impossible to contour depth to basement data in some areas without deflecting the contours, particularly in the vicinity of Sutter Buttes.

In the western and northern parts of the Valley where few wells reach basement rocks, structure contours are drawn on top of the Cretaceous rocks. Throughout the area of the map, Cretaceous rocks are unconformably overlain by a variety of younger deposits ranging in age from Paleocene in the southwest, to Eocene in the midsection, to Pliocene in the northern part of the Valley. Choosing the top of the Cretaceous section as a datum obviously obscures our ability to differentiate Early and Late Tertiary deformation to some extent, but the top of the Cretaceous rocks is the only universal datum that can be readily identified throughout the Valley. Several dated horizons, such as the Miocene Lovejoy Basalt and the base of the Pliocene Tuscan and Tehama Formations have aided our interpretation of late Cenozoic deformation where those units can be unequivocally identified in the well records. Because the younger units rest unconformably on top of the Cretaceous rocks, some variation in elevation of the top of the Cretaceous section is due to post-Cretaceous erosion and not necessarily to late Cenozoic deformation. The amount of error introduced in our structural interpretation by this circumstance of nature varies from place to place and it appears to be greatest in the central part of the Valley near Sutter Buttes where the Eocene Princeton submarine channel was localized by pre-Capay Formation movement on the Willows fault (Redwine, 1972).

Control points for structure contours on top of the Cretaceous rocks around the margin of the Valley from Oroville to the Dunnigan Hills come from

published 1:250,000 scale geologic maps with some modification from our field work.

Interpretation of basement contours

A significant deflection in basement contours exists beneath Sutter Buttes. This anomaly in basement topography was shown first by Smith (1964) and mentioned briefly by Williams and Curtis (1977, p.6), who noted more than 395 m (1300 ft) of local relief on the basement surface but offered no interpretation of the anomaly. It seems likely that most, if not all, of the upwelling of the basement surface is related to volcanic intrusion in Sutter Buttes, but we suggest further that some of the basement uplift may be related to east-side-up movement on the Willows fault.

Data from deep wells north of Sutter Buttes indicate a major deflection in the basement surface that could reflect a northeast-trending fold or fault, or both. All of these possible structural configurations were investigated and we conclude that the structure in the area is a northeast-trending fold faulted along its southeast limb. The fault is interpreted to be a steeply dipping to vertical normal fault with southeast-side-down displacement. Both the fold and fault appear to die out to the northeast.

Southeast of Sutter Buttes variations in the slope of the basement surface are shown by northeast-trending zones of relatively close-spaced and broadly-spaced contours. The basement surface may dip eastward locally in those areas marked by broadly spaced contours (see Jacobson, 1981), but well data are too sparse to locate closed contours in this area if, in fact, they exist at the chosen contour interval.

From Sacramento south to the Stockton fault, the slope of the basement steepens significantly west of the -1500 m contour. This change in basement slope lies near the eastern edge of the Great Valley positive gravity and magnetic anomalies that Cady (1975) interpreted to represent ophiolitic oceanic crust tectonically juxtaposed against Sierran basement rocks to the east. Two wells south of Sacramento, however, report granite and "gneiss" at 1954 m and 2861 m, respectively, suggesting that the interpreted suture between oceanic and Sierran basements is not marked by the topographic break in the basement surface at the -1500 m contour. The topographic break at the -1500 m contour appears to be controlled in part at least by the extension of the Willows fault southeast of Sutter Buttes.

From Sutter Buttes north to Chico, a number of wells penetrate basement rocks reported as diorite, gabbro, noritic gabbro, and serpentine. Not surprisingly, this part of the Sacramento Valley is characterized by large positive gravity and magnetic anomalies (Cady, 1975) marking the northern part of the inferred Great Valley ophiolitic basement. Some thin sections of gabbro and diorite from wells in this area, contained in a collection of thin sections of basement rocks held by the California Academy of Sciences, reveal remarkably fresh coarse- and medium-grained clinopyroxene-plagioclase rocks that show pronounced cumulate textures. These textures, previously unrecognized, provide supporting evidence for the interpretation of the source rocks of the Great Valley anomaly as oceanic crust.

South and east of Sutter Buttes several wells penetrate rocks reported as granite, granodiorite, metavolcanic rocks, and "gneiss" typical of rocks exposed in the Sierran foothillls. The outline of granitic plutonic rocks, shown on the map, was determined from reported basement rocks augmented by our interpretation of residual isostatic gravity data (Roberts and others, 1981). The boundary between the Sierran basement and mafic and ultramafic rocks of probable oceanic basement trends about N45°E from Sutter Buttes to Oroville and it is clearly marked by significant changes in the gravity and magnetic patterns of the respective areas. The basement contours do not reflect this inferred lithologic change and the northeast-trending fault north of Sutter Buttes is contained within the mafic-ultramafic basement terrane.

Sierran crystalline rocks are exposed in several deep canyons cut through the Pliocene volcanic rocks of the Tuscan Formation east of Chico (Harwood and others, 1981). The mafic-ultramafic basement appears to abut against Sierran basement rocks along a major basement fault beneath the Chico monocline. This tectonic juxtapositioning of basement terranes was proposed first by Griscom (1973) and the basement fault he proposed from geophysical data is confirmed by stratigraphic data. The basement fault beneath the Chico monocline shows east-side-up displacement with a minimum stratigraphic throw of 367 m (1200 ft) on the basement surface.

Structural features in the Valley fill

Structure contours drawn on top of the Cretaceous rocks outline a large number of diversely oriented folds and faults distributed throughout the Valley. Some of these structures, such as the Corning domes, the Chico monocline, and the Dunnigan Hills anticline, have topographic expression and were recognized in the early geomorphic studies of the Valley by Kirk Bryan (1923). Most of the other structures do not have obvious surface expression and they were discovered during exploration and development of the numerous small gas fields in the Valley. Although detailed reports have been published for many of the gas fields, few reports have synthesized data from these studies into detailed structural analyses of the Valley as a whole. Noteworthy exceptions to this generalization exist, however, and include the early stratigraphic and structural synthesis by Safonov (1968), the detailed study of the Princeton submarine channel system by Redwine (1972), and the continuing efforts of Charles Jennings and the staff of the California Division of Mines and Geology to compile available data from the Valley into small-scale maps of the entire state (Jennings, 1977).

The extent of many of the faults, particularly the complex pattern of the Willows fault and the relationship between that fault system and many folds in the northern Valley, have not been reported previously. Analyses of well logs, which are the basis for most reports of individual gas fields, commonly do not provide sufficient data to interpret unequivocally the structure of the area. If recognizable stratigraphic units in the well logs are at different elevations in adjacent wells, it is generally impossible to determine if the units are offset by folding or faulting, or both, without additional data from surface exposures or seismic reflection profiles. Our interpretation of the structural relationships in the Valley is based on data from well logs augmented by detailed mapping of the surficial deposits by Helley and a brief, but exceedingly valuable, glimpse at seismic reflection profiles run by Seisdata Services Inc.

Willows Fault System

The main stem of the Willows fault was discovered in the subsurface rocks of the northern Valley when it was penetrated by the Marathon Oil Company (formerly Ohio Oil Company)"Capital Company" No. 1 well during development of the Willows-Beehive Bend gas field in the late 1950's (Calif. Div. Oil and Gas, 1960; Alkire, 1962; 1968). From the discovery well, Redwine (1972) traced the Willows fault southeast to Sutter Buttes and he suggested that it extended northwest of the discovery well possibly connecting with the surface fault mapped west of the Orland Buttes (Anderson and Russell, 1939; Jennings and Strand, 1960). Redwine (1972) documented displacement on this 40 km (25 mi) segment of the main stem of the fault and concluded that it dipped 74° or steeper to the east and showed reverse, east-side-up movement that decreased upward in the geologic section. He found that the Princeton submarine channel was localized, in part, by movement on the fault and that vertical separation in the discovery well varied from about 488 m (1610 ft) on top of the Cretaceous rocks to about 477 M (1575 ft) on the top of the Eocene Capay Formation. At Orland Buttes, the Willows fault offsets the Miocene Lovejoy Basalt and the Pliocene Tehama Formation.

Data from a number of sources indicate that the Willows fault is far more extensive and complex than previously thought. The first clue that the Willows fault branched into a multi-strand fault system was provided by an analysis of seismicity of the northern Valley and Sierran foothills after the Oroville earthquake. Marks and Lindh (1978) located a number of small-magnitude earthquakes that originated near the discovery well in the Willows-Beehive Bend gas field and extended north for a distance of about 30 km (20 mi) rather than following the known, northwest trend of the Willows fault. The trend of seismic events suggested that a north-trending fault splayed off from the main stem of the Willows fault and passed west of the Corning domes. Analysis of well records in the Corning gas fields by the Sacramento Petroleum Association (1962), however, did not identify a fault west of the Corning domes, but that study did show an anticlinal fold in the area with about 121 m (400 ft) of maximum closure on the base of the Tehama Formation in the north dome and a steeply dipping southeast-trending fault located at the north end of south Corning dome.

Recent seismic reflection profiles in the area have identified a major north-trending, steeply east-dipping reverse fault that passes west of the Corning domes and the Greenwood anticline. Displacement of reflecting horizons increases with depth on this north-trending fault indicating progressive deformation through time similar to the pattern of deformation on the main stem of the Willows fault in the Willows-Beehive Bend gas field. From well-log data, the pattern of earthquakes shown by Marks and Lindh (1978), surficial mapping, and the seismic reflection profiles, we conclude that the Corning domes and the Greenwood anticline formed by east-side-up drag on the north-trending Corning fault which splays off from the main stem of the Willows fault. The location of this north-trending splay fault north of Red Bluff is unknown, if, in fact, it extends north of the Red Bluff fault.

The youngest deposits deformed by the Corning fault are gravels of the Pleistocene Red Bluff Formation, the age of which has been bracketed by overlying and underlying volcanic rocks radiometrically dated at 0.45 and 1.09 m.y., respectively (Harwood and others, 1981).

The location of the Willows fault system north and northwest of Orland Buttes is not closely controlled by direct evidence in either the surface or subsurface rocks. Wells are sparse in this area of the Valley, particularly wells located west of the probable trace of the main stem of the Willows fault, and, for that reason, the structure contours are very generalized and of little value in locating even major structures. Several pieces of evidence, however, point to a pattern of deformation in northwestern Tehama County that is remarkably similar to deformation associated with the Corning fault and the main stem of the Willows fault to the south and east.

First, the north northwest-trending fault, shown as the Malton fault east of Orland Buttes and extending at least 32 km (20 mi) northward toward Red Bank, was crossed by two seismic lines run by Seisdata Services, Inc. Their profiles show a steeply east-dipping fault with east-side-up displacement that increases with depth. The broad anticlinal dome identified by Redwine (1972, section AA') southeast of Red Bank lies east of the Malton fault and appears to bear the same genetic relationship to that fault as the Corning domes bear to the Corning fault.

The base of the Tehama Formation occurs at an elevation of -17 m (55 ft) in the McCulloch Oil Corporation "McCulloch Sunray Anchordogry" no. 1 well (sec. 7 T25N R4W) east of the Malton Fault and at -297 m (980 ft) in the Occident Petroleum Corporation "Harris" no. 1 well (sec. 23 T26N R5W) west of the fault. This difference in elevation on the base of the Tehama is due to the combined effects of doming east of and offset on the Malton fault. Relatively extensive deposits of Red Bluff gravels cap the interfluves east of the Malton fault, but only a few scattered patches of Red Bluff gravel occur west of the fault. The western limit of the extensive Red Bluff deposits is generally aligned along the Malton fault trace suggesting that the Red Bluff was stripped from the area west of the Malton fault either by deformation on that fault or by uplift on the Willows fault to the west. The northern extent of the Malton fault is not known.

Our projection of the Willows fault into the Cold Fork and Elder Creek faults, and possibly into the Paskenta fault mapped by Jones and others (1969) is based primarily on the outcrop pattern of the Tehama Formation. North of Elder Creek, the Tehama Formation dips gently east and the Nomlaki Tuff Member is at the base of the Tehama or is, at most, a few tens of feet above the base of the Pliocene section. South of Elder Creek, however, the Tehama dips more steeply into the valley and the Nomlaki Tuff is a few hundred feet above the base of the Tehama. This outcrop pattern of the Tehama Formation suggests that the Great Valley Sequence was topographically higher and projected farther east into the Valley north of the Willows fault prior to deposition of the Pliocene rocks. The position of the Nomlaki Tuff relative to the base of the Tehama on opposite sides of the Willows fault indicates that the Tehama filled a topographic low southwest of the fault prior to eruption of the Nomlaki Tuff about 3.4 m.y. ago. We interpret the topographic low, reflected by the thicker basal part of the Tehama, to be the result of east-side-up movement on the Willows fault prior to and possibly during deposition of the early phases of the Tehama Formation. If this interpretation is correct, Late Cenozoic movement on the Willows-Elder Creek fault system has been significantly different, in style and amount of displacement, from the Cretaceous movement on the Elder Creek-Cold Fork-Paskenta fault system oulined by Jones and Irwin (1971).

Jones and Irwin (1971) inferred at least 96 km (60 miles) of left-lateral displacement of the Early Cretaceous (Valanginian) shoreline along the combined Cold Fork-Elder Creek-Paskenta faults. They concluded that this deformation commenced shortly after deposition of the Valanginian rocks and continued concurrently with deposition until at least mid Late Cretaceous time. Well documented vertical displacement of Late Cretaceous and younger rocks on the Willows fault in the Beehive-Bend gas field is not incompatible with left-lateral displacement on the Elder Creek fault system to the northwest, but it does indicate that the inferred lateral displacement was accompanied by a major component of east-side-up vertical movement. This vertical movement is consistent with the interpretation that the Elder Creek fault system represents tear faults in the upper plate of the Coast Range Thrust (Jones and Irwin, 1971) along which the Klamath Mountain terrane moved upward and westward over the Coast Range province.

Chico Monocline

The Chico monocline is a northwest-trending southwest facing flexure that bounds the northeast side of the Sacramento Valley between Chico and Red Bluff, California. East of the monocline, Pliocene volcanic rocks of the Tuscan Formation dip less than 5 degrees southwest, but bedding steepens to 20 degrees or more along the monoclinal flexure where the Tuscan dips beneath Quaternary deposits of the valley. The trace of the monocline is characterized by a complex surface pattern of anastomosing fault strands that show both valley-side-down and east-side-down displacements of small magnitude (Harwood and others, 1981).

The structure contours drawn on top of the Cretaceous rocks in the vicinity of the monocline indicate clearly that the Cretaceous strata are flexed and faulted by a major northwest-trending fault at depth beneath the surface trace of the monocline. By projecting the unconformity between the Cretaceous rocks and the basement from the Sierran foothills into the valley north of Chico, it is possible to demonstrate a minimum of 367 m (1200 ft) of displacement on the surface of the basement along the master fault beneath the Chico monocline. This fault appears to be a major tectonic boundary, with a long and complex tectonic history, along which the Sierran basement to the east was juxtaposed against highly magnetic, dense basement of ophiolitic composition to the west (Cady, 1975; Griscom, 1973). These basement terranes were tectonically juxtaposed prior to deposition of the Upper Cretaceous Chico Formation.

The Chico monocline, however, is a late Cenozoic tectonic feature. It formed after deposition of the Tuscan Formation, which began about 3.4 m.y. ago with the explosive eruption of the Nomlaki Tuff Member and prior to the eruption of the basalt of Deer Creek about 1.09 m.y. ago (Harwood and others, 1981). Late Cenozoic displacement on the Chico monocline fault has been predominently east-side-up with an apparent component of left-lateral movement that contributed to the formation of the Salt Creek, Tuscan Springs, and Sevenmile domes at the north end of the monocline and possibly influenced the northeast-trending Inks Creek folds system and Battle Creek fault zone further northwest.

There is some indication that the Chico monocline fault may be active. The basalt of Deer Creek is offset, but the amount of offset is small. Similarly, a few faults along the monocline show scarps about 1 m in height in the surface of the Tuscan Formation (Harwood and others, 1981). These observations indicate movement on the monocline fault system within the past million years. In their study of regional seismicity after the Oroville earthquake, Marks and Lindh (1978) identified two events that lay west of the Oroville aftershock zone and at a depth of 40 km, significantly below the main cluster of aftershocks associated with the Oroville earthquake. We interpret those deep events to have occurred on the basement fault beneath the Chico monocline and not on the Cleveland Hills fault where most of the aftershock events were located.

Battle Creek Fault Zone

The Battle Creek fault zone strikes east-northeast across the Sacramento Valley between Red Bluff and Redding, California. East of the Sacramento

River the Battle Creek fault zone is marked by a pronounced south-facing escarpment that extends from the river northeastward toward Lassen Peak for a distance of 32 km (20 mi). Fault strands within this part of the fault zone dip steeply southeast and show predominantly south-side-down, normal fault movement (see Harwood and others, 1980; Helley and others 1981). Vertical displacement on the fault zone increases from about 45 m (148 ft)just east of the Sacramento River to 330 m (1089 ft) at Black Butte, and to about 440 m (1452 ft) north of Manton, California. A small component of right-lateral strike slip movement is suggested by fractures on some of the fault strands, but the exact amount of lateral displacement is not known.

West of the Sacramento River, the valley of Cottonwood Creek is probably controlled by the Battle Creek fault system, but modern stream activity and agricultural practices obscure any young traces of the faults east of the South Fork of Cottonwood Creek. At South Fork Cottonwood Creek and along Red Bank Creek, Late Quaternary terraces show evidence of young faulting (see Helley and others, 1981). To the west-southwest, the faults in the terrace deposits merge into previously mapped faults in the Red Bluff and Tehama Formations and, on strike, they appear to merge with tear faults in the upper plate of the Coast Range Thrust.

Coarse volcanic fanglomerate, correlated here with the Red Bluff Formation by soil stratigraphy and geomorphic surface, is offset by the Battle Creek fault zone east of the Sacramento River and dates the major movement as younger that 1.09 m.y. B.P. The Rockland Pumice Tuff Breccia of Wilson (1961) (referred to as the ash of Mount Maidu by Helley and others, 1981) appears to have been channeled, in part, by the Battle Creek fault escarpment suggesting that some of the faulting, at least, occurred prior to 0.45 m.y. ago; the age of the Rockland Pumice Tuff Breccia (Meyer and others, 1980).

Inks Creek Fold System

A set of northeast-trending folds, referred to as the Inks Creek fold system by Helley and others (1981), deforms the rocks south of the Battle Creek fault zone and structurally controls the major loops in the Sacramento River at Jelly School and the nearby Table Mountain. The southwest plunging fold set is clearly shown by the structure contours drawn on top of the Cretaceous rocks and the major anticline in the fold set produces a closure of about 485 m (1600 ft) on top of the Cretaceous section. Axial traces of the folds change strike to the northeast and the trace of the anticline appears to merge with the Battle Creek fault system and die out eastward within the fault zone. This geometric relationship suggests a genetic relationship between the Battle Creek fault zone and the Inks Creek folds system.

If this interpretation is correct, evidence on the age of the Inks Creek fold system provides data on the age of movement on the Battle Creek fault zone. At Round Mountain, about 3 km southwest of Jelly School, the Rockland Pumice Tuff Breccia of Wilson (1961) rests unconformably on the eroded western edge of the Red Bluff Formation at an elevation of 160 m (528 ft). We assume that the ash was deposited in the ancestral channel of the Sacramento River, which apparently formed a large westward bend at that time extending from Bloody Island on the north to the vicinity of Bend on the south. Uplift and erosion of the Red Bluff had begun prior to deposition of the ash. In contrast to the occurrence of the ash at Round Mountain, alluvial deposits of the lower part of the Riverbank Formation are found at an elevation of 120 m (396 ft) in this region and they flank the present sinuous course of the Sacramento River through the structurally controlled loops of the river at Jelly School and Table Mountain. Clearly, the Sacramento River was forced into its tortuous course around the Inks Creek fold system by Early Riverbank time. We conclude, therefore, that the Inks Creek fold system and, at least, some of the displacement on the Battle Creek fault zone developed in the time span between 450,000 years B.P., the age of the ash, and about 400,000 years B.P., the age of the lower part of the Riverbank Formation (Marchand and Allwardt, 1981).

Red Bluff Fault

The Red Bluff fault is a subsurface structure that extends southwest of Red Bluff, California, for a distance of at least 15 miles (25 km). West of Red Bluff, there is no surface feature associated unequivocally with the fault and its location is taken from the Geologic Map of California (Jennings, 1977). Apparently Jennings included the fault on that map based on seismic reflection data obtained from private industry (see Oliver and Griscom, 1980). We have not seen that data or any other seismic profiles that might cross the fault. Griscom (1973) inferred the existence of a major northeast-trending fault in the area from magnetic data.

East of Red Bluff, the Tuscan Formation is warped into a broad northeast-trending anticline, the axial trace of which roughly coincides with the northeast projection of the Red Bluff fault. Structure contours drawn on the top of the Cretaceous rocks northeast of Red Bluff also reflect a broad-topped northeast-trending, southwest plunging anticline in the area. There is no indication that the Tuscan Formation is faulted at the surface along the N.70° E projection of the Red Bluff fault. The southeast limb of the anticline defined by the structure contours, however, may be faulted at depth, but surface and subsurface data are too sparse to either prove or refute that structural possibility. Between Tuscan Springs and the Humble "Cone Ranch No. 1" well (sec. 20, T.27N.R2W.), the top of the Cretaceous is vertically displaced about 1433 m (4750 ft) in a distance of less than 8 km (5 mi). The displacement is due to warping and faulting on the Chico monocline fault as well as folding and possibly faulting along the northwest projection of the Red Bluff fault.

From reinterpretation of the longitudinal section given by Redwine (1972, sect. FF'), the base of the Tehama Formation could be offset, down-to the south, by as much as 141 m (465 ft) across the Red Bluff fault just east of Red Bluff. Because of the lack of northeast-trending surface faulting in the Tuscan to the east, however, it seems unlikely that all of that differential elevation is due to fault displacement; much of it may be related to folding over a fault at depth.

Capay Valley-Rumsey Hills area

Cache Creek drains east from Clear Lake and enters the Sacramento Valley west of Woodland, through the tectonically controlled depression of Capay Valley. To the west, Capay Valley is flanked by the eastern slope of the Coast Ranges that contain a remnant of Eocene marine sandstone and shale of the Capay Formation (see Redwine, 1972) resting unconformably on upper

Cretaceous marine rocks (Kirby, 1943a). Beds in the Capay and underlying rocks dip east 25 to 55 degrees. The Rumsey Hills lie immediately east of Capay Valley and are composed of the same upper Cretaceous rocks exposed to the west but, here, the Cretaceous rocks lie in the core of a faulted anticline and are unconformably overlain by nonmarine sandstone and shale of the Pliocene Tehama Formation. The Capay Formation is not present in the Rumsey Hills or in the Capay Valley, where scattered subsurface and surface data indicate that the Tehama rests unconformably on upper Cretaceous rocks.

On the floor of Capay Valley, the Tehama and older rocks have been eroded and the channels filled with a variety of Quaternary alluvial deposits. Alluvial deposits of the upper part of the Modesto Formation indicate that Cache Creek entered the Sacramento Valley through a channel cut in the Tehama Formation near the west boundary of Capay Valley in Late Wisconsin time. During the past 12,000 years, or so, the course of Cache Creek has shifted eastward so that the creek now exits Capay Valley through a sharp gorge cut into the relatively resistant upper Cretaceous rocks at the southern end of Rumsey Hills. The shift in the course of Cache Creek coupled with surface and subsurface data showing faulting in the Tehama provide strong evidence for Late Cenozoic tectonism in the Capay Valley.

Along the west flank of the Rumsey Hills, Kirby (1943b) mapped a northwest-trending, east-dipping thrust, the Sweitzer fault, and a lower ancilliary thrust, the Eisner fault; both faults placed upper Cretaceous rocks in contact with the Tehama. Recent mapping by David Wagner of the California Division of Mines and Geology has reinterpreted the Sweitzer and Eisner faults as west-dipping normal faults. Our work has identified high angle faults along both the east and west flanks of Capay Valley but the eastern fault appears to lie west of the Sweitzer fault.

Dunnigan Hills Anticline- Hungry Hollow Fault

In 1923 Bryan recognized accordant summit elevations capped by Red Bluff gravel on a series of northwest-trending dissected uplands near Woodland, California, that he called the Hungry Hollow Hills but which are now known as the Dunnigan Hills. The northeast flank of the upland is bounded by a linear escarpment that Bryan called the Hungry Hollow Fault. He recognized at least 121 m (400 ft) of down-to-the-east displacement at the north end of the fault scarp and about 60 m (200 ft) of offset in the south at Cache Creek (Bryan, 1923, p. 79).

Bryan's early work, combined with the topographic relief in the area, made the Dunnigan Hills a prime target for early seismic reflection studies that resulted in the discovery of the Dunnigan Hills gas field in 1946 (Rofe, 1962). The gas-producing structure is a doubly plunging, northwest-trending anticline along which various sandstone beds in the upper Cretaceous rocks are unconformably capped by the Eocene Capay Formation. This major structure is shown on the surface by topographic relief and by the Red Bluff gravel that wraps around the northwest-plunging nose of the fold and occurs in scattered patches along the east flank, on the crest line, and at the southeast-plunging nose of the fold. Oat Valley Creek and Bird Creek are antecedent to the fold and change from a southeast to a northeast course approximately at the axial trace of the fold.

Data from a recent well drilled near Zamora, California, by the Water Resources Division of the U. S. Geological Survey provides new information on the amount of Late Cenozoic deformation in the area. A conspicuous volcanic ash bed, encountered at a depth of 137 m (450 ft) (R. Page, 1981 oral commun.), has been correlated tentatively by mineralogy and chemical composition with the Rockland Pumice Tuff Breccia of Wilson (1961) by C. Meyer and A. M. Sarna-Wojcicki of the U. S. Geological Survey (1982 oral commun.) Because the ash occurs directly above the Red Bluff gravel elsewhere in the Valley (Harwood and others, 1981; Helley and others, 1982), it is assumed that the ash overlies the Red Bluff in the Zamora well giving a minimum of 220 m (720 ft) vertical displacement on the Red Bluff. This vertical separation is the combined effect of folding on the Dunnigan Hills anticline and displacement on the Hungry Hollow fault.

Midland Fault

The Midland fault is a major subsurface structure that was discovered in the Sacramento Delta during development of the Rio Vista gas field between 1936 and 1943 (Frame, 1944). Through extensive drilling, the fault was extended about 25 km (15 mi) north of the Rio Vista field to the Maine Prairie gas field (Arleth, 1968), but north of that field the location of the Midland fault is uncertain. Redwine (1972) proposed that the Sweitzer fault, mapped by Kirby (1943b) in the Rumsey Hills, was the northwest continuation of the Midland fault. Although Jennings (1977) showed the Midland-Sweitzer fault connection, suitably queried, on the Geologic Map of California, that interpretation is no longer considered correct (C. Jennings, oral commun. 1981). The location of the Midland fault south of the Rio Vista gas field is uncertain.

In the Rio Vista gas field, the Midland fault is a north-trending, steeply west-dipping to vertical fault zone that offsets Paleocene and Eocene rocks down-to-the-west in a series of fault blocks. Early in the development history of the Rió Vista gas field, it became apparent that movement on the Midland fault had controlled local patterns of Tertiary sedimentation. Frame (1944) noted that the Capay Formation was significantly thicker west of the Midland fault and he suggested that maximum movement occurred on the fault during or at the close of Capay deposition. Although the Capay Formation shows the most significant syntectonic thickening across the fault, all of the Eocene and Paleocene units show some differential thickening west of the fault (Burroughs and others, 1968). Almgren (1978) presents a detailed analysis of depositional and tectonic cycles in the southern Sacramento Valley in which he demonstrates approximately 610 m (2010 ft) of episodic movement on the Midland fault between the Early Paleocene and Early Oligocene. There is no indication that Early Oligocene or younger deposits are offset by the Midland fault; therefore, it appears that the Midland fault was an active structural feature on the Early Tertiary continental margin but that it has not been active in the Late Cenozoic.

Faults in the Sierran Foothills

Clark (1960) combined data from a number of sources with his own field observations to produce the first regional structural synthesis of the Sierran foothills. In that study, he defined the Foothill fault system as a collection of northwest-trending, steeply east-dipping to vertical faults that tectonically separate distinctive belts of Paleozoic and Mesozoic rocks for more than 320 km (200 mi) along strike in the western foothills of the Sierra Nevada. He recognized that the component faults in the system were actually complex fault zones marked by multiple fault strands and intensely sheared, cataclastic, and crumpled rock, which were associated geographically, in many areas, with major bodies of sheared serpentinite. On the basis of limited paleontologic and radiometric data, he concluded that the major tectonic activity of the Foothill fault system occurred in the Late Jurassic.

Although displacement of Tertiary volcanic units was recognized locally along segments of the Foothill fault system after Clark's study (Bateman and Warhaftig, 1966), few investigations were made into the Late Cenozoic deformational history of the fault system before the Oroville earthquake in August 1975. That seismic event produced ground rupture on the Cleveland Hills faults (Clark and others, 1976) and opened the question of potential Late Cenozoic deformation within the whole Foothills fault system.

In their earthquake evaluation studies of the Auburn Dam area, Woodward Clyde Consultants (1977) made a regional analysis of potential Late Cenozoic deformation along many linear features related to the Foothill fault system and they trenched those linear features that had direct bearing on their Auburn dam study. This effort is, by far, the most comprehensive study of Late Cenozoic deformation of the Foothill fault system and it provides most of the data for our analysis of those strands of the fault system in the border zone between the Sierran foothills and the Sacramento Valley.

Cohasset Ridge Fault

Cohasset Ridge is a prominant south southwest-trending interfluve located northeast of Chico, California, between the major drainages of Big Chico Creek and Deer Creek. The ridge is capped by at least two essentially contemporaneous basalt flows that appear to have originated in the Butte Mountain area (not shown on the map) on the southwest slope of a Pliocene volcano named Mount Yana by Lydon (1968). The basalt flowed southwestward in channels eroded in the underlying Tuscan Formation, but subsequent erosion has inverted the topography so that the basalt now stands as the highest unit on the ridge. The basalt of Cohasset Ridge is the youngest bedrock unit south of the Deer Creek drainage and it represents the final phase of volcanism that reached the Sacramento Valley from Mount Yana. The upper-most flow of the basalt has been dated at 2.41 m.y (Harwood and others, 1981).

East of Brushy Mountain, the basalt of Cohasset Ridge is abruptly truncated, on the east, by a steeply east-dipping fault that strikes about N.40°E., roughly parallel to the Chico monocline fault. Aune (cited in Woodward Clyde Consultants, 1977) first recognized this fault, which he called the Cohasset Ridge fault, and concluded that the eastern equivalents of the basalt of Cohasset Ridge were faulted down-to-the east about 30 m (100 ft) along the normal fault. The Cohasset Ridge fault can be traced north of Deer Creek through an intensely fractured zone in the Tuscan Formation to the vicinity of Mill Creek where it becomes obscured by a complex pattern of west and northwest-trending arcuate faults that are shown in generalized fashion on the map. Although the area south of Deer Creek is heavily forested and the slopes are covered by a veneer of colluvium, the trace of the Cohasset Ridge fault is defined by a prominent topographic linear, observed by Rich and Steele (1974), that extends nearly to Magalia where it apparently is intersected by the Magalia fault.

Available data indicate that the Cohasset Ridge fault is a northwest-trending steeply east-dipping fault that has experienced at least 30 m (100 ft) of down-to-the-east normal movement in the past 2.41 m.y.

Magalia Fault

About 9 km (6 mi) north of the settlement of Magalia, the Cohasset Ridge fault is intersected by a N.20°W. trending fault zone, shown on the map as the Magalia fault. Extensive mine workings, which followed Tertiary auriferous gravel deposits at the base of the Tertiary volcanic sequence in the area, provide detailed data on the nature and local extent of the Magalia fault (Gassaway, 1899; California Dept. of Natural Resources, 1930; Woodward Clyde Consultants, 1977)

Although the Magalia fault is shown as a single fault on the map, detailed mine maps indicate that the fault is actually a complex fault zone composed of numerous fault strands that show different orientations and amounts of displacement. In the Dix mine at the north end of the mining district, the gold-bearing gravels are offset 28 m (90 ft) down-to-the east. Southeastward along the trace of the Magalia fault at the Black Diamond mine, the gravel deposits are offset from 68 m (225 ft) down-to-the east. Farther southeast at the Magalia mine the channel deposits are offset down to the west from 2 to 11 m (5 to 38 ft) along three reverse faults that trend N60 W and dip 58°NE.

From the mining records it appears that the various fault strands in the Magalia fault zone have experienced episodic and different movement through the Tertiary with both normal east-side-down and reverse east-side-up displacement being recorded. The relative ages of this disparate movement pattern in the Magalia fault are unknown.

Cleveland Hills Faults

The Cleveland Hills faults, as shown on the map, coincide with surface ruptures that occurred during the Orovile earthquake in August 1975. During that seismic event, the ground surface failed in a 3.8 km (6 mi) long en echelon pattern of north and north-northwest trending normal faults that showed at least 55 mm of horizontal separation across the surface ruptures and as much as 180 mm of down-to-the-west, vertical separation (Clark and others, 1976). Aftershocks of the Oroville earthquake defined a zone of seismic activity, assumed to coincide with the controlling fault, that dipped about 60° W. and trended nearly due north (Bufe and others, 1976).

Trenches dug across the zone of surface rupture by the California Department of Water Resources and logged by Akers and McQuilkin (1975) showed a gouge zone about 2 m wide in the bedrock below the surface ruptures that was flanked by 2 to 4 m of intensely fractured rock transitional into the country rock of foliated greenstone. The gouge zone contained anastomosing shear zones of deformed gouge that provided evidence of repeated earlier faulting along the zone of the ground failure. Earlier deformation in the area is supported also by 30 to 60 m (10 to 20 ft) of apparent down-to-the-west offset of an erosion surface of probable Pleistocene age (Aune, 1975) across the Cleveland Hills faults.

About 5.7 km (9 mi) northwest of the Cleveland Hills faults, Creely (1965) mapped a north-trending, steeply east-dipping fault that offset the base of Pleistocene or older gravel deposits about 2 m down-to-the-west. Clark and others (1976) reported a second fault in the area that showed minor down-to-the-east offset of the gravel deposit.

Faults Southeast of Oroville

In their earthquake evaluation of the Auburn Dam area, Woodward Clyde Consultants (1977) identified a number of prominant linear features in the Sierran foothills southeast of the Cleveland Hills faults. With the exception of the northeast- and north-trending Highway 49 and Hancock Creek lineament zones, the linear features they investigated had a northwest trend that coincides closely with the projected trace of the Chico monocline fault. The linear features were trenched extensively, logged in detail (Woodward Clyde Consultants, 1977,) and trench data were integrated with surficial geologic investigations in the respective areas. Evidence of movement in the past 10 m.y. (Woodward Clyde Consultants' definition of late Cenozoic) was detected in the trenches across the northwest-trending linear features, which are shown on our map as late Cenozoic faults with the same names as those used by Woodward Clyde Consultants for the lineaments.

Deformation in the bedrock exposed in the trenches is remarkably similar to that shown in trenches across the Cleveland Hills faults. In most areas, bedrock beneath the surface lineaments contained one or more zones of slickensided clay-rich gouge a few meters wide or less. The gouge commonly contained anastomosing shear zones composed of poly-deformed gouge and thin clay seams that indicated multiple phases of deformation. Rock adjacent to the gouge zones commonly was highly fractured, bleached, or manganese stained and injected by thin quartz veins. In some trenches a paleosol was present resting unconformably on bedrock and, locally, that paleosol was offset along the faults marked by the gouge zones. That evidence lead Woodward Clyde Consultants (1977) to conclude that at least some of the faulting had occurred in the past 100,000 years. Based on the evidence presented by Woodward Clyde Consultants (1977) and our observations in many of the trenches that they excavated during that study, we agree with their conclusions.

References Cited

Akers, R. J., and McQuilkin, M. J., 1975, Geological investigations of the Oroville eathquake, in Sherbourne, R. W., and Hauge, C. J., eds., Oroville, California earthquake 1 August 1975, California Division of Mines and Geology Special Report 124, p. 45-52.

Alkire, J. H., 1962, Willows-Beehive Bend gas field, California: in Bowen, O. E., Jr., ed., Geologic guides to the gas and oil fields of northern California: California Div. of Mines and Geology Bulletin 181, p. 105-109.

Alkire, J. H., 1968, Willows-Beehive Bend gas field: in Beebe, B. W. and Curtis, B. F., eds., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, pt. II, p. 639-642.

Almgren, A. A., 1978, Timing of Tertiary submarine Canyons and marine cycles of deposition in the southern Sacramento Valley, California, in, Stanley, D. J., and Kelling, Gilbert, eds., Sedimentation in submarine canyons, fans, and trenches: Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania, p. 276-291.

Anderson, C. A., and Russell, R. D., 1939, Tertiary formations of northern Sacramento Valley, California: California Journal of Mines and Geology, v.35, no. 3, p. 219-253.

Arleth, K. H., 1968, Maine Prairie gas field, Solano Conty, California, in Beebe, B. W., and Curtis, B. F.., eds., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, pt I, p. 79-84.

Aune, Q. A., 1975, Geomorphic setting of the Cleveland Hills fault, Butte Co., California, in Sherburne, R. W., and Hauge, C. J., eds. Oroville, California earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 41-44.

Bateman, P. C., and Warhaftig, C., 1966, Geology of the Sierra Nevada, in Bailey, E. H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 107-172.

Bryan, Kirk, 1923, Geology and ground-water resources of Sacramento Valley, California: U. S. Geological Survey Water-Supply Paper 495, 285 p.

Bufe, C. G., Lester, F. W., Lahr, K. M., Seekins, L. C., and Hanks, T. C., 1976, Oroville earthquakes: Normal faulting in the Sierra Nevada foothills: Science, v. 192, p. 72-74.

Burroughs, E. , Beecroft, G. W., and Barger, R. M., 1968, Rio Vista gas field, Solano, Sacramento, and Contra Costa Counties, California, in Beebe, B. W., and Curtis, B. F., eds; Natural gases of North America: American Association of Petroleum Geolgists Memoir 9, v. 1, pt I, p. 93-101.

Cady, J. W. 1975, Magnetic and gravity anomalies in the Great Valley and western Sierra Nevada metamorphic belt California: Geological Society of America Special Paper 168, 56p.

California Division of Oil and gas, 1960, California oil and gas fields maps and data sheets, part 1, San Joaquin-Sacramento vallies and northern coastal regions: California Division of Oil and Gas, San Francisco 493 p.

California Division of Oil and Gas, 1964, Exploratory wells drilled outside of oil and gas fields in California to December 31, 1963: California Division of Oil and Gas, San Franciso, 320 p.

California Department of Natural Resources, 1930, Mining in California: California Division of Mines, v. 26, no. 4, p. 383-412.

California Department of Water Resources 1978, Evaluation of ground water resources, Sacramento Valley: California Department of Water Resources Bulletin, 118-6, 136 p.

Clark, L. D., 1960, Foothill fault system, western Sierra Nevada, California: Geological Society of America Bulletin, v. 71, pp 483-496.

Clark, M. M., Sharp, R. V., Castle, R. O., and Harsh, P. W., 1976, Surface faulting near Lake Oroville, California in August, 1975: Seismiological Society of America Bulletin, v. 66, no. 4, p. 1101-1110.

Creely, R. S., 1965, Geology of the Oroville quadrangle, California: California Division of Mines and Geology Bulletin 184, 86 p.

Dickinson, W. R., 1979, Cenozoic plate tectonic setting of the Cordilleran region in the United States; in Cenozoic paleogeography of the western United States, Armentrout, J. M., Cole, M. R., and TerBest, Harry, J., eds; Society of Economic Paleontologists and Mineralogists, Los Angeles, California p. 1-13.

Frame, R. G., 1944, Rio Vista gas field: California Division of Oil and gas, Summary of operations, California Oil Fields, v. 30, no. 1, p. 5-14.

Gassaway, E. M., 1899, The Magalia, California, drift mine: Mining and Scientific Press, p. 372-373 and 400-401.

Griscom, Andrew, 1973, Bouguer gravity map of California, Redding sheet: California Division of Mines and Geology, scale 1:250,000, 13 p text.

Harwood, D.S., Helley, E. J., Barker, J. A., Griffin, E. A., 1980, Preliminary geologic map of the Battle Creek fault zone, Shasta and Tehama Counties, California: U. S. Geological Survey Open-File Report 8-474, scale 1:24,000.

Harwood, D. S., Helley, E. J., Doukas, M. P., 1981, Geological map of the Chico monocline and northeastern part of the Sacramento Valley: U. S. Geological Survey Investifations Map I-1238, scale 1:62,500.

Helley, E. J., Harwood, D. S., Barker, J. A., Griffin, E. A., 1981, Geologic map of the Battle Creek fault zone and adjacent parts of the northern Sacramento Valley, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-1298, scale 1:62,500.

Ingersoll, R. V., 1978, Paleogeography and paleotectonics of the late Mesozoic forearc basin of northern and central California, in Mesozoic paleogeography of the western United States, Howell, D. G., and McDougall, K. A., eds., Society of Economic Paleotologists and Mineralogists, Los Angeles, California, p. 471-482.

Jacobson, J. B., 1981, Reflection seismic expression of the cross sectional stratigraphy and structure of the southern Sacramento Valley: in Graham, S. A., ed., Field guide to the Mesozoic-Cenozoic convergent margin of northern California; American Association of Petroleum Geologists Pacific Section. v. 50.

Jennings, C. W., and Strand R. G., 1960, Geologic map of California, Olaf P. Jenkins edition, Ukiah sheet: California Division of Mines and geology, scale 1:250,000.

Jennings, C. W., 1977, Geologic map of California: California Division of Mines and Geology, scale 1:750,000.

Jones, D. L., Bailey, E. H., and Imlay, R. W., 1969, Structural and stratigraphic significance of the Bachia zones in the Colyear Springs-Paskenta area, California: U. S. Geological Survey Professional Paper 647-A, p. A1-A24.

Jones, D. L., and Irwin, W. P., 1971, Structural implications of an offset Early Cretaceous shoreline in northern California: Geological Society of America Bulletin, v. 82, p. 815-822.

Kirby, J. M., 1943a, Upper Cretaceous stratigraphy of the west side of the Sacramento Valley south of Willows, Glenn County, California: American Association of Petroleum Geologists Bulletin, v. 27, no. 3, p. 279-305.

______, 1943b, Rumsey Hills area, in Jenkins, O. P., ed, Geologic formations and economic development of the oil and gas fields of California: California Division of Mines and Geology Bulletin 118, p. 601-605.

Lydon, P. A., 1968, Geology and lahars of the Tuscan Formation, northern California, in Coats, R. R., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology, a memoir in honor of Howell Williams: Geological Society of America Memoir 116, pp. 441-475.

Marchand, D. E., and Allwardt, Alan, 1981, Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California: U. S. Geological Survey Bulletin 1470, 70 p.

Marks, S. M. and Lindh, A. G., 1978, Regional seismicity of the Sierran foothills in the vicinity of Oroville, California: Seismological Society of America Bulletin v. 68, p. 1103-1115.

May, J. C. and Hewitt, R. L., 1948 , The basement complex in well samples from the Sacramento and San Joaquin Valleys, California: California Journal of Mines and Geology, vol 44 no. 2, pp 129-158.

Meyer, C. E., Woodward, M. J., Sarna-Wojciki, A. M., and Naeser, C. W., 1980, Zircon fission-track age of 0.45 million years on ash in the type section of the Merced Formation, west-central California: U. S. Geological Survey Open-File report 80-1071

Munger, 1981 Map Book, California-Alaska Oil-Gas-Geothermal fields, Los Angeles, p. W-1 - W-20.

Oliver, H. W., and Griscom, Andrew, 1980, Great Valley, in Oliver, H. W., ed, Interpretation of the gravity map of California and its continental margin: California Division of Mines and Geology Bulletin 205, p. 27-30.

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U. S. Geological Survey Water-Supply Paper 1497, 241 p.

Redwine, L. E., 1972, The Tertiary Princeton Submarine Valley system beneath the Sacramento Valley, California: University of California, Los Angeles, Ph. D. Thesis, Los Angeles, California 480 p.

Rich, E. I., and Steele, W. C., 1974, Geologic structures in northern California as detected from ERTS-1 satellite imagery: Geology, v. 2, no. 4, p. 165-169.

Roberts, C. W., Jachens, R. C., and Oliver, H. W., 1981, Preliminary isostatic residual gravity map of California: U. S. Geological Survey Open-File report 81-573, scale 1:750,000.

Rofe, Rafael, 1962, Dunnigan Hills gas field, California; in Geological guide to the gas and oil fields of northern California, O. E. Bowen, Jr., ed.: California Division of Mines and Geology Bulletin 181, p. 119-132.

Sacramento Petroleum Association, 1962, The Corning and South Corning gas fields, California, in Geologic guide to the gas and oil fields of northern California: California Division of Mines and Geology Bulletin 181, p. 101-102.

Safonov, Anatole, 1968, Stratigraphy and tectonics of Sacramento Valley, in Beebe, B. W., and Curtis, B. F., eds., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v.1, pt II. p. 611-635.

Smith, M. B., 1964, Map showing distribution and configuration of basement rocks in California (North Half) (South Half): U. S. Geological Survey Oil and Gas Investigations Map OM-215.

Williams, Howell, and Curtis, G. H., 1977, The Sutter Buttes of California; A study of Plio-Pleistocene Volcanism: University of California Publications in Geological Sciences, vol. 116, 56 p.

Wilson, T. A., 1961., The geology near Mineral, California: University of California, Berkeley, M. A. Thesis, 90 p.

Woodward Clyde Consultants, 1977. Earthquake evaluation Studies of the Auburn Dan area: Eight volumes, Woodward Clyde Consultants, San Francisco, California.