Geologic Hazard Evaluation to Support Environmental Studies Documentation

SR 710 North Study

Los Angeles County, California

Prepared for

Caltrans
CALIFORNIA DEPARTMENT OF TRANSPORTATION

Metro
Los Angeles County
Metropolitan Transportation Authority

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Executive Summary

Introduction

The California Department of Transportation (Caltrans), in cooperation with the Los Angeles County Metropolitan Transportation Authority (Metro), selected the CH2M HILL team to provide alternatives analysis, preliminary engineering, and environmental studies documentation for the State Route (SR) 710 North Study. The SR 710 North Study included a geologic hazards study consisting of geotechnical, geologic, and seismic evaluations for the five alternatives selected within the SR 710 North Study Area. The results of the geologic study conducted by CH2M HILL are summarized in this report.

The proposed alternatives for the project include a No Build Alternative and four alternatives involving transportation improvements: Transportation System Management/ Transportation Demand Management (TSM/TDM), Bus Rapid Transit (BRT), Light Rail Transit (LRT), and Freeway Tunnel. A geologic evaluation was conducted for each alternative and included an assessment of the following:

- Regional geologic setting
- Physiography and topography
- Stratigraphy and structure
- Seismic hazards
- Groundwater
- Naturally occurring oil and gas
- Non-seismic geologic hazards

Regional Geology, Faulting, and Seismicity

The SR 710 North Study Area encompasses portions of the San Gabriel Valley, the southern San Rafael Hills, the Elysian Hills, and the Repetto Hills. These areas are within a transition zone between the northwest-southeast-trending Peninsular Ranges physiographic province to the south, and the east-west-trending Transverse Ranges province to the north.

Table ES-1 presents the generalized stratigraphic column specific to the SR 710 North Study Area and lists the formations in vertical sequence from youngest to oldest.

The geologic structure of the area is a result of ongoing compressional geologic forces that have resulted in uplift of the San Gabriel Mountains, and folding of the rocks within the hills present in the SR 710 North Study Area. These compressional forces have yielded active, potentially active, and inactive faults crossing the SR 710 North Study Area. The only confirmed active fault identified in the SR 710 North Study Area that could produce ground rupture is the Raymond fault. The Raymond fault is considered to be the most important fault with regard to the potential for causing surface rupture in the area of the alternatives. In addition, two potentially active faults are present in the SR 710 North Study Area: the Eagle Rock and San Rafael faults. For the purposes of this study, it is assumed that the Eagle Rock and San Rafael faults are also active. The Raymond, Eagle Rock, and San Rafael faults cross the Freeway Tunnel Alternative at tunnel depth. The Raymond and San Rafael faults cross the LRT Alternative at tunnel depth, and the BRT Alternative at the surface. Strong ground shaking may occur in the SR 710 North Study Area as the accumulated strain on these and other regional faults is released.

TABLE ES-1
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol (Figure 2-1)/ Cross Section Symbol (Figures 3-1 and 3-2) [a]	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qw, Qf, Qyf, Qya / Qal	Holocene (Quaternary)	0 to 11,000	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Old Alluvium	Qof, Qoa, Qvoa / Qal	Pleistocene (Quaternary)	11,000 to 2 million	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Fernando	Tss, Tsh / Tfcg, Tfsl	Pliocene (Tertiary)	2 to 5 million	Predominantly claystone, siltstone, and mudstone, with some sandstone and conglomerate. Marine deposits.
Puente (includes Monterey, Modelo, and an Unnamed Shale)	Tss, Tsh / Tpss, Tpsl	Late Miocene (Tertiary)	5 to 11 million	Claystone, siltstone, diatomaceous siltstone, mudstone, shale, and sandstone. Laminated to thinly bedded, locally thickly bedded, marine deposits.
Topanga	Tss, Tsh / Tt, Ttsl	Middle Miocene (Tertiary)	11 to 16 million	Siltstone, mudstone, sandstone, and conglomerate, with local volcanic intrusions. Thinly to thickly bedded, marine deposits.
Basement Complex Rocks, Wilson Quartz Diorite	Gr / Wqd	Cretaceous and Pre Cretaceous	120 to 160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

[a] Figures are provided at the end of the Geologic Hazard Evaluation main report.

Groundwater

Groundwater levels vary considerably across the SR 710 North Study Area, occurring as deep aquifers and as shallow perched zones. Several of the faults within the study area act as groundwater barriers with different levels on either side of the fault. A major part of the alluvium is an aquifer. The underlying rock formations contain groundwater but are not aquifers. However, perched groundwater might be present within local sandstone beds and faulted and/or fractured zones.

Groundwater conditions within each of the build alternatives are highly variable, ranging from near the ground surface to over 200 feet below ground surface (bgs). Groundwater levels for the build alternatives are summarized as follows:

- The groundwater levels within the overall SR 710 North Study Area are applicable to the TSM/TDM Alternative. Groundwater levels for the overall SR 710 North Study Area range from 10 to 450 feet bgs. Historically highest groundwater levels range from 5 to 200 feet bgs.
- Groundwater levels for the BRT Alternative range from 20 feet bgs near the Raymond fault (near Arroyo Seco Parkway) in South Pasadena to 330 feet bgs in the vicinity of West Main Street in Alhambra.
- Groundwater levels for the LRT Alternative range from approximately 10 feet bgs south of Valley Boulevard to 160 feet bgs immediately south of the Raymond fault.
- Groundwater levels for the Freeway Tunnel Alternative range from approximately 10 feet bgs in the vicinity of the southern portal to over 250 feet bgs at the northern end of the alternative.

Geologic and Geotechnical Evaluation of Alternatives

The geologic setting and geologic hazards along each of the alternatives for the SR 710 North Study are summarized in the following sections. The intent of these summarizes is to identify conditions that affect the design, construction, and operation of the alternative. Methods that can be used to mitigate the geologic hazards are also identified.

No Build Alternative

The SR 710 North Study, No Build Alternative does not include any of the improvements included in the projects Build Alternatives. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. It is possible that the construction of those improvements could result in short-term and/or permanent effects related to geology and seismicity. Those effects would be analyzed and mitigated, if needed, as each of those projects/improvements is advanced for implementation.

TSM/TDM Alternative

The TSM/TDM Alternative consists of strategies and improvements to increase efficiency and capacity for all modes in the transportation system with lower capital cost investments and/or lower potential impacts. In addition to intersection and local street improvements, Intelligent Transportation Systems, changeable message signs, active traffic management, expanded bus service, bus service improvements, and bicycle facility improvements, this alternative includes one new bridge (SR 710 Connector Underpass, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16). All TSM/TDM elements are included in the BRT Alternative with the exception of Improvement L-8, and the reversible lane component of Improvement L-3. All TSM/TDM elements are included in the LRT and Freeway Tunnel Alternatives with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative. TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards accounting for potential geologic hazards.

The TSM/TDM improvements are situated primarily within alluvial soils. Areas underlain by artificial fill soils are to be anticipated locally within some of the TSM/TDM improvements. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present below the TSM/TDM improvements at depth. TSM/TDM Alternative improvements are not expected to be adversely affected by these conditions, as they are the same soil and rock types supporting existing similar developments. Considering the proposed improvements associated with the TSM/TDM Alternative, the primary geologic hazards that could affect the alternative include seismic shaking, liquefaction, groundwater, and expansive materials and compressible soils; these and other potential geologic hazards present along the alternative are summarized in this report.

BRT Alternative

BRT Alternative improvements include BRT trunk line arterial street and station improvements, more frequent bus service, new bus feeder services, enhanced connecting bus services, as well as TSM/TDM improvements as described above. The BRT Alternative would be designed and constructed in accordance with Metro BRT Design Criteria accounting for potential geologic hazards.

The entire extent of the BRT Alternative is situated within alluvial soils. Areas underlain by artificial fill soils are to be anticipated locally along the alternative. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present along the alternative at depth. BRT Alternative development is not expected to be adversely affected by these conditions, as they are the same soil and rock types supporting existing transit systems. Considering the proposed improvements associated with the BRT Alternative, the primary geologic hazards that could affect the alternative include seismic shaking, liquefaction, groundwater, and expansive materials and compressible soils; these and other potential geologic hazards present along the alternative are summarized in this report.

LRT Alternative

The LRT Alternative of the SR 710 North Study involves substantial improvements, including a dedicated guideway and a bored tunnel segment, as well as TSM/TDM improvements as described previously. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. Two directional tunnels are proposed with tunnel diameters approximately 20 feet each, and the crown of the tunnels located approximately 60 feet bgs along most of the tunnel.

Considering the proposed improvements associated with the LRT Alternative, the primary geologic hazards that could affect the alternative include fault-induced ground rupture, seismic shaking, liquefaction, soil and bedrock variability, slope instability, and groundwater; these and other potential geologic hazards present along the alternative are summarized in this report.

Design and construction of the LRT Alternative would follow Metro Rail Design Criteria for tunneling and deep excavations to account for geologic hazards. The overhead and tunnel portal sections of the LRT Alternative would also be designed in accordance with Metro Rail Design Criteria, accounting for the various geologic units at the support locations.

The LRT Alternative is underlain by a variety of geologic units including artificial fill soils, alluvial soils, and sedimentary bedrock (Fernando, Puente, and Topanga Formations). These geologic units would determine foundation requirements for the elevated sections of the LRT Alternative, as well as tunneling design and construction methods within the tunnel segment. Control of potentially unstable ground conditions and groundwater inflows during tunneling may be provided by specialized tunnel boring machines (TBMs) with face-control capabilities. These machines generally utilize either earth-pressure balance (EPB) or slurry methods. To ensure that water flows are controlled at the tunnel heading, behind the TBM, and during tunnel operation, a relatively watertight support system may be required, such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system.

The LRT Alternative crosses one active fault (the Raymond fault) and one potentially active fault (the San Rafael fault). Future studies should be performed to evaluate the activity of the San Rafael fault; however, for planning purposes, this fault is treated as an active fault. Preliminary fault rupture displacement estimates have been prepared for the LRT Alternative, based on Metro Maximum Design Earthquake criteria. A left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter are estimated for the design of the tunnel at the Raymond fault across a fault zone 25 meters in width. A left-lateral offset of 0.5 meter and a reverse-vertical offset of 0.25 meter are estimated for the design of the tunnel at the San Rafael fault across a fault zone 50 meters in width. The potential fault offsets require design features that would allow the tunnel lining to accommodate the anticipated ground displacement. For fault displacements such as those estimated for the Raymond and San Rafael faults at the LRT Alternative, it is possible to construct an oversized tunnel, or vault, for the portion of the tunnel in the fault zone and for areas susceptible to ground rupture. For this concept, the portion of the tunnel in the fault zone is enlarged to form a vault outside the design lines of the tunnel and backfilled with crushable materials. The vault is large enough to accommodate the movement of the fault. This method, utilizing a robust lining system, has been recommended as the preliminary design concept for the LRT Alternative fault crossings.

The Upper Elysian Park Blind Thrust fault generated Coyote Pass escarpment transects the elevated portion of the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in the city of Monterey Park. Potential ground movements along the elevated segment of the LRT Alternative need to be further evaluated if this alternative is selected, and potential ground movements would have to be taken into consideration during design.

Freeway Tunnel Alternative

The Freeway Tunnel Alternative of the SR 710 North Study involves either a single- or dual-bore tunnel approximately 4.2 miles in length, as well as TSM/TDM improvements described previously. Each bored tunnel would have an outside diameter of approximately 58.5 feet; the crown of each tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. Short segments of cut-and-cover tunnels would be located at the south and north termini to provide access via portals to the bored tunnels.

Considering the proposed improvements associated with the Freeway Tunnel Alternative, the primary geologic hazards that could affect the alternative include fault-induced ground rupture, seismic shaking, soil and bedrock variability, and groundwater; these and other potential geologic hazards present along the alternative are summarized in this report.

The Freeway Tunnel improvements will require engineering and construction techniques similar to those used for the LRT Alternative. To account for geologic hazards, design and construction of the Freeway Tunnel Alternative would follow the Federal Highway Administration (FHWA) *Technical Manual for Design and Construction of Road Tunnels - Civil Elements* (FHWA, 2009) and project-specific seismic design criteria developed in a future phase of the project.

The Freeway Tunnel Alternative is underlain by a variety of geologic units including artificial fill soils, alluvial soils, sedimentary bedrock (Fernando, Puente, and Topanga Formations), and igneous and metamorphic bedrock (Wilson Quartz Diorite). Preliminary fault rupture displacement estimates have been prepared for the Freeway Tunnel Alternative based on Caltrans Safety Evaluation Earthquake criteria. A left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter are estimated for design of the tunnel at the Raymond fault across a fault zone 25 meters in width. A left-lateral offset of 0.5 meter and a vertical reverse offset of 0.25 meter are estimated for design of the tunnel at the Eagle Rock and San Rafael faults across a fault zone 50 meters in width. The fault rupture mitigation proposed for the LRT Alternative was initially considered for the Freeway Tunnel Alternative. However, the size of the bored tunnel (58.5 feet in diameter) and the anticipated ground conditions in and around the faults raised constructability issues as well as risk, cost, and schedule implications. Subsequently, a vault section utilizing steel segmental lining was determined to be more cost effective and less risky than an oversized vault excavation.

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Contents

Section **Page**

Section **Page**

Appendixes

Table

Figures

Section **Page**

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Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
APEQFZ	Alquist-Priolo Earthquake Fault Zone
ARS	acceleration response spectra
ATM	active traffic management
bgs	below ground surface
BRT	Bus Rapid Transit
Cal/OSHA	California Department of Occupational Safety and Health
Cal State LA	California State University, Los Angeles
Caltrans	California Department of Transportation
CDMG	California Division of Mines and Geology
CDOGGR	California Division of Oil, Gas & Geothermal Resources
CDSM	cement deep soil mixing
CDWR	California Department of Water Resources
CEQA	California Environmental Quality Act
CGS	California Geological Survey (formerly California Division of Mines and Geology)
CMS	changeable message signs
ECI	Earth Consultants International
EPB	earth-pressure balance
EPFT	Elysian Park Fold and Thrust Belt
FHWA	Federal Highway Administration
g	acceleration due to gravity
GIS	geographic information system
GPS	global positioning system
H:V	horizontal to vertical
I	Interstate
ISA	Initial Site Assessment
ITS	Intelligent Transportation Systems
km	kilometer(s)
LACDPW	Los Angeles County Department of Public Works
LRT	Light Rail Transit
L:V	lateral to vertical
MDE	Maximum Design Earthquake
Metro	Los Angeles County Metropolitan Transportation Authority

M_L	earthquake Richter magnitude (local magnitude)
M_S	surface wave magnitude
mm/yr	millimeters per year
Mmax	maximum moment magnitude
MRZ	Mineral Resource Zone
MSGW	Main San Gabriel Watermaster
M_W	earthquake moment magnitude
NEPA	National Environmental Policy Act
NISZ	Newport-Inglewood Structural Zone
O&M	operations and maintenance
PDL	potential disturbance limit
PGA	peak ground acceleration
RBMB	Raymond Basin Management Board
ROW	right-of-way
SCEC	Southern California Earthquake Center
SEE	Safety Evaluation Earthquake
SR	State Route
TBM	tunnel boring machine
TDM	Transportation Demand Management
TSM	Transportation System Management
UEPBT	Upper Elysian Park Blind Thrust fault
USGS	United States Geological Survey
WRD	Water Replenishment District of Southern California

SECTION 1

Introduction

The California Department of Transportation (Caltrans), in cooperation with the Los Angeles County Metropolitan Transportation Authority (Metro), selected the CH2M HILL team to provide alternatives analysis, preliminary engineering, and environmental studies documentation for the State Route (SR) 710 North Study. The SR 710 North Study included a geologic hazards study consisting of geotechnical, geologic, and seismic evaluations for each of the project alternatives. This report documents the results of the geologic hazard study conducted by CH2M HILL. Caltrans and Metro will utilize this study during evaluations of the technical, operational, and financial feasibility of the SR 710 North Study Alternatives, as described in Section 1.2.

1.1 Scope of Work

This study was developed to evaluate the geologic hazards within each of the selected alternatives and included the following tasks.

- Compile and review available information including geotechnical data, as well as geologic and seismic reports and maps.
- Evaluate the compiled data to characterize the geologic hazards within each alternative.
- Provide generalized design recommendations to address the identified geologic hazards in support of the environmental studies documentation.
- Prepare this Geologic Hazard Evaluation report.

Work was carried out by CH2M HILL geotechnical staff and its primary subconsultant, Earth Consultants International (ECI). ECI provided support by leading the fault characterization for the study.

1.2 Project Description

Caltrans, in cooperation with Metro, proposes transportation improvements to improve mobility and relieve congestion in the area between SR 2 and Interstates 5, 10, 210, and 605 (I-5, I-10, I-210, and I-605, respectively) in east/northeast Los Angeles and the western San Gabriel Valley. The SR 710 North Study Area, as depicted in Figure 1-1, is approximately 100 square miles and generally bounded by I-210 on the north, I-605 on the east, I-10 on the south, and I-5 and SR 2 on the west. Caltrans is the lead agency under the National Environmental Policy Act (NEPA) and the California Environmental Quality Act (CEQA).

The following purpose and need have been established for the SR 710 North Study.

- The purpose of the proposed action is to effectively and efficiently accommodate regional and local north-south travel demands in the SR 710 North Study Area of the western San Gabriel Valley and east/northeast Los Angeles, including the following considerations:
  - Improve efficiency of the existing regional freeway and transit networks.
  - Reduce congestion on local arterials adversely affected due to accommodating regional traffic volumes.
  - Minimize environmental impacts related to mobile sources.
- The lack of continuous north-south transportation facilities in the SR 710 North Study Area has the following consequences, which have been identified as the elements of need for the project:
  - Degradation of the overall efficiency of the larger regional transportation system.
  - Congestion on freeways in the SR 710 North Study Area.
  - Congestion on the local streets in the SR 710 North Study Area.
  - Poor transit operations within the SR 710 North Study Area.

There are five alternatives being considered in the SR 710 North Study. These alternatives are listed below and described in the following subsections.

- No Build
- Transportation System Management/Transportation Demand Management (TSM/TDM)
- Bus Rapid Transit (BRT)
- Light Rail Transit (LRT)
- Freeway Tunnel

The figures included in this report display the potential disturbance limit (PDL) of each alternative. In areas where the PDL is outside the project limits, minimal work will be conducted. Major construction will take place within the project limits of each alternative as stated in the project descriptions below.

1.2.1 No Build Alternative

The SR 710 North Study, No Build Alternative does not include any of the improvements included in the projects Build Alternatives. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. It is possible that the construction of those improvements could result in short-term and/or permanent effects related to geology and seismicity. Those effects would be analyzed and mitigated, if needed, as each of those projects/improvements is advanced for implementation. Figure 1-2 illustrates the projects in the No Build Alternative.

1.2.2 Transportation System Management/Transportation Demand Management (TSM/TDM) Alternative

The TSM/TDM Alternative consists of strategies and improvements to increase efficiency and capacity for all modes in the transportation system with lower capital cost investments and/or lower potential impacts. The TSM/TDM Alternative is designed to maximize the efficiency of the existing transportation system by improving capacity and reducing the effects of bottlenecks and chokepoints. Components of the TSM/TDM Alternative are shown in Figure 1-3.

- TSM strategies increase the efficiency of existing facilities (that is, TSM strategies are actions that increase the number of vehicle trips a facility can carry without increasing the number of through lanes). TSM strategies include Intelligent Transportation Systems (ITS) improvements consisting of traffic signal upgrades, synchronization and transit signal prioritization, arterial changeable message signs (CMS), and arterial video and speed data collection systems; local street and intersection improvements; and active traffic management (ATM) consisting primarily of arterial speed data collection and CMS.
- TDM strategies focus on regional means of reducing the number of vehicle trips and vehicle miles traveled as well as increasing vehicle occupancy. TDM strategies facilitate higher vehicle occupancy or reduce traffic congestion by expanding the traveler's transportation options in terms of travel method, travel time, travel route, travel costs, and the quality and convenience of the travel experience. The TDM strategies include reducing the demand for travel during peak periods, reducing the use of motor vehicles, shifting the use of motor vehicles to uncongested times of the day, encouraging rideshare and transit use, eliminating trips (that is, telecommuting), and improving transportation options, as well as expanded bus service, bus service improvements, and bicycle facility improvements.

The TSM/TDM Alternative includes one new bridge (SR 710 Connector Underpass, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16). All TSM/TDM elements are included in the BRT Alternative with the exception of Improvement L-8, and the reversible lane component of Improvement L-3. All TSM/TDM elements are included in the LRT and Freeway Tunnel Alternatives with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative.

1.2.3 Bus Rapid Transit (BRT) Alternative

The BRT Alternative would provide high-speed, high-frequency bus service through a combination of new, dedicated, and existing bus lanes, and mixed-flow traffic lanes to key destinations between East Los Angeles and Pasadena. The proposed route length is approximately 12 miles. Figure 1-4 illustrates the BRT Alternative.

The BRT Alternative includes the BRT trunk line arterial street and station improvements, frequent bus service, new bus feeder services, and enhanced connecting bus services. The BRT Alternative also includes TSM/TDM improvements as described above.

The 12-mile route would begin at Atlantic Boulevard and Whittier Boulevard to the south; follow Atlantic Boulevard, Huntington Drive, Fair Oaks Avenue, and Del Mar Boulevard; and end with a terminal loop in Pasadena to the north. Buses operating in the corridor would be given transit signal priority from a baseline transit signal priority project that will be implemented separately by Metro.

A total of 17 BRT stations with amenities would be placed on average, at approximately 0.8-mile intervals, on average, at major activity centers and cross streets. Typical station amenities would include new shelters, branding elements, seating, wind screens, leaning rails, variable message signs (next bus information), lighting, bus waiting signal, trash receptacles, and stop markers. Some of these stops will be combined with existing stops, while in some cases new stops for BRT will be provided.

1.2.4 Light Rail Transit (LRT) Alternative

The LRT Alternative would include passenger rail operated along a dedicated guideway, similar to other Metro light rail lines, as well as operations within a tunnel segment. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. The LRT Alternative also includes TSM/TDM improvements as described in Section 1.2.2. Figure 1-5 illustrates the LRT Alternative.

The LRT Alternative would begin at an aerial station on Mednik Avenue adjacent to the existing East Los Angeles Civic Center Station on the Metro Gold Line. The alternative would remain elevated as it travels north on Mednik Avenue, west on Floral Drive, north across Corporate Center Drive, and then along the west side of I-710, primarily in Caltrans right-of-way (ROW), to a station adjacent to California State University, Los Angeles (Cal State LA). The alternative would descend into a tunnel south of Valley Boulevard and travel northeast to Fremont Avenue, north below Fremont Avenue, and easterly to Fair Oaks Avenue. The alternative would then cross below SR 110 and end at an underground station below Raymond Avenue, adjacent to the existing Fillmore Station on the Metro Gold Line.

Two directional tunnels are proposed with tunnel diameters approximately 20 feet each, the crown of the tunnels would be located approximately 60 feet below ground surface (bgs). Supporting tunnel systems include emergency evacuation cross passages for pedestrians, a ventilation system consisting of exhaust fans at each portal and an exhaust duct along the entire length of the tunnel, fire detection and suppression systems, communications and surveillance systems, and 24-hour monitoring, which is similar to the existing LRT system.

Seven stations would be located along the LRT Alternative at Mednik Avenue in East Los Angeles, Floral Drive in Monterey Park, Cal State LA, Fremont Avenue in Alhambra, Huntington Drive in South Pasadena, Mission Street in South Pasadena, and Fillmore Street in Pasadena. The Fremont Avenue Station, the Huntington Drive Station, the Mission Street Station, and the Fillmore Street Station would be underground stations. New park-and-ride facilities would be provided at all of the proposed stations except the Mednik, Cal State LA, and Fillmore Stations.

A maintenance yard to clean, maintain, and store light rail vehicles would be located on both sides of Valley Boulevard at the terminus of SR 710. A track spur from the LRT mainline to the maintenance yard would cross above Valley Boulevard.

1.2.5 Freeway Tunnel Alternative

The Freeway Tunnel Alternative starts at the existing southern stub of SR 710 in Alhambra, just north of I-10, and connects to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena. In addition, the Freeway Tunnel Alternative also includes TSM/TDM improvements as described in Section 1.2.2.

The Freeway Tunnel Alternative includes two design variations, a dual-bore and single-bore tunnel. The dual-bore design variation includes two tunnels that independently convey northbound and southbound vehicles. The single-bore design variation includes one tunnel that carries both northbound and southbound vehicles. Both tunnel design variations include roadway improvements outside the north and south portal areas. Figure 1-6 illustrates the dual-bore and single-bore tunnel design variations for the Freeway Tunnel Alternative. Each of these design variations is described in more detail below.

- **Dual-Bore Tunnel:** The dual-bore tunnel variation is approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation would consist of dual two-level bored tunnels with two lanes on each level and in each direction. Each bored tunnel would have an outside diameter of approximately 58.5 feet; the crown of each tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. Vehicle cross passages would be provided throughout this tunnel variation that would connect one tunnel to the other for use in an emergency situation.

  Short segments of cut-and-cover tunnels would be located at the south and north termini to provide access via portals to the bored tunnels. The portal at the southern terminus would be located south of Valley Boulevard. The portal at the northern terminus would be located north of Del Mar Boulevard. No intermediate interchanges are planned for the tunnel.

- **Single-Bore Tunnel:** The single-bore tunnel design variation is also approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation would consist of a single, two-level, bored tunnel with two lanes on each level in each direction. The bored tunnel would also have an outside diameter of approximately 58.5 feet, with the crown of the tunnel located approximately 120 to 250 feet bgs along most of the tunnel. The single-bore tunnel would be in the same location as the northbound tunnel in the dual-bore tunnel design variation.

Both tunnel design variations would include the following tunnel support systems: emergency evacuation for pedestrians and vehicles; air scrubbers; a ventilation system consisting of exhaust fans at each portal, an exhaust duct along the entire length of the tunnel, and jet fans within the traffic area of the tunnel; fire detection and suppression systems; communications and surveillance systems; and 24-hour monitoring. Operations and maintenance (O&M) control buildings would be constructed at the northern and southern ends of the tunnel. In addition, both tunnel design variations include roadway improvements outside the north and south portal areas. There would be no operational restrictions for the tunnel, with the exception of vehicles carrying flammable or hazardous materials.

Five operational variations have been identified for the Freeway Tunnel Alternative, including:

- Freeway Tunnel Alternative with Tolls
- Freeway Tunnel Alternative without Tolls
- Freeway Tunnel Alternative with Trucks Excluded
- Freeway Tunnel Alternative with Trucks Excluded and with Tolls
- Freeway Tunnel Alternative with Toll and Express Bus

1.3 Regulatory Setting

This Geologic Hazard Evaluation was prepared in support of the Environmental Studies Documentation Phase for the SR 710 North Study in Los Angeles County, California. The evaluation characterizes and then provides general recommendations necessary to address potential geologic hazards that are present within the five selected SR 710 North Study Alternatives. This study included evaluation of geologic conditions, faulting, seismicity, secondary seismic hazards, groundwater conditions, and the presence of naturally occurring oil and gas with respect to each of the project alternatives.

Caltrans' Standard Environmental Reference, Chapter 7 - Topography/Geology/Soils/Seismic (Caltrans, 2013a) was utilized in preparing this report. The California Geological Survey (CGS) Guidelines for Preparing Geologic Reports for Regional-Scale Environmental and Resource Management Planning (CGS, 2013) also was used.

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SECTION 2
Geologic Setting

The geologic setting for the SR 710 North Study Area is relatively complex. It involves various physiographic and topographic conditions, a variable stratigraphy composed of alluvial soils and bedrock, variable groundwater conditions, active and potentially active faults, and potential for ground shaking. These existing conditions are used to evaluate the potential for geologic hazards within each of the alternatives as discussed in Section 3 of this report.

2.1 Regional Geology

This section describes the general geologic setting covering the SR 710 North Study Area and is largely based on existing geologic information, supplemented by information collected during the SR 710 North Study exploration program. Details of the SR 710 North Study geotechnical exploration program are included in the *Preliminary Geotechnical Report* prepared for the project (CH2M HILL, 2014a).

2.1.1 Physiography and Topography

The SR 710 North Study Area primarily consists of the western San Gabriel Valley, the southernmost San Rafael Hills, and the Repetto Hills. These areas are within the transition zone between the northwest-southeast-trending Peninsular Ranges physiographic/geologic province on the south, and the east-west-trending Transverse Ranges province on the north. The topography of the SR 710 North Study Area is shown in Figure 2-1.

The western part of the SR 710 North Study Area consists of the Repetto Hills, a group of small hills and valleys between the Santa Monica Mountains (Transverse Ranges) on the west and the Puente Hills (Peninsular Ranges) on the southeast. The Repetto Hills include Mount Washington, Monterey Park Hills, and the Montebello Hills, as well as several unnamed hills along the western edge of the San Gabriel Valley. In the SR 710 North Study Area, elevations within the Repetto Hills range from approximately 870 feet between Monterey Road and SR 110, to 200 feet at the western toe of the hills near Rosemead Boulevard. The San Rafael Hills are located between the Repetto Hills and the Verdugo Hills, and border the SR 710 North Study Area on the northwest. Elevations in the San Rafael Hills portion of the SR 710 North Study Area range from approximately 1,000 feet near SR 134 and Arroyo Seco, to 600 feet in the vicinity of SR 110 and the Arroyo Seco.

The eastern half of the SR 710 North Study Area is within the San Gabriel Valley, which is bordered by the Puente Hills and San Jose Hills on the south and east, and by the San Gabriel Mountains on the north. The San Gabriel Valley is a relatively flat-floored valley between the San Gabriel Mountains on the north, the San Jose Hills on the east, the Puente Hills on the south, and the Repetto/Verdugo/San Rafael Hills on the west. The northern margin of the valley is characterized by a series of ancient alluvial fans emanating from the San Gabriel Mountains (Lamar, 1970). The valley floor gently descends southerly from elevations of 700 to 1,000 feet along the northern margin to approximately 300 to 400 feet in the south. The gradual descent is interrupted locally by an arcuate escarpment (ranging from about 10 to 150 feet high) extending from the Monrovia area to the South Pasadena area and westerly into the hills of Glendale and Los Angeles. Associated with this escarpment are closed depressions, springs, reverse-tilted fan surfaces, and small ridges. All of these features are due to repeated displacements by the Raymond fault.

As discussed in Section 2.1.4, major drainages in the SR 710 North Study Area are the Los Angeles River in the west, and the Rio Hondo and San Gabriel River in the east. Smaller intermittent drainages (from west to east) are Arroyo Seco in the Repetto and San Rafael Hills, and the Alhambra/San Pasqual Wash, Rubio Wash, Eaton Wash, Arcadia Wash, and Santa Anita Wash in the western and central parts of the San Gabriel Valley. There are numerous southwest-northeast-trending dry drainages in the Repetto Hills that are remnants (that is, antecedent drainages) of a drainage system that was active during the wetter periods of the Pleistocene ice ages (more than 20,000 years ago).

2.1.2 Stratigraphy

Regional geologic maps (Lamar, 1970; CGS, 2012; Dibblee, 1989a, 1989b, 1991, 1998, and 1999; Yerkes and Campbell, 2005; Morton and Miller, 2003) indicate that the SR 710 North Study Area is underlain by nonmarine Quaternary-age (approximately less than 2 million years old) alluvium, marine Tertiary-age (approximately 2 to 16 million years old) sedimentary rocks, and Cretaceous and Pre-Cretaceous (120 to 160+ million years old) crystalline basement complex of igneous and metamorphic rocks.

Table 2-1 presents the generalized stratigraphic column specific to the SR 710 North Study Area and lists the formations in vertical sequence from youngest to oldest. The alluvial deposits are underlain by Tertiary-age sedimentary rocks or basement complex rocks. The Tertiary-age rocks crop out in the Repetto and San Rafael Hills and underlie the Quaternary deposits in the valleys. These Tertiary-age sedimentary formations consist of the Fernando Formation, Puente Formation, and Topanga Formation.

In the northern portion of the SR 710 North Study Area, the Tertiary-age formations and/or Quaternary-age alluvium are underlain by basement complex rocks. These basement complex rocks are composed of Cretaceous and pre-Cretaceous igneous intrusive rocks (diorite, quartz diorite, and quartz monzonite). These igneous rocks commonly have weak metamorphism in the form of aligned dark minerals (foliation). The basement complex rocks contain pre-Cretaceous metamorphic rocks (for example, gneiss).

The subsections following Table 2-1 summarize the characteristics of the geologic formations encountered within the SR 710 North Study Area. The bedrock descriptions presented in this report (including rock hardness and bedding spacing) are based on the Caltrans *Soil and Rock Logging, Classification, and Presentation Manual* (Caltrans, 2010). The surficial distribution of earth units within the SR 710 North Study Area is shown in the SR 710 North Study Geologic Map (Figure 2-1).

TABLE 2-1
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol (Figure 2-1)/ Cross Section Symbol (Figures 3-1 and 3-2)	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qw, Qf, Qyf, Qya / Qal	Holocene (Quaternary)	0 to 11,000	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Old Alluvium	Qof, Qoa, Qvoa / Qal	Pleistocene (Quaternary)	11,000 to 2 million	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Fernando	Tss, Tsh / Tfcg, Tfsl	Pliocene (Tertiary)	2 to 5 million	Predominantly claystone, siltstone, and mudstone, with some sandstone and conglomerate. Marine deposits.
Puente (includes Monterey, Modelo, and Unnamed Shale)	Tss, Tsh / Tpss, Tpsl	Late Miocene (Tertiary)	5 to 11 million	Claystone, siltstone, diatomaceous siltstone, mudstone, shale, and sandstone. Laminated to thinly bedded, locally thickly bedded, marine deposits.
Topanga	Tss, Tsh / Tt, Ttsl	Middle Miocene (Tertiary)	11 to 16 million	Siltstone, mudstone, sandstone, and conglomerate, with local volcanic intrusions. Thinly to thickly bedded, marine deposits.
Basement Complex Rocks (includes Wilson Quartz Diorite)	gr / Wqd	Cretaceous and Pre Cretaceous	120 to 160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

2.1.2.1 Quaternary Alluvium

Quaternary alluvial materials are encountered throughout the SR 710 North Study Area. The alluvial materials consist of interbedded lenses and/or discontinuous layers of fine-grained sediment (clay and silt) and coarse-grained materials (sand and gravel) that generally increase in strength with depth. These materials are generally divided into Young and Old Alluvium.

The Young Alluvium is limited to shallow depths in active drainage channels that currently carry runoff across the area; this includes the drainage (Dorchester Channel) that is located along the existing SR 710, generally south of Valley Boulevard. The Old Alluvium crops out at the surface as alluvial fans and terrace deposits dissected by the active drainage channels. Old alluvial materials also underlie Young Alluvium and are observed at deeper depths. Hard to very hard cobble-size rocks are common within the Young and Old Alluvium; some hard to very hard boulders also may be scattered throughout the unit. Within the Old Alluvium, the cobbles and boulders are moderately hard to hard, and much more weathered than in the Young Alluvium.

From a geologic perspective, the alluvial soils are considered unconsolidated because the soils lack cementation typically associated with rock formations. The Old Alluvium is slightly more consolidated than the Young Alluvium. Bedding within these deposits is essentially horizontal but is poorly developed, commonly lenticular, and discontinuous. The contact between the alluvial materials and underlying bedrock is expected to be irregular because the alluvium has covered landscapes developed by erosion into older deposits.

2.1.2.2 Fernando Formation

The Siltstone and Conglomerate Members of the Pliocene-age Fernando Formation are present within the SR 710 North Study Area. The Siltstone Member consists primarily of dark gray to black, massive, very soft to moderately soft marine claystone and siltstone. Scattered, hard concretions and very thin to thin hard layers occur within the Siltstone Member. The Siltstone Member grades upward into the white-to-brick-red Conglomerate Member, which is composed of conglomeratic sandstones, conglomerates, and interbedded sandstones, all of which are believed to have been deposited in near-shore marine conditions as a deep marine basin was filled.

The gravel- to cobble-sized rocks of the Conglomerate Member consist of moderately hard to hard, well-rounded igneous rocks and up to 40 percent angular fragments of hard sandstone, limestone, and shale similar to the underlying sedimentary rocks in the area. The Conglomerate Member is fine- to coarse-grained, poorly consolidated, massive, very soft to moderately soft, and micaceous with scattered gravel-sized moderately hard rocks.

The Fernando Formation overlies the Puente Formation with both conformable and unconformable contacts. According to Lamar (1970), the Siltstone Member and Conglomerate Member can be over 4,300 and 1,500 feet thick, respectively.

2.1.2.3 Puente Formation

The deep-water marine rocks of the late Miocene Puente Formation are present within the SR 710 North Study Area. Various geologists have assigned different formational names to the same rocks. Such names include Puente, Monterey, Modelo, and Unnamed Shale (Dibblee, 1989a and 1989b; Lamar, 1970; Weber, 1980). These assignments are basically nothing more than nomenclatural preferences of the individuals; these sedimentary rocks within the SR 710 North Study Area largely have similar engineering and tunneling properties. The name Puente Formation, as used by Lamar (1970), is followed throughout this report.

According to the dominant rock type, the Puente Formation is divided into several members as follows, from older to younger: sandstone, shale, diatomaceous siltstone/shale, and siltstone units. The Sandstone Member consists predominantly of thick to very thickly bedded fine-grained very soft to moderately hard sandstone and silty sandstone with scattered laminations to thick interbeds of siltstone and shale. Individual beds and intervals of these rocks are friable, weakly cemented, and susceptible to softening in the presence of water, but other beds are strongly cemented. The Shale Member consists predominantly of thinly bedded to laminated and fissile soft to moderately hard shales with thin interbeds to laminations of fine-grained sandstone and siltstones.

The Diatomaceous Siltstone/Shale Member is represented by thinly bedded to laminated very soft to moderately soft diatomaceous siltstones. Finally, the Siltstone Member generally consists of thinly bedded to laminated very soft to moderately hard siltstones with medium to thick interbeds to laminations of fine-grained sandstone.

The degree of weathering in these rocks decreases with increasing depth from decomposed to fresh. The rocks contain locally hard to very hard, strongly cemented interbeds and concretions. These cemented zones were not over 3 feet in thickness and are not anticipated to be laterally continuous over long distances.

According to Lamar (1970), the thicknesses of the sandstone, shale, diatomaceous siltstone, and siltstone units in the Repetto Hills are over 800, 300, 950, and 2,700 feet, respectively. The Puente Formation unconformably overlies the Topanga Formation.

2.1.2.4 Topanga Formation

The middle-Miocene-age Topanga Formation occurs as three separate units within the SR 710 North Study Area (Lamar, 1970). These units include a lower Siltstone Member, middle Sandstone Member, and upper Conglomerate Member. The rocks of the Topanga Formation tend to be coarser-grained north of the Raymond fault.

The Siltstone Member consists of thinly bedded to laminated and fissile very soft to moderately hard siltstones and shales, with fine- to coarse-grained sandstone interbeds that present a rhythmically bedded sequence typical of turbidity current deposits. Beds of tuff and tuffaceous sandstones were noted at the upper portion of the unit (Lamar, 1970). The rocks of this unit are commonly very similar to those of the Siltstone Member of the Puente Formation; some geoscientists, in fact, have mapped them as Puente Formation (Dibblee, 1989a; Weber, 1980).

The Sandstone Member consists of laminated to moderately bedded, medium- to coarse-grained very soft to moderately hard sandstone with thin interbeds and laminations of fine-grained sandstone, siltstone, and/or shale with some conglomerate beds. Individual beds and intervals of these rocks are friable, weakly cemented, and susceptible to softening in the presence of water.

The Conglomerate Member generally consists of moderately hard to hard, well-rounded to subangular rock fragments derived from the basement complex of the San Gabriel and Verdugo Mountains. Rock fragments of the Topanga Formation are commonly within an uncemented, friable, sandy matrix that allows the rock fragments to be broken out of the matrix with little difficulty. The conglomerate and breccia range from extremely large, house-sized blocks to fine, gravel-sized rock. More commonly, however, the conglomerates consist of rounded cobbles and fine gravel in a medium- to coarse-grained friable arkosic sand matrix. Some beds are strongly cemented with calcium carbonate and are hard to very hard and resistant rocks. In addition, this unit includes scattered sandstone beds.

Localized, strongly cemented, thin calcareous and siliceous concretions were reported as scattered through all units of the Topanga Formation (CH2M HILL, 2010). Additionally, scattered, strongly cemented, very thin to thin beds and lenses were reported throughout the formation. The cemented zones, layers, and concretions are generally hard to very hard. These hard layers, zones, and/or concretions were not observed to be over 3 feet thick and are not anticipated to be laterally continuous over large distances.

2.1.2.5 Basement Complex Rocks

Bedrock within the northern part of the SR 710 North Study Area consists of the Cretaceous-age basement complex rocks exposed in the San Rafael Hills where it is designated as Wilson diorite or quartz diorite (Dibblee, 1989a; Lamar, 1970). However, these rocks comprise a wide suite of lithologies, including diorite, monzonite, quartz diorite, quartz monzonite, and gneissic diorite. These are the same rocks that compose the San Gabriel Mountains north of the SR 710 North Study Area. For SR 710 North Study, this rock unit is referred to as the Wilson Quartz Diorite.

The rock consists primarily of plagioclase feldspars with quartz, hornblende, and biotite. Regardless of the variable lithologies, these rocks have similar engineering properties. Although the rocks are generally moderately soft to hard, they are highly fractured. The highly fractured nature of the Wilson Quartz Diorite, as observed within the SR 710 North Study Area, yields a rock mass that is generally readily friable.

2.1.3 Geologic Structure

The San Gabriel Basin is a large down-warp created by regional north-northeast to south-southwest-directed compressional geological forces that have uplifted the San Gabriel Mountains and folded the rocks in adjacent hills. The Elysian, Repetto, and San Rafael Hills in the western part of the SR 710 North Study Area are primarily a result of Quaternary-age folding and uplift. The faults and folds in the hills largely trend southeasterly from the Santa Monica Mountains to the Puente Hills and are commonly referred to as the Elysian Park Fold and Thrust Belt (EPFT) (Davis and Namson, 1998).

The only known active surface fault in the SR 710 North Study Area is the Raymond fault, although almost the entire area is underlain by the active Upper Elysian Park and Puente Hills blind thrust faults (Shaw and Suppe, 1996; Shaw et al., 2002). An active fault is defined by the State of California as a fault that has experienced surface displacement within the Holocene Epoch (roughly the last 11,000 years) (Bryant and Hart, 2007). The Eagle Rock and San Rafael faults are generally considered to be potentially active. A potentially active fault is defined by the State of California as a fault that has experienced surface displacement within the Quaternary period (the last 1.6 million years), but has not been confirmed to have younger Holocene displacements (Bryant and Hart, 2007). The faults considered capable of generating seismic activity within the SR 710 North Study Area are described in Section 2.2.

Numerous inactive (pre-Holocene), intra-formational faults are present within the SR 710 North Study Area, as shown in the SR 710 North Study Geologic Map (Figure 2-1). These faults likely formed as a result of the Miocene-Pliocene tectonic regime (approximately 16 to 2 million years ago).

A northwest-southeast-trending intra-formational (Puente Formation) fault has been mapped transecting the northern SR 710 terminus at Valley Boulevard by Lamar (1970). The fault is mapped as queried by Lamar (1970) where it transects the two bedrock knobs situated northwest and southeast of the intersection of Valley Boulevard and SR 710. As the fault crosses Valley Boulevard, the fault is mapped as being concealed beneath the older (Pleistocene-age) alluvial soil that blankets the site. An aerial photograph evaluation conducted previously for the SR 710 Tunnel Technical Study (CH2M HILL, 2010) did not reveal any lineaments or other features indicative of a fault within the alluvial soils in this area. In addition, a seismic line was conducted across the concealed trace of this fault in 2010 (CH2M HILL, 2010). The seismic line indicated the possible presence of a linear feature at depth in this area. The feature could not be traced across seismic marker beds shallower than approximately 125 feet bgs. This fault, if it exists, and similar faults mapped in this area were considered by Lamar (1970) to be pre-Pliocene in age. There is no evidence that would indicate this fault has moved in the Pleistocene or Holocene, and good geologic evidence to show that it has not.

2.1.4 Groundwater and Surface Water

The SR 710 North Study Area is located within four alluvial groundwater basins of the South Coast Hydrologic Region. The subject basins include the San Fernando, Raymond, Main San Gabriel, and (Los Angeles) Central basins, which are separated by bedrock upland areas and/or faults. The bedrock units within the SR 710 North Study Area generally do not contain substantial amounts of groundwater. However, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. Substantial amounts of groundwater inflows are expected locally in alluvial deposits. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are over 100 feet higher than the levels on the south side of the fault. In addition, the potentially active (Eagle Rock and San Rafael faults) and inactive faults may also act as groundwater barriers. The alternatives, groundwater basins, and bedrock upland areas are shown in Figure 2-2.

Historically highest groundwater levels within the SR 710 North Study Area range from 5 to 200 feet bgs. In the overall study area, groundwater levels vary considerably, ranging from 10 to 450 feet bgs. Groundwater levels for the BRT Alternative range from 20 feet bgs near the Raymond fault (near Arroyo Seco Parkway) in South Pasadena to 330 feet bgs in the vicinity of West Main Street in Alhambra. Groundwater levels for the LRT Alternative range from 10 feet bgs in the area between I-10 and Valley Boulevard to roughly 150 feet bgs south of the Raymond fault. Groundwater levels for the Freeway Tunnel Alternative range from 10 feet bgs in the area between I-10 and Valley Boulevard, to over 250 feet bgs at the northern end of the alternative.

No major springs are known to occur in the upland bedrock areas within the SR 710 North Study Area. Rainfall runoff flows into drainage structures and alluvial soils.

The groundwater basins contain permeable alluvial materials that can transmit large amounts of groundwater. Groundwater from these basins is a primary source of the water supply for the region. A brief description of these basins is provided below (from the California Department of Water Resources [CDWR], 2003, and 2004a through 2004d).

- The San Fernando Basin includes the water-bearing sediments beneath the San Fernando Valley, Tujunga Valley, Browns Canyon, and the alluvial areas surrounding the Verdugo Mountains near La Crescenta and Eagle Rock. The basin is bounded on the north and northwest by the Santa Susana Mountains, on the north and northeast by the San Gabriel Mountains, on the east by the San Rafael Hills, on the south by the Santa Monica Mountains and Chalk Hills, and on the west by the Simi Hills. The water-bearing sediments consist of the lower Pleistocene Saugus Formation (not observed within the SR 710 North Study Area), and Pleistocene and Holocene alluvium. The groundwater in this basin is mainly unconfined with some confinement within the Saugus Formation in the western part of the basin and in the Sylmar and Eagle Rock areas. TSM/TDM improvements are located within this basin, as shown in Figure 2-2.
- The Raymond Basin includes the water-bearing sediments bounded by the contact with consolidated basement rocks of the San Gabriel Mountains on the north and the San Rafael Hills on the southwest. The west boundary is delineated by a drainage divide at Pickens Canyon Wash. The southeast boundary is the Raymond fault, which acts as a barrier to groundwater flow southward into the San Gabriel Basin. The water-bearing materials of the Raymond Basin are typically unconfined, dominated by unconsolidated Quaternary alluvial sediments deposited by streams flowing out of the San Gabriel Mountains. A portion of each of the alternatives is located within this basin, as shown in Figure 2-2.
- The Main San Gabriel Basin includes the water-bearing sediments underlying most of the San Gabriel Valley. This basin is bounded on the north by the Raymond fault and the contact between Quaternary sediments and basement rocks of the San Gabriel Mountains. Exposed consolidated rocks of the Repetto, Merced, and Puente Hills bound the basin on the south and west. The Chino fault and the San Jose fault form the eastern boundary. The water-bearing materials of this basin are dominated by unconsolidated to semi-consolidated alluvium deposited by streams flowing out of the San Gabriel Mountains. These deposits include Pleistocene and Holocene alluvium and the lower Pleistocene San Pedro Formation. A portion of each of the alternatives is located within this basin, as shown in Figure 2-2.
- The (Los Angeles) Central Basin is bounded on the north by a surface divide called the La Brea High, and on the northeast and east by emergent less-permeable Tertiary rocks of the Elysian, Repetto, Merced, and Puente Hills. Throughout the Central Basin, groundwater occurs in Holocene and Pleistocene sediments deposited by streams and rivers flowing out of the San Gabriel Mountains and Elysian, Repetto, Merced, and Puente Hills. The Central Basin is historically divided into forebay and pressure areas. In the SR 710 North Study Area, the Los Angeles forebay of the Central Basin has unconfined groundwater conditions. The southern portions of the BRT and LRT Alternatives are located within this basin, as shown in Figure 2-2.

The SR 710 North Study Area is located within the Los Angeles River Watershed, which covers over 834 square miles from the eastern portions of Santa Monica Mountains to the San Gabriel River Watershed in the east. The San Gabriel River Watershed covers approximately 640 square miles. The alternatives and surface water features are shown in Figure 2-3.

The Los Angeles River flows from its headwaters in the mountains in northwestern Los Angeles County into the San Fernando Valley and eastward to the northern corner of Griffith Park where the channel turns southward through the Los Angeles Narrows before it flows south across the coastal plain to the Pacific Ocean. The Los Angeles River is confined within a concrete and riprap-lined channel in most of the SR 710 North Study Area; however, small portions are open and allow infiltration into the alluvium underlying the aqueduct. Major tributaries in the SR 710 North Study Area drain the San Gabriel Mountains and include Arroyo Seco, Compton Creek, and Rio Hondo. There are spreading grounds and open quarries along these tributaries that capture surface water for groundwater recharge.

The San Gabriel River flows from its headwaters in the San Gabriel Mountains southward through the Whittier Narrows before it flows south across the Coastal Plain to the Pacific Ocean. Channel flows pass through different sections in the San Gabriel River, diverting from the riverbed into four different spreading grounds for controlled flow and groundwater recharge above the Whittier Narrows Dam.

Flows in the Los Angeles River, San Gabriel River, and tributary washes occur primarily in the winter months in response to precipitation. These surface water flows are ephemeral and are controlled by partially concrete-lined drainage structures. Surface water recharges the alluvial groundwater basins when storm flows occur mostly by gravity drainage, because the water table elevations are below the bottom of the riverbeds and washes. The water within the channels either flows downstream or infiltrates into the subsurface. In general, there is no base flow of groundwater to surface water after storm flows recede because groundwater is below the bottom of these surface water features. Therefore, any lowering of the water table in alluvial areas due to groundwater dewatering from construction, or from O&M activities associated with the proposed alternatives, should not affect the surface water features.

2.1.5 Naturally Occurring Oil and Gas

Naturally occurring oil, tar seeps, and/or gas were not encountered during any of the current or previous investigations conducted along the SR 710 North Study Alternatives. Based on information available from the California Division of Oil, Gas, & Geothermal Resources (CDOGGR, 2005 and 2012), and as shown in Figure 2-4, no abandoned or existing oil wells are located within the immediate vicinity of the alternatives. The information in Figure 2-4 shows that there are nearby oil wells, but the number and density of the wells are such that they are not expected to have an effect on the SR 710 North Study Alternatives.

Naturally occurring oil and gas could be encountered in any of the formations in the SR 710 North Study Area. However, based on experience with the construction of other tunnels in Los Angeles, naturally occurring oil and gas is most likely to be encountered within the Puente Formation. Localized deposits of oil and gas may be present at any depth in the Puente Formation.

2.2 Faulting

The faults of greatest importance to the study are described below and shown in Figure 2-5. Within the SR 710 North Study Area, only the Raymond fault is identified as an active fault under the Alquist-Priolo Earthquake Fault Zone (APEQFZ) Act, which implies a potential for surface rupture (Bryant and Hart, 2007). Such a designation indicates the fault is known to have experienced surface offsets within the last 11,000 years and its location is well defined. Potentially active faults may not be identified as active per the APEQFZ Act simply because their locations are not well defined and/or they have not been confirmed to have surface ruptures in Holocene time. Within the SR 710 North Study Area, the San Rafael and Eagle Rock faults (see Figure 2-1) are considered potentially active faults. Additional investigation will be required to adequately characterize the activity of the San Rafael and Eagle Rock faults. For planning purposes, the Eagle Rock and San Rafael faults are considered active, as discussed in the Fault Rupture Evaluation Technical Memorandum prepared for this project (CH2M HILL and ECI, 2013), which is included in Appendix A of this report.

There are very limited data concerning the slip rates or recurrence intervals of surface-rupturing earthquakes for the Raymond fault and the remaining Transverse Ranges Southern Boundary faults. As such, there is difficulty in providing reasonable values for fault displacements. These Southern Boundary faults are all relatively short, and if any ruptured individually, it would generate displacements of less than 1 meter. However, there are some discussions that these faults could rupture together (Marin et al., 2000; Weaver and Dolan, 2000), with slip transferring from one to the other, in a cascading event that would result in a larger magnitude event and much larger displacements on each of the faults. A detailed discussion regarding the fault rupture hazard within the SR 710 North Study Area is presented in the Fault Rupture Evaluation Technical Memorandum (see Appendix A).

2.2.1 Nearby Regional Faults

This section provides a summary of the nearby regional faults that affect the seismicity of the Los Angeles area and potentially create a geologic hazard for the SR 710 North Study Area. In addition to identifying the general location of these faults, the activity and potential magnitude of an earthquake associated with these faults are also summarized.

2.2.1.1 Transverse Ranges Southern Boundary Faults – Malibu Coast, Santa Monica, and Hollywood Faults

One of the major fault systems in the Los Angeles Basin is along the southern edge of the Santa Monica Mountains separating Mesozoic plutonic rocks from Tertiary and Quaternary sedimentary rocks. The fault system—commonly referred to as the Transverse Ranges Southern Boundary Faults—consists primarily of the Malibu Coast, Santa Monica, Hollywood, and Raymond faults (Southern California Earthquake Center [SCEC], 2001). Although the Raymond fault is included in this fault system, the importance of the Raymond fault to the SR 710 North Study warranted a separate discussion, which is presented in Section 2.2.2.1.

The Santa Monica Mountains, which form the southern edge of the fault system, rise abruptly to 1,500 to 2,000 feet above the Los Angeles Basin floor and are indicative of a large vertical component of faulting (Meigs et al., 1999). Earthquake focal mechanisms and local geologic relationships suggest about equal amounts of reverse faulting with a left-lateral component. It is uncertain whether this is accomplished by strain partitioning on separate faults or oblique slip on one dominant fault.

The Hollywood, Santa Monica, and Malibu faults have been shown to have ruptured the ground surface within the past 11,000 years, and all of these faults have a similar left-lateral reverse sense of slip. Paleoseismic studies of the Hollywood and Santa Monica faults (Dolan et al., 1997, 2000a, and 2000b) suggest that these two faults have recurrence intervals of about 10,000 years, and that the Santa Monica fault last broke 1,000 to 3,000 years ago, while the Hollywood fault last ruptured 6,000 to 9,000 years ago. Studies of the Malibu fault also identify it as having Holocene displacements with a recurrence interval of 4,000 to 5,000 years (Drumm, 1992).

The great length of the Transverse Ranges Southern Boundary Fault system suggests that it is capable of generating a large earthquake (approximately 7.5 magnitude), but the discontinuous nature of faulting and the lack of temporal correlation of the most recent paleoseismic events suggest that the individual fault segments behave independently at least some of the time. Based on their individual lengths, the shorter segments would not be expected to generate a maximum earthquake as large as 7.0. Dolan et al. (1997) postulated an event of approximately M_W 6.6 for the Hollywood fault (M_W = earthquake moment magnitude). The earthquake recurrence interval is very long and could be more than 10,000 years. In addition, documented slip rates are only about 0.5 millimeter per year (mm/yr), but this estimate suffers from lack of data and similar inconsistencies between slip accumulation and the timing of its release. Even at 0.5 mm/yr, a 10,000-year recurrence interval would require the release of 5 meters of accumulated strain per earthquake, a value that appears to be improbable, and which leads to concerns that either the slip rate is too high or the earthquake recurrence is more frequent. Caltrans (2013b) assumes a slip rate of 0.3, 1.0, and 0.9 mm/yr and a maximum moment magnitude (Mmax) of 6.6, 7.0, and 6.6 for the Malibu Coast, Santa Monica, and Hollywood faults, respectively.

The slip kinematics of the Malibu Coast, Santa Monica, and Hollywood faults are similar to the Raymond fault (discussed in Section 2.2.2.1); that is, dominantly left-lateral with a reverse component, which is why they are frequently considered as individual parts of a larger fault system. Currently, the collected paleoseismic data for these faults do not support temporally coincident ruptures, although the data set is small. For analysis purposes, however, these faults could still be considered as rupturing together with the Raymond fault in various rupture scenarios (CH2M HILL and ECI, 2013).

2.2.1.2 Puente Hills Thrust Fault System

The Puente Hills Thrust fault system is the name currently given to a series of northerly dipping, blind, subsurface thrust faults extending approximately 40 to 45 kilometers (km) along the eastern margin of the Los Angeles Basin. Shaw and Shearer (1999) synthesized oil company data and seismicity to interpret three discrete thrust faults underlying the La Brea/Montebello Plain (Los Angeles Segment), Santa Fe Springs Plain (Santa Fe Springs Segment), and Coyote Hills (Coyote Hills Segment). These faults form an en-echelon arrangement from the northern Los Angeles Basin to the southern part of the Puente Hills.

Down-dip projection of the Santa Fe Springs Segment of the Puente Hills faults extends to the approximate area of the 1987 Whittier earthquake hypocenter, which Shaw and Shearer (1999) relocated to about 16 km in depth. Subsequent work on the fault system (Shaw et al., 2002) infers that the en-echelon segments of the Puente Hills Thrust are related, and displacements are transferred from one segment to the next. Using empirical data on rupture area, magnitude, and coseismic displacement, Shaw et al. (2002) estimated a potential for earthquakes of M_W 6.5 to 6.6 for individual segments, and M_W 7.1 for linked ruptures. The recurrence intervals for these events are approximately 400 to 1,320 years for single events and 780 to 2,600 years for magnitude 7.1 events. Caltrans (2013b) assumes a slip rate of 0.9 mm/yr and a Mmax of 6.9 for the Puente Hills fault-Los Angeles section (the closest segment to the SR 710 North Study Area as shown in Figure 2-6).

The exact geometry and location of the Puente Hills fault system is unclear; the fault system may extend north and underlie the entire SR 710 North Study Area. Although the Puente Hills fault system might generate strong ground motion in the SR 710 North Study Area, it is not considered to be capable of generating surface rupture.

2.2.1.3 Alhambra Wash Fault (Elsinore Fault Zone – Whittier Segment)

The Alhambra Wash fault is a short northwest-southeast-trending fault in the southern part of the San Gabriel Valley. The fault is mapped from near SR 60 on the southeast to San Gabriel Boulevard on the northwest (California Division of Mines and Geology [CDMG], 1991; Treiman, 1991; Bullard and Lettis, 1993). This portion of the fault is designated as an APEQFZ and, therefore, is considered to be active.

Several investigators (Yerkes and Campbell, 2005; Dibblee, 1999) have mapped their interpretation of the fault to continue northwest of San Gabriel Boulevard past I-10 into the city of Alhambra and further northwest. However, Yeats (2004) indicates that there is no oil well data to support such an interpretation and states that the associated geomorphic features do not extend northwest of I-10.

Gath et al. (1994) estimated right-lateral, northeasterly dipping normal oblique slip with a lateral slip rate of about 0.1 to 0.2 mm/yr and a vertical slip rate of about 0.08 mm/yr. The potential for surface displacement on the Alhambra Wash fault is poorly known and must be based on empirical earthquake relationships. Using worldwide empirical data on earthquake magnitude and fault length as documented by Wells and Coppersmith (1994), the Mmax of an event on the Alhambra Wash fault could be about 6.25, though it is unlikely to rupture separately from the Whittier fault.

The Alhambra Wash fault is not included in the Caltrans (2013b) fault database. However, the Alhambra Wash fault is believed to be a northerly extension of the Elsinore fault zone – Whittier segment. The Whittier segment is a roughly 40-km-long, northeasterly dipping, northwest-southeast-trending, right-lateral strike-slip fault with a minimum slip rate of about 2.5 mm/yr (Gath, et al., 1992; SCEC, 2013a). Caltrans (2013b) assumes the same slip rate of 2.5 mm/yr and a Mmax of 6.9 for the Whittier segment of the Elsinore fault zone.

2.2.1.4 Additional Nearby Faults

Three other active fault systems have been recognized in the general area of the SR 710 North Study. These faults contribute to the overall seismicity of the area.

- The Newport-Inglewood fault zone is a roughly 75-km-long, northwest-southeast-trending, right-lateral strike-slip fault with local reverse slip (SCEC, 2013b). The Newport-Inglewood fault is mapped extending from central Orange County near the coast, to near the foothills of the Santa Monica Mountains in the Westwood/Beverly Hills area (United States Geological Survey [USGS], 2010). Caltrans (2013b) assumes a slip rate of 1.0 mm/yr and a Mmax of 7.2 for the Newport-Inglewood fault zone.
- The Sierra Madre fault zone is a roughly 75-km-long, east-west- to northwest-southeast-trending, reverse fault (SCEC, 2013c). The Sierra Madre fault is located near the southern toe of the San Gabriel Mountains. Movement along this fault, and the San Andreas fault, located near the northern toe of the San Gabriel

Mountains has resulted in the ongoing uplift of the San Gabriel Mountains. Tucker and Dolan (2001) measured a minimum reverse offset of 4 meters in the last event, yielding a reverse slip rate of 0.9 mm/yr with more than 8,000 years since the last rupture. These results imply over 7 meters of accumulated strain, which would result in a Mmax greater than 7.5 earthquake if released in a single event. Caltrans (2013b) assumes a slip rate of 2.0 mm/yr and a Mmax of 7.2 for the Sierra Madre fault zone (Strands B and C).

- The Clamshell-Sawpit fault is a roughly 18-km-long, southwest-northeast-trending, reverse fault (SCEC, 2013d) that may have been the source of the 1991 Mmax 5.8 Sierra Madre earthquake (Hauksson, 1994). The Clamshell-Sawpit fault is mapped near the northeastern end of the Raymond fault, within the Angeles National Forest, north of the Monrovia area (USGS, 2010) and may represent the eastern end of the Raymond fault. Caltrans (2013b) considers the Clamshell-Sawpit fault to be a splay of the Sierra Madre fault zone, and assigns a slip rate of 0.5 mm/yr and a Mmax of 6.6 for the Clamshell-Sawpit splay.

2.2.2 Active Faults within the SR 710 North Study Area

Two active fault systems have been identified in the SR 710 North Study Area. These include the Raymond fault and the EPFT. The location, activity, and approximate date of last rupture for these faults are summarized in the following subsections.

2.2.2.1 Raymond Fault

One of the major faults with regard to the SR 710 North Study Area is the Raymond fault (also known as the Raymond Hill fault); the location of this fault is shown in Figures 2-1, 2-5, and 2-6. The State of California (CGS) has established an APEQFZ along the Raymond fault from the San Gabriel Mountains in the east to near the intersection of Avenue 50 and York Boulevard on the west, as shown in Figure 2-9.

The Raymond fault extends southwesterly from the Sierra Madre fault zone at the base of the San Gabriel Mountains through the communities of Monrovia, Arcadia, San Marino, and Pasadena to the Raymond Hill area of South Pasadena, where the Raymond fault trends more westerly through the communities of South Pasadena, Highland Park, and possibly into Los Angeles. The length of the fault is roughly 19 to 25 km, depending on which interpretation is accepted. The fault forms a gentle arc, convex toward the south across the alluvial deposits of the San Gabriel Valley, potentially joining with the Clamshell-Sawpit fault at the base of the San Gabriel Mountains to the east, and the Hollywood fault to the west. The fault is best expressed in the area of San Marino to South Pasadena, where it forms a prominent escarpment up to 30 to 46 meters high.

A prominent linear gravity anomaly extending easterly from the southern margin of the Santa Monica Mountains, under the Los Angeles River plain, and into the Repetto Hills indicates that the Hollywood fault may extend easterly into the Repetto Hills, and has led to the interpretation by some that the Hollywood and Raymond faults may be interconnected (Chapman and Chase, 1979). However, the westerly continuation of the Raymond fault into the Los Angeles River floodplain is uncertain, and the earthquake/rupture histories are very different (Weaver and Dolan, 2000). Others (for example, Dolan et al., 1995) have suggested that the Raymond fault may be a tear fault associated with the uplift of the Verdugo Mountains via the Eagle Rock and/or San Rafael faults. A discussion of potential rupture scenarios is presented in the Fault Rupture Evaluation Technical Memorandum (see Appendix A).

The most recent major surface rupture on the Raymond fault occurred in Holocene time, most likely around 2,000 years ago, but potentially as long as 6,000 years ago (Crook et al., 1987; Weaver and Dolan, 2000). The average recurrence interval for surface rupturing events may be about 3,300 years (Weaver and Dolan, 2000), though temporal clustering has been proposed to both shorten and lengthen that recurrence interval.

The Raymond fault is a north-dipping, east-west-trending fault that has a dominant left-lateral sense of offset (Jones et al., 1990; Weaver and Dolan, 2000), though some north-side-up reverse slip is also likely. The percentage of lateral to vertical (L:V) slip varies along the trace of the fault; it has been estimated at about a 5:1 L:V ratio (see Appendix A).

Currently, there is little consensus on the rate of slip of the Raymond fault. Geological trenching studies across the fault scarp indicate average slip rates between 0.5 and 2.0 mm/yr (Dolan et al., 2000a; SCEC, 2013e).

More recently, the rate of slip has been estimated to be as high as 4 +1/-0.5 mm/yr (Yeats, 2012), based on a regional modeling study (Walls et al., 1998).

As discussed above, there remains considerable inconsistency in the published data for the Raymond fault. Caltrans (2013b) currently assumes a slip rate of 2.0 mm/yr and a Mmax of 6.7 for the Raymond fault, implying a recurrence interval of 250 to 500 years with an offset of 0.5 to 1.0 meter per event. Additional discussion regarding the various fault scenarios involving the Raymond fault is presented in the Fault Rupture Evaluation Technical Memorandum (see Appendix A). Further evaluation of the Raymond fault will be needed as the project proceeds. The Raymond fault is mapped crossing the TSM/TDM (Improvements I-18 and T-2), BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figure 2-1.

2.2.2.2 Elysian Park Fold and Thrust Belt (EPFT)

The EPFT was initially described by Davis et al. (1989) who postulated that the Los Angeles area is underlain by a series of deep master detachment faults, probably of Miocene age, and that most of the Quaternary uplift in the region is caused by reverse slip along the reactivated detachments. This north-south convergence results in blind-thrust faulting with folding at bends and kinks in the detachment fault, expressed at the surface as a series of east-west oriented hills. The blind-thrust model was initially embraced primarily because the 1987 Whittier earthquake occurred near one of the postulated thrust ramps beneath the EPFT. Subsequent work (for example, Shaw and Suppe, 1996; Oskin et al., 2000; Bullard and Lettis, 1993; Shaw and Shearer, 1999; Shaw et al., 2002) has highly modified the original model, and currently, most seismic hazard analyses recognize only the Upper Elysian Park Blind Thrust fault (UEPBT).

As shown in Figures 2-5 and 2-7, the concealed trace of the UEPBT has been mapped just north of the I-710/I-10 interchange. The UEPBT is theorized to be bound by the Hollywood fault to the northwest and the Alhambra Wash fault (the northerly extension of the Elsinore/Whittier fault zone) to the southeast (Oskin et al., 2000; Shaw et al., 2002). The UEPBT has been modeled dipping to the north at angles ranging from 30 to 60 degrees from horizontal (Oskin et al., 2000); the actual dip of the fault is unknown at this time.

Shaw and Suppe (1996) estimated earthquake magnitudes associated with these seismic events on the UEPBT ranging from 6.6 to 7.3, with recurrence intervals in the range of 340 to 1,000 years. The CGS, following the lead of Oskin et al. (2000), models the UEPBT as a feature about 18 km long and dipping 50 degrees northeasterly with a slip rate estimate of approximately 1.3 ± 0.4 mm/yr. Caltrans (2013b) assumes a slip rate of 1.9 mm/yr and a Mmax of 6.6 for the UEPBT.

Because the UEPBT does not extend to the surface, it does not meet the criteria of having a well-defined location, which is a requirement to be considered an active fault as defined by the State of California (Bryant and Hart, 2007). Moreover, movements along the UEPBT have resulted in local coseismic deformation at the surface. Oskin et al. (2000) have identified numerous folds and escarpments, some of which are visible at the surface, that have formed as a result of movement along the UEPBT. As shown in Figure 2-7, these features have been mapped in the area generally south of York Boulevard in northeast Los Angeles, north of SR 60 in East Los Angeles, west of Rosemead Boulevard in the Whittier Narrows area, and east of Van Ness Avenue in the Hollywood area. Of these features, the Coyote Pass escarpment (Figure 2-7) is considered to be the feature of most concern (Oskin et al., 2000). Investigations following the 1994 Northridge earthquake found ground deformation on structures geomorphically similar to the Coyote Pass Escarpment (Hart et al., 1995; Treiman, 1995). The uplift caused by the Northridge blind thrust produced folding, minor (bending moment) faulting, and fracturing of the ground surface along the northeast flank of the Pico Anticline near Newhall, California. Here, investigators found up to 19 centimeters of vertical offset along faults and tensional surface fracturing (Treiman, 1995).

The Coyote Pass escarpment transects the Freeway Tunnel Alternative just north of Floral Drive, and the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in Monterey Park. The very eastern end of the escarpment is mapped transecting the BRT Alternative in the vicinity of Brightwood Street, also in Monterey Park. A deformation study on the Coyote Pass escarpment was conducted at the intersection of Soto Street and First Street in Los Angeles for the Metro Gold Line Soto Station, a subterranean LRT station (ECI, 2001). The Soto Station is located at the toe of the Coyote Pass escarpment. The station is roughly 2.5 miles west of where the escarpment crosses the SR 710 North Study LRT Alternative and 4 miles west of the BRT Alternative. The ECI (2001) study indicated that deformation at the Coyote Pass escarpment (at the Soto Station) has a recurrence interval of 2,800 to 3,900 years; however, no data were available to constrain the timing of the most recent event. Each event was estimated to result in uplift of 60 to 85 centimeters, yielding tightening of the synclinal fold hinge of 0.21 to 0.43 degrees per event. This deformation would result in an estimated 0.3 percent volumetric compressive strain along the axis hinge line over an area approximately 8 meters wide; a second scenario presented indicated a 0.1 percent volumetric strain along the axis hinge line over an area 23 meters wide (ECI, 2001). The top of the escarpment would also experience uplift, differential tilting, and extensional strains during a UEPBT event. Although this deformation was not quantified by ECI (2001), it would presumably be similar in magnitude to deformation across the synclinal axis, though extensional and potentially more broadly dispersed.

Although the ECI study was 2.5 to 4 miles west of the Build Alternatives, the deformations estimated by ECI (2001) can be hypothesized as also occurring at the Build Alternatives at the Coyote Pass escarpment. Several additional folds related to the UEPBT have been mapped transecting the BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figure 2-7. Based on the available data, it appears that these folds also experience coseismic deformation during an event on the UEPBT; however, the rate of deformation is substantially less than that discussed above for the Coyote Pass escarpment. Bullard and Lettis (1993) indicate that fold deformation has migrated to the south since the late Tertiary (roughly 5 million years ago). This southerly migration indicates that folds present north of the Monterey Park and Montebello Hills are subject to substantially less deformation than those south of the hills. This concurs with the findings of Oskin et al. (2000), which identify the Coyote Pass escarpment (located at the southerly toe of the Monterey Park Hills) as the feature of primary concern. Although minor coseismic deformation may occur on the folds north of the hills, the amount of deformation at or near the surface (if any) should be substantially less than that of the Coyote Pass escarpment.

2.2.3 Potentially Active Faults within the SR 710 North Study Area

The only potentially active faults within the SR 710 North Study Area are the Eagle Rock and San Rafael faults. Existing geologic maps (Lamar, 1970; Dibblee, 1989a and 1989b; Yerkes and Campbell, 2005; City of Pasadena, 2002) show different locations for the Eagle Rock and San Rafael faults. The principal difference is that Lamar (1970) maps the San Rafael and Eagle Rock faults as separate features.

The San Rafael fault extends southeasterly from within the San Rafael Hills to the northern edge of Grace Hill, Raymond Hill, and the smaller associated knolls, essentially along the same trace as Dibblee's Eagle Rock fault. At the eastern end, Lamar splits the fault into two splays or branches—one extends through the top of Raymond Hill, and the other is a dotted line (that is, a subsurface fault) trending more easterly past Arroyo Parkway and into the hills north of the main trace of the Raymond fault. Lamar maps the Eagle Rock fault to the south of the San Rafael fault within the knolls and projecting south of Raymond Hill, similar to that shown in Figure 2-1. The Eagle Rock and San Rafael faults do not extend across the Raymond fault but appear to join with it in a relationship that is not well understood. Some transfer of strain between the Raymond and Verdugo faults may be accommodated along the Eagle Rock and San Rafael faults.

The Eagle Rock/San Rafael fault is generally considered to be the southern continuation of the Verdugo fault (Yeats, 2004). No paleoseismic studies have been published for the Verdugo fault. The Eagle Rock/San Rafael fault zone also has no quantitative investigations, though all three faults are considered to be potentially active. Caltrans classifies the Eagle Rock and San Rafael faults as one fault and as a continuation of the Verdugo fault. According to the Caltrans (2013b) fault database, the Verdugo-Eagle Rock fault is estimated to have a slip rate of 0.6 mm/yr and a Mmax of 6.8.

The Eagle Rock and San Rafael faults seem to merge just west of Raymond Hill; it is possible that Raymond Hill is being elevated as a result of this strain transfer between the San Rafael and Raymond faults. However, a joint rupture involving these faults cannot be a common event, because the tectonic geomorphology of the Eagle Rock/ San Rafael fault is much less developed than that of the Raymond fault, suggesting it has a lower slip rate or longer recurrence interval to refresh it on the landscape. Despite this observation, the tectonic geomorphology of the

Raymond fault is much better developed east of Arroyo Seco, near its intersection with the Eagle Rock/San Rafael faults. No data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/ San Rafael faults, nor on the Verdugo fault farther northwest.

Based on the SR 710 North Study, the locations of the Eagle Rock and San Rafael fault, where they cross the alternatives, are shown in Figures 2-1, 2-7, 3-1, and 3-2. The San Rafael fault is mapped crossing the TSM/TDM (Improvements L-1 and T-2), BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figures 2-1, 2-7, 3-1 and 3-2. The Eagle Rock fault is mapped crossing only the Freeway Tunnel Alternative, as shown in Figures 2-1, 2-7, and 3-2. The fault locations shown in Figures 2-5 and 2-6 are generalized based on the regional mapping studies referenced in the figures.

As indicated above, the activity of the Eagle Rock and San Rafael faults is unknown at this time. Additional investigation and analysis would be performed to evaluate the activity of these faults, and to develop a set of appropriate fault offset estimates for design purposes. Additional discussion regarding the various fault scenarios involving the Eagle Rock and San Rafael faults is presented in the Fault Rupture Evaluation Technical Memorandum (see Appendix A).

2.3 Seismicity and Seismic Ground Shaking

The seismicity and level of potential ground shaking within the SR 710 North Study Area have been investigated during many past studies. Results of these studies show that the area has been subjected to ground shaking in the past and may be shaken again in the future. As the SR 710 North Study project advances, special studies will be required to address seismic ground shaking and potential secondary seismic hazards.

2.3.1 Historical Seismicity

The SR 710 North Study Area is located within seismically active southern California. The present-day seismotectonic stress field in the Los Angeles region is one of north-northeasterly compression. This is indicated by the geologic structures, by earthquake focal-mechanism solutions, and by geodetic measurements (global positioning system [GPS] and very long baseline interferometry). These data suggest crustal shortening of between 5 and 9 mm/yr across the greater Los Angeles area, and extension of less than 2.5 mm/yr in the east-west direction. Crustal shortening of about 6 mm/yr occurs in the study region, but much of this is being accommodated on the Sierra Madre fault north of the SR 710 North Study Area.

The epicenter maps for the Los Angeles area show widespread seismicity throughout the region; earthquakes of M_W 4.0 and greater are shown in Figure 2-8. Although earthquakes occur near known faults, the earthquakes are difficult to directly associate with mapped faults. Part of this difficulty is because the basin is underlain by several subsurface thrust faults (blind faults).

The largest earthquakes in the region were the 1994 Northridge, the 1971 San Fernando, the 1933 Long Beach, the 1987 Whittier, and the 1988 Pasadena earthquakes (Figure 2-8). Characteristics of these earthquakes are summarized below.

- **1994 Northridge earthquake:** The 1994 Northridge earthquake had an M_W of about 6.7 (surface wave magnitude [M_S] 6.8; earthquake Richter magnitude [M_L] 6.4), and occurred on a southerly dipping subsurface fault, which was unknown prior to the earthquake. The epicenter of the event was in the center of the San Fernando Valley. The main shock occurred at a depth of about 19 km. Earthquake aftershocks clearly defined the rupture surface dipping about 35 degrees southerly from a depth of about 2 to 3 km to 23 km (Hauksson et al., 1995).
- **1971 San Fernando earthquake:** The 1971 San Fernando earthquake (M_W 6.7, M_S 6.4, M_L 6.4) was of similar size to the 1994 Northridge event but involved surface rupture. The 1971 event occurred on a northerly dipping thrust fault that dips from the northern side of the San Fernando Valley to a depth of about 15 km under the San Gabriel Mountains. Several mapped surface faults were involved such as the Sylmar, Tujunga, and Lakeview faults. These faults are commonly considered to be part of the Sierra Madre fault system, which

extends northwesterly from the north side of the San Gabriel Valley into the San Fernando Valley and easterly to the Cucamonga fault in the San Bernardino area.

- **1933 Long Beach earthquake:** Another major historical earthquake in the Los Angeles region was the 1933 Long Beach event, which had a magnitude of about M_W 6.4 (M_L 6.3). This earthquake did not rupture the surface, but is believed to have been associated with the Newport-Inglewood Structural Zone (NISZ), a major strike-slip fault in the Los Angeles Basin (Benioff, 1938). The association was based on abundant ground failures along the NISZ trend (but no unequivocal surface rupture was identified). Reevaluation of the seismicity data by Hauksson and Gross (1991) relocated the 1933 earthquake hypocenter to a depth of about 9.6 km below the Huntington Beach-Newport Beach city boundary.
- **1987 Whittier earthquake:** The 1987 Whittier earthquake (M_L 5.9, M_W 5.9) occurred on the Puente Hills Thrust fault, which is a subsurface (blind) fault dipping under the Puente Hills to about 16 km beneath the San Gabriel Basin (Shaw and Shearer, 1999). This event did not rupture the ground surface. The M5.4 aftershock had an epicenter roughly 8 km from the center of the SR 710 North Study Area and occurred on a northwest-trending strike-slip fault that correlates well with the Alhambra Wash fault.
- **1988 and 1991 Pasadena earthquakes:** Two small earthquakes occurred in the Pasadena region in 1988 and 1991. The 1988 earthquake had a magnitude of 5.0 (M_L) (M_W 4.9) and is postulated to have occurred on the Raymond fault at a depth of about 10 miles (16 km) (Jones et al., 1990). Focal-mechanism solutions indicate that this event was associated with left-lateral, strike-slip faulting. The 1991 earthquake had a magnitude of 5.8 (M_L) and occurred at a depth of about 7.5 miles (12 km) below the San Gabriel Mountains. The focal mechanism indicated pure thrust faulting. This event is believed by Hauksson (1994) to have occurred on the Clamshell-Sawpit fault splay of the Sierra Madre fault zone.

2.3.2 Seismic Ground Shaking

During an earthquake, seismic waves are produced that emanate in all directions from the fault rupture. Seismic waves can produce strong ground shaking that is typically strongest near the fault and attenuates as the waves move away from the source. The severity of ground shaking is controlled by the interaction of magnitude, distance, and the type, thickness, and condition of underlying geologic materials. Areas underlain by unconsolidated recent alluvium or artificial fill may amplify the strength and duration of strong ground motion.

The SR 710 North Study Area may be subject to seismic ground shaking at some point in the future. Preliminary seismic design parameters for the SR 710 North Study Area are presented in the Preliminary Earthquake Acceleration Response Spectra (ARS) Technical Memorandum (CH2M HILL, 2013), which is included in Appendix B of this report. The parameters were obtained from the Caltrans (2013b) ARS Web site, Version 2.2.06 (http://dap3.dot.ca.gov/ARS_Online) and the USGS (2008) ground motion model-interactive Web application (https://geohazards.usgs.gov/deaggint/2008).

2.3.3 Potential Seismic Hazards

A number of geologic hazards can result from a seismic event. These hazards range from fault-induced ground rupture to liquefaction to tsunamis and seiches. Brief descriptions of these hazards are provided in the following discussion. The risk of each of these hazards is further discussed within the hazard review for each alternative in Section 3.

- **Fault-Induced Ground Rupture:** Fault-induced ground rupture could occur where active or potentially active faults cross the alternatives. At these locations, a potential exists for permanent ground displacement along the fault during an earthquake. The nature of the rupture could be vertical movement, horizontal movement, or some combination of vertical and horizontal movement. Displacements could exceed 1 meter, depending on the length of the fault rupture and magnitude of the earthquake. The rate of displacement would be very rapid, giving little time to plan for the event. Since it is very difficult to prevent or control displacements associated with fault-induced ground rupture, at locations where a high risk of rupture is anticipated, special provisions must be taken during design of the alternative to meet seismic performance objectives relative to collapse, damage, and post-event operations. Based on this study, known active faults (Raymond fault), and potentially active faults assumed to be active (the San Rafael and Eagle Rock faults), that cross the SR 710 North Study Alternatives are shown in Figures 2-1, 2-7, 2-9, 3-1, and 3-2. The Raymond, Eagle Rock, and San Rafael faults cross the Freeway Tunnel Alternative at tunnel depth. The Raymond and San Rafael faults cross the LRT Alternative at tunnel depth, and the BRT Alternative at the surface.

- **Coseismic Deformation:** UEPBT-generated coseismic deformation has been observed along the Coyote Pass escarpment, as discussed in Section 2.2.2.2. The coseismic deformation was observed as broad-scale folding parallel to the escarpment axis. The Coyote Pass escarpment, as well as several additional less-active folds related to the UEPBT, have been mapped transecting the BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figure 2-7.
- **Liquefaction:** During strong ground-shaking, loose, saturated, cohesionless soils in the upper 50 to 75 feet bgs can experience a temporary loss of shear strength and ground deformations can occur. This phenomenon is known as liquefaction. The potential for liquefaction will depend on a combination of the density of the soil, the grain-size distribution, the depth below the ground surface, and the location of the water table. Consequences of liquefaction could include loss in bearing capacity of foundations, lateral flow or spreading of the ground, and post-earthquake settlement. Areas identified as having experienced liquefaction during historical times, or where the anticipated geological conditions indicate a potential for liquefaction, are shown in Figure 2-9.
- **Seismically Induced Landslides:** The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. Consequences could include adverse loading on structures located on or adjacent to ground that moves. Areas identified as having experienced seismically induced landslides in the past, or where the anticipated geologic conditions indicate a potential for seismically induced landslides, are shown in Figure 2-9.
- **Seismically Induced Settlement:** Loose, unsaturated granular soils also are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table within the SR 710 North Study Area. These settlements can result in total and differential settlement of soils supporting structures, roadways, and utilities. The magnitude of these settlements will depend on the type of structure, the characteristics of the soil below the structure, and the level of ground shaking. Areas most susceptible to seismically induced settlement will generally be the same as those identified as susceptible to liquefaction in Figure 2-9.
- **Seismically Induced Inundation:** Seismically induced inundation can occur when an earthquake causes catastrophic failure of a water-retaining structure such as a reservoir, dam, or levee; and subsequent flooding occurs due to the release of water from the structure. The County of Los Angeles (2012) has prepared a Dam and Reservoir Inundation Routes Map, which includes the SR 710 North Study Area. As shown in Figure 2-10, portions of the SR 710 North Study Area are located within a dam and inundation route.
- **Tsunamis and Seiches:** Tsunamis are waves typically generated offshore or within large, open bodies of water primarily during subaqueous fault rupture or a subaqueous landslide event. Seiches are waves generated within a large closed body of water, also caused either by subaqueous fault rupture or landslide events or by ground oscillations from distant earthquakes. Because of the distance between the SR 710 North Study Area and large bodies of water, the potential impact to the project due to a tsunami or seiche is negligible.

2.4 Potential Non-Seismic Geologic Hazards

Potential geologic hazards that may exist within the SR 710 North Study Area under static (gravity) loading conditions are briefly summarized below. Additional discussion of these non-seismic geologic hazards is provided with the review of each project alternative in Section 3.

- **Slope Stability:** The stability of a slope depends on the inclination, geology and geologic structure, soil and rock strength, and ground and surface water conditions within the slope. Hillside areas and the SR 710 North Study Alternatives are shown in Figure 2-1. Areas with slopes have a potential hazard from slope failures.

In addition, excavating, grading, or fill work during construction might introduce temporary slope stability hazards.

- **Ground Settlement and Collapsible Soils:** Ground settlement can occur when new loads are added to soil, or when a change in water levels results in a decrease in pore water pressures within compressible soils. Collapsible soils consist predominantly of sand- and silt- size particles arranged in a loose "honeycomb" structure. This loose structure is held together by small amounts of water-softening cementing agents, such as clay or calcium carbonate. When the soil becomes wet, these cementing agents soften and the honeycomb structure collapses and generate ground settlement. Both conditions could potentially occur within the SR 710 North Study Area.
- **Expansive Materials:** Expansive soils are clay-rich soils that swell and shrink with wetting and drying. The mineralogy and percentage of clay-sized particles present within a soil determines the potential for expansive behavior. The shrink-swell capacity of expansive soils can result in differential movement beneath foundations. Clay-rich soils are locally present within the SR 710 North Study Area. Bedrock units also can exhibit expansive properties due to the clay content within the bedrock. Potentially expansive bedrock materials anticipated in the SR 710 North Study Area include the claystone and siltstone members of the Fernando, Puente, and Topanga Formations.
- **Erosion:** Erosion occurs when rock and/or soil surfaces are exposed to weathering. Erosion is a constant ongoing process that can be successfully controlled using engineered controls. The potential for erosion varies with soil type, amount of vegetation, and slope steepness. The surficial soil types present in the SR 710 North Study Area are shown in Figure 2-11; these data were obtained from the Los Angeles County Department of Public Works (LACDPW) Hydrology Manual (LACDPW, 2006), and Web-based geographic information system (GIS) viewer (http://ladpw.org/wrd/hydrologygis/) (LACDPW, 2013). The susceptibility to erosion of the surficial soils within the SR 710 North Study Area was delineated based on the Soil Erodibility Factor, or "K-Factor" established by the USGS (1994), as shown in Figure 2-12. Results indicate that the SR 710 North Study Area is in an area of moderate erosion potential.
- **Regional Subsidence:** Regional subsidence results from the withdrawal of groundwater and/or hydrocarbons from the subsurface. As the groundwater or hydrocarbons are pumped out of the ground, the resultant voids or pores are compressed under the pressures of the soils above. Accumulation of the compression results in subsidence of the ground surface. The potential for this hazard to affect the SR 710 North Study Area is low, because groundwater withdrawal is restricted and managed; and, where performed, is compensated by reinjection of water in volumes similar to what is withdrawn.
- **Contaminated Soil and Groundwater:** Soil and groundwater contamination is addressed in the Phase I Initial Site Assessment (ISA) for the SR 710 North Study (CH2M HILL, 2014b).
- **Flooding:** The SR 710 North Study would not involve a noteworthy encroachment into the 100-year base floodplain, would not be inconsistent with existing watershed and floodplain management programs, and would not result in incompatible floodplain development (CH2M HILL, 2014c).

2.5 Mineral Resources

The SR 710 North Study Area is located within the San Gabriel Valley Production-Consumption Region (CGS, 2010). Prior to 2010, all of the lands within the San Gabriel Valley Production-Consumption Region were classified by the State of California as containing notable aggregate resources and designated as Mineral Resource Zone (MRZ)-2. MRZ-2 is defined generally as an area where notable mineral deposits are or may be present (CDMG, 1982; California Office of Mine Reclamation, 2007). However, due to urbanization of the region, the CGS in 2010 updated the mineral land classification for aggregate in the San Gabriel Valley Production-Consumption Region and reduced the MRZ-2 designations for the entire consumption region into smaller sectors (CGS, 2010). The SR 710 North Study Alternatives are not located within a currently defined MRZ, according to the CGS (2010).

SECTION 3

Geologic Setting and Geologic Hazards along Each Alternative

The geologic setting and geologic hazards along each of the five alternatives for SR 710 North Study are summarized in this section. The intent of these summaries is to identify conditions that affect the design, construction, and operation of the alternative. Generalized methods that can be taken to mitigate the geologic hazards are also identified.

The appropriate seismic design criteria for a tunnel structure will depend on whether the LRT or the Freeway Tunnel Alternative is selected for implementation. Metro Supplemental Seismic Design Criteria will be used for the LRT Alternative. It uses "Important Transit Facility" for LRT classification. Two levels of seismic event, consisting of Maximum Design Earthquake (MDE) and Operating Design Earthquake, must be considered for LRT tunnel design, in accordance with the Metro Supplemental Seismic Design Criteria, (Metro, 2013b).

For this preliminary design phase to support the environmental documentation, the Caltrans seismic design criteria for an Ordinary Nonstandard facility were used as the basis for seismic design of the Freeway Tunnel Alternative. This facility classification is equivalent to Recovery Route classification. Two levels of seismic event, consisting of Safety Evaluation Earthquake (SEE) and Functional Evaluation Earthquake, could be considered for the freeway tunnel design. Project site-specific seismic design criteria would be developed in future design phases and used for final design of the freeway tunnel. According to the Caltrans design criteria, the same seismic design criteria used for bored tunnel also could be used for the cut-and-cover tunnel section, portal structures, retaining walls, and slopes.

3.1 No Build Alternative

The generalized descriptions of the geologic setting presented in Section 2 of this report are applicable to the No Build Alternative of the SR 710 North Study. The SR 710 North Study, No Build Alternative does not include any of the improvements included in the projects Build Alternatives. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. It is possible that the construction of those improvements could result in short-term and/or permanent effects related to geology and seismicity. Those effects would be analyzed and mitigated, if needed, as each of those projects/improvements is advanced for implementation.

3.2 TSM/TDM Alternative

The TSM/TDM Alternative includes intersection and local street improvements, ITS, CMS, ATM, expanded bus service, bus service improvements, and bicycle facility improvements. In addition, one new bridge (SR 710 Connector Underpass, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16) are proposed in this alternative. The TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards. All TSM/TDM elements are included in the BRT Alternative with the exception of Improvement L-8 and the reversible lane component of Improvement L-3. All TSM/TDM elements are included in the LRT and Freeway Tunnel Alternatives with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative. A generalized discussion of the geologic setting and potential geologic hazards for the TSM/TDM Alternative is presented below.

3.2.1 Physiography and Topography

The TSM/TDM improvements are located in the northwestern portion of the Repetto Hills and western San Gabriel Valley. See Section 2.1.1 for further discussion of the physiography and topography within the SR 710 North Study Area.

3.2.2 Stratigraphy and Geologic Structure

The TSM/TDM improvements are situated primarily within alluvial soils as depicted in Figure 2-1. Areas underlain by artificial fill soils are to be anticipated locally within some of the TSM/TDM improvement limits. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present below the TSM/TDM improvements at depth. Where local street improvements, the SR 710 Connector Underpass, and the Garfield Avenue Bridge widening are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for the underlying geologic units present.

3.2.3 Groundwater and Surface Water

Groundwater levels vary widely within the SR 710 North Study Area. See Section 2.1.4 for a discussion of the groundwater conditions present within the SR 710 North Study Area. Surface water within the SR 710 North Study Area generally infiltrates into the ground, or drains by sheet flow into engineered drainage structures. No TSM/TDM improvements cross any major drainages. Where local street improvements and new or widened bridges are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for groundwater and surface water.

3.2.4 Naturally Occurring Oil and Gas

Considering the type of improvements proposed and the underlying geologic framework, the potential for naturally occurring oil or gas to be encountered during construction or operation of the TSM/TDM improvements is low.

The SR 710 Connector Underpass and Garfield Avenue Bridge Widening would be supported by deep foundations. Where anticipated, appropriate precautions would be necessary in accordance with California Department of Occupational Safety and Health (Cal/OSHA) requirements for dealing with potential naturally occurring oil and gas during construction of the deep foundations for the bridge structure supports.

3.2.5 Active Faulting

Typically, local street improvements (such as those proposed with TSM Improvement T-2) are not protected against fault-induced surface rupture. If the roadway is damaged due to fault rupture, the repairs would be minor and quickly facilitated. The two bridge improvement sites (SR 710 Connector Underpass and Garfield Avenue Bridge widening) are not transected by an active or potentially active fault.

3.2.6 Seismic Ground Shaking

The potential to experience substantial seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards for seismic ground shaking.

The effects of seismic ground shaking can be accommodated by applying geotechnical and structural design recommendations that protect structures from experiencing irreparable amounts of damage based on the anticipated seismic loads.

3.2.7 Liquefaction

As shown in Figure 2-9, a number of the TSM/TDM improvements are located within an area delineated as a Liquefaction Hazard Zone. Where local street improvements and new or widened bridges are proposed, the

TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for liquefaction.

Typically, roadway improvements at grade are not protected against liquefaction. If the roadway is damaged due to liquefaction, the repairs would be minor and quickly facilitated. At the proposed new and widened bridge locations, various methods are available to alleviate the effects of potential liquefaction, including the use of ground improvement or deep foundations.

3.2.8 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Figure 2-9, none of the TSM/TDM improvements are located within a seismically induced Landslide Hazard Zone. There are no known landslides mapped within or adjacent to the TSM/TDM Alternative improvements.

3.2.9 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table within the SR 710 North Study Area. Where local street improvements and new or widened bridges are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for seismically induced settlement.

3.2.10 Seismically Induced Inundation

One TSM/TDM improvement (Improvement I-2, located at the intersection of Eagle Rock Boulevard and York Boulevard) is located within a potential dam inundation area, as shown in Figure 2-10. The Eagle Rock Reservoir, which is located on the north side of SR 134 approximately 1,500 feet west of the SR 134/Figueroa Street interchange, would be the source of the inundation in this area. TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards for scour and water inundation. If seismically induced inundation were to occur during the design life of the improvements, it would be a very rare occurrence. The inundation would be short-lived and the effects of any resultant scour or water inundation could be easily facilitated or accounted for during design and construction.

3.2.11 Tsunamis and Seiches

The TSM/TDM improvements are not located adjacent to any large bodies of water or at elevations that could be flooded by tsunamis or seiches. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

3.2.12 Slope Stability

As shown in Figure 2-1, few of the TSM/TDM improvements are located within or adjacent to hillside areas. Aside from Improvement T-2, no other slopes will be substantially impacted by the TSM/TDM improvements. Where local street improvements and new or widened bridges are proposed on or adjacent to hillside areas, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for slope instability.

There are numerous geotechnical methods available to address a potentially unstable slope. These methods can include the construction of buttress fills or shear keys, surface or subsurface drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.2.13 Ground Settlement and Collapsible Soils

Localized areas within the SR 710 North Study Area that are underlain by alluvial soils (see Figure 2-1) may be prone to ground settlement or collapsible soils. Where local street improvements and new or widened bridges are proposed on alluvial soils, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for ground settlement and collapsible soils.

Geotechnical design recommendations for ground settlement and collapsible soils typically consist of removal and recompaction of the problematic soils, implementing ground improvements, or designing the proposed improvements to be able to withstand the anticipated settlements.

3.2.14 Expansive Materials

Clay-rich expansive soils and bedrock are present locally throughout the SR 710 North Study Area. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations. Where local street improvements and new or widened bridges are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for expansive materials.

Geotechnical design recommendations for expansive material typically consist of removal and replacement with non-expansive soils, utilizing chemical treatment, or designing the proposed improvements to be able to withstand the shrink-swell forces anticipated based on the expansion potential of the material.

3.2.15 Erosion

As shown in Figure 2-12, the surficial soils present at the TSM/TDM improvements have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with applicable Caltrans and local (city and county) standards.

Engineered controls include incorporating proper gradients on surface slopes, using drainage collection and retention devices, and implementing appropriate erosion-control measures such as silt fences, mulch, and erosion mats.

3.2.16 Regional Subsidence

The TSM/TDM improvements are located within managed groundwater basins. The basin management agencies limit rapid and/or excessive withdrawal of groundwater from the basins. As such, the potential for regional subsidence-related impacts is considered very low.

3.2.17 Soil and Groundwater Contamination

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014b).

3.3 BRT Alternative

BRT Alternative improvements include BRT trunk line arterial street and station improvements, more frequent bus service, new bus feeder services, and enhanced connecting bus services. The BRT Alternative includes the same improvements proposed for the TSM/TDM Alternative with the exception of Improvement L-8, and the reversible lane component of Improvement L-3. A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative, as well as associated generalized geotechnical design recommendations are presented in Section 3.2. The BRT Alternative improvements would be designed and constructed in accordance with applicable Metro BRT Design Criteria (Metro, 2008). A generalized discussion of the geologic setting and potential geologic hazards along the BRT Alternative as well as associated generalized geotechnical design recommendations are presented below.

3.3.1 Physiography and Topography

The BRT Alternative commences in the Los Angeles Basin, then extends north across the Repetto Hills and along the western edge of the San Gabriel Valley. Elevations along the alternative vary from 175 feet at Olympic Boulevard in East Los Angeles, to 395 feet near Sevilla Street, to 385 feet near Garvey Avenue in Monterey Park. The alternative then ascends to roughly 840 feet at its northern terminus near Green Street in Pasadena. These grade changes do not present constraints to the development, as they are consistent with grade already in use by transit systems.

3.3.2 Stratigraphy and Geologic Structure

The entire extent of the BRT Alternative is situated within alluvial soils as depicted in Figure 2-1. Areas underlain by artificial fill soils are to be anticipated locally along the alternative. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present along the alternative at depth. Where local street and/or station improvements are proposed, the BRT improvements would be designed to account for underlying geologic units in accordance with Metro BRT Design Criteria (Metro, 2008).

3.3.3 Groundwater and Surface Water

Groundwater levels for the BRT Alternative range from 20 feet bgs near the Raymond fault (near Arroyo Seco Parkway) in South Pasadena to 330 feet bgs in the vicinity of West Main Street in Alhambra (Main San Gabriel Watermaster [MSGW], 2010; Raymond Basin Management Board [RBMB], 2011; Water Replenishment District of Southern California [WRD], 2013a and 2013b; CH2M HILL, 2014a). Historically highest groundwater levels range from 20 feet bgs near the Raymond fault to 200 feet bgs between Huntington Drive and West Main Street (CDMG, 1998b, 1998d, and 1998f).

Surface water along the BRT Alternative generally infiltrates into the ground, or drains by sheet flow into engineered drainage structures. The alternative does not cross any major drainages. Where local street and/or station improvements are proposed, the BRT Alternative would be designed to account for groundwater and surface water in accordance with Metro BRT Design Criteria (Metro, 2008).

3.3.4 Naturally Occurring Oil and Gas

Considering the type of improvements proposed and the underlying geologic framework, the potential for naturally occurring oil or gas to be encountered during construction or operation of the BRT Alternative is low. Where anticipated, appropriate precautions would be necessary in accordance with Cal/OSHA requirements for dealing with potential naturally occurring oil and gas during construction of the deep foundations for the sign structure supports.

3.3.5 Active Faulting

The BRT Alternative crosses one active fault (the Raymond fault) and one potentially active fault (the San Rafael fault). Future studies should be performed to evaluate the activity of the San Rafael fault; however, for planning purposes, this fault is treated as an active fault. The very eastern end of the Coyote Pass escarpment of the UEPBT is mapped transecting the BRT Alternative in the vicinity of Brightwood Street, in Monterey Park

Typically, roadways constructed at grade are not protected against fault-induced surface rupture. If the roadway is damaged due to fault rupture, the repairs would be minor and quickly facilitated.

3.3.6 Seismic Ground Shaking

The potential to experience substantial seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. The BRT Alternative local street and/or station improvements would be designed and constructed in accordance with applicable Metro BRT Design Criteria (Metro, 2008) for seismic ground shaking.

The effects of seismic ground shaking can be accommodated by applying geotechnical and structural design recommendations that protect structures from collapse and, where appropriate, from experiencing irreparable amounts of damage based on the anticipated seismic loads.

3.3.7 Liquefaction

As shown in Figure 2-9, the BRT Alternative is not located within an area delineated as a Liquefaction Hazard Zone. However, localized deposits of liquefiable soils could be identified during future investigations. Where local street and/or station improvements are proposed, the improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for liquefaction.

Typically, roadway improvements at grade are not protected against liquefaction. If the improvements are damaged due to liquefaction, the repairs would be minor and quickly facilitated. At the BRT stations, various methods are available to alleviate the effects of potential liquefaction, including the use of ground improvement or deep foundations. Stations can also be moved to an area without liquefaction hazards.

3.3.8 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Figure 2-9, a portion of the BRT Alternative is located within a seismically induced Landslide Hazard Zone, generally between Harding Avenue and Garvey Avenue in Monterey Park. There are no known landslides mapped along or adjacent to the BRT Alternative. Where local street and/or station improvements are proposed, the BRT Alternative would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for seismically induced landslides.

3.3.9 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table along the BRT Alternative. Where local street and/or station improvements are proposed, the BRT improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for seismically induced settlement.

3.3.10 Seismically Induced Inundation

The BRT Alternative is not located within a potential dam inundation area, as shown in Figure 2-10.

3.3.11 Tsunamis and Seiches

The BRT Alternative is not located adjacent to any large bodies of water and is located at a minimum elevation of 175 feet. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

3.3.12 Slope Stability

The BRT Alternative will traverse hillside areas (see Figure 2-1). Where local street and/or station improvements are proposed on or adjacent to hillside areas, the improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for slope instability.

There are numerous geotechnical methods available to address a potentially unstable slope. These methods can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.3.13 Ground Settlement and Collapsible Soils

Local areas along the BRT Alternative that are underlain by alluvial soils (see Figure 2-1) may be prone to ground settlement or collapsible soils. Where local street and/or station improvements are proposed on alluvial soils, the improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for ground settlement and collapsible soils.

Geotechnical design recommendations for ground settlement and collapsible soils typically consist of removal and replacement of the problematic soils with structural fill, surcharging the problematic ground, implementing ground improvements, or designing the proposed improvements to be able to withstand the anticipated settlements.

3.3.14 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along the BRT Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations. Where local street and/or station improvements are proposed, the improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for expansive materials.

Geotechnical design recommendations for expansive material typically consist of removal and replacement with non-expansive soils, utilizing chemical treatment, or designing the proposed improvements to be able to withstand the shrink-swell forces anticipated based on the expansion potential of the material.

3.3.15 Erosion

As shown in Figure 2-12, the surficial soils present along the BRT Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with Metro BRT Design Criteria (Metro, 2008).

Engineered controls include incorporating proper gradients on surface slopes, using drainage collection and retention devices, and implementing appropriate erosion-control measures such as silt fences, mulch, and erosion mats.

3.3.16 Regional Subsidence

The BRT Alternative is located within managed groundwater basins. The basin management agencies limit rapid and/or excessive withdrawal of groundwater from the basins. As such, the potential for regional subsidence-related impacts is considered very low.

3.3.17 Soil and Groundwater Contamination

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014b).

3.4 LRT Alternative

The LRT Alternative includes a passenger rail operated along a dedicated guideway, similar to other Metro light rail lines, as well as a bored tunnel segment. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. Two directional tunnels are proposed with tunnel diameters approximately 20 feet each, and the crown of the tunnels located approximately 60 feet bgs along most of the tunnel. The LRT Alternative includes the same improvements proposed for the TSM/TDM Alternative with the exception of Improvements T-1. A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative is presented in Section 3.2. A generalized discussion of the geologic setting and potential geologic hazards along the LRT Alternative and the associated generalized geotechnical design recommendations are presented below.

3.4.1 Physiography and Topography

The LRT Alternative commences in the Los Angeles Basin, then extends north across the Repetto Hills and along the western edge of the San Gabriel Valley. As shown in the geologic cross section for the LRT Alternative (Figure 3-1), elevations along the alternative vary from 275 feet at SR 60, to 340 feet at Ramona Boulevard in Monterey Park, to 440 feet at Cal State LA, to 380 feet near Hellman Avenue. The topography then ascends to an approximate elevation of 780 feet at the northern terminus of the alternative near California Boulevard in Pasadena.

An LACDPW detention basin is present immediately west of the intersection of Corporate Center Drive and Corporate Place (approximate Station 66+00, shown in Figure 3-1). This basin is bounded by the I-710 mainline embankment on the northwest; parking lots and local streets surround the remainder of the basin. The eastern basin embankment is on the order of 30 to 40 feet high and has slopes generally inclined at 1.5:1 to 2:1 (horizontal to vertical [H:V]). This channel is mapped as alluvial soil (Figure 2-1); however, artificial fill soils likely compose the upper portion of the basin embankment.

Natural and human-made slopes are present along the LRT Alternative. In the area of the Blanchard Landfill (located on the west side of I-710, north of the LRT crossover of I-710), the slopes range in height from

40 to 230 feet and are generally inclined at 1.5:1 to 2:1 (H:V). In the area of Cal State LA, slopes up to 100 feet tall are present, generally inclined at 1.5:1 to 2:1 (H:V). Blanchard Landfill, Cal State LA (athletic fields and building structures), and commercial developments are situated atop the natural and human-made slopes in these areas.

3.4.2 Stratigraphy and Geologic Structure

As shown in Figure 3-1, the LRT Alternative is underlain by a variety of geologic units including artificial fill soils; alluvial soils; sedimentary bedrock of the Fernando, Puente, and Topanga Formations; and Wilson Quartz Diorite igneous and metamorphic bedrock. Routine design and construction methods can be used where the LRT Alternative is supported either at grade or on elevated structures. However, for tunneled sections of the LRT Alternative, special design and construction considerations would be required to successfully tunnel through alluvial soils and the various bedrock units, as summarized below.

3.4.2.1 Artificial Fill Soils

Artificial fill soils are present at the surface along portions of the LRT Alternative. Where encountered, the fills were generally observed to be fine-grained with some coarse-grained constituents. Cross sectional limits of the larger fills present along the alternative are shown in Figure 3-1. Along the alternative, the fill soils range in thickness from 10 to 40 feet between Floral Drive and I-710, in the vicinity of the I-710 and I-10 interchange, and in the vicinity of Valley Boulevard. In addition, local fills are to be expected at the surface throughout the alternative, and are related to the existing improvements.

3.4.2.2 Alluvial Soils

Alluvial soils are present within the Los Angeles Basin and San Gabriel Valley portions of the LRT Alternative, as well as within local drainages within the Repetto Hills. The alluvial soils are either present at the surface, or buried beneath artificial fill soils. The alluvial soils are described in Section 2.1.2 of this report. Cross sectional limits of the alluvial soils along the alternative are shown in Figure 3-1. The alluvial soil thickness is quite variable along the alternative, ranging from roughly 200 feet near the southern terminus, to 50 feet in the vicinity of Valley Boulevard, to 220 feet at the northern terminus. From a geologic perspective, the alluvial soils are unconsolidated in the sense that they lack cementation associated with rock formations.

Unconsolidated and/or water-saturated alluvial soil deposits would likely be encountered in excavations for the portal, the Alhambra Station, and along segments of the LRT tunnel. Open excavation and tunneling in unconsolidated and/or saturated alluvium have the potential for high groundwater inflows and flowing ground conditions at the heading of the excavation, which could result in loss of ground and settlement of the ground surface. Groundwater inflows are also anticipated in the fractured/sheared rock and adjacent to fault zones, which may act as groundwater barriers. During construction, excavation of a tunnel using a pressurized-face tunnel boring machine (TBM) would actively control groundwater inflows at the tunnel heading. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

Tunneling methods are available to handle saturated alluvium conditions. Pressure face TBMs generally utilize either earth-pressure balance (EPB) or slurry methods to provide active face control to limit ground loss while excavating. Such machines have been used successfully on previous tunneling projects in Los Angeles, and this technology could be applied to the LRT Alternative. To limit ground loss, the construction contractor could be required to use a pressurized-face TBM, have a robust excavated material monitoring system, and employ a grouting system along the shield of the TBM. While a pressurized face TBM would likely be required for the project, evaluation of whether it can or will be used in open mode would be evaluated in the future. Comprehensive, real-time monitoring with geotechnical-tunnel data management software and implementation of observational approach to construction management would be implemented during construction of the LRT Alternative tunnel.

3.4.2.3 Bedrock Units

Bedrock is present either at the surface or below the artificial fill and/or alluvial soils along the LRT Alternative. The bedrock units include sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite. These bedrock units are described in Section 2.1.2. Cross sectional limits and the distribution of the bedrock units present along the alternative are shown in Figure 3-1.

Bedrock types along the alternative are summarized as follows:

- Fernando Formation bedrock from the southern terminus to the I-710/I-10 interchange
- Puente Formation from the interchange north to near Meridian Avenue in Alhambra
- Fernando Formation continuing north to roughly Commonwealth Avenue
- Puente Formation from north of Commonwealth Avenue to near Main Street
- Topanga Formation from Main Street to the San Rafael fault (near Glenarm Street) in Pasadena
- Wilson Quartz Diorite north of the San Rafael fault

Some inherent variability exists between the sedimentary formations present along the alternative, including occasional hard to very hard cemented layers and concretions, and the presence of cobbles. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for the variable geologic units anticipated along the alternative.

The generalized geologic structure within the sedimentary units along the alternative is shown in Figure 3-1. Variations from the conditions shown in Figure 3-1 should be expected. Numerous intra-formational faults are present within the SR 710 North Study Area as shown in Figure 2-1. These faults formed as a result of the past tectonic regime and are considered to be inactive. See Section 3.4.5 for a discussion of the active faults present along the LRT Alternative.

The structure within the Fernando, Puente, and Topanga Formations will be variable, ranging from massively bedded to laminated. In addition, numerous intra-formational faults and fractures are present locally within these units. These sedimentary units are expected to require immediate support in the tunnel excavations proposed for this alternative, which could be provided by the TBM and a precast concrete segmental lining system.

Tunnel excavation for the LRT Alternative would be through several different geologic units. The tunnel excavation methods would need to address a range of geologic conditions including alluvium (soil) and weak sedimentary rocks. This would require the use of tunneling equipment adaptable to the variable range of rock characteristics anticipated, such as rock hardness, tunnel face stability, and muck characteristics or a flexible approach that allows methods to be changed to suit the geology.

Regardless of the excavation methods, special provisions will be necessary to address the inherent variability of the Puente and Topanga Formations, such as the cemented layers and concretions, the variability between conglomerate, sandstone, siltstone, claystone, mudstone, and shale, and potential fault gouge. These layers would be considered in the design of tunnel excavation equipment. TBMs can be designed to handle this wide range of ground conditions. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for the structure of the geologic units along the alternative.

3.4.3 Groundwater and Surface Water

Historically highest groundwater levels (CDMG, 1998b, 1998d, and 1998f) along the LRT Alternative range from 40 feet bgs near the Raymond fault in South Pasadena to 200 feet bgs near West Main Street in Alhambra and near Caesar Chavez Avenue in Monterey Park.

The estimated depth to groundwater along the LRT Alternative is shown in Figure 3-1. Groundwater is shallowest south of Valley Boulevard where measurements as shallow as 10 feet bgs were observed. The deepest groundwater levels are on the order of 160 feet bgs at the southern terminus of the project and immediately south of the Raymond fault.

The bedrock units along the LRT Alternative generally do not contain substantial amounts of groundwater. However, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are substantially higher than the levels on the south side of the fault. In addition, the potentially active San Rafael fault and inactive faults may act as groundwater barriers. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

The groundwater levels modeled during this evaluation are based on review of existing information (MSGW, 2010; RBMB, 2011; WRD, 2013a and 2013b), and the groundwater levels documented during the previous and current studies in the SR 710 North Study Area.

Groundwater inflows could occur while tunneling below the groundwater table, especially in the saturated alluvium. This inflow would be actively controlled during construction of a tunnel utilizing a pressurized-face TBM to limit groundwater infiltration at the tunnel heading. To ensure that water flows are controlled behind the TBM, a relatively watertight support system would be required, such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system. To prevent or minimize water inflows into the tunnel during construction, supplemental grouting operations may be used in conjunction with the precast concrete segmental lining system. The precast concrete segmental lining system typically has double rubber gaskets, with appropriate cross gaskets, to control both water and gas inflows in the temporary and permanent condition. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for groundwater inflows during tunneling.

Groundwater inflows also could occur during construction of the portal for launching the TBM and at the Alhambra Station, where construction may occur below the groundwater table. The groundwater table at the site of the three other underground stations is deeper than the base slab level of the stations, based on the available information. The portal area and Alhambra Station may be temporarily dewatered prior to excavation to facilitate construction if the excavation support system is not watertight (such as the proposed soldier piles and lagging systems). The dewatering or the excavation wall system would be designed such that the surrounding groundwater table would experience minimal, temporary drawdown. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for groundwater inflows at deep excavation.

Surface water along the LRT Alternative generally either infiltrates into the ground, or drains by sheet flow into engineered drainage structures. The alternative does not cross any major drainages. Temporary lowering of the water table in alluvial areas due to potential dewatering from construction or O&M activities associated with the LRT Alternative should not affect the surface water features because groundwater is below the bottom of the local and regional surface water features.

3.4.4 Naturally Occurring Oil and Gas

As shown in Figure 3-1, a portion of the tunnel segment of the LRT Alternative is anticipated to be constructed within Puente Formation bedrock. There is a low to moderate potential of encountering naturally occurring oil and/or gas, most likely within the Puente Formation along the tunnel segment of the LRT Alternative. Naturally occurring oil and/or gas could also be found within any of the geologic formations within the SR 710 North Study Area. If encountered, the tunnel could be classified by Cal/OSHA as a "Gassy or Potentially Gassy Operation," and, if so designated, compliance with Cal/OSHA guidelines for tunneling in gassy conditions would be required.

The presence of naturally occurring oil and gas is not unusual, especially in the Los Angeles region, and special tunneling equipment, air monitoring, ventilation methods, and safety procedures have been developed to allow tunnel construction in a safe manner. These techniques have been successfully applied to numerous subterranean projects completed in the Los Angeles region. Between I-10 and the portal area south of Valley Boulevard, the LRT Alternative elevated guideway drilled shafts would be founded in Puente Formation bedrock. The potential for encountering natural gas during construction of the drilled shafts for this structure is considered low to moderate. To adequately characterize the potential to encounter naturally occurring oil and gas along the LRT Alternative, detailed geotechnical investigations would be conducted during final design. Where anticipated, appropriate precautions would be implemented in accordance with Cal/OSHA requirements for naturally occurring gases.

3.4.5 Active Faulting

As shown in Figure 2-1, the tunneled section of the LRT Alternative crosses one active fault (the Raymond fault) and one potentially active fault (the San Rafael fault). The LRT Alternative does not cross the Eagle Rock fault. Future studies should be performed to evaluate the activity of the San Rafael fault; however, for planning purposes, this fault is treated as an active fault.

The invert of the LRT tunnel in the vicinity of these faults would be located roughly 70 to 100 feet bgs. Preliminary fault rupture displacement estimates have been prepared for the LRT Alternative, as summarized in the Fault Rupture Evaluation Technical Memorandum (see Appendix A). Results of the fault evaluation suggest that the magnitude and zone of fault movement for each of the faults are as follows, based on Metro MDE criteria:

- A left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter are estimated for the design of the tunnel at the Raymond fault across a fault zone 25 meters in width.
- A left-lateral offset of 0.5 meter and a reverse-vertical offset of 0.25 meter are estimated for the design of the tunnel at the San Rafael fault across a fault zone 50 meters in width.

These potential offsets require special design features that would allow the tunnel lining to accommodate the anticipated ground displacement. For small displacements, a flexible lining system could be designed for the fault zone. A special lining could consist of segments with shorter segmented lining elements that would better accommodate flexibility than standard segments (Federal Highway Administration [FHWA], 2009). An advantage of using a special lining in the fault zone is that the tunnel would not have to be modified to accommodate the fault displacements; however, this method is not practical for fault displacements in excess of about 0.15 to 0.30 meter, depending on the fault geometry, tunnel size, and tunnel lining details.

For fault displacements (greater than 0.15 to 0.30 meter), such as those anticipated for the Raymond and San Rafael faults, it is possible to construct an oversized tunnel, or vault, for the portion of the tunnel in the fault zone and for areas susceptible to ground rupture (FHWA, 2009). This approach has been used successfully for several other tunnel projects. For this concept, the portion of the tunnel in the fault zone is enlarged to form a vault outside the design lines of the tunnel and backfilled with crushable materials. This vault is large enough to accommodate the movement of the fault. This method, utilizing a robust lining system has been recommended as the preliminary design concept for the LRT Alternative fault crossings (Jacobs Associates and CH2M HILL, 2014).

As discussed in Section 2.2.2.2, the UEPBT-generated Coyote Pass escarpment transects the elevated portion of the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in Monterey Park (Figure 2-7). The Coyote Pass escarpment is considered the primary concern with regard to potential coseismic deformation during an earthquake on the UEPBT. Additional study of the Coyote Pass escarpment would provide estimates of the amount of coseismic deformation anticipated where this feature crosses the LRT Alternative. Potential ground movements along the elevated segment of the LRT Alternative would have to be taken into consideration during design. This would include evaluating the locations of the guideway supports, and the amount of differential displacement that could be tolerated along the guideway structure.

3.4.6 Seismic Ground Shaking

The potential to experience substantial seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. Details as to the levels of ground shaking estimated along the LRT Alternative are presented in the Preliminary Earthquake ARS Technical Memorandum (see Appendix B).

As detailed in the ARS technical memorandum, the calculated peak ground accelerations (PGAs) for a return period of 2,500 years range from 0.90g to 1.18g along the LRT Alternative (g = acceleration due to gravity). Design and construction of the LRT Alternative would follow Metro Rail Design Criteria (Metro, 2013a) for seismic shaking.

Experience in California and worldwide shows that bored tunnels generally perform well during earthquake ground shaking, typically suffering less damage than surface structures. Because they are embedded in the ground, they move with the ground, and thus, their motion is not magnified by the pendulum effect that occurs when an above-ground structure is shaken by an earthquake (Hashash et al., 2001). The effects of seismic ground shaking can be accommodated by applying geotechnical and structural design recommendations that protect structures from experiencing irreparable amounts of damage based on the anticipated seismic loads.

3.4.7 Liquefaction

As shown in Figure 2-9, the LRT Alternative, primarily in the vicinity of I-10 and west of Corporate Place, is located within a Liquefaction Hazard Zone. If warranted based on future studies, key features of this alternative (above ground or bored tunnel,) would be designed for liquefaction and its associated hazards. Design and construction of the LRT Alternative would follow Metro Rail Design Criteria (Metro, 2013a) for liquefaction.

The occurrence of liquefaction could lead to loss of foundation support, reduction in lateral support of deep foundations, flow and lateral spreading, and liquefaction-induced settlement. Where these mechanisms could result in unacceptable soil or structural response, ground improvements such as dynamic compaction, stone columns, jet grouting, cement deep soil mixing (CDSM), and compaction grouting, among others, would reduce the potential for liquefaction.

3.4.8 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Figure 2-9, the LRT Alternative, generally from Corporate Place north to I-10, is located within a seismically induced Landslide Hazard Zone. However, there are no known landslides mapped along or adjacent to the LRT Alternative. The above ground segments of the LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for potential landslides.

If seismically induced slope stability issues are identified outside the bored tunnel limits of the LRT Alternative, there are numerous geotechnical methods available to address this hazard. This can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.4.9 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table in areas outside the bored tunnel limits of the LRT Alternative. The settlement issue could be critical at the portal for the tunnel and ground densification could be used to address settlement concerns. These improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for seismically induced settlement.

3.4.10 Seismically Induced Inundation

The LRT Alternative in the immediate vicinity of I-10 is located within a potential dam inundation area as shown in Figure 2-10. The inundation zone identified is related to seismically induced failure of the Laguna Regulating Basin.

The Laguna Regulating Basin is an ungated basin (CH2M HILL, 2014d) intended to collect sediment from runoff entering the basin. The LACDPW has no record of the Laguna Regulating Basin ever being filled to capacity since its construction in 1967 (CH2M HILL, 2014d). During the rare occurrences where inflow exceeds outflow within the basin, the amount of time the runoff would be pooled within the basin would be limited because the basin is allowed to run off freely.

If the Laguna Regulating Basin was to be filled and a seismic event caused failure of the basin, the inundation would be short-lived. This portion of the LRT Alternative would be elevated approximately 80 feet above existing grade (see Figure 3-1) and supported on bridge piers. Potential scour of the ground surface around structural elements such as bridge foundations would be addressed via applicable Metro design standards for scour.

The LRT portal is located over 4,500 feet north of the identified inundation zone, and is situated more than 50 feet higher than the top of the Laguna Regulating Basin embankment. As such, the potential for seismically induced inundation from the Laguna Regulating Basin to affect the tunnel portion of the LRT Alternative is very low.

3.4.11 Tsunamis and Seiches

The LRT Alternative is not located adjacent to any large bodies of water. The alternative is located at a minimum elevation of 275 feet. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

3.4.12 Slope Stability

The LRT Alternative traverses hillside areas (see Figure 2-1). In areas where improvements may affect existing slopes and/or developments atop existing slopes, detailed evaluations of the geologic units and geologic structure of these slopes would be conducted. These evaluations would yield the appropriate data required to conduct analyses and provide the geotechnical recommendations needed for the design and construction of the proposed hillside improvements. The portions of the LRT Alternative that are located outside the bored tunnel and are proposed on or adjacent to hillside areas would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for slope instability.

There are numerous geotechnical methods available to address a potentially unstable slope. These methods can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.4.13 Ground Settlement and Collapsible Soils

Local areas along the LRT Alternative that are underlain by alluvial soils (see Figure 2-1) may be prone to ground settlement or collapsible soils. Where improvements are proposed on alluvial soils, the improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for ground settlement and collapsible soils.

Ground settlement can also occur as a result of ground loss during deep excavations, such as tunneling. Construction of a tunnel utilizing a pressurized-face TBM would actively control ground loss at the tunnel heading during construction. In addition, systematic ground improvement measures on a localized basis could be implemented, including a combination of dewatering, permeation grouting, or jet grouting to stabilize the deposits and reduce the loss of ground.

Detrimental ground settlement from new structures or earth loads can be alleviated by removal and replacement of the settlement- or collapse-prone soils, ground improvement measures, and structural support systems.

3.4.14 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along some of the surficial improvement areas and portions of the bored tunnel of the LRT Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations.

Where expansive materials are identified, the improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for expansive materials.

Geotechnical design recommendations for expansive material typically consist of removal and replacement with non-expansive soils, utilizing chemical treatment, or designing the proposed improvements to be able to withstand the shrink-swell forces anticipated based on the expansion potential of the material.

3.4.15 Erosion

As shown in Figure 2-12, the surficial soils present along the LRT Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with Metro Rail Design Criteria (Metro, 2013a).

Engineered controls include incorporating proper gradients on surface slopes, using drainage collection and retention devices, and implementing appropriate erosion-control measures such as silt fences, mulch, and erosion mats.

3.4.16 Regional Subsidence

The LRT Alternative is located within managed groundwater basins. The basin management agencies limit rapid and/or excessive withdrawal of groundwater from the basins. As such, the potential for regional subsidence-related impacts is considered very low.

3.4.17 Soil and Groundwater Contamination

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014b).

3.5 Freeway Tunnel Alternative

The Freeway Tunnel Alternative consists of either a single- or dual-bore tunnel approximately 4.2 miles in length. Each bored tunnel would have an outside diameter of approximately 58.5 feet; the crown of each tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. Short segments of cut-and-cover tunnels would be located at the southern and northern termini to provide access via portals to the bored tunnels. The portal at the southern terminus would be located south of Valley Boulevard. The portal at the northern terminus would be located north of Del Mar Boulevard. Both tunnel design variations include roadway improvements outside the north and south portal areas. Some of the Freeway Tunnel improvements will require specialty engineering and construction techniques in order to comply with the *Technical Manual for Design and Construction of Road Tunnels - Civil Elements* (FHWA, 2009), *AASHTO LRFD Bridge Design Specifications* (American Association of State Highway and Transportation Officials [AASHTO], 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014). The Freeway Tunnel Alternative would include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvements T-1 and T-3. A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative and associated preliminary design recommendations are presented in Section 3-2. A generalized discussion of the geologic setting and potential geologic hazards along the Freeway Tunnel Alternative and associated generalized geotechnical design recommendations are presented below.

3.5.1 Physiography and Topography

The Freeway Tunnel Alternative is primarily located along the western edge of the San Gabriel Valley; a small portion of the alternative is located within the Repetto Hills (generally between Moffatt Street and Lyndon Street in South Pasadena). As shown in the geologic cross section for the Freeway Tunnel Alternative (Figure 3-2), elevations along the alternative vary from 345 feet at I-10, to 545 feet at Newtonia Drive in Los Angeles, to 740 feet near Flores De Oro within the Repetto Hills, to 650 feet near Monterey Road in South Pasadena. The topography along the alternative then ascends to an approximate elevation of 800 feet at the northern terminus of the alternative near Del Mar Boulevard in Pasadena.

3.5.2 Stratigraphy and Geologic Structure

As shown in Figure 3-2, the Freeway Tunnel Alternative is underlain by a variety of geologic units including artificial fill soils; alluvial soils; sedimentary bedrock of the Fernando, Puente, and Topanga Formations; and Wilson Quartz Diorite igneous and metamorphic bedrock.

3.5.2.1 Artificial Fill Soils

Artificial fill soils are present at the surface along portions of the Freeway Tunnel Alternative. Where encountered, the fills were generally observed to be fine-grained with some coarse-grained constituents. Cross sectional limits of the larger fills present along the alternative are shown in Figure 3-2. Along this alternative, the fill soils range in thickness from 10 to 40 feet in the vicinity of the I-710 and I-10 interchange, and in the vicinity of

Valley Boulevard. In addition, local fills are to be expected at the surface throughout the alternative, and are related to the existing improvements.

3.5.2.2 Alluvial Soils

Alluvial soils are present at the surface along the San Gabriel Valley portions of the Freeway Tunnel Alternative, as well as in local drainages within the Repetto Hills. The alluvial soils are either present at the surface, or overlain by artificial fill soils. The alluvial soils are described in Section 2.1.2. Cross sectional limits of the alluvial soils along the alternative are shown in Figure 3-2. The alluvial soil thickness is quite variable along the alternative, ranging from roughly 40 feet in the vicinity of Valley Boulevard, to 280 feet thick near Arroyo Seco Parkway (SR 110) in South Pasadena, to 200 feet at the northern terminus near Green Street in Pasadena.

Like the LRT Alternative, unconsolidated and/or water-saturated alluvial soil deposits would likely be encountered in excavations for the portals and along segments of the tunnel for the Freeway Tunnel Alternative. Open excavation and tunneling in unconsolidated and/or saturated alluvium have the potential for high groundwater inflows and flowing ground conditions at the heading of the excavation, which could result in loss of ground and settlement of the ground surface. Groundwater inflows also are anticipated in the fractured/sheared rock and adjacent to fault zones, which may act as groundwater barriers. During construction, excavation of a tunnel using a pressurized-face TBM would actively control groundwater inflows at the tunnel heading. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault. Pressurized-face TBMs generally utilize either EPB or slurry methods to provide active face control to limit ground loss while excavating. Such machines have been used successfully on previous tunneling projects in Los Angeles, and this technology could be applied to the Freeway Tunnel Alternative. To limit ground loss, the construction contractor could be required to use a pressurized-face TBM, have a robust excavated material monitoring system, and employ a grouting system along the shield of the TBM. While a pressurized face TBM would likely be required for the project, evaluation of whether it can or will be used in open mode would be evaluated in the future. Comprehensive real time monitoring with geotechnical-tunnel data management software and implementation of observational approach to construction management would be implemented during construction of the Freeway Tunnel Alternative tunnel. Design and construction of the Freeway Tunnel Alternative would follow the FHWA Technical Manual (FHWA, 2009) for tunneling and deep excavations in unconsolidated sediments.

3.5.2.3 Bedrock Units

Bedrock is present either at the surface or buried beneath artificial fill and/or alluvial soils along the Freeway Tunnel Alternative. The bedrock units include sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite. These bedrock units are described in Section 2.1.2. Cross sectional limits and distribution of the bedrock present along the alternative are shown in Figure 3-2 and summarized below:

- Puente Formation bedrock from the I-710/I-10 interchange north to near Norwich Avenue in Los Angeles
- Fernando Formation from Norwich Avenue north to near Huntington Drive
- Puente Formation continuing north to roughly Newtonia Drive in South Pasadena
- Topanga Formation from Newtonia Drive north to near Lyndon Street
- Wilson Quartz Diorite from Lyndon Street north to the Raymond fault (near Arroyo Seco Parkway [SR 110] in South Pasadena)
- Topanga Formation between the Raymond fault and San Rafael fault (near Hurlbut Street in Pasadena)
- Wilson Quartz Diorite from the San Rafael fault north to the northern terminus of the project near Green Street in Pasadena

Some inherent variability exists between the sedimentary formations present along the Freeway Tunnel Alternative, including occasional hard to very hard cemented layers and concretions, and the presence of cobbles.

Although the rocks of the Wilson Quartz Diorite unit are generally moderately hard to hard, they are highly fractured. The highly fractured nature of the Wilson Quartz Diorite, as observed within the SR 710 North Study Area, yields a rock mass that is generally hard but readily friable. These units may require immediate support in the tunnel excavations proposed for the Freeway Alternative, which could be provided by the TBM and a precast concrete segmental lining system. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), accounting for the variable geologic units anticipated along the alternative.

The generalized geologic structure within the sedimentary units along the alternative is shown in Figure 3-2. Variations from the conditions shown in Figure 3-2 should be expected. Numerous intra-formational faults are present within the SR 710 North Study Area as shown in Figure 2-1. These faults formed as a result of the past tectonic regime and are considered to be inactive. See Section 3.5.5 for a discussion of the active faults present along the Freeway Tunnel Alternative.

The structure within the Fernando, Puente, and Topanga Formations will be variable, ranging from massively bedded to laminated. In addition, numerous intra-formational faults and fractures are present locally within these units. These sedimentary units are expected to require immediate support in the tunnel excavations proposed for this alternative.

Tunnel excavation for the Freeway Tunnel Alternative would be through several different geologic units. The tunnel excavation methods would need to address a range of geologic conditions including alluvium (soil), weak sedimentary rocks, and stronger granitic-type rocks. This would require the use of tunneling equipment adaptable to a range of formation hardness, face stability, and muck characteristics or a flexible approach that allowed methods to be changed to suit the geology. TBMs can be designed to handle this wide range of ground conditions.

Tunneling machines are available for this wide range of ground conditions, including convertible TBMs that can be operated in open mode (for rock) or in closed mode (for soil or other unstable ground conditions).

Regardless of the excavation methods, special provisions will be necessary to address the inherent variability of the Wilson Quartz Diorite, Puente and Topanga Formations, such as the structural variability between stronger granitic-type rocks and weaker sedimentary rocks, and potential fault gouge. This variability would be considered in the design of tunnel excavation equipment. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), accounting for the structure of the geologic units along the alternative.

The tunnel portal sections of the Freeway Tunnel Alternative also would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), accounting for the various geologic units at the portal support locations.

3.5.3 Groundwater and Surface Water

Historically highest groundwater levels (CDMG, 1998b, 1998d, and 1998f) along the Freeway Tunnel Alternative range from 50 feet bgs near the Raymond fault in South Pasadena to 200 feet bgs near Huntington Drive in Los Angeles.

The estimated depth to groundwater along the Freeway Tunnel Alternative is shown in Figure 3-2. Groundwater is shallowest south of Valley Boulevard where measurements as shallow as 10 feet bgs were observed. The deepest groundwater levels are on the order of 250 feet bgs at the northern terminus of the alternative near SR 134 in Pasadena.

The bedrock units within the Freeway Tunnel Alternative generally do not contain substantial amounts of groundwater. However, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are substantially higher than the levels on the south side of the fault. In addition, the potentially active (Eagle Rock and San Rafael) faults and inactive faults may also act as groundwater barriers. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

The groundwater levels modeled during this evaluation are based on review of existing information (MSGW, 2010; RBMB, 2011; WRD, 2013a and 2013b), and the groundwater levels documented during the previous and current studies in the SR 710 North Study Area.

Groundwater inflows could occur while tunneling below the groundwater table, especially in the saturated alluvium. This inflow could be controlled during tunnel construction utilizing a pressurized-face TBM that would limit groundwater infiltration at the tunnel heading. To ensure that water flows are controlled behind the TBM, a relatively watertight support system would be required, such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system. To prevent or minimize water inflows into the tunnel during construction, supplemental grouting operations may be used in conjunction with the precast reinforced-concrete lining system. The precast concrete segmental lining system typically has double rubber gaskets, with appropriate cross gaskets, to control both water and gas inflows in the temporary and permanent condition. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), accounting for groundwater inflows during tunneling.

Groundwater inflows also could occur during construction of the south portal for launching the TBM where excavation will likely occur below the groundwater table. The excavation support for the south portal could be designed to be watertight, or alternatively, dewatering could be used to lower the groundwater table temporarily. The dewatering or the excavation wall system would be designed such that the surrounding groundwater table would experience minimal, temporary drawdown. Because of the relatively deep groundwater elevations compared to the depth of the bottom of the tunnel, groundwater control does not appear to be an issue for tunnel construction at the north portal. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), accounting for groundwater inflows at deep excavation.

Surface water along the Freeway Tunnel Alternative generally either infiltrates into the ground or drains by sheet flow into engineered drainage structures. The alternative does not cross any major drainages. Temporary lowering of the water table in alluvial areas due to potential dewatering from construction or O&M activities associated with the Freeway Tunnel Alternative would not affect the surface water features because groundwater is below the bottom of the local and regional surface water features.

3.5.4 Naturally Occurring Oil and Gas

As shown in Figure 3-2, a portion of the Freeway Tunnel Alternative bored tunnel is anticipated to be constructed within Puente Formation bedrock. There is a low to moderate potential of encountering naturally occurring oil and/or gas most likely within the Puente Formation along the subterranean portion of the Freeway Tunnel Alternative. Naturally occurring oil and/or gas could also be found within any of the geologic formations within the SR 710 North Study Area. If naturally occurring oil and/or gas is encountered, the tunnel could be classified by Cal/OSHA as a “Gassy or Potentially Gassy Operation,” and, if so designated, compliance with Cal/OSHA guidelines for tunneling in gassy conditions would be required.

The presence of naturally occurring oil and gas is not unusual, especially in the Los Angeles region, and special tunneling equipment, air monitoring, ventilation methods, and safety procedures have been developed to allow tunnel construction in a safe manner. These techniques have been successfully applied to numerous subterranean projects completed in the Los Angeles region.

Some of the Freeway Tunnel Alternative improvements that are located outside the bored tunnel limits would be founded in Puente Formation bedrock. The improvements are generally located between I-10 and Valley Boulevard and include the south cut-and-cover tunnel structure, Hellman Avenue bridge replacement, and the Route 710/10 Separation widening. The potential for encountering natural gas during construction of the drilled shafts for these structures is considered low to moderate. To adequately characterize the potential to encounter naturally occurring oil and gas along the at grade portion of the Freeway Tunnel Alternative, detailed geotechnical investigations would be conducted during the final design. Where anticipated, appropriate precautions could be implemented in accordance with Cal/OSHA requirements for naturally occurring gases.

3.5.5 Active Faulting

The tunneled section of the Freeway Tunnel Alternative crosses one active fault (the Raymond fault) and two potentially active faults (the Eagle Rock and San Rafael faults). Future studies may reveal that the Eagle Rock and San Rafael faults are inactive; however, for planning purposes, these two faults are treated as active faults.

The invert of the tunnel for the Freeway Tunnel Alternative in the vicinity of these faults would be located roughly 160 to 230 feet bgs. Based on Caltrans design guidelines (Caltrans, 2013c), preliminary fault rupture displacement estimates have been prepared for the Freeway Tunnel Alternative as summarized in the Fault Rupture Evaluation Technical Memorandum (see Appendix A). Results of the fault evaluation suggest that the magnitude and distribution of fault displacement for each fault are as follows, based on Caltrans SEE criteria:

- A left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter are estimated for the design of the tunnel at the Raymond fault across a fault zone 25 meters in width.
- A left-lateral offset of 0.5 meter and a vertical reverse offset of 0.25 meter are estimated for the design of the tunnel at the San Rafael and Eagle Rock faults across a fault zone 50 meters in width.

These potential offsets require design features that would allow the tunnel lining to accommodate the anticipated ground displacement. For fault displacements such as those anticipated for the Raymond, Eagle Rock, and San Rafael faults, it is possible to construct an oversized tunnel, or vault, for the portion of the tunnel in the fault zone and for areas susceptible to ground rupture (FHWA, 2009). This approach has been used successfully for several other tunnel projects. For this concept, the portion of the tunnel in the fault zone is enlarged to form a vault outside the design lines of the tunnel and backfilled with crushable materials. This vault is large enough to accommodate the movement of the fault and can be excavated to allow repair and realignment of the tunnel lining. This method was initially considered for the freeway tunnel conceptual vault section. However, the size of the excavation and the anticipated ground conditions in and around the faults raised constructability issues as well as risk, cost, and schedule implications while performing the oversized excavation work. Therefore, other approaches were evaluated. Subsequently, a vault section utilizing steel, segmental lining was determined to be more cost effective and less risky than an oversized vault excavation. This approach is feasible because the magnitude of design fault offsets is relatively small compared to the thickness of the precast concrete segmental lining system and therefore recommended as the preliminary design concept for the Freeway Tunnel Alternative fault crossings (Jacobs Associates and CH2M HILL, 2014).

The UEPBT-generated Coyote Pass escarpment transects the Freeway Tunnel Alternative roughly 700 feet north of Floral Drive, near the southern end of the alternative south of I-10 (Figure 2-7). No improvements associated with the Freeway Tunnel Alternative single-bore option are proposed south of I-10. The improvements related to the dual-bore option would be limited to above ground improvements such as striping. As such, the potential movements along the Coyote Pass escarpment would have very low effect on the improvements proposed within the Freeway Tunnel Alternative.

3.5.6 Seismic Ground Shaking

The potential to experience substantial seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. Details as to the levels of ground shaking estimated along the Freeway Tunnel Alternative are presented in the Preliminary Earthquake ARS Technical Memorandum (see Appendix B).

As detailed in the ARS technical memorandum, the calculated PGAs for a return period of 1,000 years range from 0.75g to 0.84g along the Freeway Tunnel Alternative. Design and construction of the Freeway Tunnel Alternative would follow the FHWA Technical Manual (FHWA, 2009), *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for seismic shaking.

Experience in California and worldwide shows that bored tunnels generally perform well during earthquake ground shaking, typically suffering less damage than surface structures. Because they are embedded in the ground, they move with the ground, and thus, their motion is not magnified by the pendulum effect that occurs when an above-ground structure is shaken by an earthquake (Hashash et al., 2001). The effects of seismic ground shaking can be accommodated by applying geotechnical and structural design recommendations that protect structures from experiencing irreparable amounts of damage based on the anticipated seismic loads.

3.5.7 Liquefaction

As shown in Figure 2-9, a portion of the at-grade segment of the Freeway Tunnel Alternative, generally south of I-10, is located within a Liquefaction Hazard Zone. If needed based on future geotechnical studies, key features of the surface improvements along this alternative would be designed for liquefaction and its associated hazards. Design and construction of the Freeway Tunnel Alternative would follow the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for liquefaction.

The occurrence of liquefaction could lead to loss of foundation support, reduction in lateral support of deep foundations, flow and lateral spreading, and liquefaction-induced settlement. These issues could be critical at the portals for the tunnel. Where these mechanisms could result in unacceptable soil or structural response, ground improvements such as dynamic compaction, stone columns, jet grouting, CDSM, and compaction grouting, among others, would reduce the potential for liquefaction. The liquefaction potential beneath the Freeway Tunnel Alternative bored tunnel segment is considered low.

3.5.8 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Figure 2-9, the Freeway Tunnel Alternative in the vicinity of I-10 and near Summit Drive in South Pasadena is located within or adjacent to a seismically induced Landslide Hazard Zone. However, there are no known landslides mapped along or adjacent to the Freeway Tunnel Alternative. The surface improvements of the Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for landslides.

If seismically induced slope stability issues are identified outside the bored tunnel limits of the Freeway Tunnel Alternative, there are numerous geotechnical methods available to address this hazard. These methods can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.5.9 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table in areas outside the bored tunnel limits of the Freeway Tunnel Alternative as shown in Figure 3-2. The settlement issue could be critical at the portals for the tunnel and ground improvements could be used to address settlement concerns. The Freeway Tunnel improvements would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for seismically induced settlement.

3.5.10 Seismically Induced Inundation

The Freeway Tunnel Alternative in the immediate vicinity of I-10 is located within a potential dam inundation area as shown in Figure 2-10. The inundation zone identified is related to seismically induced failure of the Laguna Regulating Basin.

The Laguna Regulating Basin is an ungated basin (CH2M HILL, 2014d) intended to collect sediment from runoff entering the basin. The LACDPW has no record of the Laguna Regulating Basin ever being filled to capacity since its construction in 1967 (CH2M HILL, 2014d). During the rare occurrences where inflow exceeds outflow within the basin, the amount of time the runoff would be pooled within the basin would be limited because the basin is allowed to run off freely. Potential scour of the ground surface around structural elements such as bridge foundations would be addressed via applicable Caltrans design standards for scour.

The Freeway Tunnel southern portal is located over 4,000 feet north of the identified inundation zone, and is situated more than 50 feet higher than the top of the Laguna Regulating Basin embankment. As such, the potential for seismically induced inundation from the Laguna Regulating Basin to affect the tunnel portion of the Freeway Tunnel Alternative is very low.

3.5.11 Tsunamis and Seiches

The Freeway Tunnel Alternative is not located adjacent to any large bodies of water, and the alternative is located at a minimum elevation of 345 feet. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

3.5.12 Slope Stability

The Freeway Tunnel Alternative traverses hillside areas as shown in Figure 2-1. In areas where improvements may affect existing slopes and/or developments atop existing slopes, detailed evaluations of the geologic units and geologic structure of these slopes would be conducted. These evaluations would yield the appropriate data required to conduct analyses and provide the geotechnical recommendations needed for the design and construction of the proposed hillside improvements. The portions of the Freeway Tunnel Alternative that are located outside the bored tunnel and are proposed on or adjacent to hillside areas would be designed in accordance with *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012) and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for slope instability.

There are numerous geotechnical methods available to address a potentially unstable slope. These methods can include the construction of buttress fills or shear keys, proper drainage systems, and the installation of deep foundations or retaining wall systems, among others.

3.5.13 Ground Settlement and Collapsible Soils

Freeway Tunnel Alternative surface improvements that are underlain by alluvial soils (see Figure 2-1) may be prone to ground settlement or collapsible soils. Where improvements are proposed on alluvial soils, the improvements would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for ground settlement and collapsible soils.

Ground settlement also can occur as a result of ground loss during deep excavations, such as tunneling. Construction of a tunnel utilizing a pressurized-face TBM would actively control ground loss at the tunnel heading during construction. In addition, systematic ground improvement measures on a localized basis could be implemented, including a combination of dewatering, permeation grouting, or jet grouting to stabilize the deposits and reduce the loss of ground.

Detrimental ground settlement from new structures or earth loads can be alleviated by removal and replacement of the settlement- or collapse-prone soils, implementation of ground improvement methods, and structural support systems.

3.5.14 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along some of the surficial improvement areas and portions of the bored tunnel segment of the Freeway Tunnel Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (FHWA, 2009), *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for expansive materials.

Geotechnical design recommendations for expansive material typically consist of removal and replacement with non-expansive soils, utilizing chemical treatment, or designing the proposed improvements to be able to withstand the shrink-swell forces anticipated based on the expansion potential of the material.

3.5.15 Erosion

As shown in Figure 2-12, the surficial soils present along the Freeway Tunnel Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

Engineered controls include incorporating proper gradients on surface slopes, using drainage collection and retention devices, and implementing appropriate erosion-control measures such as silt fences, mulch, and erosion mats.

3.5.16 Regional Subsidence

The Freeway Tunnel Alternative is located within managed groundwater basins. The basin management agencies limit rapid and/or excessive withdrawal of groundwater from the basins. As such, the potential for regional subsidence-related impacts is considered very low.

3.5.17 Soil and Groundwater Contamination

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014b).

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SECTION 4
Limitations

This Geologic Hazard Evaluation has been prepared for the exclusive use of Caltrans and Metro for specific application to the SR 710 North Study in Los Angeles County, California. This report has been prepared in accordance with generally accepted geological and geotechnical engineering practices. No other warranty, express or implied, is made.

The geotechnical and geological information contained in this report is based on data obtained from review of available sources of information such as geological maps and documents, as-built plans, and previous and current field investigations within the SR 710 North Study Area. The logs of soil and rock borings utilized during this study indicate subsurface conditions only at specific locations and times, and only to the depths penetrated. The borings do not necessarily reflect variations that could exist between locations or possible changes that might take place with time and depth. These variations could change some of the hazards discussed in this report. In addition, information about faulting and seismicity is continually being advanced in the Los Angeles area as new scientific work is carried out. These studies could change the level of hazard from faulting and ground shaking, as well as associated hazards, leading to either reduced or increased hazard. As these discoveries are made, the hazard evaluation for each of the alternatives may have to be updated.

In the event that any change in the nature, design, or location of the SR 710 North Study Alternatives occurs, the conclusions and recommendations of this report should not be considered valid unless such changes are reviewed, and the conclusions of this report are modified or verified in writing by CH2M HILL's geotechnical staff. CH2M HILL is not responsible for any claims, damages, or liability associated with the reinterpretation or reuse of the data in this report by others.

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SECTION 5
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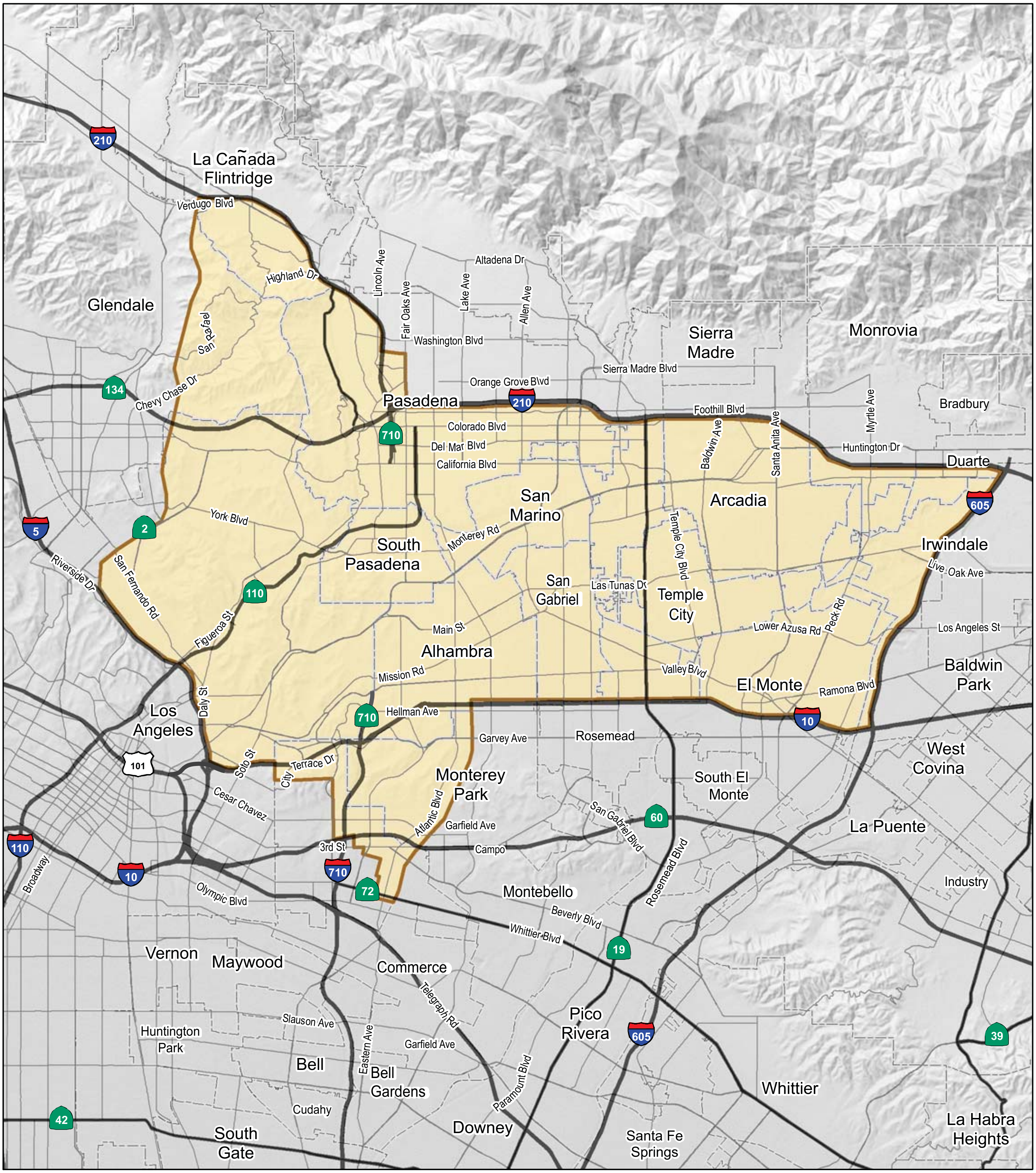
Figures



LEGEND

SR 710 North Study Area

FIGURE 1-1

N

0 1.25 2.5
MILES

SR 710 North Study

Project Location

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

SOURCE: ESRI (2008); LSA (2013)

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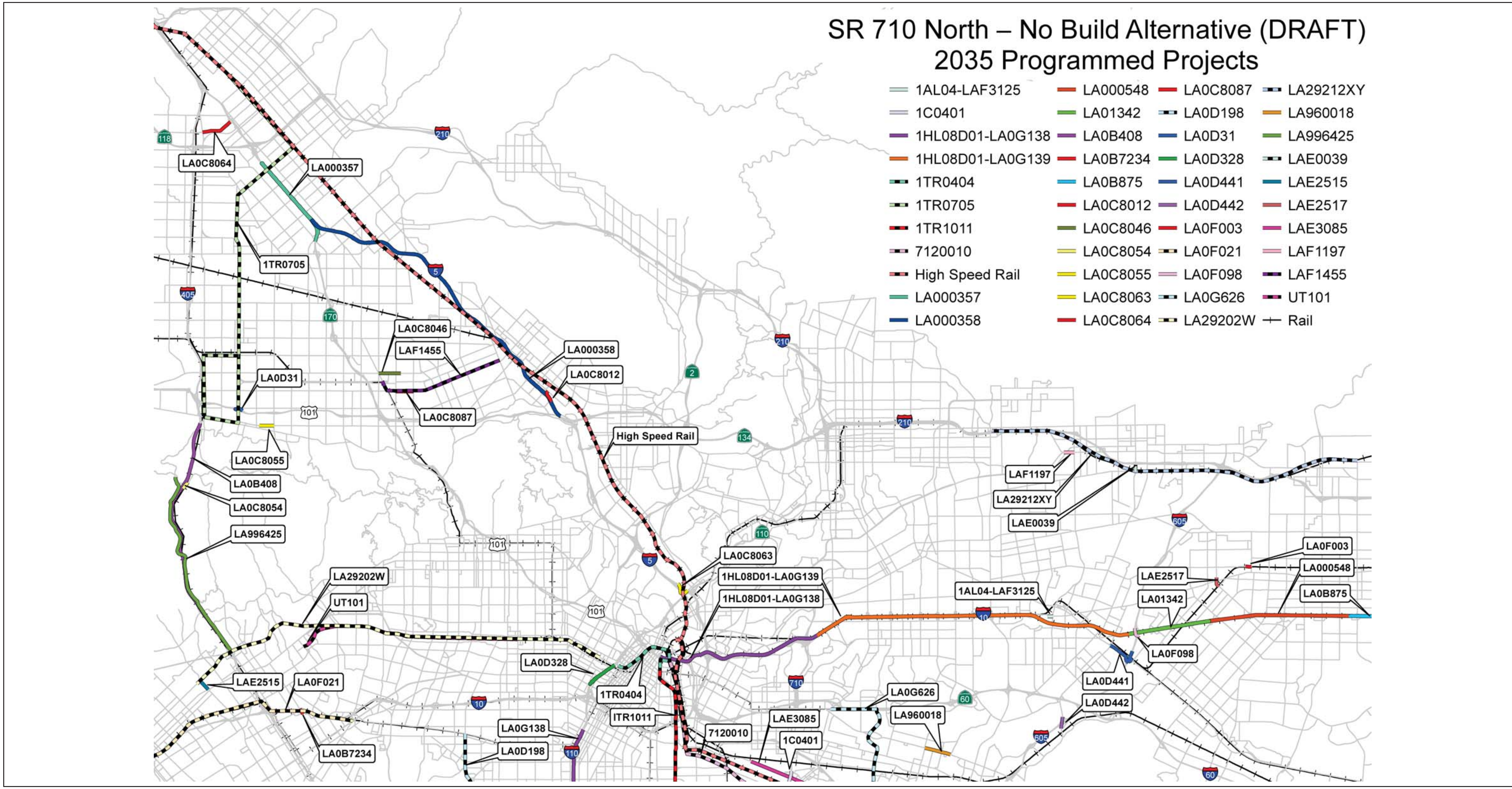

FIGURE 1-2

N

NOT TO SCALE

SOURCE: CH2M HILL (2013)

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SR 710 North Study

No Build Alternative

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

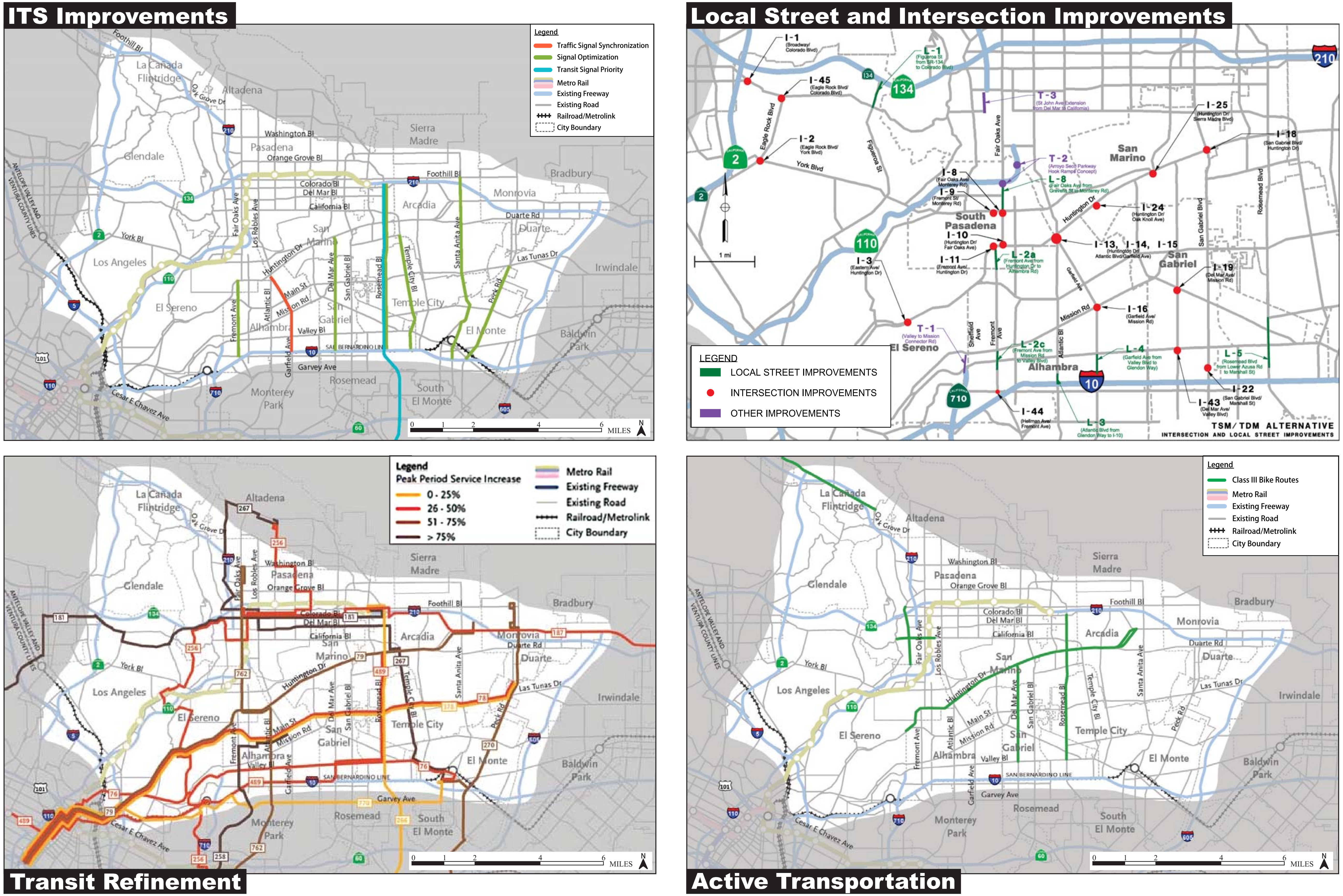

FIGURE 1-3

SR 710 North Study

TSM/TDM Alternative

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

SOURCE: CH2M HILL (2013)
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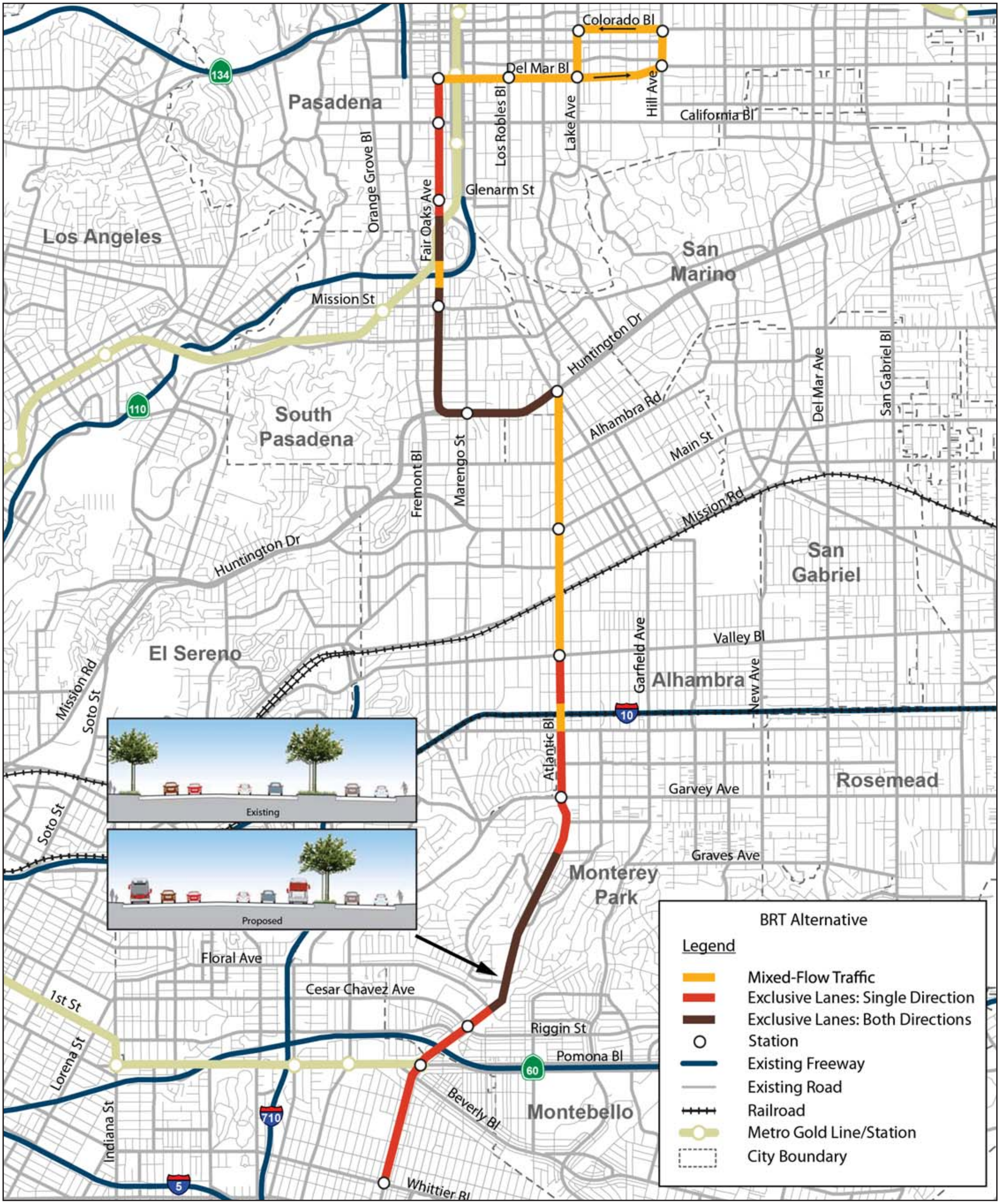

FIGURE 1-4

N

0 .5 1.0
MILES
SOURCE: CH2M HILL (2013)
I:\CHM1105\G\BRT Alternative.cdr (10/27/14)

SR 710 North Study

BRT Alternative

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

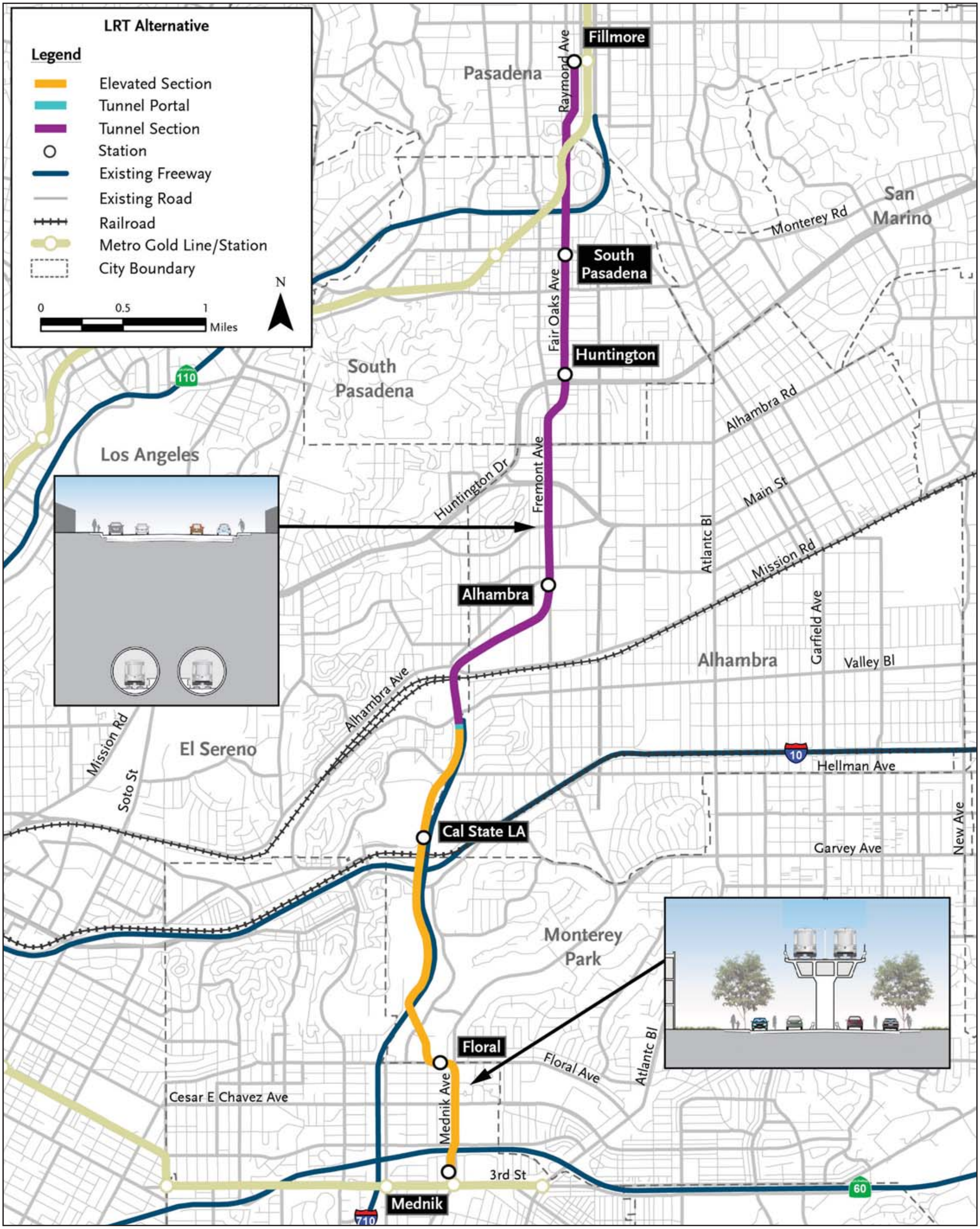

FIGURE 1-5

SR 710 North Study

LRT Alternative

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

N
0 .5 1
MILES

SOURCE: AECOM (2013)

I:\CHM1105\G\LRT Alternative.cdr (10/27/14)

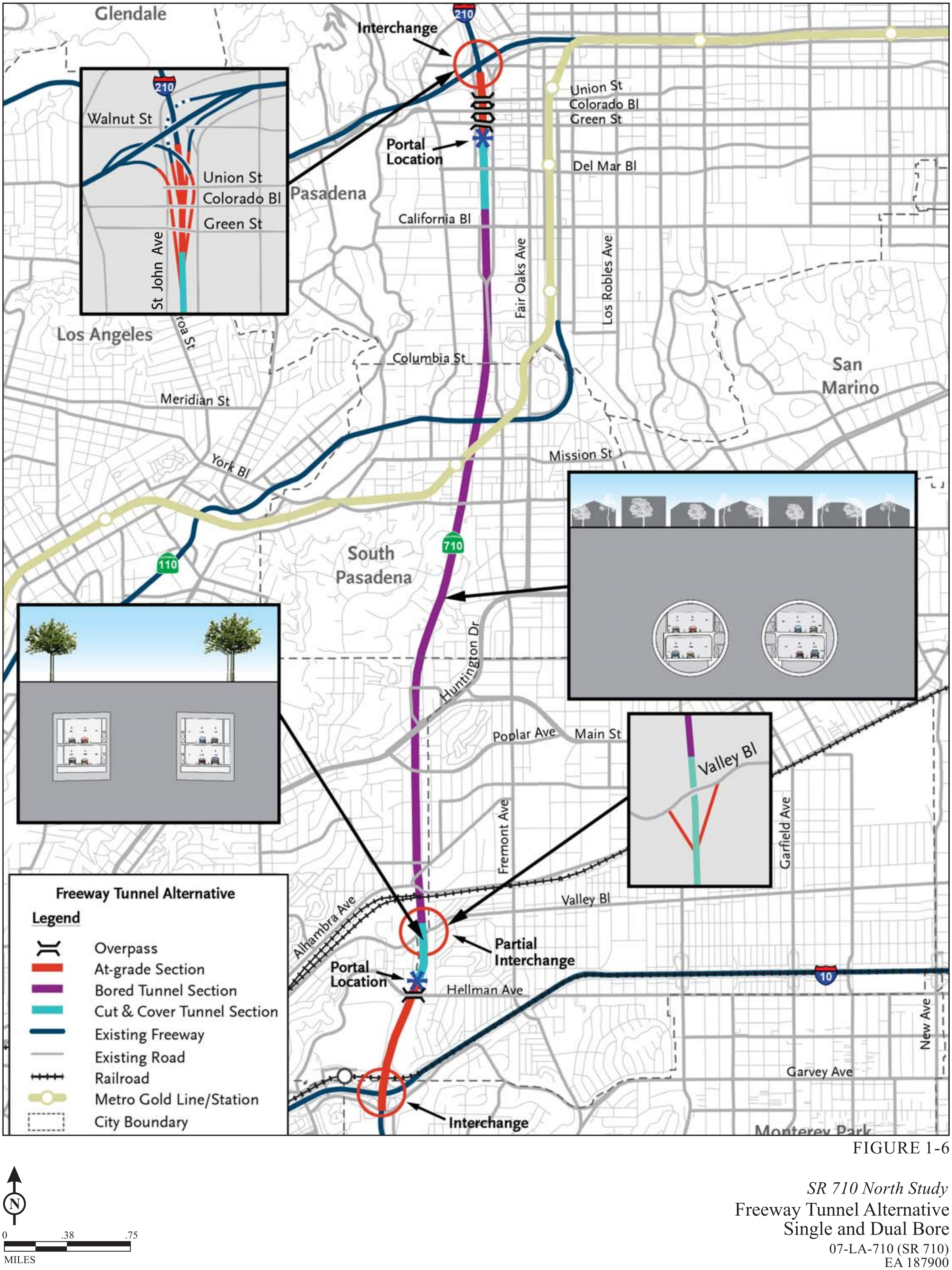

FIGURE 1-6

SR 710 North Study
Freeway Tunnel Alternative
Single and Dual Bore

07-LA-710 (SR 710)
EA 187900
EFIS 0700000191

SOURCE: CH2M HILL (2013)

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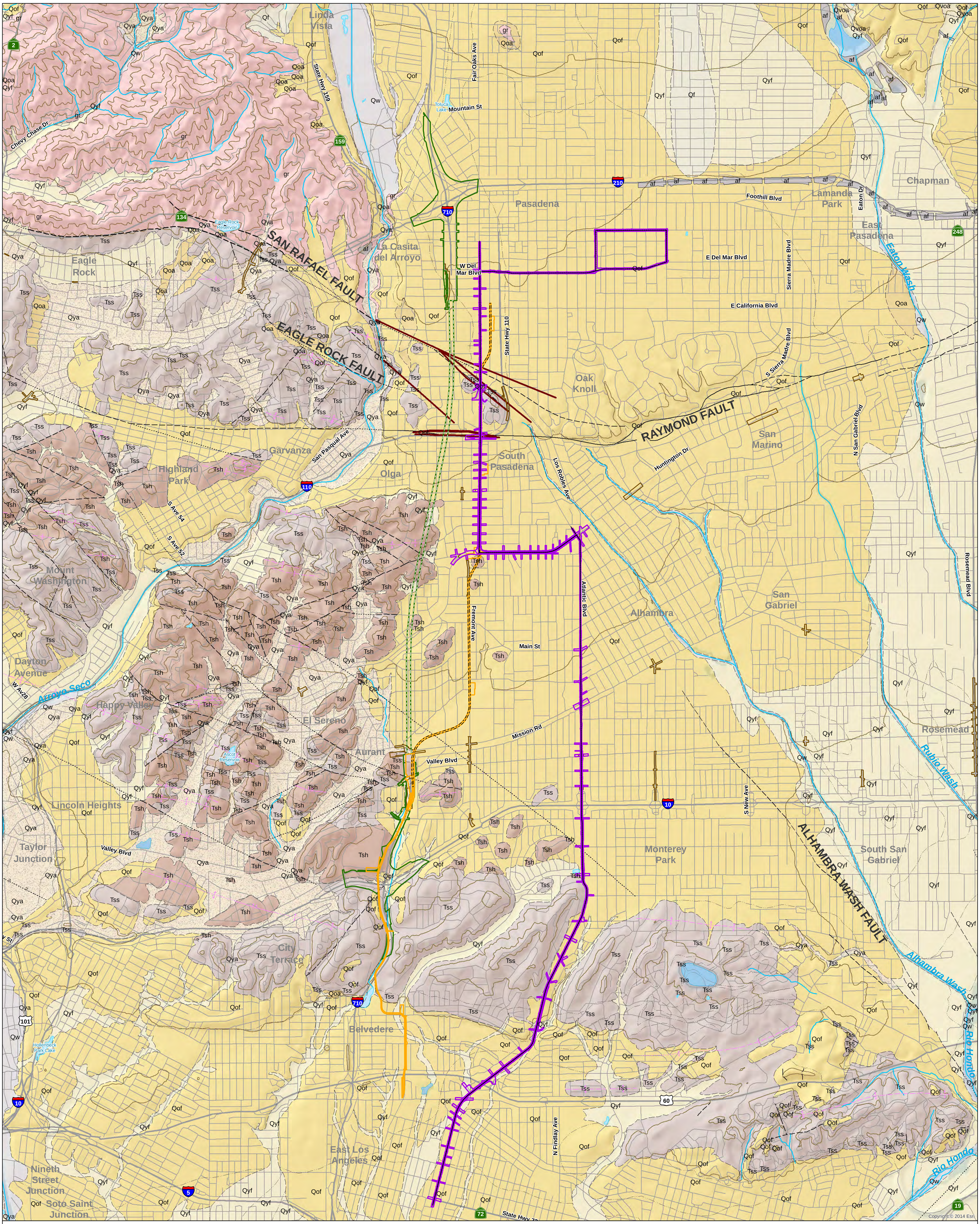

Legend

SR 710 North Study Alternatives

- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- BRT Alternative PDL, with Centerline
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence

Symbols

- Eagle Rock, Raymond and San Rafael faults, location based on this study

Base Map:

- Elevation Contour
- Roads
- Stream
- Water Bodies

- anticline, identity and existence certain, location approximate
- anticline, identity and existence certain, location concealed
- overturned anticline, identity and existence certain, location accurate
- syncline, identity and existence certain, location approximate
- syncline, identity and existence certain, location concealed
- contact, identity and existence certain, location accurate
- contact, identity and existence certain, location approximate
- contact, identity or existence questionable, location approximate
- reference contact, identity and existence certain, location concealed
- reference contact, identity or existence questionable, location approximate
- reference contact, identity and existence certain, location approximate
- reference contact, identity and existence certain, location accurate
- fault, identity and existence certain, location accurate
- fault, identity and existence certain, location approximate
- fault, identity and existence certain, location concealed
- fault, identity or existence questionable, location approximate
- fault, identity or existence questionable, location concealed
- reverse fault, identity and existence certain, location approximate
- reverse fault, identity and existence certain, location concealed
- thrust fault, identity and existence certain, location accurate
- thrust fault, identity and existence certain, location approximate
- thrust fault, identity and existence certain, location concealed
- thrust fault, identity and existence certain, location concealed
- water boundary

af	Artificial Fill - deposits of fill resulting from human construction, mining, or other quarrying activities; includes engineered fill for buildings, roads, dams, airport runways, harbor facilities, and waste landfills
Qw	Alluvial Wash Deposits - unconsolidated sandy and gravelly sediment deposited in recently active channels of streams and rivers; may contain loose to moderately loose sand and silty sand
Qf	Alluvial Fan Deposits - uncosolidated boulders, cobbles, gravel, sand, and silt recently deposited where a river or stream issues from a confined valley or canyon; sediment typically deposited in a fan-shaped cone; gravel sediment generally more dominant than sandy sediment
Qyf	Young Alluvial Fan Deposits - unconsolidated to slightly consolidated, undissected to slightly dissected boulder, cobble, gravel, sand, and silt deposits issued from a confined valley or canyon
Qya	Young Alluvial Valley Deposits - unconsolidated to slightly consolidated, undissected to slightly dissected clay, silt, sand, and gravel along stream valleys and alluvial flats of larger rivers
Qof	Old Alluvial Fan Deposits - slightly to moderately consolidated, moderately dissected boulder, cobble, gravel, sand, and silt deposits issued from a confined valley or canyon
Qoa	Old Alluvial Valley Deposits - slightly to moderately consolidated, moderately dissected clay, silt, sand, and gravel along stream valleys and alluvial flats of larger rivers
Qvoa	Very Old Alluvial Fan Deposits - moderately to well-consolidated, highly dissected clay, silt, sand, and gravel along stream valleys and alluvial flats of larger rivers; generally uplifted and deformed
Tss	Coarse-grained Tertiary age formations - primarily sandstone and conglomerate. Includes Fernando (Tf), Puente (Tp) and Topanga (Tt) Formations
Tsh	Fine-grained Tertiary age formations - includes fine-grained sandstone, siltstone,mudstone, shale, siliceous and calcareous sediments. Includes Fernando (Tf), Puente (Tp) and Topanga (Tt) Formations
Tv	Tertiary age formations of volcanic origin
pKm	Cretaceous and pre-Cretaceous metamorphic formations of sedimentary and volcanic origin
gr	Granitic and other intrusive crystalline rocks of all ages. Includes Wilson Quartz Diorite (Wqd)
	Water

Base map: Modified from CGS, 2012

Figure 2-1
Geologic Map
SR 710 North Study
Los Angeles County, California

N

0 2,000 4,000 Feet

0 750 1,500 Meters

CH2MHILL

DVR R:\LACOUNTYMTA_SR710_GAP_200001218\MAPFILES\GEOHAZARDREPORT\GEOTECHNICAL_OVERVIEW_V6.MXD RANHORN 11/5/2014 1:22:12 PM

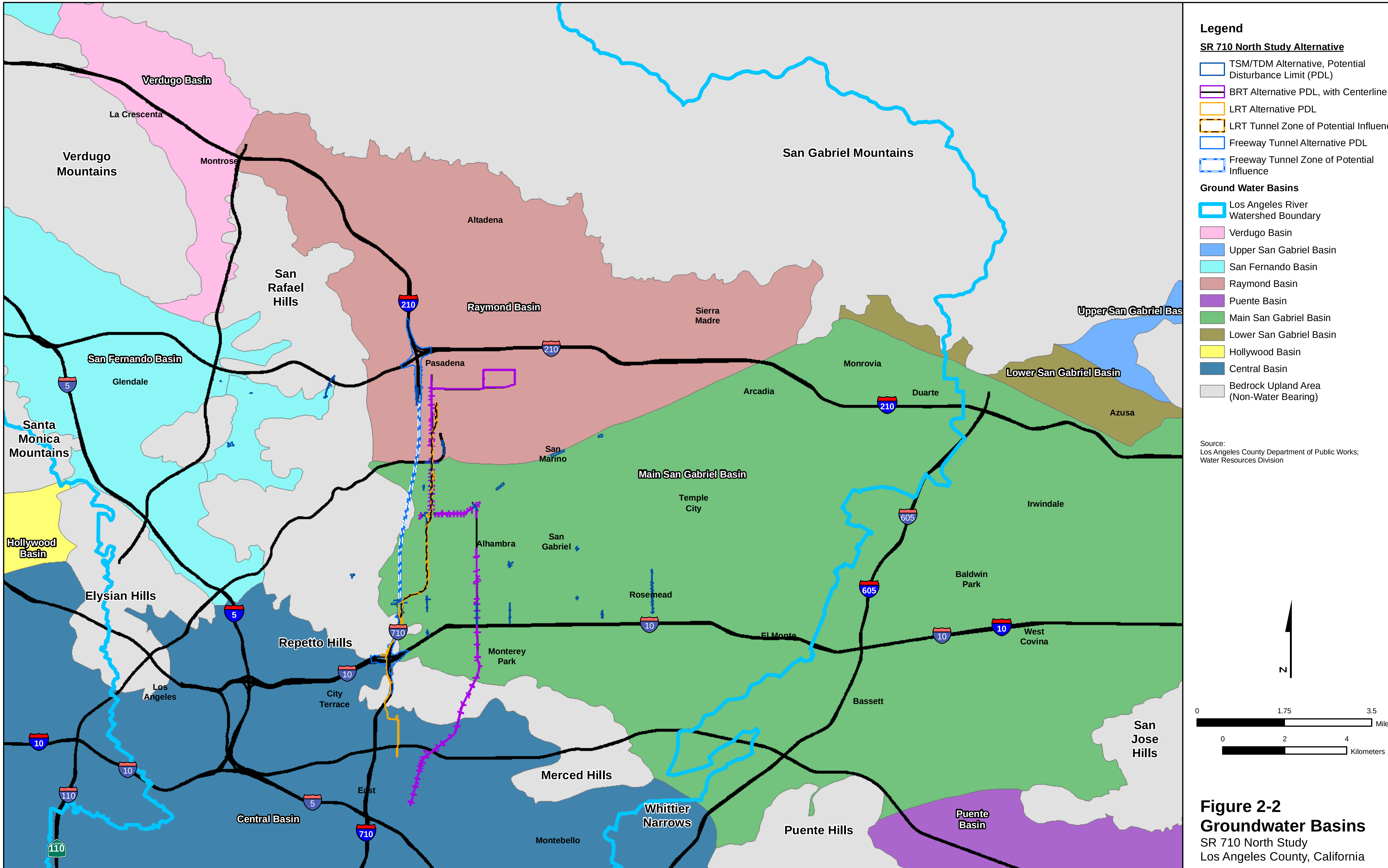

Figure 2-2
Groundwater Basins
SR 710 North Study
Los Angeles County, California

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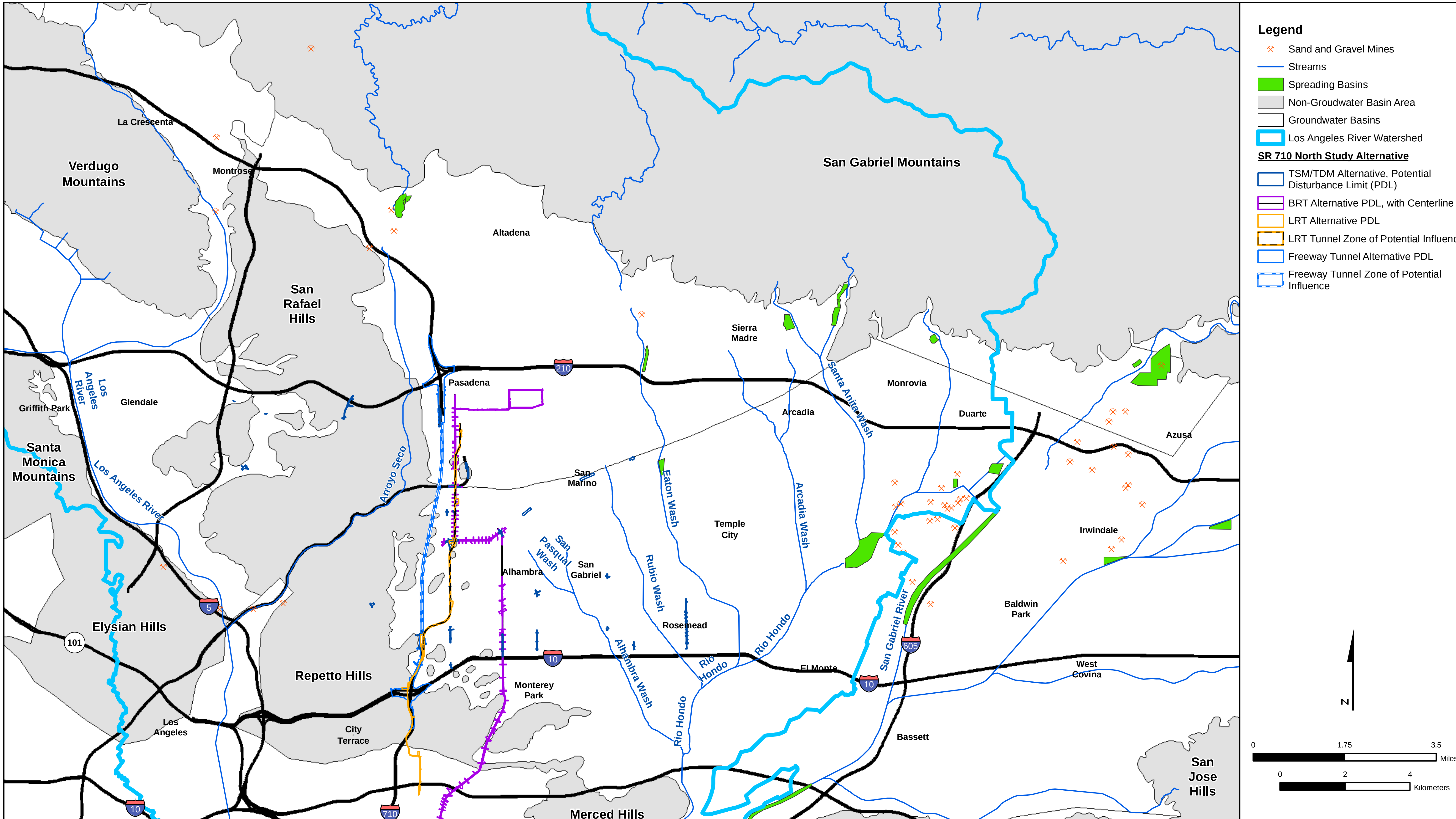

Figure 2-3
Surface Water Features
SR 710 North Study
Los Angeles County, California

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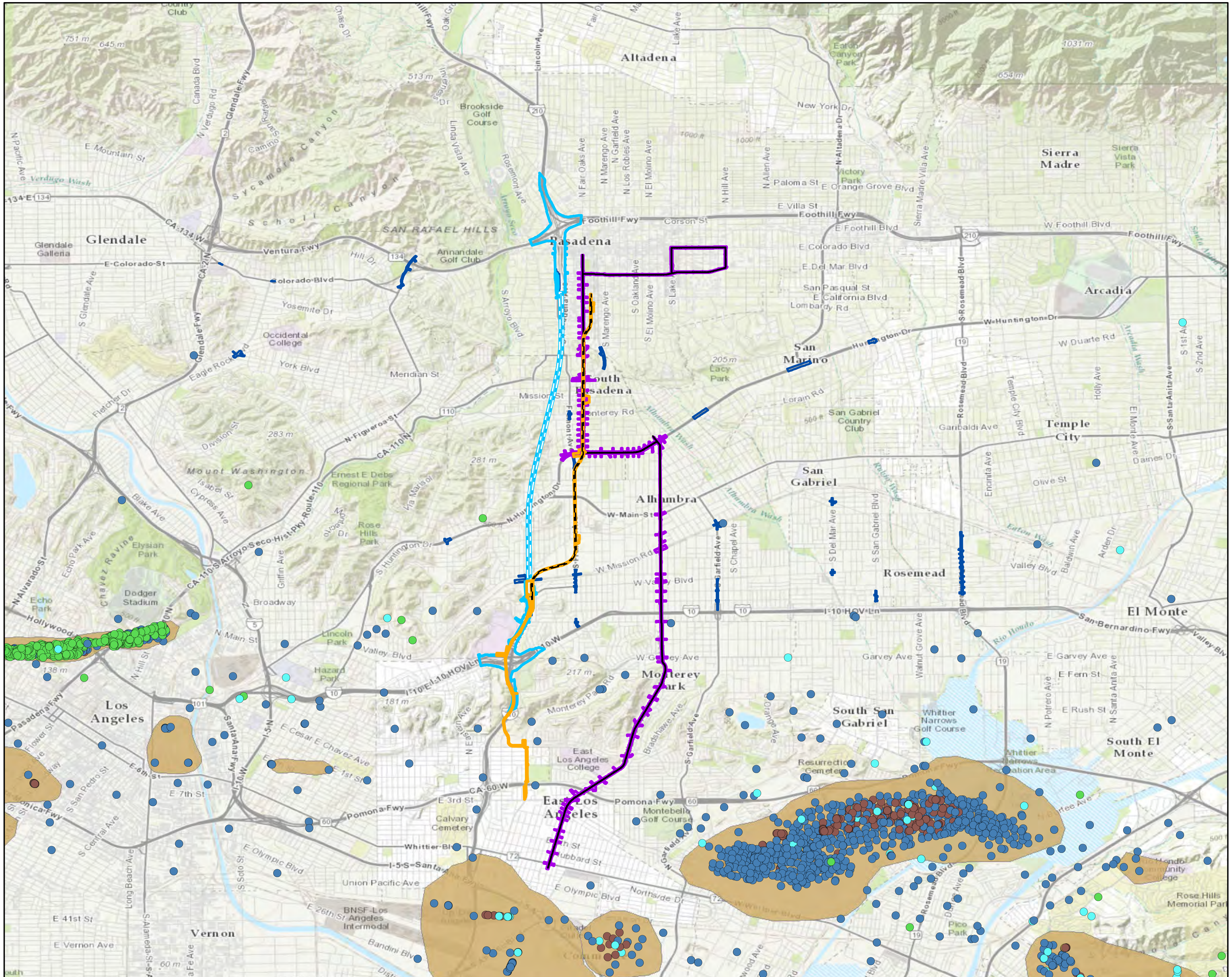
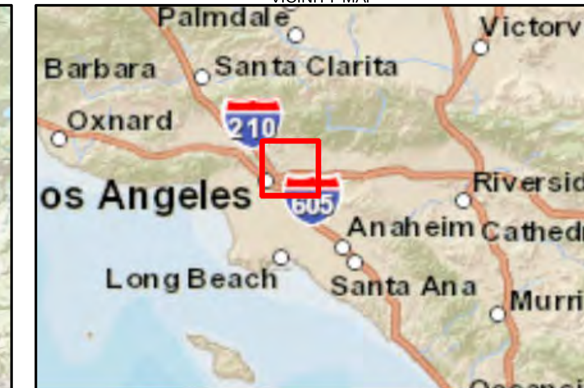




LEGEND

Well Status

- Active
- Buried
- Idle
- New
- Plugged
- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- BRT Alternative PDL, with Centerline
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence
- Oil Fields

Sources:
1) Department of Oil, Gas, and Geothermal Resources, 2005, Oil and Gas Field Database. Available at ftp://ftp.consrv.ca.gov/pub/oil/Data_Catalog/Oil_and_Gas/Oil_fields/. Accessed September 17, 2013.
2) Department of Oil, Gas, and Geothermal Resources, 2012, Well Database. Available at http://conservation.ca.gov//dog/maps/Pages/GISMapping2.aspx. Accessed September 17, 2013.
3 - Topography base map streamed from ESRI (September, 2014)

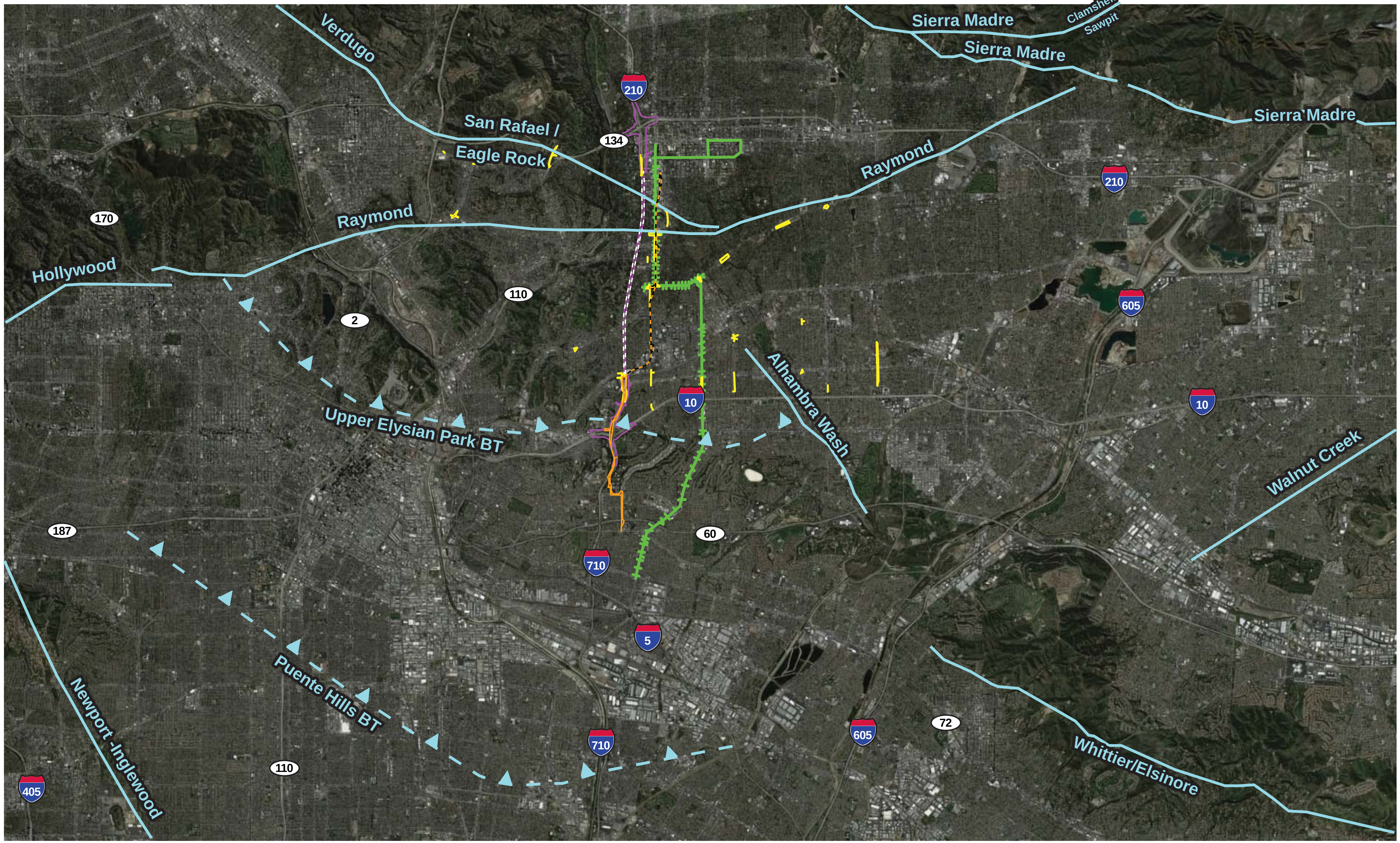
N

0 3,750 7,500
Feet

FIGURE 2-4
Oil and Gas Well Location Map
SR 710 North Study
Los Angeles, California

<ACP>UNK R:\LACountyMTA_SR710_Gap_200001218\MapFiles\GeohazardReport\Oil&Gas_Overview_v4.mxd ranhorn 11/5/2014 10:53:58 AM</ACP>

CH2MHILL.



Aerial image © Google Earth, 2013. Annotation by CH2M HILL, 2013.

LEGEND

- Approximate Fault Location with Name (BT = Blind Thrust, Subsurface Fault, Barbs on Upper Block)
- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- BRT Alternative PDL, with Centerline
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence

North

0 2.5 5

Approximate scale in miles

FIGURE 2-5

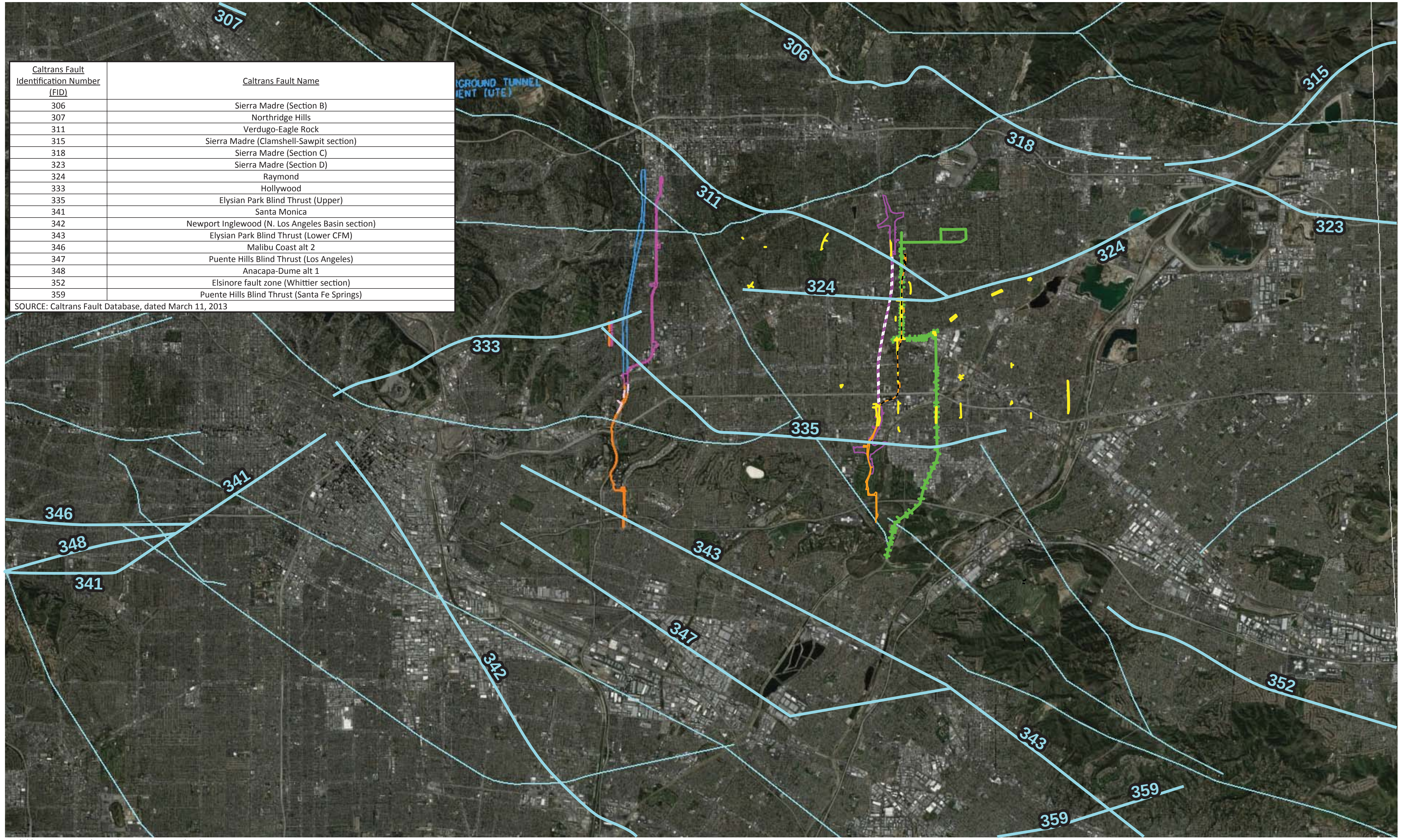
FAULT LOCATION MAP

SR 710 North Study,
Los Angeles County, California

Fault Data from: Plesch et al, 2007 and USGS, 2010; with modifications based on this study.

CH2MHILL

SCO428908.03.19.01.11 SR710_fault_map_rev10.ai 11/14



Caltrans Fault Identification Number (FID)	Caltrans Fault Name
306	Sierra Madre (Section B)
307	Northridge Hills
311	Verdugo-Eagle Rock
315	Sierra Madre (Clamshell-Sawpit section)
318	Sierra Madre (Section C)
323	Sierra Madre (Section D)
324	Raymond
333	Hollywood
335	Elysian Park Blind Thrust (Upper)
341	Santa Monica
342	Newport Inglewood (N. Los Angeles Basin section)
343	Elysian Park Blind Thrust (Lower CFM)
346	Malibu Coast alt 2
347	Puente Hills Blind Thrust (Los Angeles)
348	Anacapa-Dume alt 1
352	Elsinore fault zone (Whittier section)
359	Puente Hills Blind Thrust (Santa Fe Springs)

SOURCE: Caltrans Fault Database, dated March 11, 2013

Aerial image © Google Earth, 2013. Annotation by CH2M HILL, 2013.

LEGEND

- Approximate Fault Location with Caltrans FID (see table above)
- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- BRT Alternative PDL, with Centerline
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence

North

0 2.5 5

Approximate scale in miles

FIGURE 2-6
REGIONAL FAULT MAP
SR 710 North Study,
Los Angeles County, California

CH2MHILL

SCO428908.03.19.01.11 SR710_regional_fault_map_rev5.ai 11/14

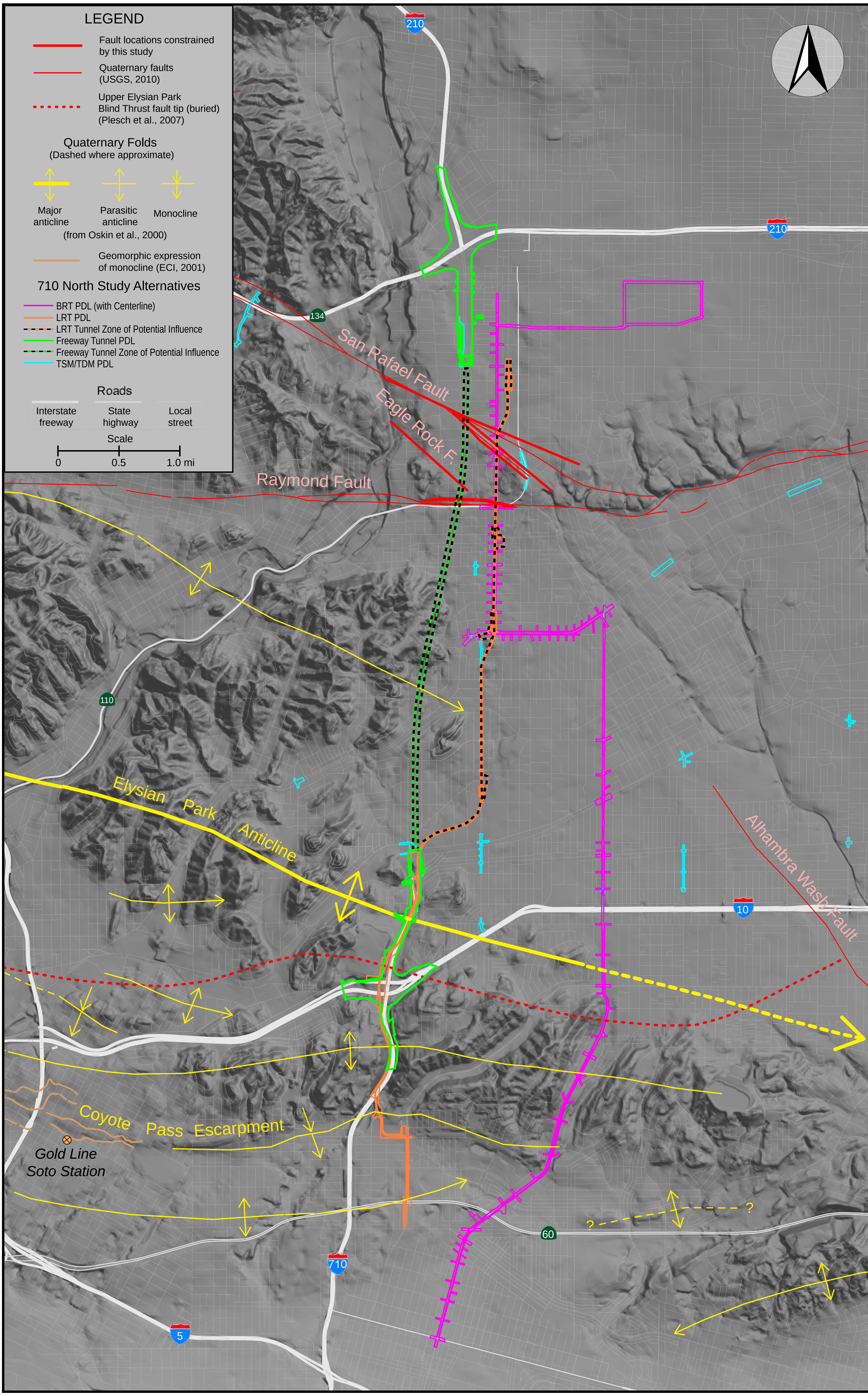
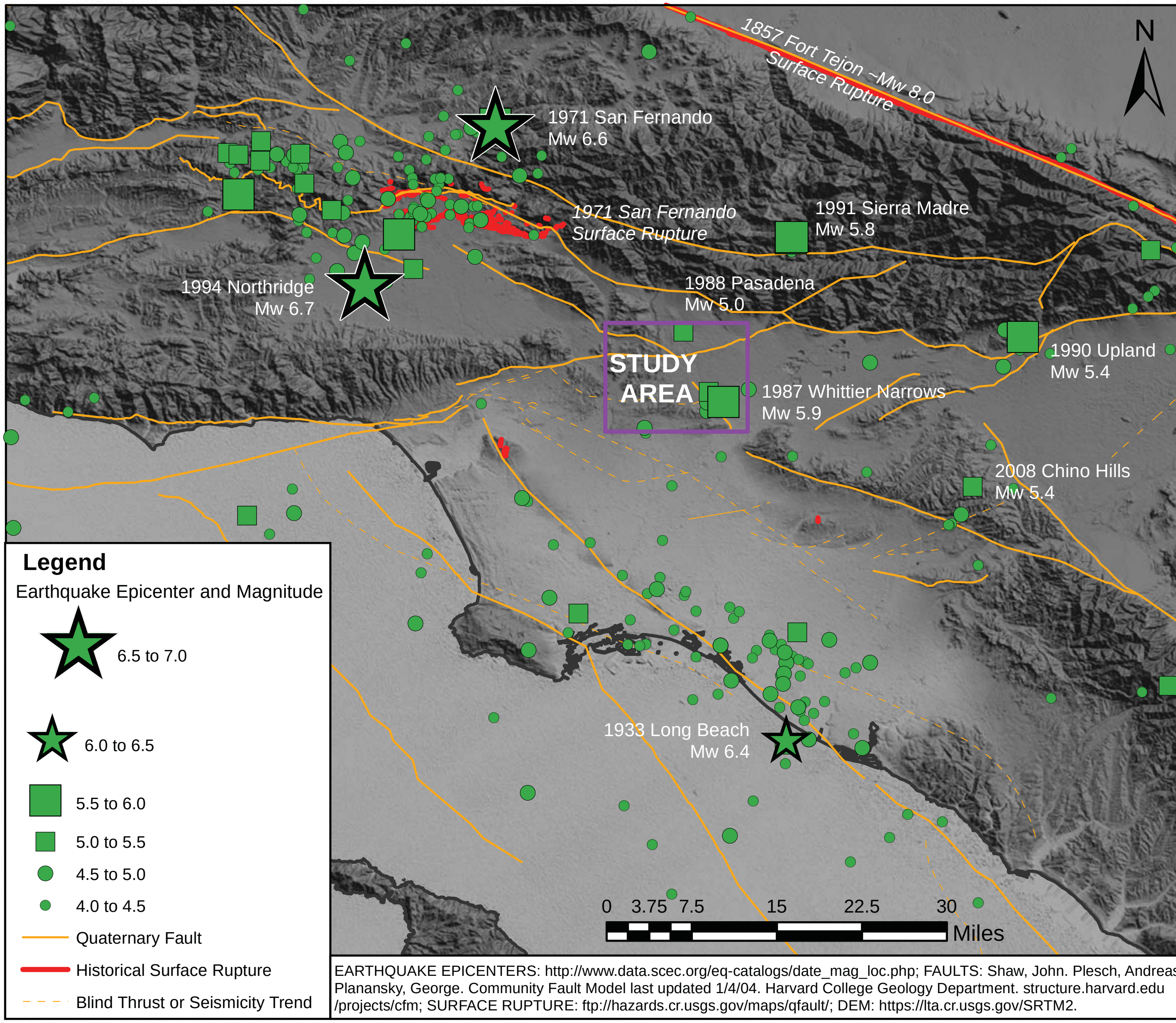


FIGURE 2-7
ELYSIAN PARK BLIND THRUST FAULT AND FOLD MAP
SR 710 North Study, Los Angeles County, California

SCO428908.03.19.01.11 SR710_elysian_park_rev4.ai 11/14

CH2MHILL.



EARTHQUAKE EPICENTERS: http://www.data.scec.org/eq-catalogs/date_mag_loc.php; FAULTS: Shaw, John. Plesch, Andreas. Planansky, George. Community Fault Model last updated 1/4/04. Harvard College Geology Department. structure.harvard.edu /projects/cfm; SURFACE RUPTURE: ftp://hazards.cr.usgs.gov/maps/qfault/; DEM: https://lta.cr.usgs.gov/SRTM2.

FIGURE 2-8
HISTORICAL SEISMICITY MAP
SR 710 North Study
Los Angeles County, California

CH2MHILL.

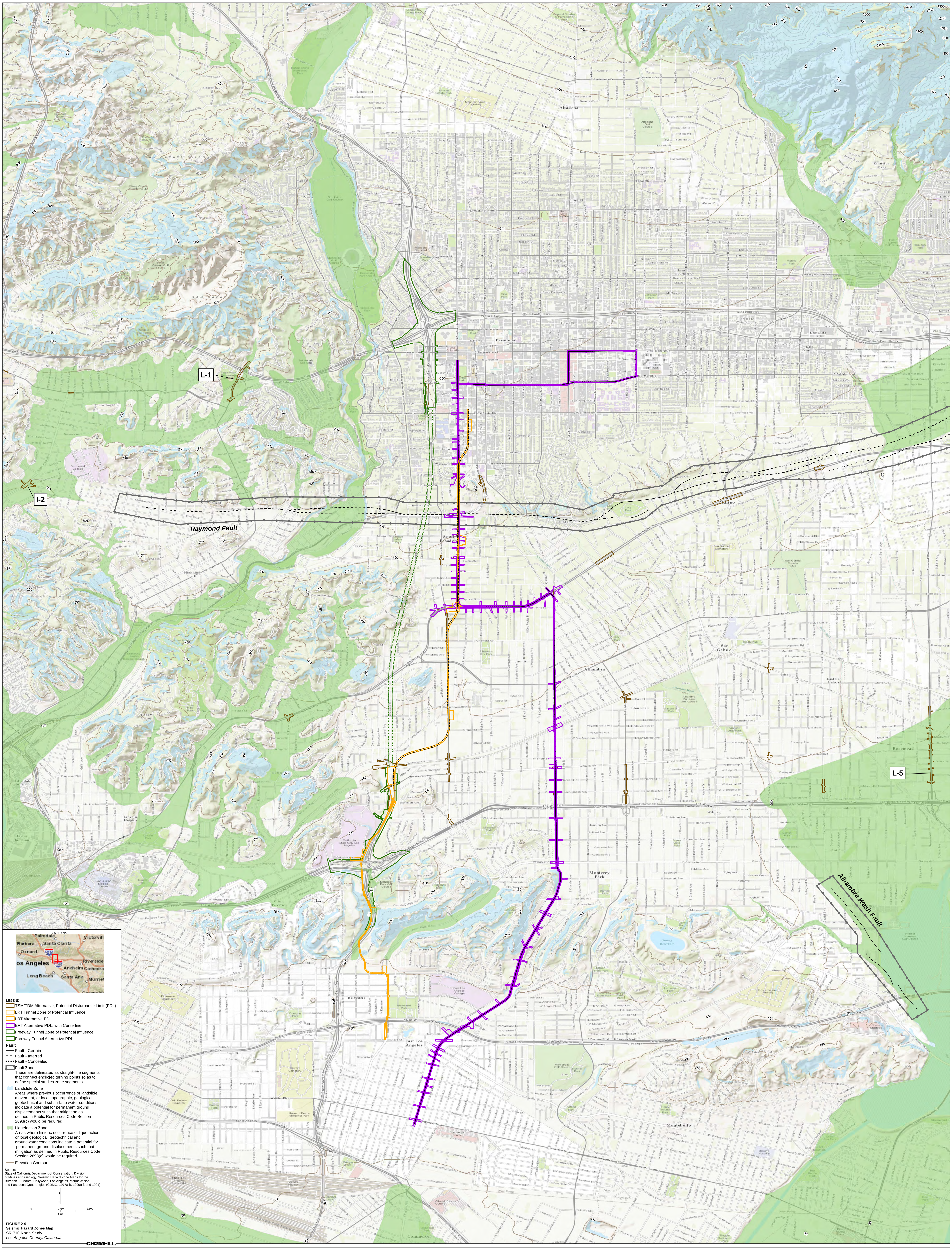


FIGURE 2-9
Seismic Hazard Zones Map
SR 710 North Study
Los Angeles County, California

DVR R:\LACOUNTYMTA_SR710_GAP_200001218\MAPFILES\GEOHAZARDREPORT\SEISMIC_OVERVIEW_E_V4.MXD

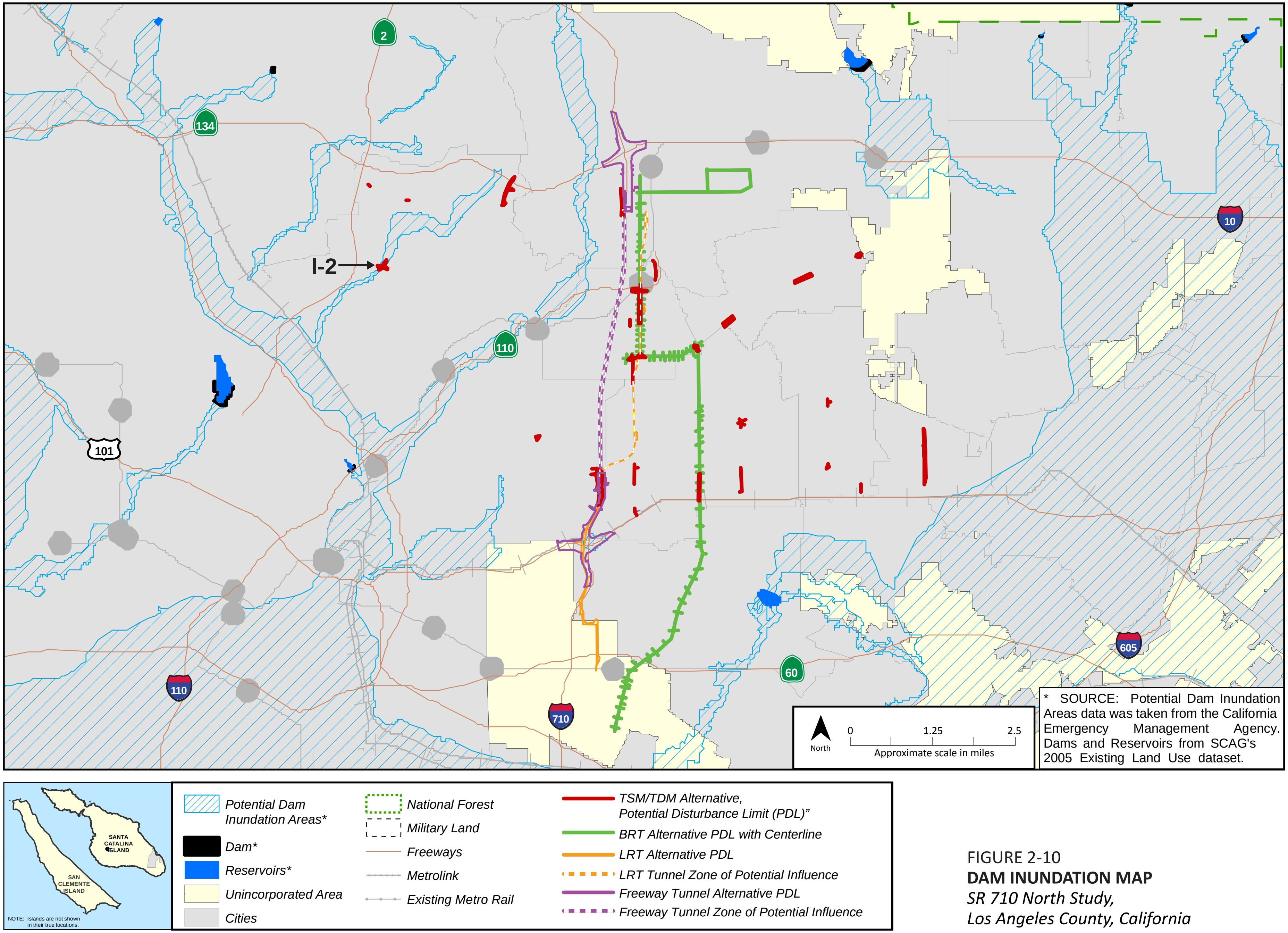
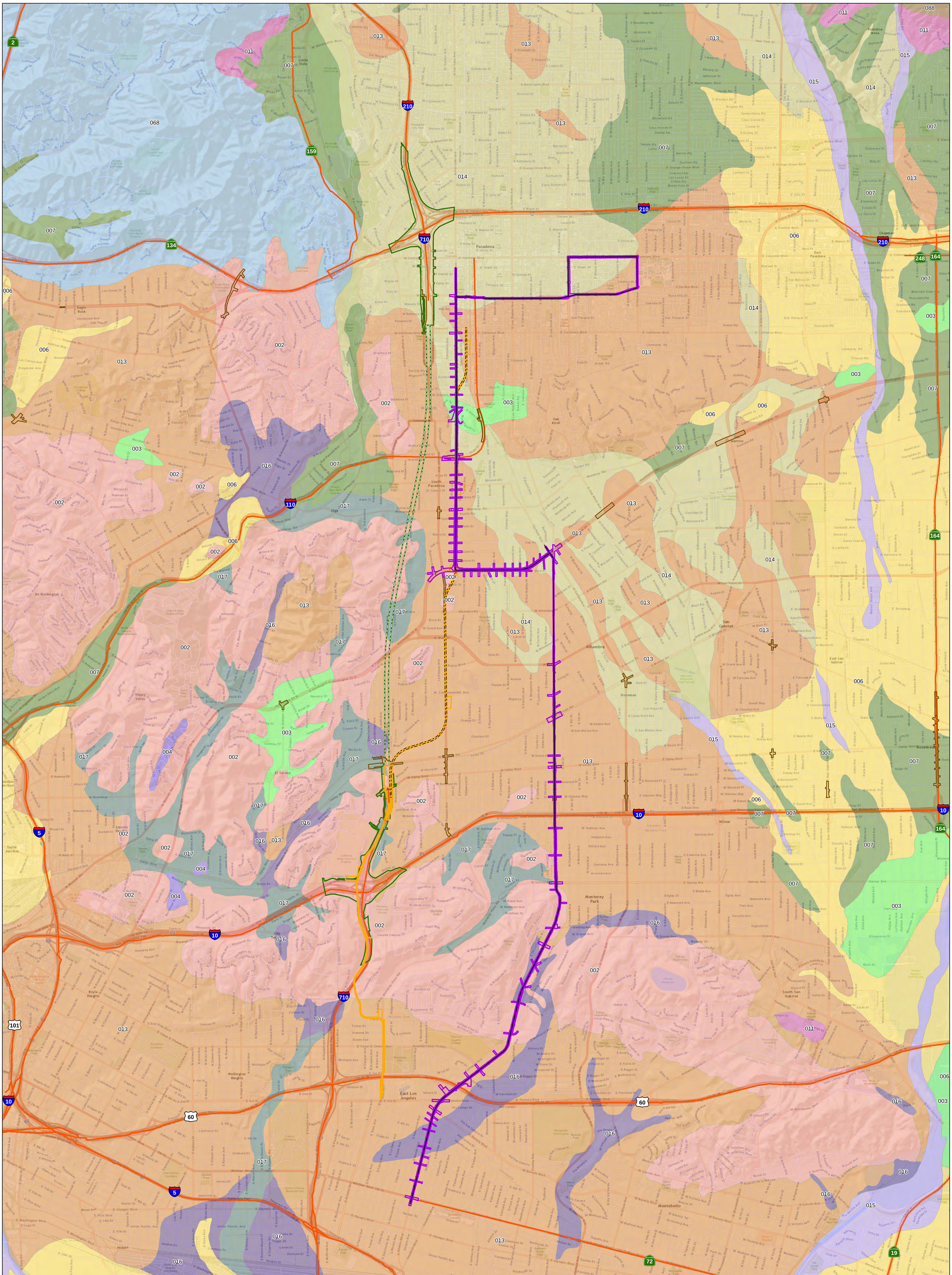


FIGURE 2-10
DAM INUNDATION MAP
SR 710 North Study,
Los Angeles County, California

CH2MHILL



Legend

- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- BRT Alternative PDL, with Centerline
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence

Soils

- 002 - ALTAMONT CLAY LOAM
- 003 - CHINO SILT LOAM
- 004 - DIABLO CLAY LOAM
- 006 - HANFORD FINE SANDY LOAM
- 007 - HANFORD GRAVELLY SANDY LOAM
- 011 - PLACENTIA LOAM
- 013 - RAMONA LOAM
- 014 - RAMONA SANDY LOAM
- 015 - TUJUNGA FINE SANDY LOAM
- 016 - YOLO LOAM
- 017 - YOLO CLAY LOAM

References:
1 - Road base map streamed from ESRI (September, 2014)
2 - Los Angeles County Department of Public Works, 2006. Hydrology Manual. January.
3 - Los Angeles Department of Public Works. 2013. Hydrology Map, A GIS viewer application to view the data for the hydrology manual. http://ladpw.org/wrd/hydrologygis/. Accessed on September 18.

N

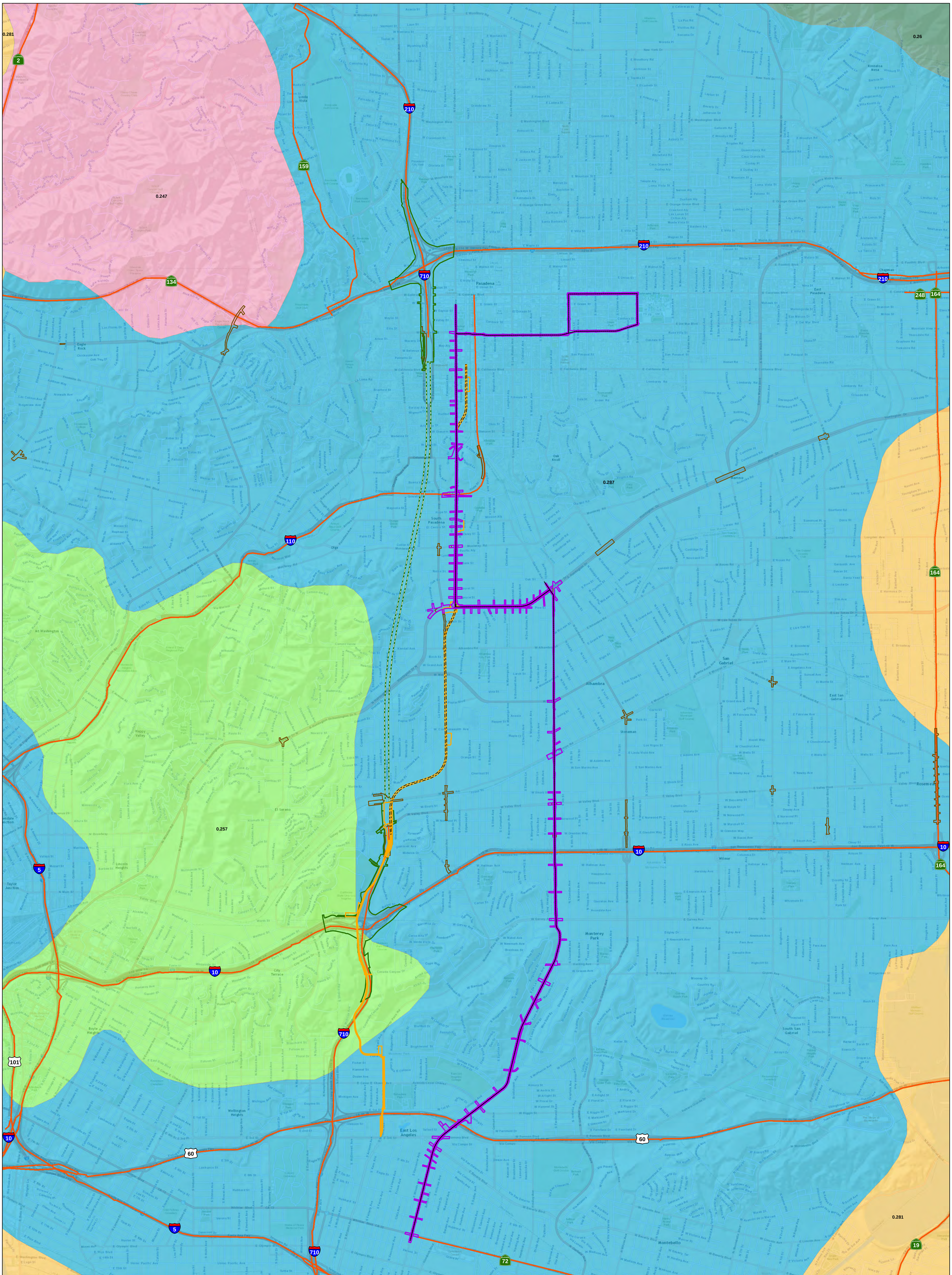
0 2,000 4,000 Feet

0 750 1,500 Meters

Figure 2-11
Surficial Soils Map
SR 710 North Study
Los Angeles County, California

CH2MHILL

DVR R:\LACOUNTYMTA_SR710_GAP_200001218\MAPFILES\GEOHAZARDREPORT\SOILS_OVERVIEW_D_V4.MXD RANHORN 11/5/2014 1:36:19 PM



Legend

- TSM/TDM Alternative, Potential Disturbance Limit (PDL)
- BRT Alternative PDL, with Centerline
- LRT Alternative PDL
- LRT Tunnel Zone of Potential Influence
- Freeway Tunnel Alternative PDL
- Freeway Tunnel Zone of Potential Influence

K-Factor

- 0.247
- 0.257
- 0.26
- 0.281
- 0.287

Soil Susceptibility to Erosion	K-Factor
Low	0.05 to 0.20
Moderate	0.20 to 0.40
High	>0.40

N

0 2,000 4,000 Feet

0 750 1,500 Meters

References:
1 - NRCS-USDA State Office of Michigan, 2013. Revised Universal Soil Loss Equation (RUSLE) Technical Guide. Available at http://www.iwr.msu.edu/rusle/kfactor.htm. Accessed September 19, 2013
2 - STATSGO- U.S. Department of Agriculture, 1994. Available at http://water.usgs.gov/lookup/getspatial?muid Accessed September 19, 2013
3 - Road base map streamed from ESRI (September, 2014)

Figure 2-12
Soil Erodibility Map
SR 710 North Study
Los Angeles County, California

CH2MHILL

DVR R:\LACOUNTYMTA_SR710_GAP_200001218\MAPFILES\GEOHAZARDREPORT\SOILS_OVERVIEW_D_USGS_KFACT_V4.MXD RANHORN 11/5/2014 1:32:02 PM

VE=5X
H:1"=1000'; V:1"=200'

0 1" 2"

Notes: 1) Existing profile based on topographic survey by Warner Engineering and Surveying Inc. for the SR 710 North Study. Mapping datums are NAD 1983 and NAVD 1988

2) The geology interpreted on this cross section is approximated, based on the geologic sources referenced in the text of this report and a limited number of widely spaced borings. Significant, additional detailed geologic investigation will be required to adequately characterize the geologic conditions along the alignment.

3) The alignment shown on the cross section, and associated stationing is based on the SR 710 North Study Advanced Conceptual Engineering Plans prepared for the Light Rail Transit Alternative by AECOM, dated February, 2014.

Geologic Cross Section
SR 710 North Study - Light Rail Transit Alternative

LEGEND

UNITS

Af	ARTIFICIAL FILL
Qal	ALLUVIAL SOIL
Tfcg	FERNANDO FORMATION, CONGLOMERATE MEMBER
Tfsl	FERNANDO FORMATION, SILTSTONE MEMBER
Tpsl	PUENTE FORMATION, SILTSTONE MEMBER
Tpss	PUENTE FORMATION, SANDSTONE MEMBER
Tt	TOPANGA FORMATION, UNDIFFERENTIATED
Ttss	TOPANGA FORMATION, SANDSTONE MEMBER
Ttcg	TOPANGA FORMATION, CONGLOMERATE MEMBER
Ttsl	TOPANGA FORMATION, SILTSTONE MEMBER
Wqd	WILSON QUARTZ DIORITE

SYMBOLS

ALL LOCATIONS ARE APPROXIMATE. QUERIES INDICATE UNCERTAINTY.

- GEOLOGIC CONTACT
- INACTIVE FAULT
- ACTIVE OR POTENTIALLY ACTIVE FAULT
- INTRAFORMATIONAL CONTACT
- GENERALIZED BEDDING
- ESTIMATED TOP OF GROUNDWATER TABLE
- Z3-G7 SEISMIC LINE (CH2M HILL, 2010), WITH PROJECTION
- A-13-020 TD-149.8' GEOTECHNICAL BORHOLE WITH TOTAL DEPTH AND PROJECTION:
  - A, R, RC, O-13-001 - CH2M HILL, THIS STUDY
  - R-09-Z1B8 - CH2M HILL, 2010
  - NM-B3 - NINYO AND MOORE, 1999
  - EMI-3 - EARTH MECHANICS INC, 2006
  - ES-2 - CALTRANS, 1974

FIGURE 3-1
LRT ALTERNATIVE GEOLOGIC CROSS SECTION
SR 710 North Study
Los Angeles County, California

CH2MHILL.

Notes: 1) Existing profile based on topographic survey by Warner Engineering and Surveying Inc. for the SR 710 North Study. - Mapping datums are NAD 1983 and NAVD 1988

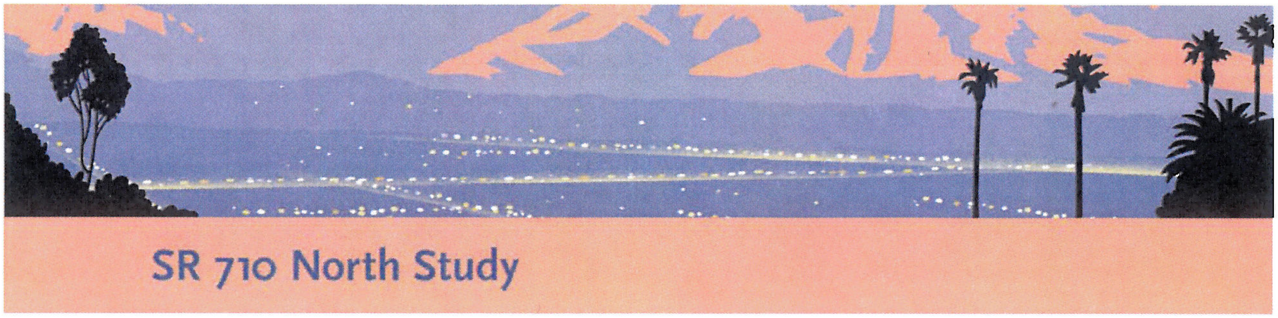
2) The geology interpreted on this cross section is approximated, based on the geologic sources referenced in the text - of this report and a limited number of widely spaced borings. Significant, additional detailed geologic investigation will be required to adequately characterize the geologic conditions along the alignment.

3) The alignment shown on the cross section, and associated stationing is based on the SR 710 North Study Project - Report prepared for the Freeway Tunnel Alternative Preliminary Project Plans by CH2M HILL, dated February 2014.

FIGURE 3-2
FREEWAY TUNNEL ALTERNATIVE GEOLOGIC CROSS SECTION
SR 710 North Study
Los Angeles County, California

CH2MHILL.

Appendix A
Fault Rupture Evaluation Technical Memorandum



TECHNICAL MEMORANDUM

Fault Rupture Evaluation for the SR 710 North Study, Los Angeles County, California

PREPARED FOR: Michelle Smith/Metro

COPY TO: Caltrans

PREPARED BY: Eldon Gath, P.G., C.E.G./Earth Consultants International
Dario Rosidi, Ph.D., P.E., G.E./CH2M HILL
Ravee Raveendra, P.E., G.E./CH2M HILL

DATE: December 10, 2013

PROJECT NUMBER: 428908

REGISTERED PROFESSIONAL ENGINEER
MAHESWARAN RAVEENDRA
No. GE2743
Exp: 6/30/2015
GEOTECHNICAL
STATE OF CALIFORNIA

REGISTERED GEOLOGIST
ELDON M. GATH
No. EG 1292
CERTIFIED ENGINEERING GEOLOGIST
STATE OF CALIFORNIA
Expires: 3/31/2014

Introduction

This technical memorandum presents the results of preliminary fault rupture evaluations completed as part of environmental documentation for the State Route (SR) 710 North Study. Five Alternatives are being evaluated during the ongoing environmental documentation process. The five Alternatives are No Build, Transportation System Management/ Transportation Demand Management (TSM/TDM), Bus Rapid Transit (BRT), Light Rail Transit (LRT), and Freeway Tunnel. Figure 1 shows the general vicinity of the SR 710 North Study area.

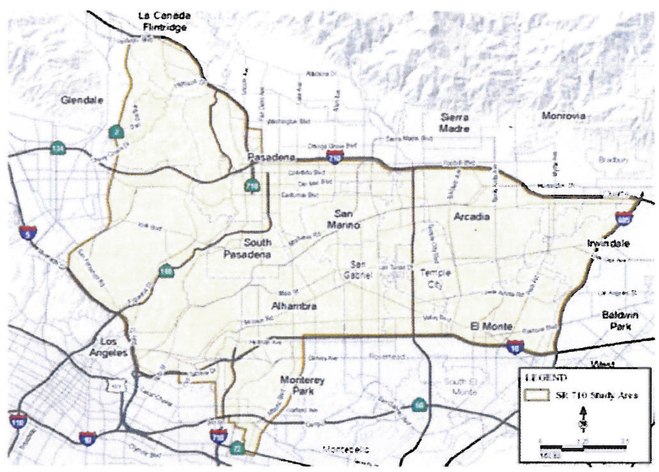


Figure 1. *SR 710 North Study Area.*

Fault ruptures are a particularly important consideration during the environmental assessment of two of the SR 710 North Study Alternatives: the Freeway Tunnel and LRT Alternatives. Both Alternatives will be located in tunnels over much of their lengths:

- Freeway Tunnel (Dual Bore Option): The proposed Freeway Tunnel Alternative includes approximately 60-foot-diameter, 4.2-mile-long, twin bored tunnels and cut-and-cover tunnels at both ends of the bored tunnels. The freeway tunnels will extend from the existing southern stub of SR 710 in Alhambra, north of I-10, and connect to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena. The invert of each tunnel will be roughly parallel to the ground surface at an average depth of about 200 feet below ground surface (bgs), except at the portals where the tunnels daylight.
- LRT: The LRT Alternative will consist of twin bored tunnels approximately 4.5 miles long, and would be located between Valley Boulevard on the south and the existing Fillmore Station on the Metro Gold Line on the north.

Metro

Caltrans

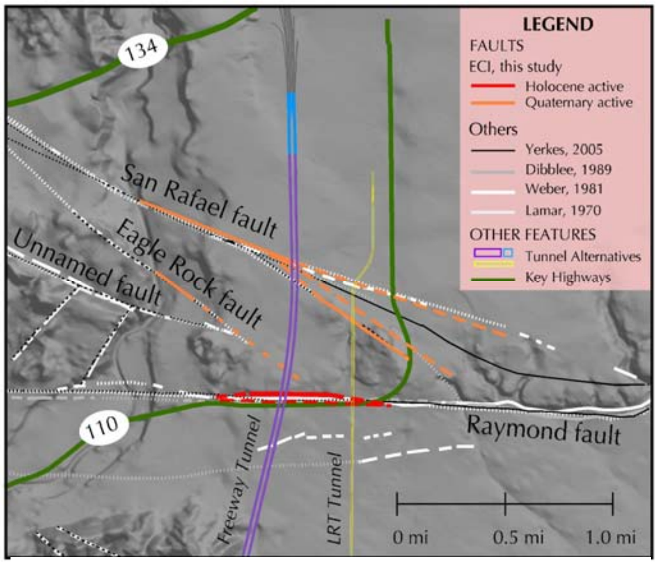


Figure 2. *Map of the potentially active faults that may impact the proposed tunnel routes (there are different mapping interpretations and locations for San Rafael, Eagle Rock, and other northwest-trending faults, but in this discussion, they are collectively referred to as the Eagle Rock-San Rafael fault zone).*

The LRT Alternative would also consist of approximately 3.0 miles of overhead structure from the Metro Civic Center Station on the south to Valley Boulevard on the north. The LRT tunnel invert depth is approximately 80 feet bgs; the diameter is approximately 20 feet.

The two proposed tunnel alignments will both cross active fault zones (Figure 2), necessitating a discussion in the environmental documentation of the potential hazards caused by the fault zone crossings and whether these hazards can be reasonably mitigated in future design. In order for the environmental documentation to discuss the hazards and methods for mitigating the impact of fault crossings, the potential displacements across the tunnel alignments, if one of the faults were to rupture during a seismic event, needs to be estimated.

A preliminary assessment of fault displacements for the two Alternatives was performed using deterministic and probabilistic fault displacement hazard analyses (DFDHA and PFDHA, respectively). For the DFDHA, several approaches for estimating fault displacement (Wells and Coppersmith, 1994; Hanks and Bakun, 2008; Wesnousky, 2008) based on fault length alone were compared, but Wells and Coppersmith was used to estimate fault displacement because it is the most commonly used in practice. For the PFDHA, probabilistic methods (Youngs et al., 2003; Petersen et al., 2011; Chen and Petersen, 2011) were used to quantify the magnitude of displacement for a given earthquake return period, consistent with Metropolitan Transportation Authority (Metro) and California Department of Transportation (Caltrans) seismic design criteria. These displacement evaluations considered the San Rafael, Eagle Rock, and Raymond faults, which are the three principal fault systems crossing the LRT and Freeway Tunnel alignments.

This technical memorandum begins the discussion on how to develop tunnel displacement estimates using the DFDHA and PFDHA methods. The memorandum presents a brief summary of the geologic data that are available and how those data may fit together with the regional fault systems, including potential ruptures from one fault onto another. It also presents the preliminary results of DFDHA and PFDHA that were performed to estimate the fault rupture displacements at the fault-tunnel crossing locations during future earthquakes on the Raymond, Eagle Rock, and San Rafael faults. These displacement estimates are based on return periods and seismic performance guidance required by Caltrans and Metro for earthquake ground motions.

The results presented herein were developed based on limited geologic data on the faults, and therefore should be considered preliminary and subject to change in the subsequent design phases. The design displacement estimations were limited by an absence of paleoseismic studies for some of the faults, by a lack of replicated quantitative data in the studies, and by inconsistencies in the data across paleoseismic studies, as explained later in this memorandum. Additional field investigation and studies should be conducted after the preferred Alternative is selected to update and verify these fault displacement estimates.

Fault Background Data

Figures 3 and 4 show generalized locations of the faults discussed in this technical memorandum. Table 1 summarizes the consensus information of the faults that could contribute to the rupture hazard at the tunnels. There are very limited data concerning the slip rates or recurrence intervals of surface-rupturing earthquakes for any of these faults; there are two published paleoseismic studies for the Raymond fault, one study for the Hollywood and Santa Monica faults, and none for the other faults. As such, there is difficulty in providing reasonable values for fault displacements. All of these faults are relatively short, and individually would generate displacements of less than 1 meter. However, there are some discussions within the scientific community that these faults could rupture together (Marin et al., 2000; Weaver and Dolan, 2000), with slip transferring from one to the other, in a cascading event that would result in a larger magnitude event and much larger displacements on each of the faults. The following subsections provide a discussion of each of the primary faults in the area and then identify potential fault models that could result in fault displacements across the tunnels.

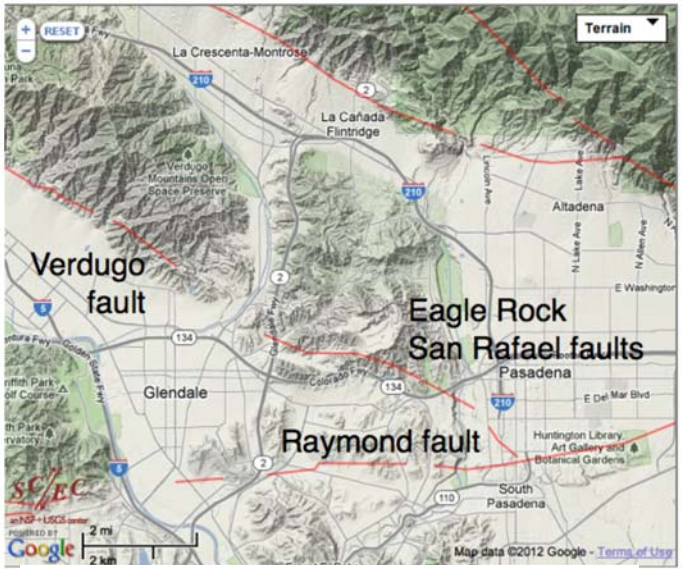


Figure 3. *Map of the potentially active faults that may impact the proposed tunnel routes involving a complex rupture of the Eagle Rock and/or San Rafael faults with the Verdugo fault.*

Figure 4. *Map of the potentially active faults that may impact the proposed tunnel routes through a complex rupture involving the Raymond and multiple fault segments to the west. Sierra Madre fault (S-M) and Clamshell Sawpit fault (C-S) also are shown.*

TABLE 1
Summary of Fault Data*
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Magnitude	Slip Rate (mm/yr)	Recurrence Intervals (years)	Comment
Raymond	21	6.7	0.5 - 2.0	3,000	Slip rate and recurrence poorly constrained: 4 to 5 mm/yr has also been reported.
Eagle Rock	11	6.2	0.3 - 0.6	10,000+	Slip rate and recurrence unconstrained.
Verdugo	21	6.7	0.6	10,000	Slip rate and recurrence unconstrained.
Hollywood	15	6.6	0.9	10,000	Slip rate and recurrence poorly constrained.
Santa Monica	24	7.0	1.0	10,000	Slip rate and recurrence poorly constrained.
Malibu	34	6.6	0.3	10,000	Slip rate and recurrence poorly constrained.

* Data sourced from referenced papers, the Southern California Earthquake Center (SCEC) online fault database [http://www.data.scec.org/significant/fault-index.html] and Caltrans fault database (Caltrans, 2012).
km – kilometer(s)
mm/yr – millimeters per year

Raymond Fault

The primary active fault through the tunnels is the Raymond fault (Bryant, 1978). This north-dipping, east-west-trending fault has a dominant left-lateral sense of offset (Jones et al., 1990), though some north side up reverse slip is also likely. The percentage of lateral to vertical (L:V) slip varies along the trace of the fault; it has been estimated at a ratio of about 5:1 (L:V). Within the tunnel crossings, a case could be made that the vertical displacement is 75 feet across a horizontal displacement of 2,300 feet, resulting in a 30:1 (L:V) ratio based on the cumulative offset of the Pasadena fan.

Figure 5 depicts logs of two paleoseismic trenches on the Raymond fault. There is similarity in the expression of the fault in both trenches even though the trenches were excavated miles apart. Although not noted in either study, similar near-surface partitioning frequently isolates the strike-slip movement component onto the steeper fault, while the shallower fault accommodates most of the compressional movements.

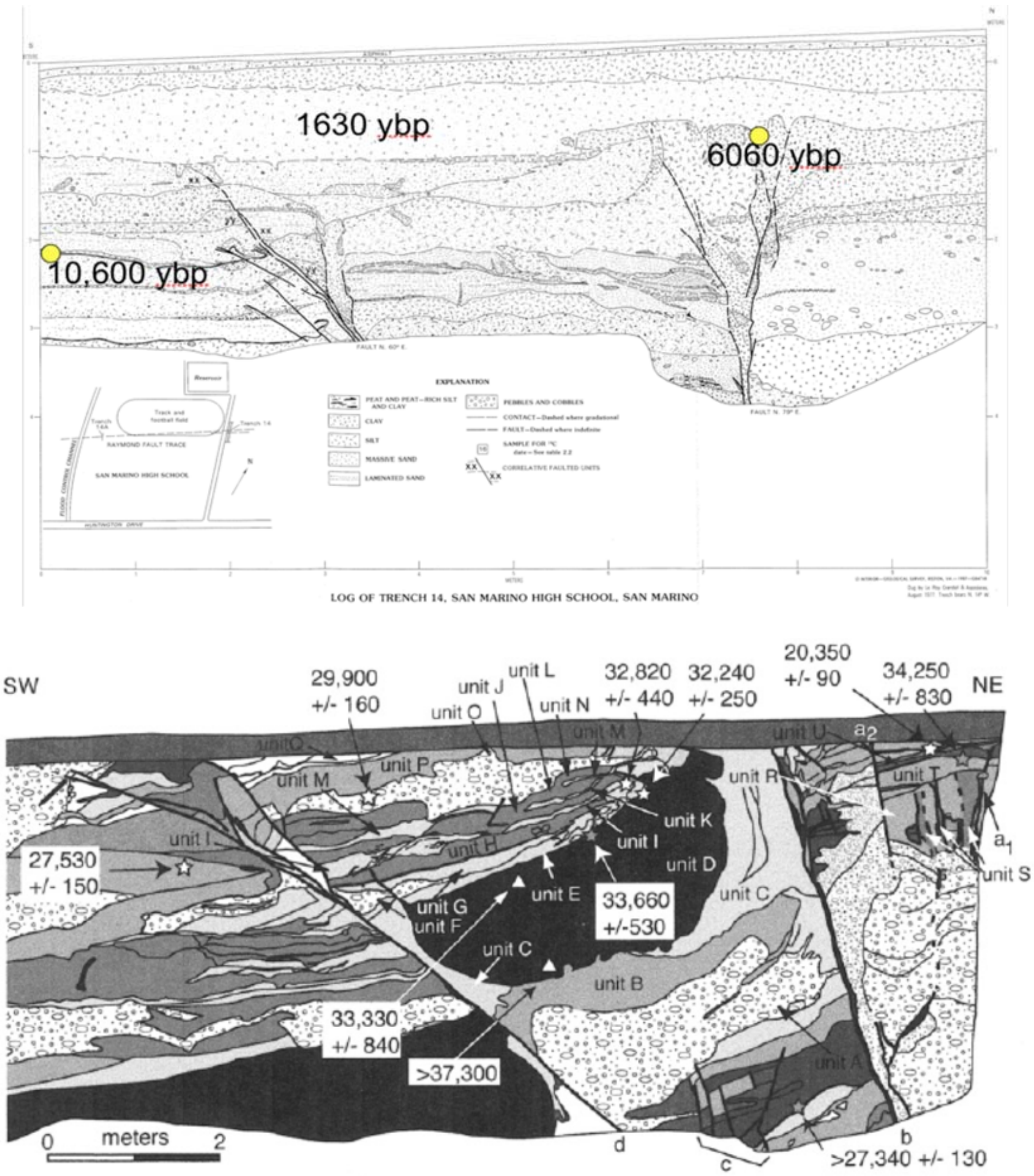


Figure 5. *Logs of paleoseismic trenches on the Raymond fault.* ***Upper*** *(Crook et al., 1987) shows the most recent event constrained between 1,600 and 6,000 years ago.* ***Lower*** *(Weaver and Dolan, 2000) was interpreted to show five surface-rupturing events between 27,000 and ~40,000 years ago.*

Three paleoseismic studies have been conducted for the Raymond fault (Crook et al., 1987; Weaver and Dolan, 2000; Dolan et al., 2000c). These studies have shown that it has experienced multiple surface-rupturing earthquakes in the last 40,000 years (see Figure 5), but the results also generate conflicting interpretations for the average recurrence interval between events, as well as the date of the last event. While these data may be interpreted as an example of temporal clustering of events, it also could be interpreted as missed events in the paleoseismic records due to inconsistent stratigraphic preservation.

Based on a series of events between 27,000 and 40,000 years ago, Weaver and Dolan (2000) calculated a recurrence interval of about 3,300 years for the Raymond fault. However, based on offsets of younger deposits, the recurrence interval could be as long as 5,000 to 10,000 years between events. The last event is inferred to have occurred between 1,000 and 2,000 years ago (Weaver and Dolan, 2000), though this estimate is somewhat poorly constrained.

A subsequent study showed a post-25,000-year channel offset of 42 meters resulting in a slip rate of 1.5 mm/yr along a 10-meter-wide zone of almost pure left-lateral strike-slip faulting (Dolan et al., 2000c; Marin et al., 2000). The California Geological Survey (CGS) lists the Raymond slip rate as low as 0.5 mm/yr (CGS, 2013), while the (still draft) Unified California Earthquake Rupture Forecast (UCERF3) fault compilation by Dawson and Weldon (2012) reports a 2.0 mm/yr slip rate using the same data as Marin et al. (2000). Yeats (2012, p. 108), however, reports a slip rate of 4 +1/-0.5 mm/yr for the Raymond fault, a value that seems too high based on the geomorphic expression of the fault.

Table 1 provides a summary of fault data used in the scenario analysis discussed below.

Hollywood, Santa Monica, and Malibu Faults

The Hollywood, Santa Monica, and Malibu faults also have been shown to have ruptured to the surface in the past 10,000 years, and all have a similar left-lateral reverse sense of slip. Paleoseismic studies of the Hollywood and Santa Monica faults (Dolan et al., 1997, 2000a, and 2000b) suggest that these two faults have recurrence intervals of about 10,000 years, and that the Santa Monica fault last broke 1,000 to 3,000 years ago, while the Hollywood fault last ruptured 6,000 to 9,000 years ago.

The slip kinematics of the Hollywood, Santa Monica, and Malibu faults are similar to the Raymond fault; that is, dominantly left-lateral with a reverse component, which is why they are frequently considered as individual parts of a larger fault system. Currently, the collected paleoseismic data for these faults do not support temporally coincident ruptures, although the data set is small. For analysis purposes, however, these faults could still be considered as rupturing together with the Raymond fault in various rupture scenarios.

Verdugo, Eagle Rock, and San Rafael Faults

The Eagle Rock/San Rafael fault zone has no quantitative investigations. The Eagle Rock fault is considered by some to be the southern continuation of the Verdugo fault (Yeats, 2004), and is also listed in the Caltrans Fault Database (Caltrans, 2012); however, there is no discussion of how the strain from the Verdugo would be apportioned across the Eagle Rock and San Rafael splays. No paleoseismic studies have been published for the Verdugo fault.

As discussed previously, the scenario of combining the Raymond fault with a rupture on the Eagle Rock fault has no field evidence to confirm its plausibility. But the Eagle Rock (and San Rafael) faults do seem to merge just west of Raymond Hill, and it is possible to infer that Raymond Hill is being elevated as a result of this strain transfer. A joint rupture cannot be a common event, however, because the tectonic geomorphology of the Eagle Rock fault is much less developed than that of the Raymond fault, suggesting it has a lower slip rate or longer recurrence interval to refresh it on the landscape.

Despite this observation, the tectonic geomorphology of the Raymond fault is much better developed east of Arroyo Seco, near its intersection with the Eagle Rock/San Rafael faults. No data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/San Rafael faults, nor on the Verdugo fault farther northwest.

Proposed Fault Rupture Models

At the tunnel-fault crossing locations, or just slightly east of them, the Eagle Rock and unnamed faults join with the Raymond fault, and its geomorphic expression becomes much stronger on the landscape. This could indicate that the Raymond fault is structurally linked in some manner to the Verdugo-Eagle Rock/San Rafael fault system, and that the rate of slip on the Raymond fault changes west-to-east at this location of the fault (see Figure 6). All of the paleoseismic investigations on the Raymond fault lie to the east of this interaction, and therefore may not be truly representative of the paleoseismic behavior of the fault at the proposed tunnel locations, if this scenario is viable.

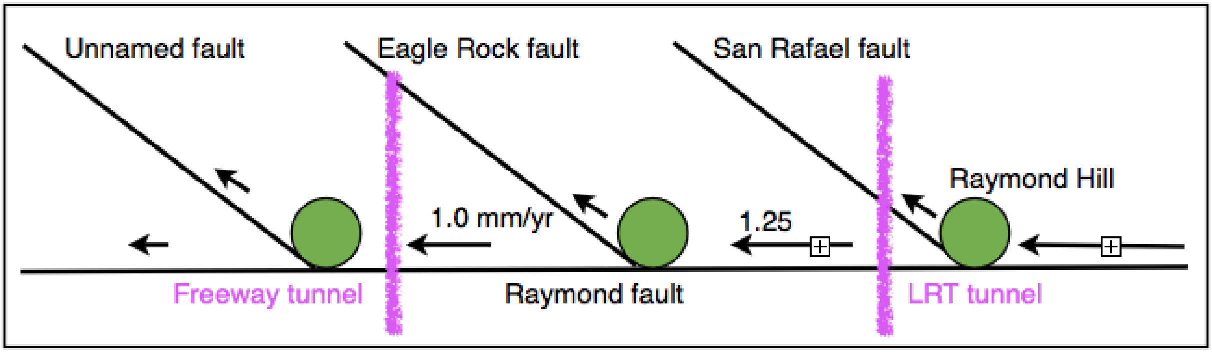


Figure 6. *Schematic illustration of a possible structural interaction that would bleed slip off the Raymond fault and onto the Eagle Rock/San Rafael fault system.*

The model shown in Figure 6 does not satisfy the current mapping of the faults across the northeast margin of the hills. However, it satisfies a mechanism to explain the topographic uplifts and left-lateral displacements on the secondary faults. As with the other fault parameters, there are inconsistencies between existing mapping interpretations and the assumed fault parameters based on published sources.

Another possible scenario is that the Raymond fault ruptures easterly onto the Clamshell Sawpit segment (see Figure 4), thereby involving the Sierra Madre fault. This is another untested hypothesis, because no paleoseismic studies have been completed on the Clamshell Sawpit fault or on this portion of the Sierra Madre fault. Because of all these uncertainties, it seems premature to include additional structural models into the current analysis. For that reason, this analysis concentrates on the Raymond fault as a single source, with some consideration on the cascading rupture scenarios with the Hollywood, Santa Monica, and Malibu faults.

Implications of Cascading Rupture Scenarios

A number of uncertainties exist for the fault systems that are located in or near the LRT and Freeway Tunnel alignments. One of the key uncertainties is whether separate seismic events could cascade as a single large rupture scenario, as has been suggested. The idea of cascading events is important as the resulting displacements could increase appreciably from those associated with single events. Two possible cascading scenarios involving the Raymond fault are discussed in the following sections.

Raymond–Hollywood Fault System

One scenario involves a combination of the Raymond and Hollywood faults into a single cascading event. A number of factors suggest this is a very unlikely event:

- Existing geologic data are inadequate to resolve the inconsistencies between slip rate, earthquake recurrence, and earthquake magnitude/displacement.
- The slip rate on the Raymond fault has been geologically constrained at about 1.5 to 2 mm/yr. This fits the various models and the geomorphic expressions of the fault better than the higher reported value of 4 to 5 mm/yr.
- At 1.5 mm/yr, the displacement events should occur on average every 350 to 700 years. This is highly divergent from the 3,000–5,000–10,000-year recurrence intervals derived from the paleoseismic studies.
- Temporal clustering of events or missing paleoseismic events are both Alternative interpretations to explain the average recurrence interval inconsistency. Temporal clustering means that the average 3,000-year recurrence interval is defined by two to four temporally close earthquake events followed by a long quiescence period.
- At a 3,000–5,000–10,000-year recurrence and at 1.5 mm/yr, the strain accumulation would be 4.5, 7.5, and 15 meters, which could be the clue that temporal clustering of events is the norm because these large displacement events are not credible for the Raymond fault alone or even with adjacent faults.

- In order to generate such large displacements in single events, the length of the fault must be increased by linking it to other faults in a "cascade" rupture.

Based on fault geometry, the Hollywood fault is the most likely fault to either transfer slip onto the Raymond or to accommodate slip from the Raymond fault, but there are difficulties with this linkage.

- Taking the date of the last rupture on the Hollywood fault as approximately 6,000 to 9,000 years ago (Weaver and Dolan, 2000), and the last event on the Raymond fault as less than 2,000 years ago, it appears that these two faults do not always rupture together. But it is still possible that they do occasionally rupture together, perhaps whenever the Hollywood fault ruptures, or that rupture-linking events have been missed in the paleoseismic data.
- The Hollywood fault has a recurrence interval of 10,000 years. Combining the lengths of the Raymond and Hollywood faults would result in a fault length of 35 km, capable of M6.9 and only 0.8 to 1.3 meter of surface displacement; this is well below the amount needed to account for the 42 meters of displacement in <25,000-year-old deposits, as measured by Dolan et al. (2000c).
- Linking the Santa Monica and Malibu faults to the Hollywood-Raymond scenario does result in larger event displacements; however, such linkages are also not supported by the current geological studies, and it is considered to be implausible.
- The problem cannot be solved deterministically from the existing paleoseismic data, because there are too many conflicting results and interpretations within those data.

At this time, it does not seem realistic to design for a scenario event involving the Raymond and Hollywood fault systems. This scenario cannot be demonstrated geologically and has probabilities as low as 1 in 10,000+ years, which would include any of the fault linkage scenarios.

Raymond–Eagle Rock/San Rafael Fault System

The second cascading scenario involves the Raymond, Eagle Rock, and San Rafael fault systems. A number of factors suggest this is also a very unlikely event:

- The Eagle Rock fault zone is more complex than the Raymond because there are three subparallel faults (San Rafael, Eagle Rock, and an unnamed fault) to consider, there are very little hard data to evaluate, and the faults are more difficult to locate precisely using only borings.
- Any of the three faults could be more of the primary hazard than the other two, but equally plausible arguments can be made that they are all three similar in hazard potential, or are all effectively inactive faults now and pose no hazard.
- If they were to rupture separately as individual fault strands, their displacements would be 0.2 to 0.3 meter. Even if they were to rupture as a part of the Verdugo fault system, their displacements would be only about 1 meter.
- Of the three, only the San Rafael fault may traverse the Freeway Tunnel Alternative because the Eagle Rock and unnamed faults may terminate against the Raymond just west of the alignment.
- The width of the Eagle Rock/San Rafael faults through the Freeway Tunnel is probably small (less than 10 meters), but the three faults are separated through a distance of almost 1,000 meters.
- The drilling did reduce the uncertainty in locations of both the Raymond and San Rafael fault traces to less than 25 meters, but left open the possibility of minor secondary faults below the resolution of the drilling correlations.
- The subsurface investigation completed few borings on both sides of the Raymond and San Rafael faults in an attempt to better refine their location, width, and (in the case of the San Rafael) hazard potential.

At this time, it does not seem realistic to design for this scenario event, as it also cannot be demonstrated geologically and has probabilities as low as 1 in 10,000+ years, which would include any of the fault linkage scenarios.

Deterministic Fault Displacement Hazard Analysis (DFDHA)

An initial estimate of fault displacements was made by conducting a DFDHA. The earthquake magnitudes and the average and maximum surface rupture displacements for the faults crossing the project were estimated in the DFDHA using the length of the faults. The regression plots of Wells and Coppersmith (1994) were utilized for these estimations, as shown in Figures 7 and 8, for the various joint or cascading rupture scenarios. Figure 7 shows the various scenarios for the Raymond-Eagle Rock fault system; Figure 8 illustrates the Raymond-Hollywood rupture scenarios.

On the left-side of Figures 7 and 8, the 21-km length of the Raymond fault results in an earthquake magnitude of M6.6 to 6.9 and displacements per event of 0.5 to 0.9 meter. On the right-side plots, the Raymond fault (red) rupture is progressively combined in length with other scenario fault segments, resulting in progressively longer faults capable of larger earthquake magnitudes and rupture displacements. Table 2 summarizes these potential cascading events and their displacement magnitudes estimated using the Wells and Coppersmith (1994) plots. The assigned probabilities for the joint rupture events are best estimates based on available data.

TABLE 2
Fault Rupture Scenarios involving the Raymond Fault
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Magnitude	Rupture* (meters)	Probability (years)	Comment
Raymond	21	6.7	0.5 - 0.9	1/3000	Single fault scenario.
Eagle Rock/San Rafael	11	6.2	0.2 - 0.3	1/10,000	Single fault scenario on one or the other.
Verdugo + Eagle Rock/San Rafael	32	6.8	0.7-1.1	1/10,000	Combined based on Caltrans Fault Database.
Raymond + Eagle Rock	32	6.8	0.7 - 1.1	1/10,000	Unlikely scenario.
Raymond + Eagle Rock + Verdugo	53	7.0	1.7 - 2.0	1/15,000	Very unlikely scenario.
Raymond + Hollywood	36	6.9	0.8 - 1.3	1/10,000	Plausible scenario.
Raymond + Hollywood + Santa Monica	60	7.3	1.8 - 4.0	1/15,000	Improbable scenario.
Raymond + Hollywood + Santa Monica + Malibu	94	7.5	3.0 - 7.0	1/20,000	Very improbable scenario.

* Average and maximum rupture displacements.

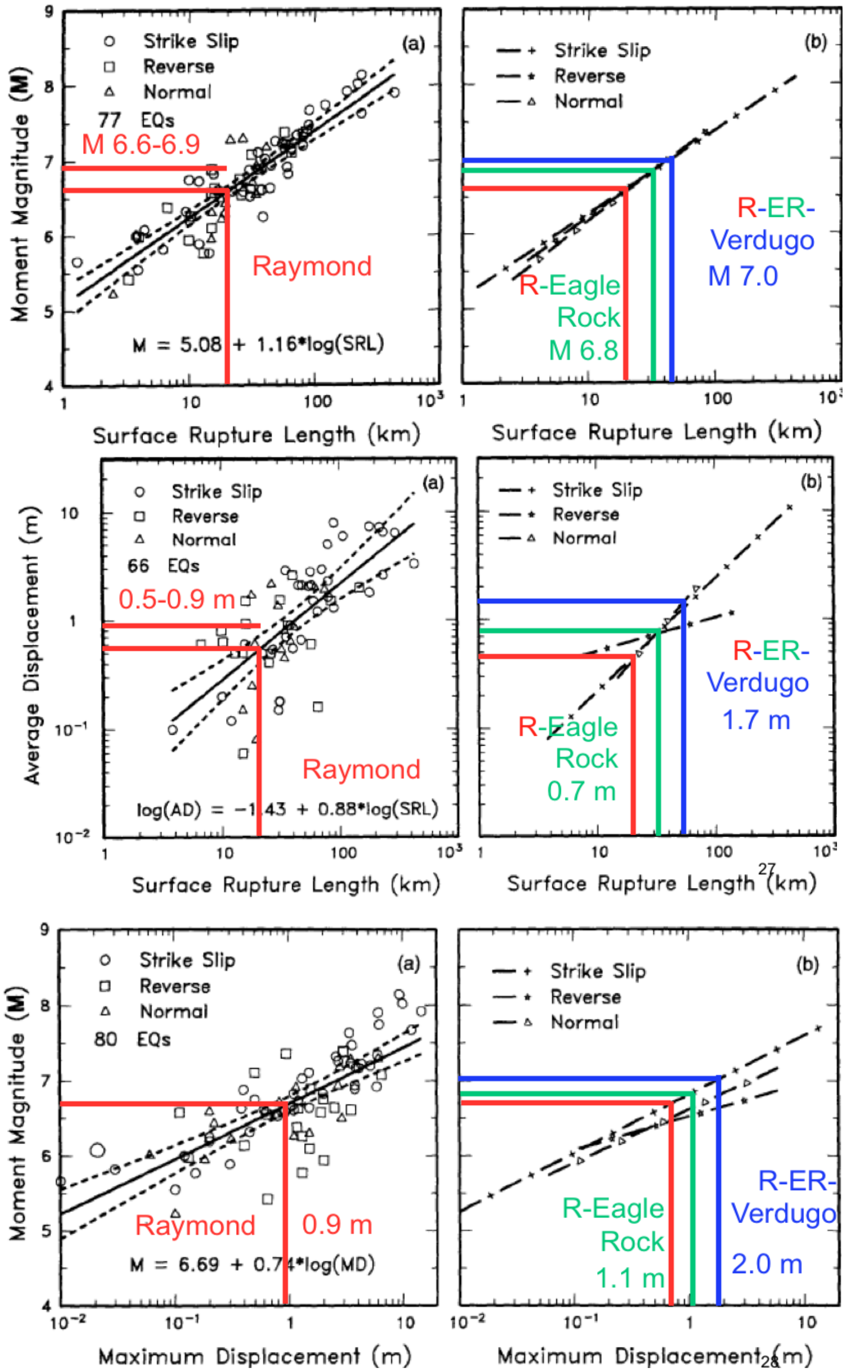


Figure 7. *Series of plots showing the increase in earthquake magnitudes and surface rupture offsets, as the length of the fault increases in a cascading rupture using the regression equation plots of Wells and Coppersmith (1994): Raymond-Eagle Rock Fault System.*

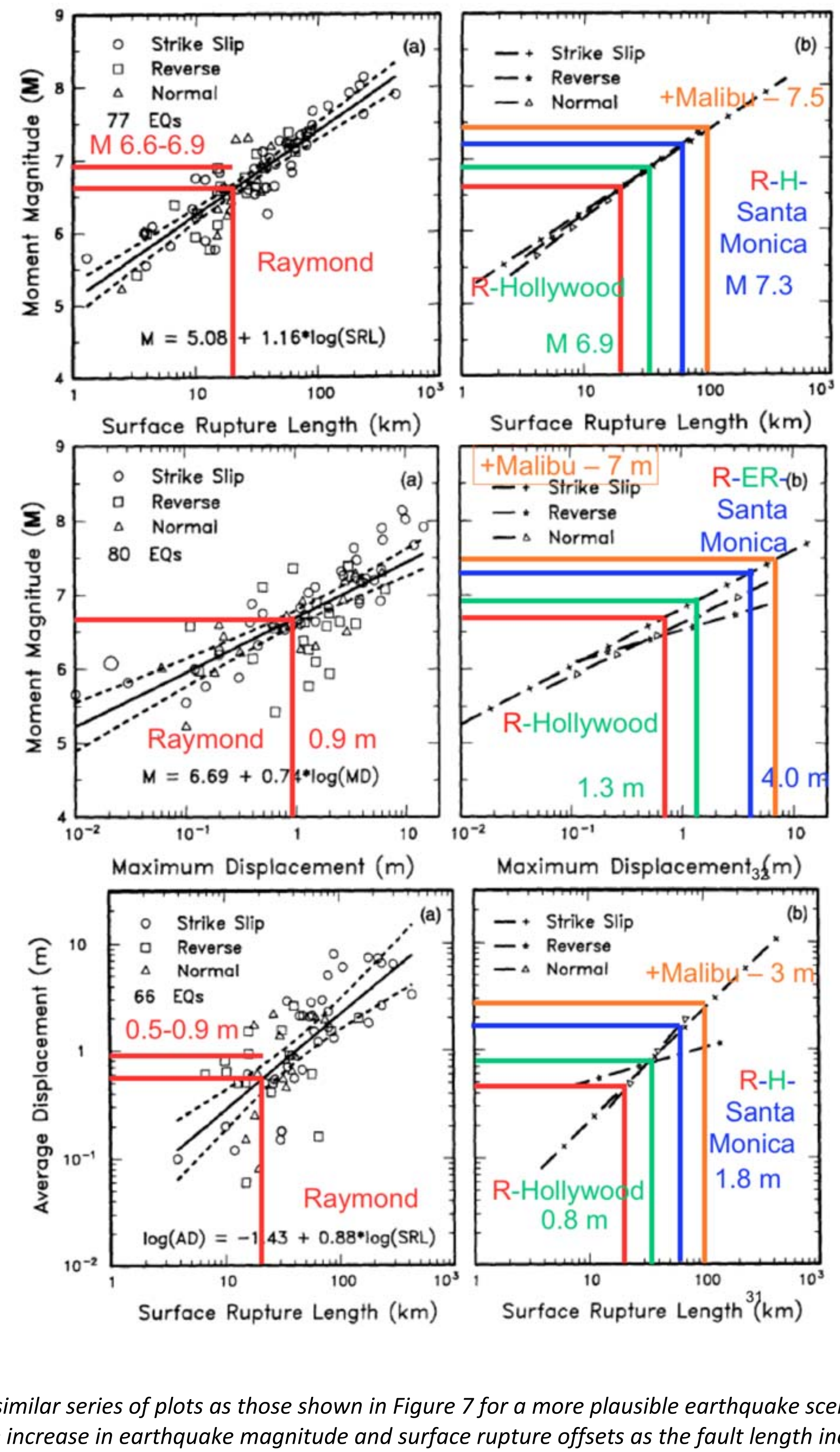


Figure 8. *A similar series of plots as those shown in Figure 7 for a more plausible earthquake scenario showing the increase in earthquake magnitude and surface rupture offsets as the fault length increases in a cascading rupture using the regression plots of Wells and Coppersmith (1994): Raymond-Hollywood-Santa Monica and Malibu Fault System.*

Note that Hanks and Bakun (2002 and 2008) and Wesnousky (2008) have reanalyzed and updated the Wells and Coppersmith plots. However, at these lower-magnitude ranges, the differences are not significant in the Hanks and Bakun model. Wesnousky (2008) replotted the Wells and Coppersmith data set by adding in more data from recent earthquakes. He generated three different fault length relationships for strike-slip faults (Relationships A, B, and C), as shown in Figure 9. Using these displacement relationships would result in larger average and maximum displacements than those estimated using the Wells and Coppersmith (1994) models, especially if the Power Law and Log-Linear relationships (B and C relationships) are used. Currently, there is no agreement on the validity of one relationship over the others, as all are considered statistically valid. The results from these Wesnousky (2008) relationships for a Raymond fault rupture of 21 km are as follows:

- Relationship A – Linear: 0.2-meter average and 0.6-meter maximum
- Relationship B – Power Law: 0.9-meter average and 2.2-meter maximum
- Relationship C – Log-Linear: 0.7-meter average and 1.6-meter maximum

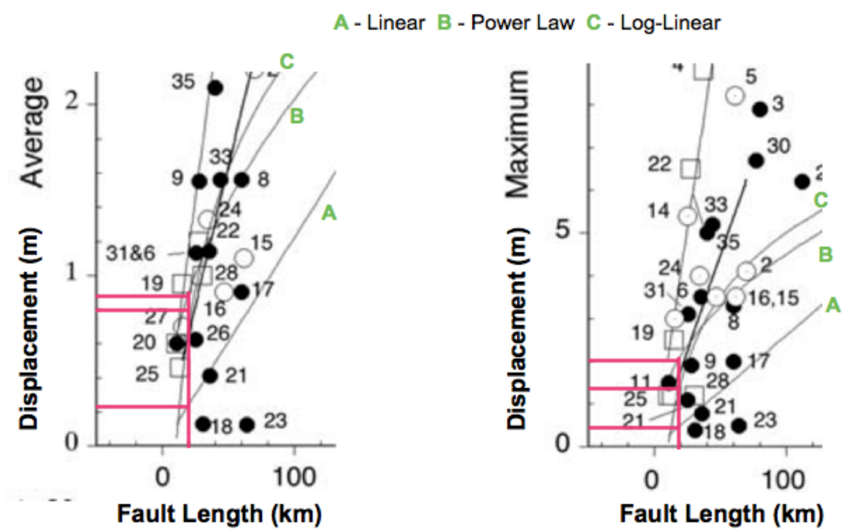


Figure 9. *Fault length – displacement plots for the Raymond fault using the Wesnousky (2008) plots. Lines A, B, and C are for strike-slip faults.*

Probabilistic Fault Displacement Hazard Analysis (PFDHA)

A PFDHA was performed for the Raymond and Eagle Rock/San Rafael faults to estimate the displacements as a function of annual rate of surface-fault displacement. The fault rupture displacements from cascading ruptures involving the Raymond fault with the Hollywood, Santa Monica, and Malibu were not considered in the PFDHA, since these cascading events cannot be demonstrated geologically and have probabilities as low as 1 in 10,000+ years. For the Eagle Rock/San Rafael fault, a combined rupture with the Verdugo fault was used in the analysis, based on the scenario shown in the Caltrans fault database (2012). For the current study, fault rupture due to principal faulting on a strike-slip fault, which is the primary faulting style of the Raymond and Verdugo-Eagle Rock/San Rafael faults, was considered.

Methodology

The methodology used in this study follows the model (Earthquake Approach) initially proposed by Youngs et al. (2003), as modified by Petersen et al. (2011) and Chen and Petersen (2011). In this model, the annual rate (v) of fault surface displacement that exceeds a specified value, d, at a site location, k, is expressed as:

$$v_k(D > d) = \propto (m^0) \int_{m^0}^{m^u} f(m)\, [\, \mathrm{P_k}(sr \neq 0 \backslash m) * \mathrm{P}\,(D > d) \backslash m)]\, dm$$

Where: $\propto (m^0)$ = annual rate of all earthquakes with magnitudes ≥ m^o

m^0 = minimum magnitude considered (M_w 5.0 was used for this study)

f (m) = probability density function of magnitude

$\mathrm{P_k}(sr \neq 0 \backslash m)$ = conditional probability that fault rupture extends to the surface (or to tunnel depth) at location k, given an earthquake with magnitude m occurs

$\mathrm{P}(D > d \backslash m)$ = conditional probability that fault displacement exceeds d, given an earthquake with magnitude m occurs

In the above equation, only the principal faulting from earthquake occurrences is considered; no secondary (distributed) fault displacement and uncertainty in the location of fault trace are modeled. The fault crossing model definition is shown in Figure 10.

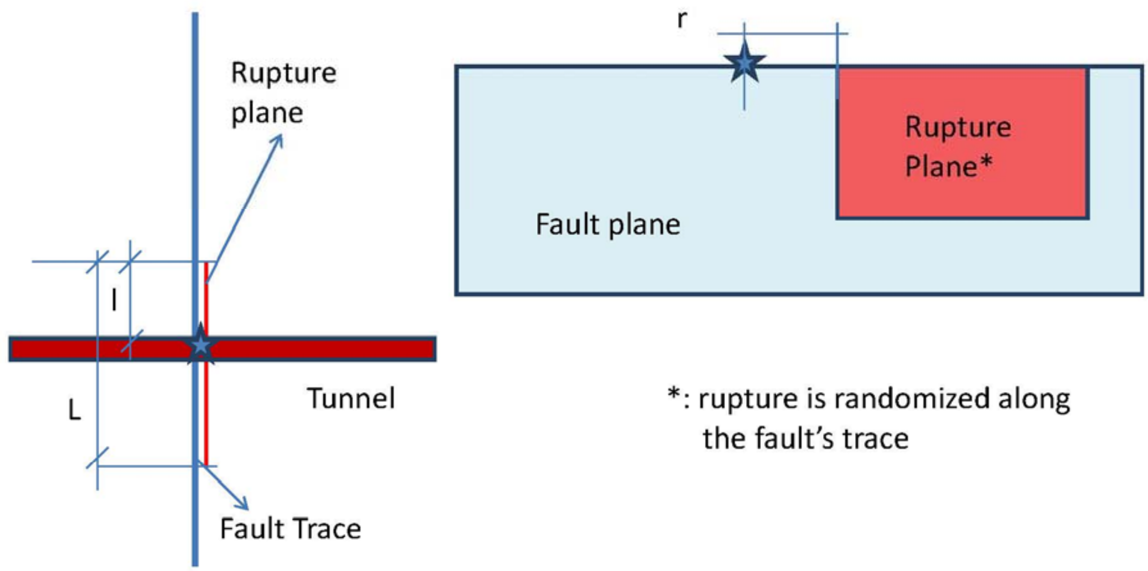


Figure 10. *Definition of Fault Crossing Model.*

The probability that nonzero displacement occurs at the tunnel depth at location k, $P_k(sr \neq 0 \backslash m)$, is calculated by randomizing the earthquake hypocenter along the fault trace and taking the ratio of fault ruptures that extend to the tunnel depth (or within a specified distance, Δ, from the tunnel depth) to the total number of ruptures for a given magnitude m. Specifically, this conditional probability of having surface rupture is estimated using the model proposed by Wells and Coppersmith (1994) for all faulting mechanisms, as follows:

$$P_k(sr \neq 0 \backslash m) = \frac{e^{a+b*m}}{1 + e^{a+b*m}} \; for \; r \leq \Delta$$

$$= 0 \qquad for \; r > \Delta$$

Since the term for the probability of having a displacement at the ground surface is included in the analyses, the hypocenter depth is not randomized. For the conditional probability that fault displacement exceeds a specified value, d, the bilinear model of Petersen et al. (2011) for strike-slip faulting was utilized:

$$\ln(D) = 1.7969 * m + 8.5206 * \left(\frac{l}{L}\right) - 10.2855 \; for \; \frac{l}{L} < \left(\frac{l}{L}\right)'$$

$$= 1.7658 * m - 7.8962 \qquad for \; \frac{l}{L} \geq \left(\frac{l}{L}\right)'$$

$$\left(\frac{l}{L}\right)' = -0.0036 * m + 0.2804$$

The standard deviations for the first and second equations in natural log units are 1.2906 and 0.9624, respectively.

Seismic Source Characteristics for PFDHA

The seismic source parameters used in the PFDHA for the Raymond and Verdugo-Eagle Rock/San Rafael faults are listed in Table 3, along with the weights assigned to the various parameter values. .

TABLE 3
Seismic Sources Parameters for PFDHA
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Seismogenic Depth (km)	Magnitude Recurrence Model	Slip-rate (mm/yr)	Maximum Magnitude
Raymond	21	13 (0.2) 15 (0.6) 17 (0.2)	Characteristic (1.0)	1.0 (0.3) 1.5 (0.3) 2.0 (0.3) 5.0 (0.1)	6.5 (0.2) 6.7 (0.6) 6.9 (0.2)
Verdugo + Eagle Rock/San Rafael	32	13 (0.2) 15 (0.6) 17 (0.2)	Characteristic (1.0)	0.6 (1.0)	6.6 (0.2) 6.8 (0.6) 7.0 (0.2)

* Values in parentheses are weights.

Four slip-rates were assigned to the Raymond fault, with the majority of weight (90 percent) given to the most probable values of 1.0 to 2.0 mm/yr (see Table 1) and a small weight (10 percent) assigned to the high value reported by Yeats (2012). The characteristic earthquake magnitude recurrence model and a b-value of 1.0 were used for the analyses.

Results of PFDHA

The calculated fault rupture hazard curves for the Raymond and Verdugo-Eagle Rock/San Rafael faults are shown in Figure 11. The calculations were performed for a Δ value of 200 meters to account for the depths of the freeway and LRT tunnels and at the LRT fault crossing locations. Since the fault crossing locations at the LRT and freeway tunnels are close to each other (relative to the length of the fault), the results calculated herein for the LRT tunnel can also be used for the freeway tunnel.

As can be seen from Figure 11, the median fault displacements at the tunnel-Raymond fault crossing location for return periods of 1,000 and 2,500 years are ±5 centimeters (0.05 meter) and ±55 centimeters (0.55 meter), respectively. The calculated displacements at the tunnel-Verdugo-Eagle Rock fault crossing location for the same return periods are insignificant (less than 1 centimeter [0.01 meter]).

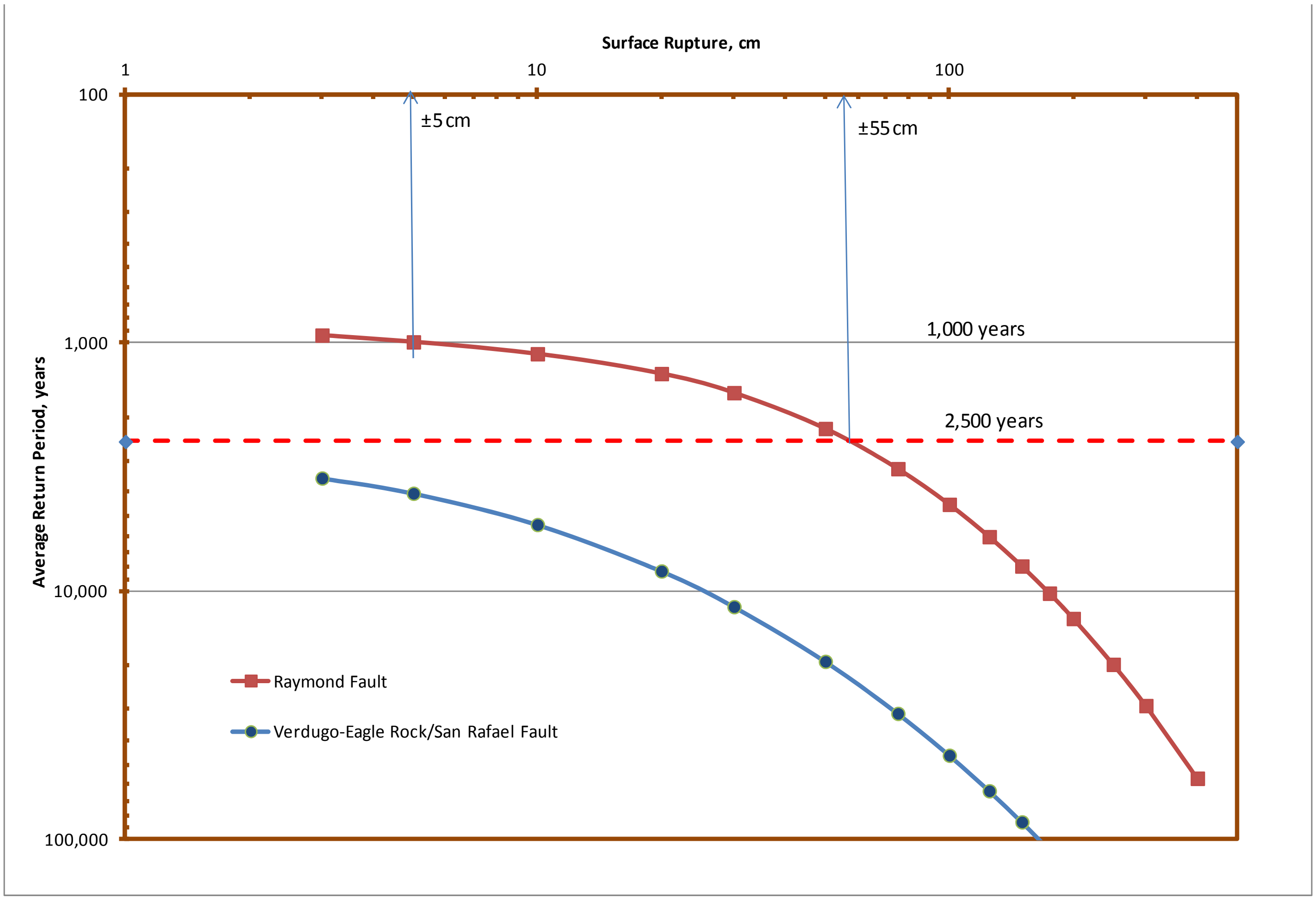


Figure 11. *Calculated Fault Displacement Hazard Curves for Raymond and Verdugo-Eagle Rock/San Rafael Faults.*

Seismic Design Criteria

The appropriate seismic design criteria for the tunnels, relative to fault displacement, will depend on whether the LRT or the Freeway Tunnel option is selected for implementation. The following two sections summarize the criteria for each of these options.

LRT Tunnel

Metro Supplemental Seismic Design Criteria (Revision 5, 2013) will be used for the LRT. It uses "Important Transit Facility" for LRT classification. Two levels of seismic event, consisting of Maximum Design Earthquake (MDE) and Operating Design Earthquake (ODE), must be considered for LRT tunnel design in accordance with the Metro Supplemental Seismic Design Criteria.

- The MDE is defined as ground motion with a 2,500-year return period; the performance under the MDE event is as follows:
  - No collapse.
  - Structures are allowed to behave in an inelastic manner.
- The ODE is defined as ground motion with a 150-year return period; the performance under the ODE event is as follows:
  - Tunnel remains serviceable; no interruption in rail service during or after ODE.
  - Structures behave essentially elastic.

Relative to Metro's seismic design criteria, the MDE and ODE requirements would have to be satisfied for fault displacements that have an average return period of 2,500 years and 150 years, respectively.

Freeway Tunnel

No Caltrans seismic design criteria for tunnels are currently available. For this preliminary design phase to support the environmental documentation, it was agreed that the Caltrans seismic design criteria for an Ordinary Nonstandard facility will be used as the basis for seismic design of the Freeway Tunnel Alternative. This facility classification is equivalent to Recovery Route classification. Two levels of seismic event, consisting of Safety Evaluation Earthquake (SEE) and Functional Evaluation Earthquake (FEE), should be considered for the Freeway Tunnel design. Project site-specific seismic design criteria will be developed in future design phases and used for final design of the Freeway Tunnel.

- The SEE is defined as ground motion with a 1,000-year return period; the performance under the SEE event is as follows:
  - Minimal to moderate damage may occur, as long as moderate damage is confined to local areas.
  - The ductility of the tunnel should be between 2.5 and 3.0, similar to the ductility used in bridge capacity design.
- The FEE is defined as ground motion with a 100-year return period; the performance under FEE is to ensure that the tunnel is fully functional with minimal damage.

Relative to Caltrans seismic design criteria, the SEE and FEE requirements would have to be satisfied for fault displacements that have an average return period of 1,000 years and 100 years, respectively.

Design Summary

The fault rupture displacements at the fault crossing locations, relative to different design criteria for the LRT and Freeway Tunnel Alternatives, are summarized below.

LRT Tunnel

The seismic design criteria for the LRT are based on a fault rupture displacement with a return period of 2,500 years for the MDE and 150 years for the ODE, as discussed above. The following displacements are recommended for preliminary design.

- **Raymond Fault:** The deterministic estimates for the average and maximum offsets using the Wells and Coppersmith (1994) model are 0.5 meter and 0.9 meter, respectively. The probabilistic estimate for the MDE is 0.55 meter, while that for the ODE is less than 0.05 meter. As discussed above, these estimates are for ruptures on the Raymond fault only; no cascading ruptures were considered because of their low probability of occurrence.

Because of the large range of inconsistencies in the geological understanding of the Raymond fault, as discussed above, a left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter is considered appropriate for the Raymond fault, across a fault zone of 25 meters in width. This is based on the maximum rupture displacement for a 21-km-long fault, with a 20 percent vertical uplift component distributed onto one major and several minor fault strands. At the proposed tunnel depth, it is estimated that 75 to 100 percent of this displacement would occur on a single (main) fault strand, while any additional deformation would most likely be distributed on the hanging wall (north side).

Note that somewhat larger displacements than Wells and Coppersmith (1994) are obtained with the Power Law and Log-Linear formula of Wesnousky (2008), while a smaller value is obtained from his linear formula. However, the Wells and Coppersmith (1994) model is the most widely used model in practice and is considered appropriate for these preliminary estimates.

- **Verdugo-Eagle Rock and San Rafael Faults:** The deterministic estimate for maximum offset using the Wells and Coppersmith (1994) model for the 11-km Eagle Rock or San Rafael fault is 0.3 meter left-lateral and 0.2 meter reverse-vertical. Combining the Verdugo fault would increase the fault length to 32 km and the maximum offset would increase to 1.1 meters. The probabilistic displacements for MDE and ODE were estimated to be insignificant.

  As discussed previously, no data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/San Rafael faults, nor on the Verdugo fault farther northwest. These faults are not in Alquist-Priolo Act fault zones, and per the Caltrans Memo to Designers (2013), they are not candidates for fault displacement mitigation. In addition, there is a large range of inconsistencies in the geological understanding of these faults and the uncertainty as to how they would rupture together and how they would interact with the Raymond fault in a joint rupture. For the purpose of this technical memorandum, prepared for the environmental documentation process, the Verdugo-Eagle Rock and San Rafael faults are considered active, though they could have a 10,000+ year recurrence rate.

  Because only the San Rafael strand of the Verdugo-Eagle Rock/San Rafael fault zone trends across the LRT tunnel alignment, it seems reasonable to reduce the 1.1 maximum displacement of the entire fault zone by about 50 percent. For the conceptual/preliminary design, therefore, preliminary design values of 0.5 meter left-lateral and 0.25 meter reverse-vertical could be considered for the LRT tunnel crossing. While this is likely a 10,000+ year event scenario, there are insufficient fault data presently to preclude it in the preliminary/conceptual design phase. These preliminary fault offset values should be updated by performing additional geological/fault investigations in future design phases.

Freeway Tunnel

The seismic design criteria for the Freeway Tunnel are based on fault rupture displacement with a return period of 1,000 years for the SEE and 100 years for the FEE, as discussed above. The following displacements are recommended for preliminary design.

- **Raymond Fault:** The deterministic estimates for the average and maximum offsets using the Wells and Coppersmith (1994) model are 0.5 meter and 0.90 meter, respectively. The probabilistic estimate for the SEE is 0.05 meter, while that for the FEE would be less than 0.05 meter. Similar to the LRT tunnels, these estimates are for ruptures on the Raymond fault only, without any contributions from the cascading events.

  Per the Caltrans Memo to Designers (2013), the design fault offset is taken as the larger of:

  – Deterministically derived *average* displacement

  – Probabilistically derived displacement consistent with a 5 percent in 50 years probability of exceedance or a 975-year return period

  Displacement estimates from the DFDHA exceed displacements from the PFDHA, and therefore, the deterministically derived average displacement should be used as a basis of design according to the Caltrans Memo to Designers (2013). Based on this Caltrans procedure, a left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter can be considered for the Raymond fault, across a fault zone of 25 meters in width. This is based on the average rupture displacement for a 21-km-long fault, with a 20 percent vertical uplift component distributed onto one major and several minor fault strands.

At the proposed tunnel depth, it is estimated that 75 to 100 percent of this displacement would occur on a single (main) fault strand, while any additional deformation would most likely be distributed on the hanging wall (north side).

- **Verdugo-Eagle Rock and San Rafael Faults:** Based on the Wells and Coppersmith (1994) model, the average deterministic displacement for an 11-km fault is 0.2 meter left-lateral and 0.1 meter reverse-vertical (can be assigned across a fault zone 50 meters in width). Combining the Verdugo fault would increase the fault length to 32 km and the average offset would increase to 0.7 meter. The SEE and FEE probabilistic displacements were estimated to be insignificant and are less than 0.01 meter.

  As discussed above in the LRT design summary, there are no published or unpublished data that indicate the San Rafael or Verdugo-Eagle Rock faults have had Holocene-age offsets. These faults are also not in Alquist-Priolo Act fault zones, and per the Caltrans Memo to Designers (2013), they are not candidates for fault displacement mitigation.

  Because the San Rafael and Eagle Rock strands of the Verdugo-Eagle Rock/San Rafael fault zone trend across the Freeway Tunnel alignment at separate locations, it seems reasonable to reduce the 1.1 maximum displacement of the entire fault zone by about 50 percent at each fault. For preliminary design, the above-mentioned deterministic fault offsets for the LRT tunnels (0.5 meter left-lateral and 0.25 meter reverse-vertical) could be considered for the Freeway Tunnel. While this is likely a 10,000+ year event scenario, there are insufficient data to preclude it in the preliminary/conceptual design phase. These preliminary fault offset values should be updated by performing additional geological/fault investigations in future design phases after the preferred Alternative is selected.

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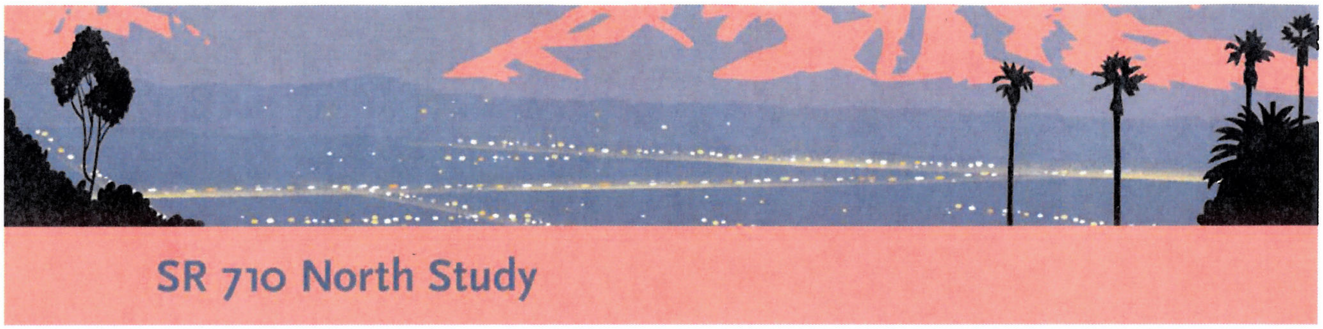
Appendix B
Preliminary Earthquake Acceleration Response Spectra Technical Memorandum



TECHNICAL MEMORANDUM

Preliminary Earthquake Acceleration Response Spectra, SR 710 North Study, Los Angeles County, California

PREPARED FOR:	Michelle Smith/Metro
COPY TO:	Caltrans
PREPARED BY:	Dario Rosidi, Ph.D., P.E., G.E./CH2M HILL Hisham Nofal, Ph.D., P.E., G.E./CH2M HILL Ravee Raveendra, P.E., G.E./CH2M HILL
DATE:	December 10, 2013
PROJECT NUMBER:	428908

REGISTERED PROFESSIONAL ENGINEER
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Introduction

This technical memorandum presents the results of preliminary seismic ground motion evaluations completed as part of environmental documentation for the State Route (SR) 710 North Study. Five Alternatives are being evaluated during the ongoing environmental documentation process. The five Alternatives are No-Build, Transportation System Management/ Transportation Demand Management [TSM/TDM], Bus Rapid Transit [BRT], Light Rail Transit [LRT], and Freeway Tunnel. Figure 1 shows the general vicinity of the SR 710 North Study area.

Seismic ground motions are an important consideration during the environmental assessment for two of the SR 710 North Study Alternatives: the Freeway Tunnel and the LRT. Both Alternatives, briefly described below, will be located in tunnels over much of their lengths:

- Freeway Tunnel (Dual Bore Option): The proposed Freeway Tunnel Alternative includes approximately 60-foot-diameter, 4.2-mile-long twin bored tunnels and cut-and-cover tunnels at both ends of the bored tunnels. The freeway tunnels will extend from the existing southern stub of SR 710 in Alhambra, north of Interstate (I)-10, and connect to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena. The invert of each tunnel will be roughly parallel to the ground surface at an average depth of about 200 feet below ground surface (bgs), except at the portals where the tunnels daylight.
- LRT: The LRT Alternative will consist of twin bored tunnels approximately 4.5 miles long, and will be located between Valley Boulevard on the south and the existing Fillmore Station on the Metro Gold Line on the north. The LRT Alternative will also consist of approximately 3.0 miles of overhead structure from the Metro Civic Center Station on the south to Valley Boulevard on the north. The LRT tunnel invert depth is approximately 80 feet bgs; the diameter is approximately 20 feet.

The two proposed tunnel alignments are located in a seismically active region of southern California and will cross through active fault zones, necessitating the development of earthquake ground motions along these alignments for design of the tunnels and aboveground structures. The discussion and development of fault rupture displacements at the tunnel crossing locations are presented in a separate technical memorandum titled, *Fault Rupture Evaluation for the SR 710 North Study, Los Angeles County, California* (CH2M HILL and Earth Consultants International [ECI], 2013).

This technical memorandum presents preliminary peak ground accelerations (PGAs) and peak ground velocities (PGVs) for the conceptual design of the proposed tunnels and other project features within the Freeway Tunnel and LRT Alternatives, as required for the environmental assessment. In addition, 5 percent damped acceleration response spectra (ARS) were also developed for the elevated LRT sections. These ground motion parameters were developed using the probabilistic and deterministic ground motions obtained from the United States Geological Survey (USGS) and California Department of Transportation (Caltrans) Web sites. The ground motions were developed based on the subsurface conditions interpreted from the limited geotechnical field investigations conducted by CH2M HILL during the current study and the SR 710 Tunnel Technical Study (CH2M HILL, 2010), and therefore are preliminary.

These preliminary ground motion parameters will be updated in the future once a decision is made on the final Alternative for development. Additional field investigations will be conducted in future phases of the project to provide more specific geotechnical information for the selected Alternative. The results of these future field investigations will be used to update and verify these parameters after the preferred Alternative is selected.

Previous CH2M HILL Field Investigation

The SR 710 Tunnel Technical Study field investigation was conducted from January to May 2009 (CH2M HILL, 2010). The program included nine core borings, geophysical surveys along three seismic reflection lines, and 14 multichannel analysis of surface wave (MASW) tests in the vicinity of the proposed LRT and Freeway Tunnel Alternatives. The typical depth of the core borings was about 400 feet; the lengths of the seismic line ranged from approximately 1,600 feet to 1,900 feet; and the depth of measurement for the MASW was up to 200 feet. The information obtained from these explorations and previous studies was used to develop a preliminary interpretation of geologic and groundwater conditions along the proposed Alternatives.

SR 710 North Study Field Investigation

The current field investigation program involved explorations along the tunnel alignments for the LRT and Freeway Tunnel Alternatives, and in proximity to faults that have been identified near these tunnel alignments. The purpose of these additional explorations was to supplement previous geotechnical information by collecting additional geologic and groundwater information specific to the Freeway Tunnel and LRT alignments.

The following types and depths of investigations were carried out:

- LRT Alignment: Six hollow-stem auger (HSA)/rotary wash (RW) borings were drilled to a depth of approximately 100 feet bgs for the LRT alignment. These explorations were located along the LRT alignment to characterize the subsurface conditions and were placed between the previously drilled boring locations.
- Freeway Tunnel Alignment: Five HSA/rotary core borings associated with the Freeway Tunnel alignment were drilled to depths up to 280 feet bgs to evaluate the subsurface materials in the vicinity of the proposed tunnel. The explorations were widely spaced and located between the previously drilled boring locations.
- Fault Characterization Studies: Ten HSA borings at depths ranging from 75 to 125 feet within the alluvial soils, and two sonic borings at depths ranging from 270 to 280 feet were drilled for characterization of the Raymond, Eagle Rock, and San Rafael faults. The explorations were closely spaced and located on both sides of the faults.

Sampling intervals within the HSA/RW borings varied from every 5 feet in soils to continuous sampling within the bedrock. Continuous sampling was conducted to the total depth of the boring within the sonic borings and the HSA borings performed for the fault characterization. The previous and current CH2M HILL boring locations are shown in Figure 2.

Subsurface Conditions

Based on the current and previous field exploration data, the site conditions that could affect the project design and construction can be summarized as follows:

- The subsurface conditions along the proposed LRT and Freeway Tunnel alignments consist of various soil and rock deposits including alluvium, weak sedimentary rock (Fernando, Puente, and Topanga Formations), and igneous and metamorphic basement complex rocks (Wilson Quartz Diorite).
- The rock formations within the proposed area for the tunnel sections of each alignment exhibit a wide range of strength (from very weak to weak sedimentary rocks, to weak to higher-strength igneous and metamorphic rocks).
- The alluvium at the tunnel portals and along the elevated portion of the LRT alignment comprises primarily medium-dense to very dense sand and silty sand with localized beds or lenses of gravel, cobbles, and clay.
- The groundwater varies considerably along the proposed tunnel alignments, and generally occurs in the alluvial deposits. The estimated depth ranges from about 20 feet near the south end of the Freeway Tunnel to more than 100 feet near the northern terminus of the proposed Freeway Tunnel and LRT alignments. Rock formations in the project area are not considered water-bearing layers.

Liquefaction potential in the alluvial soils at the tunnel portals and along the elevated and tunnel portions of the LRT alignment will be evaluated in future design phases after field explorations are completed within the potential liquefiable areas.

Earthquake Sources

The proposed Alternatives are located within a seismically active region of southern California, dominated by active northwest-trending strike-slip and reverse faults. Fault data and information from several sources were reviewed for this study, including the California Geological Survey (CGS), USGS, Caltrans, and Southern California Earthquake Center (SCEC).

Significant active and potentially active faults are mapped within the general vicinity of the project area. The seismic sources that may generate strong earthquake ground shaking along the proposed alignments, as well as their seismic source parameters, are listed in Table 1. The locations of the proposed Alternatives relative to these faults and the more distant faults are shown in Figure 3.

TABLE 1
Summary of Nearby Active and Potentially Active Faults
SR 710 North Study, Los Angeles County, California

Fault Name	Faulting Style[1]	Probability of Activity	Maximum/ Characteristic Magnitude	Dip (degrees/ direction)
Raymond	ss	1.0	6.7	79 (N)
Hollywood	ss	1.0	6.6	70 (N)
Raymond + Hollywood	ss	1.0	6.9	70-79 (N)
Verdugo – Eagle Rock/San Rafael	r	1.0	6.8	55 (NE)
Alhambra Wash (East Montebello)	rl-r-o	1.0	6.25	NA
Elsinore Fault Zone (Whittier)	ss	1.0	6.9	75 (NE)
Sierra Madre Fault Zone (Clamshell – Sawpit)	r	1.0	6.6	50 (N)
Sierra Madre Fault Zone (Sierra Madre)	r	1.0	7.2	53 (N)
Newport – Inglewood – (North Los Angeles Basin)	ss	1.0	7.2	88 (NE)
Puente Hills Blind Thrust (LA)	r	0.5	6.9	27 (NE)
Upper Elysian Park	r	0.5	6.6	50 (N)

Source: CGS (2002), USGS (2008a), Caltrans Fault Data Base (2012), SCEC (2012), ECI (2013), and CH2M HILL (2010)
[1] ll – left-lateral; rl – right-lateral; r – reverse; o – oblique; ss – strike-slip
N = north; NE = northeast; NA = not available

The active seismic sources that cross the proposed alignments are the Raymond fault and the Verdugo-Eagle Rock-San Rafael fault system. There are hypotheses that the Raymond fault may rupture together with the adjacent Hollywood, Santa Monica, and Malibu faults, or with the Eagle Rock and Verdugo faults. However, these cascading fault rupture events are judged to be unlikely or improbable (CH2M HILL and ECI, 2013), and are not considered in the ARS development.

Shear Wave Velocity Data

Seismic velocity measurements were made in the nine core borings (CH2M HILL, 2010) using downhole geophysical methods. These tests were conducted to obtain the shear and compressional wave velocities of the various soil and rock strata underlying the proposed alignments. Depths of the velocity measurements extend from the ground surface to approximately 200 to 300 feet bgs, depending on location.

Velocity data obtained from these measurements are grouped as follows:

1. Alluvial Deposits: Consisting of clay, silt, and sand, with gravels, cobbles, and some boulders. Shear wave velocity data from borings R-09-Z1B8, R-09-Z2B5, R-09-Z3B2, R-09-Z3B3, R-09-Z3B4, R-09-Z3B8, R-09-Z3B12, and R-09-Z4B4 were used to estimate the shear wave velocity profile in the alluvial deposits.
2. Sedimentary Rock: Including Tertiary-age Fernando, Puente, and Topanga Formations. Because of the large scatter in the velocity data measured in these formations, the sedimentary rock group was further divided into very weak and weak rocks. Velocity data for the very weak rocks were obtained from borings R-09-Z1B8, R-09-Z3B8, R-09-Z3B12, and R-09-Z4B4; data for weak rock were obtained from boring R-09-Z3B6.
3. Metamorphic and Igneous Rock: Including the basement complex rocks that consist of Mesozoic-age crystalline igneous and metamorphic rocks. Velocity data for this group were obtained from borings R-09-Z3B2, R-09-Z3B3, and R-09-Z3B4.

Plots of the measured shear wave velocities and the calculated means and means plus-and-minus one standard deviation versus depth for these three geologic groups are depicted in Figure 4. Compressional wave velocities obtained during the downhole geophysical testing are summarized in CH2M HILL (2010).

Preliminary Geologic Profiles

Review of the generalized geologic cross-sections developed along the Freeway Tunnel and LRT alignments identified soil and rock conditions with variable thicknesses and properties. These variable subsurface conditions will result in earthquake ground motions of different characteristics along the proposed alignments.

For this preliminary seismic evaluation, geologic profiles at nine locations (FT-1 through FT-5 on the Freeway Tunnel alignment, and LRT-1 through LRT-4 on the LRT alignment) were selected to represent the variation in the subsurface conditions and their proximity to the nearby seismic sources. Geologic profiles FT-1 through FT-5 and LRT-3 and LRT-4 represent site conditions along the tunnel alignments, while those at LRT-1 and LRT-2 represent site conditions along the elevated LRT structure (surface structure). The locations of these selected geologic profiles for the Freeway Tunnel and LRT alignments are shown in Figure 5.

For the development of ARS, including PGA and PGV, the average shear wave velocity in the upper 100 feet of the underlying foundation soils/rocks was used to account for the effects of local soils. For underground tunnels, the shear wave velocity that will affect the ground motions was assumed to be the average value within the 100-foot soil/rock column directly underlying the invert of the tunnel. Shear wave velocities at the tunnel depth ranged from 1,800 feet per second (fps) to 2,500 fps, and therefore generally represented firm-ground/soft-rock conditions.

For this preliminary evaluation, average shear wave velocities were used to predict the spectral acceleration values at the ground surface for the elevated LRT alignment and PGA and PGV at the tunnel inverts using published ground motion attenuation relationships. This approach is believed to be conservative for the tunnel sections since the ground motions below the tunnel do not capture near-surface ground motion increases, which are included in the ground motion attenuation relationships, and therefore, will likely result in an overestimating of ground motions, particularly for the deeper Freeway Tunnel Alternative. Spectral acceleration values estimated using the attenuation relationships are for the free-field outcropping motions, and could be adjusted for the effects of reflected waves and dynamic responses of the overlying soil deposits and tunnel structure. Dynamic site-specific response analysis will be performed in subsequent design phases to quantify these effects.

Table 2 summarizes the average shear wave velocities of the 100-foot zones below the tunnel inverts and elevated LRT section at the selected geologic profile locations.

TABLE 2
Selected Geologic Profiles and Average Shear Wave Velocities
SR 710 North Study, Los Angeles County, California

Geologic Profile	Approximate Station[1] (feet)	Latitude/Longitude (degrees)	Geology Types	Approximate Tunnel Invert Depth (feet)	Average Shear Wave Velocity[2] (fps)
			Tunnel Profiles		
FT-1	1480+30 (A-line)	34.072/-118.161	Alluvium/Sedimentary Rock	40	1,800
FT-2	1520+00 (A-line)	34.082/-118.161	Alluvium/Sedimentary Rock	180	2,500
FT-3	1656+00 (A-line)	34.119/-118.156	Alluvium/Sedimentary Rock	220	2,500
FT-4	1692+00 (A-line)	34.129/-118.155	Alluvium/Sedimentary Rock/ Metamorphic and Igneous Rock	205	2,500
FT-5	1734+90 (A-line)	34.141/-118.155	Alluvium/Metamorphic and Igneous Rock	70	1,800
LRT-3	263+00 (LRT-line)	34.095/-118.152	Alluvium/Sedimentary Rock	75	2,000
LRT-4	351+40 (LRT-line)	34.119/-118.150	Alluvium/Sedimentary Rock	95	1,900
			Elevated LRT Profiles		
LRT-1	11+00 (LRT-line)	34.035/-118.162	Alluvium/Sedimentary Rock	NA	1,300[3]
LRT-2	65+90 (LRT-line)	34.047/-118.166	Sedimentary Rock	NA	1,300[3]

1 A-line refers to stations along the Freeway Tunnel alignment; LRT-line refers to stations along the LRT alignment.
2 Average shear wave velocity of the 100-foot zones below the tunnel invert.
3 Average shear wave velocity of the 100-foot zone below the ground surface.
fps = feet per second
NA = not applicable

Estimated Earthquake Ground Motions

Preliminary ARS curves were developed in this study at the two geologic profile locations along the elevated LRT alignment (LRT-1 and LRT-2). For the geologic profiles that represent the site conditions along the tunnels (FT-1 through FT-5, LTR-3 and LTR-4), only PGA and PGV were estimated. The response spectra represent 5 percent damped responses for horizontal motions.

Both probabilistic and deterministic methods were utilized to estimate the 5 percent damped ARS values. In the probabilistic analysis, response spectral values for various ground motion return periods were calculated by considering the site and regional seismic sources and their seismic parameters and activities. In the deterministic analysis, ground motions were estimated from the occurrences of maximum earthquakes on nearby seismic sources at their closest distances to the geologic profile locations.

Probabilistic Response Spectra for Horizontal Motion

The probabilistic ARS values at the selected geologic profile locations were estimated using the 2008 USGS ground motion model, as provided in the USGS interactive Web application (https://geohazards.usgs.gov/deaggint/2008; Petersen et al., 2008). For each of the selected profiles, the USGS ground motion model was used to provide spectral accelerations for 10 periods at hazard levels of 1 percent, 2 percent, 5 percent, 10 percent, 20 percent, and 50 percent probabilities of exceedance in 50 years. These probabilities of exceedance correspond to average return periods (ARPs) of 4,975 years, 2,475 years, 975 years, 475 years, 224 years, and 72 years, respectively.

The calculated spectral values were subsequently used to develop hazard curves for the 10 periods and 9 profile locations. The 5 percent damped response spectra for ARPs of 100, 150, 1,000, 1,500, and 2,500 years were then estimated from these hazard curves by interpolating between calculated values. These interpolations were made to provide ground motions at return periods consistent with Caltrans and Metro criteria (see Seismic Design Criteria section below for discussion of Caltrans and Metro criteria). The average shear wave velocities in the 100-foot zone below the tunnel inverts or ground surface for the elevated LRT section used in the hazard calculations for the selected geologic profiles are listed in Table 2. The near-fault and basin effects were applied to the calculated probabilistic spectra following Caltrans procedures (Caltrans, 2013). This procedure accounted for near-fault effects by increasing the spectral values by 20 percent for periods greater than 1.0 second, and linearly up to 20 percent for periods between 0.5 and 1.0 second.

Figures 6 and 7 show the calculated probabilistic ARS curves for the various ARPs at the two elevated LRT geologic profile locations (LRT-1 and LRT-2). In addition, the Caltrans online probabilistic ARS curves are also included in these figures. Note that the Caltrans online ARS curves are for ground motions with a return period of 975 years; hence they are slightly lower than the ARS curves calculated for a 1,000-year return period. The PGA and PGV values at the nine selected profile locations along the LRT and Freeway Tunnel alignments were estimated for a number of ground motion return periods. The PGV values were estimated from the 1.0-second spectral acceleration using the formula given by the Federal Highway Administration (FHWA) in *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* (FHWA, 2009). The estimated PGA and PGV values are summarized in Table 3.

TABLE 3
Summary of Estimated PGA and PGV Values
SR 710 North Study, Los Angeles County, California

Profile Location	Peak Ground Acceleration (PGA) (g)				Peak Ground Velocity (PGV) (inch/sec)			
	(100 years)	(150 years)	(1,000 years)	(2,500 years)	(100 years)	(150 years)	(1,000 years)	(2,500 years)
Tunnel Profiles								
FT-1	0.23	0.30	0.78	1.07	13	16	44	64
FT-2	0.21	0.28	0.75	1.05	10	13	35	50
FT-3	0.23	0.30	0.84	1.15	11	14	40	57
FT-4	0.23	0.30	0.84	1.13	11	14	40	57
FT-5	0.25	0.33	0.84	1.14	13	17	46	65
LRT-3	0.24	0.31	0.80	1.09	13	17	45	64
LRT-4	0.24	0.32	0.87	1.18	14	18	51	73
Elevated LRT Profiles								
LRT-1	0.24	0.30	0.67	0.90	17	21	51	72
LRT-2	0.24	0.30	0.71	0.97	15	19	49	71

g = acceleration due to gravity

inch/sec = inches per second

The calculated PGA values along the proposed Freeway Tunnel alignment at a depth of approximately 200 feet bgs vary from 0.75g to 0.84g for the ground motions with a return period of 1,000 years. Along the LRT alignment, the calculated PGAs for a return period of 1,000 years range from 0.67g to 0.87g.

Table 4 summarizes the magnitude-distance combinations and largest contributors that control the PGA for the 975-year return period ground motion at the selected profile locations. As shown in Table 4, the PGAs along the two proposed alignments are dominated by the Raymond fault and the Upper Elysian Park blind thrust fault system.

TABLE 4
Controlling Magnitude-Distant Pairs at Selected Geologic Profiles (PGA for 975-year return period ground motion)
SR 710 North Study, Los Angeles County, California

	Controlling Seismic Event		
Profile Location	**Mean Distance (km)**	**Mean Magnitude**	**Largest Contributor**
Tunnel Profiles			
FT-1	6.3	6.6	Upper Elysian Park
FT-2	6.0	6.6	Upper Elysian Park
FT-3	4.7	6.6	Raymond fault
FT-4	5.2	6.6	Raymond fault
FT-5	6.0	6.6	Raymond fault
LRT-3	6.2	6.6	Upper Elysian Park
LRT-4	4.8	6.6	Raymond fault
Elevated LRT Profiles			
LRT-1	8.5	6.6	Upper Elysian Park
LRT-2	7.4	6.6	Upper Elysian Park

km = kilometer(s)

Deterministic Response Spectra for Horizontal Motion

Five percent damped deterministic median ARS values were calculated by CH2M HILL using the Caltrans ARS online tool (version 2.2.06; http://dap3.dot.ca.gov/ARS_Online). For each of the selected profiles, ground motions were estimated from the controlling fault(s) as the average of the median spectral values predicted from the attenuation relationships developed by Chiou and Young (2008) and Campbell and Bozorgnia (2008). The maximum magnitudes, faulting styles, and distances to the various seismic sources are based on the Caltrans fault database (2012). Similar to the probabilistic analysis, the near-fault and basin effects were applied to the deterministic spectra following Caltrans procedures. Figures 6 and 7 depict the calculated deterministic ARS, in comparison to the probabilistic ARS for the two elevated LRT geologic profile locations.

The deterministic ground motions are dominated by the Upper Elysian Park and Puente Hills blind thrust fault systems along the southern portion of the alignments, while the Raymond fault controls the hazards along the northern portion of the proposed Alternatives.

The calculated median PGA along the proposed Freeway Tunnel alignment varies from 0.62g to 0.74g, while the same value along the LRT alignment ranges from 0.62g to 0.69g. These deterministic PGA values at the selected profile locations are lower than the probabilistic PGA values estimated for the 975-year return period (or nominal 1,000-year return period).

Seismic Design Criteria

The appropriate seismic design criteria will depend on whether the LRT or the Freeway Tunnel Alternative is selected for implementation. The following subsections summarize the Caltrans and Metro seismic design criteria for each of these options.

LRT

Metro Supplemental Seismic Design Criteria (Revision 5, 2013) will be used for the LRT. It uses "Important Transit Facility" for LRT classification. Two levels of seismic event, consisting of Maximum Design Earthquake (MDE) and Operating Design Earthquake (ODE), must be considered for LRT tunnel design, in accordance with this Metro Supplemental Seismic Design Criteria.

- The MDE is defined as ground motion with a 2,500-year return period; the performance under the MDE event is as follows:
  - No collapse.
  - Structures are allowed to behave in an inelastic manner.
- The ODE is defined as ground motion with a 150-year return period; the performance under the ODE event is as follows:
  - Tunnel remains serviceable; no interruption in rail service during or after ODE.
  - Structures behave essentially elastic.

Freeway Tunnel

No Caltrans seismic design criteria for tunnels are currently available. For this preliminary design phase to support the environmental documentation, it was agreed that the Caltrans seismic design criteria for an Ordinary Nonstandard facility will be used as the basis for seismic design of the Freeway Tunnel. Project site-specific seismic design criteria will be developed in future design phases and used for final design of the Freeway Tunnel.

This facility classification is equivalent to Recovery Route classification. Two levels of seismic event, consisting of Safety Evaluation Earthquake (SEE) and Functional Evaluation Earthquake (FEE), must be considered for the Freeway Tunnel design.

- The SEE spectral acceleration at any period is defined as the largest of the following (Caltrans, 2013):
  - A probabilistic spectral value for a 5 percent chance of being exceeded in 50 years, which is equivalent to an ARP of 975 years.
  - A deterministic median spectral value estimated using the maximum magnitude, as defined by CGS, for any faults near the site.
  - A minimum spectral value defined as the median spectral value generated by a magnitude 6.5 earthquake on a strike-slip fault at a distance of 12 km from the site.

  The design spectrum is further modified to account for the near-fault and basin effects by increasing the spectral values by 20 percent for periods greater than 1.0 second, and linearly up to 20 percent for periods between 0.5 and 1.0 second. As mentioned above, the deterministic PGA values at the selected profile locations are lower than the 975-year probabilistic PGA values; therefore, the 975-year (or nominal 1,000-year) probabilistic values should be used for SEE.

  The performance criteria under SEE are as follows:
  - Minimal to moderate damage may occur, as long as moderate damage is confined to local areas.
  - The ductility of the tunnel should be between 2.5 and 3.0, similar to the ductility used in bridge capacity design.
- The FEE is defined as ground motion with a 100-year return period; the performance under FEE is to ensure that the tunnel is fully functional with minimal damage.

Based on the seismic design discussion with Caltrans for the Freeway Tunnel Alternative, the same seismic design criteria used for bored tunnel also should be used for the cut-and-cover tunnel section, portal structures, retaining walls, and slopes.

Vertical Ground Motions

A preliminary assessment of vertical ground motions was made, as these ground motions may be critical for the seismic design of tunnels and elevated structure, particularly if the site is located within 10 km of an active fault

(Applied Technology Council/Multidisciplinary Center for Earthquake Engineering Research [ATC/MCEER], 2003). Both the Freeway Tunnel and LRT Alternatives cross active faults, and therefore, vertical ground motions warrant consideration.

The PGA and 1.0-second spectral acceleration for vertical motion were developed using vertical-to-horizontal (V/H) ratios proposed by Bozorgnia and Campbell (2004) and by Gulerce and Abrahamson (2011). These ratios are a function of period, site distance, earthquake magnitude, anticipated site conditions, and ground motion intensity.

Based on the results of probabilistic and deterministic analyses, the ground motions along the Freeway Tunnel and LRT alignments are dominated by earthquakes with magnitudes between 6.6 and 6.9, occurring at distances less than 10 km. Using the average of the above two models and considering the ranges of magnitude, distance, expected site conditions, and design earthquakes, preliminary V/H ratios of 0.85 and 0.52 were determined for the PGA and 1.0-second spectral acceleration values, respectively, for vertical motion along the tunnel sections. For the elevated LRT sections, V/H ratios of 0.95 and 0.45 were estimated for the PGA and 1.0-second spectral values, respectively. These V/H ratios will be updated during future phases of the project using the results of additional investigations and after the preferred Alternative is selected.

Conclusions

Preliminary design earthquake ground motion parameters (5 percent damped response spectra and PGA and PGV values) have been developed for the proposed Freeway Tunnel and LRT Alternatives at nine locations along the alignments. Both probabilistic and deterministic response spectra were developed and used. The probabilistic ground motions were estimated for ARPs of 100, 150, 1,000, 1,500, and 2,500 years using the USGS hazard model. For the deterministic ground motions, the median spectral values of the controlling fault(s) were calculated using ground motion attenuation relationships recommended by Chiou and Young (2008) and Campbell and Bozorgnia (2008).

Results of these analyses show that PGAs could range from 0.75g to 0.84g for the Freeway Tunnel alignment and from 0.67g to 0.87g for the LRT alignment, based on a 7 percent probability of exceedance in 75 years (nominal 1,000-year return period). Based on median deterministic methods, median PGAs range from 0.62g to 0.74g for the Freeway Tunnel alignment and from 0.62g to 0.69g for the LRT alignment. Vertical motions at the zero-second (that is, PGA) and 1.0-second periods are estimated to be roughly 85 and 52 percent of the corresponding horizontal ground motion values, respectively, along the tunnel sections. For the elevated LRT sections, vertical motions at PGA and 1.0-second periods are estimated to be roughly 95 and 45 percent of the corresponding horizontal ground motion values, respectively.

The effects of the overlying soil/rock deposits and tunnel structure to the design ground motions were not considered in this preliminary evaluation; however, they will be evaluated in the future design phases. Liquefaction potential of the alluvial deposits and the effects to ground motions and the 5-percent-damped response spectra for horizontal and vertical motions also will be evaluated.

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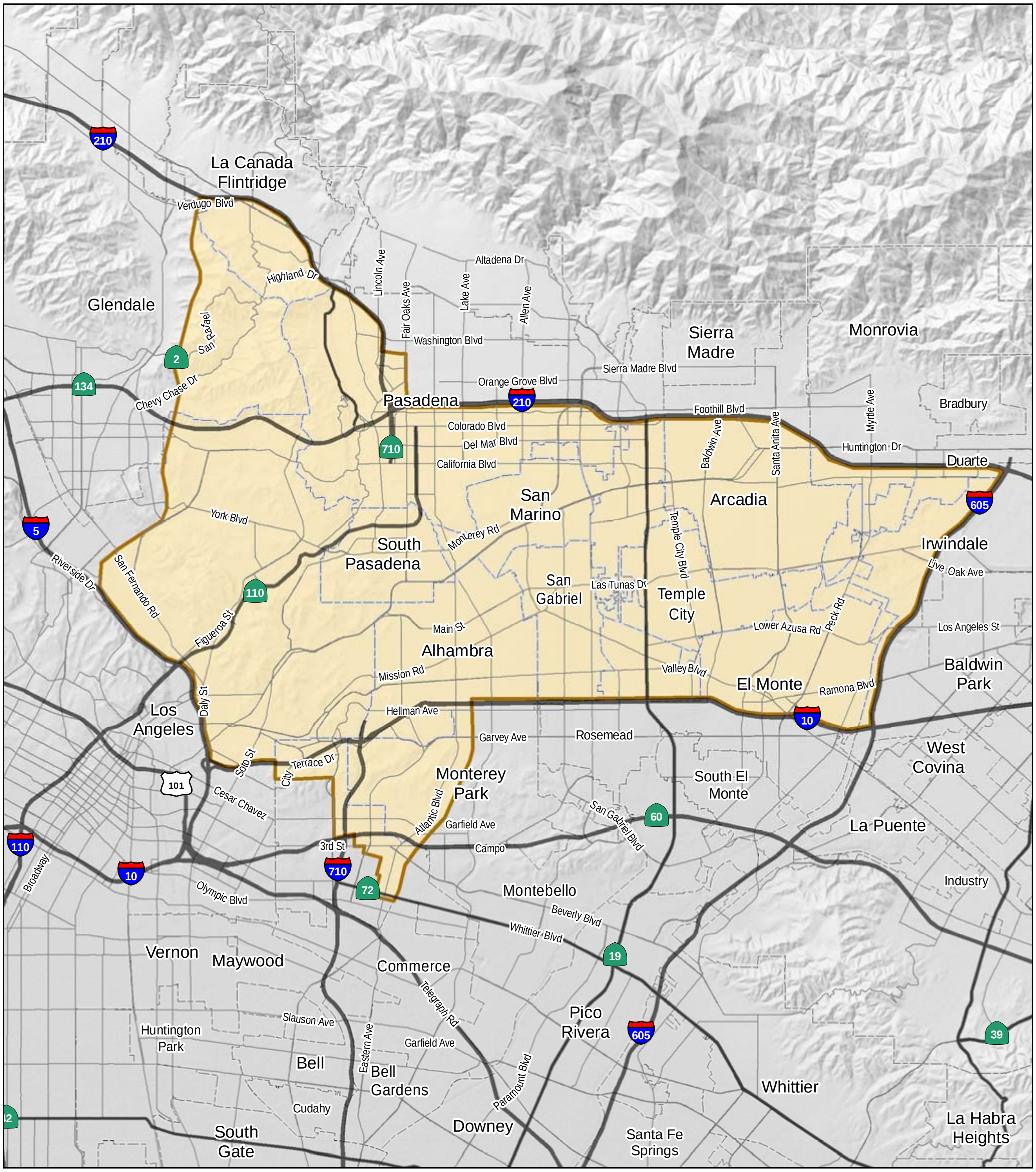
Figures



LEGEND

SR 710 North Study Area

N

0 1.25 2.5
MILES

FIGURE 1
STUDY AREA MAP
SR 710 North Study,
Los Angeles County, California

SOURCE: ESRI (2008)

CH2MHILL.

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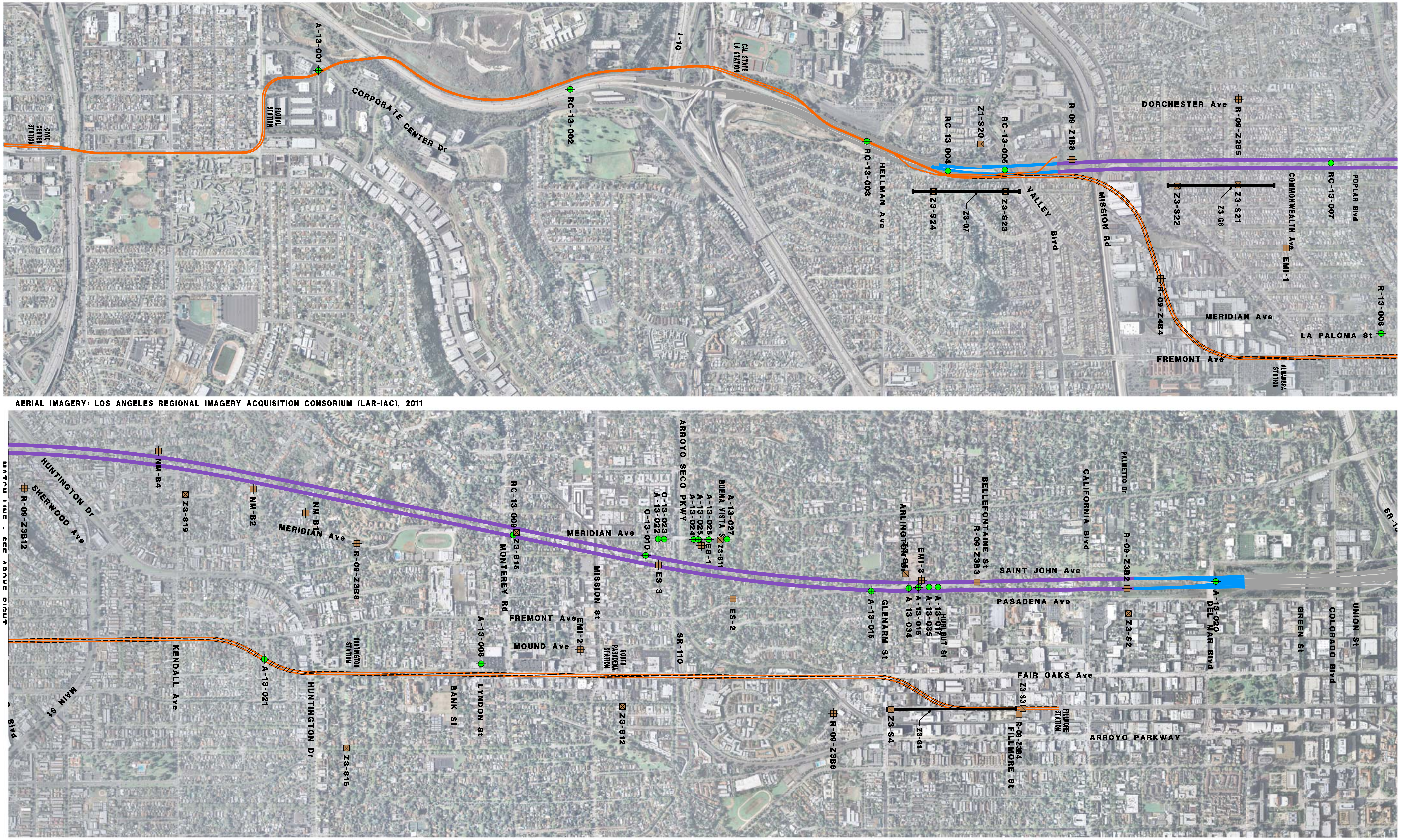

LEGEND:

(blue)	FREEWAY TUNNEL ALTERNATIVE, CUT & COVER TUNNEL
(purple)	FREEWAY TUNNEL ALTERNATIVE, BORED TUNNEL
(gray)	FREEWAY TUNNEL ALTERNATIVE, SURFACE
(orange line)	LRT ALTERNATIVE, ELEVATED
(orange dashed line)	LRT ALTERNATIVE, TUNNEL
A, R, RC, or O-13-001	CURRENT BORINGS (CH2M HILL and ECI, 2013)
Z3-G6	SEISMIC REFLECTION LINE (CH2M HILL, 2010)
Z3-S22	MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW), (CH2M HILL, 2010)
NM-B4; EMI-3; ES-2	PREVIOUS BORINGS (Ninyo and Moore, 1999; Earth Mechanics Inc., 2006; Caltrans, 1974)

0 600' 1200' 1800'

SCALE: 1" = 600'

FIGURE 2

Boring Location Map

SR 710 North Study,

Los Angeles County, California

CH2MHILL.

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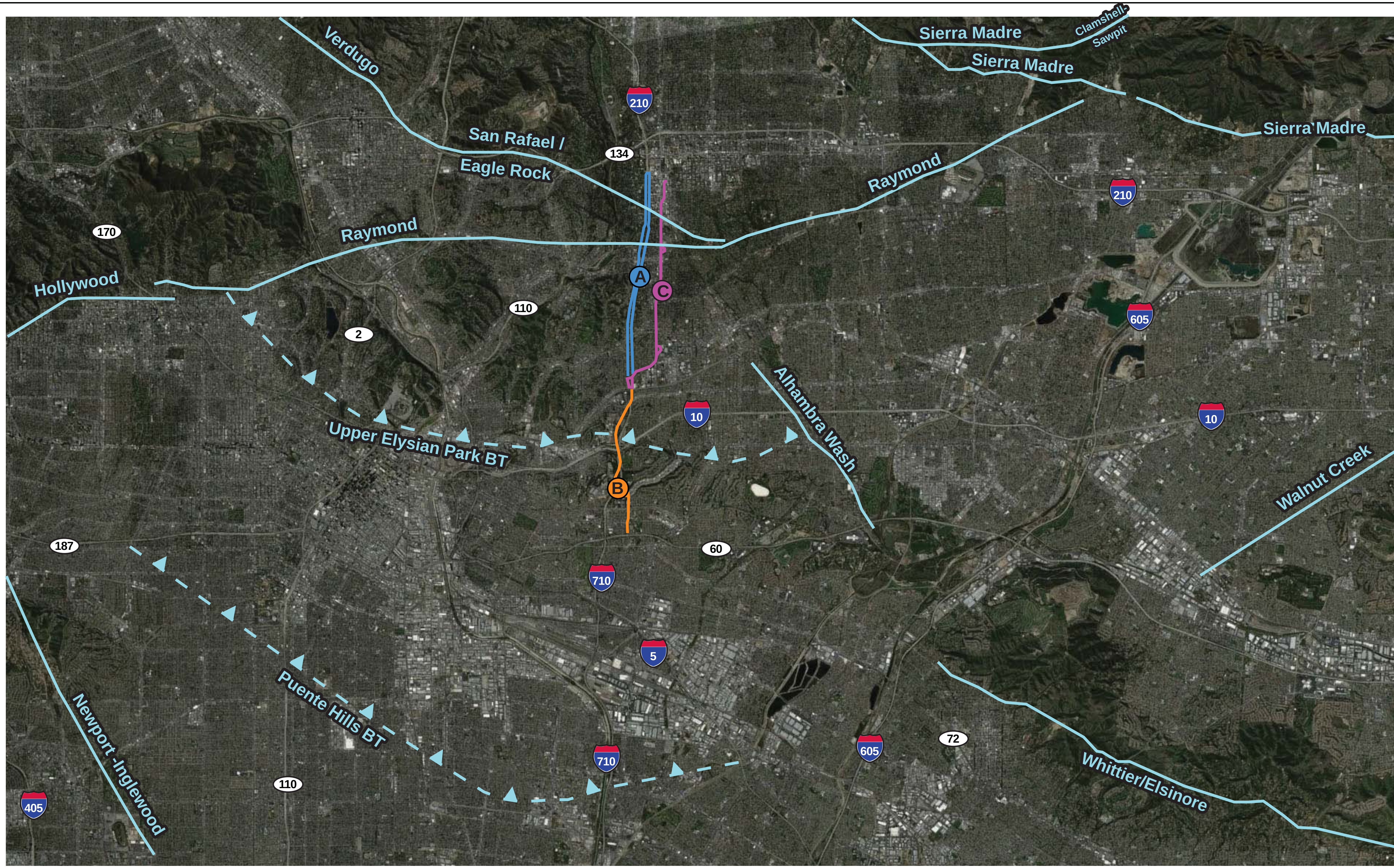


Aerial image © Google Earth, 2013. Annotation by CH2M HILL, 2013.

LEGEND

Approximate Fault Location with Name (BT = Blind Thrust, Subsurface Fault, Barbs on Upper Block)

(A) Freeway Alternative

(B) LRT Alternative Overhead

(C) LRT Alternative Tunnel

North

0 2.5 5

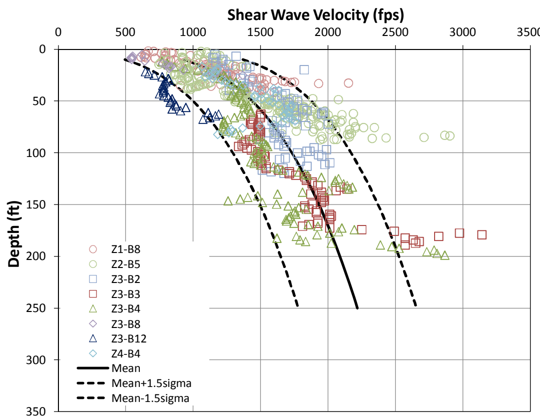
Approximate scale in miles

Fault Data from: Plesch et al., 2007 and USGS, 2010; with modifications based on this study.

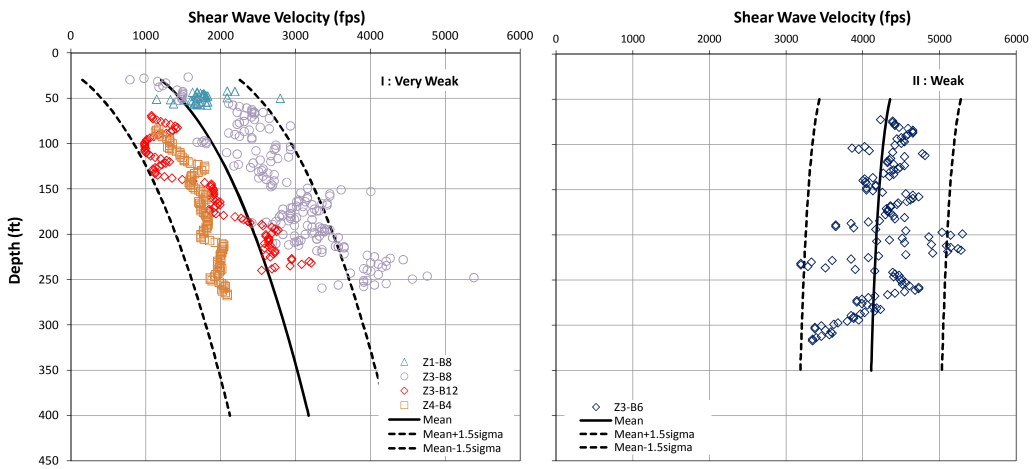
FIGURE 3
FAULT LOCATION MAP
SR 710 North Study,
Los Angeles County, California

CH2MHILL.

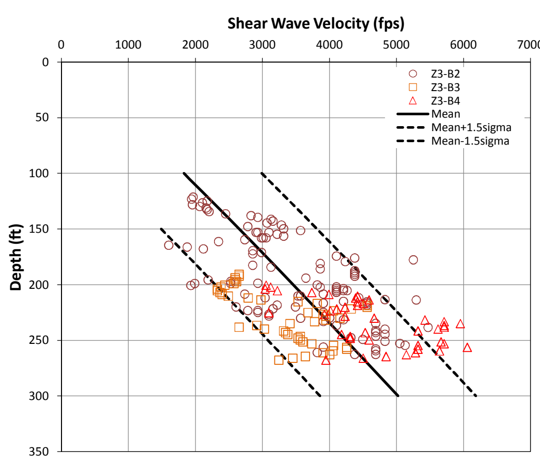
SCO428908.03.19.01.11 fault_location_map.ai 9/13



(a) Alluvial Deposits

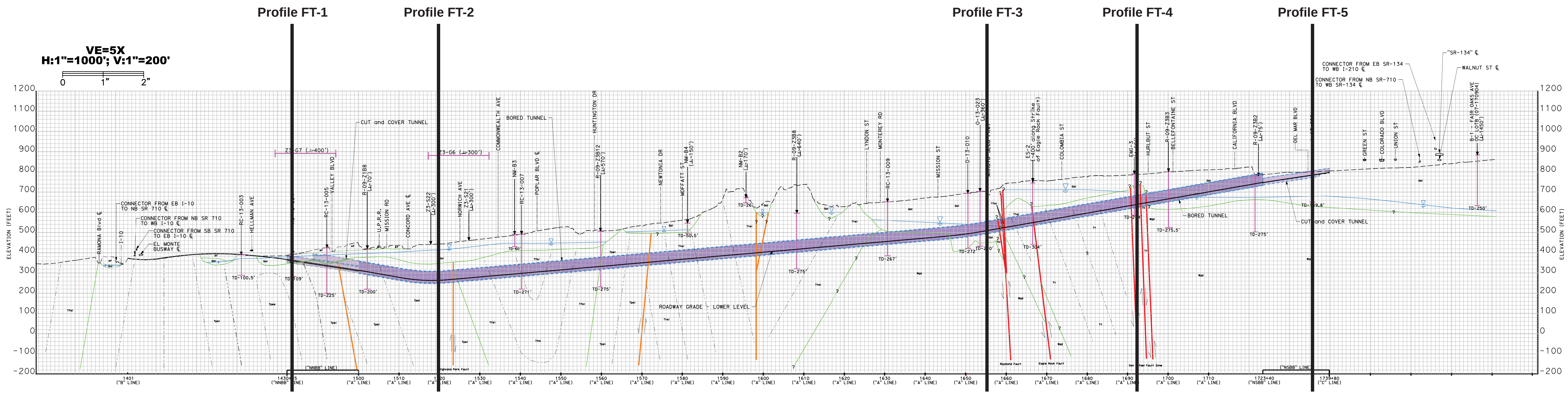


(b) Sedimentary Rocks

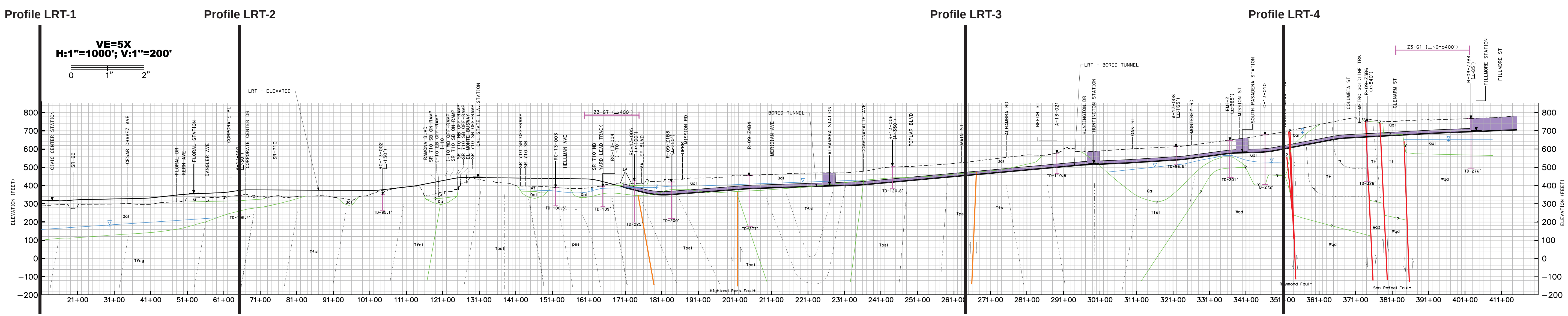


(c) Metamorphic and Igneous Rocks

FIGURE 4
Shear Wave Velocity Profiles
SR 710 North Study,
Los Angeles County, California

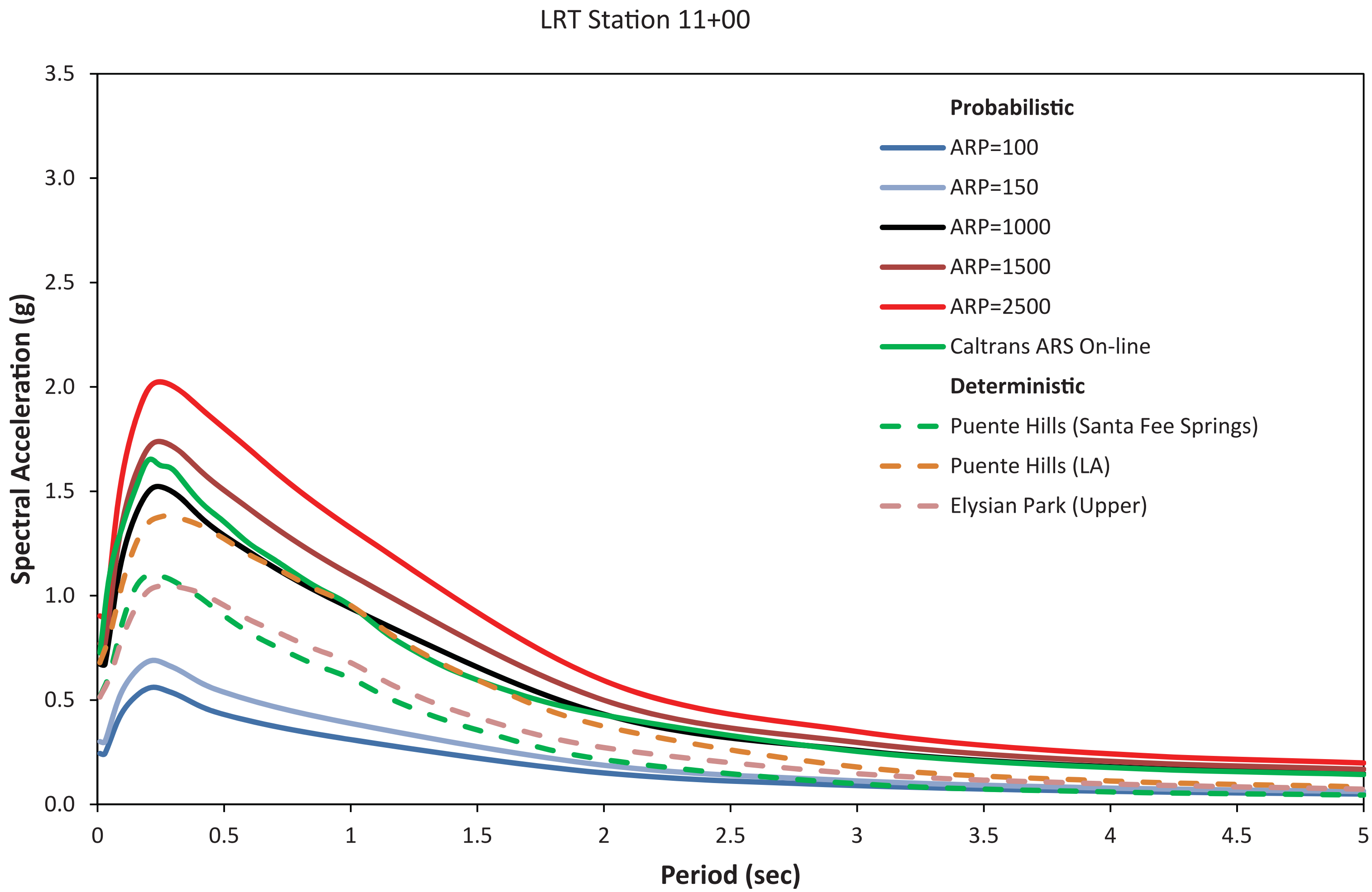


(a) Freeway Tunnel Alignment



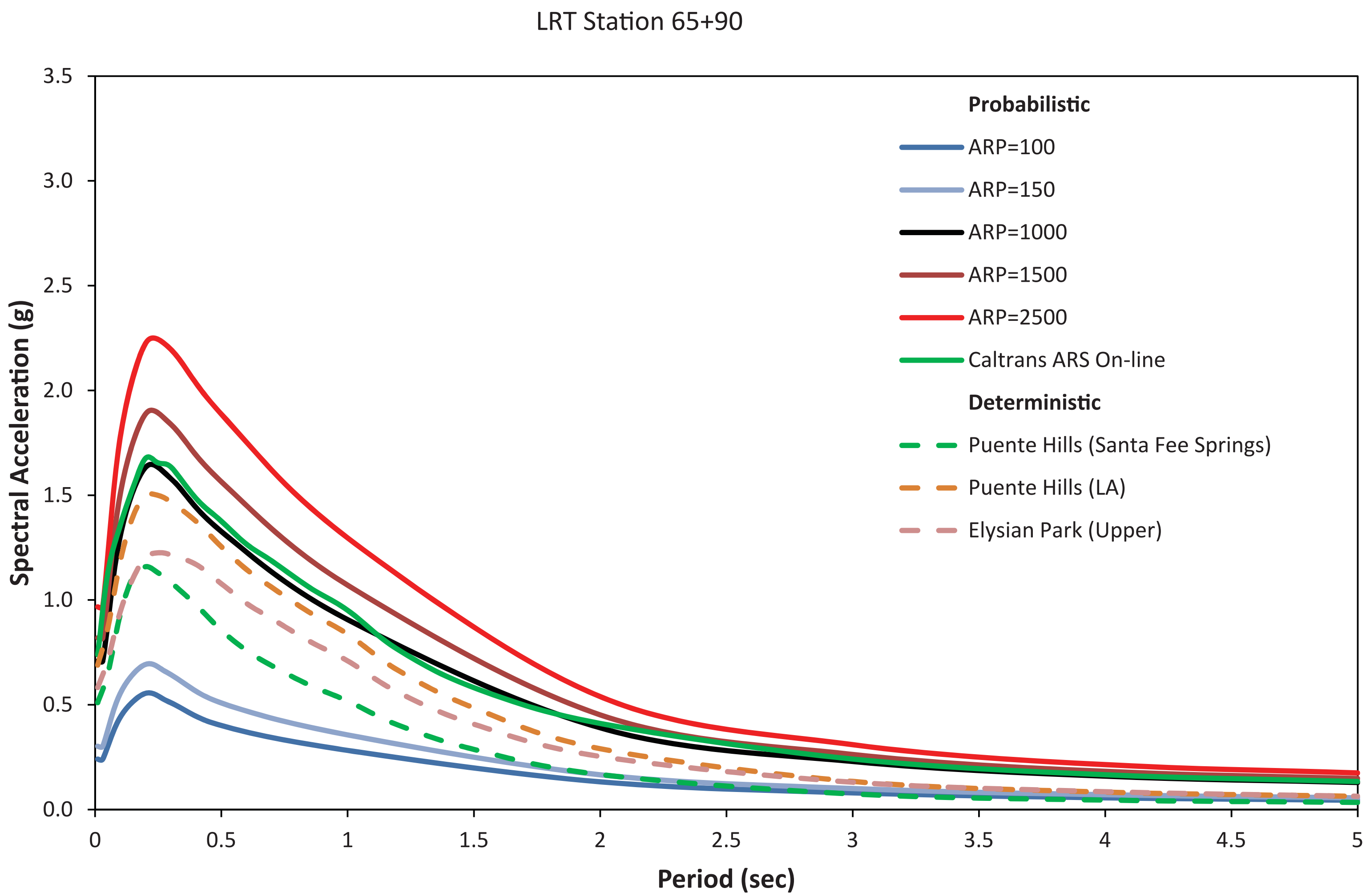
(b) LRT Alignment

FIGURE 5
Geologic Cross Sections
SR 710 North Study,
Los Angeles County, California



Five percent damping acceleration response spectra for geologic profile LRT-1

FIGURE 6
ARS Curve, Profile LRT-1
SR 710 North Study,
Los Angeles County, California



Five percent damping acceleration response spectra for geologic profile LRT-2

FIGURE 7
ARS Curve, Profile LRT-2
SR 710 North Study,
Los Angeles County, California

CH2MHILL