Appendix G
Fault Investigation Technical Memorandum

TECHNICAL MEMORANDUM

Preliminary Investigation of the Eagle Rock, Raymond, and San Rafael Faults, Freeway Tunnel and Light Rail Transit Alternatives, SR 710 North Study, Los Angeles County, California

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Introduction

This technical memorandum (TM) is provided as an appendix to the *Preliminary Geotechnical Report, State Route (SR) 710 North Study, Los Angeles County, California,* prepared by CH2M HILL, February 2014 (main report). The purpose of this TM is to provide technical support for how the Raymond, San Rafael, and Eagle Rock faults were located through the Freeway Tunnel and Light Rail Transit (LRT) Alternatives. Details of the structural geology and neotectonics of this complex area (Bryant, 1978; Crook et al., 1987; Weaver and Dolan, 2000) are not included in this TM because they are discussed in detail in the main report and associated appendices. The boring logs, associated laboratory data and photographs of the cores collected during the SR 710 North Study fault investigation are included in the appendixes of the main report.

Multiple alternative mapping locations for the subject faults were found during our initial research (Lamar, 1970; Weber, 1980; Dibblee and Ehrenspeck, 1989a and 1989b; Yerkes and Campbell, 2005); these were compiled and are shown in Figure 1 and on Plate 1. The geologic investigation that was completed as part of this project did allow us to better define the locations of the faults and fault splays, and in some cases provides data that could be used in future studies specifically to assess the future rupture hazard posed by these faults.

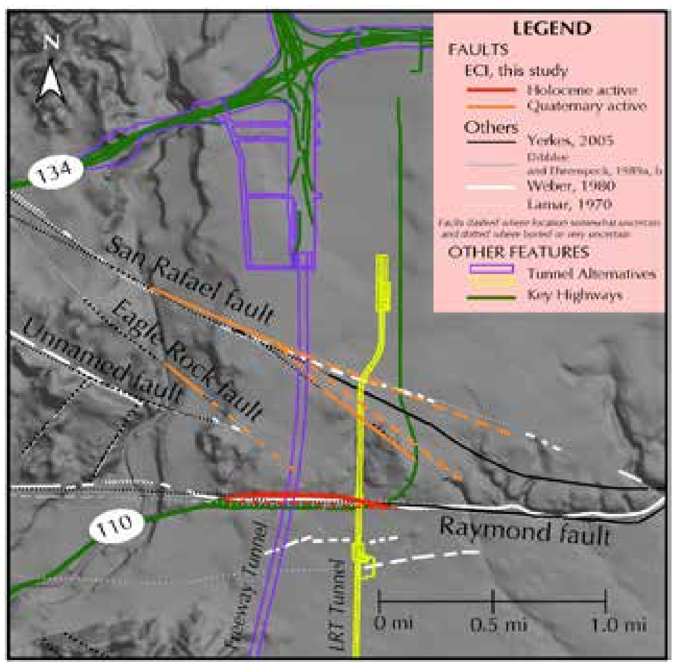

Figure 1. *Map of the potentially active faults that may impact the proposed tunnel routes. There are different mapping interpretations and locations for San Rafael, Eagle Rock, and other northwest-trending faults, but in this discussion, they are collectively referred to as the Eagle Rock-San Rafael fault zone. An expanded version of this figure is included as Plate 1 in this TM.*

Metro

Evolution of the Investigation Program

Based on an examination of previous work in the study area, historical data, existing maps, and the SR 710 North Study Alternatives, we initially planned for five deep sonic borings (250+ feet, or 50 feet below the proposed tunnel invert) on opposite sides of the Raymond fault in South Pasadena. The purpose of the borings was to determine the geological conditions at the proposed tunnel depths and to attempt to better localize the fault trace, both in the near surface and at depth (Figure 2).

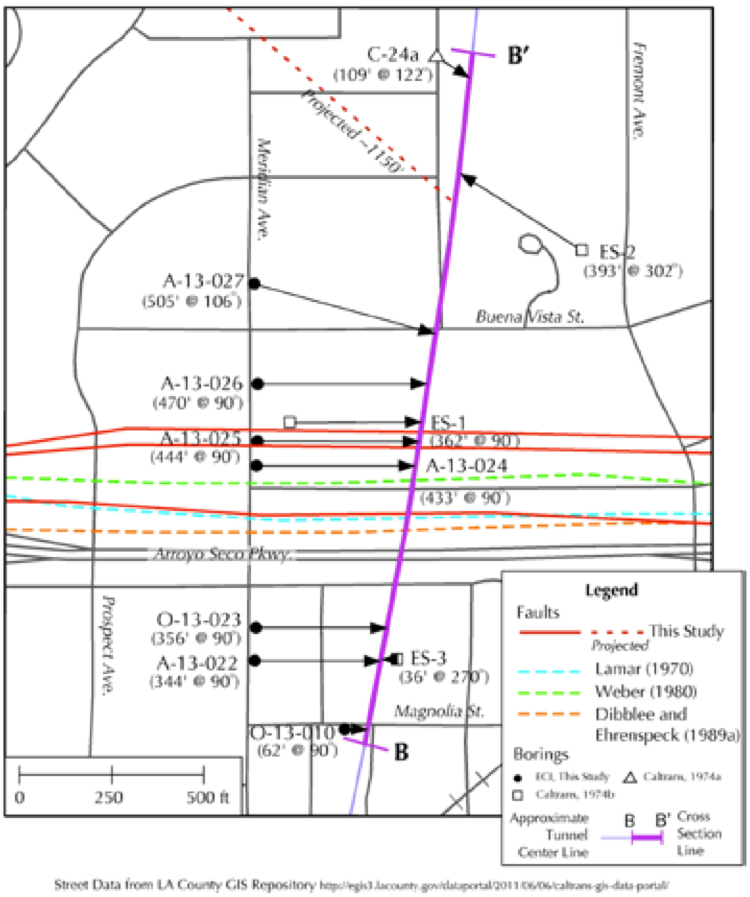

Figure 2. *Map of the boring locations along the Raymond fault zone, shown relative to the Freeway Tunnel Alternative and how they were projected onto the geologic cross sections that are discussed in the following sections. Also shown are the various mapped fault traces for the Raymond fault by others, and the location as determined in this study. Faults identified in this study are shown where they are projected to intersect the ground surface.*

In the review of the Phase 1 alternatives, reports were found (Hydrologue, 2011a) that indicated the San Rafael fault could be an active Holocene fault. Because it could cross both tunnel alternatives farther to the north in Pasadena (Figure 1), this fault, and by close association the Eagle Rock and an unnamed fault, became new exploration targets. The original boring program was modified to better evaluate the impact of these faults on the alluvial sediments, and to more accurately locate them at the tunnel crossings. As part of the SR 710 Tunnel Technical Study (CH2M HILL, 2010) geophysical studies were conducted across some of these fault strands, but the results were equivocal, and called for additional investigation.

During the permitting process, we first proposed to perform several closely spaced cone penetrometer (CPT) transects with the intended purpose of detecting offset alluvial units across the fault zones. However, after reviewing the geology of the site with the CPT contractors, it was concluded that there was a low likelihood of successfully obtaining useful CPT data because of the coarse gravel and cobbles in the subsurface, and the CPT plan was abandoned in favor of using continuously cored auger borings excavated to depths of about 100 feet. We preserved two of the deep sonic borings south of the Raymond fault because geologic data were required at tunnel depth to resolve questions about alluvial depth. But we used five shallower auger borings on the north side of the Raymond and Eagle Rock faults (Figure 2), and five additional auger borings centered on both sides of the mapped traces of the San Rafael fault. These auger borings were only ±100 feet deep, well short of the tunnel depth, but were intended only to explore the alluvial stratigraphy across the faults to more accurately locate the faults, and if possible, gain data on their potential activity. Siting the borings had its challenges as we were limited to streets of sufficient width to accommodate the drill rig along with two-lane traffic flow, and could not block driveways. The finalized fieldwork plan consisted of boring transects across the Raymond (Figure 2) and San Rafael (Figure 3) fault zones, with five hollow-stem auger borings per transect, with irregular spacing of the borings as dictated by the site constraints.

The transect across the Raymond fault zone was plotted north-south along Meridian Avenue in South Pasadena, between Highland Street and Magnolia Street (Figure 2). The transect across the San Rafael fault zone was plotted north-south along Pasadena Avenue in Pasadena, between Columbia Street and Hurlbut Street (Figure 3). Some limitations on location for all of the borings were due to the presence of overhead power lines and trees, making it difficult to get optimal spacing between the borings. The sonic borings were sited on Magnolia Street and on Meridian Avenue in South Pasadena. The sonic boring on Meridian Avenue was performed within the transect of hollow-stem auger borings; it was relocated here because the original planned location on Grevalia Street could not be sufficiently cleared of underground utilities.

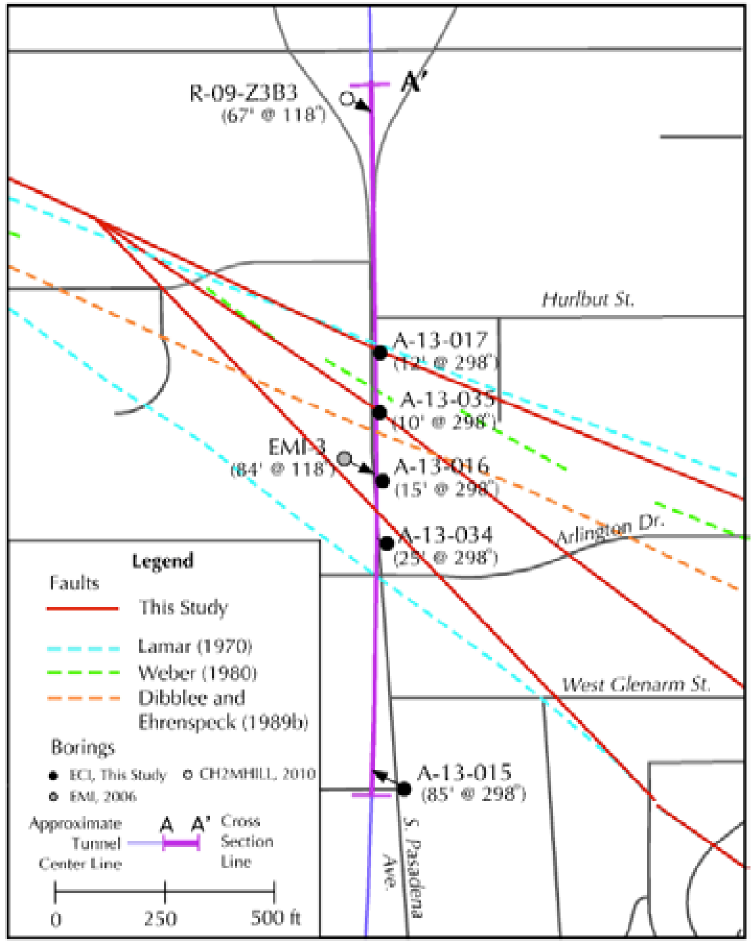

Figure 3. *Map of the boring locations for the San Rafael fault zone, shown relative to the Freeway Tunnel Alternative and how they were projected onto the geologic cross sections that are discussed in following sections. Also shown are the various mapped fault traces for the San Rafael by others, and the location as determined in this study. Faults identified in this study are shown where they are projected to intersect the ground surface.*

Field Investigation Program

For this project, ECI handled contracting of the drilling company, the waste removal company, Underground Service Alert (USA) screening, and supplemental third-party utility clearance by GEO Vision geophysical services for the drill sites. CH2M HILL handled organization of traffic control, city permitting for the drill sites, and supervision of the design and installation for the vibrating wire piezometer in one of the deep sonic borings. Waste removal services, which included drop-off of waste drums and timely removal of the full drums, were contracted to Belshire Environmental Services, Inc. (Belshire). Traffic control was contracted to Statewide Traffic Safety and Signs (Statewide).

Hollow-Stem Auger Borings. All 10 hollow-stem auger borings conducted for the fault investigation were drilled by Martini Drilling Corporation using a CME-75 drilling rig. Each boring was completed in one day and terminated in either alluvial deposits or bedrock. All holes were drilled with 8.5-inch auger bits with a 3-inch core sampler diameter. Depending on the material and relative difficulty in drilling, each drill run (or sample length) was either 2.5 or 5 feet long. Retrieved samples were stored in wooden boxes at 15 feet per sample per box, and photographed in the field. The Martini Drilling crew consisted of one driller and one helper. An ECI geologist was present for the entire drilling process.

Typical hollow-stem auger boring activities included setup of traffic control, mobilization of the drill rig, hand auguring through the upper 5 feet below ground surface (bgs) to ensure that no unexpected obstructions were encountered, drilling and sample recovery until bedrock or desired depth was achieved, demobilization of the drill rig, removal of waste drums by Belshire, and removal of traffic control by Statewide. In addition, periodic volatile organic compound (VOC) tests were performed on samples collected by hand during drilling to ensure that VOC gas did not exceed prescribed limits. No VOC hits were detected in any of the samples. Each boring was completed and grouted, the waste drums removed, and the site cleaned and vacated by the end of each work day.

Sonic Borings. Two deep borings were drilled by Boart Longyear using a 600 T Rotosonic drilling rig. The primary purpose of these borings was to determine the depth of bedrock south of the previously mapped location of the Raymond fault in the vicinity of the Freeway Tunnel and LRT Alternatives. Prior borings conducted in this area by the California Department of Transportation (Caltrans) had shown what seemed to be an anomalously deep top of bedrock.

For these borings, the intended depth was 270 feet or top of bedrock, whichever came first. The sonic borings employed two different sampling methods. Based on the Los Angeles County Metropolitan Transportation Authority's (Metro) TAC requirements, the top 100 feet of each boring was sampled using 5-foot-long 4-inch-diameter polyvinyl tubes. Below 100 feet, the sonic core samples were captured using polyvinyl bags with variable run lengths, some as long as 19 feet. Core samples were stored in wooden boxes, storing up to 10 feet per box. The Boart Longyear drilling team consisted of one driller and two helpers. An ECI geologist oversaw the entire drilling process.

A typical sonic boring included setup of traffic control, mobilization of the drilling rig, hand augering through the first 5 feet to ensure that no unexpected obstructions were encountered, drilling and sample recovery until bedrock or desired depth was achieved, demobilization of the drilling rig, removal of waste drums by Belshire, and removal of traffic control. On the second day of drilling the sonic borings, the City Engineer required us to install noise cancellation barriers (Figure 4) because of complaints from neighbors. Noise cancellation barriers were installed prior to the start of drilling on day three for the first boring, and before starting the second sonic boring. Periodic VOC tests were performed on samples collected by hand during drilling to ensure that VOC gas did not exceed prescribed limits. No hits were recorded. For the sonic borings, traffic control remained in place until the end of the boring activities, and was not removed at the end of each day. A vibrating wire piezometer was installed in boring O-13-010 at a depth of 196 feet.

Figure 4. *The sonic drill rig with the noise cancellation barriers in place.*

Results of the Field Investigation

The hollow-stem auger borings were preliminarily logged in the field. Field logging of the sonic borings was not feasible due to the poly tubes utilized during sampling. The detailed logging of the sonic core samples took place at the ECI office after the completion of drilling. In order to log the polyvinyl tube sample from the sonic borings, it was necessary to extricate the sample from the tubes by using a diamond bladed angle grinder to make two longitudinal cuts down the tubes and remove the top half (Figure 5). All core samples were logged in accordance with the 2010 edition of the Caltrans Soil and Rock Logging, Classification, and Presentation Manual. Each core box was photographed; and the core was stored at the ECI office.

Figure 5*. Cutting open the poly tubes used in the upper 100 feet of both sonic borings.*

The geologic units encountered in the borings drilled for this study included artificial fill, alluvial deposits, and bedrock units.

The depth and lithology of bedrock for each of the borings are listed in Table 1 and plotted on separate cross sectional transects for the Freeway Tunnel and LRT Tunnel Alternatives (Plates 2 and 3, respectively). Generalized descriptions of the geologic units and soils exposed in the borings are provided below.

Artificial Fill. Each of the borings in this study encountered between 0.7 and 1.5 feet of artificial fill consisting of aggregate road base gravel. The one exception to this was sonic boring O-13-010 where the road bed was placed directly upon the alluvial deposits.

Alluvial Deposits. Directly beneath the pavement section, the borings exposed alluvial deposits ranging from 48 to greater than 272 feet deep. These deposits consist primarily of poorly sorted, fine- to coarse-grained sand, gravels, and cobbles of fluvial and alluvial fan origin, sourced from the nearby San Gabriel Mountains. The most common rock lithology is granodiorite and granite, with mafic-rich metamorphic clasts less common. Most of these alluvial fan sediments to the depth explored are brown to yellowish brown in color (10YR hue); although a few redder layers and buried soil horizons were observed locally. The soils are described separately and in more detail below. The size of the clasts observed in the borings was limited by the 3-inch diameter of the core barrel or 4-inch sonic tube, but many of the clasts were actually cored through, indicating that they were larger. The coarse-grained nature of these deposits indicates a high-energy depositional environment, and an overall deposition pattern of cross bedding and interbedded units. Given these variations, it can be expected that coarse-grained deposits may not correlate well from one boring to the next, at least not individual layers, although it was possible that overall coarse-grained packages be matched across the borehole transect. Thin layers or beds of fine sand to silty sand were also observed in the cores. These beds are interpreted as overbank deposits of the Arroyo Seco and other local drainage channels, and generally represent either single events or a very short period of time in the stratigraphy.

Soils and Paleosols. Various degrees of soil development were observed at the top of all the borings for this study. Soil development, in the form of organic-rich (A) soil horizons, and reddened clay-enriched, argillic (Bt) horizons were observed, usually within the first 5 feet below of the aggregate base. The notable exception to this was found in sonic boring O-13-010 where in addition to an A-horizon and the Bt soil development, a prominent Bk (calcic) zone of soil development was encountered. This indicates the presence of a long stable alluvial surface, likely of mid-Pleistocene age. Additionally, several paleosol zones of soil development were encountered at depth in most of the borings. Essentially, these buried soils represent prior surfaces of the valley floor, and the degree of soil development exhibited by each of these soils can be used to approximate the length of time that a particular surface was exposed to soil-forming processes before it was buried by more recent alluvial fan deposition. A strongly developed (Bt) paleosol was logged on the top of the bedrock at several of the borings, especially at O-13-023 where it was up to 20 feet thick.

Bedrock Units. Bedrock lithology varied by location. The northern borings along the transect through the San Rafael fault zone encountered Topanga Formation rocks (Lamar, 1970), which varied between sandstone and conglomerate and were classified here as either undifferentiated or as the conglomerate part of the upper member of the Topanga. Farther south, in the transect along the Raymond fault zone, the bedrock was identified as the siltstone part of the lower member of the Topanga Formation. South of the Pasadena Freeway (SR 110), the Late Cretaceous Wilson Quartz Diorite (Dibblee and Ehrenspeck, 1989b; Lamar, 1970) was encountered at a depth of approximately 250 feet, with the Tertiary rock missing from the geologic column. One interpretation for why the Tertiary units are missing from the section is that this area is the site of a paleo-Arroyo Seco channel and the Tertiary section of the Topanga Formation found further north has been removed by channel incision.

Groundwater. Groundwater was encountered sporadically and at varied depths across the borings; however, given the faulting in the area this is not unexpected. Groundwater depths are summarized in Table 1. Deeper groundwater (151 to 161 feet bgs) was found in the sonic borings (0-13-010 and O-13-023), which is expected since these borings are on the foot wall of the Raymond fault. Farther north, in the Eagle Rock/San Rafael fault zone, groundwater depths varied between 40 and 85 feet, with variations owing primarily to the complexity of the fault zone.

TABLE 1
Fault Investigation Boring Summary Table
SR 710 North Study, Los Angeles County, California

Boring No.	A-13-015	A-13-016	A-13-017	A-13-022	A-13-024	A-13-025	A-13-026	A-13-027	A-13-034	A-13-035	O-13-010	O-13-023
Drilling Method (Sample Diameter)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Hollow-stem auger (3 inch)	Rotosonic (4 inch)	Rotosonic (4 inch)
Date(s) Drilled	3-08-13	3-06-13	3-4-13	3-18-13	3-19-13	3-20-13	3-21-13	3-22-13	3-07-13	3-05-13	3-4-13 to 3-8-13	3-11-13 to 3-14-13
Northing/Easting (NAD83, CA Zone 5)	1868621.79/ 6514906.45	1869322.87/ 6514854.40	1869613.60/ 6514849.25	1865463.63/ 6514130.55	1865992.79/ 6514138.52	1866058.78/ 6514139.21	1866214.01/ 6514140.84	1866484.70/ 6514134.81	1869179.67/ 6514864.10	1869478.77/ 6514848.72	1865277.86/ 6514376.75	1865552.07/ 6514135.20
Elevation (NAVD 88)	778.26 feet	785.38 feet	788.70 feet	696.34 feet	715.59 feet	720.94 feet	736.07 feet	751.89 feet	783.71 feet	787.19 feet	693.46 feet	698.11 feet
Total Depth	103.6 feet	65 feet	100 feet	110 feet	125 feet	125 feet	110 feet	100 feet	85 feet	73 feet	272 feet	270 feet
Depth of Alluvium	90 feet	51 feet	95 feet	110+ feet	125+ feet	125+ feet	103.3 feet	95.4 feet	73.6 feet	48.3 feet	272+ feet	249.5 feet
Bedrock Unit Encountered	Topanga Formation (undifferentiated)	Topanga Formation (undifferentiated)	Topanga Formation (undifferentiated)	NE	NE	NE	Topanga Formation (Siltstone member)	Topanga Formation (Siltstone member)	Topanga Formation (undifferentiated)	Topanga Formation (Conglomerate member)	NE	Wilson Quartz Diorite
Groundwater Depth (During Drilling)	67.8 feet	NE	NE	NE	NE	NE	40 feet	55 feet	85 feet	NE	151 feet	161 feet
Piezometer Sensor Depth	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	196 feet	N/A
Borehole Abandonment	Portland Cement, 3/8/2013	Portland Cement, 3/6/2013	Portland Cement, 3/4/2013	Portland Cement, 3/18/2013	Portland Cement, 3/19/2013	Portland Cement, 3/20/2013	Portland Cement, 3/21/2013	Portland Cement, 3/22/2013	Portland Cement, 3/7/2013	Portland Cement, 3/5/2013	Piezometer Installed on 3/08/2013	Portland Cement, 3/14/2013

N/A – not applicable
NE – not encountered

Geologic Structure Interpretation

To better constrain the locations of the San Rafael, Eagle Rock, and Raymond faults at tunnel depths for the Freeway Tunnel and LRT Alternatives, we constructed geologic cross sections using borehole data obtained for this study, as well as data from older boreholes (Plates 2 and 3). Cross section lines follow the approximate centerlines of the proposed tunnels. Where possible, borings drilled for this study bracket mapped faults (Lamar, 1970; Dibblee and Ehrenspeck, 1989a and 1989b; Weber, 1980) or geomorphic features identified as part of this study that mark the possible expression of faults at the ground surface. Borings are projected onto the cross section line parallel to the local structural grain based on information from published geological maps (see Figures 2 and 3). Figure 6 provides a legend for the subsequent cross sections presented in this TM.

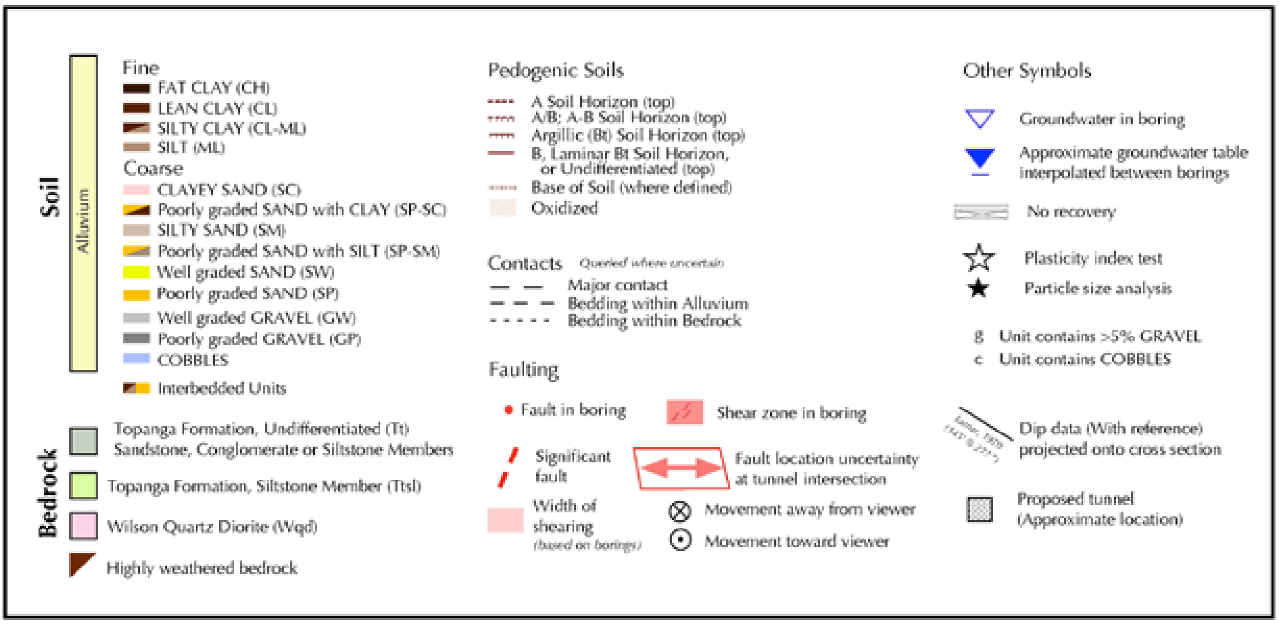

Figure 6. *Legend from Plates 2 and 3, used for all of the following geologic cross section figures in this TM.*

Between borings, we correlate laterally continuous horizons including the top of bedrock, distinctive packages of fine- and coarse-grained alluvium, and pedogenic soils developed into the alluvium. We also note the continuity of groundwater. Faults are identified by discontinuities in these horizons or markers. Because spacing of the borings is not close enough to constrain actual fault offsets, discontinuities are inferred where the slope of a contact between two borings varies significantly from the surface gradient of ~1 degree. Given the wide spacing between some borings, we use additional information to constrain fault locations, including faults or shear zones in older borings, tectonic scarps at the ground surface, available seismic lines, and mapping by others. Where the location of a fault could not be constrained well, we note the uncertainty of the fault location at tunnel depth. The uncertainty is reported as a horizontal range for the center of the proposed tunnel. Fault dip is based on supplemental information from published maps or reports. For faults that cross the section obliquely, we show the apparent dip of the fault on the section. To facilitate the discussion of features on each section, we use local station numbers except when describing the extent of each cross section.

Freeway Tunnel Alternative

Plate 2 Section A-A’ is constructed between Freeway Tunnel “A” Line station 1684 + 58 and 1700 + 84 using five new continuous hollow-stem auger borings, including from north to south: A-13-017, A-13-035, A-13-016, A-13-034, and A-13-015 (Figure 3). These borings ranged in depth from 65 to approximately 104 feet. Borings R-09-Z3B3 (CH2M HILL, 2010) and EMI-3 (Earth Mechanics, Inc. [EMI], 2006) with depths of 276 and 204 feet, respectively, were also used for the section. All borings extend into bedrock.

The section extends through Quaternary alluvium (Qal), Miocene sedimentary rock of the Topanga Formation (Tt), and Cretaceous crystalline basement rock of the Wilson Quartz Diorite (Wqd). The section crosses strands of the

San Rafael fault mapped by Lamar (1970), Yerkes and Campbell (2005), Weber (1980), and Dibblee and Ehrenspeck (1989b). Qal consists of interbedded fine and coarse fan deposits. Because most of the new borings did not penetrate the Topanga Formation far enough to clearly distinguish between the sandstone or conglomerate members, we do not differentiate between the two, and instead show the Topanga Formation as undifferentiated.

The section shows deep alluvium (~190 feet thick) to the north, a bedrock high between stations 600 and ~1000, which is likely related to the San Rafael fault, and shallower alluvium (74 to 91 feet thick) south of station 600. The proposed Freeway Tunnel Alternative would extend through Tt between stations 0 and about 1000. Based on mapping of bedrock exposures to the northwest of the section by Lamar (1970), bedding between stations 0 and 600 dips approximately 60 degrees north. Between stations ~1100 and 1600, the tunnel would cut through Wqd and Qal. Based on the depth of bedrock in boring R-09-Z3B3, the contact between Wqd and Qal is located within and subparallel to the tunnel cut. Between stations 1000 and 1100, the tunnel traverses the main strand of the San Rafael fault and possible secondary strands to the south. Table 1 shows the materials and structures traversed by the tunnel in Cross Section A-A'. Table 2 summarizes the minimum and maximum extents that the Freeway Tunnel Alternative intersects geological units and structures in the vicinity of the San Rafael Fault zone.

TABLE 2
Constraints on Bedrock and Faulting at Freeway Tunnel Depth, San Rafael Fault Crossing
SR 710 North Study, Los Angeles County, California

Unit or Fault	Plate 2 Cross Section Station (feet)	Notes
Alluvium	1035 (+50/-25) to 1600	Southern extent contingent on location of San Rafael fault. Could also be up to several hundred feet north because depth of bedrock is not constrained between A-13-017 and R-09-Z3B3.
Topanga Formation	0 to 1035 (+50/-25)	Northern extent contingent on location of San Rafael fault.
Wilson Quart Diorite	1035 (+50/-25) to 1600	Southern extent contingent on location of San Rafael fault.
San Rafael fault – Main Strand	1035 to 1050 (both +50/-25)	
San Rafael fault splay	900 to 910 (both +110/-10)	
San Rafael fault splay	665 to 680 (both +40/-55)	

San Rafael Fault – Main Strand. We see evidence that the main strand of the San Rafael fault and possibly two secondary fault strands cross the section (Figure 7). Between borings R-09-Z3B3 and A-13-017, bedrock changes from Wqd to Tt and the top of bedrock rises over 80 feet. The same relation in bedrock exposures in the Arroyo Seco drainage, approximately 3,700 feet to the northwest, marks the main trace of the San Rafael fault and indicates that the main strand of the fault is located between the two borings. Although the fault is not exposed in either boring, the fault is likely close to boring A-13-017 between stations 1000 and 1100 considering the projection of the fault southwest from the Arroyo Seco using the strike of the fault in bedrock exposures on either side of the drainage and to the northwest. Weber (1980) reports that the fault is likely very steep to vertical through this area. We calculate an apparent dip of ~79 degrees for the fault based on an 80 degree dip.

Continuity of fine-grained alluvial units between boring A-13-017 and borings to the north and south suggests the fault does not disturb the upper ~30 feet of alluvium. Although no quantitative age dating of alluvium was done for this study, the degree of soil development in the upper alluvium suggests that the upper alluvial surface is pre-Holocene. A lack of continuity of deeper alluvial units between borings could be the result of faulted alluvium, or lateral facies changes. Because spacing of the borings is too wide to distinguish between the two, we query the fault into the base of the alluvium.

Crystalline basement in the hanging wall of the fault suggests a reverse sense of motion. This is not consistent with the apparent normal separation of the top of bedrock across the fault. However, if the motion of the fault includes a significant lateral component, the apparent drop in bedrock to the north could be explained by the lateral juxtaposition of paleotopography. We assign a tentative left lateral component of motion to the fault based on Weber (1980) who reported a left laterally offset drainage along the strike of the fault to the southwest of the section. Alternatively, the fault may no longer be active, and the drop in bedrock actually reflects incision of a drainage channel rather than a tectonic feature. We query an apparent down to the north offset in the top of the bedrock to be consistent with the drop in bedrock to the north. Additional subsurface information is required to confirm or refute this.

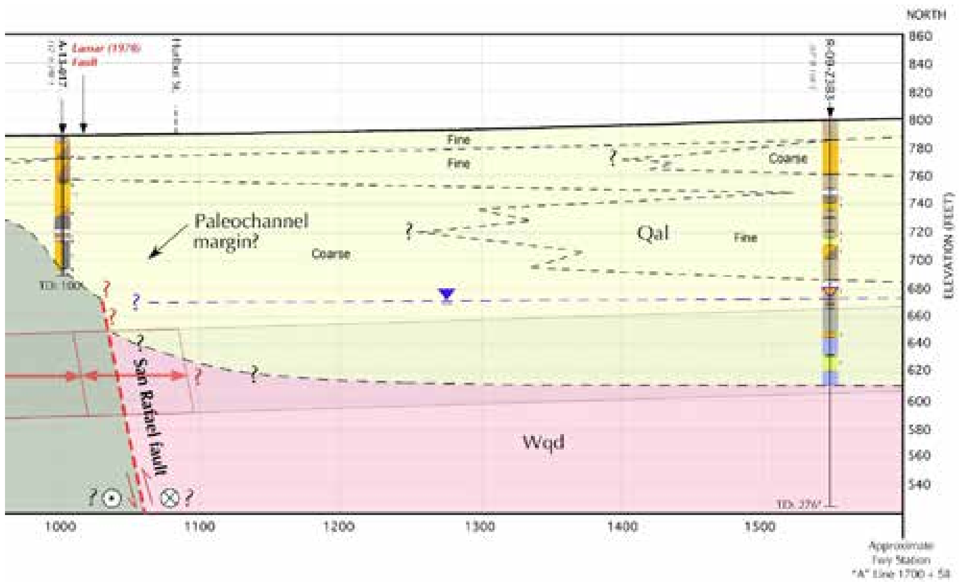

Figure 7. *Northern end of Plate 2 Cross Section A showing the interpreted location of the main trace of the San Rafael fault. Freeway Tunnel Alternative is shown in light gray shading. Fault location uncertainty zone is shown by red arrows across tunnel section.*

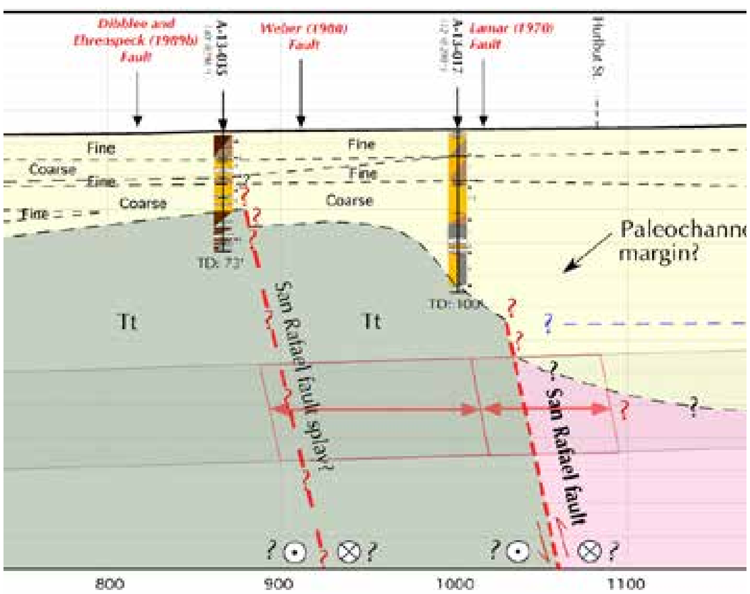

Figure 8. *Southward continuation of Figure 7 showing a secondary strand of the San Rafael fault south of the main trace. The secondary fault was interpreted due to a step in the bedrock surface, which could be erosional. The Freeway Tunnel Alternative is shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

At tunnel depth, we place an asymmetrical ~75-foot-wide horizontal uncertainty on our best estimate for the fault location; a 50-foot uncertainty to the north of the fault to account for uncertainty in our fault projection from the Arroyo Seco or a lower fault dip, and a 25-foot uncertainty to the south in case the fault was not visible in massive, coarse-grained alluvial units in boring A-13-017. The main strand cannot be farther south than boring A-13-017 or we would have seen Wqd rather than Tt in the boring. The proposed tunnel intersects the zone of uncertainty between stations 1010 and 1100. This zone is wider than the horizontal zone of uncertainty because of the angle at which the top and bottom of the tunnel and the dipping faults intersect.

San Rafael fault – Secondary Strands. Drops in the top of Tt bedrock between borings could mark two secondary splays of the San Rafael fault south of the main strand. Between A-13-035 and A-13-017 the top of bedrock drops about 45 feet to the north (Figure 8). Although this drop could be the expression of a channel margin, as discussed above, the close proximity of this drop to the main strand of the San Rafael fault suggests that it could be due to faulting. We tentatively place a fault strand adjacent to boring A-13-035 because bedrock from this boring was less competent than in other borings to the south, possibly reflecting a weakness in the rock due to nearby faulting (Figure 8). Without direct information on fault dip, we assign a dip of 80 degrees based on Weber (1980) and calculate an apparent dip of 78 degrees based on the angle that the fault intersects the section. The continuity of a contact between coarse- and fine-grained units indicates that the fault does not extend into the upper ~30 feet of alluvium.

Because the fault was not observed in the borings, we assign a large uncertainty for its location extending the full width between the two borings. The width of the zone of uncertainty for the location of the fault at tunnel depth is approximately 120 feet wide. Accounting for the apparent dip of the fault, the tunnel intersects the fault zone and its associated zone of uncertainty between stations 890 and 1020. Furthermore, we cannot rule out the possibility that other splays occur between the two borings.

Between borings A-13-016 and A-13-034, a southward drop of 24 feet in the top of bedrock could mark a more southerly splay of the San Rafael fault (Figure 9). As with other strands of the fault, a fine-grained unit about 30 feet bgs is not disturbed by faulting as shown by the similarity in the gradients of these units with the ground surface. At the base of the alluvial section, a clayey sand that correlates across the fault between borings A-13-035 and EMI-3 has a steeper gradient than the ground surface, suggesting this unit is folded or offset. Because we did not see this unit in boring A-13-016, this correlation is not robust and we query the fault into the base of the alluvium.

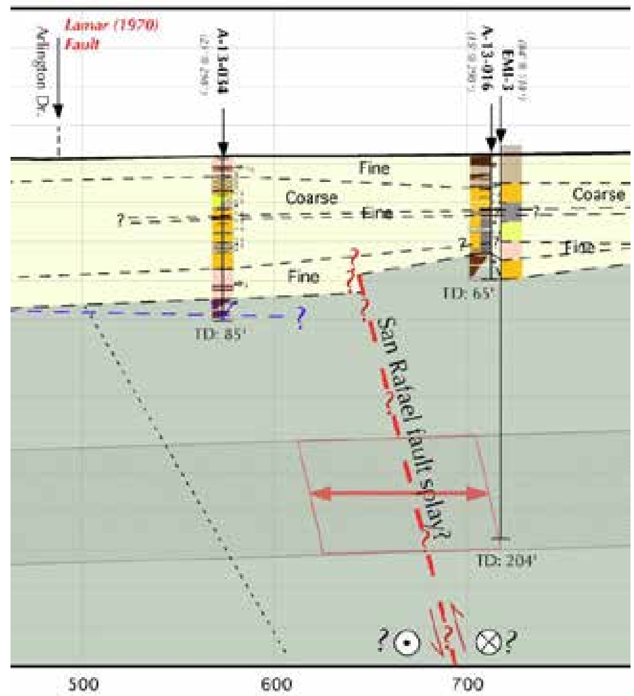

Figure 9. *Southward continuation of Figure 8 showing another potential secondary strand of the San Rafael fault that was interpreted due to a step in the bedrock surface, which could be erosional. The Freeway Tunnel Alternative is shown in light gray shading. The fault location uncertainty zone is shown by red arrows across tunnel section.*

We give this fault the same dip as the fault splay to the north. The apparent dip is approximately 76 degrees, a couple of degrees lower than the strand to the north because this fault likely intersects the cross section line at a more oblique angle. Without additional constraints on where this potential fault is located in the subsurface, we place it midway between the borings at the top of bedrock, and assign an asymmetrical uncertainty of 40 feet to the north and 55 feet to the south. This uncertainty is defined by the furthest point that the fault could be projected north or south without intersecting a boring. Within uncertainty, this fault intersects the tunnel between stations 610 and 720.

Another drop in the top of bedrock, ~20 feet down to the north, occurs between borings A-13-035 and EMI-3. Five feet south of EMI-3, the top of bedrock in boring A-13-016 is only 4 to 5 feet lower than in A-13-035. Because EMI-3 is projected over 80 feet to the cross section line in contrast to much shorter projections for A-13-035 (10 feet) and A-13-016 (15 feet), we believe that the drop is probably due to EMI-3 being out of the plane of the section. The slope for the top of bedrock between A-13-035 and A-13-016 matches the slope of the ground surface, suggesting that there is no deformation between these two borings.

Because the tops of bedrock units within the alluvium have a slightly steeper gradient than the ground surface between borings A-13-034 and A-13-015, we cannot rule out the possibility of additional minor faulting or folding between these borings.

Plate 2 Section B-B' extends from Freeway Tunnel "A" Line Station 1650 + 24 to 1669 + 24 and is constructed using 11 borings, including 5 new continuous hollow-stem auger borings, 2 new sonic borings, and 4 borings from previous studies (Figure 2). The auger borings range in depth from 100 to 125 feet bgs and include, from north to south, A-13-027, A-13-026, A-13-025, A-13-024, and A-13-022. The sonic borings range in depth from 270 to

272 feet bgs and include O-13-023 and O-13-010. The other borings range in depth from 195 to 351 feet bgs and include C-24a (Caltrans, 1974a); and ES-1, ES-2, and ES-3 (Caltrans, 1974b). Borings are projected to the cross section line along local structural grain, which is approximately east-west in the vicinity of the Raymond fault and northwest-southeast along the projection of the Eagle Rock fault.

Section B-B' extends through Quaternary Alluvium (Qal), Topanga Formation (Tt), and Wilson Quartz Diorite (Wqd). Based on the presence of siltstone and claystone in several borings, we assign part of Tt to the siltstone member (Ttsl) of Lamar (1970). The section crosses traces of the Raymond fault mapped by Lamar (1970), Weber (1980), and Dibblee and Ehrenspeck (1989a). Lamar (1970) shows the Eagle Rock fault ending approximately 1,150 feet northwest of the section. The fault parallels a linear ridge that extends beyond the mapped fault trace. If the ridge is the surface expression of the Eagle Rock fault, the fault may continue southeast of its mapped extent and could project through the northern part of the section.

Deep alluvium underlain by Wqd characterizes the southern half of the section and relatively shallow alluvium over Ttsl and Tt in the north half of the section. The transition between deep and shallow alluvium corresponds well with the location of the Raymond fault. The area south of the Raymond fault contains up to 270 feet of alluvium. The deep alluvium could be in a graben down-dropped between the Raymond fault and unidentified fault to the south. Conversely, the deep alluvium may not have a tectonic origin, but rather the expression of a paleochannel of the Arroyo Seco that flows along the Raymond fault.

Along-strike projection of bedrock orientations from Lamar (1970), approximately 1,200 to 1,600 feet southeast to the section, suggest that bedrock in the hanging wall of the Raymond fault dips moderately to steeply north. Bedding observed in the borings suggests that bedrock in the hanging wall is highly contorted, with dips ranging from subhorizontal to subvertical. The Freeway Tunnel Alternative passes through Qal between stations 0 and a minimum of station 700, with our best estimate at station 860. Tt/Ttsl extends at least between stations 900 and 1900, with our best estimate of station 790 for the lower extent. The transition from Qal to Ttsl occurs along the Raymond fault zone. Table 3 summarizes the minimum and maximum extents that the Freeway Tunnel Alternative intersects geological units and structures.

TABLE 3
Constraints on Bedrock and Faulting at Freeway Tunnel Depth, Eagle Rock and Raymond Fault Crossings
SR 710 North Study, Los Angeles County, California

Unit or Fault	Cross Section Station (feet)	Notes
Alluvium	0 to 860	Northern extent of alluvium is poorly constrained. Could be 100 feet or more further to the south.
Topanga Formation	790 to 1,900	Southern extent of Topanga is not well constrained. Could be 100 feet or more further to the south.
Wilson Quart Diorite	Not Applicable	Tunnel does not intersect this unit.
Raymond fault zone	770 to 920 (both +25/-100)	Extent of three primary faults and associated uncertainty is based on drops in the top of bedrock in A-13-025 and A-13-027 that suggest faults could extend up to 200 feet further north. Width of active fault zone is much less than entire fault zone.
Eagle Rock fault	1,580 to 1,615 (both +10/-75)	May die out west of the Alternative and be expressed only as a fold across the tunnel.

Raymond Fault. Multiple lines of evidence constrain the active strands of the Raymond fault zone between boring A-13-026 and the Pasadena Freeway (Figure 10). Faulting in the bedrock and older alluvium may extend as far north as boring A-13-027. Generally, bedrock and groundwater drop 200 and 160 feet, respectively, across the fault; and bedrock changes from Topanga Formation in the hanging wall to Wilson Quartz Diorite in the footwall.

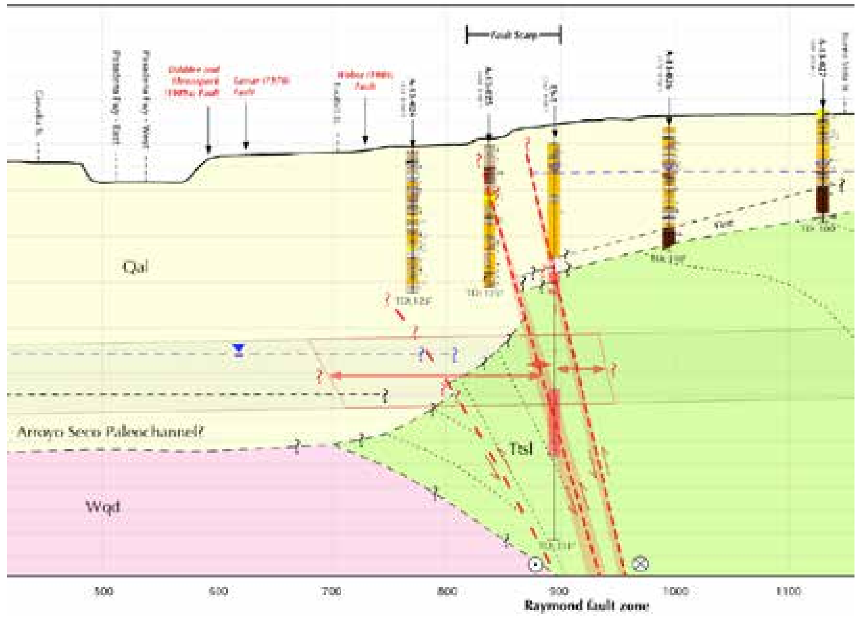

Figure 10. *Interpretation of the Raymond fault zone (Plate 2 Section B-B') within the Freeway Tunnel Alternative shown in light gray shading. Fault location uncertainty zone is shown by red arrows across the tunnel section.*

Two zones of shearing and faulting in boring ES-1 correlate well with disruptions of groundwater, alluvium, and surface scarps, suggesting that these zones define the main strands of the Raymond fault zone. Caltrans (1974b) interprets a loss of sample within boring ES-1, between depths of 104 and 117.4 feet as a possible fault zone that continues to a depth of 127 feet. A groundwater barrier in Qal and a pronounced scarp at the surface between borings ES-1 and A-13-025 support extending this fault through the alluvium to the ground surface. The linearity of the scarp in map view suggests the fault dips steeply to the north. Connecting the fault from the highest fault zone in ES-1 to the top of the scarp allows a maximum dip for this fault of approximately 75 degrees. The absence of a break in groundwater or abrupt surficial scarps north of ES-1 suggests that this fault marks the northern edge of the active strands of the Raymond fault zone. Large drops in the top of bedrock between A-13-027 and ES-1 do not preclude additional faults in the top of bedrock and base of alluvium. A more likely interpretation is that the drops in the top of bedrock are due to folding in the hanging wall of the Raymond fault. Because groundwater does not change gradient across this zone, we assume that any faulting or folding does not affect the upper part of the alluvium.

In boring A-13-025, we observed a possible fault at about 44 feet that truncates the top of a silty sand. Projecting a line from near the base of the surface scarp through the fault in A-13-025 intersects a zone of "tough claystone" in boring ES-1 interpreted by Caltrans (1974b) as a rehealed fault gouge breccia. The faulted alluvium in boring A-13-025 and corresponding scarp at the ground surface suggest the zone of brecciated bedrock in ES-1 along the downdip projection of these features as an active strand of the Raymond fault. Based on the projection between the surface and boring A-13-015, the fault dips approximately 70 degrees to the north.

Faulting and shearing in the interval between the two shear zones in ES-1 suggests that the two fault strands border a zone of intense deformation bounded by primary strands of the Raymond fault. To the south of the faults, we do not see evidence of faulting in boring A-13-024; although Lamar (1970), Weber (1980), and Dibblee and Ehrenspeck (1989a) all place faults between A-13-024 and the Pasadena Freeway. It is plausible that a fault extends beneath A-13-024 toward the vicinity of the faults mapped by others. Because we have no data to confirm or refute the presence of faulting in this area, we query a low angle fault strand into the alluvium.

Borings ES-3 and O-13-023 revealed that bedrock south of the Raymond fault zone is composed of Wqd. Because the dip slip component of motion on the Raymond fault should place older rock in the hanging wall over younger rock in the footwall, Wqd should be over Ttsl. However, if the contact between Wqd and Ttsl in the footwall is folded down to the north, this allows for a component of dip slip motion on the southernmost strand of the Raymond fault and places Ttsl against Ttsl.

At tunnel depth, we assign a combined horizontal uncertainty of about 240 feet for the three fault strands. Most of this uncertainty (nearly 190 feet) is due to a complete lack of information on the location of the inferred southern strand of the Raymond fault. The complexity of the fault zone defined by the northern two strands makes it difficult to assign robust uncertainties to these individual strands. A combined uncertainty of approximately 70 feet encompasses both fault zones, and includes massive alluvium in boring ES-1 that could contain additional fault strands. The width of this assigned uncertainty is consistent with the width of the surficial scarp along the updip projection of the faults. At tunnel depth, the proposed tunnel intersects the fault zone (within assigned uncertainties) between about stations 670 and 945. If drops in bedrock north of the fault zone are related to faulting, the tunnel could intersect faults for an additional 200 feet north of the main fault zone.

Eagle Rock Fault. At the surface, the mapped trace of the Eagle Rock fault projects across section B-B' approximately between stations 1400 and 1500 (Figure 11). This is in the vicinity of the surface projection of a "Probable major fault" in boring ES-2 that dips 65 degrees. We speculate that this could be the extension of the Eagle Rock fault and calculate an apparent dip of approximately 61 degrees based on the strike of the fault projection, the strike of the cross section, and the reported fault dip.

The distance between borings in the vicinity of the Eagle Rock fault is too wide to speculate about the activity of the fault. We query a fault offset in the top of the bedrock to indicate that the fault could be late Quaternary active. There are no scarps where the fault projects to the surface. Additional faults and shear zones in ES-2 could be the expression of the Eagle Rock fault splaying into multiple minor fault strands as it dies out to the southeast.

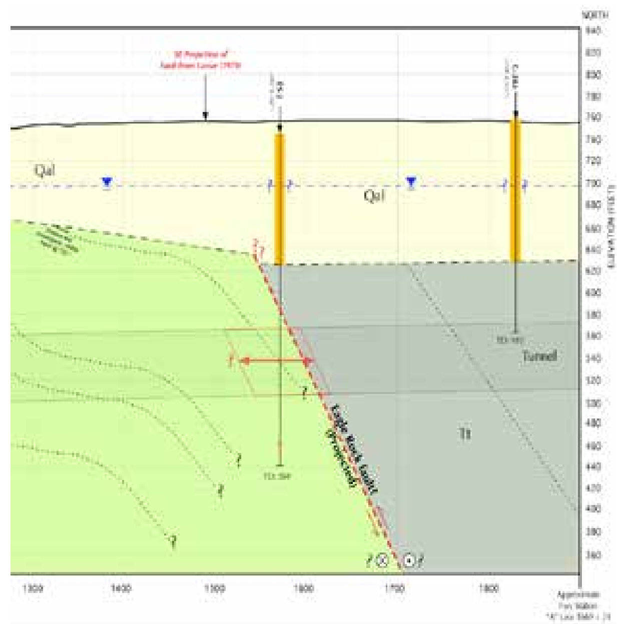

Figure 11. *Interpretation of the Eagle Rock fault (Plate 2 Section B-B') within the Freeway Tunnel Alternative shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

We assign an asymmetrical horizontal uncertainty of approximately 85 feet to encompass other faults and shear zones in boring ES-2.

LRT Alternative

Plate 3 Section A-A' is 1,700 feet long and constructed between LRT "A" Line stations 370 + 48 and 387 + 48 (Figure 12). No new data were collected in the vicinity of this section. The section is constructed using only one new boring, A-13-017, which is projected southwest 1,515 feet from the Freeway Tunnel Alternative. The projection of the boring is approximately along the strike of the San Rafael fault. From previous studies, we used four shallow borings (B-2, B-5, B-9, and B-10) ranging in depth from 50 to 60 feet (Hydrologue, 2011b), and one deep boring (R-09-Z3B6) with a depth of 326 feet (CH2M HILL, 2010). The Hydrologue (2011b) borings lacked elevation data and were projected across a relatively flat surface to the ground elevation at the cross section line. Boring A-13-017 was projected to the ground surface along the cross section line to be consistent with constraints on the top of bedrock in the Hydrologue (2011b) borings. This is also consistent with the topographic gradient between the two cross section lines. In an alternate interpretation, a bedrock high could lie between A-13-017 and boring B-2, although we did not see a need to do this. Lastly, we used data for the depth, type of bedrock, and groundwater from

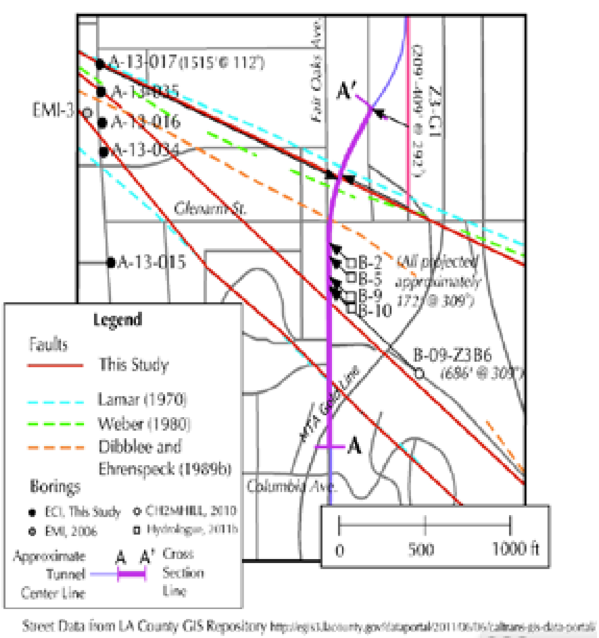

Figure 12. *Map of the LRT Alternative showing previously mapped interpretations of the San Rafael fault zone, and the interpretation from this study. Boring locations are shown along with arrows indicating their projections onto the cross section.*

borings R-09-Z3B3 and R-09-Z3B4, which are located north of the section; and we used seismic line Z3-G1 (CH2M HILL, 2010) to constrain the northern extent of the San Rafael fault.

Plate 3 Cross Section Line A-A' is characterized by deep alluvium (~180 feet) at the northern end of the section, between about stations 1350 and 1700; shallow alluvium (~70 feet thick) between stations 800 and at least 1350, and a thin veneer of alluvium between stations 230 and 800. The section crosses the main strand of the San Rafael fault and two potential fault splays. The transition from deep to more shallow alluvium occurs in the vicinity of the main strand of the San Rafael fault. The transition to a thin veneer of alluvium is due to the projection of the cross section line along the west slope of Raymond Hill. Lamar (1970) shows alluvium along the southern extent of the cross section, whereas Dibblee and Ehrenspeck (1989b) map this area as bedrock. Borings A-13-017 and R-09-Z3B6 and mapping by Lamar (1970) and Dibblee and Ehrenspeck (1989b) constrain the extent of the Topanga Formation between stations 0 and approximately 1395. Based on bedrock orientations from Lamar (1970) and Dibblee and Ehrenspeck (1989b), the Topanga Formation is folded into a north-plunging anticline between the two fault splays. South of the southern fault splay, bedding dips west, and the strike of bedding is parallel to the cross section line, resulting in apparent horizontal bedding on the cross section.

Based on boring R-09-Z3B4, relations observed to the northwest in the Arroyo Seco, and the cross section for the Freeway Tunnel Alternative, the Wilson Quartz Diorite likely extends north of the main strand of the San Rafael fault between stations 1395 to 1700. The LRT tunnel intersects alluvial deposits (Qal) between stations 800 and 1700, and Topanga Formation (Tt) between stations 0 and ~1340 (Table 3). The extent to which the tunnel cuts the Topanga Formation is poorly constrained due to the lack of borehole data. The tunnel does not cut through the Wilson Quartz Diorite (Wqd).

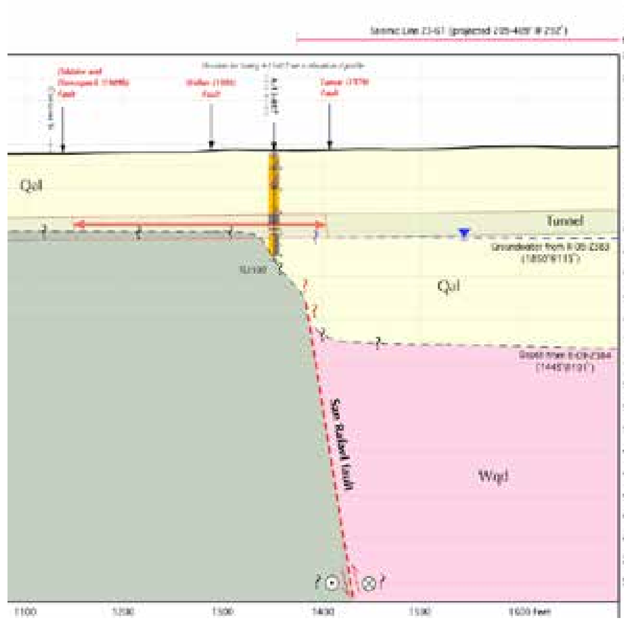

Figure 13. *Main trace of the San Rafael fault that projected along strike to the LRT Alternative (Plate 3 Section A-A'), shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

San Rafael fault – Main Strand. In the vicinity of the LRT cross section, the main strand of the San Rafael fault is very broadly constrained between Tt in boring R-09-Z3B6 to the south and Wqd in boring R-09-Z3B3 to the north (Figure 13). Seismic line Z3-G1, which lies several hundred feet east of the section, contains a sharp reflector without any significant discontinuities at the depth of bedrock in boring R-09-Z3B4. Our interpretation of these data is that the fault lies south of the seismic profile. Projecting the seismic line northwest and boring A-13-017 southeast along our best estimate for the strike of the main strand of the San Rafael fault, based on the projection of the fault between the Arroyo Seco and the Freeway Tunnel Alternative cross section and mapped strands by Lamar (1970) and Weber (1980), constrains the location of the fault between stations 1370 and 1420. We assign a dip of 80 degrees based on Weber (1980) and calculate an apparent dip of about 78 degrees. The sense of motion is the same as for the Freeway Tunnel Alternative section.

Because the available boring data do not allow us to determine if the fault cuts alluvium, we query the fault cutting the top of bedrock. A lack of scarps in the ground surface suggests the fault does not extend to the surface. We assign an asymmetrical uncertainty of about 260 feet to the fault location. The northern limit of the fault is well constrained by the seismic line and is assigned an uncertainty of 20 to 30 feet. The southern limit is poorly constrained due to the large distance between boring A-13-017 and the LRT Alternative cross section line. Furthermore, the lack of other borings to bedrock in the vicinity of the main strand of the San Rafael fault does not allow us to rule out possible bends or steps in the fault. Dibblee and Ehrenspeck (1989a), for example, show a southwest step in the fault east of the LRT Alternative section line. Therefore, we assign an uncertainty of 225 feet to the south. The southern limit is defined by the mapped trace of the fault by Dibblee and Ehrenspeck (1989a).

If the fault extends into alluvium, it would project through the LRT Alternative between stations 1370 and 1375, or as far as 1145 to 1410 within uncertainty. Table 4 summarizes the minimum and maximum extents that the LRT Alternative intersects geological units and structures in the vicinity of the San Rafael Fault zone.

TABLE 4
Constraints on Bedrock and Faulting at LRT Tunnel Depth, San Rafael Fault Crossing
SR 710 North Study, Los Angeles County, California

Unit or Fault	Cross Section Station and Uncertainty (feet)	Notes
Alluvium	800 to 1,700	None
Topanga Formation	0 to 1,340 (+70)	None
Wilson Quart Diorite	Not Applicable	Tunnel does not intersect this unit.
San Rafael – Main Strand	1,370 (-225) to 1,375 (+35)	Fault may not project through tunnel.
San Rafael fault splay	735 (-50) to 740 (+50)	None
San Rafael fault splay	345 (-50) to 350 (+50)	None

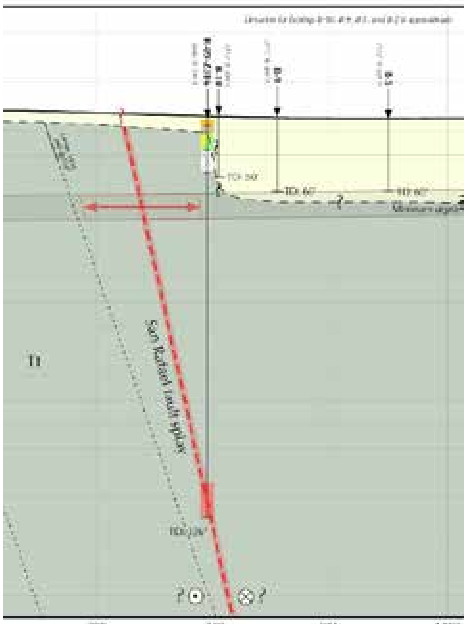

Figure 14. *Interpreted secondary splay of the San Rafael fault that projected along strike to the LRT Alternative (Plate 3 Section A-A'), shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

San Rafael fault splays. Existing borehole data provide direct evidence for two faults that we interpret as splays of the San Rafael fault. We connect these splays to the fault splays observed on the Freeway Tunnel Alternative section and assign dips of 80 degrees to the north, consistent with Weber (1980). Apparent dip for both faults is 77 degrees. We infer a similar sense of motion for these splays as for the splays on the Freeway Tunnel Alternative section.

A significant shear zone in the lower ~30 feet of boring R-09-Z3B6 defines the northern splay (Figure 14). We assume that this fault dips north, consistent with the San Rafael fault. We assign a dip of 80 degrees based on Weber (1980) and calculate an apparent dip of about 77 degrees. The fault intersects the LRT Alternative between stations 735 and 740. We assign a symmetrical uncertainty of 100 feet to account for minor variations in dip. A 25-foot step down to the north between borings R-09-Z3B6 and B-9 is likely an artifact of projecting boring R-09-Z3B6 onto the cross section line. Because this part of the line is constructed along a drainage, bedrock adjacent to the line will have a higher elevation, thus projecting borings onto the line will produce apparent steps. If, however, the step is due to a fault, then it is captured in the uncertainty for the fault splay. The fault would have to be nearly vertical, or it would have been noted in boring R-09-Z3B6.

The southern splay (Figure 15) is based on mapping by Lamar (1970) that projects a bedrock fault through the LRT Alternative section. We

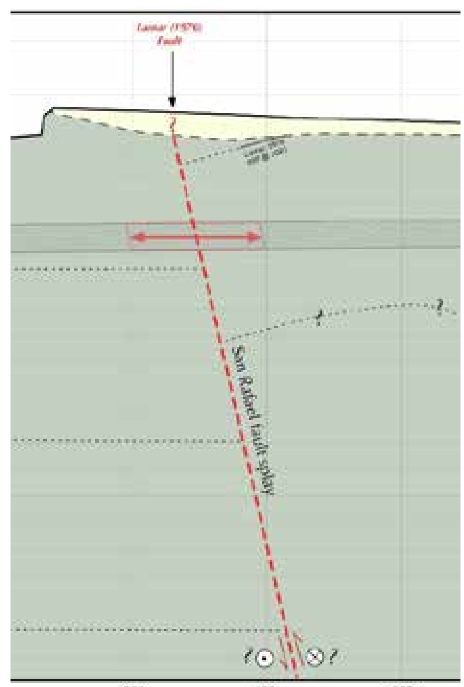

Figure 15. *Interpreted additional secondary splay of the San Rafael fault that projected along strike to the LRT Alternative, shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

assign an uncertainty of 100 feet for this splay to account for variations in dip. The fault intersects the section between stations 345 and 350, or within uncertainty, between stations 295 and 400. Similar to the Freeway Tunnel Alternative section, we have no data on the age of activity of these fault splays.

Raymond fault. Plate 3 Section B-B' is 1,500 feet long and extends from "A" Line stations 345 + 32 to 360 + 32. Due to the anticipated similarities in geologic units, morphology, and faulting, this section is constructed based on selected borings projected east 1,660 to 2,400 feet. Boring locations and their projections onto the section are shown in Figure 16. The cross section line extends down an alluvial fan developed over the Raymond fault sourced from a drainage that runs between Raymond Hill and Grace Hill to the west. We locate the main traces of the

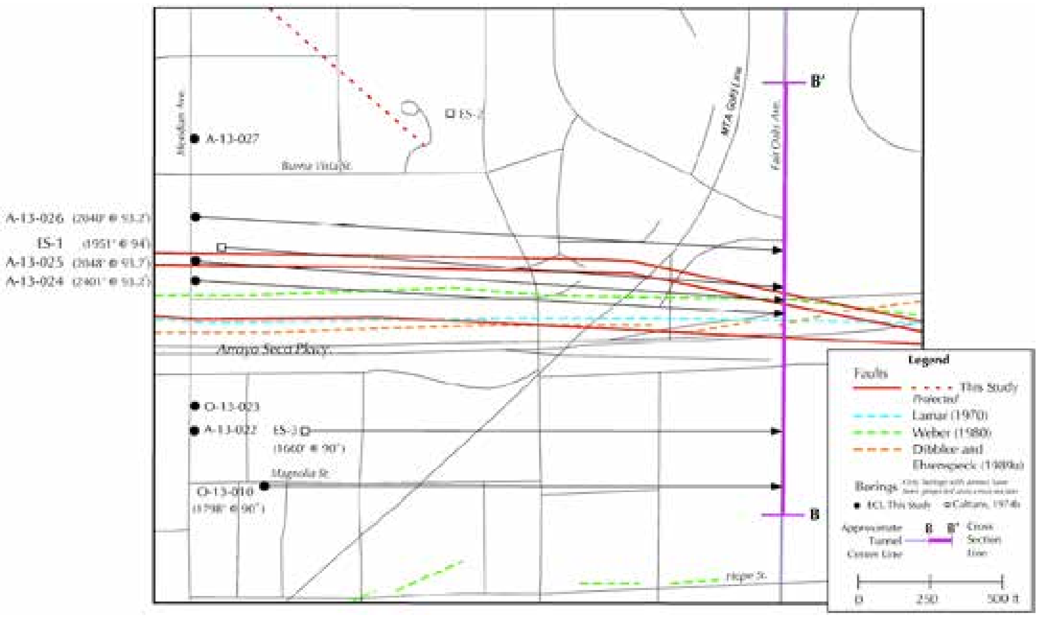

Figure 16. *Map of the LRT Alternative showing previously mapped interpretations of the Raymond fault zone, and the interpretation from this study. Boring locations are shown along with arrows indicating their projections onto the cross section.*

Raymond fault based on the east-southeast projection of the prominent fault scarp observed in the Freeway Tunnel Alternative cross section (Figure 17). In the vicinity of the LRT Alternative section, the scarp bends a few degrees south, disappears across the fan, and appears again southeast of the fan. We locate the main strands of the Raymond fault based on the projection of the scarp across the fan. The southern extent of the inferred frontal fault is constrained by the mapped trace of the Raymond fault by Dibblee and Ehrenspeck (1989a) and the Pasadena Freeway, south of which there are no geomorphic features indicative of active faulting. The extent of the units and faulting at the elevation of the LRT Alternative tunnel are shown in Table 5.

TABLE 5
Constraints on Bedrock and Faulting at LRT Tunnel Depth, Raymond Fault Crossing
SR 710 North Study, Los Angeles County, California

Unit or Fault	Cross Section Station and Uncertainty (feet)	Notes
Alluvium	0 to 800 (-50) to 900	Alluvium may extend north.
Topanga Formation	800 (-50) to 900	None
Wilson Quart Diorite	Not Applicable	Tunnel does not intersect this unit.
Raymond fault	640 to 790 (+90)	Width of active fault zone much less than entire fault zone.

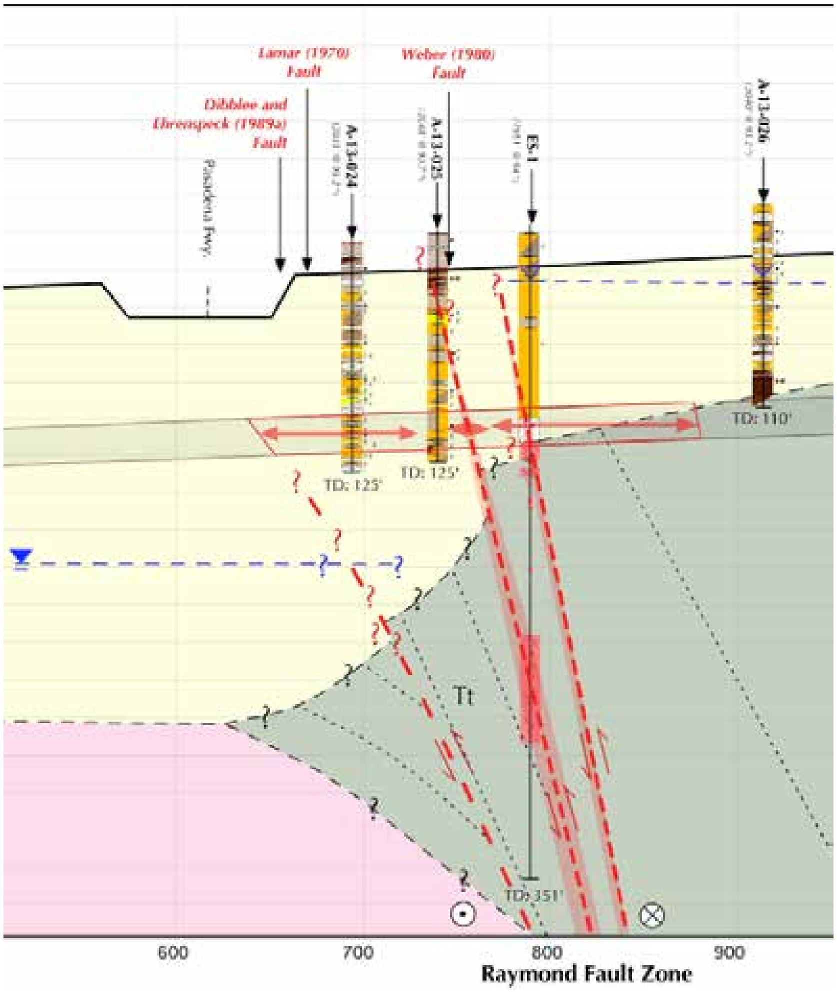

Figure 17. *Interpretation of the Raymond fault zone within the LRT Alternative (Plate 3 Section B-B'), shown in light gray shading. The fault location uncertainty zone is shown by red arrows across the tunnel section.*

Future Study Recommendations to Address Fault Deformations

The current and previous geologic investigations performed in the SR 710 North Study area have better constrained where the Raymond, San Rafael, and Eagle Rock faults cross the proposed Freeway Tunnel and LRT Alternatives. But the spatial locations of these faults at tunnel depths still have large uncertainties that will affect design mitigation decisions. These studies also have found suggestions that the San Rafael fault may not be active as defined by the project specifications (Holocene rupture), but those studies are not conclusive. Therefore, prior to construction of any of the Alternatives, additional geologic studies should be done to address the remaining uncertainties in fault locations, fault zone width, and activity. Below we summarize outstanding issues and potential solutions for each fault with respect to the Freeway Tunnel and LRT Alternatives.

Freeway Tunnel Alternative

San Rafael Fault

The San Rafael fault crosses the Freeway Tunnel Alternative in the City of Pasadena between Hurlbut Street and Arlington Drive. Data from the new hollow-stem auger borings and from previous studies constrain the main strand of the fault to the near vicinity of Hurlbut Street with two or more potential secondary fault strands to the south. Existing data are insufficient to constrain the northern extent of the fault very well, or to quantify the activity or displacement per event. There are indications that the younger alluvial deposits may not be affected by faulting, but the borings are too far apart to be definitive, and the age of those deposits is not constrained.

Problem: A 500-foot-wide gap between borings leaves the location of the main strand of the San Rafael fault poorly constrained to the north. The location and width of the main fault zone should be better constrained to help characterize subsurface conditions for tunneling.

Solution: Additional borings should be drilled to constrain the location and width of the main strand of the fault. Based on existing subsurface data, the main fault in the vicinity of the Freeway Tunnel Alternative is characterized by a northward drop of over 80 feet in the top of bedrock, and a change in bedrock across the fault from the Topanga Formation in the south to Wilson Quartz Diorite in the north. These distinctive markers offer a good opportunity to better constrain the fault location. Based on the strike of the fault in bedrock exposures to the northwest, the fault likely passes through the southern portion of the 500-foot-wide gap. Thus, the proposed borings could be limited to within 100 to 200 feet of the existing southernmost boring. Boring depth would be between 100 and 200 feet deep.

Problem: It is unknown whether the San Rafael fault is Holocene active. To date, there are no published data that conclusively show that the San Rafael fault has experienced Holocene rupture. An unpublished consulting report by Hydrologue, Inc. (2011a) suggests that the fault zone includes multiple strands that do displace Holocene sediments. However, the lack of clear geomorphic expression of the fault on Pleistocene alluvial fan surfaces is inconsistent with these findings. Additional studies should be conducted to better constrain the activity of the fault.

Solution: In the vicinity of the Freeway Tunnel Alternative, the main strand of the San Rafael is mapped through an area with 100 to 200 feet of alluvium, likely including Holocene- and Pleistocene-age deposits. Previous studies indicate that this alluvium contains fine-grained units and pedogenic soils that can be correlated between borings. We propose a transect of closely spaced borings (nominal 10-foot spacing, where conditions permit) to identify whether previously identified alluvial marker units are continuous or disrupted across the fault. For efficiency, this study should be done in conjunction with work to constrain the location of the main strand of the fault. Samples should be collected for optically stimulated luminescence dating of the alluvium. Any charcoal recovered from the borings should be dated to provide additional constraints on the age of the alluvium. There may be an opportunity for more detailed geologic trenching studies in this area; however, the only suitable trenching locations may be located outside the limits of the Alternative. This may be the only realistic way to gather the necessary geologic and paleoseismic data needed for these faults.

Problem: The displacement per event for the San Rafael fault has not been quantified.

Solution: If the San Rafael fault is shown to be Holocene active, an attempt should be made to quantify vertical separations in the highest alluvial or pedogenic units deformed by faulting. These results would be done in parallel with the same samples obtained from the additional drilling to determine activity on the fault.

Raymond Fault

Rupture along the Raymond fault is the primary seismic hazard to the Freeway Tunnel and LRT Alternatives. Its location across a densely urbanized environment makes the study of this fault extremely difficult. Nevertheless, additional geologic and seismic characterization is required.

Problem: The relationships between alluvium, sedimentary bedrock, and crystalline bedrock at tunnel depth are poorly characterized in the vicinity of the Raymond fault.

Solution: Supplemental borings between A-13-025 and A-13-024 will increase the understanding of subsurface conditions in this complex area.

Problem: Existing data allow for a southern fault strand that, within uncertainty, could extend the width of the fault zone over 150 feet southward.

Solution: Supplemental core borings between A-13-025 and the Pasadena Freeway would help determine whether additional active fault strands exist south of the primary fault as mapped in this study.

Problem: Published data and opinions on the Raymond fault span almost a full order of magnitude on all of the important kinematic values for the fault. Slip rates vary from 0.5 to 5 millimeters per year (mm/year). Recurrence intervals vary from 1,000 to more than 6,000 years. Earthquake rupture displacement estimates vary from 0.5 to more than 5 meters. It is necessary to bring better data to the problem of displacement magnitude and risk so that design decisions can proceed.

Solution: A detailed geologic trenching study is the ideal method to evaluate the kinematics of a fault. However, the only suitable trenching locations may be located outside the limits of the Alternative. This may be the only realistic way to gather the necessary geologic and paleoseismic data needed for these faults.

Eagle Rock Fault

Problem: Existing data cannot resolve whether the Eagle Rock fault crosses the Freeway Tunnel Alternative or merges into the Raymond fault farther to the west. Currently, the fault is projected across the alternative due to surface geomorphology and distributed shear zones identified in bedrock.

Solution: A transect of hollow-stem auger borings, with 40-foot spacing and ~150 feet deep across the southeast projection of the Eagle Rock fault would identify any significant changes in bedrock or significant deformation within alluvium that would characterize a fault zone.

Problem: If the San Rafael fault is shown to be inactive, the Eagle Rock fault also is likely to be inactive. However, if the San Rafael fault is found to be Holocene active, there is an increased possibility that the Eagle Rock fault is active. There are currently no data, published or unpublished, on the activity of the Eagle Rock fault.

Solution: If the San Rafael fault is found to be active, we recommend studies to characterize the activity of the Eagle Rock fault. The study would entail finding an area with Pleistocene and Holocene alluvium where the location of the Eagle Rock fault can be well constrained, and drilling closely spaced hollow-stem auger borings across the fault. There may be an opportunity for more detailed geologic trenching studies in this area; however, the only suitable trenching locations may be located outside the limits of the Alternative. This may be the only realistic way to gather the necessary geologic and paleoseismic data needed for these faults.

LRT Alternative

A main strand and two or more potential secondary strands of the San Rafael fault, and the Raymond fault zone cross the LRT Alternative.

San Rafael Fault

Problem: The main strand of the San Rafael fault is very poorly constrained through the LRT Alternative. Although the northward limit of where the main strand extends is constrained by seismic data, the southern limit is unconstrained. Our current interpretation of where the fault is located in the vicinity of the alternative is based on borehole data that is projected from over 2000 feet to the northwest, and published geologic maps.

Solution: Because the fault is marked by a drop in the top of bedrock to the north, and a change in bedrock across the fault from Topanga Formation on the south to Wilson Quartz Diorite on the north, the location of the fault can be easily constrained with a series of borings. A transect of hollow stem borings drilled to bedrock depth and spaced 40-50 feet apart along Fair Oaks Avenue, or an adjacent parallel street would provide the information required to constrain the location and width of the main fault zone.

Problem: It is unknown whether the San Rafael fault is Holocene active.

Solution: A transect of closely spaced (~10 foot spacing) hollow stem auger borings in alluvium across the fault would determine whether the fault is active (see discussion for the determining activity of the San Rafael fault in the Freeway Tunnel Alternative Section, above). There may be an opportunity for more detailed geologic trenching studies in this area; however, the only suitable trenching locations may be located outside the limits of the Alternative. This may be the only realistic way to gather the necessary geologic and paleoseismic data needed for these faults.

Problem: Coseismic slip for the San Rafael fault has not been quantified based on actual field data.

Solution: See discussion for the determining activity of the San Rafael fault in the Freeway Tunnel Alternative Section, above.

Raymond Fault

Problem: The active strand of the Raymond fault is constrained within an approximately 250 foot zone through the LRT Alternative. This locational uncertainty also exists with respect to the TSM/TDM Improvement T-2 in the vicinity of Fair Oaks Avenue and SR 110, where a retaining wall on the south side of SR 110 is proposed. Our current interpretation of where the fault is located in the vicinity of the LRT Alternative is based on borehole data that is projected from over 1500 feet to the west, published geologic maps, and surface geomorphology.

Solution: A transect of closely spaced, continuously-cored borings from the SR 110 northward along Fair Oaks Avenue could help to narrow down the location of the Raymond fault. There may be an opportunity for more detailed geologic trenching studies in this area; however, the only suitable trenching locations may be located outside the limits of the Alternative. This may be the only realistic way to gather the necessary geologic and paleoseismic data needed for these faults.

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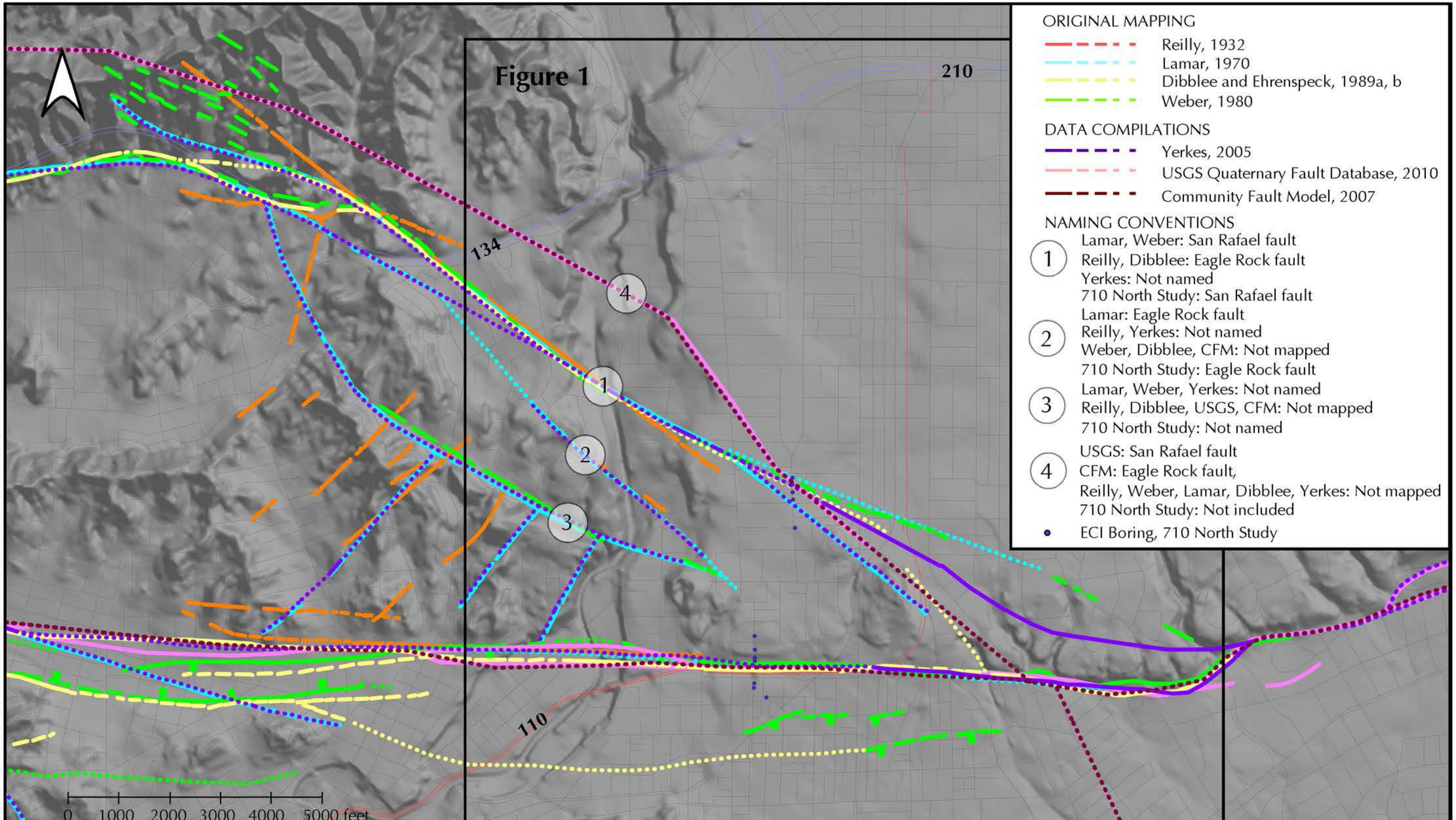
Plates



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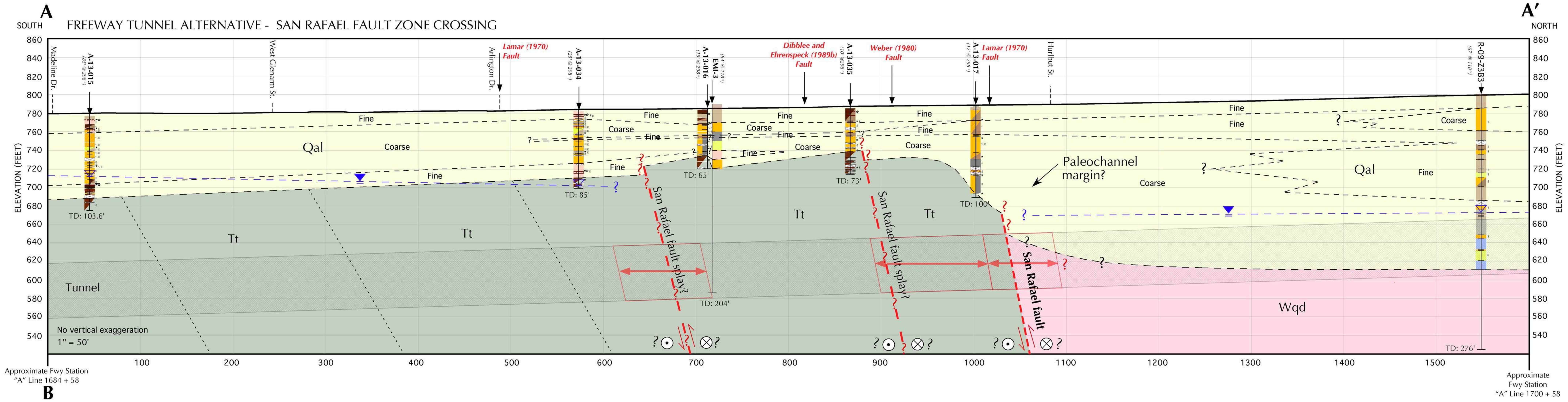
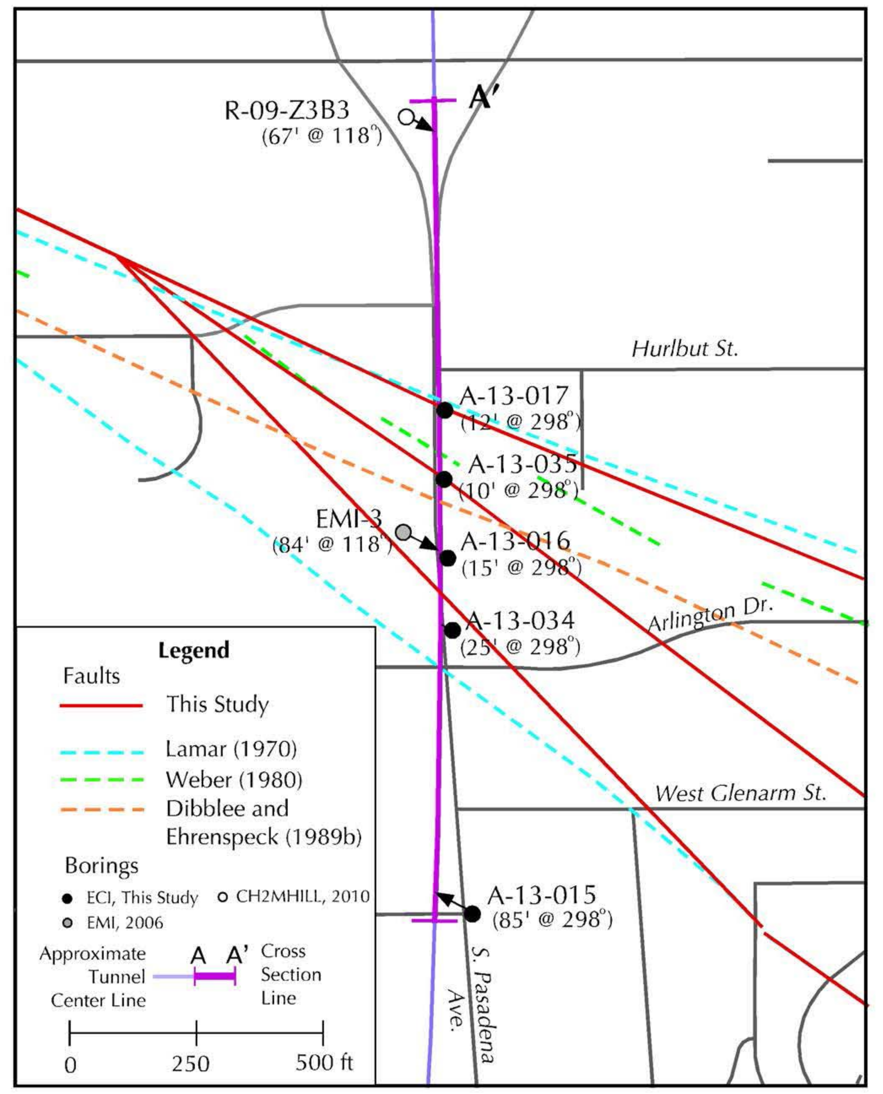
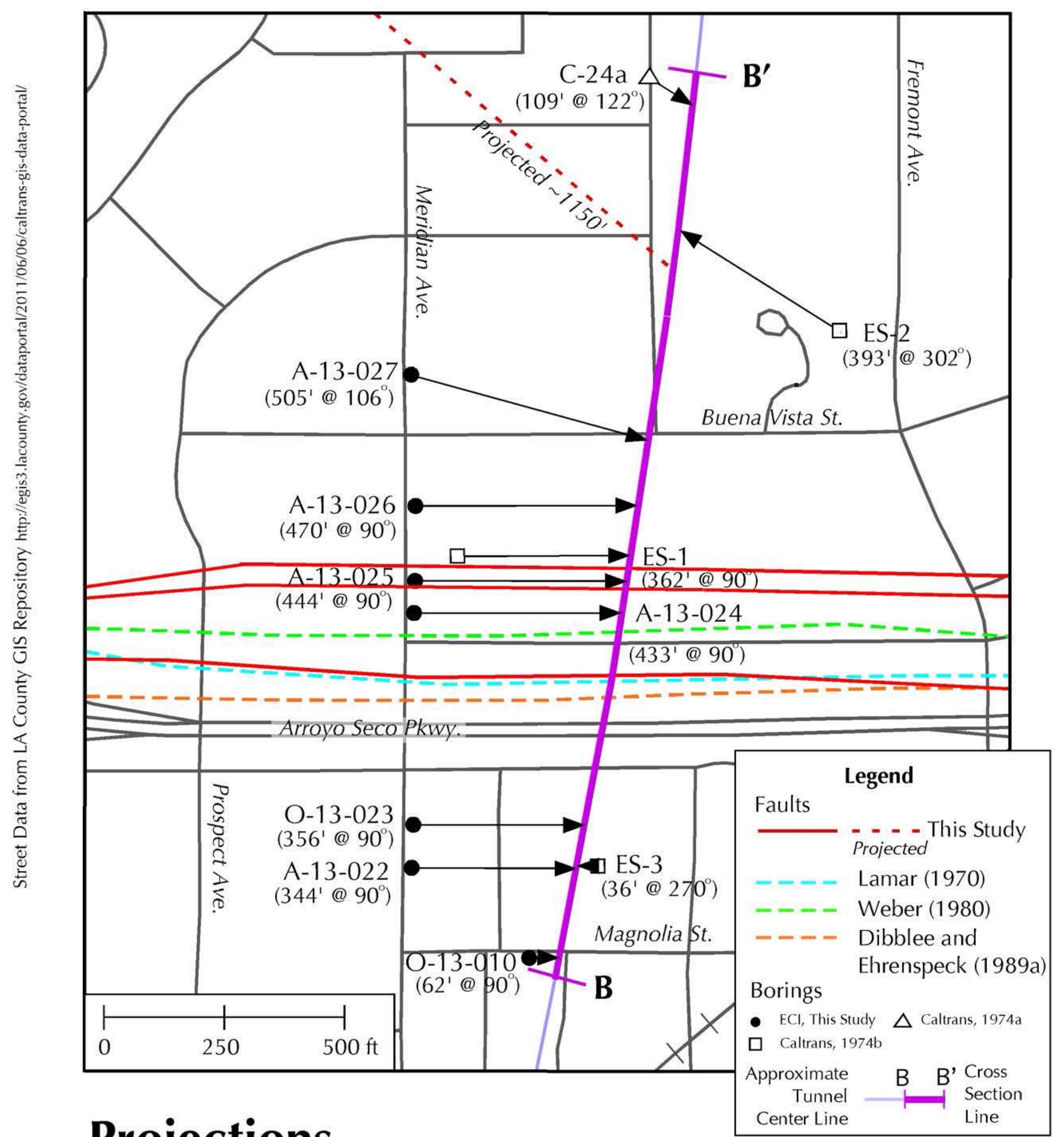
Compilation of Historical Mapping of the San Rafael, Eagle Rock and Raymond Faults

Plate 1



Location Maps





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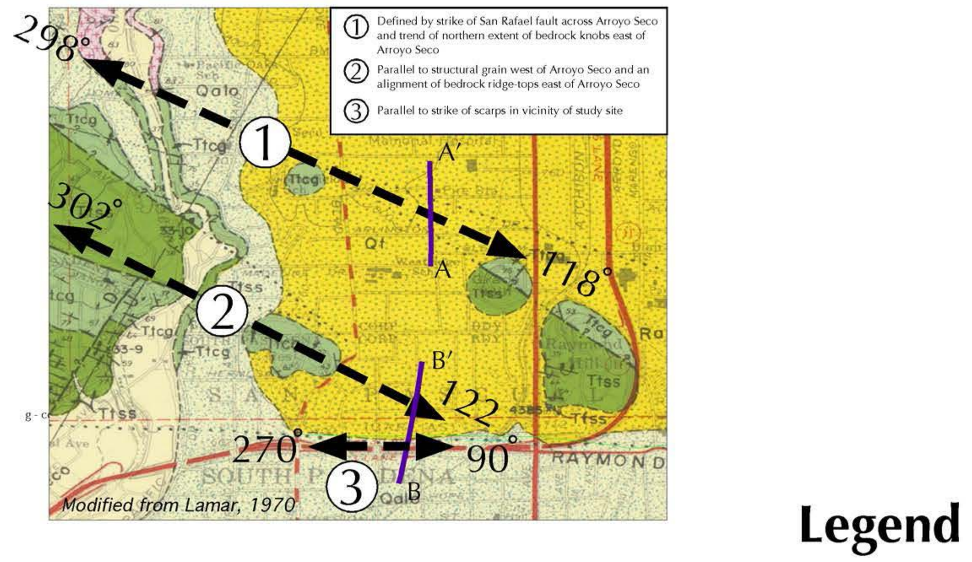

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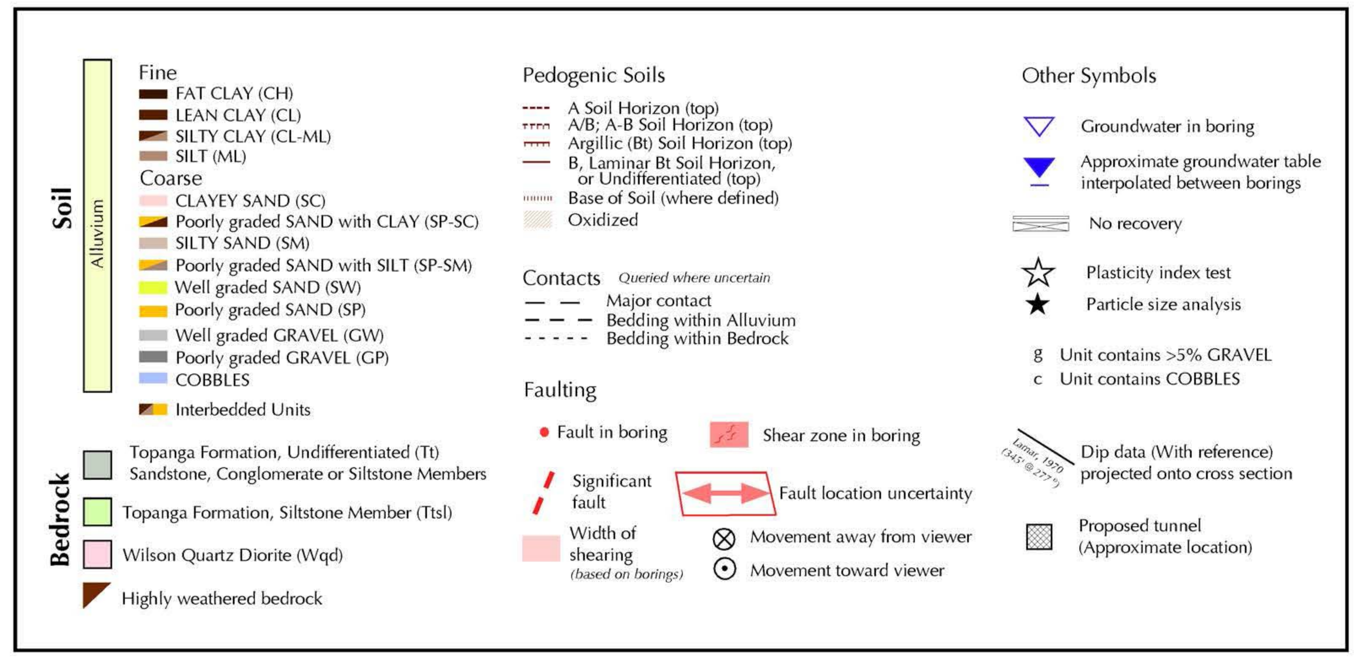

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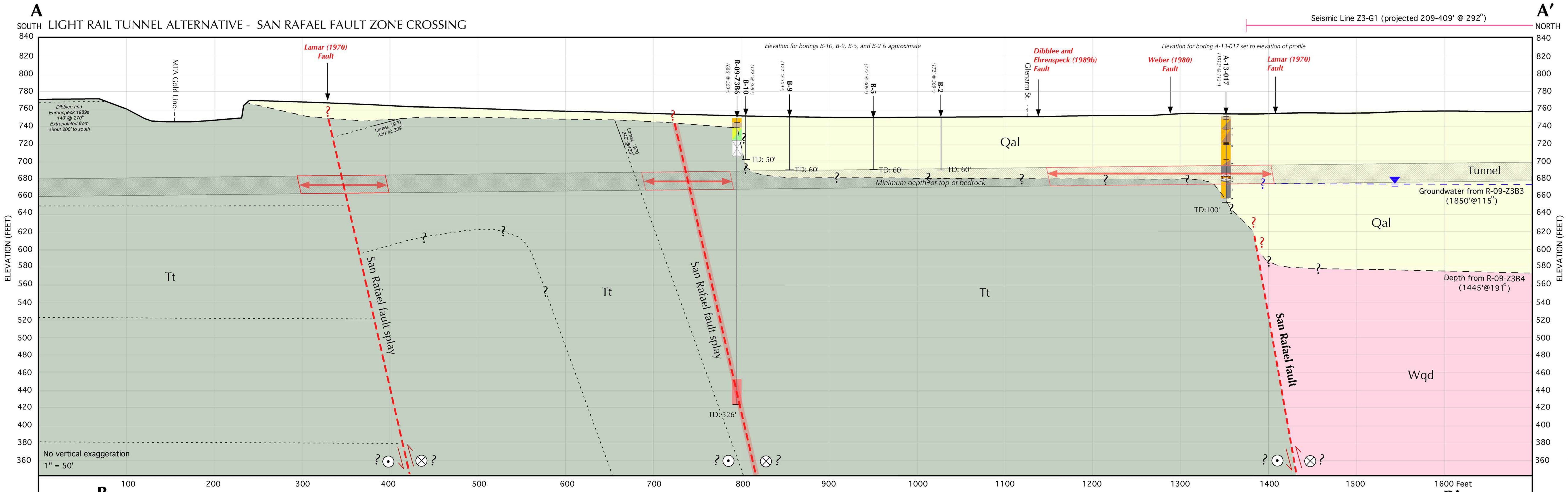
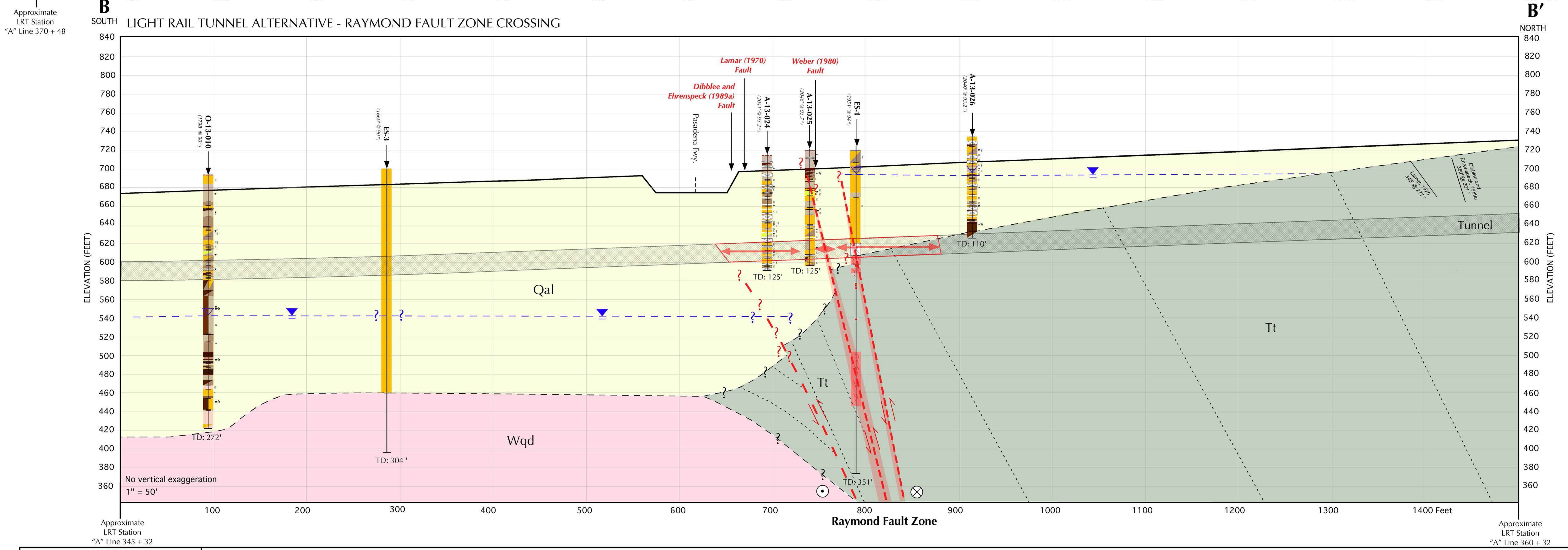
SR 710 North Study, Freeway Tunnel Alternative, Geological Cross Sections Across the San Rafael, Eagle Rock and Raymond Fault Zones

Plate 2





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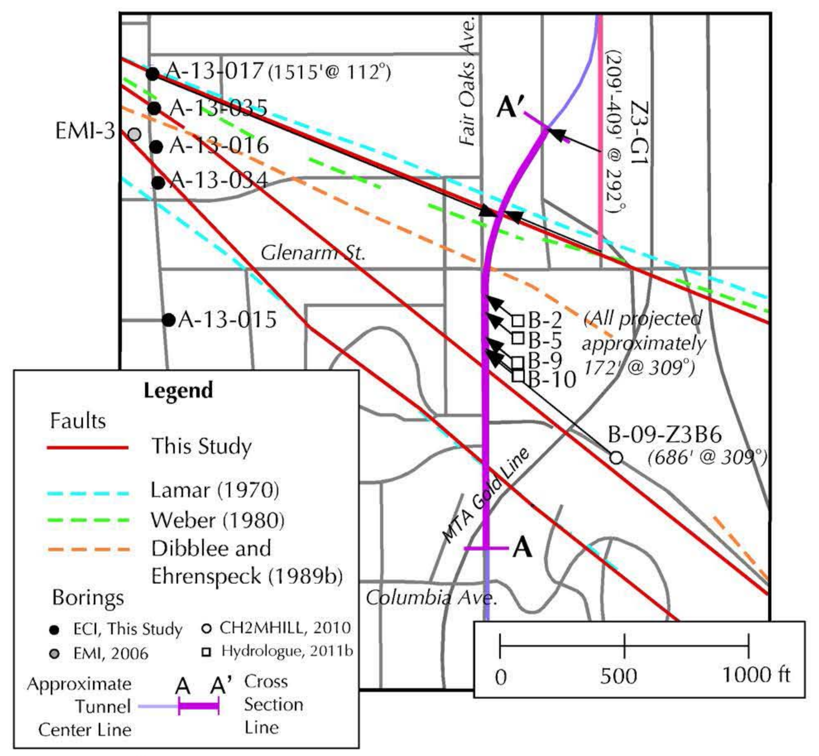
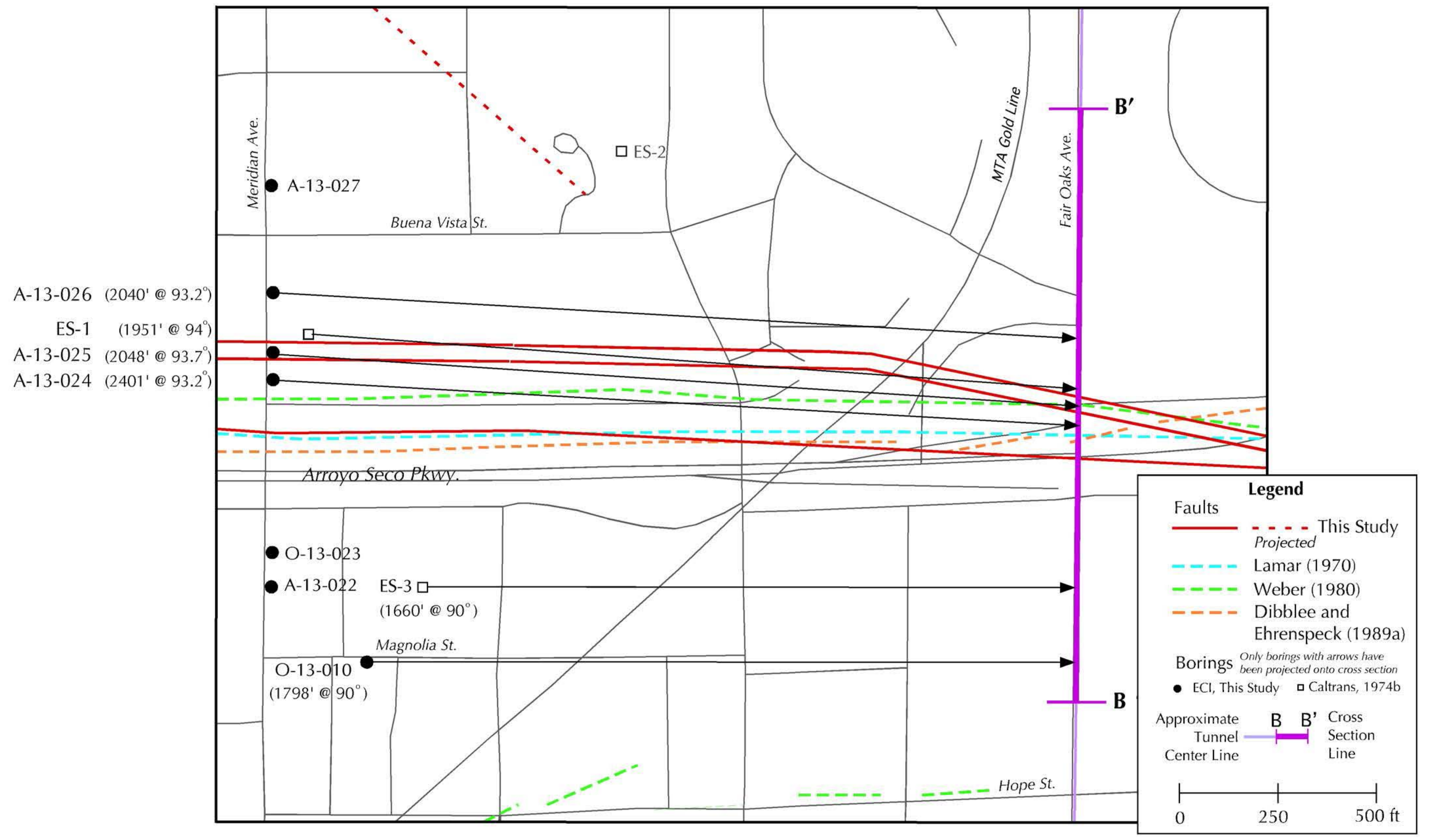


Street Data from LA County GIS Repository



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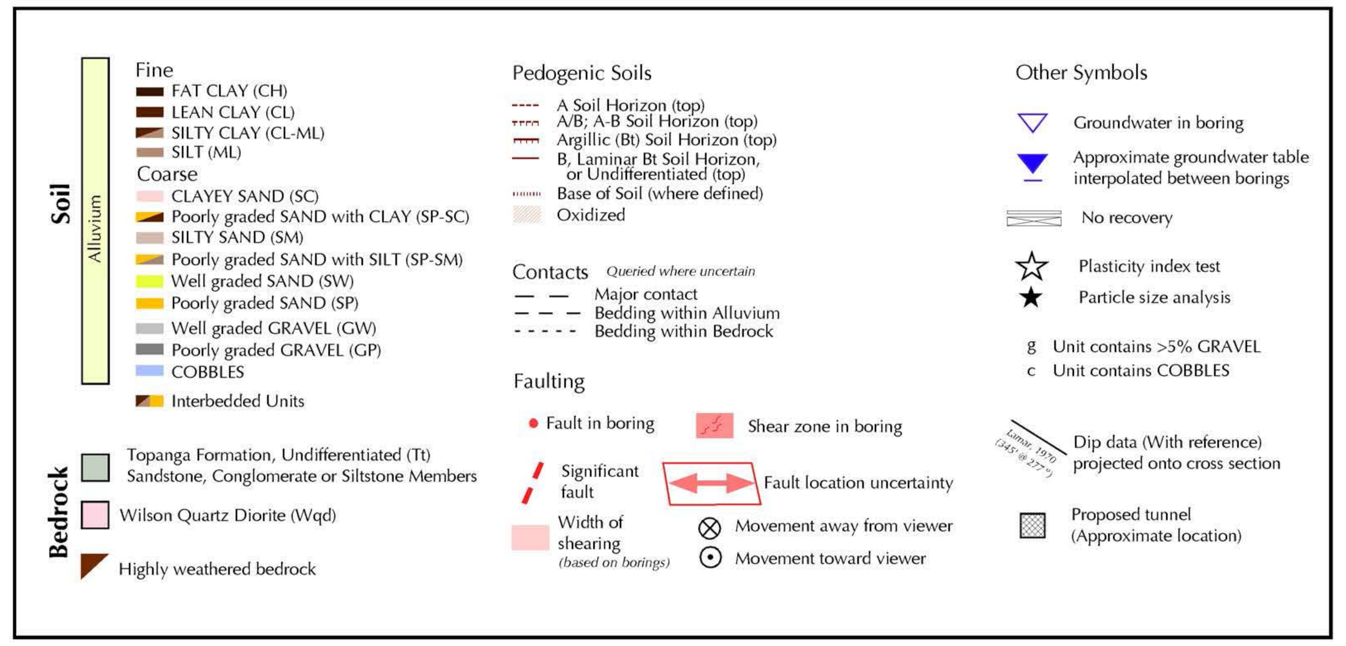

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SR 710 North Study Light Rail Tunnel Alternative Geologic Cross Sections Across the San Rafael and Raymond Fault Zones

Plate 3