Route 710 Tunnel Feasibility Technical Assessment

Task Order PS-4310-1268-01-5-2

FINAL
Technical Memorandum Task 3.1
GEOTECHNICAL EVALUATATION

Submitted to:

Metro
Los Angeles County Metropolitan Transportation Authority

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January 6, 2006

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1.0 Introduction

This Technical Memorandum (TM), Geotechnical Evaluation Memorandum for Proposed 710 Tunnels, Task 3.1, was prepared to report review of previous geotechnical studies that have been conducted by Metro and others within the project study area. A summary of previously prepared documents related to geologic conditions has been compiled for Task 2.2 of this study, Literature Review. This TM provides information on available geotechnical, geologic and hydrogeological information including faults, seismic hazard data, and potential subsurface gas occurrences. This TM is intended to supplement and further characterize geotechnical and geologic information presented in the Metropolitan Transportation Authority (Metro) Technical Advisory Panel (TAP) 2005 report, "I-710 Gap Closure Road Tunnel, Report on Tunneling Feasibility: Preliminary Geological and Geotechnical Evaluation and Review of Associated Tunneling Technologies". This memorandum is a result of reviews and analyses of existing geological studies, geotechnical reports, soil boring logs, rock coring logs, water data, seismicity data, and pertinent documents from other projects in the area. Recommendations for follow-up field investigations are also provided.

2.0 Project Summary

The 710 Freeway (Long Beach Freeway), a 37 km route in Los Angeles County, California, connects Long Beach, other nearby beach communities, and the Ports of Long Beach and Los Angeles with distribution centers to the north. The freeway ends at the I-10 freeway in Monterey Park leaving an approximately 7.2 km gap in this route between the San Bernardino Freeway (I-10) on the south and the Foothill and Ventura Freeways (210 Freeway and State Route 134 Freeway) to the north in Pasadena (Figure 1).

The tunnel concept is currently envisaged as two subparallel bores with a potential for an interchange somewhere along Huntington Drive. The actual route is still to be determined but a preliminary concept would include extending the tunnel northward from near the end of the existing 710 Freeway, near Valley Boulevard and California State University, toward Huntington Drive, under Raymond and Grace Hill, and continuing northward under the Fair Oaks Boulevard area in South Pasadena to join the existing Foothill and Ventura freeways in the city of Pasadena.

3.0 Previous Investigations

Relevant geotechnical field studies within the project site include a study performed by Caltrans in 1973 and a study performed by Ninyo & Moore in 1999 for the proposed 710 extension. The 1973 Caltrans study consisted of geologic mapping, aerial reconnaissance and three deep rock borings. The 1999 Ninyo & Moore investigation included a review of data from previous investigations, geologic mapping, four soil borings, and laboratory testing.

Several soil borings from Caltrans for designs and improvements at the 710/210 Interchange and at the 710/I-10 Interchange provide good descriptions of soil encountered at the two ends of the proposed tunnel alignment. A geologic cross section developed by Crook et al, 1987 includes three well logs at the northern segment of the tunnel study alignments. The locations of borings from these studies are shown on the topographic map in Figure 2.

Previous tunneling projects in the greater Los Angeles area may also be relevant for the proposed 710 tunnel because as they extended through the same geologic formations as are present along the proposed alignment. Several tunnels were constructed in the Los Angeles region in the 1960s and 70s. Most of these tunnels were water projects by the Metropolitan Water District and the Los Angeles County Flood Control District. The tunneling experience of the Metro Rail Red Line in the 1990s is the first major tunneling project in recent years and is important to this project because it was driven through some of the same geologic formations (the Fernando, Monterey/Puente, and Topanga) that would be encountered along the proposed alignment.

The following reports and published papers document previous studies relevant to this geotechnical evaluation:

- "Geologic Map of the Los Angeles Quadrangle, Los Angeles County, California," Dibblee, T.W., 1989.
- "Geologic Map of the Pasadena Quadrangle, Los Angeles County, California," Dibblee, T.W., 1989.
- "Geology and ground water storage capacity of valley fill," Division of Water Resources Bulletin 45. 1934.
- "Geology of Elysian Park-Repetto Hills area," Lamar, 1970.
- "Geotechnical Report Route, 7" California Department of Transportation, January 1974.
- "I-710 Gap Closure Road Tunnel, Report on Tunneling Feasibility: Preliminary Geological and Geotechnical Evaluation and Review of Associated Tunneling Technologies," MTA Tunnel Advisory Panel, 2005.
- "Interstate 710 Extension Investigation," Ninyo & Moore, 1999.
- "Quaternary geology and seismic hazard of the Sierra Madre and associated faults, western San Gabriel Mountains," Crook and others, 1987.
- "Seismic Hazard Evaluation of the Los Angeles 7.5-Minute Quadrangle, Los Angeles County, California," California Department of Conservation, 1998.
- "Seismic Hazard Evaluation of the Pasadena 7.5-Minute Quadrangle, Los Angeles County, California," California Department of Conservation, 1998.
- Various boring logs from Caltrans bridge facilities at 710 and 210 Interchange and at 710 and I-10 Interchange.

4.0 Regional Geology and Tectonics

The Los Angeles region lies along the boundary of the Western Transverse Ranges on the north and the Peninsular Ranges on the south. The region is characterized by northerly trending hills and valleys on the south and east-west trending hills and valleys on the north. The Los Angeles region is an area of active geological deformation (tectonics) and earthquakes. Presently the site region is one of regional crustal compression oriented in a north-northeast direction as indicated by geological structure, earthquakes, and both land and space geodetic surveys. The region is contracting at about 5 to 9 mm/year. The boundaries between the mountains and the valleys is generally coincident with geological earthquake faults. Figure 3 shows the major physiographic elements and active faults in the region.

Formation of the Los Angeles region has a complicated geologic history. Within much of the area, the basement rock is buried beneath sedimentary and volcanic rocks no older than Miocene age (~10 to 20 million years ago). Basement rocks in the region were unroofed and exposed across wide areas when the Farallon tectonic plate, which was being subducted from the west, stopped subducting below the area (Atwater and Stock, 1998). Upon cessation of subduction, regional tectonic depression accompanied by extension and strike-slip faulting occurred oblique to the continental margin and appears to have been associated with the clockwise rotation of the Transverse Ranges (Luyendyk et al, 1980); the rotation occurred along many of the existing faults. During late Pliocene and Quaternary time (the past 4 million years), the regional tectonic regime transitioned from extension to compression. Compression has been accommodated along faults previously formed by extension (Wright 1991; Crouch and Suppe, 1993). During the transition, some middle Miocene normal faults were reactivated as reverse and strike-slip faults (Rivero et al, 2000). Blind thrust faults and folds may have begun to form about this time. In the project area, evidence for the Pliocene onset of the compressive deformation is derived from the folding of rocks deposited between early Pliocene and Miocene time.

The present tectonic regime appears to have been in place since middle Pleistocene time and the present-day configuration of the Los Angeles region would have been recognizable about 200,000 to 300,000 years ago, although the sea may have still occasionally migrated into some low-lying coastal channels (Ponti, 1989).

Except for a few marginal zones, the geologic structure of the San Gabriel basin is relatively simple and is characterized by relatively flat-lying, late-Quaternary (between 700,000 years ago and the present day) strata overlying folded Pliocene to Miocene-age strata. The central part of the basin is a deep trough that rises abruptly due to faulting and folding at the Sierra Madre fault zone.

Most surface geological faults in the region such as the Sierra Madre, Hollywood, and Whittier faults occur along basin margins. In addition to the known surface faults, the Los Angeles region appears to be underlain by subsurface thrust and reverse faults (commonly referred to as "blind thrust" faults). "Blind" thrust faults are shallow-dipping reverse faults which terminate before reaching the surface. When the fault breaks, therefore, it may produce uplift and ground shaking, but no clear surface rupture. This makes location of the fault and determination of the fault hazard difficult. Most large earthquakes associated with these subsurface features are most likely to originate at great depths (e.g. about 17 to 20 km). The 1987 Whittier earthquake occurred on one of these northerly dipping buried faults that extend under the San Gabriel basin from under the Repetto and Puente Hills south of the site. The 1994 Northridge earthquake occurred on a southerly dipping buried fault below the San Fernando Valley.

The bulk of seismotectonic activity in the San Gabriel Basin region during Quaternary time appears to have occurred along the Sierra Madre, Hollywood, and Whittier faults which border the more prominent uplifts in the Los Angeles Basin. The Raymond Hill fault (also referred to as the Raymond fault) had activity but probably at a lesser rate. If these characteristics can be applied basin wide, the greatest tectonic activity within late Pleistocene time has occurred primarily in proximity to the major surface faults such as the Santa Monica-Hollywood, Newport Inglewood Structural Zone, Whittier, and Sierra Madre faults. The subsurface thrust faults within the region have not been active enough to create similar prominent uplifts, and only a few (e.g. Santa Fe Springs) have even subtle recognizable surface expression.

5.0 Site Geology

The project site lies within a highly urbanized region in the Los Angeles Region in southern California (Figure 4). The proposed tunnel study alignment is along the western margin of the San Gabriel Basin which constitutes a broad southerly sloping plain within the transition zone between the Western Transverse Ranges and the Peninsular Ranges. The northern reach of the proposed route (north of the Raymond Hill fault) is commonly referred to as the Raymond Basin. The San Gabriel/Raymond Basin(s) is bordered on the north by the San Gabriel Mountains, on the west by the Repetto Hills, on the south by the Puente Hills, on the east by the San Jose Hills.

The basin floor comprises broad alluvial fans, gently sloping to the south-southeast, overlying folded sedimentary rocks in the southern part of the alignment and crystalline basement rocks in the northern part. Most of the route is characterized by flat ground or subtle small rounded rises, but several higher hills occur just west of the alignment. Elevations along the alignment range from about 248 m in the north to about 128 m in the south for an elevation change of about 120 m. The highest elevation along the route is at Raymond Hill which rises to an elevation of about 253 m. Outcrops of folded bedrock occur locally as small hills and knolls along the alignment and in the Repetto Hills west of the alignment.

6.0 Stratigraphy

The stratigraphy and the structure of the site vicinity are presented on the longitudinal section along tunnel study alignment in Figure 5, 6, 7, and 8. From the San Bernardino Freeway (I-10) north to the concealed extension of the York Boulevard fault (at Mission Street), the stratigraphy consists generally of thinly-bedded Tertiary (67 to 2 million years) shale and siltstone of the Puente (Monterey) Formation unconformably overlain by Quaternary (less than 10,000 years) alluvium. It should be noted that different investigators have assigned different names to the same formations. Generally speaking, the Monterey and the Puente formations are very similar rocks of about the same age and, for engineering purposes, can be considered the same lithologic unit.

From Ninyo & Moore's 1999 borings B-1, B-3, and B-4, and previous geologic mapping, thickness of alluvium is estimated to be greatest near Orange Street (between Concord and Commonwealth Avenues), possibly up to 30 m. Elsewhere in this southern portion of the project area, alluvium is likely to be on the order of 6-18 m thick.

As shown in Caltrans borings ES-1 and ES-3 between the York Boulevard and Raymond Hill fault zones (from approximately Mission Street to immediately north of the Pasadena Freeway) is a region of highly sheared and deformed sedimentary units unconformably overlain by dense to very dense Quaternary alluvium. Boring ES-3 encountered crystalline basement rock (granodiorite) at a depth of 73 m below ground surface, at an elevation of approximately 140 m MSL; no granodiorite was encountered in boring ES-1, which bottomed at an elevation of approximately 114 m MSL. However, as only the most generalized logging of cuttings (in contrast to continuous coring) was undertaken for the boring from 0 to 73 m depth, at this time it is not possible to adequately describe the stratigraphy between the York Boulevard fault and the Raymond Hill fault.

From the Raymond Hill fault zone north to the concealed trace of the Eagle Rock fault (near Glenarm Street), strata consist of poorly to massively bedded Tertiary silty shale, sandstone, and conglomerate of the Topanga Formation (Figures 7 and 8). These beds structurally overlie younger siltstone and shale of the Monterey Formation due to sharp folding which, locally, has turned the strata upside down. The Topanga rocks are highly weathered and overlain by thin slope wash and soil deposits formed in-situ on the slopes of Raymond Hill.

The tunnel study alignment from the Eagle Rock fault northward to the Foothill and Ventura freeways is underlain by sands and gravels deposited in an alluvial fan overlying crystalline basement rock. The depth of alluvium thickens to the north; at the northernmost reach of the tunnel study alignment, the depth of alluvium is as much as a hundred meters or more. This area comprises a mixed-use old residential and business area with little recent development; therefore, there is little geotechnical data on the deeper rocks.

The following sections describe the geologic units, and where they will be encountered, with respect to the tunnel study alignment as assumed for the MTA TAP 2005 report, "I-710 Gap Closure Road Tunnel, Report on Tunneling Feasibility: Preliminary Geological and Geotechnical Evaluation and Review of Associated Tunneling Technologies". The tunnel study alignment may change with future adjustments.

6.1 Crystalline Basement Rock

Along tunnel profile, basement rock may only be encountered from north of the Eagle Rock fault near Glenarm Street to the Foothill and Ventura freeways. Basement rock will likely consist of Cretaceous quartz diorite subdivided into the following units: **qd,** a massive, non-gneissoid quartz diorite; and **gqd,** and massive to gneissoid quartz diorite, which locally includes unmapped biotite-rich gneiss.

There is little subsurface information on these rocks. While crystalline basement rock has been encountered in a few well borings north of the Eagle Rock fault, the geological logging for those borings was generalized and is of limited usefulness. Caltrans boring ES-3, located further south, in a shear zone between the York Boulevard and Raymond Hill faults, encountered granodiorite basement rock. The rock, described as mostly soft, weathered to highly weathered, and "mushy", may not be typical of basement rock north of the Eagle Rock fault. The nearest surface exposures are in Arroyo Seco about a kilometer to the west of the alignment. Figure 9 shows a typical outcrop in Arroyo Seco and a small sample of the rock.

6.2 Topanga Formation

The Topanga Formation, of middle and/or late Miocene age marine and possibly nonmarine origin, unconformably overlies crystalline basement rock. Along tunnel profile it would be encountered north the Raymond Hill fault zone to the Eagle Rock fault. Along this reach, the Topanga Formation is found at or very near surface to an estimated 3,000-ft depth (Dibblee, 1989). The formation is subdivided into three units: **Ttqdc,** a gray to brown, crudely bedded conglomerate and breccia, all composed of biotite hornblende quartz diorite in semi-friable sandstone matrix; **Ttsc,** a light gray to brown, semi-friable sandstone, and interbedded brown sandy to silty shale, semi- siliceous shale, and pebble-conglomerate of quartz diorite detrius; and **Ttqdb,** a gray to brown breccia, massive to vaguely bedded, composed of angular detritus and a few rounded cobbles and boulders, all of biotite hornblende quartz diorite.

Figure 10 shows a typical highly weathered outcrop on the north side of Raymond Hill and a close-up of the same exposure showing 5 to 13 cm size pebbles and cobbles in a coarse sand matrix.

6.3 Monterey/Puente Formation

The Monterey/Puente Formation will be encountered between approximately Hellman Avenue to Valley Boulevard and from Hampton Terrace to the York Boulevard fault (Mission Street) along the conceptual tunnel profile (Figure 5, 6, and 7). As stated previously, the Monterey and Puente formations are shown interchangeably on various maps. These formations are very similar in characteristics, therefore no attempt is made to distinguish between them for tunneling characterization. The Monterey/Puente Formation is a marine deposit of middle- to late-Miocene age and conformably overlies and the Topanga Formation. The Monterey/Puente Formation is subdivided into three units: **Tmsh,** a white-weathering, thin-bedded, platy, siliceous shale which is locally porcelaneous and silty; **Tmss,** a tan to light gray, semi-friable, arkosic sandstone which includes some interbedded silty shale; and **Tmsl,** a gray, micaceous silty shale and siltstone. Tmsl rocks are considered by Lamar (1970) to be part of the Topanga Formation. Figure 11 shows a typical outcrop of Tmsl siltstone from this formation in the South Pasadena anticline area of the central part of the alignment.

6.4 Unnamed Shale

The late-Miocene-age marine unnamed shale of Dibblee is referred to as a member of the Puente Formation by others (e.g. Lamar, 1970). Along the tunnel profile this material would be encountered between the San Bernardino Freeway to Hellman Avenue and Valley Boulevard to Hampton Terrace. The shale is subdivided into two units: **Tush,** a gray to light-brown, thinly bedded, silty clay shale, locally containing scattered large calcareous nodules; in places the subunit contains thin interbeds of fine-grained sandstone; the lower part locally contains thin lenses of light tan, platy, semi-siliceous or diatomaceous shale; **Tuss** consists of light gray to tan, semi-friable, sandstone with thin interbeds of silty shale.

Figure 12 (upper frame) shows a typical exposure near Valley Blvd. The lower frame in Figure 12 is a close-up of the thinly bedded, soft, white diatomaceous shale so typical of this formation.

6.5 Fernando Formation

The Fernando Formation includes over a thousand meters thickness of Pliocene siltstone, sandstone, pebbly sandstone, and conglomerate. The formation is generally soft, poorly indurated, and friable. The formation is most extensive just south of the alignment, but may occur locally. The geotechnical properties of this formation are not greatly different than the soft Monterey/Puente rocks.

6.6 Quaternary Alluvium

Surficial sediments unconformably overlie bedrock along the flat-lying ground surface of tunnel study alignment. While depth of alluvium is not well-known throughout the project site, based on previous borings by Caltrans, Ninyo & Moore, and well-logs, it is not believed to exceed 30 m in thickness and is likely much less in most of the project site. Except for at tunnel portals, it is unlikely that Quaternary deposits will be encountered along tunnel profile. Quaternary alluvium is divided into the following subunits: **Qa,** unconsolidated Holocene floodplain deposits of silt, sand and gravel; **Qg,** Holocene stream channel deposits of gravel, sand and silt; and **Qof,** Pleistocene alluvial fan gravel and sand.

7.0 Major Faults

7.1 Sierra Madre Fault

The Sierra Madre fault is one of the major faults in the Los Angeles region and lies along the southern margin of the San Gabriel Mountains and along the northern edge of the San Fernando Valley and the San Gabriel Valley (Figure 3). The fault is recognized by juxtaposition of rock types, shearing and crushing along the fault line, and by linear landforms (geomorphology). The fault is primarily a thrust fault that has thrust the ancient crystalline igneous and metamorphic rocks of the San Gabriel Mountains up and over young Quaternary-age alluvial deposits. The fault zone is very complex and over much of its length comprises several subparallel branches. The fault may also be divided into segments along length with somewhat different rupture characteristics and histories. For example, the Raymond Hill fault intersects the Sierra Madre fault in the Sierra Madre area and aligns with similar faults (Clamshell-Sawpit faults) north of the Sierra Madre fault (Figure 3), thus suggesting a fundamental discontinuity in the Sierra Madre fault.

About 20 km of the westernmost part of the Sierra Madre fault ruptured during the 1971 San Fernando earthquake (moment magnitude, M_w = 6.7). The 1971 event was characterized by reverse faulting along a northerly dipping thrust fault. Geological studies of the 1971 rupture suggested that a previous rupture had occurred on this fault within the prior few hundred years. In 1991, a M_w 5.8 earthquake below the San Gabriel Mountains is believed by some to have occurred on the Clamshell-Sawpit branch of the Sierra Madre fault zone.

Geological studies have indicated that the average rate of displacement for the Sierra Madre fault may be up to about 3 to 4 mm/year. Information on slip rates is scarce, as the average time between large ground rupturing earthquakes on the Sierra Madre fault is poorly known. The best available information indicates that large earthquakes on the Sierra Madre fault occur at intervals between a few hundred years to a few thousand years (~ 5000 years, Crook et al., 1987).

Geological and paleoseismological studies (Rubin et al., 1998) suggest that two prehistoric ruptures within the past 15,000 years had large displacements typical of earthquakes in the M_w = 7.0 to 7.5 range. These studies suggested an average slip rate of 0.6 mm/yr, but this is based on only one locality within a very long and complex fault system and therefore this rate may not be representative. The paleoseismological studies of Tucker and Dolan (2001) on the eastern part of the fault revealed a similar minimum slip rate of 0.6 to 0.9 mm/yr and an elapsed time interval since the most recent surface rupture of 8,000 years or more, but their investigation was also limited to only one of several possible subparallel faults so the slip rate may be higher when all branches are considered. The California Geological Survey (2002) used a slip rate of 2.0 mm/yr.

The limited documentation of Quaternary faulting on the Sierra Madre fault makes it difficult to assess its earthquake capability. Based on worldwide empirical fault-length/earthquake-magnitude relationships (Wells and Coppersmith, 1994), the Sierra Madre fault is capable of producing earthquakes in the 7.0 to 7.5-magnitude range. If the fault ruptures one of the segments independently, earthquakes of M_w = 7.0 are more likely; if more than one segment ruptures together, larger earthquakes are possible.

7.2 Santa Monica-Hollywood Fault System

One of the major faults in the Los Angeles Basin is the frontal fault system along the southern edge of the Santa Monica Mountains, separating Mesozoic-age plutonic and metamorphic rocks from Tertiary sedimentary rocks. The fault system consists of the Santa Monica and Hollywood faults and smaller segments such as the Malibu and Potrero faults (Figure 3). The Santa Monica Mountains rise abruptly to 500-600 meters above the Los Angeles Basin floor and are indicative of a large vertical component of faulting as well as a left-lateral component. The fault system is not identified as an Earthquake Fault Zone (EFZ) (formerly known as an Alquist-Priolo special study zone) because it does not fulfill the well-defined surface location criteria of the Alquist-Priolo Act. This difficulty is at least partly due to the discontinuous nature of faulting; that is, the fault zone appears to be a zone of discontinuous faults and folds rather than one continuous break.

The Metro Rail Red Line has driven a tunnel through the Hollywood segment of the fault system. The tunneling and boring program found the plutonic rocks of the Santa Monica Mountains uplifted and thrust over 80 to 100 m of alluvium and colluvium (Guptill et al, 1997). The fault zone consists of about a 100-meter-wide, northerly dipping, gouge and sheared zone with a principal dislocation about a meter wide.

There have been no large historical earthquakes associated with the Santa Monica-Hollywood fault system, but geological studies (e.g. Crook and Proctor, 1992; Drumm, 1992; Dolan et al, 2000) have documented late-Quaternary faulting. Although it seems certain that the fault system is one of the major active features in the Los Angeles Basin, success at determining slip rates and recurrence intervals has been limited. The most recent surface rupture on the Hollywood fault appears to have occurred 6,000 to 9,000 years ago (Dolan et al., 2000).

Traditionally, geoscientists have considered the Santa Monica and Hollywood faults to be connected. However, there appears to be a large mismatch or step over where the right-lateral strike-slip Newport-Inglewood Structural Zone (NISZ) meets the Santa Monica fault. Some geoscientists believe that the NISZ continues northerly as the Beverly Hills lineament and provides an interconnection between the three features. A review of oil-field data suggest that the Santa Monica fault may merge with the Las Cienegas or Los Angeles fault and related faults and folds.

The great length of the fault system suggests that it is capable of generating a large earthquake (M_W~7.5) but the discontinuous nature of faulting suggests that faults may behave independently and perhaps a smaller maximum earthquake (M_W~7.0 to 7.25) is more appropriate. The recurrence interval for these large events is long, perhaps several thousand years.

7.3 Raymond Hill Fault

One of the major faults along the project alignment is the Raymond Hill fault or as commonly referred to, the Raymond fault. The Raymond Hill fault is about 26 km long and extends approximately east-west through the communities of San Marino, Arcadia, and South Pasadena (Figure 3).

The Raymond Hill fault is characterized by left-lateral oblique reverse slip. This fault dips at about 75 degrees to the north. The rate of slip is between 0.10 and 0.22 mm/yr. The fault has been considered by some geoscientists to be interconnected with the Hollywood fault because they have similar trends and similar types of displacement. However, the disparity between recurrence intervals and the age of latest surface rupture suggests they are discrete features. The Caltrans seismic map considers Raymond Hill fault as part of the Malibu Coast-Santa Monica-Hollywood-Raymond fault system (MMR) and is assigned an earthquake magnitude of 7.5.

The most recent major rupture occurred in Holocene time, about 1,000 to 2,000 years ago (Weaver and Dolan, 2000). From paleoseismic and trenching studies of the slip rate of the Raymond Hill fault, there is geological evidence of at least eight surface-rupturing events along this fault in the last 40,000 +/- years. At least five surface ruptures occurred in the past 40,000 years. However, four of these events occurred between 31,500 and 41,500 years ago (Weaver and Dolan, 2000). This indicates that surface ruptures occur over very irregular intervals and may be more random than systematic.

The Raymond Hill fault is one of several faults that are fundamental to the understanding of the mechanism of plate-boundary deformation in the greater Los Angeles area. The exact nature of the slip along the Raymond Hill fault has been a subject of much debate. The fault produces a very obvious south-facing scarp along much of its length, and this has many geoscientists favoring reverse-slip as the predominant sense of fault motion. However, there are also places along this scarp where left-lateral stream offsets of several hundred meters can be seen. The matter cannot be conclusively resolved until the Raymond Hill fault ruptures at the surface. A few geoscientists have speculated that the Pasadena earthquake of 1988 (M_w =4.9) occurred on the Raymond Hill fault; the motion of this quake was predominantly left-lateral, with a reverse component only about 1/15th the size of the lateral component. This corresponds very well with a scarp height of about 30 meters (reverse slip) versus a left-lateral stream offset of about 400 meters (lateral slip), which are found along the scarp of the Raymond fault south of Pasadena. However, small earthquakes such as the 1988 event commonly occur on minor associated faults and may not be reliable indicators of what the master fault will do during larger events and therefore, the correlation should be regarded with skepticism. If the Raymond Hill fault is indeed primarily a left-lateral fault, it could be responsible for transferring slip westerly and southward from the Sierra Madre fault zone to other fault systems. If significant left-lateral motion occurs on the Raymond Hill fault, this could provide a critical constraint for kinematic models of deformation in Southern California.

7.4 York Boulevard Fault

The York Boulevard fault trends east-west through the Repetto Hills. Very little is known about the fault and it is not believed to be active. In the central part of the fault, Pliocene-age rocks are inferred to be faulted against basement rocks. The vertical separation would be more than 3050 m (Lamar, 1970). The slip rate is unknown.

The fault is projected across the proposed alignment by Dibblee (1989) and is shown as a subsurface fault south of the Raymond Hill fault on Figure 4.

7.5 Eagle Rock Fault

The Eagle Rock fault trends southeasterly for about 18 km from the southwestern flank of the Verdugo Hills across the southern part of Pasadena (Figure 3). The fault appears to be a northerly dipping thrust fault. Very little is known about the fault. The slip rate is probably on the order of less than 0.1 mm/yr (Wesnousky, 1986). The fault may be interconnected with the Verdugo fault to the northwest. The fault extends toward the projection of the Alhambra Wash fault but no evidence of any connection has ever been suggested.

8.0 Seismicity

The southern Los Angeles area is seismically active. Table 1 lists the larger historical earthquakes to have occurred in Southern California. There is little concentration or clustering of earthquakes in the Los Angeles Basin and seismicity in the Los Angeles Basin does not clearly correlate to surface faults. About 40 percent of the seismic moment cannot be attributed to known faults (Ward, 1994).

The largest historical earthquake within the Los Angeles Basin was the 1933 Long Beach earthquake of M_W = 6.4 (Richter magnitude, M_L = 6.3). Within the Ventura Basin, the 1971 San Fernando (M_L = 6.4, M_W = 6.7) earthquake occurred along the northern margin of the San Fernando Valley within a zone of mapped surface faults. The more-recent 1994 Northridge (M_L = 6.4, M_W = 6.7) earthquake also occurred in the San Fernando Valley but occurred on a southerly dipping fault and was not associated with surface faults. The1987 Whittier earthquake (M_L = 5.9, M_W = 5.9) occurred on a subsurface fault dipping northerly under the San Gabriel Basin from the southwestern flank of the Coyote Hills.

Two small but locally significant earthquakes occurred in the Pasadena region in 1988 and 1991. The 1988 earthquake had a magnitude of 4.9 (M_W) and may have occurred on the Raymond Hill fault at a depth of about 16 km (Jones et al, 1990). Focal- mechanism solutions, based on the direction of slip in an earthquake and the orientation of the fault on which it occurs, indicate that this event was associated with left-lateral, strike-slip faulting. The 1991 earthquake had a magnitude of 5.8 (M_W) and occurred at a depth of about 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 a splay of the Sierra Madre fault zone called the Clamshell-Sawpit fault.

Table 1. Notable Earthquakes in Site Region

DATE	MAGNITUDE, M_w	LOCATION	CAUSATIVE FAULT
1769	6.0(?)	Los Angeles Basin	Unknown
1812	7.0 (?)	San Juan Capistrano	San Andreas (?)(Wrightwood)
1827	5.5 (?)	Los Angeles region	Unknown
1855	6.0 (?)	Los Angeles region	Unknown
1857	7.9	Fort Tejon	San Andreas
1910	5.5 (?)	Glen Ivy Springs	Elsinore
1930	5.2	Santa Monica Bay	offshore fault
1933	6.3	Long Beach	Newport-Inglewood
1971	6.5	San Fernando	Sierra Madre
1973	5.2	Point Mugu	offshore subsurface (?) fault
1979	5.2	Offshore Malibu	offshore subsurface fault
1987	5.9	Whittier	Subsurface thrust fault
1988	4.9	Pasadena	Raymond (?)
1991	5.8	Sierra Madre	Sierra Madre fault (Clamshell-Sawpit branch)
1994	6.7	Northridge	Subsurface thrust fault (Oakridge fault ?)

9.0 Structure Along Tunnel Study Alignment

Along tunnel study alignment, the bedrock units are folded into a series of synclines and anticlines and broken by at least 3, possibly 4, major faults. The complex structure of the project site is a result of large-scale regional tectonics, including the oblique contraction of the Los Angeles Basin through a combination of strike-slip and thrust faulting near-surface and at depth.

Strike of bedding throughout the project site is generally southeast-northwest to east-west. From the San Bernardino Freeway north to approximately Valley Boulevard is the Elysian Park anticline. The axis of the northwest-trending anticline is positioned approximately at Hellman Avenue. Oskin, et. al (2000) estimated the contraction rate of the Elysian Park anticline to be 0.6-1.1 mm/yr. South of Hellman Avenue, beds are steeply dipping to the south to locally overturned. North of Hellman Avenue, beds dip moderately to steeply to the northeast into a syncline structure centered approximately at Orange Street.

From Orange Street north to approximately Main Street, bedding dips moderately to steeply to the south-southwest. Near Main Street, bedding generally becomes very steep to locally overturned.

Between Main Street and Alhambra Road is the axis of a very tight fold within the bedrock. The southern arm of a syncline is defined by moderately to locally steeply dipping beds from approximately Alhambra Road north to Spruce Street, the syncline axis. Beds of the northern arm of this syncline dip moderately to the south and are cut by the York Boulevard fault near Mission Street.

The York Boulevard fault, whose surface trace is concealed and assumed to the cross tunnel study alignment near Mission Street, and the nearby Raymond Hill fault zone, crossing the alignment at the Pasadena Freeway, are believed to have similar orientation, striking east-west and steeply north-dipping (approximately 75°). Between the two faults is a wide zone of localized, high-angle shearing and deformation.

In Caltrans boring ES-2, located between Raymond Hill and Pasadena Freeway, at a depth of 49 m, a potential fault dipping 65° was identified. No information on strike or dip of this unnamed fault has been found. Boring log descriptions of units above and below this fault suggest that it has thrust Topanga Formation sandstone over micaceous siltstone of the Monterey Formation. Based on bedding orientation and the orientation of the nearby Raymond Hill fault, the unnamed fault likely dips to the north.

Between the unnamed ES-2 fault and the Eagle Rock fault just north of Glenarm Street, the massive to poorly bedded Topanga Formation is generally moderately to steeply dipping to the northeast. Lamar(1970) maps a fault through the northern part of the hill.

The Eagle Rock fault is projected to cross tunnel study alignment just north of Glenarm Street. Orientation of the fault is not well-defined, but is presumed to dip 60-75°NE. Other regional maps also project the San Rafael fault through the area into the same area as the Eagle Rock fault, but it cannot be determined at this time if the San Rafael fault intersects the study area.

10.0 Groundwater

Limited information is available on groundwater at depth within the project site. The California Geological Survey map shows the highest historical water level. However, it can be assumed that ground water withdrawal has lowered ground water levels throughout the region (Figure 13 and Figure 14).

The shallow 1999 Ninyo & Moore borings, conducted during the winter, all encountered groundwater between approximately 10-14 m depth, near the boundary between Quaternary alluvium and bedrock. Likely this was only perched groundwater, having accumulated above a relatively impermeable soil layer. Of the Caltrans borings, drilled during the summer, only ES-1 encountered any groundwater, at a depth of 10 m and was noted to be likely perched. Well C-23f, located just south of the Pasadena Freeway and identified in the 1974 Caltrans report, was drilled in 1938 to a depth of 142 m. No groundwater elevation is given in the Caltrans report.

The California Geological Survey seismic hazard reports for the Pasadena and Los Angeles Quadrangles include generalized maps of the historically highest groundwater levels and borelog data locations (Figure 13 and 14). On these maps, the only bore log data from locations within the 710 project area are near Concord Avenue in the southern half of the project site and Glenarm Street in the northern half. Historically highest groundwater elevations at those locations are shown to be more than 61 m below surface and 12 m depth respectively. As Glenarm Street is near the axis of a large syncline filled with poorly consolidated alluvium, it is unclear if the groundwater elevation there represents the elevation of perched groundwater or of the regional aquifer.

Groundwater levels within the Raymond Hill fault zone historically were much higher than present and the fault zone is a barrier to ground water movement (Conkling et al, 1934). Marshes and artesian wells occurred at several localities along the trace of the fault and are said to have provided water for Native Americans and early settlers and missionaries.

Groundwater in the Raymond Basin, north of Raymond Hill, is indicated by two Los Angeles county wells. These wells indicated water at a level of 50 to 53 m below ground surface in 1974 and 1999. These depths are about 3-6 m lower than was documented in the 1930s by (Conkling et al, 1934).

11.0 Engineering Properties

The California Geological Survey (CGS) has compiled shear-strength data in the region surrounding the alignment to evaluate the stability of geologic materials under earthquake conditions. As none of locations of rock and soil samples taken for evaluation lie within the project area, these findings may be used only as very general guidelines for anticipated material strengths. Geologic units were grouped on the basis of average angle of internal friction (average ϕ) and lithologic character. The findings are summarized in Table 2 and Table 3; sampling locations are shown in Figure 15 and Figure 16. No CGS test data was available for the Fernando Formation.

The crystalline basement rock is essentially coarse-grained, highly weathered granodiorite. However, slow coring time during exploratory drilling suggests potential tunneling difficulties relative to other geologic formations encountered within the project area. Hard quartz veins scattered within the granodiorite may pose an additional challenge.

The Topanga Formation consists of a sandstone member and a conglomerate and conglomeratic sandstone member. The sandstone member of Topanga Formation is well bedded fine to coarse-grained sandstone with discontinuous seams of carbonized wood and lignite coal. Bedding ranges from about 1 mm in thickness for the fine-grained sandstone strata to a maximum thickness of 3 m for the coarse-grained strata. Interbedded are conglomeratic sandstone beds that contain boulders up to 1 m in diameter. Conglomerates and conglomeratic sandstone are irregularly interbedded massive to well-bedded strata. Rock sizes range from 7.5 cm to large boulders of 1 m in diameter.

Shear-wave velocity (V_s), the velocity of seismic waves in which medium particles move perpendicular to the propagation direction, is used to determine rock properties and rock strength (e.g., porosity, Poisson's ratio, bulk and shear moduli). The seismic wave velocity of rock may vary depending on its fluid content, precise mineral composition, degree of compaction, and strength of cementation, among other factors. V_s of the Topanga Formation at the tunnel elevation is likely to be on the order of 1220 to 1680 meters per second; this range corresponds generally to firm to hard rock.

Monterey/Puente Formation ranges from dull white or light gray, low-density, diatomaceous shale to hard, resistant well-bedded tan to gray siliceous shale. The diatomaceous shale tends to readily part along plane of stratification and has a high slaking potential. Furthermore when submerged underwater, the diatomaceous shale absorbs water rapidly with hissing sound and disintegrates into silty clay. Seismic velocities of the formation are generally between 450 to 1070 meters per second for shear waves (V_s) (corresponding generally to dense soil and firm to hard rock). For compressional waves (V_p), in which particles in the medium move parallel to the propagation direction, velocities are expected to be between 1830 to 2600 meters per second.

The characteristics of Quaternary alluvium in the northern part of the alignment has been shown by numerous holes drilled for the Metro Pasadena Goldline light rail (Law/Crandall, 1993). Typical materials encountered were sand, silt, clay and gravel mixtures. Gravel in the alluvium comprised about 10 to 20 percent and large cobbles and boulders in the 25 to 30 cm size were commonly encountered. The alluvium consists of unconsolidated poorly sorted sand and gravel. Recent alluvium has Standard Penetration Test (SPT) blowcounts of approximately 20 – 30 blows per 0.3 m and old alluvium shows much higher blowcounts in the range of 50 to over 70 blows per 0.3 m, indicating very dense material.

Previous experience by EMI in the general vicinity also provides a general characterization of the materials likely to be encountered in the proposed tunnel. The bedrock (Monterey/Puente Formation) encountered in boreholes in the Elysian Hills-Mt. Washington part of the Elysian Hills anticline area, a short distance west of the proposed alignment, consisted of thin to massive sandstone beds and thin-bedded to laminated claystone, siltstone, and shale. These rocks are similar to those cropping out in the adjacent hills.

The sandstones in the Elysian Hills-Mt. Washington area are gray to dark gray, ranging from fine- to coarse-grained but predominantly medium grained, and generally soft and friable. Most of these do not have any cementation and can be disaggregated by finger pressure. However, occasional (<1 %), beds of light gray sandstone are hard to very hard due to cementation by calcite. The thickness of the sandstone beds recovered in the core drilling ranged from laminae (<1 cm thick) interbedded with thin claystone and siltstone to beds about 1 m thick. The adjacent outcrops in the Elysian Hills indicate that thicker beds on the order of 1.5 to 2 m thick may also occur.

Fine-grained materials such as claystone, siltstone, and shale occurred as thin beds in the Elysian Hills-Mt. Washington area and are generally soft to moderately soft and calcareous. These are generally various shades of gray and grayish brown to black. Bedding thicknesses range from paper-thin laminae to a few centimeters (commonly 3 to 4 cm). These fine-grained materials are more commonly cemented by calcium carbonate than the sandstones but still comprise weak rock, breaking under manual pressure or with light hammer blows.

Both the sandstones and the fine-grained beds are weathered and oxidized in approximately the upper 2 to 3 m. Below about 3 m depth they are fresh and unoxidized. The rocks are generally moderately to slightly fractured. Joint frequency is generally moderate (~1 per 0.3 m), but intensely fractured zones (3-4 fractures per 0.3 m) were encountered in every boring. Bedding-plane joints are common in the fine-grained materials. Joints are generally tight and clean. Joint roughness ranges from smooth to rough with the smooth joints most commonly occurring as bedding-plane joints in the shale and claystone. No rigorous statistical joint analysis was conducted, but joint orientation seemed to cover the entire range of dips from horizontal to vertical (i.e. random).

Another site along Soto Street just west of the southern part of the project area is on the south limb of the east-west trending Elysian Park anticline that projects to the southern part of the alignment. The borings were drilled with a hollow-stem auger into the Miocene-age Monterey/Puente Formation, which is predominantly fine-grained, thinly bedded siltstone and claystone (commonly called shale) and sandstone. These materials are soft rock, commonly altered to clay in borings where the material is in a constantly moist state such that they are difficult to distinguish from firm sandy alluvium. The sandstones generally are fine- to medium-grained with a significant component of silt (10 to 40 %). Where these same materials are exposed at the surface, they dry out and become soft rock. The sandstones are largely uncemented and friable, and appear more similar to sand than to sandstone. Rarely, borings encountered hard, cemented sandstone beds that were impermeable, and could not be penetrated by the hollow stem auger.

Table 2. Los Angeles Quadrangle Shear Strength Groups

Group	Lithology	# of Tests	Mean/Median Angle of Internal Friction, ϕ (deg)	Group Mean/Median Angle of Internal Friction, ϕ (deg)	Group Mean/Median Shear Strength, C (psf)
Group 1	Unnamed shale, Tuss/Tush	10	36.5/37	35/35	410/350
	Monterey Fm, Tmsl	20	35.6/36		
	Topanga Fm, Ttsc	10	35.6/36		
	Monterey Fm, Tmss	26	33.7/32		
Group 2	Topanga Fm, Ttqdc	24	30.2/31	28.4/28	523/500
	Alluvium, Qa	13	29.8/31		
Group 3	Monterey Fm, Tmsh	11	23.8/24	23.8/24	368/200
Not evaluated	Topanga Fm, Ttqdb				
	Alluvium, Qg				
	Alluvium, Qof				

Table 3. Pasadena Quadrangle Shear Strength Groups

Group	Lithology	# of Tests	Mean/Median Angle of Internal Friction, ϕ (deg)	Group Mean/Median Angle of Internal Friction, ϕ (deg)	Group Mean/Median Shear Strength, C (psf)
Group 1	Granitic	35	37/37	38/37	557/500
	Dioritic	14	37/36		
	Granodioritic	7	44/42		
	Gneissic	1	35/35		
Group 2	Tt, Undifferentiated Topanga Formation	52	34/35	34/35	487/338
Group 3	Alluvium, Qa	29	32/30	31/30	285/250
	Alluvium, Qof	6	29/29		
	Alluvium, Qg	10	32/31		

12.0 Potential Subsurface Gas Occurrence

The 710 tunnel study alignment will not pass through any known operating or abandoned oil or gas fields or identified methane zones (Figure 17). The nearest active oil fields, the Boyle

Heights and Union Station oil fields, lie approximately 4.8 and 6.7 km southwest of the southern end of the proposed tunnel study alignment. No known tar or oil seeps occur along tunnel study alignment. However, discontinuous seams of lignite coal have been found within the Topanga Sandstone and occurrences of methane and natural gas have been noted throughout the Los Angeles Basin. Therefore, it should be considered possible that the tunnel may encounter gassy conditions south of the Eagle Rock fault.

North of the Eagle Rock fault, it is not anticipated that the tunnel will encounter gassy conditions, as it will pass through quartz diorite and Quaternary alluvium.

13.0 Proposed Project Site Investigation

EMI will be conducting a limited field investigation in order to further determine soil, rock and groundwater properties within the project area. The field investigation will be conducted in accordance with industry standards and current Caltrans requirements. Proposed are 3, 61-m deep borings: Boring 05-1, located along Westboro St, between Commonwealth and Concord Avenues in Alhambra; Boring 05-2, located on Mission Street in South Pasadena; and Boring 05-3, located between Fairoaks Ave and Orange Grove Blvd in South Pasadena.

The purpose of Boring 05-1 is to investigate the depth of overlying Quaternary alluvium, determine groundwater level, and to investigate the engineering properties of the Fernando Formation through which the tunnel would be driven. The current geologic interpretation indicates that the tunnel would not be located within the Quaternary alluvium at this location, however it is necessary to obtain field data to confirm that interpretation.

Boring 05-2 will be drilled in order to further refine our interpretation of the extent of the quartz diorite encountered in Caltrans boring ES-1, the structure of the Monterey Formation, and clarify uncertainties of boundaries among the geologic units in this zone.

To the south of California Boulevard, we have interpreted the contact between the Old Alluvium (Qof) and underlying quartz diorite to be a moderate to low-angle contact, based on nearby well data. Boring 05-3 will refine that interpretation, and provide groundwater data and geotechnical properties of the Qof.

With the additional data supplied by these three borings, the geologic profile (Figure 5, 6, 7, and 8) can be refined and the engineering properties of formations along the tunnel study alignment can be more accurately defined for further project planning.

14.0 References

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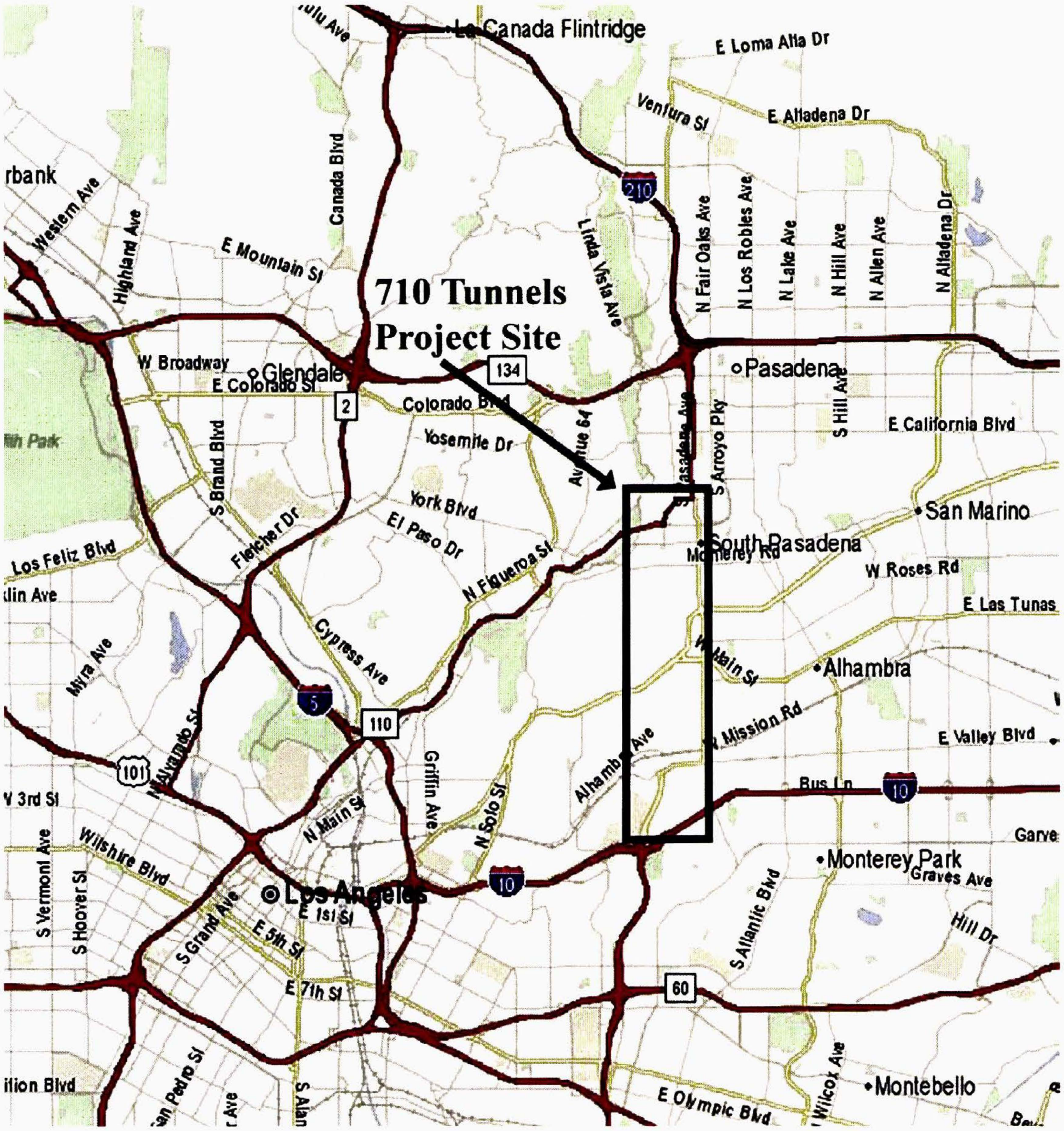
Figures

Figure 1. Map of 710 Tunnel Project Location, Los Angeles County, California



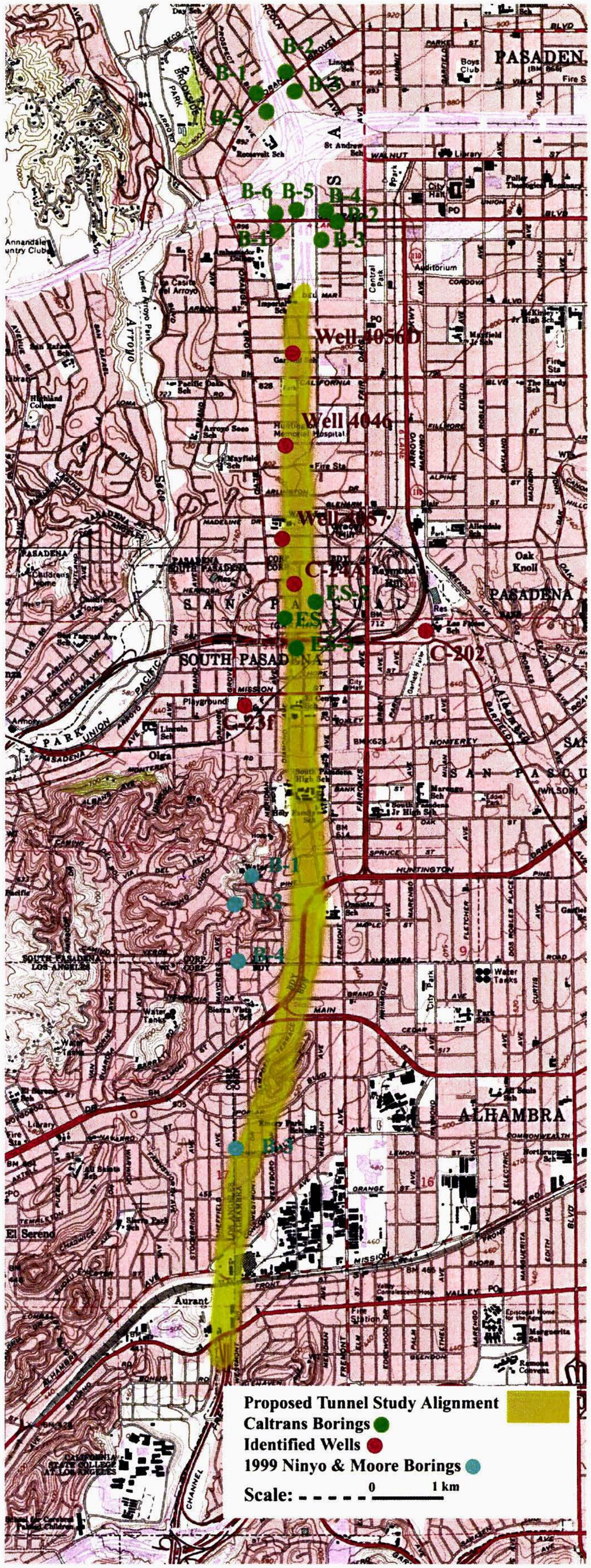
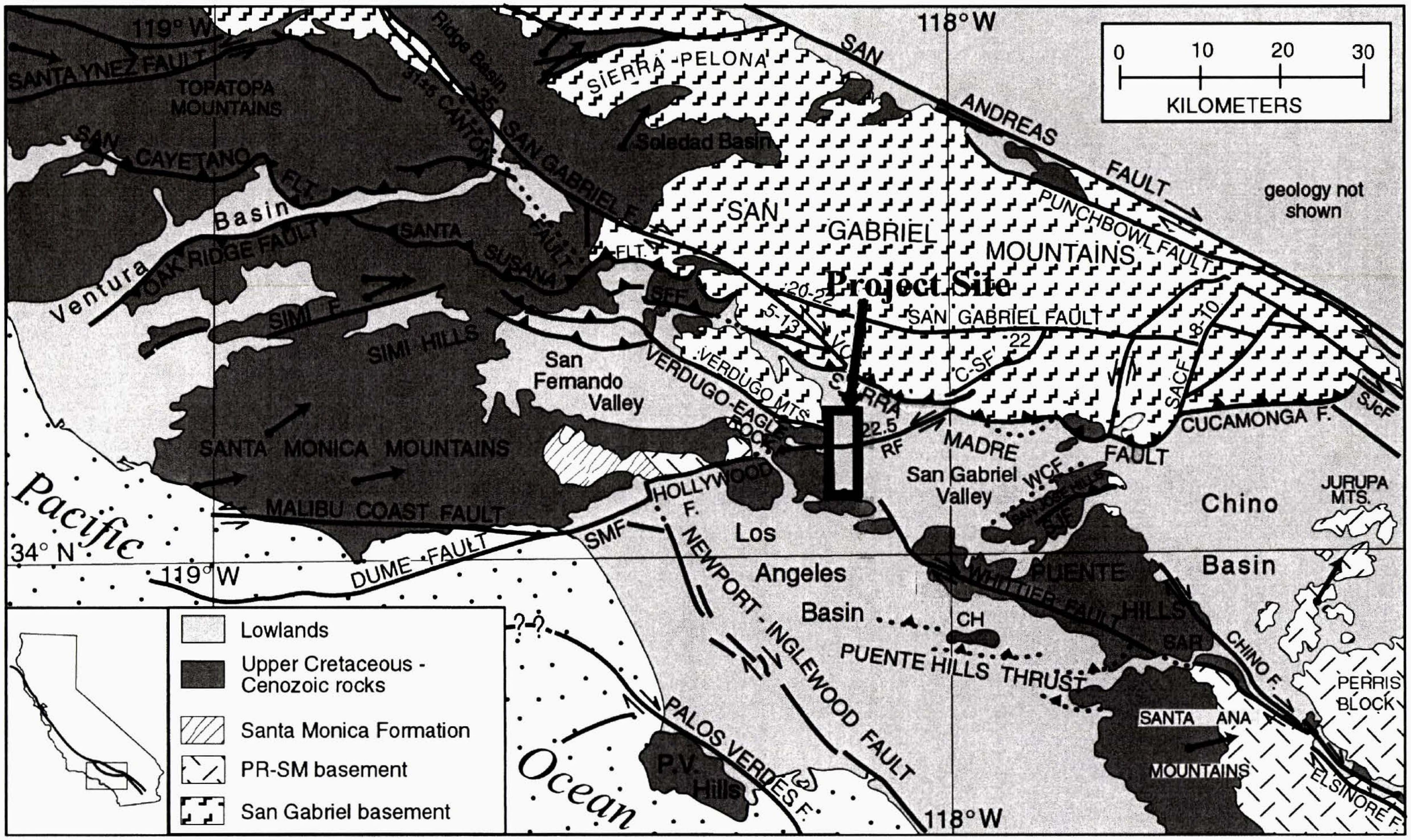


Figure 2. Topographic Map of Project Site and Boring Locations.

Figure 3. Map of Regional Physiography and Active Faults (Yeats, 2004)



Map of part of central Transverse Ranges locating San Gabriel Valley and surrounding regions. Faults shown in heavy lines, dotted where covered or blind; numbers refer to strike-slip offset, in kilometers, from Yeats, 2004.
Abbreviations: C-SF—Clamshell-Sawpit fault; CH—Coyote Hills; PV Hills—Palos Verdes Hills; RF—Raymond Hill fault; SACF—San Antonio Canyon fault; SAR—Santa Ana River; SFF—San Fernando fault; SJF—San Jose fault; SJcF—San Jacinto fault; SMF—Santa Monica fault; VCF—Vasquez Creek fault; WCF—Walnut Creek fault. PR-SM basement refers to basement rocks of the Peninsular Ranges and Santa Monica Mountains; San Gabriel basement refers to heterogeneous basement of San Gabriel Mountains, including Pelona Schist. Arrows not associated with faults show paleomagnetic declination of Miocene and older rocks

Figure 4. Geologic Map (Dibblee, 1989)

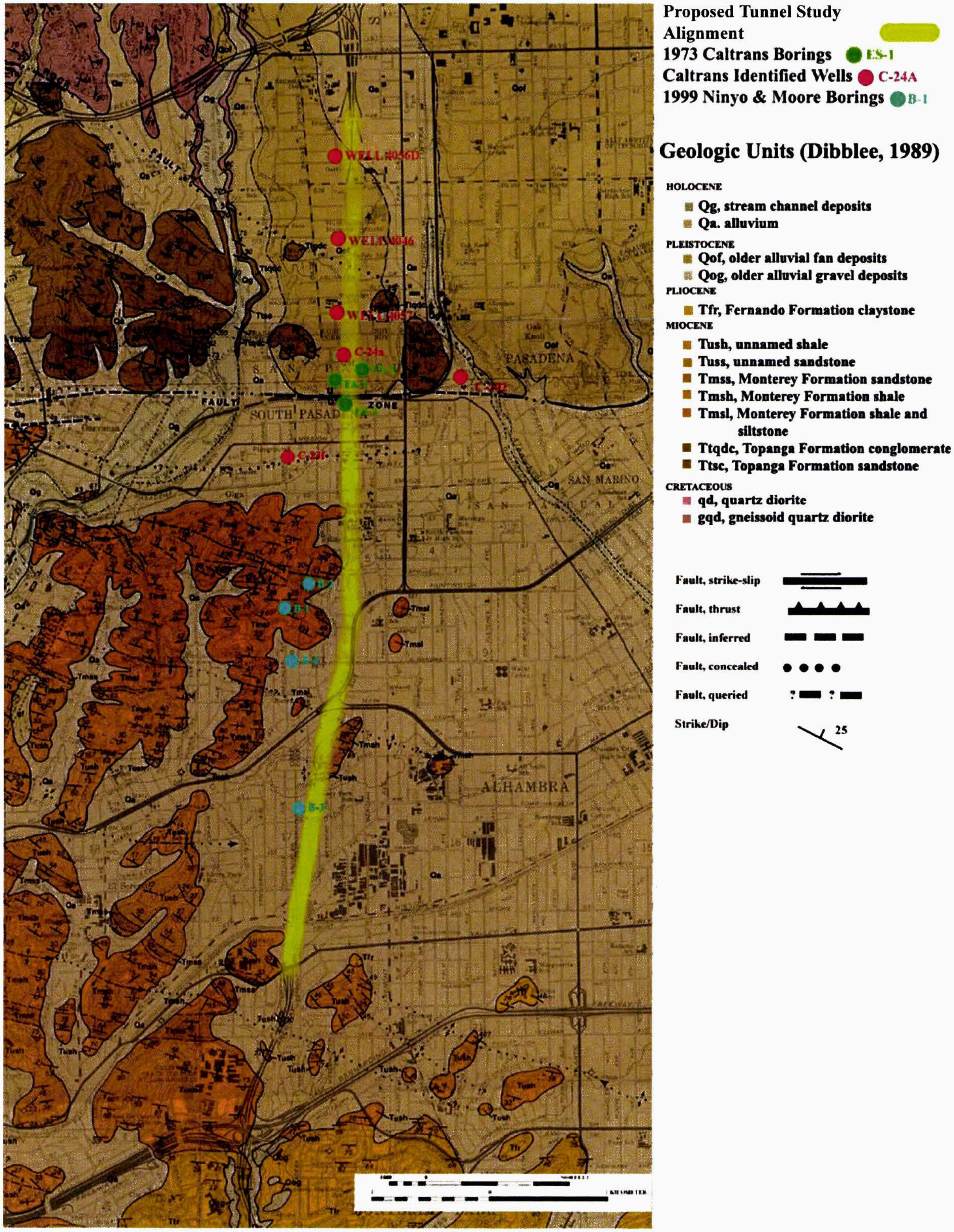


Figure 7. Longitudinal Cross Section, Spruce Street to Glenarm Street.

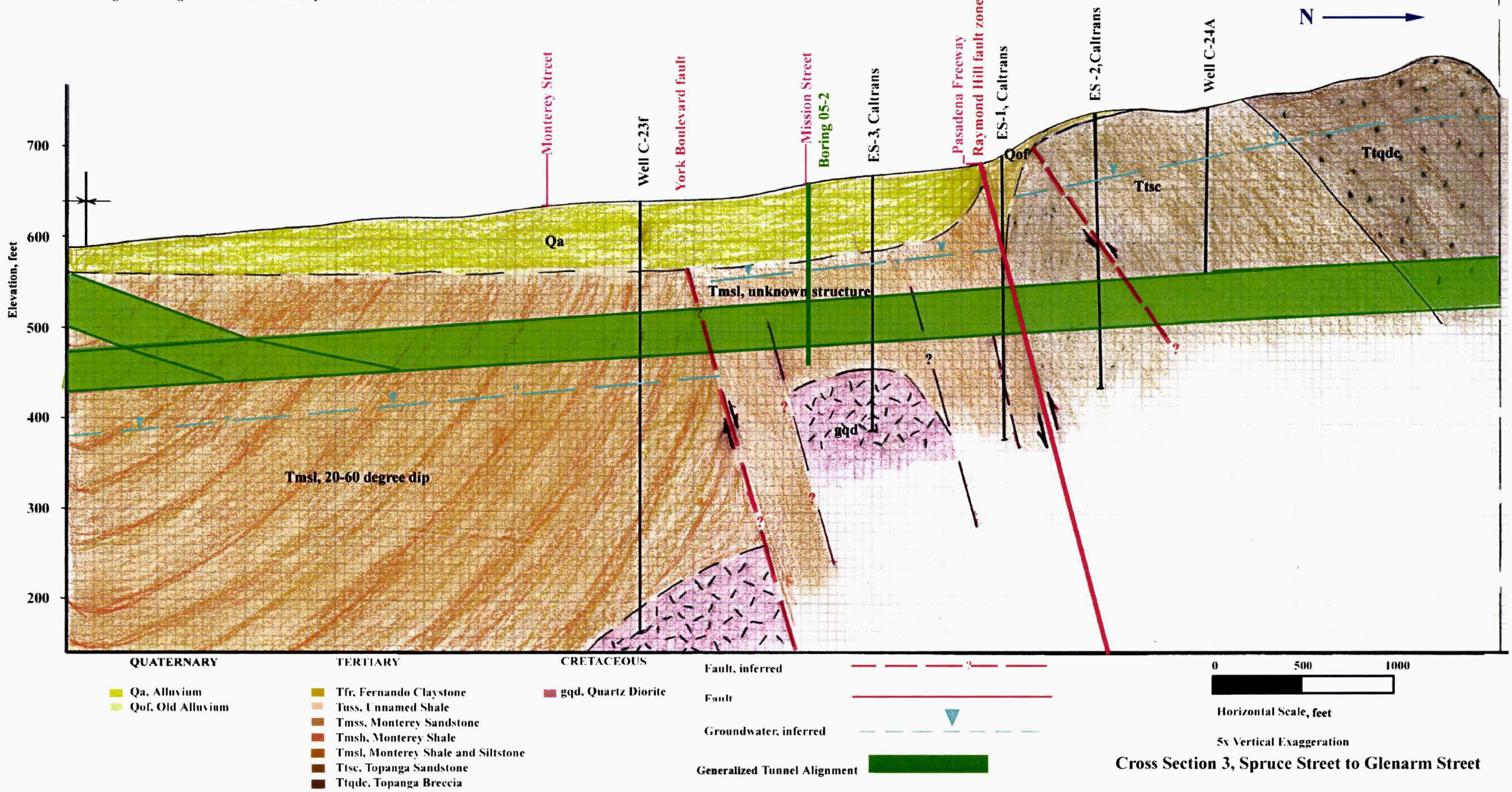


Figure 6. Longitudinal Cross Section, Orange Street to Spruce Street.

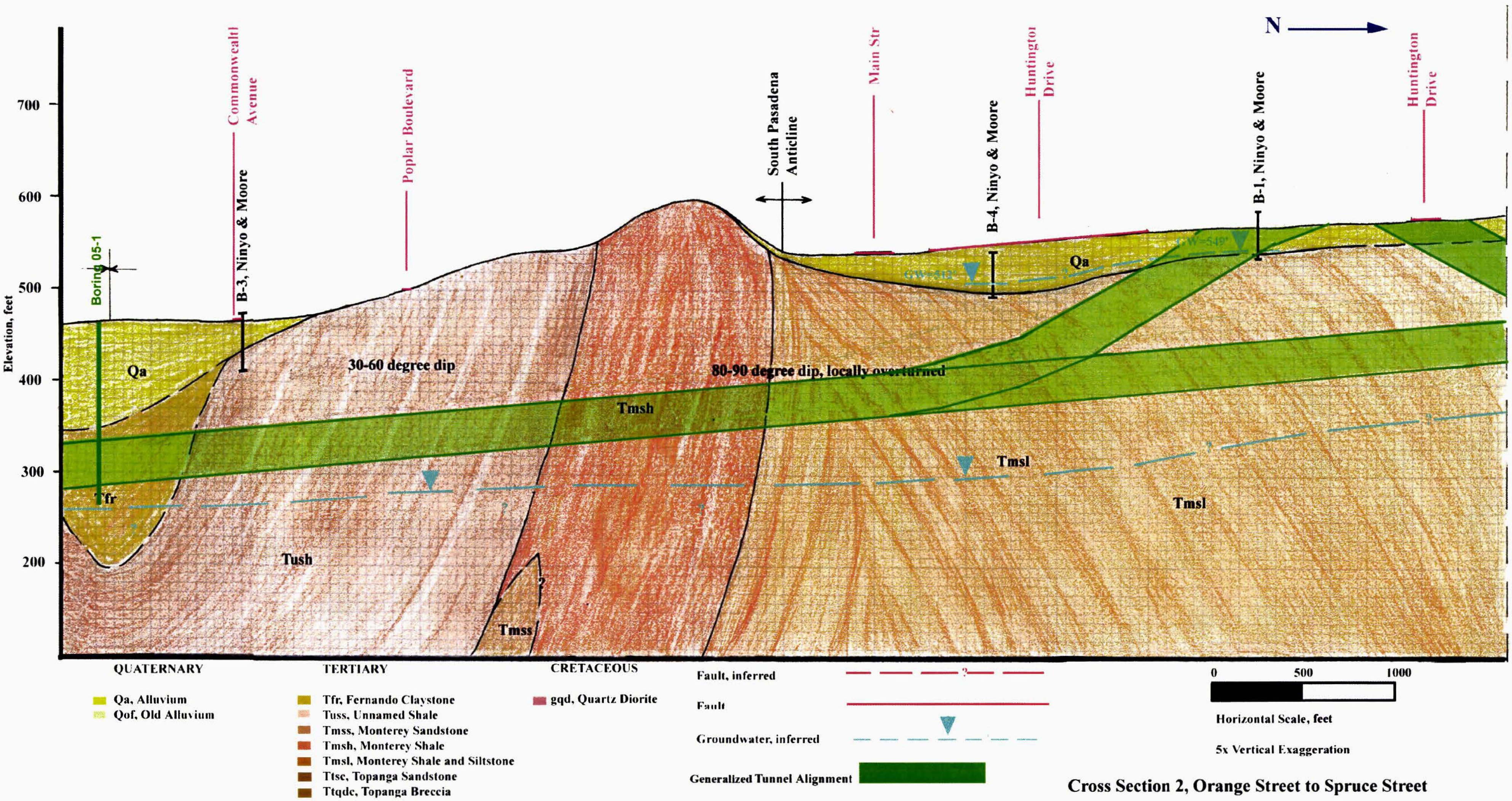
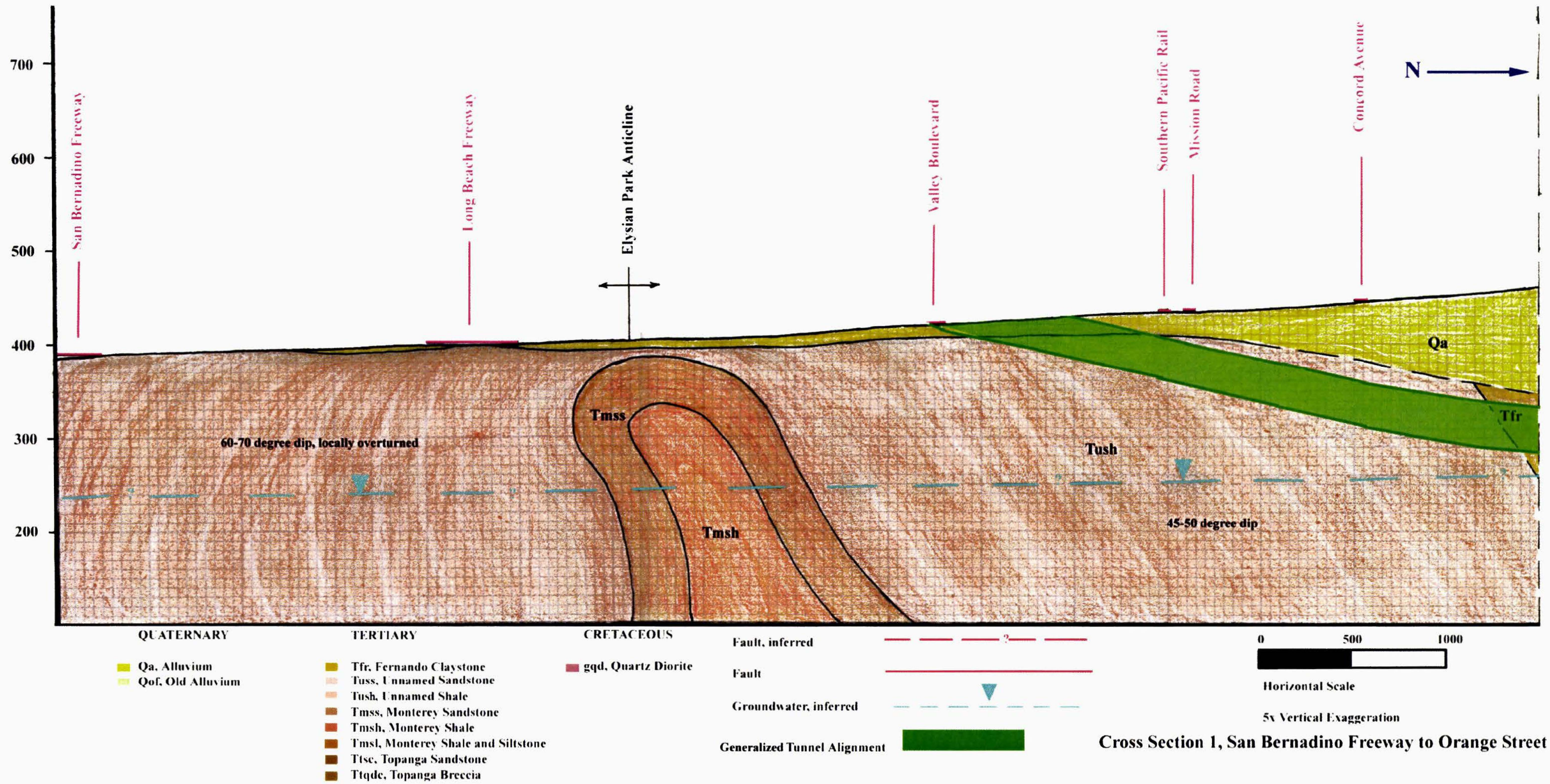
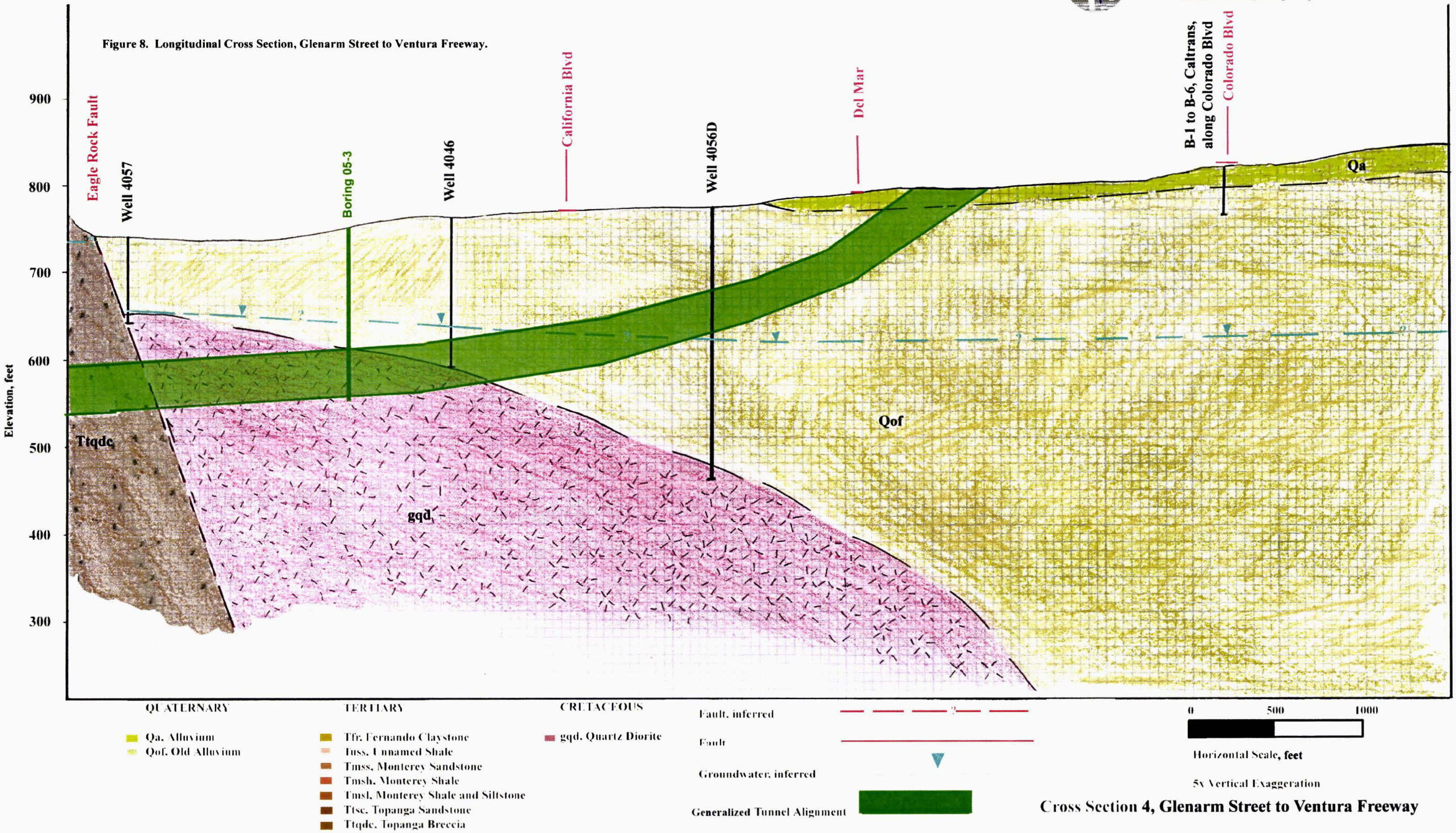


Figure 5. Longitudinal Cross Section, San Bernardino Freeway to Orange Street.



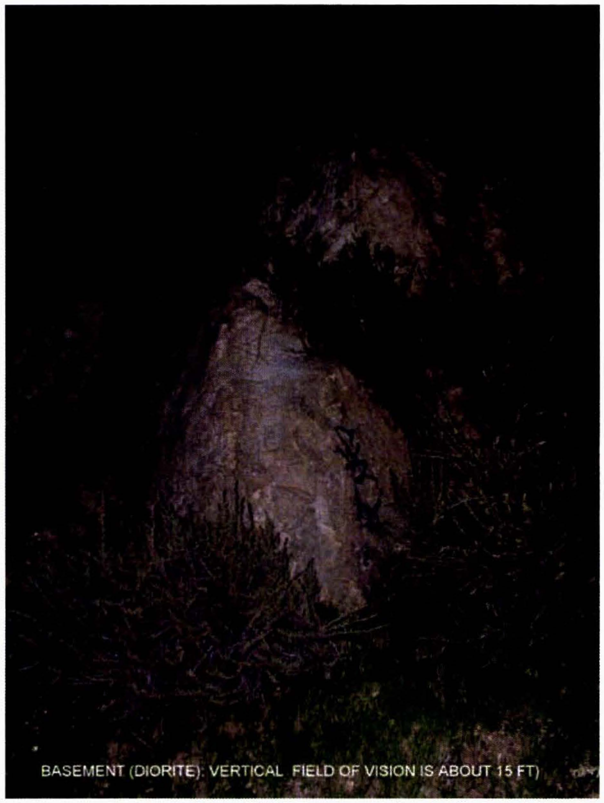
Cross Section 1, San Bernadino Freeway to Orange Street

Figure 8. Longitudinal Cross Section, Glenarm Street to Ventura Freeway.



Cross Section 4, Glenarm Street to Ventura Freeway

Figure 9. Photographs of Basement Rocks.



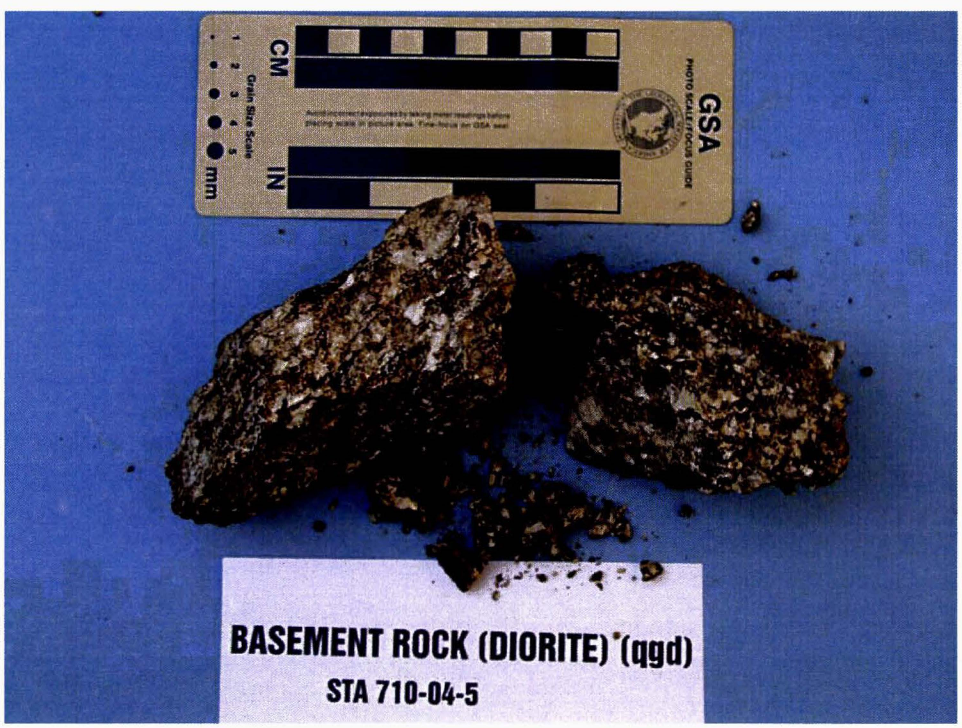


Figure 10. Photographs of Topanga Formation.

Figure 11. Photographs of Monterey/Puente Formation Siltstone.

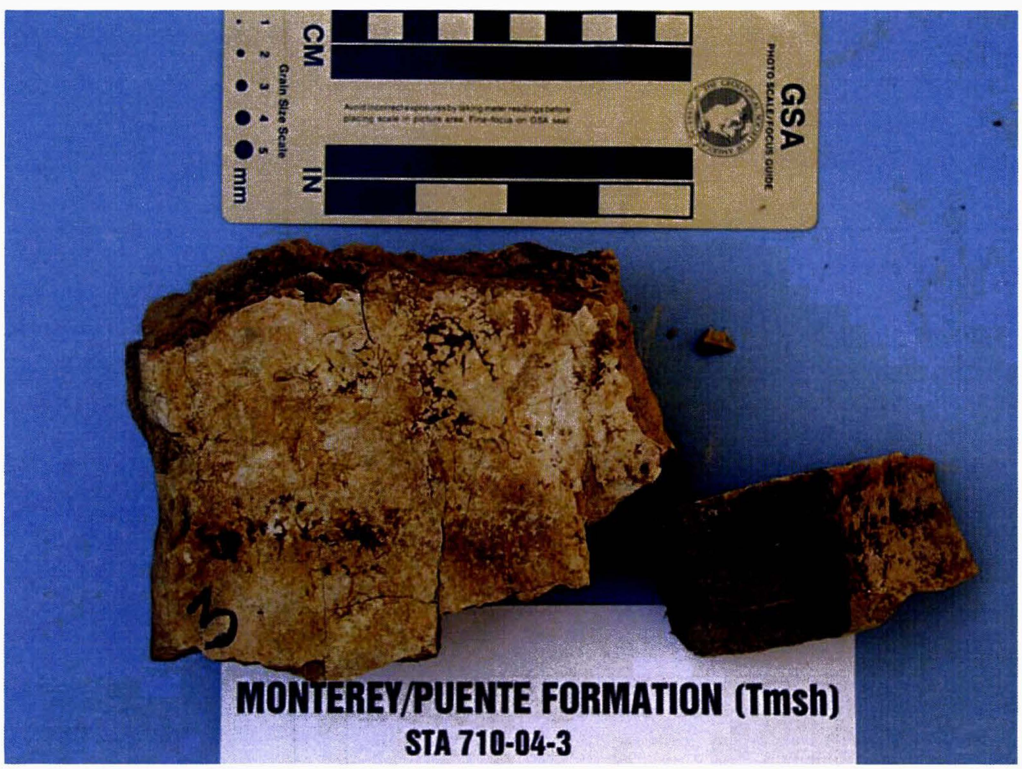


Figure 12. Photographs of Monterey/Puente Diatomaceous Shale and Siltstone.

Figure 13. Historically High Ground Water Contours in Los Angeles Quadrangle.

Base map enlarged from U.S.G.S. 30 x 60-minute series

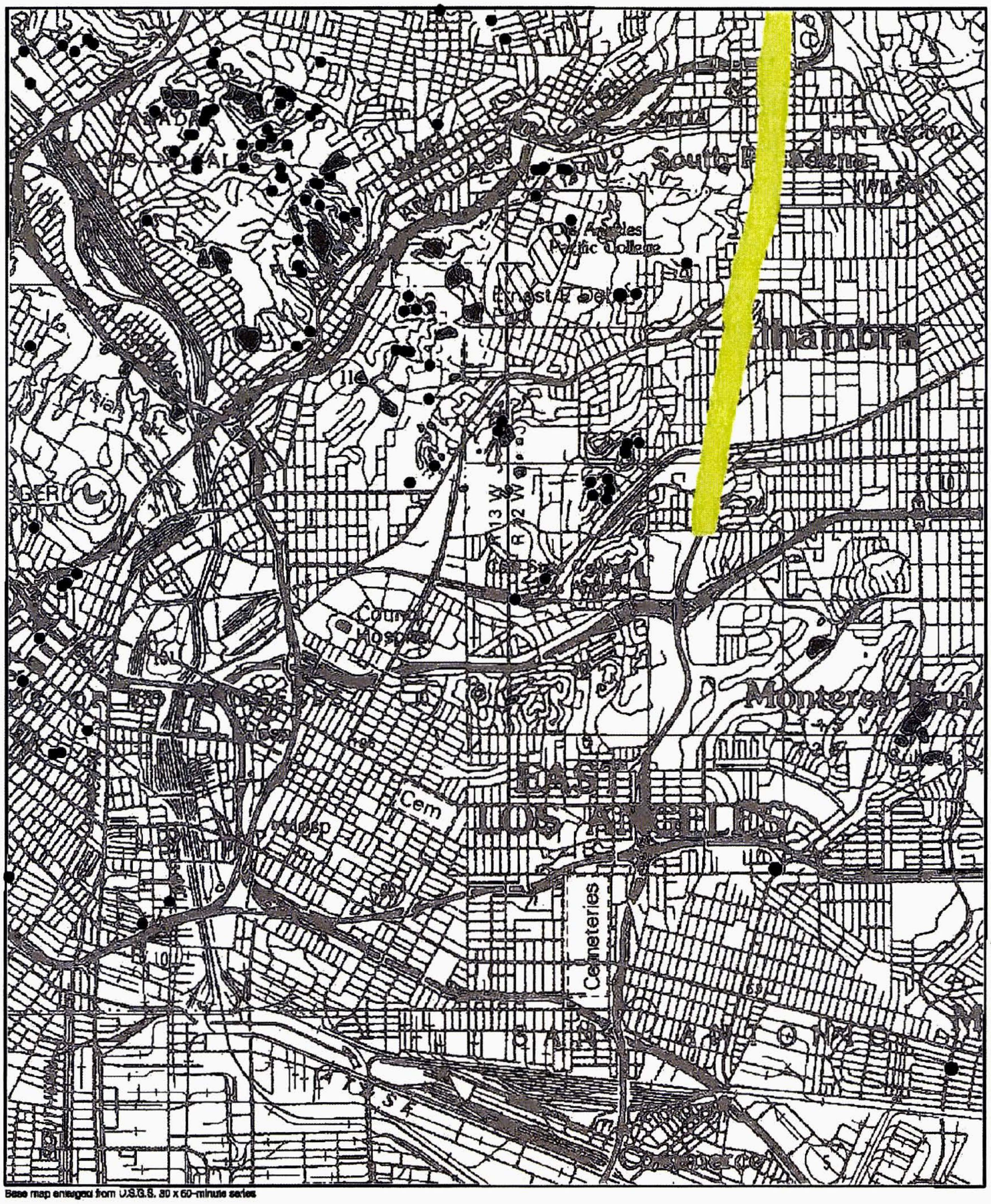
Historically Highest Ground Water Contours and Borehole Log Data Locations, Los Angeles Quadrangle.

● Borehole Site — 30 — Depth to ground water in feet — Tunnel Study Alignment

ONE MILE

SCALE

Figure 15. Locations of Shear Strength Sampling in Los Angeles Quadrangle.



Shear Test Sample Locations, Los Angeles Quadrangle.

● shear test sample location — landslide — areas of significant grading — Tunnel Study Alignment

ONE MILE
SCALE

Figure 14. Historically High Ground Water Contours in Pasadena Quadrangle.

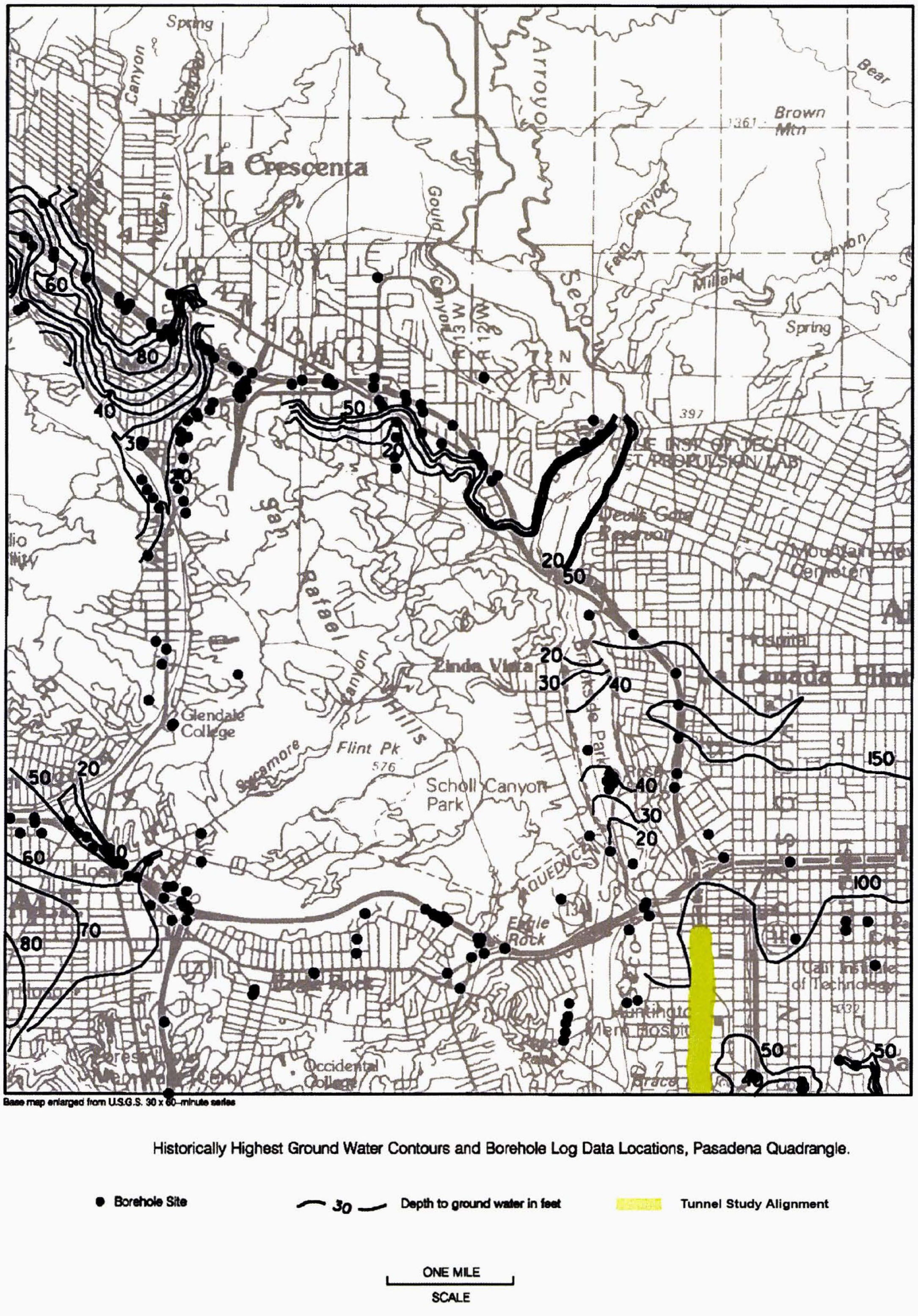


Figure 16. Locations of Shear Strength Sampling in Pasadena Quadrangle.

Figure 17. LADPW Methane Zone Map