FINAL TECHNICAL REPORT

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Assessment and Documentation of Transpressional Structures, Northeastern Diablo Range, for the Quaternary Fault Map Database: Collaborative Research with William Lettis & Associates, Inc., and the U.S. Geological Survey

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U. S. Geological Survey
National Earthquake Hazards Reduction Program

ASSESSMENT AND DOCUMENTATION OF TRANSPRESSIONAL STRUCTURES, NORTHEASTERN DIABLO RANGE, FOR THE QUATERNARY FAULT MAP DATABASE: COLLABORATIVE RESEARCH WITH WILLIAM LETTIS & ASSOCIATES, INC., AND THE U.S. GEOLOGICAL SURVEY

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Abstract

This study presents a new digital map compilation of Quaternary faults and folds in the northeastern Diablo Range and northwestern San Joaquin Valley. Map-scale folds that deform late Neogene and younger strata in the proposed study area include the Panoche Hills anticline, Mt. Oso anticline, Patterson Pass anticline and the Altamont Hills anticline. Reverse and thrust faults associated with the folds include the Corral Hollow-Carnegie fault, Patterson Pass fault, and Elk Ravine fault. In general, these folds, reverse faults and thrust faults all strike west-northwest, oblique to the Greenville fault and other eastern strands of the San Andreas system. The west-northwest-trending contractional structures generally are bounded on the east by northwest-striking faults that exhibit evidence for both strike-slip and reverse separation of late Neogene and Quaternary strata. These faults include the San Joaquin/Orestimba, Black Butte and Midway faults. Previous studies (Unruh et al., 1992) have attributed Quaternary uplift, tilting and folding along the northeastern Diablo Range piedmont to underthrusting and propagation of an east-tapering tectonic wedge, similar to the model proposed by Wentworth et al. (1984) for shortening in the epicentral region of the 1983 Coalinga earthquake to the south. The tectonic wedge model assumes that regional crustal shortening along the western margin of the Central Valley is directed at a high angle to the strike-slip faults of the plate boundary. In detail, however, folds and reverse faults in the study area generally are oblique rather than parallel to strike-slip faults of the San Andreas system, and they exhibit a right-stepping, en echelon pattern typical of dextral wrench structures. GPS data document northwest-directed dextral motion as far east as the physiographic boundary between the Diablo Range and Central Valley, and locally within the western Central Valley (Prescott et al., 2001; d'Alessio et al., 2005). These observations are consistent with distributed transpressional deformation rather than partitioning of plate motion into pure strike-slip faulting and shortening directed at a high angle to the plate

boundary, as envisioned by the tectonic wedge model. The implications of transpressional kinematics for seismic hazards at the latitude of the study region is that rather than blind thrust fault sources parallel to and underlying the range front, as assumed in the Working Group 1999 model for seismic sources along the western San Joaquin Valley margin (i.e., sources "GV07" and "GV08"), blind thrust faults are oblique to the trend of the range front, and separated by right en echelon steps. This pattern of faulting generally implies smaller blind thrust fault sources and a lower potential for multi-segment ruptures than the fault geometry assumed by WG99. In addition, the range-front faults (San Joaquin/Orestimba; Black Butte and Midway) may have a previously unrecognized component of strike-slip displacement, implying that reverse slip rates derived for the faults from vertical separation of Quaternary surfaces across the range front may underestimate the true rate of oblique slip.

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1.0 Introduction

The goal of this study is to analyze and compile digital point and line data on the locations of Quaternary folds, thrust and reverse faults (including blind faults), and strike-slip faults along the boundary between the northern Diablo Range and northwestern San Joaquin Valley for incorporation into the Northern California Quaternary Fault Map Database (NCQFMD). This compilation includes data on the geologic characteristics of the faults in an ArcGIS-compatible format, as specified by the U.S. Geological Survey. This compilation builds on the 1999 Working Group characterization of thrust and reverse faults in the San Francisco Bay area.

The primary geographic area for this study is the eastern Diablo Range front at the latitude of Livermore and Tracy, and extending approximately south to the latitude of the Panoche Hills (Figure 1). Map-scale folds that deform late Neogene and younger strata in the proposed study area include the Mt. Oso anticline, Patterson Pass anticline and the Altamont Hills anticline (Figure 1). Reverse and thrust faults associated with the folds include the Corral Hollow-Carnegie fault, Patterson Pass fault, and Elk Ravine fault (Figure 2). In general, these folds, reverse faults and thrust faults all strike west-northwest, oblique to the dextral Greenville fault. The west-northwest-trending contractional structures generally are bounded on the east by northwest-striking faults that exhibit reverse, and locally strike-slip, separation of late Neogene and Quaternary strata. These faults include the San Joaquin/Orestimba, Black Butte and Midway faults (Figure 2 and 3).

This study is a collaborative effort with the U.S. Geological Survey, and is being coordinated by Dr. Russell Graymer of (USGS-Menlo Park). In an email communication dated 11 November 2004, Dr. Graymer outlined his research priorities for participants in the NCQFMD project as follows:

1) Provide “fault traces in GIS”;
2) Evaluate “fault strand rank”;
3) Evaluate “location uncertainty:’
4) Characterize “geomorphic expression”; and
5) Compile “site-specific point data”.

Geologic mapping of Quaternary faults and folds in the study region was compiled at the largest available scale and, where necessary, digitized and georeferenced. The metadata description of the mapping is presented in Section 3.0 and Table 1 of this Report.

2.0 Tectonic Setting

The study region lies along the eastern margin of the boundary between the Pacific Plate and the Sierra Nevada-Central Valley (Sierran) microplate. Global Positioning System (GPS) geodesy documents about 38 mm/yr of distributed dextral shear directed toward N30°W across this boundary at the latitude of the San Francisco Bay area (d'Alessio et al., 2005). In general, the relative motion between the plates is directed more toward the west than the average trend of the plate boundary, resulting in oblique convergence and net transpressional deformation. At a very large scale, the transpressional deformation is expressed by late Cenozoic uplift of the coastal ranges (Argus and Gordon, 2001); locally, the deformation is accommodated by thrust and reverse faults, many of which are blind and underlie actively growing anticlines.

Late Cenozoic crustal shortening in the study region was evaluated by Unruh et al. (1992), who attributed Quaternary uplift, tilting and folding along the eastern Diablo Range piedmont to underthrusting and propagation of an east-tapering tectonic wedge, similar to the model proposed by Wentworth et al. (1984) for shortening in the epicentral region of the 1983 Coalinga earthquake to the south. The tectonic wedge model assumes that regional crustal shortening along the western margin of the Central Valley is directed at a high angle to the strike-slip faults of the plate boundary. Subsequent characterization of potential seismic sources along the western margin of the Central Valley by the 1996 Working Group assumed a more general model of segmented, west-dipping blind thrust faults that accommodate east- to northeast-directed shortening at a high angle to the plate boundary.

In detail, however, the tectonic wedge model is not consistent with the observed kinematics in this region. For example, the easternmost strike-slip faults of the San Andreas system at this latitude include the Ortigalita and Greenville faults (Figure 1 and Figure 4). Folds and reverse faults in the study area generally are oblique rather than parallel to these strike-slip faults, and they exhibit a right-stepping, en echelon pattern typical of dextral wrench structures (Figure 1). Northwest directed dextral motion can be measured as far east as the physiographic boundary between the Diablo Range and Central Valley, and locally within the western Central Valley (Prescott et al., 2001; d'Alessio et al., 2005), which is not consistent with the model for shortening directed at a high angle to the plate boundary along the eastern margin of the Diablo Range.

The observed northwest dextral motion and oblique, right-stepping geometry of the folds and thrust faults require an alternative model to the assumption of plate-normal convergence in the tectonic wedge model of Wentworth et al. (1984) and Unruh et al. (1992). As a working hypothesis, we suggest that transpressional plate motion in the study area is driven by oblique slip on reverse faults and active shortening in restraining step-overs among strike-slip faults. Recent paleoseismic investigations indicate that the late Quaternary slip rate on the Ortigalita strike-slip fault south of the study area is about 2 ± 1 mm/yr (Anderson and O'Connell, 2005). The Ortigalita fault dies out as a well-defined geomorphic feature south of Del Puerto Canyon. Some of the dextral slip on the

Ortigalita fault likely is transferred in a left-restraining step across Mt. Oso anticline at the southern end of the proposed study area to the Greenville fault (Figure 4). Unruh and Sawyer (1998) observed that the tectonic-geomorphic expression of Greenville fault as a Quaternary-active structure increases significantly north of its intersection with the western margin of the Mt. Oso anticline, consistent with this hypothesis (Figure 3).

Additional left-restraining transfer of slip may also occur north of the Mt. Oso anticline and drive distributed transpressional deformation east of the Greenville fault. For example, net slip on the San Joaquin and Black Butte faults may include a component of dextral motion that is transferred to structures like the Midway fault, Patterson Pass anticline and Corral Hollow-Carnegie fault in a left-restraining geometry. This model for eastern Diablo Range deformation is similar to that proposed by Unruh and Sawyer (1995) for the Mt. Diablo fold and thrust belt, which is a contractional domain in a left-restraining step-over between the Greenville and Concord faults directly northwest of the proposed study area (Figure 2).

The implication of this model for seismic hazards at the latitude of the study region, which includes the rapidly growing Livermore-Tracy corridor, is that rather than blind thrust fault sources parallel to and underlying the range front, as currently assumed in the Working Group 1999 model for seismic sources along the western San Joaquin Valley margin (i.e., sources “GV07” and “GV08”), shortening appears to be accommodated by blind thrust fault sources that are oblique to the trend of the range front, and separated by right en echelon steps. This pattern of faulting generally implies smaller blind thrust fault sources and a lower potential for multi-segment ruptures than the fault geometry assumed by WG99. The restraining step-over model also implies that the slip rates on blind thrust faults are more directly related to slip rates on the bounding strike-slip faults, rather than regional plate-boundary-normal shortening rates (Unruh and Lettis, 1998).

3.0 Metadata

The database was compiled in ArcGIS 9.2, a Geographic Information System created by Environmental Systems Research Institute (ESRI, Redlands, California). The comprehensive database consists of the fault and fold compilation database, supporting metadata, and this report. The fault map database consists of one ARC shapefile (*Diablo_Range_NEHRP.shp*), which was created and attributed according to the NCQFMD format for incorporation into the Bay Area Quaternary fault map database.

The map traces of these structures were compiled at the largest available scale from published and unpublished sources. We compared the newly compiled fault traces with the "Fault Traces of California Map" (1994) by Charles Jennings (Figure 4). Where necessary, we made minor revisions to the Jennings fault traces and added new faults and fold that post date the Jennings map data. The compilation includes published and unpublished data from reliable sources. The general geographic region and the corresponding authorship associated with each region are listed below (Table 1).

Table 1. Geographic area to source author matrix.

Geographic Area	**Source**
Mnt. Oso region	Maddock (1964) and Dibblee (1980, 1981, 1982)
Tracy, Lone Tree Creek & Patterson's Pass regions	Sowers et. al., (1993) and Noller et. al., (1993)
San Luis dam area and north along the range front	Anderson and Piety (2001)
Southwestern Sacramento Valley	Sterling (1992, 2006, 2007), Sowers et. al., (1993) and Noller et. al., (1993)
Ortigalita and San Luis Dam area	Jennings (1994) and Anderson and Piety (2001)
Contra Costa, Alameda and Stanislaus Counties	Jennings (1994), Crane, R. (1988; geologic maps of 7.5' quadrangles)
Tracy, Midway, Wilcox Ridge, Cedar Mnt, & Copper Mnt.	Dibblee (1980, 1981, 1982) and Crane (1995)
East Bay and regional structure	Unruh and Sundermann (2006)
Panoche Hills region	Dibblee (1971 and 1975) and Lettis (1982 and 2007)

Our priority for compiling map data was to use the most up-to-date state of knowledge at the largest scale possible. As a result, our preference for interpretive analysis was digital GIS files followed by original manuscripts and finally published stable originals.

Stable source maps were scanned using a large-format color scanner with a resolution of 600 dots per inch. The scanned maps were georeferenced into our working coordinate system for vectorization using the Georeferencing extension in ArcGIS 9.2. Georeferencing was accomplished with control points linked to map edge tics and cultural features in a heads-up digitization process. The link table was intentionally saturated to facilitate sub-meter root mean square horizontal error. The georeferenced maps were vectorized using heads-up digitization and drawn as accurately as possible at the map scale of 1:24,000. Attribute tables were completed within GIS and follow the NCQFMD format.

Vectorized maps and acquired digital files were compiled at a map scale of 1:24,000. Although the digital format of the dataset permits viewing the data at a larger scale, the detail and accuracy of the drawing is compromised at any scale larger than 1:24,000. Viewing the data at a larger scale will not generate any greater detail than that presented at the original scale and should not be used for investigations requiring greater detail.

3.1 Fault Rank (FRANK) Criteria

Dr. Graymer (written communication, 2004), defined a fault strand activity rating (FRANK) with five categories; Primary, Secondary, Tertiary, Questionable and Probably Not Active. For this study the following criterion were used to place each fault trace and fold axis into one of those five categories.

Primary:
- A fault with a surface trace greater than 10 km in length.
- Indication by one or more sources of Quaternary activity.
- A fold with an axial length greater that 5 km, and which is identified as Quaternary in age by two or more sources.

Secondary:
- A fault/fold with a mapped length/extent of less than 10 km.
- If only one source suggests Quaternary activity.
- A source identifies the fault/fold as a minimally active trace.

Tertiary:
- A fault/fold with a mapped length/extent of less than 1 km.
- Splays or small strands off of a higher ranked fault.
- A source identifies the fault/fold as a minimally active trace.

Questionable:
- If the activity of the fault/fold is called into question by one or more sources.
- Fault or fold axis does not deform Quaternary deposits, but is included because the context of surrounding and interacting features suggests it may be Quaternary active.

Probably Not Active:
- If included in the Jennings compilation (1994), but subsequent references conclude the structure is inactive.

4.0 Fault Meta Data Summary/Expansion

This section provides additional explanation of the characterization of faults, folds and their attributes in the GIS database.

4.1 The West Tracy Thrust Fault (blind)

Fault strand rank= Primary

Location certainty, blind West Tracy Thrust fault surface trace = Approximate
The West Tracy fault is well imaged as a moderately to steeply west-dipping fault on seismic reflection lines (Sterling, written communication, 2006; J. Weber, personal communication, 2006). For this study, the trace and extent of the West Tracy fault were compiled from maps and proprietary data provided by R. Sterling (2006-2007 personal communication).

Geologic expression:
The West Tracy fault strikes northwest-southeast and is mapped for a total distance of about 70 km parallel to the eastern flank of the northern Diablo Range between the Marsh Creek outlet and south of the Hospital Creek drainage (Figure 1 and 2; Sterling, personal communication 2006-2007). The fault has no documented surface trace on small-scale geologic maps published by the state of California (Figure 4; Rogers, 1966; Wagner et al., 1991), and is known primarily from analysis of proprietary borehole data and seismic reflection data acquired for oil and gas exploration (Sterling, 1992). R. Sterling (written communication, 2006) provided interpretation of proprietary seismic reflection lines, which indicates the West Tracy fault is a moderately to steeply west-dipping fault. The reflection data provide clear evidence for west-side-up reverse displacement on the fault, including offset of reflectors associated with Cretaceous marine strata at depth and monoclinal folding above the fault tip (Sterling, 1992; R. Sterling, written communication, 2006). The fault dies out as a discernable feature in the upper 1-2 seconds depth two-way time on seismic time sections, and fold displacement can be traced above the fault tip to the shallowest reflectors imaged in the data. Angular unconformities are present in the shallow reflectors that indicate progressive uplift and fold deformation has occurred during deposition of the youngest imaged strata. The folded shallow reflectors project updip to exposures of northeast-dipping deposits along the eastern Diablo Range front mapped as “Pliocene-Pleistocene gravels” by Crane (1995b; Brentwood 7.5 minute quadrangle). The “Plio-Pleistocene gravels” unconformably overlie more steeply dipping strata mapped by Crane (1995b) as Miocene Neroly Formation. Geologic mapping at 1:250,000 scale by the State of California (Rogers, 1966) shows a contact between older and younger Quaternary deposits that follows the buried trace of the West Tracy fault. The older deposits are preferentially associated with the hanging wall of the fault, consistent with Quaternary uplift. We interpret these map relations as prima facie evidence for Quaternary uplift and fault-propagation folding above the West Tracy fault.

Notes and References:
Very limited data are available to estimate the rate of slip and recent behavior of the West Tracy fault. In addition to the reverse separation visible in reflection profiles, we infer a component of right-lateral slip on the West Tracy fault given its northwest strike sub-parallel to regional Pacific-Sierran plate motion, and the fact that it is parallel to the Black Butte-Midway faults, which exhibit evidence for dextral-reverse oblique slip. We assume that the slip rate of the West Tracy fault is less than that of the Midway/Black Butte fault zone (Sections 4.3.1-4.3.4) because it lies farther to the east, consistent with geodetic data that document eastward decreasing rates of dextral motion across the Pacific-Sierran plate boundary (Prescott et al., 2001; d'Alessio et al., 2005). A vertical separation rate of 0.07 mm/yr is estimated based on about 800 ft (244 m) of relief on a basal Miocene unconformity across the fault as reported by Sterling (1992), and an assumed duration of deformation (active during the past ~3.5 Ma). The true slip rate is higher than 0.07 mm/yr if there is a component of horizontal strike-slip displacement.

Crane, R.C., 1995a, Geologic map of the Midway 7.5 minute quadrangle.
Crane, R.C., 1995b, Geologic map of the Brentwood 7.5 minute quadrangle.
d'Alessio, M. A., Johanson, I. A., Bürgmann, R, Schmidt, D. A., and M. H. Murray. 2005, Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities. Journal of Geophysical Research 110, doi:10.1029/2004JB003496.
Prescott, W.H., Savage, J.C., Svarc, J.L., and Manaker, D., 2001, Deformation across the Pacific-North American plate boundary near San Francisco, California: Journal of Geophysical Research, v. 106, no. B4, p. 6673-6682.
Rogers, T.H., 1966, San Jose Sheet, Geologic Map of California: California Division of Mines and Geology 2° sheet, 1:250,000 scale.
Sterling, R., 2006-2007, Written & personal communication.
Sterling, R., 1992, Intersection of the Stockton and Vernalis faults, southern Sacramento Valley, California, in Chevron, V.B., and Edmondson, W.F., eds, Structural Geology of the Sacramento Basin: American Association of Petroleum Geologists Miscellaneous Publication 41, Pacific Section, p. 143-151.
Wagner, D.L., Bortugno, E.J., and McJunkin, R.D., 1991, Geologic map of the San Francisco-San Jose quadrangle: California Division of Mines and Geology, Regional Geologic Map Series, 1:250,000 scale.
Weber, J., 2006, Personal Communication.

4.2 The Vernalis Thrust Fault (blind)

Fault strand rank= Primary

Location certainty, blind Vernalis Thrust fault surface trace = Approximate
The Vernalis fault is a northwest-striking, moderately to steeply west-dipping fault in the subsurface of the western San Joaquin Valley, about 9 –12 km east of the physiographic front of the Diablo Range (Figures 1 and 2). The Vernalis fault extends for roughly 65 km between towns of Tracy and Patterson (Sterling written communication 2006-2007).

Exploration geologists who have examined proprietary subsurface data suggest that the fault may continue an unknown distance south of Patterson, so the full length of the fault is poorly known (Scott Hector, personal communication, 2006). The exact trace and extent of the Vernalis fault for this compilation is from maps and proprietary data provided by Sterling (2006-2007 personal communication).

A small-scale map in Sterling (1992) shows the northern end of the Vernalis fault curving to the west and terminating against the southern end of the West Tracy fault. This pattern may represent a link between the two faults and transfer of slip (Figure 2). R. Sterling (1992) originally inferred a component of left-lateral motion on the Vernalis fault, but now feels it is more likely that there is a component of right-lateral motion (Sterling, written communication, 2006), which is consistent with the current tectonic regime and geodetic data indicating measurable NW dextral shear extending to the western margin of the Central Valley at the latitude of the Delta (Prescott et al., 2001; d'Alessio et al., 2005).

Geologic expression:

We infer Quaternary activity of the Vernalis fault based on the systematic occurrence of older Quaternary deposits on the upthrown hanging wall block. Geologic maps of the 2° San Jose (Rogers, 1966) and San Francisco-San Jose quadrangles (Wagner et al., 1991) published by the state of California show Pleistocene fluvial deposits on the upthrown western side of the fault, and generally younger basin deposits on the downthrown side. The contact between the older and younger deposits closely follows the buried fault trace in the subsurface. The Vernalis fault also may exert control on local stream and drainage patterns. For example, the course of the San Joaquin River closely follows the buried trace of the fault for a minimum of 35 km between Patterson and Tracy, and the stream is confined to the inferred downthrown eastern block. This pattern continues north and west of Tracy, where the Vernalis fault turns more toward the west and streams like Tom Paine slough and Old River are confined to the downthrown block and appear to be deflected parallel to fault strike. These geomorphic relations are consistent with late Quaternary west-up motion on the fault, expressed as uplift of the hanging wall block and local fault-propagation folding above the fault tip.

Notes and References:

The Vernalis fault is known primarily from analysis of proprietary borehole data and seismic reflection data acquired for oil and gas exploration (Sterling, 1992; S. Hector, personal communication, 2006). Subsurface relations imaged in the reflection data suggest that the fault is a subvertical to steeply west-dipping structure that has accommodated west-side-up separation (Sterling, 1992). Interpreted reflection profiles published by Sterling (1992) show reverse separation of a Miocene unconformity across the Vernalis fault. The fault appears to die out above the offset unconformity and below the earth's surface, but folding of the layered reflectors can be traced above the tip of the fault to the top of the seismic record section. Sterling (1992) describes stratigraphic and structural relationships imaged by seismic reflection data indicating "movement as recently as late Pliocene."

d'Alessio, M. A., Johanson, I. A., Bürgmann, R, Schmidt, D. A., and M. H. Murray. 2005, Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities. Journal of Geophysical Research 110, doi:10.1029/2004JB003496.
Hector, S., 2006, Personal Communication.
Prescott, W.H., Savage, J.C., Svarc, J.L., and Manaker, D., 2001, Deformation across the Pacific-North American plate boundary near San Francisco, California: Journal of Geophysical Research, v. 106, no. B4, p. 6673-6682.
Rogers, T.H., 1966, San Jose Sheet, Geologic Map of California: California Division of Mines and Geology 2° sheet, 1:250,000 scale.
Sterling, R., 1992, Intersection of the Stockton and Vernalis faults, southern Sacramento Valley, California, in Chervon, V.B., and Edmondson, W.F., eds, Structural Geology of the Sacramento Basin: American Association of Petroleum Geologists Miscellaneous Publication 41, Pacific Section, p. 143-151.
Sterling, R., 2006-2007 Written & personal communication.
Wagner, D.L., Bortugno, E.J., and McJunkin, R.D., 1991, Geologic map of the San Francisco-San Jose quadrangle: California Division of Mines and Geology, Regional Geologic Map Series, 1:250,000 scale.

4.3.1 The Black Butte Reverse-Oblique Fault

Fault strand rank= Secondary

Location certainty, Black Butte Reverse fault surface trace = Certain-Approximate
The Black Butte fault is a northwest-striking, moderately to steeply west-dipping Quaternary fault along the physiographic boundary between the northern Diablo Range and northwestern San Joaquin Valley, located approximately 10 km southeast of the city of Tracy (Figure 2; Crane, 1988; Sowers et. al., 1993).

Geologic expression:
Sowers et al. (1992) documented about 180 m of west-side-up displacement of an early to middle Quaternary pediment surface across the Black Butte fault in the vicinity of Corral Hollow (Figure 2). Although these geomorphic and structural relations provide evidence for Quaternary activity on the fault, there is significant uncertainty in the age of the deformed surface, as well as the correlation of the pediment across the fault.

Notes and References:
Given the northwest strike of the fault and recent geodetic studies that suggest moderate rates of NW-directed dextral shear extend out to the eastern margins of the Pacific-Sierran plate boundary at the latitude of the San Francisco Bay area (d'Alessio et al., 2005), we believe it is likely that the Black Butte fault accommodates a component of dextral motion in addition to the observed reverse displacement.

Based on the preponderance of evidence, we interpret the Black Butte and Midway faults as a single structure that accommodates dextral-reverse displacement. We estimate a range in slip rate for the Black Butte fault from the inferred displacement of the pediment and middle to early Pleistocene age estimates (Sowers *et al*., 1992), and an inferred horizontal to vertical (H:V) ratio for the components of slip. If it is assumed that the offset pediment ranges in age from about 300 ka to 1 Ma, then the corresponding range in long-term average vertical separation rate is about 0.2-0.6 mm/yr. With an assumed 3:1 ratio of strike-slip to dip-slip displacement, the implied rate of net oblique slip is less than 0.6-1.8 mm/yr.

We assume that the activity rate of the Black Butte and Midway faults (section 4.3.4) is comparable, and thus discount the upper end of the range in the estimated slip rate on the Black Butte fault in favor a range that better overlaps the slip rate estimates of both structures (i.e., 0.1-1.0 mm/yr).

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

d'Alessio, M. A., Johanson, I. A., Bürgmann, R, Schmidt, D. A., and M. H. Murray. 2005, Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities. Journal of Geophysical Research 110, doi:10.1029/2004JB003496.

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open file Report 93-225.

4.3.2 The Black Butte Anticline

Fault strand rank= Tertiary

Location certainty, Black Butte Anticline axis surface trace = Certain-Concealed
Crane (1998) shows the northwest plunging anticline axis paralleling the Black Butte and San Joaquin/Orestimba faults for approximately 4 km Southeast of Corral Hollow (Figures 1 and 2).

Geologic expression:
The anticline occurs in the hanging wall of the Southwest-dipping Black Butte fault, and closely parallels the Black Butte fault South of Corral Hollow (Figures 1 and 2). We interpret the anticline to be a fault-propagation fold associated with the Black Butte fault. The anticline deforms Lower Pleistocene deposits (Crane, 1988).

Notes and References:

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

4.3.3 The Midway/Black Butte Anticline

Fault strand rank= Secondary

Location certainty, Midway/Black Butte anticline axis surface trace = Certain

Geologic expression:
This short, west- northwest trending fold occurs between the Black Butte and Midway faults (Figure 2; Crane, 1988). The anticline deforms Cretaceous and Tertiary deposits but not the Quaternary fluvial deposits. The structure exhibits an average 20 degree dip on the fold limbs (Crane, 1988 and Sowers et. al., 1992).

Notes and References:
The geomorphic expression and geometry of the Midway/Black Butte anticline suggests the structure may act as a restraining bend or step-over connecting the Black Butte and Midway faults (Figures 1 and 2).

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.3.4 The Midway Fault

Fault strand rank= Secondary

Location certainty, Midway Fault trace = Certain-Approximate
The late Cenozoic Midway fault strikes northwest and is separated from the northwest end of the Black Butte fault by a left en echelon step across the small west-northwest-trending Midway/Black Butte anticline (Figure 2) that deforms Miocene-Pliocene strata (Section 4.3.3).

Geologic expression:
Geologic mapping by Crane (1988) documents about 800 m of apparent right-lateral offset of an unconformable contact between Cretaceous and Miocene strata across the Midway fault in the SW 1/4 of section 19, T.2S., R.4E. Paleoseismic trenching investigations of the Midway fault conducted in 2004 by Geocon, Inc. documented late Pleistocene surface rupture on the fault (David Bieber, Geocon, Inc., personal communication, 2007). Slickensides on the exposed fault plane indicate dominantly subhorizontal displacement (Bieber, personal communication, 2007). Based on analysis of stereo aerial photography, Bieber (2002) interpreted geomorphic features along the fault to indicate left-lateral displacement. This interpretation is contrary to the dextral

offset of the Miocene-Cretaceous contact mapped by Crane (1988), but it is possible that the apparent dextral offset could have been created by differential uplift of the eastern block of the fault.

Notes and References:
Based on these data and observations, we conclude that the Midway fault is an active structure that primarily accommodates strike-slip displacement. Bieber's (2002) interpretation that the Midway fault is a left-lateral structure is intriguing: if this is correct, then the fault is a kinematic anomaly within the dextral Pacific-Sierran plate boundary. Alternatively, if the Midway fault is a right-lateral structure, then the small anticline separating the Black Butte and Midway faults is a restraining bend or step-over connecting the two structures (Section 4.3.3).

Based on the preponderance of evidence indicating dominantly right-lateral motion on NW-striking faults along the Pacific-Sierran plate boundary, we infer that the Midway fault is a dextral structure. We estimate a long-term average rate of dextral offset of about 0.2 mm/yr based on 800 m of late Cenozoic right-separation and an assumed duration of deformation (active during the past ~3.5 Ma).

Bieber, David W., 2002, The Midway Fault, A Left-Lateral Fault in a Right-Lateral World (Abs): Association of Engineering Geologists News, Volume 45, p. 56, Poster Session, AEG Annual Convention, Reno, Nevada, September 2002.

Bieber, D.W., 2007, Personal Communication.

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

4.4 The San Joaquin/Orestimba

Fault strand rank= Primary

Location certainty, San Joaquin/Orestimba fault trace = Concealed- Approximate
The San Joaquin/Orestimba fault is marks the physiographic boundary between the Diablo Range and the Central Valley. The fault parallels the range front from the Corral Hollow creek outlet in the North to the Garzas creek outlet in south. The fault is commonly divided into a northern and southern section, split at Del Puerto Creek outlet (Figures 1- 3). The depiction of the North fault trace was based upon the work of Sowers and others (1993) and Noller and others (1993), who followed previous workers in referring to the structure as the San Joaquin fault. The southern trace is generally bound by Del Puerto Creek to the north and Garzas Creek to the south. The trace of the fault is compiled from Jennings (1994; Figure 4), with additional confirmation of location certainty from Anderson & Piety (2001). Anderson & Piety (2001) consider the trace identified as the San Joaquin fault to be the surface expression of blind reverse/thrust fault they call the Orestimba fault. Thus, the trace on this map will be referred to by both

names to avoid confusion with previous maps (e.g. Jennings, 1994) and allow for future researchers to apply interpretations from both nomenclatures.

Geologic expression:
Northern and southern traces have accommodated west-side-up thrust fault motion. The northern part of the San Joaquin/Orestimba fault dies out as the trace starts to parallel the Black Butte fault and Black Butte anticline axis (Figure 1 and 2). Anderson & Piety (2001) estimated a slip rate of 0.4-0.6 mm/yr with roughly 60 meters of uplift along the fault since 200-300 ka. The southern portion of the fault exhibits the greatest uplift along the eastern Diablo Range in Del Puerto Canyon. Evidence for the San Joaquin/Orestimba fault terminates northward at the outlet for Garzas Creek. The southern terminus of San Joaquin/Orestimba fault is a right en echelon step to the Quinto fault (Anderson & Piety, 2001).

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.
Noller, J.S., Sowers, J.M, and Lettis, W.R., 1993, Quaternary geology of the Solyo and Lone Tree Creek 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-224.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Patterson and Crows Landing 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-223.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.5 The Midland Reverse Fault (blind)

This fault is included in the shape file submitted for this Report. However, additional information is not presented here as it can be found in more detail and with a more expanded context in the compilation report completed by Unruh and Sundermann (2006).

Unruh, J.R., Sundermann, S., 2006, Digital compilation of thrust and reverse fault data for the Northern California Map Database: Collaborative research with William Lettis & Associates, Inc., and the U.S. Geologic Survey: Final Technical Report submitted to the U.S. Geological Survey, National Hazards Reduction Program, Award No. 05-HQ-GR-0054, 20 p.

4.6.1 The Patterson Pass Fault

Fault strand rank= Secondary

Location certainty, Patterson Pass fault surface trace = Certain

Geologic expression:
The Patterson Pass fault is 21 km long and divided into two converging “splays” (Figures 1 and 2). Along strike the dominant sense of motion changes from reverse to right-lateral (Crane, 1988). Numerous splays occur along the fault. The linear NW-SE trend of the fault trace is disturbed by multiple anticlinal and synclinal features (Patterson Pass anticline and syncline, Mount Diablo antiform and the Altamont Hills anticline), which may be deforming the main fault trace (Crane, 1988). The fault cuts mid-Tertiary bedrock and is inferred to cut Quaternary landslide deposits. The trace is locally concealed under Quaternary fluvial deposits (Sowers, 1993).

Notes and References:
Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open file Report 93-225.

4.6.2 The Patterson Pass Anticline

Fault strand rank= Secondary

Location certainty, Patterson Pass anticline axis surface trace = Certain

Geologic expression:
The Patterson Pass anticline has deformed Pleistocene deposits (Sowers et. al., 1993). The axis is approximately 4.4 km in length, and is sub-parallel to the Elk Ravine and the Carnegie faults (Figure 2). The axial trace is tangential to the Patterson Pass fault and is associated with a sharp bend in the fault trace (Crane, 1988).

Notes and References:
Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.6.3 The Patterson Pass Syncline

Fault strand rank= Secondary

Location certainty, Patterson Pass syncline axis surface trace = Certain

Geologic expression:
The Patterson Pass syncline has deformed Pleistocene deposits. The axial trace is approximately 6.54 km in length. The fold axis diverges from the northwest end of the Coral Hollow-Carnegie fault trace (Figure 2) and parallels some of the bends in the Patterson Pass fault. The southern syncline terminus rejoins the Coral Hollow-Carnegie fault a few kilometers north of where the two faults diverge. (Crane, 1988)

Notes and References:

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

4.7 The Altamont Hills Anticline

Fault strand rank= Questionable

Location certainty, Altamont Hills anticline axis surface trace = Approximate

Geologic expression:
The Altamont Hills anticline parallels the Patterson Pass fault (PPF) and the Elk Ravine thrust fault (ERTF) traces for a total distance of approximately 7.7 km, plunging out to the southeast (Huey, 1948). This structure bridges the separation between the PPF and ERTF (see Figure 2), maintaining the trend of the northern section of the PPF that is continued in the ERTF trace. The anticline deforms Upper Miocene deposits (Crane, 1988).

Notes and References:

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.
Huey, A.S., 1948, Geology of the Tesla quadrangle, California: California Division of Mines and Geology Bulletin 140, 75 p. maps.

4.8 The Elk Ravine Thrust Fault

Fault strand rank= Secondary

Location certainty, Elk Ravine thrust fault surface trace = Approximate

Geologic expression:
The Elk Ravine thrust fault trace is approximately 16 km long with a linear northwest-southeast-trending trace (Figure 2). The fault cuts Tertiary bedrock and middle Pleistocene deposits and is inferred to cut Early Holocene deposits (Sowers et. al., 1993). The fault plane is described by Sowers (1993) as vertical, with the southern-most splays exhibiting a westerly dip. The fault breaks into five splays at its southern terminus near Corral Hollow canyon. The most northern splay sharply curves to an east-west trend, perpendicular to the Midway/Black Butte anticline and terminates against the Black Butte fault at the mouth of Corral Hollow canyon (Sowers et. al., 1993).

Notes and References:
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.9.1 The Corral Hollow-Carnegie Fault

Fault strand rank= Secondary

Location certainty, Corral Hollow-Carnegie Fault Surface trace = Certain

Geologic expression:
The Corral Hollow-Carnegie fault (CH-CF) splays southward from the Greenville fault on the eastern edge of the Livermore valley, then turns to a northwest-southeast strike parallel to the trend of the Diablo Range (Figure 2). The fault cuts Early Holocene deposits and is locally concealed by landslide deposits. The CH-C fault alternates between dominantly thrust to right-lateral movement along strike to the southeast (Crane, 1988). As the fault approaches the Coral Hollow Canyon and intersects the Patterson Pass syncline, undeformed Quaternary deposits overlie the fault and the fault branches into two main strands: the Corral Hollow and the Carnegie faults. The fault is approximately 10 km long, not included two minor splays (Sowers et. al., 1993).

Notes and References:
Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.
Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.9.2 The Carnegie Fault

Fault strand rank= Tertiary

Location certainty, Carnegie fault surface trace = Certain-Inferred

Geologic expression:
The north end of the Carnegie fault splays from the Corral Hollow-Carnegie fault and strikes northwest-southeast, parallel to Coral Hollow valley (Figure 2). As the Carnegie fault merges with the valley the Patterson Pass fault terminates against the Carnegie fault, and the strike of the fault changes to a more east-west orientation (Figures 1 and 2). The fault cuts early Holocene deposits and is concealed by some Quaternary landslide deposits (Sowers et. al., 1993). In the vicinity of Corral Hollow it rejoins with the Corral Hollow fault and is concealed by Quaternary fluvial deposits (Sowers et. al., 1993). The southern terminus occurs as the fault exits Corral Hollow and intersects the "inactive" or Tertiary active trace of the Tesla fault (Dibblee, 1980). The total length of the Carnegie fault surface trace is approximately 9.8 km.

Notes and References:

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Cedar Mountain quadrangle, Alameda and San Joaquin Counties, California: United States Geological Survey Open-File Report 80-850, 1:24,000 scale.

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.9.3 The Corral Hollow Fault

Fault strand rank= Probably Not Active

Location certainty, Corral Hollow fault surface trace = Certain-Inferred

Geologic expression:
The Corral Hollow fault cuts Miocene strata and is concealed by Quaternary landslide and fluvial deposits. The Corral Hollow fault splays from the northwest-southeast trending Corral Hollow-Carnegie fault and turns east-west parallel to Corral Hollow valley (Figure 2). The fault is concealed in the valley as its inferred trace terminates against the Carnegie fault. The total length of the Corral Hollow fault is 8.7 km.

Notes and References:

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

4.10.1 The Tesla–Ortigalita Fault

Fault strand rank= Probably Not Active

Location certainty, Tesla-Ortigalita fault surface trace = Certain-Inferred
The Tesla-Ortigalita fault connects the inactive Tesla fault near Lone Tree Creek, to the active North Ortigalita fault near the Orestimba Creek canyon (Figure 1).

Geologic expression:
The total length of Tesla-Ortigalita fault and all splays is 79 km. The fault trace is irregular and is apparently folded around the axis of the Mount Oso anticline (Maddock, 1964). Multiple fault strands and splays indicate the defuse deformation associated with this fault. The fault cuts Upper Cretaceous bedrock and is concealed by Quaternary fluvial, alluvial and colluvial deposits (Dibblee, 1981, Lone Tree Creek and Solyo quadrangles; and 1982, Wilcox and Copper Mountain quadrangles).

Notes and References:

Dibblee, T.W., Jr., 1981, Preliminary geologic map of the Solyo quadrangle, San Joaquin and Stanislaus Counties, California: United States Geological Survey Open-File Report 81-465, 1:24,000 scale.

Dibblee, T.W., Jr., 1981, Preliminary geologic map of the Lone Tree Creek quadrangle, San Joaquin and Stanislaus Counties, California: United States Geological Survey Open-File Report 81-466, 1:24,000 scale.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Wilcox Ridge quadrangle, Stanislaus County, California: United States Geological Survey Open-File Report 82-392, 1:24,000 scale.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Copper Mountain quadrangle, Stanislaus County, California: United States Geological Survey Open-File Report 82-393, 1:24,000 scale.

Maddock M.E., 1964, Geologic map and sections of the Mount Boardman quadrangle, Santa Clara and Stanislaus Counties, California: California Division of Mines and Geology Map Sheet 3, scale 1:62,500.

4.10.2 The Mt. Oso Anticline

Fault strand rank= Primary

Location certainty, Mount Oso anticline axis surface trace = Approximate-Inferred

Geologic expression:
Mount Oso anticline WNW-ESE and plunges to the southeast toward the major bend of the Tesla-Ortigalita fault trace near Del Puerto Creek (Raymond, 1970). The anticline axis merges or terminates against the Greenville fault. The total length of anticline is 27.3 km (Dibblee, 1980 and 1981). We interpret Mount Oso anticline as a left-

restraining step-over between the dextral northern Ortigalita and the Greenville fault zones (Figures 1 and 4).

Notes and References:

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Cedar Mountain quadrangle, Alameda and San Joaquin Counties, California: United States Geological Survey Open-File Report 80-850, 1:24,000 scale.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Wilcox Ridge quadrangle, Stanislaus County, California: United States Geological Survey Open-File Report 82-392, 1:24,000 scale.

Maddock M.E., 1964, Geologic map and sections of the Mount Boardman quadrangle, Santa Clara and Stanislaus Counties, California: California Division of Mines and Geology Map Sheet 3, scale 1:62,500.

Raymond, L.A., 1970, Cretaceous sedimentation and regional thrusting, northeastern Diablo Range, California: Geologic Society of America Bulletin, v. 81, p. 2123-2128, 2 figures.

4.10.3.1 The Ortigalita North Fault

Fault strand rank= Primary

Location certainty, Ortigalita North fault surface trace = Approximate-Inferred
The northern reach of the Ortigalita North fault lies between Del Puerto Creek and Orestimba Creek (Dibblee, 1982), and was suggested as possible rupture segment by Anderson & Piety (2001). Mapping of the fault south of Orestimba Creek to the southeastern edge of San Luis reservoir is based on Jennings (1994) with modifications by Anderson & Piety (2001).

Geologic expression:
Geomorphic expression of the fault is characterized by laterally continuous lineaments, scarps, deflected drainages, and other off-set geomorphic features (Figure 1). The fault offsets late Pleistocene gravels ~ 7 m and channel features by up to 25 m, establishing the preferred slip rate of about 1.0-2.0 mm/yr over 10-25 ka (Anderson & Piety, 2001). The total length of the fault ranges between 35-55 km, reflecting uncertainty in the full northern extent of activity (Figure 1). The reach of the Ortigalita fault north of the junction with the Tesla-Ortigalita fault is mapped by Dibblee (1982) as not cutting any Quaternary deposits. Anderson and Piety (2001) suggest that this section probably is not active, but requires further detailed investigation.

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Wilcox Ridge quadrangle,

Stanislaus County, California: United States Geological Survey Open-File Report 82-392, 1:24,000 scale.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.10.3.2 The Ortigalita South Fault

Fault strand rank= Primary

Location certainty, Ortigalita South fault surface trace = Certain-Inferred
The northern end of the Ortigalita South fault is located in the northwest edge of the San Luis reservoir, and its southern terminus is demarked by multiple splays and strands in the northern Panoche Valley (Figures 1 and 3). The compiled fault trace for this study is based on Jennings (1994) and with corrections suggested by Anderson & Piety (2001).

Geologic expression:
The Ortigalita South fault has dominantly right-lateral movement marked by linear features in the Franciscan Complex, and aligned Quaternary deposits and landforms (Figure 3). Sections of the fault in Los Banos valley exhibit discontinuous scarps offsetting Tulare Formation (Pleistocene) gravels. The Ortigalita South fault scarps have up to 2 meters of vertical displacement occurring in the last 3 ka. The approximate slip rate of the southern section is approximately 0.2-1.0 mm/yr, which is somewhat lower than the slip rate of the Ortigalita North fault. The total length of this fault is variable (17-65 km) depending on the inclusion of southern splays and the point of division between the Southern and Northern reaches. (Anderson & Piety, 2001).

Notes and References:
Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.11.1 The Basalt Hill Fault

Fault strand rank= Tertiary

Location certainty, Basalt Hill fault surface trace = Approximate

The Basalt Hill fault bounds the west side of Basalt Hill and the northeastern margin of Los Banos Valley (Figure 3). The compiled Basalt Hill fault trace is from Jennings (1994) with modifications by Anderson & Piety (2001).

Geologic expression:
The range front bounded by the Basalt Hill fault has no sharp lineaments or scarps. This fault is considered to be part of the "Los Banos Hills fault system", a dominantly east-dipping reverse fault system (Anderson & Piety, 2001). Approximately 100 meters of offset has occurred in the 535 ka for an estimated slip rate of 0.2 mm/yr. The total length of this fault is approximately 13-17 kilometers. (Anderson & Piety, 2001)

Notes and References:
Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.11.2 The Los Banos Creek Thrust Fault

Fault strand rank= Tertiary

Location certainty, Los Banos Creek Thrust fault surface trace = Approximate
The Los Banos Creek fault extends from the west side of the Basalt Hills to the southern end of Los Banos Valley (Figure 3). The compiled trace of the Los Banos Creek fault trace is from Jennings (1994) with modifications by Anderson & Piety (2001).

Geologic expression:
This fault is proximal to the Ortigalita south fault and may accommodate some strike-slip deformation. The fault is identifiable by its west-facing 5-10 meter high scarp (in 200-300 ka deposits), which extends for roughly 6 km. This fault is considered to be part of the "Los Banos Hills fault system", a dominantly east-dipping reverse fault system (Anderson & Piety, 2001). Based on the magnitude of offset on 200-300 ka deposits the estimated slip rate is 0.04 to 0.1 mm/yr. The total length of this fault is approximately 6-8 kilometers. (Anderson & Piety, 2001).

Notes and References:
Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California

Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.11.3 The Carrisalito Fault

Fault strand rank= Tertiary

Location certainty, Carrisalito fault surface trace =Approximate
The Carrisalito fault is located north of Los Banos Valley and extends to Carrisalito Flat (Figure 3). The Carrisalito fault trace was mapped based on Jennings (1994) and corrections suggested by Anderson & Piety (2001).

Geologic expression:
This fault may intersect the Basalt Hill fault to the northeast and the Ortigalita South fault to the southwest (Figure 3). The main geomorphic expression of the Carrisalito fault is a prominent linear range front within the southeastern edge of the Los Banos Valley. This fault is considered to be part of the "Los Banos Hills fault system", a dominantly east-dipping reverse fault system (Anderson & Piety, 2001). Since 200-300 ka approximately 100 meters of offset has occurred for an estimated slip rate of 0.2-0.5 mm/yr. The total length of Carrisalito fault is approximately 11-15 kilometers. (Anderson & Piety, 2001).

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.
Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.12.1 The Salado Fault

Fault strand rank= Tertiary

Location certainty, Salado fault surface trace = Approximate
The Salado fault is located at the eastern edge of the Diablo Range near the outlet of Salado Creek (Richesin, 1996). The fault strike parallels the NW-SE-trending range front for approximately 9 km and potentially extends for a greater distance to the south (Richesin, 1996; Figure 3).

Geologic expression:
The Salado fault is defined by a north-northwest striking lineament that truncates the Pliocene Oro Loma Formation. The truncated beds suggest an east-side-up movement. The fault is paralleled on both sides by two folds. The fault slip rate is estimated at 1.6

mm/yr assuming only pure strike-slip motion offsetting mid-post Pleistocene deposits (Richesin, 1996).

Notes and References:
Richesin, D.A., 1996, Late Tertiary and Quaternary geology of the Salado Creek area, California: M.S. thesis, California Statue University, Hayward, 237 p. plus plates.

4.12.2 The Salado Anticline

Fault strand rank= Tertiary

Location certainty, Salado anticline axis surface trace = Approximate
The Salado Anticline is due east of and parallel to the Salado fault. The Salado Anticline axis trends NNW-SSE, sub parallel to the Salado fault and the range front, and plunges about 10 degrees to the southeast (Figure 1). The approximate length of the fault is 3.2 km (Richesin, 1996).

Geologic expression:
The Salado Anticline is paired with a syncline to the east, with the same trend. The Salado anticline is asymmetric and vergent toward the West, with the western limb of the fold dipping less steeply than the eastern limb (Richesin, 1996).

Notes and References:
Richesin, D.A., 1996, Late Tertiary and Quaternary geology of the Salado Creek area, California: M.S. thesis, California Statue University, Hayward, 237 p. plus plates.

4.13 The Quinto Thrust Fault

Fault strand rank= Primary

Location certainty, Quinto Thrust fault surface trace = Inferred-Approximate
The Quinto fault is bounded by Garzas Creek (5 km southwest of the San Joaquin/Orestimba southern terminus) and San Luis Creek (Figures 1 and 3). The compiled surface trace is from Jennings (1994) with modifications by Anderson & Piety (2001).

Geologic expression:
Anderson and Piety (2001) interpret the Quinto fault to be the local reach of the west-dipping, blind frontal thrust fault along the physiographic boundary between the Diablo Range and Central Valley. The Quinto fault exhibits a right-stepping en echelon geometry with the Laguna Seca and San Joaquin/Orestimba faults. The fault trace is marked by a 10-km-long, northeast-facing fold scarp. Approximately 30 meters of reverse separation has occurred since 200-330 ka, suggesting a 0.2-0.3 mm/yr reverse slip rate. (Anderson & Piety, 2001)

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.14 The Laguna Seca Thrust Fault (blind)

Fault strand rank= Primary

Location certainty, Laguna Seca thrust fault surface trace = Inferred-Approximate
The Laguna Seca thrust fault trace lies between the O'Neill Forebay and the Little Panoche Reservoir (Figure 3). The surface trace compiled into this study's database is from Jennings (1994) with modifications by Anderson & Piety (2001). The fault strike matches the Diablo Range front, with an approximately length of 36-42 km.

Geologic expression:
The Laguna Seca fault is a blind west-dipping thrust fault. The fault is characterized by broad/flat geomorphic surfaces in the hanging wall projecting above the current drainage base level of the San Joaquin Valley floor. The fault is suggested to be the en echelon continuation of the frontal thrust fault along the eastern Diablo Range. The estimated late Quaternary slip rate is 0.6-1.8mm/yr (Anderson & Piety, 2001)

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.15 The O'Neill Fault System

Fault strand rank= Tertiary

Location certainty, O'Neill fault system surface trace = Approximate.
The O'Neill fault system lies between San Luis Creek and Little Panoche Valley. The surface trace is from Jennings (1994) with modifications by Anderson & Piety (2001). The O'Neill fault system is a north-northwest striking, east-dipping set of reverse faults with a total length of 38-42 km (Anderson & Piety, 2001).

Geologic expression:

The O'Neill fault system consists of 6 distinct fault segments and a fault zone (Figures 1 and 3), and is characterized by uplifted terraces, vegetation lineaments, scarps, and drainage deflections (Table 2). Lettis (1982) interprets these structures as flexural-slip bedding plane faults, and thus not likely to be independent seismic sources.

Table 2: O'Neill fault system characteristics presented in order of northwest to southeast.

Fault Segment	**Length** +/- **2 km**	**Geomorphic expression**	**Displacement & uplift**	**~ Slip rate (mm/yr)**
O'Neill Forebay	17	Lineaments: west-facing scarps in bedrock up to 30 m high.	Max. 30m since 200-300 ka	0.1-0.3
O'Neill North	13	West-facing scarps 17-44 m high.	Max. 44m since 200-300 ka	0.1-0.4
O'Neill Central	8	Scarps	~56 m since 300-500 ka	0.1-0.2
O'Neill South	11	Scarps	53 m since 300-500 ka	0.1-0.2
Billie Wright	18	Very Subdued, west-facing scarps. Includes two parallel traces,	23 m since 40-200 ka	0.1-0.6
Salt Creek	6	Very Subdued, west-facing scarps.	21 m since 40-200 ka	0.1-0.5

Table modified from Anderson and Piety (2001).

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

Lettis, W.R., 1982, Late Cenozoic stratigraphy and structures of the Western Margin of the Central San Joaquin Valley, California: United States Geological Survey Open-File Report 82-526, 202 p. 26 maps.

4.16 The "Unnamed Faults" South of San Luis Dam.

Fault strand rank= Questionable

Location certainty, Unnamed fault surface trace = Approximate

The surface trace is from Jennings (1994) with modifications by Anderson & Piety (2001), Lettis (1982), and Dibblee (1975).

Geologic expression:

These faults are labeled "Unnamed" in the database shape file. They include approximately twelve east-dipping reverse faults, each approximately 0.5-2 km in length (Figure 3). The faults are expressed as north-northwest-striking lineaments, extending from the Little Panoche Valley (Anderson & Piety, 2001). Jennings (1994) indicated that these faults were active in the Quaternary, however subsequent authors have not included or supported this.

Notes and References:

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

Lettis, W.R., 1982, Late Cenozoic stratigraphy and structures of the Western Margin of the Central San Joaquin Valley, California: United States Geological Survey Open-File Report 82-526, 202 p. 26 maps.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.17.1 The Panoche Thrust Fault (blind)

Fault strand rank= Primary

Location certainty, Panoche thrust fault surface trace = Inferred
The Panoche thrust fault is a buried fault along the eastern front of the Panoche Hills between Little Panoche Creek and Panoche Creek (Figure 3). The compiled surface trace is from Jennings (1994) with modifications by Anderson & Piety (2001). Lettis (personal communication, 2007) suggests that the Panoche Thrust is a Primary structure that deforms the alluvial sediments of the valley.

Geologic expression:
The Panoche fault is an 18-22-km long west-dipping blind thrust fault. This fault appears to be a reach of the Diablo Ranges frontal fault, south of the Laguna Seca thrust fault, although the geomorphic expression lacks the uplifted broad, flat tilted surfaces of the Laguna Seca. The Panoche Hills fault offsets the ~740 ka Tulare Formation; since, 740 ka, the slip rate has been approximately 0.5-1.5 mm/yr. (Anderson & Piety, 2001)

Notes and References:
The Panoche thrust fault is sometimes called the Panoche Hills thrust fault by Anderson and Piety (2001); however, the primary fault is the "Panoche Thrust Fault". The Panoche Hills Thrust fault is on the western range front of the Panoche Hills, and its length is less than half of that of the Panoche Thrust fault (see Section 4.18 below).

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the

San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.18 The Panoche Hills Thrust Fault

Fault strand rank= Tertiary

Location certainty, Panoche Hills thrust fault surface trace = Inferred-Approximate
The Panoche Hills thrust fault lies along the boundary between Little Panoche Valley and the southern edge of Glaucophane Ridge. The fault defines the Panoche Hills western range front (Figure 3). The surface trace compiled for this study is from Jennings (1994) with modifications by Anderson & Piety (2001) and Lettis (1982).

Geologic expression:
This fault is a north-northwest striking thrust with the eastern block upthrown. The fault geomorphology is defined by a topographically delineated contact between Quaternary valley sediment and the Cretaceous Panoche Formation. The fault trace is approximately 8 km long (Dibblee, 1971).

Notes and References:
Please see Section 4.17 for notes on fault name confusion in literature.

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Dibblee, T.W., Jr., 1971, Geologic map of the Hernandez Valley quadrangle, Pacheco Pass, Ortigalita Peak, San Benito, Panoche Valley and Quien Sabe, California; United States Geological Survey Open-File Report 71-394, 1:62,000 scale.

Lettis, W.R., 1982, Late Cenozoic stratigraphy and structures of the Western Margin of the Central San Joaquin Valley, California: United States Geological Survey Open-File Report 82-526, 202 p. 26 maps.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

4.19.1 The Panoche Hills Anticline (1)

Fault strand rank= Primary

Location certainty, Panoche Hills Anticline (1) axis trace = Approximate
The Panoche Hills anticline (1) is the dominant structure responsible for uplift of the Panoche Hills. The fold axis trends NE-SW for a length of 10.8 km (Lettis, 2007, personal communication). The fold axis trends along the northwestern edge of the Panoche hills between Panoche creek and the Panoche Hills Thrust fault (Figure 3).

Geologic expression:
The Panoche Hills anticline is actively deforming the Panoche hills at an approximate rate of 1mm/yr (Lettis, 2007). We interpret the Panoche Hills anticline to be a potential restraining-bend between the Ortigalita fault and the southern valley margin thrust faults (Dibblee, 1975).

Notes and References:
Dibblee, T.W., Jr., 1971, Geologic map of the Hernandez Valley quadrangle, Pacheco Pass, Ortigalita Peak, San Benito, Panoche Valley and Quien Sabe, California; United States Geological Survey Open-File Report 71-394, 1:62,000 scale.
Lettis, W.R., 2007, personal communication.

4.19.2 The Panoche Hills Anticline (2)

Fault strand rank= Tertiary

Location certainty, Panoche Hills Anticline (1) axis trace = Approximate
The Panoche Hills anticline is bounded by the Panoche Hills thrust fault on the west, and the Panoche thrust fault on the east (Figure 3). The fold axis trends northwest for an approximate length of 2 km (Dibblee, 1975).

Geologic expression:
The Panoche Hills anticline deforms Quaternary alluvial deposits of the Tulare formation. The eastern limb of the fold dips ~40 degrees, the western limb dips at 5 degrees, and the axis plunges to the northwest. We interpret this anticline to be a fault-propagation-fold associated with the Panoche Hills thrust fault (Dibblee, 1975), and possibly a blind southern continuation of the southern Ortigalita fault.

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.19.3 The Panoche Hills-Creek Anticline

Fault strand rank= Primary

Location certainty, Panoche Hills-Creek Anticline axis trace = Approximate

The Panoche Hills-Creek anticline runs parallel to the Panoche Hills thrust fault (Figure 3). The fold axis trends NE-SW for a length of 5 km (Dibblee, 1971).

Geologic expression:
The Panoche Hills-Creek anticline is a tight fold that deforms rocks between the Panoche Hills thrust fault and the Panoche Hills Anticline (1) (Dibblee, 1971).

Notes and References:
Dibblee, T.W., Jr., 1971, Geologic map of the Hernandez Valley quadrangle, Pacheco Pass, Ortigalita Peak, San Benito, Panoche Valley and Quien Sabe, California; United States Geological Survey Open-File Report 71-394, 1:62,000 scale.

4.20.1 Llanada Fault

Fault strand rank= Primary

Location certainty, Llanada fault trace = Approximate-Concealed
The Llanada fault is strikes ~N45W, following the strike of the boundary between Panoche Valley and the Griswold Hills for a length of ~25 km long (Figures 1 and 3). The fault can be traced from the west end of the Panoche Valley to Tres Pinos Creek (Dibblee, 1975).

Geologic expression:
The Llanada fault exhibits evidence for south-side-up displacement. The fault deforms Pliocene rocks, and is locally concealed by Quaternary alluvial deposits (Dibblee, 1975). Lettis (personal communication, 2007) suggests that the fault is a Primary fault that transfers deformation between the Central Valley's southern margin faults and the San Andreas fault.

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.
Lettis, W.R., 2007, personal communication.

4.20.2 Llanada Anticline

Fault strand rank= Tertiary

Location certainty, Llanada Anticline axis trace = Approximate
The Llanada anticline trends E-W for a length of ~1.3 km from Mercy Hot Springs to east Quien Sabe Valley (Figure 3; Dibblee, 1975).

Geologic expression:
The Llanada anticline plunges to the east, primarily deforming Franciscan rocks (Dibblee, 1975).

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.20.3 Llanada Syncline

Fault strand rank= Tertiary

Location certainty, Llanada Syncline axis trace = Approximate
The Llanada syncline trends E-W trending oblique to the strike of the Llanada fault. The syncline axis deforms strata from Panoche Pass to the Panoche Valley (Figure 3). The syncline axis can be traced for ~1.4 km, plunging to the NW (Dibblee, 1975).

Geologic expression:
The Llanada syncline fold limbs exhibit increasing dip with increasing distance form the fold axis, changing from ~30 degrees to the distal value at 50 degrees. The syncline deforms Franciscan strata (Dibblee, 1975).

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.21 Bradford Fault

Fault strand rank= Primary

Location certainty, Llanada fault trace = Approximate-Concealed
The Bradford fault strikes NW and can be traced for about 22 km between the Panoche Valley and the Quien Sabe fault (Figure 3). The Bradford fault exhibits south-up stratigraphic offset (Dibblee, 1975).

Geologic expression:
The Bradford fault deforms Pliocene rocks and is concealed by Quaternary alluvial deposits (Dibblee, 1975). Lettis (personal communication, 2007) suggests that the fault is a Primary structure that transfers deformation between the Central Valley's southern margin faults and the San Andreas fault.

Notes and References:

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

Lettis, W.R., 2007, Personal communication.

4.22.1 Griswold Hills Anticlines

Fault strand rank= Probably Not Active

Location certainty, Griswold Hills anticlines axis traces = Approximate

The Griswold Hills anticlines are a set of four small anticlines located along the southeastern front of the Griswold Hills at Panoche Valley (Figure 3), with a combined length of ~ 17 km (Dibblee, 1975).

Geologic expression:

The Griswold anticlines all plunge to the southeast, deforming the Upper Cretaceous Panoche Formation and overlain by undeformed Quaternary landslide deposits (Dibblee, 1975).

Notes and References:

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.22.2 Griswold Hills Overturned Anticline

Fault strand rank= Tertiary

Location certainty, Griswold Hills Overturned anticline axis trace = Approximate

The Griswold Hills overturned anticline deforms strata along the northwestern edge of the Griswold Hills for a length of ~13 km (Figure 3). The fold parallels the Griswold syncline and the Llanada fault (Dibblee, 1975).

Geologic expression:

The Griswold overturned anticline deforms Pliocene rocks and is overlain by Quaternary deposits that exhibit no deformation, as mapped by Dibblee (1975).

Notes and References:

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States

Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.22.3 Griswold Hills Syncline

Fault strand rank= Secondary

Location certainty, Griswold Hills syncline axis trace = Approximate
The Griswold Hills syncline is mapped along the northern front of the Griswold Hills from the eastern tip of the Llanada fault to Tummey Gulch (Figure 3), for a total length of 28 km (Dibblee, 1975).

Geologic expression:
The Griswold Hills syncline plunges to the northwest with the limbs of the fold dipping 15-30 degrees. The fold deforms Pliocene rocks and is overlain by Quaternary deposits that exhibit no deformation (Dibblee, 1975).

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and “Tummey Hills” Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.23 Panoche Creek Fault

Fault strand rank= Secondary

Location certainty, Panoche Creek fault trace = Approximate-Certain
The Panoche Creek fault strikes NW between the two tributaries to Panoche Creek at the southeast end of Panoche Valley (Figure 3), with an approximate total length of 4.3 km (Dibblee, 1975).

Geologic expression:
The Panoche Creek fault is characterized by northeast-side-up movement, which defines the topography at the southeastern edge of Panoche Valley. The fault displaces the Cretaceous Tierra Loma Formation ~1 km. The offset formation creates the boundary between the Moreno shale and the Quaternary alluvium of the Panoche Valley (Dibblee, 1975).

Notes and References:
Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and “Tummey Hills” Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.23 Panoche Hills-Creek Fault

Fault strand rank= Probably Not Active

Location certainty, Panoche Hills-Creek fault trace = Concealed
The Panoche Hills-Creek fault dissects the southern end of the Panoche Hills (Figure 3). The total length of the fault is about 8 km (Dibblee, 1975).

Geologic expression:
The Panoche Hills Creek fault is characterized by northeast-upthrown movement, which displaces the Upper Cretaceous Panoche Formation. The fault trace is concealed by Quaternary deposits within the Panoche Creek drainage (Dibblee, 1975).

Notes and References:

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

4.24 "UnNamed" Blind fault

Fault strand rank= Primary

Location certainty, UnNamed Blind fault trace = Concealed
The unnamed buried demarcates the southern edge of the Panoche valley and the initial topography of the Griswold Hills (Figure 3). The fault trace was compiled form topography lineaments, and supported by Lettis (2007, personal communication).

Geologic expression:
The fault trace is concealed by Quaternary deposits within the Panoche Creek drainage (Dibblee, 1975). Lettis (personal communication, 2007) suggests that the UnNamed fault is a Primary structure that deforms the alluvial sediments of the valley.

Notes and References:

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.
Lettis, W.R., 2007, personal communication.

5.0 References

Anderson, L.W, and O'Connell, 2005, Styles and rates of Quaternary deformation in the San Luis area, eastern Diablo Range, California: Geological Society of America Abstracts with Programs, v. 37, no. 4, p. 106-107.

Anderson, L.W. and Piety, L.A., 2001, Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diablo Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California, U.S. Bureau of Reclamation, Seismotectonic Report 2001-2, 76 p.

Argus, D. F., and R. G. Gordon, 2001, Present tectonic motion across the Coast ranges and San Andreas fault system in central California, Geol. Soc. Am. Bull. 113, 1580-1592.

Bieber, D.W., 2002, The Midway Fault, A Left-Lateral Fault in a Right-Lateral World (Abs): Association of Engineering Geologists News, Volume 45, p. 56, Poster Session, AEG Annual Convention, Reno, Nevada, September 2002.

Bieber, D.W., 2007, Personal Communication.

Crane, R.C., 1995a, Geologic map of the Midway 7.5 minute quadrangle.

Crane, R.C., 1995b, Geologic map of the Brentwood 7.5 minute quadrangle.

Crane, R., 1988, Geologic maps of the Altamont, Antioch North, Antioch South, Brentwood, Byron Hot Springs, Diablo, Dublin, Clayton, Livermore, Midway, Tassajara, and Tracy 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

d'Alessio, M. A., Johanson, I. A., Bürgmann, R, Schmidt, D. A., and M. H. Murray. 2005, Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities. Journal of Geophysical Research 110, doi:10.1029/2004JB003496.

Dibblee, T.W., Jr., 1971, Geologic map of the Hernandez Valley quadrangle, Pacheco Pass, Ortigalita Peak, San Benito, Panoche Valley and Quien Sabe, California; United States Geological Survey Open-File Report 71-394, 1:62,000 scale.

Dibblee, T.W., Jr., 1975, Geologic map of the Ortigalita Peak, Pacheco Pass, Panoche Valley, Hollister, San Benito, Quien Sabe, and "Tummey Hills" Fifteen minute Quadrangle, San Benito, Merced, and Fresno Counties, California: United States Geological Survey Open-File Report 75-394, 1:62,500 scale.

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Cedar Mountain quadrangle, Alameda and San Joaquin Counties, California: United States Geological Survey Open-File Report 80-850, 1:24,000 scale.

Dibblee, T.W., Jr., 1981, Preliminary geologic map of the Solyo quadrangle, San Joaquin and Stanislaus Counties, California: United States Geological Survey Open-File Report 81-465, 1:24,000 scale.

Dibblee, T.W., Jr., 1981, Preliminary geologic map of the Lone Tree Creek quadrangle, San Joaquin and Stanislaus Counties, California: United States Geological Survey Open-File Report 81-466, 1:24,000 scale.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Wilcox Ridge quadrangle, Stanislaus County, California: United States Geological Survey Open-File Report 82-392, 1:24,000 scale.

Dibblee, T.W., Jr., 1982, Preliminary geologic map of the Copper Mountain quadrangle, Stanislaus County, California: United States Geological Survey Open-File Report 82-393, 1:24,000 scale.

Graymer, 2004, written communication.

Hector, S., 2006, Personal Communication.

Huey, A.S., 1948, Geology of the Tesla quadrangle, California: California Division of Mines and Geology Bulletin 140, 75 p. maps.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

Lettis, W.R., 1982, Late Cenozoic stratigraphy and structures of the Western Margin of the Central San Joaquin Valley, California: United States Geological Survey Open-File Report 82-526, 202 p. 26 maps.

Lettis, W.R., 2007, Personal Communication.

Maddock M.E., 1964, Geologic map and sections of the Mount Boardman quadrangle, Santa Clara and Stanislaus Counties, California: California Division of Mines and Geology Map Sheet 3, scale 1:62,500.

Noller, J.S., Sowers, J.M, and Lettis, W.R., 1993, Quaternary geology of the Solyo and Lone Tree Creek 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-224.

Prescott, W.H., Savage, J.C., Svarc, J.L., and Manaker, D., 2001, Deformation across the Pacific-North American plate boundary near San Francisco, California: Journal of Geophysical Research, v. 106, no. B4, p. 6673-6682.

Raymond, L.A., 1970, Cretaceous sedimentation and regional thrusting, northeastern Diablo Range, California: Geologic Society of America Bulletin, v. 81, p. 2123-2128, 2 figures.

Richesin, D.A., 1996, Late Tertiary and Quaternary geology of the Salado Creek area, California: M.S. thesis, California Statue University, Hayward, 237 p. plus plates.

Rogers, T.H., 1966, San Jose Sheet, Geologic Map of California: California Division of Mines and Geology 2° sheet, 1:250,000 scale.

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Patterson and Crows Landing 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-223.

Sowers, J.M., Noller, J.S., and Lettis, W.R., 1993, Quaternary geology of the Tracy and Midway 7.5 minute quadrangles, California: United States Geological Survey Open-file Report 93-225.

Sterling, R.H. Jr., 2006-2007. Personal Communication.

Sterling, R.H. Jr., 1992, Intersection of the Stockton and Vernalis Faults, Southern Sacramento Valley, California. *In* Cheveron, V.B., and Edmondson, W.F., eds., Structural Geology of the Sacramento Basin: Miscellaneous publication, Pacific Section, AAPG, p. 143-151.

Thrust Fault Subgroup, 1999, Report on Thrust Fault Sources to the Working Group on Northern California Earthquake Probabilities: compiled and submitted by J. R, Unruh, William Lettis & Associates, Inc., 21 p.

Unruh, J. Sowers, J., Noller, J., and Lettis, W., 1992, Tectonic wedging and late Cenozoic evolution of the eastern Diablo Range mountain front, northwestern San Joaquin

Valley, California, in Erskine, M.C., Unruh, J., Lettis, W.R., and Bartow, J.A., eds., Field Guide to the Tectonics of the Boundary Between the California Coast Ranges and Great Valley of California: Pacific Section, American Association of Petroleum Geologists, guidebook GB-70, p. 13-22.

Unruh, J. R. and T. S. Sawyer, 1995, Late Cenozoic growth of the Mt. Diablo fold-and-thrust belt, central Contra Costa County, California, and implications for transpressional deformation of the northern Diablo Range: Abstracts, Pacific Section Convention, American Association of Petroleum Geologists 47.

Unruh, J.R., and W.R. Lettis, 1998, Kinematics of transpressional deformation in the eastern San Francisco Bay region, California: Geology, v. 26, p. 19-22.

Unruh, J. R. and T. S. Sawyer, 1998, Paleoseismic investigation of the northern Greenville fault, eastern San Francisco Bay area, California: Final Technical Report submitted to the U.S. Geological Survey, National Hazards Reduction Program, Award No. 1434-HQ-97-GR-03146, 34 p.

Unruh, J.R., Sundermann, S., 2006, Digital compilation of thrust and reverse fault data for the Northern California Map Database: Collaborative research with William Lettis & Associates, Inc., and the U.S. Geologic Survey: Final Technical Report submitted to the U.S. Geological Survey, National Hazards Reduction Program, Award No. 05-HQ-GR-0054, 20 p.

Wagner, D.L., Bortugno, E.J., and McJunkin, R.D., 1991, Geologic map of the San Francisco-San Jose quadrangle: California Division of Mines and Geology, Regional Geologic Map Series, 1:250,000 scale.

Weber, J., 2006, Personal Communication.

Wentworth, C.M., Blake, M.C. Jr., Jones, D.L., Walter, A.W., and Zoback, M.D., 1984, Tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges, in Blake, M.C. Jr., ed., Franciscan Geology of Northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 163-173.

Working Group on Northern California Earthquake Probabilities, 1999, Earthquake probabilities in the San Francisco Bay region: 2000 to 2030 - A summary of findings: U.S. Geological Survey Open-File Report 99-517.

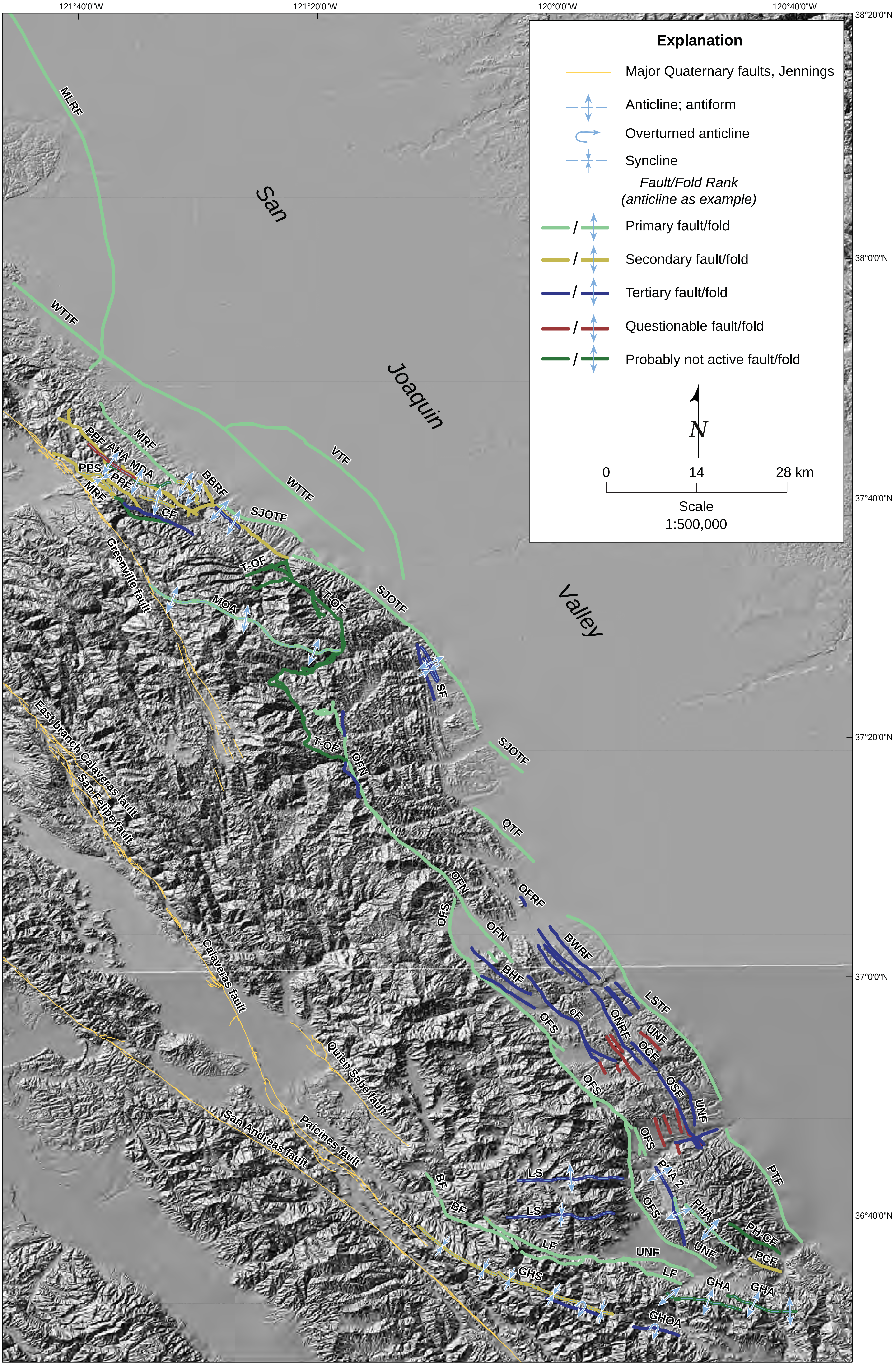

Figure 1 Area of Diablo Range with updated faults and folds.

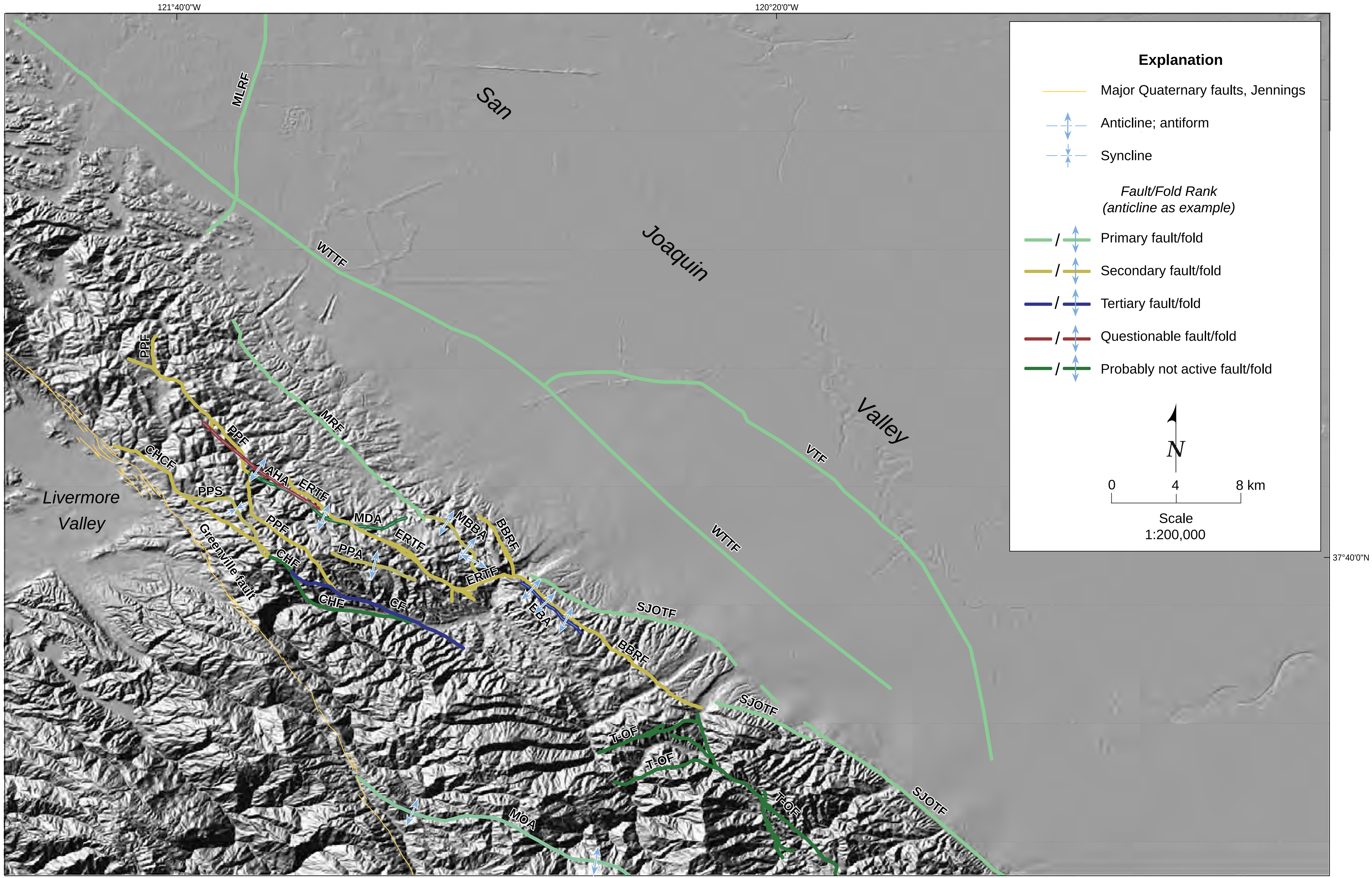

Figure 2 Northwest study area: Diablo Range updated Quaternary faults and folds.

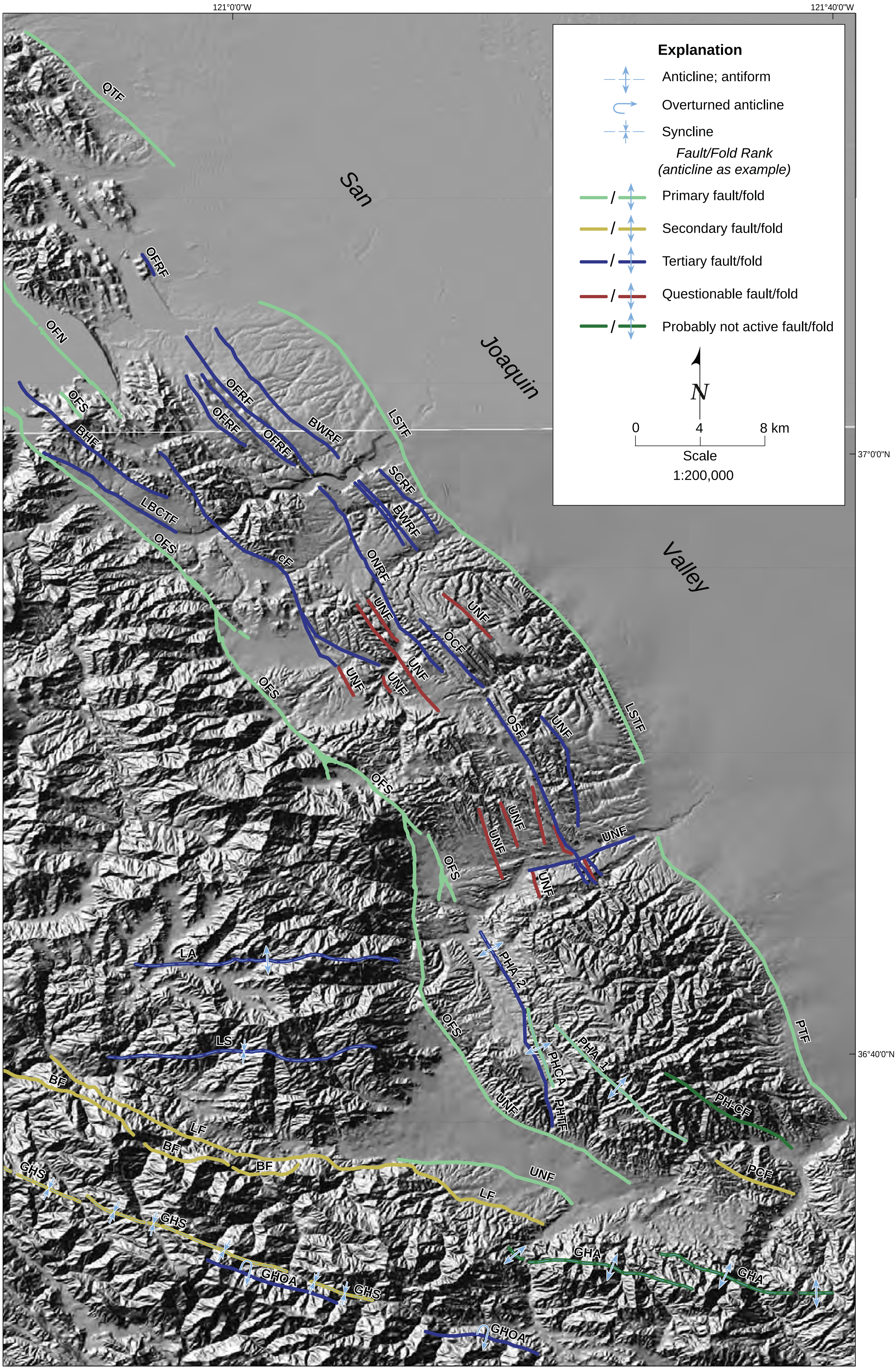

Figure 3 Southeast study area: Diablo Range updated Quaternary faults and folds.

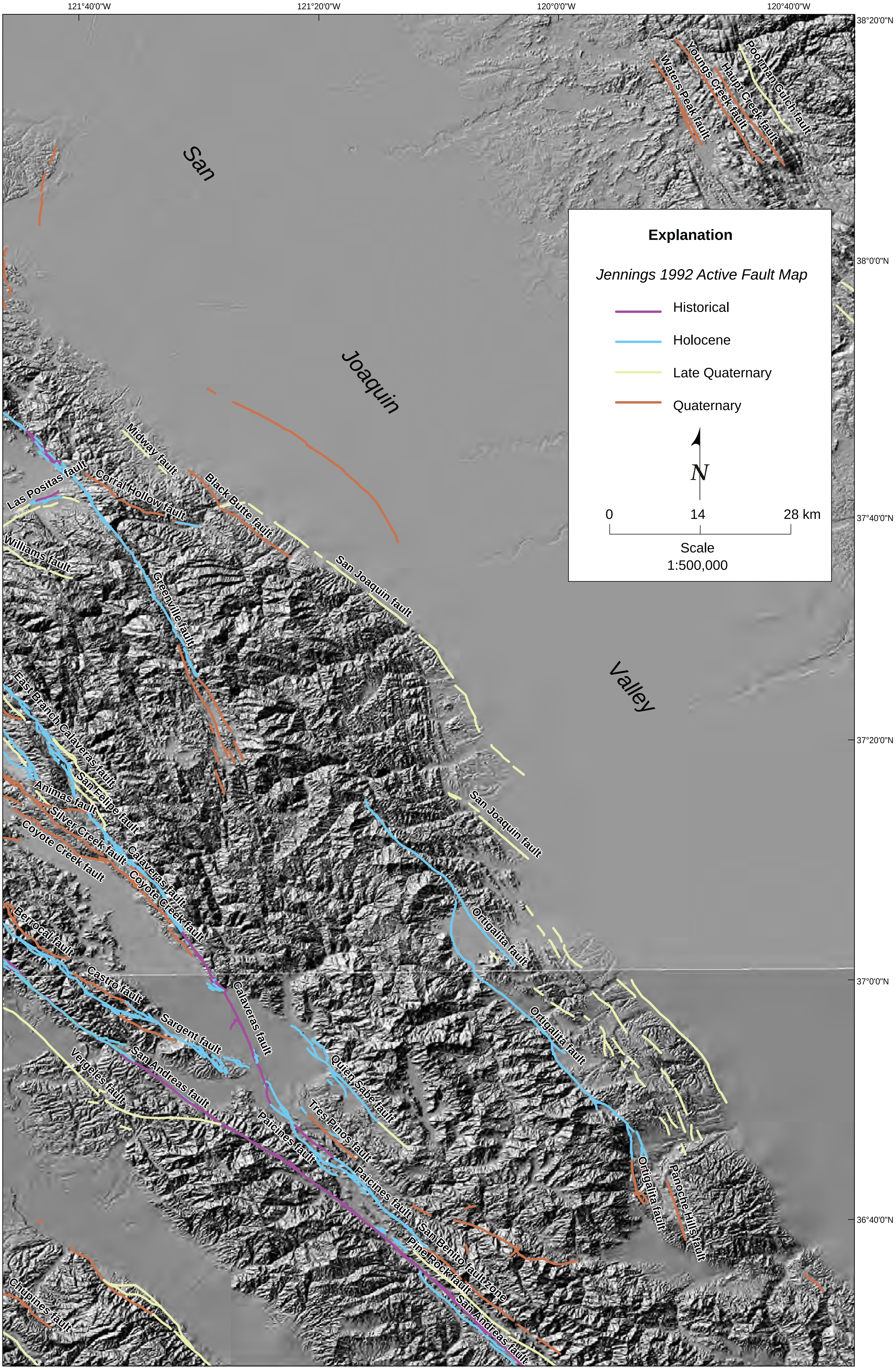

Figure 4 Area map with Jennings 1992 faults.