FINAL TECHNICAL REPORT

DIGITAL COMPILATION OF NORTHERN CALAVERAS FAULT DATA FOR THE NORTHERN CALIFORNIA 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 fault traces along the Northern Calaveras fault in the eastern San Francisco Bay region. The work described herein is part of a collaborative effort between private and academic geologists and the U.S. Geological Survey (USGS) to construct a Quaternary fault map and database for the San Francisco Bay area. The goal of this study is to compile geologic data on the active Northern Calaveras fault in a digital format for the Northern California Quaternary Fault Map Database (NCQFMD). This new compilation of fault traces revises and builds upon previous work between Calaveras Reservoir on the south and the town of Danville on the north. The digital database of fault characteristics developed in this work helps define fault-related hazards along the Northern Calaveras fault. Development of this fault database is important for adequately documenting the current understanding of the fault, and is key to the current USGS effort to develop digital, up-to-date geologic maps of the Bay area. The Northern Calaveras fault database resulting from this effort was submitted to the U.S. Geological Survey in November 2005, as summarized by Kelson (2005), Kelson and Sundermann (2006), and Sundermann and Kelson (2007). The Northern Calaveras fault data also were integrated into the USGS regional NCQFMD database, which is summarized by Graymer et al. (2006). The digital database has been revised slightly since the November 2005 submittal, and will be submitted to the USGS in conjunction with the submittal of this Final Technical Report.

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1.0 INTRODUCTION

The Calaveras fault is interpreted to consist of three primary sections (Kelson et al., 1999; Kelson, 2001; WGCEP, 2003), including the Northern, Central, and Southern sections (Figure 1). The Northern Calaveras fault is considered to be the section most likely to generate a large or moderate earthquake in the foreseeable future (WGCEP, 2003). The fault traverses the suburban and commercial corridor known as the San Ramon Valley in the eastern San Francisco Bay area, and is judged capable of generating large ($\mathbf{M} \geq 6.75$) earthquakes. The digital database of fault characteristics developed in this work helps define fault-related hazards, in particular the locations and distribution of surface rupture. Development of this fault database is important for adequately documenting the current understanding of the locations of active fault strands, and is key for USGS efforts to develop digital, up-to-date geologic maps of the San Francisco Bay area.

The goal of this study is to compile geologic and geomorphic data on the Northern Calaveras fault in a digital format for the Northern California Quaternary Fault Map Database (NCQFMD). This study is a collaborative effort with other researchers, and was coordinated by Dr. Russell Graymer of the U.S. Geological Survey (Menlo Park). The research priorities for the NCQFMD project are:

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

This effort addresses the first three of these datasets, and includes a database of interpreted fault traces according to fault strand location, rank, and uncertainty. The geomorphic expression of each strand is included as part of the subjective assessment of fault strand rank. In addition, the database is a compilation of several site-specific point datasets relevant to characterizing individual fault strands, including (1) locations of selected trenches; (2) locations of selected boreholes, and (3) locations of fault strands identified via geomorphic features, active creep, or trench exposures. Section 2 gives an overview of the Northern Calaveras fault. Section 3 describes the process used in developing the fault database, and the metadata for the fault mapping. Section 4 summarizes information on specific sub-sections of the fault, Section 5 provides conclusions, and Section 6 contains references.

The Northern Calaveras fault database resulting from this effort was submitted to the U.S. Geological Survey in November 2005, and was summarized by Kelson (2005), Kelson and Sundermann (2006), and Sundermann and Kelson (2007). The Northern Calaveras fault data also were integrated into the USGS regional NCQFMD database, which is presented by Graymer et al. (2006). This map and database of the Northern Calaveras fault complements and extends a digital database of potentially fault-related lineaments developed for the Central Calaveras fault by Witter et al. (2003), although the database for the Northern Calaveras fault interprets locations and characteristics of individual fault strands rather than potentially fault-related features. The digital database has been revised slightly since the November 2005 submittal, and will be submitted to the USGS in conjunction with the submittal of this Final Technical Report.

2.0 OVERVIEW OF THE NORTHERN CALAVERAS FAULT

The WGCEP (1999, 2003) considered the Northern Calaveras fault to extend from Danville on the north to the southern end of Calaveras Reservoir on the south (Figure 2), and assign a segment length of 28 ± 3 mi (45 ± 5 km) for the fault. The Northern Calaveras fault is distinct from the neighboring Central Calaveras fault on the south, based on several characteristics (Kelson, 2001). First, there is relatively sparse microseismicity associated with the Northern Calaveras fault (Ellsworth et al., 1982; Oppenheimer et al., 1990; Oppenheimer and MacGregor-Scott, 1992), with only one moderate historical earthquake possibly associated with the fault, the 1861 **M**5.8 San Ramon Valley earthquake. This earthquake is associated with surface cracking in San Ramon for a length of either 4 km (Jennings, 1994) or 10 to 13 km (Rogers and Halliday, 1992), although this cracking has been attributed to landsliding (Hart, 1981) or possibly strong ground shaking (WGCEP, 2003), rather than surface fault rupture. Several small- to moderate-magnitude earthquake sequences have occurred adjacent to the Northern Calaveras fault within the past forty years, as shown on Figure 2.

Second, prominent instrumental seismicity on the Central Calaveras appears to continue onto the Mission seismicity trend, rather than onto the Northern Calaveras fault (Manaker et al., 2006). This change in seismicity coincides with a change in fault strike, with the Northern Calaveras in Sunol Valley having a more northerly (about N20^{o}W) strike than the Central Calaveras fault south of Calaveras Reservoir (N30^{o}W to N35^{o}W). The two fault segments intersect near Calaveras Reservoir in a right-releasing bend geometry that has produced the Calaveras Valley pull-apart basin.

Third, the Northern Calaveras fault has a present-day creep rate of 2 to 4 mm/yr (Galehouse and Lienkaemper, 2003). This rate is substantially less than the measured creep on the Central Calaveras fault, which has a creep rate of 13.5 to 16.3 mm/yr at Coyote Ranch (Galehouse and Lienkaemper, 2003) and 14 to 16 mm/yr at Furtado Ranch (Kelson et al., 2003). Fourth, the long-term geologic slip rate on the Northern Calaveras fault is lower than that along the Central Calaveras fault, with a rate of 4 to 7 mm/yr from the Leyden Creek site (Kelson et al., 1996) and 6 ± 1 mm/yr from the Welch Creek site (Simpson et al., 1999). Both of these research sites are directly north of Calaveras Reservoir (Figure 3). WGCEP (1999, 2003) considered a slip rate of 6 ± 2 mm/yr for the Northern Calaveras fault. Paleoseismic studies on the Central Calaveras fault at San Ysidro Creek provide a substantially higher rate of 14 ± 5 mm/yr (Kelson et al., 1998; Baldwin et al., 2002).

The timing of past large earthquakes on the Northern Calaveras fault is known primarily from the Leyden Creek, Welch Creek, and Valley Crest Nursery sites, all of which are located northwest of Calaveras Reservoir (Figure 3). The Leyden Creek site provides evidence of four to six surface ruptures within the past approximately 2,500 years, suggesting a recurrence interval of 550 ± 300 years (Kelson et al., 1996). The Welch Creek site shows evidence of three ruptures within about the same time frame (Simpson et al., 1999), although the depositional environment at this site did not preserve a complete stratigraphic record that could preclude the occurrence of additional events during this time period. Observations from Leyden Creek and Welch Creek indicate that the most-recent surface-rupturing earthquake (MRE) probably occurred between about AD 1160 and 1425. At the Valley Crest Nursery site, Baldwin et al. (1998) interpret that the MRE occurred between about AD 1100 and 1300, which is probably the date of the most recent large earthquake on the Northern Calaveras fault that ruptured in Sunol Valley and at least to Leyden Creek. The clear evidence of large surface ruptures along the Northern Calaveras fault contrasts with the prevailing interpretation of the Central Calaveras fault, which is generally thought to be incapable of generating a large-magnitude earthquake (WGCEP, 1999, 2003).

3.0 MAP DEPICTION OF NORTHERN CALAVERAS FAULT TRACES

Previous digital compilations of data on the Calaveras fault includes the National Quaternary Fault and Fold database, which provides a detailed digital compilation of the characteristics of the primary sections of the Calaveras fault, extending from the town of Danville on the north to the Paicines fault on the south, near the town of Hollister (Bryant and Cluett, 1999a, 1999b, and 1999c). The California Geological Survey (CGS) also has developed over the past several decades a complementary digital GIS database of Holocene-active Alquist-Priolo ("A-P") fault traces. In addition, the CGS developed digital files depicting the areas of investigations conducted prior to 2001 for regulatory compliance with the A-P Act, although individual trenches or other relevant subsurface data are not identified in this database. Prior to the effort described in this report, these data were not linked into a consistent, comprehensive database that could be accessed for scientific research, engineering-driven seismic hazard analyses, or public outreach. A primary goal of this proposed collaborative effort is to compile these digital databases into a consistent map-based digital product for use in scientific research, consulting, and public outreach activities. As noted above, this database was submitted to the USGS in November 2005, and an updated version is being provided to the USGS in conjunction with this report.

This work compiled existing fault-related data on the 45-km-long Northern Calaveras fault between Calaveras Reservoir on the south and the town of Alamo on the north (Figure 2). Although fault traces along this fault section have been termed "elusive" (Taylor, 1992; Rogers and Halliday, 1992), there has been no comprehensive digital compilation of surface and subsurface information along the fault since development of Alquist-Priolo (A-P) maps in 1981 (Herd, 1977; Hart, 1979, 1980a, 1980b, 1981; Bryant, 1981; Hart and Bryant, 1997). Our previous analyses of the Northern Calaveras fault (Simpson et al., 1992, 1994) generated a small-scale map of possible fault-related lineaments, although this mapping pre-dates many subsurface studies along the fault related to residential developments within the A-P zone. The San Ramon Valley has undergone tremendous urbanization during the past two decades since publication of the most-recent A-P fault zonation maps, and additional subsurface data are now available for delineating active and inactive fault traces and updating fault maps. In addition, several unpublished consulting investigations and research-level exploratory trenches for the Bay Area Paleoseismology Experiment (BAPEX) provide significant new data that are important for characterizing the Northern Calaveras fault.

Our effort involved compiling existing map and trench data, including compilation of existing digital A-P maps, unpublished consultant's reports and recent research investigations. We also analyzed aerial photography taken in 1939, 1940, 1957, 1974, and 1996 along all or parts of the fault, and reviewed other relevant data (i.e., vintage topographic maps and bathymetric maps of the Calaveras Reservoir area) to interpret the locations and characteristics of primary and secondary fault traces. Trench locations were compiled from A-P and other reports onto 1:6,000-scale aerial photographs taken in 1996. The presence or absence of faults in trenches, field exposures, or borehole arrays, and the locations of known fault creep, were compiled on the detailed 1996 air photos. Parts of the fault covered by extensive landsliding also were delineated to better define the uncertainties in fault location, although there are several locations where the fault extends upward to the ground surface through large landslides deposits and is still associated with fault-related geomorphic features. The fault strands developed in this effort were compared with previously published A-P zonation maps, the statewide fault map by Jennings (1994), and a local fault-lineament map by Simpson et al. (1992), although this effort interprets the locations of active fault strands based on a substantially larger database and a more detailed analysis of available trench, creep, and borehole data that allows a greater resolution in map scale.

The primary and secondary fault traces were mapped in ArcGIS 9.1 and attributed using the NCQFMD format for incorporation into the USGS regional database. As noted, this database was submitted to the USGS Menlo Park in November 2005, in this format. Fault strands were attributed according to location certainty (e.g., certain, approximate, concealed) and confidence in the constraints on location (e.g., well, moderately, poorly constrained). The relative location certainty was assigned on the basis of exposures in cross-fault trenches, interpretations of near-surface borehole data, geomorphic features, and analysis of aerial photographs. Uncertainties related to these data sets are based primarily on the accuracy of the original data sets; in other words, on the accuracy of registering trench and borehole locations as depicted in the original consulting reports, except where data locations were verified in the field or checked using detailed aerial photography. Because active strands of the Northern Calaveras fault commonly are associated with geomorphic expression (ranging from strong to subtle), the accuracy of fault strands in this data base is better than if the mapping was based only on trench exposures.

3.1 Metadata for the Northern Calaveras Fault Database

The database was compiled using ArcGIS 9.1, a Geographic Information System created by Environmental Systems Research Institute (ESRI, Redlands, California). The comprehensive database consists of the Northern Calaveras fault compilation database, supporting metadata, and this report. The mapping consists of compiled geologic and fault data from unpublished consultant's reports and academic investigations appended with revisions by the authors to complete continuity amongst the datasets at this large geographic scale. Geologic mapping of the Northern Calaveras fault was compiled at the most detailed scale available.

The fault map database consists of three ARC shapefiles, created and attributed within the NCQFMD format for incorporation into the USGS regional database. The primary shapefile, **NorCalaveras_fault**, presents our final interpretation of the fault, at fault strand resolution, as a polyline file. Two additional shapefiles, **AP_trenches** and **NCfault_locales**, present digitization of the compiled datasets used in our interpretation. The A-P trenches polyline shapefile is a digitization of paleoseismic trench locations from Alquist-Priolo studies and research investigations performed along the Northern Calaveras fault or within about 1 km of the primary fault zone. The **NCfault_locales** point shapefile depicts the exact locations of fault exposures within individual trenches, as interpreted from trench logs in publications or consulting A-P reports, or the locations of fault strands based on prominent geomorphic expression.

Fault-related lineaments, geomorphic expressions and topographic features were mapped using stereo-paired, historic air photos taken along all or parts of the fault in 1939, 1940, 1957, 1974, and 1996. Lineament maps were compiled and scanned using a large format color scanner with a resolution of 1200 dots per inch. The scanned maps and air photos were georectified into the working coordinate system for vectorization using the Georeferencing extension in ArcGIS 9.1. 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. Fault-related features were vectorized using the rectified aerial photographs compared to digital ortho-photoquads via a heads-up digitization process, and were drawn as accurately as possible at the map scale of 1:12,000. Fault-related features were overlain onto digital topographic quadrangle maps. Site-specific trenches, boreholes or other features constraining the fault locations were compiled digitally on these topographic maps. Attribute tables were completed within the GIS and follow the NCQFMD format.

Vectorized maps and the acquired digital files were compiled at a map scale of 1:12,000. 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 1:12,000. 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.

4.0 PHYSICAL SUB-SECTIONS OF THE NORTHERN CALAVERAS FAULT

This section provides additional explanation of the characterization of Northern Calaveras fault strands and their attribution in the GIS database. Figures 4a to 4e illustrate the pattern of fault strands comprising the Northern Calaveras fault, as compiled in the digital database. This map compilation provides a basis for interpreting seven sub-sections of the fault, as suggested by fault strike, sense of slip geomorphic expression, fault-trace map pattern, and other fault characteristics (Figure 2; Table 1). In a general sense, these sub-sections are characterized by differences in relative amounts of strike-slip, transpression, and transtension (Figures 4a to 4e). The sub-sections are not likely to represent individual fault-rupture segments during large-magnitude earthquakes on the Northern Calaveras fault, although the style and pattern of surface deformation is expected to vary amongst the sub-sections. Sections 4.1 to 4.7 below addresses the primary characteristics of each of the seven sub-sections, described from the southern end of the Northern Calaveras fault near Calaveras Reservoir, northward to the northern end of the fault near the town of Alamo (Figures 4a to 4e; Table 1**)**.

Several workers have divided the Northern Calaveras fault into sub-sections, and interpreted possible earthquake rupture lengths on this basis (Simpson et al., 1992; WGNCEP, 1996; Kelson, 2001). Using primarily geomorphic features, Simpson et al. (1992) divided the Northern Calaveras fault into four sub-sections, including a 7-km-long “Calaveras Reservoir” sub-section as a transition with the Central Calaveras fault, a 9-km-long “Sunol” sub-section, a 23-km-long “San Ramon” sub-section, and a 9-km-long “Alamo” sub-section at the northern end of the fault. Simpson et al. (1992) differentiated between these sub-sections based on the fault’s location along the western and eastern margins of uplifted range blocks. The WGNCEP (1996) divided the Northern Calaveras fault into three sub-sections on the basis of simple geometric interpretation of the surface fault trace. Their fault model includes a 14-km-long “Sunol Valley” subsection, a 13-km-long “Amador Valley” subsection, and a 15-km-long “San Ramon Valley” subsection. The WGNCEP (1996) and Kelson (2001) cite the presence of “distinct right-stepovers” in the surface fault trace as the locations of sub-section endpoints. Kelson (2001) noted that the right-stepovers probably do not inhibit earthquake rupture propagation, and that the sub-sections noted by Simpson et al. (1992) and WGNCEP (1996) likely do not represent individual rupture segments. On this basis, the Working Group (2003) did not consider rupture scenarios involving sub-sections of the Northern Calaveras fault.

Table 1. Northern Calaveras fault sub-section boundaries, lengths, and orientations.

Sub-section	*Boundary*	*Latitude*	*Longitude*	Length (km)	Average Between	Azimuth Endpoints
	Via Romero	*37.849*	*-122.041*			
Danville/Alamo				**9.2**	**320˚**	**N40W**
	Deerwood Road	*37.779*	*-121.983*			
San Ramon Embayment				**2.4**	**330˚**	**N30W**
	Bollinger Canyon Road	*37.760*	*-121.972*			
Southern San Ramon Valley				**5.7**	**325˚**	**N35W**
	Koopman Canyon	*37.715*	*-121.940*			
Dublin Embayment				**2.3**	**343˚**	**N17W**
	Dublin Canyon Road	*37.695*	*-121.934*			
Pleasanton Ridge				**12.9**	**329˚**	**N31W**
	Highway 680	*37.589*	*-121.871*			
Sunol Valley				**8.5**	**336˚**	**N24W**
	Alameda Creek	*37.517*	*-121.842*			
Calaveras Reservoir				**8.7**	**335˚**	**N25W**
	Marsh Road	*37.444*	*-121.804*			

4.1 Calaveras Reservoir Sub-Section

Calaveras Reservoir inundates Calaveras Valley, which was a broad, flat-floored valley that coincides with a releasing bend between the Northern and Central Calaveras faults. This releasing bend is a well-defined segmentation point between the Northern and Central Calaveras faults, on the basis of differences in fault strike, microseismicity, and slip rates (Oppenheimer and Lindh, 1992; Wong and Hemphill-Haley, 1992; Andrews et al., 1993; Kelson, 2001; WGCEP, 2003; Manaker et al., 2006). Structural and behavioral differences between the Northern and Central Calaveras faults indicate that the Calaveras Valley releasing stepover likely strongly influences the lengths and locations of large earthquake ruptures (Kelson, 2001; WLA, 2004b, 2005).

Detailed trenching and field mapping by WLA (2004b, 2005) demonstrates that the overall pattern of faulting in Calaveras Valley involves several north-northwest-striking faults arranged in a left-stepping *en echelon* pattern (Figure 4a). This pattern extends from the southeastern corner of the reservoir, through Corral Point, and to the northwestern arm of the reservoir, and it may continue northward through the Leyden Creek site and to the Welch Creek site (Figure 4a). Analysis of existing geologic/topographic data and reconnaissance-level mapping provide information on the pattern of prominent fault strands in the vicinity of Calaveras Valley. The pre-reservoir topographic map shows that the gently north-sloping floor of Calaveras Valley had little relief, but was bordered on the west and east by topographic breaks-in-slope that likely are related to active faulting. Witter et al. (2003) and WLA (2004b, 2005) interpret that the valley contains several north-trending active fault strands, arranged in a left-stepping *en echelon* pattern (Figure 4a).

Fault strands bordering the western and eastern margins of southern Calaveras Valley (Bryant, 1981; Witter et al., 2003), are associated with topographic scarps that suggest components of down-to-the-east and down-to-the-west displacements, respectively. The eastern fault strand (Figure 4a) is a north-striking (N5^{o}W, vertical) fault that displaces gravel deposits and coincides with a prominent, 30-ft-high east-facing escarpment in late Quaternary deposits (WLA, 2005). This fault projects northward to now-inundated lineaments along the eastern valley margin identified by Bryant (1981) and Witter et al. (2003), and to a prominent west-facing break-in-slope (now inundated) south of Arroyo Hondo (Figure 4a). Exploratory trenches at Corral Point (WLA, 2004b, 2005) demonstrate predominantly dextral slip along this active fault strand. The geomorphic expression of the western fault strand at the southern end of the valley is less distinct than the eastern strand, but is coincident with a series of truncated ridge spurs and linear drainages (Witter et al., 2003). This strand projects northwestwardly toward the western margin of Calaveras Valley, and likely is a secondary strand of the fault zone. Overall, the Calaveras Valley releasing bend contains several north-striking active faults, separated by small, left- stepping *en echelon* bends or step-overs, rather than prominent, through-going fault strands.

4.2 Sunol Valley Sub-Section

The Northern Calaveras fault in Sunol Valley strikes north-northwest and consists primarily of a single fault strand west of Calaveras Road (Figure 4b). This sub-section is comparable to the "Sunol segment" of Simpson et al. (1992) and the "Sunol Valley segment" of WGNCEP (1996). This reach of the fault extends from the narrow southern end of the valley occupied by Alameda Creek, northward to the Highway 680 crossing, and is approximately 8.5 km long (Table 1). The fault characteristics are moderately well defined on the basis of several detailed fault-rupture hazard analyses conducted since 1995. Overall, the fault has a relatively linear trace near, but west of, the eastern valley margin.

In the narrow southern part of the valley, the fault has an *en echelon* pattern of left-stepping north-northwest–striking strands, which strike about N10˚W to N15˚W and are transitional with the more prominent left-stepping pattern that characterizes the fault in the Calaveras Reservoir area. In particular, the *en echelon* fault pattern continues northward from the Leyden Creek site (Kelson et al., 1996) to nearly the Welch Creek site (Simpson et al., 1999). Directly north of the Leyden Creek site, the fault enters the narrow Alameda Creek valley, and is poorly defined within at least two complex, left-stepovers between Leyden Creek and Welch Creek. North of Welch Creek, the fault trace is constrained based on evidence of creep in Calaveras Road and in the guardrail bordering the access road to the Sunol Valley Water Treatment Plant. The fault location is known based on prominent vegetation lineaments, springs, and trench excavations at the Valley Crest Nursery site (Baldwin et al., 1998; WLA, 1999; AGS, 1999). Deformation of a pipeline emplaced across the fault in the 1960s also demonstrates the presence of active fault creep at this site. Between the Sunol Valley Water Treatment Plant and the Alameda Siphons (Hetch Hetchy Aqueduct), detailed mapping of surficial deposits and fault strands (Kelson et al., 1993; WLA, 2004a) shows a fairly linear and simple fault consisting of a single primary strand, although there is no geomorphic evidence of the fault in late Holocene alluvial deposits on the Sunol Valley floor (WLA, 2004a).

At the Alameda Siphons (Hetch Hetchy Aqueduct) fault crossing, detailed analyses of multiple trenches, shallow boreholes, geophysical profiling, and surficial mapping constrains the fault to be within a 30-m-wide zone that is about 70 to 100 m west of Calaveras Road (WLA, 2004a; 2007a, b). Northward from the Alameda Siphons, the fault remains west of Calaveras Road, based on active deformation of structures along the San Antonio Pipeline (Golder, 1999), fault exposures in trenches for crossings of Pacific Gas & Electric Company pipelines near San Antonio Creek and Highway 680 (WLA, 2002, 2003a, 2003b, 2004c), and an absence of faulting in multiple trenches east of Calaveras Road conducted for Chevron Pipe Line Company (WLA, 1995, 1999). These trench data greatly improve the understanding of the location and character of faulting in the valley, and show that the fault is generally linear but may locally have minor left- or right-stepovers (Kelson et al., 2004).

The northern end of the Sunol Valley sub-section is considered to coincide with the Highway 680 crossing, where the primary fault strand changes from an orientation of about N15˚W to about N30˚W, and enters an areas of substantial topographic relief (Figure 4b). CalTrans (1991) and Purcell Rhoades &

Associates (1980) documented the fault location and character along the Highway 680 corridor, and showed that it consists of a well-developed, near-vertical shear zone. The slightly more westerly fault strike and greater topographic relief in the area north of Highway 680 suggests a larger component of transpression along the Pleasanton Ridge sub-section of the fault than along the Sunol Valley sub-section (Figure 4b).

4.3 Pleasanton Ridge Sub-Section

Between Sunol Valley and Dublin, the Northern Calaveras fault lies on the flank of the northeast-facing Pleasanton Ridge (Figures 4b and 4c), where large late Quaternary landslides commonly obscure the fault trace. This 13-km-long sub-section has a general orientation of about N30˚W to N35˚W between Highway 680 on the south and Dublin Canyon Road on the north (Table 1). Overall, the fault is associated with linear features on the mid-flank of Pleasanton Ridge (where not obscured by landslides), and with discontinuous, curvilinear northeast-facing topographic scarps along the base of range front (Figure 4c). The pattern of fault exposures and geomorphic expression suggests that this sub-section of the fault is associated with slightly transpressive deformation, in the form of right-lateral strike slip coupled with a lesser component of northeast-vergent reverse faulting.

The Pleasanton Ridge sub-section of the Northern Calaveras fault has been investigated primarily through several consulting A-P studies, with only a couple of research-level paleoseismic investigations to date. A trench exposure documented by Simpson et al. (1994) at the southern end of this sub-section (the "Vallecito Ridge site") indicated the fault location but did not provide paleoseismic information. This fault strand projects northwestward across Arroyo de la Laguna into a prominent linear drainage and topographic saddle on the northeastern flank of Pleasanton Ridge (Figure 4c). Geomorphic expression of the fault is discontinuous in an area of abundant landsliding near Castlewood Country Club, where many exploratory trenches appear to have not extended across potentially fault-related features, and no trenches were completed near the topographic break at the base of the range front AP2916 (Earth Systems Consultants, 1987). Directly north of the Castlewood area, multiple trenches for AP2272 (Applied Soil Mechanics, Inc., 1988a, b, c; 1989a, b) and AP1242 (Judd Hull and Associates, 1980a, b; Applied Geotechnical, 1983) exposed primary fault strands along linear features on the flank of the ridge (Figure 4c). However, multiple trenches excavated for these and other studies do not preclude the presence of reverse faulting along a prominent, sinuous break-in-slope at the base of the range (Figure 4c). For example, trenches for AP1289 (Earth Systems Consultants, 1981) and AP1796 (Alpha Geotechnical Consultants, 1985) do not preclude a reverse fault at the base of the range because they either did not extend across the entire width of the scarp or provide possible evidence of surface folding (i.e., on a "blind" reverse fault). We consider the continuity of these features as evidence that northeast-vergent faults are tectonic rather than a result of landslides, although locally there are many landslides at or near the base of the range.

The presence of reverse faulting along the base of the range front is confirmed by BAPEX-funded research at the South Foothill High School site (Kelson and Randolph, 2000). Trenching for this investigation demonstrated the presence of a northeast-vergent, oblique reverse fault along which Cretaceous bedrock is juxtaposed over Holocene alluvium. A landslide origin for this deformation is precluded because the fault plane steepens with depth to the southwest, and the bedrock orientations are consistent with regional orientations. The fault scarp trenched by Kelson and Randolph (2000) continues to the northwest and merges with fault-related vegetation lineaments, springs, and scarps as well as active fault strands exposed by AP1524 (Darwin Myers Associates, 1983, 1985), AP2304 (Burkland and Associates, 1973; Purcell Rhoades & Associates, 1989) and AP2488 (Berlogar Geotechnical Consultants, 1990). Near the northern end of the Pleasanton Ridge sub-section, the fault is expressed as a single, linear escarpment along the base of the range. At Laurel Creek (Figure 4c), a natural creek bank exposes a vertical, N30˚W-striking fault zone within bedrock, which coincides with a scarp developed on young alluvium.

Based on the geomorphic expression of several potentially fault-related features and several trench exposures, the Pleasanton Ridge sub-section (Figure 4c) appears to be characterized by a primary linear fault strand on the flank of the ridge, coupled with a series of discontinuous reverse faults at or near the base of the range. The pattern of geomorphic features along the range suggests that these possible reverse faults intersect the primary strike-slip fault strand at their northwestern ends, and diverge from the primary strand in a southeasterly direction (Figure 4c). Overall, the Northern Calaveras fault along this sub-section appears to have a minor restraining orientation between Highway 680 on the south to Dublin Canyon on the north.

4.4 Dublin Embayment Sub-Section

The Dublin Canyon embayment contains a short sub-section of the Northern Calaveras fault (Figure 2) between Dublin Canyon Road on the south and Koopman Canyon on the north (Figure 4d). This 2.3-km-long sub-section has a more northerly strike (about N17˚W, Table 1) than the adjacent Pleasanton Ridge sub-section (N31˚W) to the south and the adjacent Southern San Ramon Valley sub-section (N35˚W) to the north. This sub-section represents a right-stepping double bend within the Northern Calaveras fault

(Kelson, 2001). The releasing stepover formed by this double bend is about 2 km long and less than 1 km wide.

In contrast to both of its adjacent sub-sections, the Dublin Embayment sub-section contains geomorphic and geologic evidence of oblique extension (CalTrans, 1994; Kelson, 2001), based on analysis of aerial photography, exploratory trenching, and borehole data. The sub-section crosses a low-relief embayment in the East Bay Hills that contains alluvial-fan sediments deposited by Dublin Creek and Martin Creek (Figure 4d). Individual fault strands across the embayment strike northerly, and appear to be discontinuous. South of Highway 580, several trenches constrain the location of the fault to adjacent to or beneath Foothill Road (Geotechnical Engineering, Inc., 1988), (Hydro-Geo Consultants, 1991; Terrasearch, Inc., 1983; Harding-Lawson, 1981), and (Kleinfelder and Associates, 1984). Borehole data from the Highway 580 / Foothill Road interchange provide evidence of groundwater elevation differences across the fault zone, and a series of north-striking fault strands associated with extensional cracking (CalTrans, 1994). North of Highway 580, the fault is prominently expressed on 1939 vintage photography as a series of springs, vegetation lineaments, and topographic swales developed on young alluvial fans. The fault was purportedly observed in the bank of Martin Creek and was encountered in trenches for AP2846 (Terrasearch, Inc., 1976) although exploratory trenching along the northern flank of Martin Creek by Kelson and Baldwin (2000c) did not encounter distinct faulting in young alluvium. Collectively, the geologic and geomorphic data demonstrate a complex, right-stepping series of transtensional fault strands across the Dublin Canyon embayment, at least as far north as Silvergate Drive in Dublin (Figure 4d). Because the northerly fault orientation continues as far north as about Koopman Canyon before turning to a more northwesterly trend, the northern end of this sub-section is interpreted at Koopman Canyon (Figure 4d).

4.5 Southern San Ramon Valley Sub-Section

North of Koopman Canyon (Figure 4d), the Northern Calaveras fault is within an area that has been modified extensively for residential and commercial purposes. The Southern San Ramon Valley sub-section (Figure 2) contains fault strands that traverse the northeastern flank of the East Bay Hills, or border the base of the range front, between Koopman Canyon and Bollinger Canyon Road (Figure 4d). Overall, this 5.7-km-long sub-section has a more westerly strike (about N35˚W, Table 1) than the adjacent Dublin Embayment sub-section (N17˚W) to the south and the adjacent San Ramon Embayment sub-section (N30˚W) to the north. This sub-section is similar to the Pleasanton Ridge sub-section, in that it is associated with linear features on the flank of the range front, and with discontinuous, curvilinear northeast-facing topographic scarps along the base of range front (Figure 4d). The pattern of fault exposures and geomorphic expression suggests that this sub-section also is associated with slightly transpressive deformation, in the form of right-lateral strike slip coupled with a lesser component of northeast-vergent oblique reverse faulting (Kelson, 2001). Notably, both the November 2002 and February 2003 earthquake sequences in San Ramon Valley occurred adjacent to, but northeast of, this sub-section.

Many consulting investigations have been conducted along the Southern San Ramon Valley sub-section, and there is incomplete agreement among some previous data and interpretations, and with the detailed compilation presented in this report. The schematic depiction of trench relationships and lack of integration of regional (and sometimes local) information from previous analyses often affects the credibility of some previous studies. In addition, substantial grading for residential development has taken place since about 1995, and very little original topography remains along this sub-section. Compilation of data from multiple trenches and geophysical profiles, in conjunction with analysis of pre-grading aerial photography (taken in 1939 and 1996), provides an integrated dataset from which to assess the location and characteristics of this sub-section of the Northern Calaveras fault.

Field observations of several trench exposures by the authors confirm the presence of a primary, well-developed fault strand located about 300 to 500 m west of Highway 680, between Big Canyon and Corey Place (ENGEO, Inc., 1978, Geolith Consultants, 2000, Lowney Associates, 1996, 1997; ENGEO, Inc., 1976; Terrasearch, Inc., 1977; Darwin Myers Associates, 1984). Along most of this sub-section, this fairly linear strand is located on the flank of northeast-facing range front, and is not closely associated with a topographic break-in-slope or range-front escarpment. Shearing exposed in some consulting trenches has been interpreted as being related to landslide activity, although the along-strike alignment of this faulting supports the presence of a through-going, strike-slip fault strand. Locally, areas east of this primary fault strand have moderate topographic relief, and may be bordered on the northeast by secondary, northeast-vergent reverse faults. Site-specific studies across this range front provide possible evidence of local uplift (Soil Foundation Systems, 1979, ENGEO, Inc., 1978), but several studies did not extend trench exposures across the base of the range front (Lowney Associates, 1996, 1997). This sub-section is best characterized as a primary, fairly continuous strike-slip fault strand, probably associated with local secondary reverse faulting along the northeastern margin of uplifted topography. The entire zone of deformation appears to be located southwest of Highway 680 (Figure 4d).

4.6 San Ramon Embayment Sub-Section

In San Ramon, the Northern Calaveras fault crosses a range-front embayment occupied by San Catanio and San Ramon Creeks, herein termed the San Ramon embayment (Figure 2). Kelson (2001) referred to this alluviated valley as the “Crow Canyon embayment”, but this is a misnomer because Crow Canyon is located west of the crest of the East Bay Hills and does not flow into the San Ramon Valley. The San Ramon embayment contains a short sub-section of the Northern Calaveras fault (Figure 2) between Bollinger Canyon Road on the south and Deerwood Drive on the north (Figure 4d). The 2.4-km-long San Ramon Embayment sub-section has a more northerly strike (about N30˚W, Table 1) than the adjacent Southern San Ramon Valley sub-section (N35˚W) to the south and the adjacent Danville/Alamo sub-section (N40˚W) to the north. The San Ramon Embayment sub-section represents a local right-stepping double bend within the Northern Calaveras fault, and is similar to the Dublin Embayment sub-section (Kelson, 2001; Figure 2). The releasing stepover associated with the San Ramon embayment is about 2 km long and less than 1 km wide (Figure 4d).

The San Ramon Embayment sub-section contains geomorphic and geologic evidence of oblique extension, based on analysis of aerial photography, exploratory trenching, and borehole data. Between Bollinger Canyon Road and Norris Canyon Road, multiple exploratory trenches completed by Purcell Rhoades & Associates (1976) and Terrasearch, Inc., (1979) show that the fault contains a series of right-stepping, *en echelon* fault traces associated with sag ponds and discontinuous linear ridges. These sag ponds and linear ridges, although now destroyed by residential development, are clearly visible on 1939 aerial photography and on an oblique aerial photograph presented by Rogers and Halliday (1992). Extensional strike slip is indicated by the *en echelon* pattern of fault traces, coupled with the sag ponds within the range-front embayment. Notably, these features coincide with the fault trace mapped by Herd (1978), but are west of the primary trace of the Northern Calaveras fault postulated by Rogers and Halliday (1992). North of Norris Canyon Road, the fault has excellent geomorphic expression on 1937 vintage photography (prior to residential development), and suggests a broad zone of transtensional deformation across the San Ramon embayment (Figure 4d). Near Crow Canyon Road, multiple trenches (Buller Associates, 1983; ENGEO, Inc., 1977, 1978) define a linear fault trace as far north as Deerwood Road, at the northern end of this sub-section (Figure 4d). Lastly, our field observations and surveying suggests possible evidence of right-lateral creep deformation of a 1970s-era curb in the parking lot of the former San Ramon post office on Crow Canyon Road (K. Kelson, unpublished data, 2006). These data collectively demonstrate the location and character of the Northern Calaveras fault across the San Ramon embayment.

4.7 Danville -Alamo Sub-Section

Between San Ramon and Alamo, the Danville – Alamo sub-section of the Northern Calaveras fault lies along the base of the northeast-facing Las Trampas Ridge (Figure 4e), and is covered locally by large late Quaternary landslides. This 9-km-long sub-section extends between Deerwood Road (in San Ramon) on the south and Via Romero (in Alamo) on the north (Table 1), and has a more westerly strike (about N40˚W to N45˚W) than the adjacent San Ramon Embayment sub-section (N30˚W) to the south. Overall, the sub-section is associated with linear features along the base of Las Trampas Ridge (where not obscured by landslides) (Figure 4e). At the southern end of Las Trampas Ridge, this sub-section contains a prominent linear strand about 1 km southwest of the range front, as well as a series of splays along the northeastern front of the range. The geomorphic expression of the fault and the pattern of fault exposures in several trenches suggest that this sub-section is characterized by right-lateral strike slip on the southwestern strand within the range, as well as northeast-vergent, oblique reverse faulting along the range front.

Consulting investigations have been conducted only along the southern part of the Danville-Alamo sub-section, primarily because the fault west of longitude 122˚W was interpreted to be not sufficiently active and well-defined to warrant zoning as part of the A-P fault mapping program (Hart, 1980a). At the southern end of Las Trampas Ridge, the linear strand that extends northwestward across the San Ramon embayment was exposed in trenches for A-P investigations (ENGEO, Inc., 1977; 1978), and has prominent geomorphic expression north of Deerwood Drive (Figure 4e). This strand is associated with a distinct, northeast-facing scarp on young alluvial-fan deposits, as well as a groundwater barrier, numerous springs, a linear drainage valley, and a linear saddle at the northwestern end of the linear valley (Figure 4e). Unpublished trenching results north of Deerwood Road (G. Pischke, Earth Systems Consultants, pers. comm., 2005) document the fault associated with the northeast-facing scarp in alluvium, and show the presence of at least one active fault strand within the linear valley. Exploratory trenches completed for AP1443 (ENGEO, Inc., 1981) also confirm the presence of a near-vertical, well-developed fault strand extending from the linear valley northward into areas underlain by extensive landslide deposits (Figure 4e). The northwestern continuation of this fault strand beyond the area studied for AP1443 (ENGEO, 1981) is poorly constrained, because of larges landslides mantling the northeastern flank of Las Trampas Ridge as far north as the Eugene O'Neill National Historic Site (Figure 4e).

Along the northeastern flank of Las Trampas Ridge, prominent scarps, air-photo lineaments, springs, and other geomorphic features show the presence of a series of discontinuous fault strands near the base of Las Trampas Ridge (Figure 4e). Several trenches completed for A-P investigations (ENGEO, 1979, 1980, 1981; Burkland and Associates, 1974) confirm that these features coincide with fault strands. Shearing exposed in some consulting trenches has been interpreted as being related to landslide activity, although the pattern of faulting from air-photo analysis is consistent with a series of left-stepping reverse-oblique fault splays along the base of the range front in San Ramon (Figure 4e). Landsliding appears to cover the northern projection of this series of reverse-oblique fault strands on the Elworthy Ranch property (Rogers and Halliday, 1992), located between San Ramon and Danville. Rogers and Halliday (1992) interpret drillhole and bedrock-outcrop data to suggest the presence of a reverse fault along the eastern margin of Las Trampas Ridge at Elworthy Ranch. North of Danville (Figure 4e), the fault is associated with many scarps and linear hill fronts along the base of the range, including those that projected toward the Camille Lane site trenched by Simpson et al. (1994). On the basis of this trench, Simpson et al. (1994) interpreted that Holocene movement on the Northern Calaveras fault may not extend northwest of Danville. However, our recent field observations suggest that the Camille Lane trench exposures may not have extended far enough west to cross all possible fault traces, and thus that the fault probably continues northward to Alamo (at Via Romero, Figure 4e).

As noted above, recent workers identify the Northern Calaveras fault as a potential rupture segment extending from the town of Danville on the north to the southern end of Calaveras Reservoir (WGCEP, 1999, 2003; Kelson, 2001). The northern end of the fault probably coincides with the locations of the 1990 Alamo earthquake sequence (WGCEP, 2003), which occurred along a northeasterly trend east of the Northern Calaveras fault. The 1990 Alamo sequence coincides with the southern end of Castle Hill (Figure 2), where the Northern Calaveras fault appears to splay into several strands (Unruh and Kelson, 2002), and may be intersected by the Mt Diablo Thrust fault. Holocene slip at the northern end of the fault either dies out or is transferred to the Concord fault (WGCEP, 2003) and/or strike-slip faulting within the northern East Bay Hills (Simpson et al., 1992; Unruh and Kelson, 2002). Unruh and Kelson (2002) interpret that slip on the Northern Calaveras fault continues north from Alamo onto several fault strands that comprise a left-stepping, *en echelon* pattern in the northern East Bay Hills, grouped together as the Contra Costa Shear Zone. For the purposes of this study, we interpret the northern termination point of the Northern Calaveras fault to be at the town of Danville, with an uncertainty of ± 5 km. This uncertainty allows for the northern termination of the fault to extend as far north as either Castle Hill (in Alamo) or San Ramon (Figure 3).

5.0 CONCLUSIONS

This report provides an explanation of the compilation of geologic data on active strands of the Northern Calaveras fault in a digital format for the Northern California Quaternary Fault Map Database (NCQFMD). The digital database of fault characteristics developed in this work helps define fault-related hazards, in particular the locations and distribution of surface fault-strands and possible locations of surface rupture. This database builds upon and extends substantial previous compilation efforts (Bryant and Cluett, 1999a), and provides a consistent, comprehensive database that can be accessed for scientific research, engineering-driven seismic hazard analyses, and public outreach. The database was constructed to be completely seamless with the USGS-driven format for the Northern California Quaternary Fault Map Database (NCQFMD), and was compiled using ArcGIS v9.1. This detailed analysis provides a consistent database for interpreting seven sub-sections of the Northern Calaveras fault, as suggested by fault strike, sense-of-slip, geomorphic expression, fault-trace map pattern, and other fault characteristics. In a general sense, these sub-sections are characterized by differences in relative amounts of strike-slip, transpression, and transtension. These sub-sections are not likely to represent individual fault-rupture segments during large-magnitude earthquakes on the Northern Calaveras fault.

Each of the fault sub-sections has distinct characteristics, summarized here from south to north. The 9-km-long Calaveras Reservoir sub-section contains several north-trending active fault strands, arranged in a left-stepping *en echelon* pattern across the Calaveras Valley releasing stepover. The 9-km-long Sunol Valley sub-section has an *en echelon* pattern of left-stepping north-northwest–striking strands at its southern end, which transition onto a linear, N15˚W-trending fault near the eastern valley margin. The northwesterly trending, 13-km-long Pleasanton Ridge sub-section is characterized by slightly transpressive deformation, with primarily right-lateral strike slip coupled with a lesser component of northeast-vergent reverse faulting near the base of the northeast-facing range front. The 2-km-long, northerly trending Dublin Embayment sub-section represents a minor right-stepping double bend in the fault, which forms a releasing stepover that is less than 1 km wide. The 6-km-long Southern San Ramon Valley sub-section is characterized by primarily right-lateral strike slip on a linear fault strand on the flank of the East Bay Hills, coupled with a lesser component of northeast-vergent oblique reverse faulting at the base of the range. The north-striking fault strands comprising the 2-km-long San Ramon Embayment sub-section exhibit strong evidence of primarily right-lateral strike-slip; this sub-section represents a local right-stepping double bend and a releasing stepover also less than 1 km wide. The northwesterly striking 9-km-long Danville – Alamo sub-section is characterized by right-lateral strike slip on a linear fault strand within the range, as well as northeast-vergent, oblique reverse faulting along the range front. Locally, large landslide complexes overlie and obscure fault strands along the three fault sub-sections that are characterized by oblique reverse faulting along the range front (i.e., the Pleasanton Ridge, Southern San Ramon Valley, and Danville – Alamo sub-sections).

Even though variations in fault strike help define individual sub-sections, the overall pattern of the 45-km-long Northern Calaveras fault is one in which the sub-sections have progressively more westerly strikes from south to north. The sub-sections appear to alternate between having predominantly transtension and transpression, such that the fault is characterized by a complex pattern of both transtensional and transpressional displacements along its entire length from Calaveras Reservoir to the town of Alamo. Kelson (2001) interpreted that the Northern Calaveras fault consists of a series of sub-sections that have alternating restraining and releasing geometries, with the majority of the fault length characterized by slightly restraining geometries that promote local contraction and reverse faulting. Slightly releasing geometries appear to be present in Sunol Valley, at the Dublin Canyon embayment, and at the San Ramon embayment. These slight changes probably are not significant barriers to rupture propagation along the fault. However, the differences in near-surface slip vectors influence fault geomorphology and may affect interpretations of whether surface features are related to landslide or fault activity. In addition, these left- and right-stepping complications may make it difficult for local engineering geologic studies to determine the locations of active fault strands based on extrapolation of fault locations from nearby trenches.

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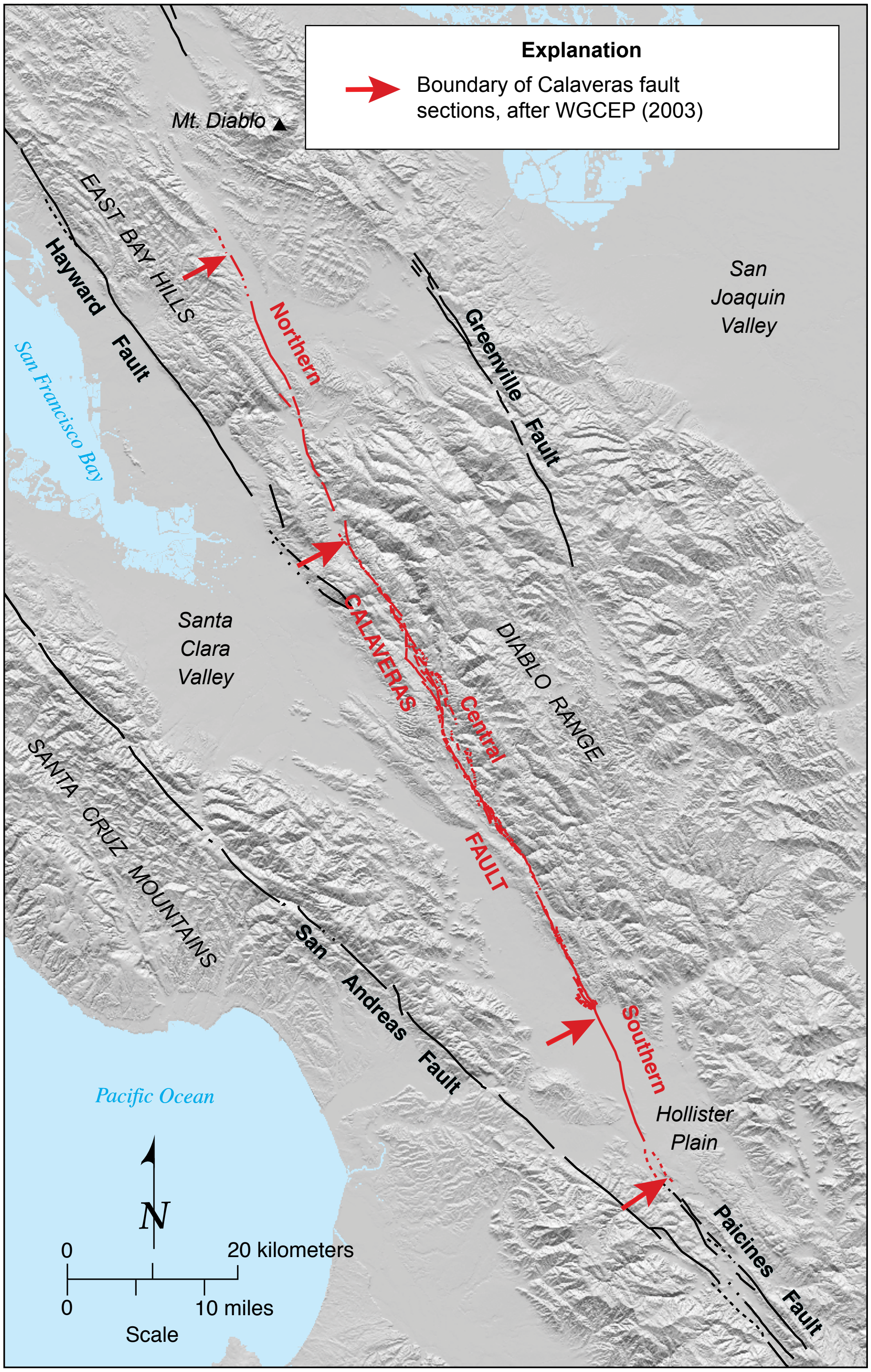
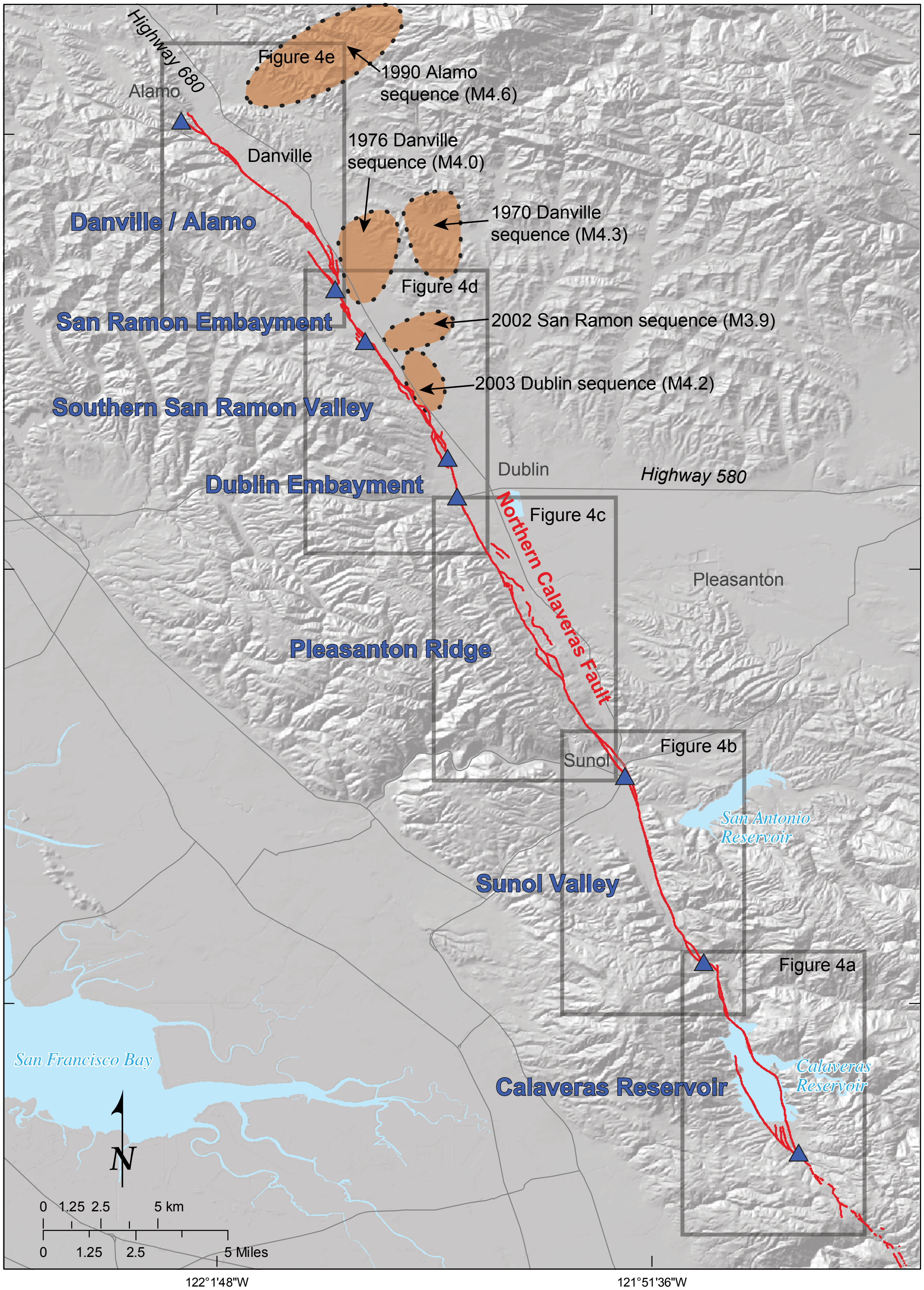
FIGURES



NORTHERN CALAVERAS FAULT

Shaded Relief Map of the Major Active Faults in the Southern San Francisco Bay Region

WLA William Lettis & Associates, Inc. | Figure 1



Explanation

▲ Sub-section boundary

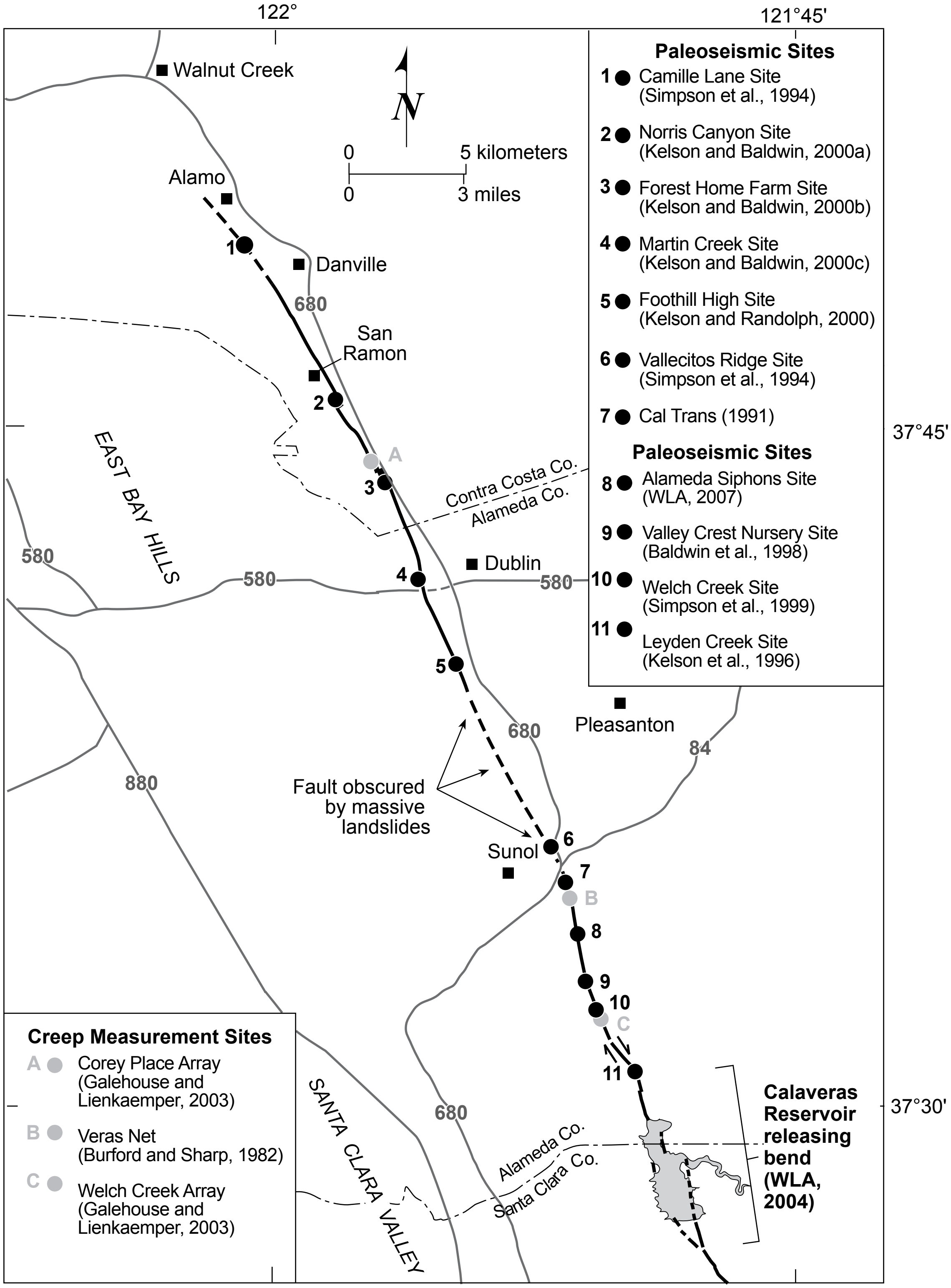
Earthquake sequence (approximate location)

NORTHERN CALAVERAS FAULT

Northern Calaveras Fault and Subsection Boundaries

WLA WILLIAM LETTIS & ASSOCIATES, INC.

Figure 2

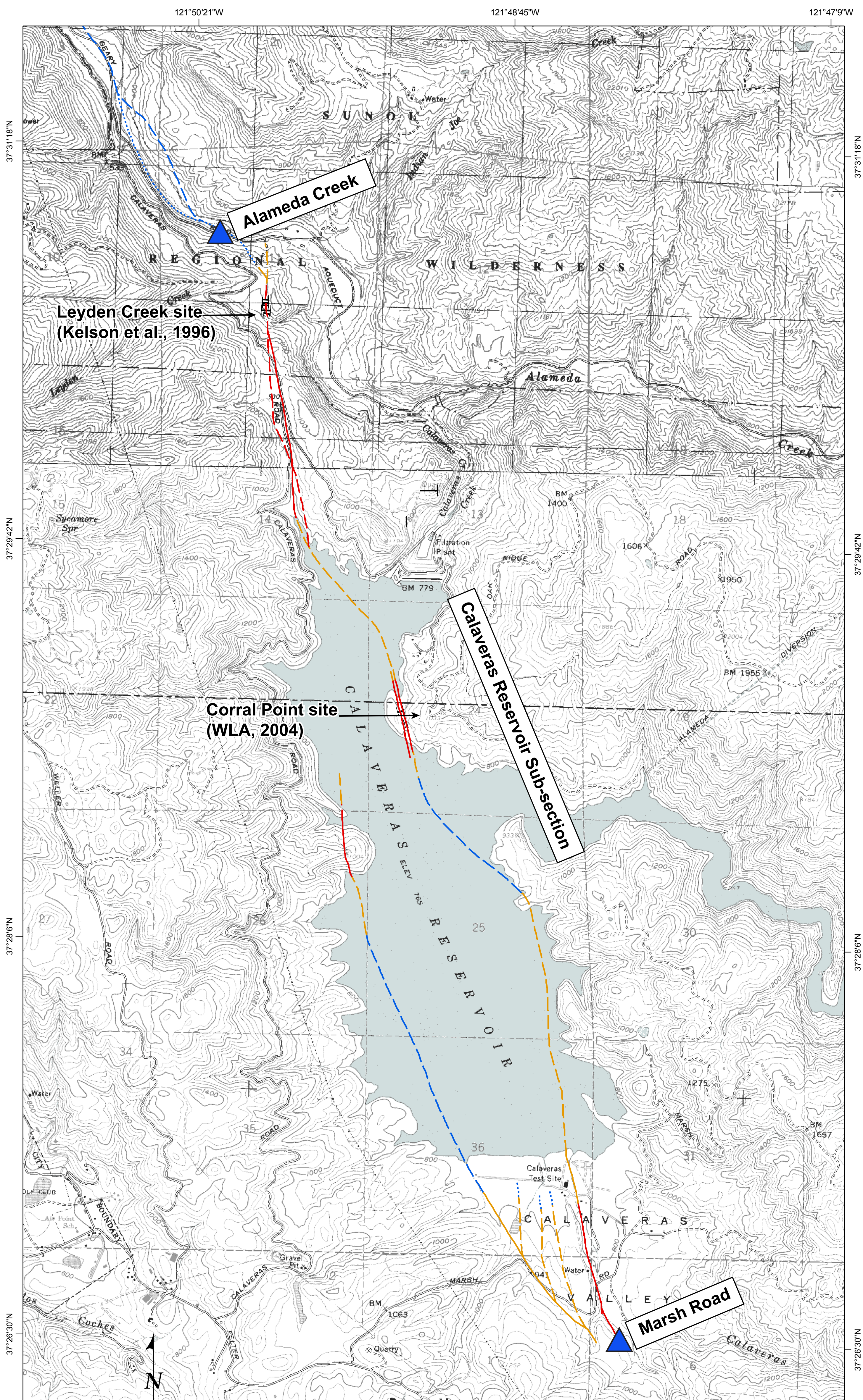


Simplified map of the northern Calaveras fault north of Calaveras Reservoir, showing the location of paleoseismologic and creep-measurement sites. Fault trace simplified from previous A-P maps (Hart, 1979, 1980, 1981; Bryant, 1981) and Kelson (2001).

NORTHERN CALAVERAS FAULT

Regional Map of Paleoseismic and Creep Measurement Sites

WLA WILLIAM LETTIS & ASSOCIATES, INC. | Figure 3



Explanation

Northern Calaveras fault

- Well constrained, Certain
- Well constrained, Approximate
- Well constrained, Concealed
- Moderately constrained, Certain
- Moderately constrained, Approximate
- Moderately constrained, Concealed
- Poorly constrained, Certain
- Poorly constrained, Approximate
- Poorly constrained, Concealed

Symbols

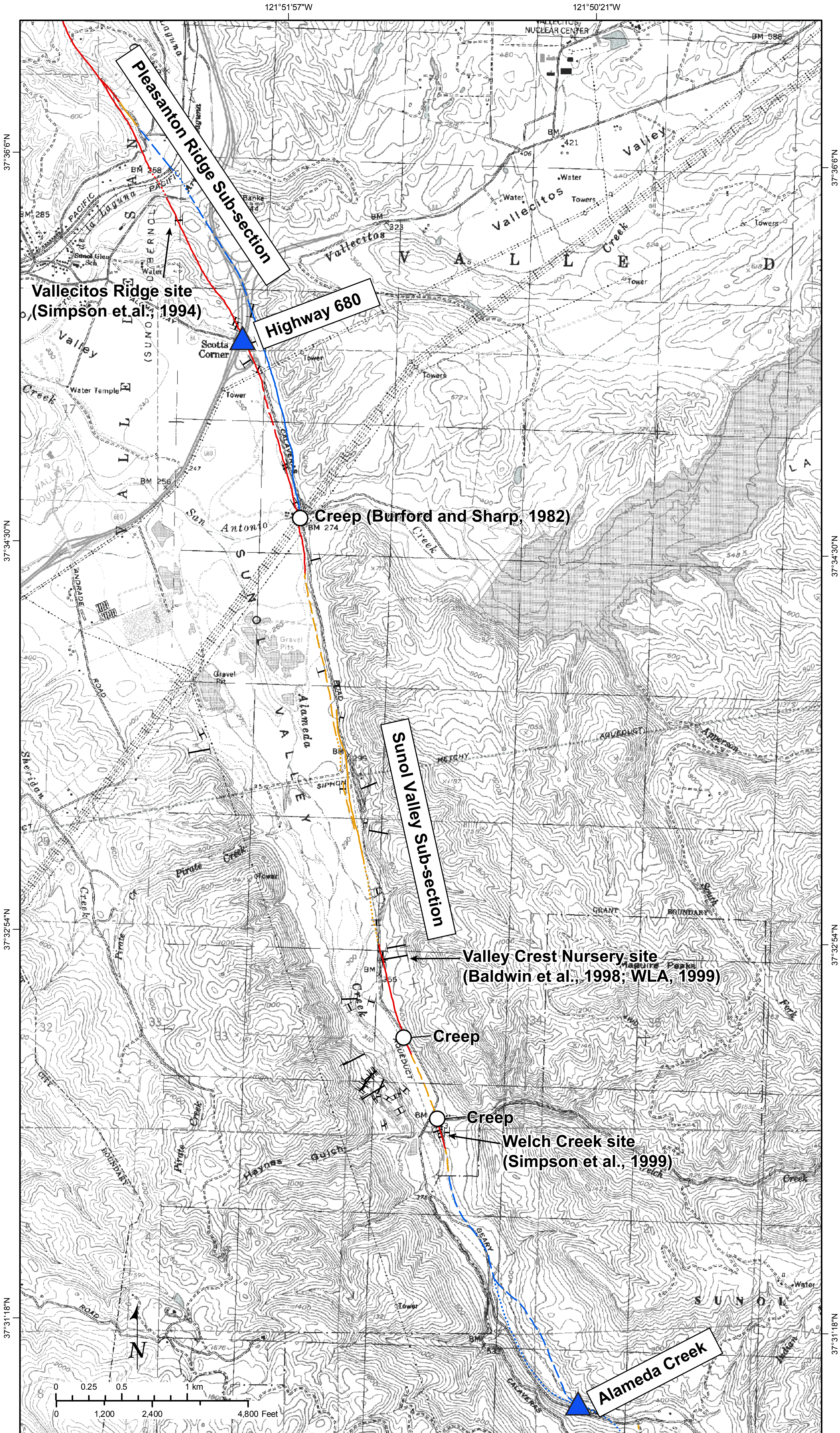
- Trench
- Fault exposures
- Subsection Boundary

N O R T H E R N   C A L A V E R A S   F A U L T

Fault Map Sub-Sections - Calaveras Reservoir

WLA William Lettis & Associates, Inc.

Figure 4a



Explanation

Northern Calaveras fault

- Well constrained, Certain
- Well constrained, Approximate
- Well constrained, Concealed
- Moderately constrained, Certain
- Moderately constrained, Approximate
- Moderately constrained, Concealed
- Poorly constrained, Certain
- Poorly constrained, Approximate
- Poorly constrained, Concealed

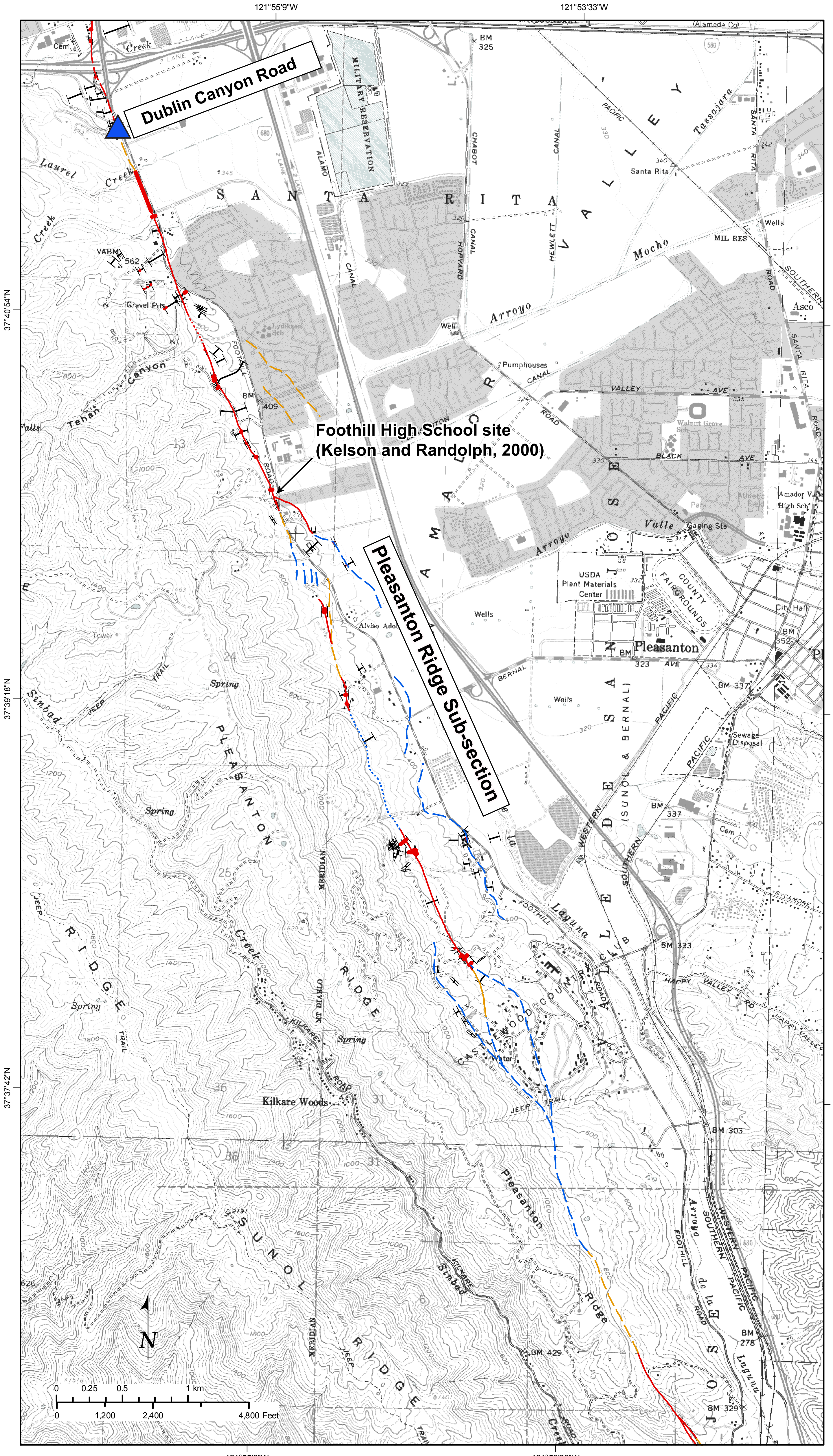
Symbols

- Trench
- Fault exposures
- Subsection Boundary

N O R T H E R N C A L A V E R A S F A U L T

Fault Map Sub-Sections - Sunol Valley

WLA William Lettis & Associates, Inc. | Figure 4b



Explanation

Northern Calaveras fault

- Well constrained, Certain
- Well constrained, Approximate
- Well constrained, Concealed
- Moderately constrained, Certain
- Moderately constrained, Approximate
- Moderately constrained, Concealed
- Poorly constrained, Certain
- Poorly constrained, Approximate
- Poorly constrained, Concealed

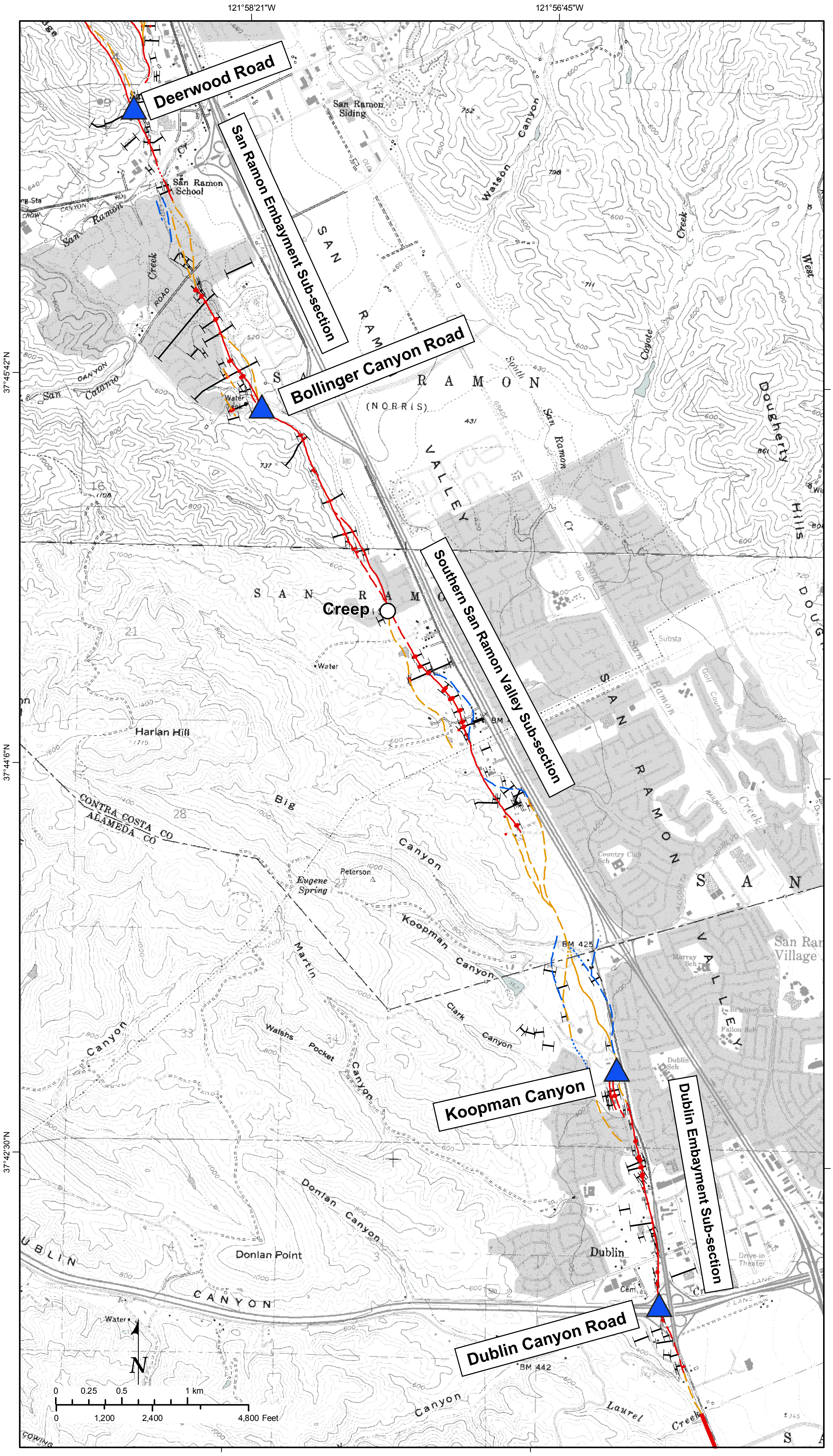
Symbols

- Trench
- Fault exposures
- Subsection Boundary

N O R T H E R N   C A L A V E R A S   F A U L T

Fault Map Sub-Sections - Pleasanton Ridge

WLA William Lettis & Associates, Inc. | Figure 4c



Explanation

Northern Calaveras fault

- Well constrained, Certain
- Well constrained, Approximate
- Well constrained, Concealed
- Moderately constrained, Certain
- Moderately constrained, Approximate
- Moderately constrained, Concealed
- Poorly constrained, Certain
- Poorly constrained, Approximate
- Poorly constrained, Concealed

Symbols

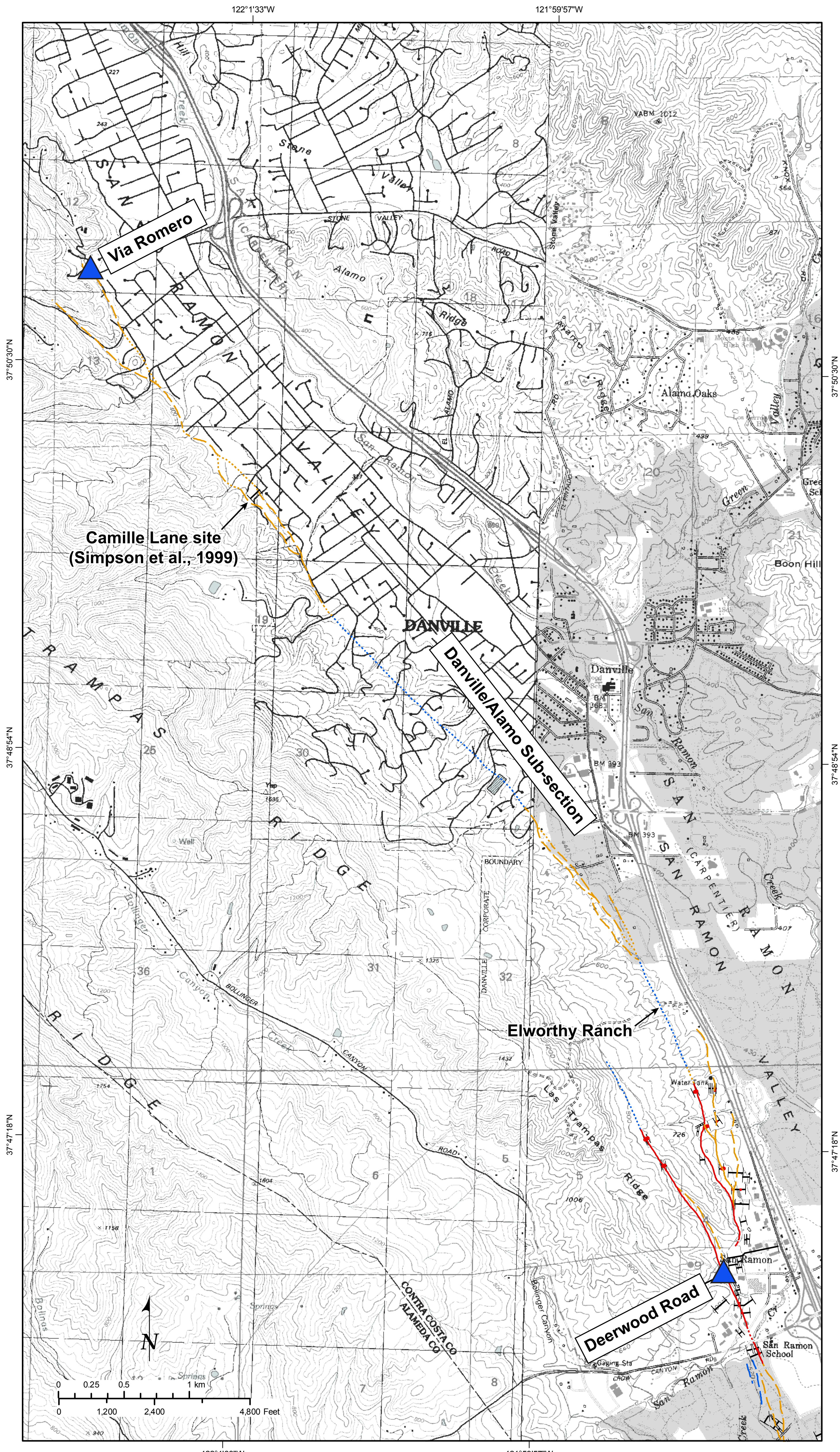
- Trench
- Fault exposures
- Subsection Boundary

NORTHERN a FAULT

Fault Map Sub-Sections - San Ramon Embayment, Southern San Ramon Valley and Dublin Embayment

WLA William Lettis & Associates, Inc.

Figure 4d



Explanation

Northern Calaveras fault

- Well constrained, Certain
- Well constrained, Approximate
- Well constrained, Concealed
- Moderately constrained, Certain
- Moderately constrained, Approximate
- Moderately constrained, Concealed
- Poorly constrained, Certain
- Poorly constrained, Approximate
- Poorly constrained, Concealed

Symbols

- Trench
- Fault exposures
- Subsection Boundaries

NORTHERN a FAULT

Fault Map Sub-Section- Danville/Alamo

WLA WILLIAM LETTIS & ASSOCIATES, INC. | Figure 4e