

California High-Speed Rail Authority

Palmdale to Burbank *Project Section Draft* *PEPD*

**DRAFT Geotechnical Tunnel
Feasibility Evaluation for High Speed
Rail Tunnels Beneath the Angeles
National Forest**

March 2017

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CALIFORNIA
High-Speed Rail Authority



U.S. Department
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TABLE OF CONTENTS

1	INTRODUCTION	1-1
2	PROJECT DESCRIPTION	2-1
2.1	Alternatives	2-1
2.1.1	SR14 Alternative	2-1
2.1.2	E1 Alternative	2-1
2.1.3	E2 Alternative	2-1
3	PURPOSE AND SCOPE	3-1
4	BACKGROUND INFORMATION	4-1
4.1	Historical Tunnel Projects in National Forests	4-1
4.2	Geotechnical Tunnel Feasibility Issues within National Forests	4-5
4.2.1	Other Geotechnical Feasibility Issues	4-5
5	GEOLOGIC AND HYDROGEOLOGIC CONDITIONS	5-1
5.1	General Geology	5-1
5.1.1	Geologic Units	5-1
5.1.2	Geologic Structures and Faults	5-2
5.1.3	Hydrogeology	5-3
5.1.4	Faulted Ground	5-4
5.2	Geologic Hazards	5-5
5.2.1	Gassy Ground	5-5
5.2.2	Corrosive Groundwater	5-5
5.2.3	Active Fault Displacement	5-6
6	ANTICIPATED TUNNEL CONDITIONS	6-1
6.1	Geologic Conditions	6-1
6.2	Abrasivity	6-1
6.3	Hydrogeologic Conditions	6-2
6.3.1	Preliminary Observations of Groundwater Behavior	6-2
6.3.2	Hydraulic Conductivity	6-3
6.3.3	Groundwater Pressures	6-4
6.4	Intact Rock Strength	6-6
6.5	Rock Mass Conditions	6-6
6.6	In-Situ Stress	6-7
6.7	Ground Conditions	6-9
6.8	Fault Zones	6-11
6.9	Summary of Tunneling Conditions	6-12
7	TUNNEL FEASIBILITY EVALUATION	7-1
7.1	ANF Feasibility Assumptions	7-1
7.2	Tunnel Design and Construction Constraints	7-1
7.2.1	Ground Conditions	7-1
7.2.2	Groundwater Pressures	7-2
7.2.3	Groundwater Flow Potential	7-2
7.2.4	Gassy Ground Mitigation	7-3
7.2.5	Corrosive Groundwater Mitigation	7-3
8	SUMMARY AND PRELIMINARY CONCLUSIONS	8-1
8.1	Ground Conditions	8-1
8.2	Hydrologic and Hydrogeologic Conditions	8-1

9 REFERENCES 9-1

Tables

Table 4-1 Southern California Tunnel Case Histories in National Forests
Table 6-1 Stationing Limits Tabulated for Anticipated Tunnel Conditions
Table 6-2 Hydraulic Conductivity by Generalized Lithology
Table 6-3 Descriptors for Groundwater Pressures
Table 6-4 Descriptors for Intact Rock Strength
Table 6-5 Descriptors for RMR and GSI
Table 6-6 Descriptors for Q
Table 6-7 Descriptors for In-Situ Stress
Table 6-8 Descriptors for Ground Conditions
Table 6-9 Angeles National Forest Tunneling Conditions Summary

Figures

Figure 2-1 Alignment Alternatives and Station Options of the Palmdale to Burbank Project Section
Figure 5-1 Geologic Map
Figure 5-2 Geologic Map Explanation
Figure 5-3 Hydrology Map
Figure 6-1 Abrasivity Correlations
Figure 6-2 Summary of Anticipated Abrasivity
Figure 6-3 Hydraulic Conductivity Correlations
Figure 6-4 Summary of Anticipated Hydraulic Conductivity
Figure 6-5 Summary of Anticipated Groundwater Pressures
Figure 6-6 Summary of Anticipated Intact Rock Strength
Figure 6-7 Summary of Anticipated Rock Mass Conditions
Figure 6-8 Summary of Anticipated In-Situ Stress
Figure 6-9 Summary of Anticipated Ground Conditions

ACRONYMS AND ABBREVIATIONS

σ_1	Major Principal Stress
σ_2	Intermediate Principal Stress
σ_3	Minor Principal Stress
σ_c	Rock Mass Strength
σ_H	Maximum Horizontal Stress
σ_v	Vertical Stress
Authority	California High-Speed Rail Authority
BMP	Best Management Practice
Ca-HCO ₃	Calcium Bicarbonate
Ca-SO ₄	Calcium Sulfate
CAI	Cerchar abrasiveness index
Cal/OSHA	California Division of Safety and Health
Caltrans	California Department of Transportation
CGS	California Geological Survey
CCR	California Code of Regulations
cm/sec	centimeter per second
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
FRA	Federal Railroad Administration
GAMA	Groundwater Ambient Monitoring and Assessment
GSI	Geological Strength Index
HSR	High-Speed Rail
ISRM	International Society for Rock Mechanics
MWD	Metropolitan Water District of Southern California
PGDR	Preliminary Geotechnical Data Report
PMT	Program Management Team
RC	Regional Consultant
RMR	Rock Mass Rating
RQD	Rock Quality Designation
SGMNM	San Gabriel Mountains National Monument
SR	State Route
SST	Seismic Specialists Team
USBR	U.S. Department of the Interior Bureau of Reclamation
USFS	United States Forest Service
VWPT	Vibrating Wire Pressure Transducers

CONVERSIONS

1 inch (in.) = 2.54 centimeter (cm)

1 foot (ft) = 0.3048 meter (m)

1 mile (mi) = 1.61 kilometer (km)

1 ft³ = 28.3 liters (l)

1 acre-foot = 4.36E+04 ft³

1 pound force (lbf) = 4.45 Newtons (N)

1 metric ton = 2,205 lbf

1 ton / square foot (tsf) = 13.88 lbf / square inch (psi)

1 psi = 6.89E-03 megaPascal (MPa)

1 MPa = 145.14 psi

1 ksf = 6.94 psi

1 bar = 0.10 MPa

1 bar = 14.5 psi

1 bar = 34.5 foot-head-freshwater

62.4 lbf/cubic feet (pcf) = 0.43 psi/ft

1 pcf = 6.37E-03 N/m³

EXECUTIVE SUMMARY

The California High-Speed Rail (HSR) Authority (Authority) proposes to construct, operate, and maintain an electric-powered HSR system in California. When completed, it will run from San Francisco to the Los Angeles Basin in under 3 hours at speeds capable of exceeding 200 miles per hour. The system will eventually extend to Sacramento and San Diego, totaling 800 miles with up to 24 stations.

The Authority and FRA are now undertaking second-tier, project environmental evaluations for several sections of the statewide system. This report is for the Palmdale to Burbank Project Section. This project section is approximately 38- to 44-mile long, and has multiple alignment alternatives under study. The project section extends through a variety of land uses and ecoregions, including urban, rural, and mountainous terrain. Each alignment alternative would involve areas of tunneling beneath the Angeles National Forest (ANF), including portions within the San Gabriel Mountains National Monument (SGMNM). A complete General Project Description is included in other documents.

Each of the alternatives under analysis in the Palmdale to Burbank Project Section is divided in three subsections: Palmdale, Central and Burbank.

This report focuses on the geotechnical feasibility of proposed tunnels under the Angeles National Forest in the San Gabriel Mountains within the Central Subsection of the Palmdale to Burbank Section.

The data obtained for the HSR project by field investigations within the ANF in support of this geotechnical feasibility report are available in the following HSRA report:

“Preliminary Geotechnical Data Report for Tunnel Feasibility, Angeles National Forest” dated December 2016.

The data presented in the preliminary geotechnical data report (PGDR) were obtained specifically to identify and evaluate field conditions within the ANF that could present feasibility constraints for design and construction. Recognizing the history of challenging tunnel design and construction for deep tunnels beneath United States Forest Service (USFS) land in Southern California, the most challenging constraints with strong potential for influencing tunnel feasibility include the following:

- Rock quality and potential effects of squeezing ground;
- In-situ stresses;
- Intersections with faults and gouge zones;
- Groundwater pressures on the tunnel lining system;
- Water draining into the tunnel both during and after construction;
- Groundwater temperature;
- Potential impacts to USFS water resources due to tunneling activities.

The data available in the PGDR include results from the following studies:

- Continuous rock coring at six sites (FS-B1, E1-B1, E1-B2, ALT-B2, ALT-B3 and C-1) to depths as great as 2,700 feet;
- Geologic Logging of nearly 9,000 feet of cored rock;
- Photographic documentation of rock core;
- In-situ hydraulic conductivity testing using single or dual packer systems;
- In situ groundwater sampling;
- In-situ rock stress/strength testing;
- Geophysical logging including caliper, electric (spontaneous potential), temperature, conductivity, natural gamma, seismic velocity, and downhole televiewer surveys; and
- Installation of vibrating wire pressure transducers (VWPTs) within each hole for measuring in-situ pressures;
- Laboratory testing of rock core samples;

- Petrographic analyses of rock thin sections; and
- Analytical testing of water samples for chemistry and radioisotopes.

The results of the geotechnical investigations within the ANF are documented in the PGDR and should be referenced as background information for the geotechnical feasibility report. The PGDR field investigations were not conducted to investigate specific tunnel alignments, but were generally focused on the critical feasibility issues as stated previously. Once a preferred alternative is determined through the environmental screening process (EIR/EIS), a more detailed and focused investigation of the preferred tunnel alignment will need to be developed and implemented for preliminary design of the tunnel excavation methods (sequential excavation methods, tunnel boring machine, etc.), construction sequence and schedule, tunnel lining system, and mitigation measures for potential impacts from challenging geotechnical conditions.

1 INTRODUCTION

The Palmdale to Burbank Project Section would be a critical link in the Phase 1 HSR system connecting San Francisco and the Bay Area to Los Angeles and Anaheim. A complete General Project Description is included in other documents and is not repeated in this report.

This report documents geotechnical feasibility of tunnel alignments beneath the Angeles National Forest (ANF) based on the "Geotechnical Data Report for Tunnel Feasibility for the Angeles National Forest" within the Palmdale to Burbank Section of the California HSR System. This report includes the following:

- Description of site geotechnical conditions within the Angeles National Forest.
- An explanation of key conditions that affect overall tunnel design and construction.
- Interpretation of geotechnical data representing the in-situ conditions along tunnels in the ANF.
- Discussion of geotechnical conditions and potential impacts on the feasibility of proposed tunnel alignments.

2 PROJECT DESCRIPTION

The approximately 38- to 44-mile Palmdale to Burbank section has multiple alignment alternatives under study. The project section extends through a variety of land uses and ecoregions, including urban, rural, and mountainous terrain. Each alignment alternative would involve areas of tunneling beneath the ANF, including portions within the San Gabriel Mountains National Monument (SGMNM).

2.1 Alternatives

This section briefly describes the Palmdale to Burbank Project Section alternatives, as they relate to the proposed tunnels beneath the ANF. For a complete General Project Description refer to other documents.

The HSR Build Alternatives for the Palmdale to Burbank Project Section include three (SR14/E1/E2) end-to-end alternatives. Figure 2-1 shows the alignment alternatives and station options. Discussion of the HSR Build Alternatives is organized from north to south.

Within the ANF of the Central Subsection, the SR14 alignment is separate from the other two alignments but joins E2 south of the ANF boundary. The E1 and E2 alignments share a common course beneath the SGMNM and then diverge southward into separate alignments through the ANF.

Figure 2-1 Alignment Alternatives and Station Options of the Palmdale to Burbank Project Section

2.1.1 SR14 Alternative

The northern limit of the SR14 Central Subsection is near Lang Station at the northern edge of the SGMNM, Station 1320+00, where a portal is located on the Vulcan Mine property south of the Santa Clara River crossing. The alignment trends southwest and exits the National Monument briefly near Station 1470+00. It enters the ANF at Sand Canyon near Station 1530+00 and crosses beneath the mountains west of Bear Divide. The tunnel leaves the ANF at Station 1705+00 but continues underground where it joins the E1 alignment south of the ANF boundary. The length of the tunnel starting at the Vulcan Mine portal to the southern edge of the ANF is approximately 7.3 miles. The highest topographic relief is within the ANF where maximum cover over the tunnel invert is approximately 2,060 feet (Station 1626+00).

2.1.2 E1 Alternative

The northern limit of the E1 alternative enters the SGMNM near Station 680+00. It traverses by tunnel beneath the National Monument for approximately 3 miles emerging in Aliso Canyon from approximate Station 720+00 to 750+00, where it enters the National Monument again in tunnel. From Station 750+00 to 860+00, E1 continues in tunnel until Arrastre Canyon, where the alignment is above ground for approximately 1.1 miles. The alignment again enters a tunnel at the north edge of the National Monument at Station 920+00 and continues in tunnel to the south side of the Angeles National Forest near Station 1620+00 a distance of 13.3 miles. Near Station 1110+00, the E1 alternative leaves the National Monument and transitions to the Angeles National Forest (ANF). The maximum depth of the tunnel invert is south of forest road 3N17, Santa Clara Divide where maximum cover over the tunnel invert is approximately 2,060 feet (Station 1166+00).

2.1.3 E2 Alternative

The E2 and E1 alternatives follow the same path in the SGMNM from Station 680+00 until Station 1020+00, where E2 takes a more easterly alignment passing beneath North Fork Station and continuing below Pacoima Canyon and then passing beneath Mendenhall Ridge. It continues south to the edge of the ANF at Station 1625+00. The maximum depth to the tunnel is at Mendenhall Ridge, where the cover over the tunnel invert is approximately 2,650 feet (Station 1338+00).

3 PURPOSE AND SCOPE

The purpose of this tunnel feasibility evaluation is to provide geotechnical information supported by preliminary geotechnical data for this project, geologic conditions and data from selected previous tunneling projects, and professional opinions that the Authority can use for assessing the feasibility of the ANF Tunnels. The three proposed alignments (Figure 2-1) include the SR14 that parallels the SR14 highway until the Santa Clara River, where it crosses the river and continues south beneath the SGMNM and the ANF. Two eastern alignments depart from the SR14 alignment immediately south of Palmdale and enter the SGMNM and ANF southwest of Acton.

The primary emphasis of this feasibility evaluation is to identify, describe, and quantify challenging technical constraints that may impact tunnel feasibility, such as extremely high groundwater pressures, high temperatures, or unavoidable impacts to water resources in the ANF. Other challenging conditions may include severely unfavorable geology, such as wide fault zones, squeezing ground and high groundwater inflows. Active faults intersecting the tunnel can also be a constraint, and are briefly addressed in this report based on data summarized from previous HSRA reports. Any one of these conditions or a combination of the conditions can represent design or construction challenges that need careful evaluation. The most challenging conditions related to groundwater pressures, high temperatures, squeezing ground and high groundwater flows are expected in the areas where the tunnels are deepest below the ground surface. Thus, the focus of the field investigations was in the high mountains within the ANF, where the feasibility of the tunnels at depth was evaluated.

This feasibility evaluation assimilates and interprets the available geotechnical data for tunnels passing beneath the ANF along three proposed alignments. The tunnel locations through the San Gabriel Mountains are shown on Figure 2-1. For this feasibility study, tunnel alignments were evaluated with respect to four feasibility categories, which comprise the main sections of this report, as follows:

- Geologic Conditions (rock mass conditions, weathering);
- Tunnel Design and Construction Conditions (hydraulic head and conductivity, temperature, and fault displacement);
- Hydrogeologic Conditions and USFS Concerns within ANF; and
- Construction Difficulties (Groundwater flow controls, Fault Zones, and state of rock stress).

The ANF feasibility evaluation team performed this evaluation by completing the following:

- Summarizing case histories of tunneling challenges in Southern California mountain ranges;
- Evaluating and interpreting available geotechnical data to develop a conceptual geological/geotechnical model of the ANF Tunnel Alignments (Geologic Profiles); and
- Interpreting field data collected from the geotechnical investigations and presented in the Authority report: "Geotechnical Data Report for Tunnel Feasibility, Angeles National Forest" for estimating groundwater pressures, ground temperatures, groundwater inflows to the tunnel, and other ground conditions.

The geotechnical investigation performed in 2016 provides the primary source of geotechnical data used for this feasibility evaluation. The geotechnical investigation included the following:

- Drilled six exploratory core holes to characterize the rock mass conditions and install groundwater monitoring instrumentation;
- Logged nearly 9,000 feet of rock core;
- Performed in-situ hydraulic conductivity testing;
- Conducted down-hole geophysical surveys;
- Conducted high-resolution acoustical televiewer surveys within stable intervals of the core holes;
- Conducted in-situ stress tests in two core holes;
- Performed geotechnical testing of samples from the anorthosite, syenite, gabbro, granite, granodiorite, shale and sandstone rock types along the alignments; and

- Compiled published geologic information for the study area.

The results of the 2016 geotechnical investigations are documented in the "Preliminary Geotechnical Data Report for Tunnel Feasibility, Angeles National Forest" (Authority, 2016).

4 BACKGROUND INFORMATION

4.1 Historical Tunnel Projects in National Forests

Historical tunnel projects in Southern California stand as examples of tunnel conditions that are typical and have served as the basis for many mitigation requirements for tunnel design, safety regulations, and construction methods in the industry. Significant case histories are summarized in Table 4-1 covering a long period of tunnel industry development, evolution of design and construction methods and general industry changes with respect to feasibility constraints. These tunnels include the San Jacinto Tunnel through the San Jacinto Mountains National Forest and State Park, the Tecolote Tunnel beneath the Santa Ynez Mountains Los Padres National Forest, Arrowhead Tunnels in the San Bernardino National Forest, and the Central Pool Augmentation Tunnel and the Irvine-Corona Expressway Tunnels in the Cleveland National Forest. Several characteristics for each of these tunnels and the accompanying impacts and mitigation methods are summarized in Table 4-1 as background information for tunnels in national forests of Southern California.

Table 4-1 Southern California Tunnel Case Histories in National Forests

Case History/ Owner / National Forest (NF)	Timeline	Length / Diameter / Overburden Depth	Host Rocks / Construction Method	Water Parameters H – Heading Flow P – Portal Flow Measured Water Pressures (bar)	Impacts and Mitigations	Historical Notes
#1 San Jacinto Tunnel / MWD / San Jacinto Mountains NF and State Park	Construction 1933-1939	13 Miles / 18 Feet / 2,600 Feet overburden	Predominantly granitic rock / Drill and blast with horseshoe and circular steel sets with gunite where needed.	H – Instantaneous Max. 16,000 gpm + 3,000 cy sand P – Max. 40,000 gpm P – 540 gpm after sealing cracks and concrete lining system. P – Sustained flow at 2,500 gpm long term. Max. Measured Pressures 43 bar with typical being 11 to 22 bar.	Tunnel flooding during construction; drove pioneer tunnels for drainage and injected cement into holes at pressures of 1,500 psi. Springs and seeps dried up in and around mountains. Grouted leaking cracks and lined the tunnel with concrete.	High groundwater flows were associated with 21 faults mapped after groundwater impacts manifested. Efforts to seal the leaks could achieve no less than 540 gpm.
#2 Tecolote Tunnel / Bureau of Reclamation / Los Padres NF	Construction 1950-1956	6.4 Miles / 7 Feet / 2,300 Feet overburden	Tertiary and Cretaceous marine sandstone and siltstone / Drill and Blast / 6-inch horseshoe H- Beam ribs with plating and lagging.	H – 1,200 to 2,800 gpm P – 9,100 gpm peak Max. Measured Pressures 26 bar.	Sustained drainage from tunnel required a combination of grouting with pressures up to 2,000 psi against 230 to 250 psi water pressures. Baseline monitoring of 125 springs and streams before construction. Reduced water flow observed at one of 125 monitored springs and spring fed streams	Monitored springs and streams. Increased flows due to Arvin-Tehachapi earthquake and after Refugio fire. Only one spring was documented to be influenced by drainage from tunnel construction.

March 2017

4-2 | Page

Case History/ Owner / National Forest (NF)	Timeline	Length / Diameter / Overburden Depth	Host Rocks / Construction Method	Water Parameters H – Heading Flow P – Portal Flow Measured Water Pressures (bar)	Impacts and Mitigations	Historical Notes
#3 Arrowhead Tunnel East Phase I / MWD / San Bernardino NF	Construction Phase I City Creek Portal 1997-2000	1.5 Miles / 19 Feet / 1,100 to 2,070 Feet overburden	Gneiss, marble beds and mafic gneiss. TBM with grout ports at front of TBM; leaky segmented concrete lining.	780 million gallons of water drained from City Creek portal. P – Exceeded Permit Limits	Water levels declined 200- feet near City Creek and perennial streams dried up during construction. Grouting in advance of TBM not effective.	First contractor completed 8,000 feet of mining. Construction was shut down due to uncontrolled water inflows and concerns from USFS and San Manuel Bandof Indians.
#3 Arrowhead Tunnel East Phase II / MWD / San Bernardino NF	Construction Phase II Strawberry Creek Portal 2003-2008	4.2 Miles / 19 Feet / 1,100 to 2,070 Feet overburden	Quartz Monzonite, granodiorite and gneiss with marble. / TBM Open or closed face mode up to 10 bar pressure and operating at 3 bar. Gasketed, bolted, reinforced concrete segmental lining rated for 40 bar pressure.	520 million gallons of water loss from Strawberry Creek portal. P – ? Max. Measured Pressures 30 bar	Water resources impacts from Phase I. Mitigation by custom designed Herknecht TBM with advanced grouting and dual mode operation. Pre- construction Grouting when one of 34 probe hole flows exceeded 0.3 gpm or if portal flow exceeded 520 gpm. Mitigation of surface water resources by artificial irrigation. Gasketed and bolted segmental concrete lining.	Contact grouting was carried out after erection of the segmental lining to fill the annular space and cut off flow along tunnel using inflatable collars for grouting. The final lining was a steel pipeline to carry the aqueduct water. For mitigation of water resources impacts, the spring and stream supplemental water distribution continued after tunnel construction. Results indicated that a standard procedure for control of groundwater in the tunnel did not apply to all conditions and the best approach was to adapt groundwater flow controls on a case-by-case basis.

Case History/ Owner / National Forest (NF)	Timeline	Length / Diameter / Overburden Depth	Host Rocks / Construction Method	Water Parameters H – Heading Flow P – Portal Flow Measured Water Pressures (bar)	Impacts and Mitigations	Historical Notes
#4 Central Pool Augmentation Tunnel / MWD / Cleveland NF	Not Constructed Feasibility Evaluation 2006-2008	10 Miles/ ~ 20 feet/ 2,200 to 2,500 Feet overburden	Meta-sandstone and meta-shale (Argillite, slate, and mudstone) Planned for TBM excavation. Developed RMR, Q and GSI for estimates of TBM performance	Hydraulic Conductivities ranged from 5x10-3 cm/sec to 5x10-5 cm/sec near surface; and 1x10-6 cm/sec to 5x10-8 cm/sec at tunnel envelope Maximum Measured Water Pressures from Vibrating Wire Piezometers (VW/PT) in Core Holes 35 bar at 2,200 feet depth 42 bar at 2,500 feet depth	Recommended dual mode TBM with gasketed, and bolted segmental concrete lining.	Measured VW/PT pressures indicated lower than estimated hydrostatic pressures at tunnel depths of 2,200 and 2,500 feet. Hydraulic conductivities decreased with greater depths. Lower pressures at depth suggest hydraulic separation (i.e. isolation) of deep water from shallow water.
# 5 Irvine Corona Expressway (ICE) Tunnels / Riverside County Transportation Commission / Cleveland NF	Not Constructed Feasibility Evaluation and Conceptual Design, TBM specifications and cost estimate. 2007-2010	11 Miles/ 52 feet vehicular and 26.5 feet rail tunnels / 1,500 feet overburden or greater to match 25 bar of water pressure. Ventilation shaft near middle of tunnel for Fire-Life Safety.	Meta-sandstone and meta-shale (Argillite, slate, and mudstone) Planned for TBM excavation. Developed RMR, Q and GSI for estimates of TBM performance	Hydraulic Conductivities ranged from 2x10-3 cm/sec to 6x10-8 cm/sec for shallower than 1,000 feet of overburden; and 3x10-6 cm/sec to 3x10-8 cm/sec at tunnel envelope of about 1,500 feet. Maximum Measured Pressures from Vibrating Wire Piezometers (VW/PT) in Core Holes 25 bar at 1,250 feet depth 30 bar at 1,500 feet depth	ICE mitigation measures were planned to establish pre-construction baseline spring and spring-fed stream flow monitoring followed by monitoring during and after tunnel construction. Recommended dual mode TBM. Lining system to be gasketed and bolted segmental high strength concrete lining. Pre- excavation grouting program. Controlled drainage would be needed for water pressures above 25 bar.	Recommended proposed tunnel profiles/depths corresponding to water pressures no greater than 25 bar (~350 psi). For tunnel sections in water pressures greater than 25 bar (i.e. deeper), it was assumed that water leakage would need to be controlled to maintain peak pressures no more than 25 bar.

March 2017

4-4| Page

California High-Speed Rail Authority Palmdale to Burbank Project Section Draft PEPP

DRAFT Geotechnical Tunnel Feasibility Evaluation for High Speed Rail Tunnels Beneath the Angeles National Forest

4.2 Geotechnical Tunnel Feasibility Issues within National Forests

Based on past tunnel project case histories in southern California, the following issues are recognized as critical for evaluating feasibility of tunnels in certain environments with challenging conditions for design and construction of transportation tunnels:

- Effects of tunnel construction and impacts to groundwater and surface water resources.
- Balancing groundwater protection measures against practical design and construction requirements.
- Defining acceptable impacts (e.g., grading) at tunnel portal locations and, if needed, at intermediate accesses for construction and fire-life safety issues.
- State of the art tunnel lining design to minimize water leakage into the tunnels under anticipated high groundwater pressures.
- Addressing the potential for high water temperatures and the impacts on fire-life safety ventilation controls.
- General rock mass conditions combined with in-situ pressures and stresses controlling ground behavior during construction.
- Squeezing ground conditions affecting tunneling methods and rates of advancement.
- Displacements from large earthquakes along active (i.e., Hazardous) faults that intersect the tunnel below ground.

The geotechnical feasibility of the ANF tunnels are discussed in Section 7.0 of this report.

4.2.1 Other Geotechnical Feasibility Issues

Adits (i.e., shafts or galleries from the ground surface to the tunnel) will be necessary for ventilation and construction access; however, these are planned in areas outside the ANF. Similar to the tunnels, where adits penetrate groundwater, these will also need to implement groundwater inflow control measures during construction and operation to reduce the potential impacts to surface and groundwater resources within the ANF.

5 GEOLOGIC AND HYDROGEOLOGIC CONDITIONS

Conceptual geologic and hydrogeologic models have been developed from the available geotechnical data and results of field investigations for this feasibility evaluation to estimate the tunneling conditions with respect to the ANF tunnel alignments (Authority, 2016). The geologic units, and structures traversed by the ANF tunnel alignments are shown on Figure 5-1. Figure 5-2 provides an explanation of the map units and symbols for Figure 5-1 and the Geologic Profiles and Anticipated Tunnel Conditions drawings in Appendix A.

Figure 5-1 Geologic Map

Figure 5-2 Geologic Map Explanation

5.1 General Geology

5.1.1 Geologic Units

The three alternative tunnel alignments traverse the western San Gabriel Mountains beneath the ANF, the Study Area. The local geology of the project Study Area is complex due to multiple stages of metamorphism, igneous intrusion, rotation, and subsequent uplift and faulting of the area over the past 1.7 billion years. Previous mapping of the San Gabriel Mountains by the California Geological Survey (CGS; Campbell et al., 2014) and the United States Geological Survey (USGS; Yerkes and Campbell, 2005) provided the surface mapping of the Study Area's geology. To supplement this existing data and check site-specific geologic information, limited geologic mapping and a subsurface investigation were conducted within the Study Area. The subsurface investigation included drilling, collecting core and performing geophysical and hydrogeological downhole tests. Detailed descriptions of the field activities, including rock coring, are provided in Section 3 of the Draft Geotechnical Data Report for Tunnel Feasibility, Angeles National Forest (Authority, 2016).

The rocks within the project Study Area include a massif of Proterozoic- to Cretaceous-age metamorphic and igneous rocks that comprise the areas of greatest relief within the San Gabriel Mountains that are bordered to the northwest and south with a lower-lying mantling of Tertiary-age and younger sedimentary rocks and surficial deposits.

The metamorphic and igneous rocks include remnants of Proterozoic gneiss that have been intruded by a Proterozoic anorthosite-gabbro complex, the Mount Lowe Granodiorite (intrusive suite) of Permian-Triassic age, Mesozoic granitic (including the Mount Josephine granodiorite) and gneissic rocks. The oldest and one of the most distinctive rocks on the Study Area is the approximately 1.7 billion year old Mendenhall Gneiss. The Mendenhall Gneiss was described and named by Oakeshott (1958). This gneiss is exposed in the Study Area north of the San Gabriel fault and south of the anorthosite-gabbro complex (Authority, 2016). It was subjected to high temperature metamorphism 1.2 billion years ago and in many areas again during the Mesozoic (Silver, 1971; Ehlig, 1975b). The anorthosite-gabbro and related rocks are exposed over an area of about 80 square miles, mostly in the Study Area. The anorthosite-gabbro complex is described in detail by Carter (1980a, 1980b and 1982) and Oakeshott (1958). The blue-gray to white andesine anorthosite is the most abundant rock type in the anorthosite-gabbro complex (Carter, 1980a) with the gabbro the next most abundant followed by the syenite. This igneous complex was emplaced 1.22 billion years ago (Silver, 1971; and Carter, 1980a). Studies by Carter (1980a) indicate the complex was initially stratiform with prominent compositional layering produced by gravitational settling of mineral crystals. The structure has subsequently become geologically complex due to several episodes of deformation and faulting. These rocks are generally coarse grained and have unusual textures.

Northwest and south of the metamorphic and igneous rock outcrops are layers of Tertiary-age sedimentary rocks. The sedimentary deposits have been both faulted against and deposited over the metamorphic and igneous rocks. In the northwest part of the Study Area, the sedimentary

layers belonging to the Vasquez, Tick and Mint Canyon Formations have been deposited. The Vasquez Formation is Oligocene to early Miocene in age and includes sandstone, mudstone, and conglomerate with interbedded andesite-basalt. The Vasquez Formation is greater than 12,000 feet thick and rests on crystalline bedrock. Overlaying the Vasquez formation is the Miocene Tick Canyon Formation, which is comprised of well-cemented conglomerate sandstone, claystone and siltstone of fluvial origin (Oakeshott, 1958). The Tick Canyon is early to middle Miocene in age. Deposited above the Tick Canyon Formation is the Mint Canyon Formation. The Mint Canyon Formation is middle to late Miocene in age (Campbell et.al. 2014) and includes semi-consolidated non-marine layers of arkosic and conglomerate sandstone, siltstone, mudstone, and an interbedded tuff near the top of the formation. The formation is fossiliferous and approximately 2,500 feet thick. In the southern part of the Study Area, the sedimentary layers belonging to the Modelo, Towsley and Saugus Formations are present. The Modelo Formation is middle to late Miocene in age and consists of layers of thinly-bedded mudstone, diatomaceous shale, siltstone with interbeds of sandstone. Its thickness varies by location, but overall can easily exceed 10,000 feet. Deposited above the Modelo Formation is the late Miocene to early Pliocene Towsley Formation. The Towsley Formation consists of interbedded marine siltstone, mudstone, sandstone and conglomerate layers. Fossils indicate the Towsley Formation was deposited in water in excess of 600 feet deep. The unit has a maximum thickness of approximately 4,000 feet, and is overlain by the Saugus Formation. The Saugus Formation is a non-marine unit that is Pliocene to Pleistocene in age. The Saugus Formation, which contains layers of sandstone, sandy conglomerate, and siltstone, may be up to 12,000 feet thick. The lithologies comprising Saugus Formation are predominantly weakly to moderately cemented.

Above the bedrock, units include surficial deposits of landslide debris and alluvium (old and young). In the Study Area, these deposits are generally found along canyon bottoms (alluvium) and along steep canyon walls (landslide debris). However, the proposed alignments within the ANF will be primarily in tunnel below the ground surface. These surficial deposits should not have an impact on tunnel design.

5.1.2 Geologic Structures and Faults

The San Andreas Fault System formed along the translational boundary between the North American and Pacific Plates during the Miocene. Convergent transform movements are responsible for the mountain building of the Transverse Ranges and the San Gabriel Mountains. The east-west oriented Transverse Ranges/San Gabriel Mountains present an anomaly in southern California where all the other mountain ranges are oriented northwest parallel to the strike of the San Andreas Fault System. Paleomagnetic data indicate that the Transverse Ranges were originally oriented north-south, with its southern and northern ends located near the latitude of present day San Diego and Anaheim, respectively (Atwater, 1998; Kamerling and Luyendyk, 1985). During the evolution of the Pacific-North America plate boundary, the Transverse Ranges broke off the North America plate and rotated as a cohesive block 80-110 degrees clockwise to its present position (Kamerling and Luyendyk, 1985). This process of rotation, which was associated with faulting, folding, and crustal upwelling in the Transverse Ranges, continued until about 5 million years ago. The development of the San Gabriel fault, generally regarded as an older strand of the San Andreas Fault System occurred during this time (Atwater, 1998). In addition to the San Gabriel fault, other active faults belonging to the San Andreas Fault System which have formed in the Project area the past few million years include the Sierra Madre (Sunland and San Fernando strands) bordering the south edge of the ANF (Figure 5-1). The San Gabriel Mountains owe their steep, youthful southern front to the uplift to the reverse faults belonging to the Sierra Madre fault. However, there are many faults within the San Gabriel Mountains, which affect the development of the geologic structure, stratigraphy and hydrogeology of the Project area, but are not considered active (i.e., experienced displacement in the past 11,000 years). These include, Agua Dulce, Pole Canyon, Oak Spring, Magic Mountain, Lonetree, Transmission Line, Laurel Canyon, Goose Berry Canyon, Bad Canyon, Mendenhall, and Slaughter Canyon faults (Figure 5-1). These inactive faults promote canyon development and erosion by juxtaposing differing lithologies/formations and promote and/or restrict groundwater movement within the interconnected fracture networks.

5.1.3 Hydrogeology

Information on the hydrogeologic conditions is limited to the data collected during the geotechnical field investigations (Authority, 2016). Although the San Gabriel Mountains are part of the Groundwater Ambient Monitoring and Assessment (GAMA) studies managed by the USGS, the data from this study located directly on any of the ANF tunnel alignments is limited.

As shown on Figure 5-2, the project area is a tectonically elevated terrain that extends from Soledad Canyon on the north to the Santa Clarita and San Fernando Valleys on the west, Tujunga Wash (i.e. Tujunga Valley) on the south and Big Tujunga Canyon to the east. The steep topographic relief of the San Gabriel Mountains is illustrated in Figure 5-3. The surface drainage pattern is governed by two approximately east-west trending drainage divides, the Santa Clara Divide and the Mendenhall Divide (Mendenhall Ridge Road) (Figure 5-3). The Santa Clara Divide extends from the Little Tujunga Canyon Road-Sand Canyon Road transition eastward to Mendenhall Ridge Road. The Mendenhall Divide extends from Little Tujunga Canyon Road at Pacoima Road north-northeasterly where it joins Santa Clara Divide. The Little Tujunga Canyon and Gold Creek drainage system captures the surface run off in the Study Area south of Mendenhall Divide. Big Tujunga Canyon is the next drainage system east of Little Tujunga Canyon-Gold Creek drainage that is south of Mendenhall Divide. Both Big Tujunga and Little Tujunga canyons drain southward into Tujunga Wash. Pacoima Canyon and its tributaries drain westward between the Santa Clara Divide and Mendenhall Divide to discharge along the northeast edge of San Fernando Valley. Numerous smaller canyons drain northward from the Santa Clara Divide into the Santa Clara River and Soledad Canyon. The smaller canyons include Sand Canyon, Iron Canyon, Pole Canyon, and Arrastre Canyon. The many small tributary canyons capture the mountain runoff and feed into the larger canyons, which discharge the majority of rainfall and snowmelt into the valleys flanking the mountains as surface runoff.

Figure 5-3 Hydrology Map

Stream flows within the local canyons vary depending on seasonal trends in precipitation, and with the topography, vegetation, and geology of the drainages. The flow of springs in the area appears to vary with seasonal precipitation; however, the current database is not sufficient to quantify the amount of water discharge from springs in the Study Area.

The groundwater table generally mimics the topography as a subdued expression of the ground surface; that is, the depth to groundwater is nearest the canyon bottoms and it is generally deeper beneath the ridgelines and mountain peaks. This is generally the case in all crystalline and metamorphic rock terrains, where steep hillsides facilitate rapid runoff of precipitation to canyon bottoms, where water is directed as runoff to larger tributaries. Infiltration is generally less on hillsides and more within canyons and valleys, where the flow gradients are lower and residence time is greater.

5.1.3.1 Hydrogeology of Rock Mass

The interaction between surface water and groundwater systems is governed largely by lithology, geologic structures (e.g., faults, joints, unconformities, etc.), weathering conditions, and in-situ stress. Conceptually, groundwater flow within rock mass occurs in two possible ways through the medium's void spaces: 1) Primary porosity, and 2) Secondary porosity. For hydrogeologic flow properties of rock masses, the terms porosity and permeability are not the appropriate terminology. The hydraulic conductivity (K) is the property that is applicable, and is highly dependent upon the connected void spaces where water flow is permissible. When the primary and secondary porosity are together or are not differentiated, this is simply referred to as the effective porosity (or effective hydraulic conductivity). In general, the effective hydraulic conductivity of rock mass tends to decrease with depth coinciding with reduction in weathering effects, fewer discontinuities and increasing lithostatic pressures.

Primary porosity is the connected void spaces of the intact rock, i.e. spaces between grains and cement or interlocking crystalline minerals comprising the rock. In poorly-cemented, granular

sedimentary rock, the primary porosity can be comparable to that of unconsolidated sediments. Conversely, for well-cemented or fine-grained sedimentary, metamorphic, and crystalline igneous rock, the primary porosity is low and prevents water transmission. Weathering processes alter the primary porosity of all rocks. Where cement or crystalline minerals are removed, the primary porosity could increase. In most cases, it is assumed that weathering of crystalline rock tends to increase their primary porosity by altering rock chemically, accentuating defects in the rock (i.e. fractures) and general opening of discontinuities.

Secondary porosity is the connected void spaces formed from discontinuities (e.g., joints, shears, faults, fractures, bedding, etc.) and geologic structures. Rock mass with persistent discontinuity systems with wide apertures open or infilled with coarse material will have a high secondary porosity. In some cases, such conduits may be further enhanced over time as flow occurs, water pressures build acting to prop open the joint, finer-particles infilling the system are flushed away, and weathering of the surrounding intact rock walls increases their local primary porosity. The orientation of the discontinuities are also important. In general, near-vertical discontinuities often are better connected to the surface as the normal stress that reduces the joint opening tends to be lower in a gravitational stress field than the normal stress acting on near-horizontal discontinuities. At some critical depth, the state of stress becomes so great that joint openings are inhibited or eliminated altogether.

Depending on the style of faulting, lithology, net displacement and other factors, faults typically impose a high-degree of anisotropy to groundwater flow. In most cases, faults act as a barrier to flow across the fault, and as a conduit for flow parallel to the fault. These established relationships are suggested within the Study Area based on the geotechnical investigations completed to date and will be further investigated and developed in later phases of study.

With respect to the behavior of groundwater systems, a rock mass aquifer can behave much more complexly than sediment aquifers or other "Darcy porous mediums." This does not preclude the possibility for rock mass to behave as a Darcy porous medium, such as sedimentary rock or virtually any homogeneously fractured or weathered rock mass (i.e., at shallow depth). However, in fractured crystalline rock mass at depth, the fracture networks dominate the hydrogeologic conditions and define the aquifers or groundwater compartments within the rock mass. Some observations of groundwater aquifers and behavior are discussed in Section 6.3.1.

5.1.4 Faulted Ground

Faults can pose significant construction difficulties for tunnels by altering the conditions of the rock mass being mined and increasing water flows into the tunnel. Therefore, faults should be anticipated and accounted for when selecting the tunnel alignment, tunneling methods and tunnel lining design.

Geologic formations that once were intact and strong become mechanically sheared and brecciated, altered, decomposed, and weak after being subjected to faulting. The degradation of the rock mass may result in face instability during mining, higher lithostatic loads on the tunnel lining system, and facilitate higher groundwater pressures and flows in and adjacent to the faults.

Faults have the potential to act both as groundwater conduits and as barriers that often result in significant variations in groundwater pressures from one side of the fault to the other. These variations in groundwater pressures are especially critical when unexpectedly encountered during tunnel mining. Also, high temperature groundwater may be channeled upward along faults to shallower depths requiring special controls to enable workers to work in the hot tunnel environment.

Three of the six core holes were placed at inclined angles in order to investigate the width and general rock mass properties of mapped faults that would intersect the tunnel alignments. The faults investigated included the Transmission Line Fault and the San Gabriel fault. In both core holes drilled through the San Gabriel fault, the rock coring operation was slowed by squeezing ground conditions and general difficulty with keeping the core hole open after tripping out drill rods. Recovery of core through the fault zones also indicated extreme brecciation of the rock,

abundant shearing and clay gouge zones for both the San Gabriel fault and the Transmission Line fault indicating that loss of core hole integrity could be attributed to either squeezing ground or swelling ground due to expansive clay properties. The width of the fault zones drilled in the core holes ranged from individual fault strands that are tens of feet wide to several hundred feet wide. The widest fault zone intersecting the alignments is the San Gabriel fault zone, whose width is greatest at the E2 alignment (e.g. composed of many fault strands). The many fault traces and shear zones at the E2 alignment are mapped as merging into a narrow zone both at the SR14 and E1 alignments. However, isolated, single fault branches are mapped up to 6,000 feet away from the merged zones at SR14 and E1 alignment suggesting the total width is comparable at the fault intersections. For tunneling progress, the most important factors are maintaining tunnel advance rate and minimizing challenging mining conditions is the cumulative or net width of gouge zones and sheared and brecciated rock. Therefore the summed (net) width of faulted ground to be encountered by the tunnel is most important for comparison between alignments with respect to ease of advancing the tunnel mining. The general widths and number of mapped faults are illustrated on the geologic profiles referenced in Section 6 of this report.

Where faults intersect tunnel construction, more water flow and greater groundwater pressures (depending on the depth below ground) should be expected. The exploratory core holes and pressure readings at difference locations along the inclined core holes through faults indicated that water pressures were almost the same on either side of the faults explored. From the data collected it is unclear that the faults investigated create a groundwater barrier where explored. However, the general hydraulic conductivity measurements indicate higher conductivity potential in the rock surrounding the fault zone with very low conductivities closest to or within the fault gouge zone. The presence of the shears and more brecciated rock are indicators of higher groundwater flows along faults and into tunnels under construction.

5.2 Geologic Hazards

Potential hazards for construction and operation of the ANF Tunnel Alignments that are directly related to the geology include:

- Gassy ground;
- Corrosive groundwater; and
- Active fault displacement.

Several of these hazards are mainly applicable to the subsurface portions of the ANF Tunnels, while others, such as faulting, may be applicable to both underground and surface portions (e.g., portals) of the ANF Tunnels.

5.2.1 Gassy Ground

Gassy ground results from the migration of flammable, toxic, or asphyxiating gases into the tunnel during construction or operation. The gas emanates from geologic materials (e.g., from oxidation of minerals), groundwater containing dissolved gas flowing into the tunnel, or petroleum occurrence in formations. Tunnel Alignments have been successfully constructed through gassy ground in southern California with proper procedures as required by the California Division of Safety and Health (Cal/OSHA). A more detailed discussion of requirements for gassy ground is presented in the California Code of Regulations (CCR). Based on the limited data available at this time, the potential for gassy ground within the ANF may exist. The risk for gassy ground is higher for tunnel lengths within or overlying Modelo Formation, which is known as a source of gas, and oil within southern California.

5.2.2 Corrosive Groundwater

Corrosive groundwater can damage components of the TBM, and over time may deteriorate the concrete compromising the performance of the tunnel structure. Although relatively high sulfate concentration is the primary cause of corrosive groundwater, gases such as carbon dioxide and hydrogen sulfide that dissolve into groundwater form acids that may also damage construction

materials. Based on the limited groundwater chemistry tests from samples of groundwater within the ANF, the potential for corrosive ground and groundwater exists.

5.2.3 Active Fault Displacement

Fault displacements result from differential movement across a fault during an earthquake due to tectonic forces shearing the Earth's crust. Depending on the size of the earthquake (i.e. magnitude representing energy release), the displacement sometimes propagates to the ground surface causing surface rupture and displacement of features straddling the fault such as geomorphic features (e.g. streams, flat surfaces) or man-made structures (e.g. roads, buildings, pipelines, etc.). Tunnels also are subject to fault displacement causing offset of the tunnel structure below ground due to relative displacement across a fault or fault zone. Restoration of a tunnel would require realignment or smoothing of the offset of the tunnel and repair of the lining system. For high-speed train projects, the track realignment would require track straightening or curvature restoration within the tunnel diameter to allow the train to maintain required speed for the project.

For the HSR project, criteria have been established to recognize and classify the potential risks of fault displacement for the railroad tunnels where they intersect Holocene-age faults. The Holocene age (activity within the past 11,700 years) applies to three faults intersected by the proposed tunnel alignments within ANF. All other faults that intersect the alignments within ANF have been inactive during the Holocene and are classified as Non-Hazardous. From north to south all three alignments intersect the same three Holocene- age faults but at different locations. The faults include San Gabriel fault, Sierra Madre fault (north), and Sierra Madre fault (south). The Sierra Madre (north and south) are Class A Hazardous faults (Holocene age with a geologic slip rate >1.0 mm/yr). The San Gabriel fault is currently classified as "Indeterminate" meaning that insufficient data exist for this fault to be assigned a classification according to the HSR criteria (California High Speed Rail Authority, 2016)).

The Seismic Specialists Team (SST) at The Authority is tasked with providing estimates of displacement for future fault activity.

6 ANTICIPATED TUNNEL CONDITIONS

We have interpreted anticipated tunnel conditions considering the tunnel configurations, geologic, hydrogeologic, and geomechanical conditions as these are relevant to the geotechnical feasibility. Our interpretations based on the limited data and available information are presented on several geologic profiles prepared for each of the ANF tunnel alignments (Appendix A – Geologic Profiles and Anticipated Tunneling Conditions).

The range of stationing considered in this feasibility summary is summarized in Table 6-1. In the summary of anticipated tunnel conditions, below-grade portions within these station limits are assumed to be tunnel. Where the alignment elevation is at-grade or where the tunnel conditions are not applicable to the material within the tunnel envelope, these lengths are not included in the summaries. When considering the tunnel alignments, a major difference that separates the SR14 alignment from the other two is it's significantly shorter length within the ANF.

Table 6-1 Stationing Limits Tabulated for Anticipated Tunnel Conditions

Alignment	Stationing		Length	
			feet	miles
SR14	1330+00	1750+00	42,000	7.95
E1	638+80	1750+00	111,120	21.04
E2	638+80	1750+00	111,120	21.04

6.1 Geologic Conditions

The interpretation of geologic conditions for the ANF tunnels is limited to the information available from six core holes completed within the Study Area, published maps and studies, and our previous project experience with some of these and similar lithologies. Considering the nearly 50 miles of tunnel that are being evaluated in this report, where the existing core holes are not located directly on an alignment (i.e., projected onto a profile), we have used these as analogs to represent the general conditions within the ANF. The geologic units, lithologies, geologic structures, geologic hazards and other key features are summarized in the geologic profiles and anticipated tunneling conditions (Appendix A).

6.2 Abrasivity

The abrasivity of the geologic units affects the amount of wear of the various pieces of mining equipment. Mining in abrasive materials requires more frequent tooling replacements to avoid overwearing vital components of the TBM cutterhead.

We have interpreted the abrasivity of the geologic units using limited testing from the ANF core holes, published information about the geologic formations, and published correlations between lithology and abrasivity. Figure 6-1 summarizes the descriptors and ranges of abrasivity and correlations used to interpret the anticipated abrasivity conditions for the ANF tunnels (Appendix A).

Figure 6-1 Abrasivity Correlations

Based on the abrasivity correlations and available data, the anticipated abrasivity conditions for the ANF tunnel alignments are summarized in Figure 6-2. From the interpreted abrasivity conditions, most of the geologic units traversed by the ANF tunnels are anticipated to exhibit high to extreme abrasivity.

Figure 6-2 Summary of Anticipated Abrasivity

6.3 Hydrogeologic Conditions

6.3.1 Preliminary Observations of Groundwater Behavior

Data collected during the ANF geotechnical investigations (HSR, 2016) help to demonstrate some trends believed to characterize the groundwater system(s) within the forest where the tunnels are proposed. These trends are relevant to the discussions of tunnel feasibility and the potential impacts on surface water resources within the forest. The characteristics are interpreted from both published data and field data reported in the Geotechnical Data Report for Tunnel Feasibility (HSR, 2016). The data include: 1) Rock mass classifications base on geologic logging of rock core; 2) Measurements of hydraulic conductivity in exploratory core holes; 3) In-Situ measurements of hydraulic pressures at varying depths; 4) Water chemistry of shallow water and deep groundwater samples; 5) Observations of springs and seeps within the ANF; and 6) Age dating of surface water samples and deep groundwater.

The rock mass data summarized from the geologic logs of rock core and acoustical televiewer surveys of five exploratory holes in the crystalline rocks of the ANF indicate a highly variable occurrence of discontinuities in the overall rock mass. In general, the rock is much more weathered, oxidized, fragmented, sheared, and pulverized near fault zones reflecting the localized mechanical degradation of the native rock due to the tectonic forces of faults. Away from faults, the condition of the rock improves with fewer discontinuities representing the broader occurrence of in-tact rock. The patterns of discontinuities assume a consistency within the rock mass leaving telltale signs of stresses within the mountain that have generated consistency of predominant joints with fairly regular spacing and orientations. Numerous sets of intersecting joints have been identified in the core resulting in varying degrees of fracturing quantified as rock quality designation (RQD). Quantification of the discontinuity spacings within the core illustrates broadly differing zones of fracturing, some with high density of fractures and other zones with virtually no fracturing. As discussed above, in-tact crystalline rock is has essentially no ability to carry or transmit water, whereas the fractures in the rock allow water storage (limited) and movement along fractures. The wide variation of discontinuities and intersecting patterns of discontinuities governs the direction and quantity of groundwater that is able to flow through the rock mass adjacent to a fault. For example, faults are zones of dislocation that displace one side of the fault past the other causing shearing and brecciation of adjacent rock with a preferred orientation of closely spaced discontinuities roughly parallel to the fault trend. With greater and greater displacement along a fault, the rock adjacent to a fault becomes a preferred path of water flow. Away from faults, the rock quality improves but still the variations in RQD can either facilitate or inhibit groundwater flow. Zones of completely intact rock can prevent groundwater flow forming an impermeable barrier within the rock mass, whereas zones of low RQD are more fractured and facilitate storage and movement of groundwater.

The in-situ hydraulic conductivity of the rock mass explored during the geotechnical investigation was measured by use of inflatable packers to isolate fractured zones of rock within each core hole. A high capacity pump apparatus forced water flow into the fractures of the isolated rock zone. The rate of water flow into the fractures in the rock was converted to effective hydraulic conductivity. The results of the in-situ packer tests indicate very low rates of flow demonstrating only a very small quantity of water is able to flow through the rock mass at very slow rates. The rate of groundwater flow is expressed in centimeters per second, which ranged through five orders of magnitude ranging 5×10^{-3} cm/sec to 5×10^{-7} cm/sec. The wide range of recorded values represents the non-uniform nature of the aquifer characteristics of the rock resulting from the variability of fracturing and interconnection between fractures. The low effective hydraulic conductivity values indicate that there is very little potential for the rock mass to yield large quantities of water. The rate of flow is also dependent on the locations and frequencies of discontinuities in the rock. The low flow potential also indicates that there is very little potential for draining wide-spread zones of water.

Hydraulic head or groundwater pressures at the tunnel depth are used as a parameter for design of the TBM and tunnel lining system. Design and construction of the tunnel and lining system will vary depending on the anticipated groundwater pressures at the tunnel depth. For example, the

measured pressures will help the designer apply the optimum lining system that minimizes water losses into the tunnel. The pressure data are also necessary for planning grouting programs to shut off water flow into or along the tunnel. Direct water pressures were measured at various depths within each of the core holes drilled in the ANF. The pressures were measured using a calibrated vibrating wire pressure transducer (VWPT), which senses pressure within isolated zones of the bedrock at varying depths. The data indicate that there is a fairly constant rate of pressure increase that tracks very well with a constantly increasing direct head of water from the shallowest (first encountered water elevation) to the deepest VWPT for core holes that crossed faults. In contrast, two deep core holes within in-tact bedrock masses suggested several zones of isolated groundwater pressures that appear to unrelated (not connected) to adjacent zones. There was a very pronounced variance from constant head increase within the anorthosite and to a lesser degree within the granodiorite rock. The deviation in pressure data from a constant head increase indicates that there are several zones or compartments of isolated groundwater within the rock mass that have lower pressures than expected. These data indicate that water zones encountered within the bedrock are not interconnected and therefore draining water from one compartment would have minimal impact on the adjacent occurrence of water. The data imply that a tunnel driven through in-tact bedrock at depth may not have any influence on the shallow groundwater (i.e. sources of springs). In contrast, the constant hydraulic head increase with depth near the fault zones explored suggests that there is an open vertical path of water to flow from shallow to deeper zones demonstrating connectivity near faults.

Water resources monitoring was implemented in the vicinity of the three tunnel alternatives beneath the ANF. The monitoring program encompassed 20 known springs at various locations on USFS land. One monitoring cycle was completed during the end of the summer season on September 16, 2016 to assess access to the sites and make initial observations of the spring conditions. The first cycle of spring observations discovered that the long preceding dry years had resulted in most all of the springs being dry or evidenced only by wet soil or greener vegetation where the spring had been identified. From this first documentation of springs in the ANF, the conclusion is that protracted drought can result in the documented springs ceasing flows during late summer. This indicates that the springs are not fed by deep sustained water resources, but that the springs are dependent on seasonal wet cycles in order to maintain their flow.

Chemistry of deep water samples collected from the geotechnical core holes were analyzed for general chemistry, for radio-carbon age dating, and for radio nuclides to compare results to published water chemistry from the GAMA analytical test results. Many of the samples collected from deep within the core holes contained residual potable water used for rock core drilling indicating that the purging cycle to remove all potable water had not been long enough to draw in the native deep groundwater for sampling. The general chemistry of the water tested by the USFS GAMA program indicates a calcium bicarbonate (Ca-HCO_3) type of water, whereas the deep water from our field exploration indicates the uniquely different chemistry of a calcium sulfate (Ca-SO_4) type of water. These differences demonstrate that the water sources for GAMA program, which are from shallow wells are not connected to the deep groundwater sampled and tested for the geotechnical investigations. The results of the carbon-14 age dating also indicates that the water collected from deep in the mountain is at least 4,500 years old and has not been replenished or recharged by younger shallow rain water. So far, the results from water chemistry testing suggest that the deep water within bedrock units beneath the ANF has not been mixing with shallow water that supplies wells and springs with water.

6.3.2 Hydraulic Conductivity

The hydraulic conductivity of the various geologic units and the groundwater pressures anticipated within the tunnel envelope are interpreted from in-situ testing and instrumentation data obtained from the six core holes within the ANF, published information for similar geologic conditions, and our previous project experience.

The hydraulic conductivity of the geologic units interacting with the tunnels are important as these affect the potential for inflows during construction and operation, and the groutability of the geologic units.

Table 6-2 summarizes the descriptors used for the anticipated hydraulic conductivity conditions for the ANF tunnels (Appendix A). For the Proterozoic- and Mesozoic-age igneous and metamorphic rock lithologies tested within the ANF core holes, we have plotted the resulting ranges of hydraulic conductivity along with compiled published ranges of data from other rock lithologies (Figure 6-3). For locations where there are data gaps, we have interpreted the hydraulic conductivity considering the rock lithology and potential fracturing.

Figure 6-3 Hydraulic Conductivity Correlations

Table 6-2 Hydraulic Conductivity by Generalized Lithology

Descriptor	Hydraulic Conductivity (K)	Lugeon	Generalized Lithology or Conditions
	cm/sec		
Very High	$10 - 10^{-1}$	>50	<ul style="list-style-type: none"> Sediments comprised of gravel Intensely fractured (karstic) limestone or basalt Rock mass with many open joints
High	$10^{-1} - 10^{-3}$	5-50	<ul style="list-style-type: none"> Sediments comprised of sand Intensely fractured igneous or sedimentary rock Rock mass with only some open joints
Moderate	$10^{-3} - 10^{-5}$	1-5	<ul style="list-style-type: none"> Sediments comprised of fine sand, or interlayers of silt or clay Coarse- to medium-grained sedimentary rocks Fractured sedimentary, igneous, and metamorphic rocks Rock mass with small joint openings, openings with impervious infill, or few joints
Low	$10^{-5} - 10^{-7}$	0.01 – 1	<ul style="list-style-type: none"> Sediments comprised predominantly of silt or clay Fine-grained sedimentary and igneous rock, metamorphic rock Rock mass with tight joints, openings with impervious infill, or few joints
Very Low	$<10^{-7}$	<0.01	<ul style="list-style-type: none"> Sediments comprised of homogeneous clay Shale and evaporite Rock mass with tight joints, openings with impervious infill, or few joints

Sources: Isherwood, 1979; Goodman, 1981; Jaeger et al., 2007; Domenico and Schwartz, 1990; USBR, 1998; Fell et al., 2005; Freeze and Cherry, 1979.

Figure 6-4 summarizes the anticipated hydraulic conductivity for the rock types cored within the ANF. Based on the data collected for the feasibility study, the SR14 alignment is anticipated to have the longest portion of tunnel within geologic units anticipated to have high hydraulic conductivity.

Figure 6-4 Summary of Anticipated Hydraulic Conductivity

6.3.3 Groundwater Pressures

The groundwater pressures are one of the key features to consider when designing and constructing a watertight tunnel lining. The feasibility for watertight linings are generally limited to magnitudes of water pressure less than about 40 bar (580 psi), based on specifications for the Hallandsås Tunnel in Sweden. The Arrowhead Tunnels lining systems were proof tested up to the 27 bar (390 psi) to meet the anticipated design requirements (Swartz et al., 2002). During construction, potential inflows are proportional to groundwater pressure gradient.

The groundwater pressures are interpreted from instrumentation data available for the six core holes within the ANF, published data of groundwater resources within the ANF [i.e., as shown on Appendix A.9 in the Draft GDR (Authority, 2016)], and topographic and hydrogeologic trends. Table 6-3 summarizes the descriptors used for the anticipated groundwater pressure conditions for the ANF tunnels (Appendix A). The groundwater pressures within the tunnel envelopes will be governed by how the tunnels penetrate the rock mass aquifer(s). Based on the limited data from the six coreholes, where multi-point vibrating wire piezometers (VWP) were installed, the tunnel envelopes will likely penetrate zones where there is only a single rock mass aquifer overlying the tunnel (i.e., an unconfined aquifer) and zones where there are several rock mass aquifers overlying the tunnel and the tunnel only penetrates one of these at a time as it traverses along the alignment (i.e., a confined aquifer). In reality, there will likely be overlapping zones where the tunnel penetrates from one rock mass aquifer to another where these zones are merged to some degree (i.e., leaky aquifer).

Based on the depth versus groundwater pressure trends observed from the instruments monitored from five coreholes within the ANF, most of the locations (i.e., all except Core Hole E1-B1) appear to deviate only slightly from that exhibited from a single unconfined rock mass aquifer. Core Hole C-1 was only recently completed and monitoring data has not been evaluated to-date. The prevalence of unconfined rock mass aquifer systems observed from the core holes within the ANF are likely biased by the core hole locations, which in several core holes were intended to investigate faults. In other words, several of the core hole locations were specifically selected to penetrate faults and resulting fractured rock mass in order to represent worst-case scenarios of rock quality.

In our interpretations of groundwater pressure, we have assumed the following cases:

- A single unconfined rock mass aquifer for all geologic units penetrated by the SR14 and E2 tunnel envelopes, and the E1 tunnel envelope with the exception of where it penetrates anorthosite-gabbro complex at depths greater than 1,000 feet. The groundwater pressure is estimated from an assumed groundwater surface and the resulting hydrostatic pressure at the elevation of the tunnel envelope.
- Multiple rock mass aquifers for the E1 tunnel envelope, where the tunnel is deeper than 1,000 feet and penetrates anorthosite-gabbro complex, the multiple rock mass aquifer system and groundwater pressure trends exhibited in the Core Hole E1-B1 VWP are superimposed to estimate the groundwater pressure at the elevation of the tunnel envelope.

Table 6-3 Descriptors for Groundwater Pressures

Descriptor	Approx. Groundwater Pressures		
	feet-head	psi	bar
Low	<175	<75	<5
Moderate	175-350	75-150	5-10
High	350-850	150-370	10-25
Very High	850-1,175	370-510	25-35
Extremely High	>1,175	>510	>35

Figure 6-5 presents a summary of the anticipated groundwater pressures. Based on the limited data and our interpretations, the E1 and E2 alignments have three to five times the lengths of tunnel where the groundwater pressures are anticipated to be very high to extremely high, compared to the SR14 alignment. The highest anticipated groundwater pressures for portions of the SR14, E1, and E2 alignments are anticipated to be as high as 50 bar (SR14 Station 1626+00), 50 bar (E1 Station 1278+00) and 60 bar (E2 Station 1328+00), respectively.

Figure 6-5 Summary of Anticipated Groundwater Pressures

6.4 Intact Rock Strength

The intact rock strength is a key feature to consider for tunnel mining and support. Where the intact rock is strong and the rock mass is unfractured, the advance rate of the TBM may be slower as it can take more time and effort to chip and digest this material at the excavation face. However, a strong and unfractured rock mass is less disturbed by the excavation process and may require less support. In zones of intact rock, grippers on the TBM can also be used to help provide thrust for the TBM. Intact rock strength will vary for the various geologic units with weathering grade and proximity to faults.

Intact rock strength data is obtained from the six core holes within the ANF, published information for similar geologic conditions, and our previous project experience. Table 6-4 summarizes the descriptors used for the anticipated intact rock strength conditions for the ANF tunnels (Appendix A). Figure 6-6 presents a summary of the anticipated intact rock strength conditions for the ANF tunnels. Based on our interpretations, the overall intact rock strength is greater for the E1 and E2 tunnels as these traverse more of the crystalline igneous and metamorphic rock of the San Gabriel Mountains. However, the E1 and E2 tunnels have longer reaches of tunnel in very soft to moderately soft rock.

Table 6-4 Descriptors for Intact Rock Strength

Rock Grade	ISRM Descriptor	Caltrans or USBR Descriptor	Unconfined Compressive Strength of Intact Rock (σ_c)
			MPa
R0	extremely weak	very soft	0.25-1.0
R1	very weak	soft	1.0-5.0
R2	weak	moderately soft	5.0-25
R3	medium strong	moderately hard	25-50
R4	strong	hard	50-100
R5	very strong	very hard	100-250
R6	extremely strong	extremely hard	>250

Source: Adapted from ISRM, 1978 and Caltrans, 2010.

Figure 6-6 Summary of Anticipated Intact Rock Strength

6.5 Rock Mass Conditions

The rock mass conditions are another key feature to consider for tunnel mining and. Rock mass conditions are used to predict ground conditions (i.e. how the ground behaves during and shortly following the excavation process), and to design the TBM and tunnel lining system. These conditions can also be used to estimate TBM advance rates, grouting characteristics, and to develop other rock mass properties for seismic engineering.

Rock mass data are obtained from the six core holes within the ANF, published information for similar geologic conditions, and our previous project experience. Table 6-5 and Table 6-6 summarize the descriptors developed by Bieniawski (1989), Hoek et al. (1995) and Barton et al. (1978) used for the anticipated rock mass conditions for the ANF tunnels (Appendix A). Rock Mass Rating (RMR) and Geological Strength Index (GSI) are closely related rock mass characterization/classification systems (Table 6-5). In treatment of the rock mass properties, the

rock mass quality (Q) is not as closely related to RMR or GSI, but is roughly correlated using the following relation (Bieniawski, 1993):

$$\text{RMR} = 9 \ln Q + 44$$

Therefore, in interpreting rock mass conditions, we have considered RMR and then correlated these to Q using the descriptor ranges and the relation cited above.

Table 6-5 Descriptors for RMR and GSI

RMR or GSI	Rock Classes	Description
0-20	I	Very Poor
21-40	II	Poor
41-60	III	Fair
61-80	IV	Good
81-100	V	Very Good

Source: Bieniawski, 1989.

Table 6-6 Descriptors for Q

Q	Rock Classes	Description
0.001-0.004	G	Exceptionally Poor
0.004-0.1	F	Extremely Poor
0.1-1	E	Very Poor
1-4	D	Poor
4-10	C	Fair
10-40	B	Good
40-100	A	Very Good
100-400	A	Extremely Good
400-1000	A	Exceptionally Good

Source: Barton et al., 1994.

Figure 6-7 presents a summary of the anticipated rock mass conditions according to RMR for the ANF tunnels. Based on limited data and our interpretations, the overall rock mass conditions are only slightly more favorable for the E1 and E2 tunnels. However, the sum of tunnel sections in very poor to poor rock mass for E1 and E2 is longer than the sum of tunnel sections in very poor to poor rock mass for SR14 by over 10,000 feet.

Figure 6-7 Summary of Anticipated Rock Mass Conditions

6.6 In-Situ Stress

The in-situ stress conditions are important for feasibility as stresses affect tunnel mining and support requirements. Anisotropic stress fields may result in TBM steering difficulties, instabilities in short spans that are temporarily unsupported, or overstressing of tunnel support. In-situ stress is governed by the lithostatic stress, which is the overlying weight of the rock mass (i.e., the

average unit weight including the intact rock, joints, groundwater and infill), and in some cases tectonic stresses caused by active faults or other geologic structures (e.g., antiforms, synforms, etc.)

As described in the Draft GDR (Authority, 2016), in-situ stress testing was performed in two core holes (Core Hole E1-B1 and ALT-B3) as part of the ANF investigation. The purpose for in-situ stress testing is to establish the magnitude and orientation of the principal stresses. Orienting the tunnel parallel to the maximum horizontal stress (σ_H) has advantages in terms of tunnel support as this stresses the lining axially (compression) instead of diametrically (e.g., both compression and tension). Conversely, orienting the tunnel parallel to σ_H may result in greater ground loads at the excavation face. However, this is still more desirable than having larger ground loads in the sidewalls. In a gravitational stress field, the vertical (σ_v) or lithostatic stress is the major principal stress (σ_1). Therefore, the intermediate (σ_2) and minor principal (σ_3) stresses are both oriented perpendicular to σ_1 and each other in the horizontal plane. In this scenario, the minimum horizontal stress (σ_h) is σ_3 and the maximum horizontal stress (σ_H) is σ_2 .

The test results from Core Hole E1-B1 over several intervals indicate the stress field within the anorthosite-gabbro complex are likely gravitational. Therefore, σ_1 can be estimated from the thickness of overburden and the total unit weight of the rock mass. For hard to extremely hard, moderately fractured to unfractured, crystalline rock mass, we estimate the total unit weight of the rock mass to be on the order of 1.20 to 1.25 psi per foot. The lateral earth pressure coefficients ($K_{o,H}$ and $K_{o,h}$) were estimated to range from 0.57 to 0.67. At Core Hole E1-B1, the orientation of the maximum horizontal stress (σ_H) is potentially northwest-southeast (approximately 136 to 316 degrees). At Core Hole ALT-B3, in-situ testing was only successful over a single interval of about 20 feet. From the tests within this interval, the σ_H was larger than the estimated lithostatic or vertical stress (σ_v). This indicates a non-gravitational or tectonic stress field. These results suggest $\sigma_1 = \sigma_H$, $\sigma_2 = \sigma_v$, and $\sigma_3 = \sigma_h$. In terms of lateral earth pressure coefficients, which are defined as the ratio of the vertical to lateral stress ($K_{o,H}$ or $h = \sigma_v / \sigma_H$ or h), these were 1.23 and 0.93. The orientation of σ_H at Core Hole ALT-B3 is potentially northeast-southwest (approximately 50 to 230 degrees).

For defining in-situ stress conditions on the geologic profiles and anticipated tunnel conditions (Appendix A), we utilize the descriptors in Table 6-7 that are related to the thickness of overburden and a range of σ_1 . Where the stress field is tectonic, σ_1 may not be vertical (i.e., the lithostatic stress), the stress field may be highly anisotropic, and stress conditions may change abruptly depending on lithology.

Table 6-7 Descriptors for In-Situ Stress

Descriptor	Cover	Major Principal Stress (σ_1)	Other
	feet	psi	
Low	<250	<300	<ul style="list-style-type: none"> Gravitational stress fields with low cover Non-gravitational stress fields with low σ_1
Moderate	250-1,000	300-1,200	<ul style="list-style-type: none"> Gravitational stress fields with moderate cover Non-gravitational stress fields with moderate σ_1
High	1,000-2,000	1,200-2,400	<ul style="list-style-type: none"> Gravitational stress fields with high cover Non-gravitational stress fields with high σ_1
Very High	>2,000	>2,400	<ul style="list-style-type: none"> Gravitational stress fields with very high cover Non-gravitational stress fields with very high σ_1
Tectonic	*Any	*Any	<ul style="list-style-type: none"> Stress field is non-gravitational, anisotropic, and can change abruptly depending on the competency of the geologic units and their distribution

Figure 6-8 presents a summary of the anticipated in-situ stress conditions for the ANF tunnels. Based on limited data and our interpretations, E1 and E2 have the greatest length of tunnels where the in-situ stress is anticipated to be high to very high. The maximum overburdens for the SR14, E1 and E2 tunnels are approximately 2,100 feet (i.e., SR14 Station 1626+00 and E1 Station 1167+00) and 2,650 feet (i.e., E2 Station 1338+00).

Figure 6-8 Summary of Anticipated In-Situ Stress

6.7 Ground Conditions

In the tunnel industry, ground condition is a term used to describe how the ground responds during or shortly following excavation. The ground conditions affect the feasibility with respect to the mining and support requirements and are related to the geomechanical properties of the geologic units or rock mass conditions, the in-situ stress, groundwater conditions and the excavation method. There are different descriptors that are applied to soil (Tunnelman's Ground Classification) and rock (Squeezing Degree). In some conditions, e.g. where the rock mass is faulted or weathered, the rock mass may be reduced to intermediate geomaterials that behave more similar to soil. Therefore, we've adopted descriptive terms compiled by Singh and Goel (1999), which include terms that are commonly used for rock or soil (Table 6-8).

For the ANF tunnels, squeezing is likely an important factor in tunnel feasibility. Squeezing occurs where the rock mass strength (σ_c) is substantially less than the reconfiguration of the stress (i.e., post-excavation stress) around the openings at the excavation face and sidewalls, the rock surrounding the TBM or lining can deform inward elastically and plastically (i.e., tunnel closure) following excavation. If this deformation is not accounted for in the design, the TBM may become frozen in the ground, or the lining could become overstressed. Although the mechanisms are different, the ground response from swelling is similar to squeezing, as swelling can result in tunnel closure and TBM entrapment. In general, substantial lengths of tunnel with ground conditions that describe soil and intermediate geomaterials occur in areas of lower in-situ stress. Therefore, these are not considered as being as critical to the tunnel feasibility. These and other ground conditions used as descriptors for the ANF tunnels (Appendix A) are summarized in Table 6-8.

Our interpretations of the ground conditions, based on the limited data, are derived from the six ANF coreholes, published information regarding the geologic units, and previous project experience. Figure 6-9 presents a summary of the anticipated squeezing ground conditions for the ANF tunnels. Based on our interpretations, the E1 and E2 tunnels are anticipated to have longer lengths of tunnel within moderate to heavy squeezing ground than the SR14 tunnel.

Figure 6-9 Summary of Anticipated Ground Conditions

Table 6-8 Descriptors for Ground Conditions

Ground Condition Description	Potential Materials	Excavation Behavior	Design and Construction Considerations
Self supporting	Unfractured to slightly fractured, hard rock mass	<ul style="list-style-type: none"> Adequate stand-up time to install support Does not require initial support 	<ul style="list-style-type: none"> Identify potential wedges, rock blocks in crown and walls requiring reinforcing as necessary during mining
Firm	Stiff, cohesive or strongly cemented soil or soil-like material	<ul style="list-style-type: none"> Adequate stand-up time to install support Does not require initial support 	<ul style="list-style-type: none"> Identify potential zones where degree of cementation is less that have the potential to run or flow

Ground Condition Description	Potential Materials	Excavation Behavior	Design and Construction Considerations
Non squeezing	Slightly to moderately fractured, hard rock mass with a stress to strength ratio less than 1	<ul style="list-style-type: none"> Adequate stand-up time to install support Does not require initial support 	<ul style="list-style-type: none"> Install tunnel support with delay necessary to allow release of strain-energy within rock mass
Ravelling	Intensely to very intensely fractured rock mass or stiff, cohesive or weakly to moderately cemented soil under moderate to high stress	<ul style="list-style-type: none"> Blocks drop from the face, crown or walls shortly after excavation. Inadequate stand-up time to install support Requires initial support, limiting unsupported spans, and/or rapid installation of support 	<ul style="list-style-type: none"> Install initial support shortly after excavating to prevent overbreakage Heavy crown and wall pressures should be considered in design
Mild squeezing	Slightly to moderately fractured, soft to hard rock mass with a stress to strength ratio greater than 1 and less than 5	<ul style="list-style-type: none"> Inadequate stand-up time to install support Excavation deforms plastically decreasing the tunnel diameter (closure) on the order of 1 to 3%. 	<ul style="list-style-type: none"> Install initial support shortly after excavating to prevent heaving in invert of tunnel Install tunnel support with little delay Side pressure should be considered in design
Moderate squeezing	Intensely to very intensely fractured, or soft rock mass with a stress to strength ratio greater than 1 and less than 5	<ul style="list-style-type: none"> Inadequate stand-up time to install support Rate of closure is more rapid than mild squeezing ground with a closure magnitude on the order of 3 to 5% 	<ul style="list-style-type: none"> Initial support should be installed as early as possible to reduce the rate of closure or to limit closure Tunnel excavation diameter should be increased to allow for desired closure Wall pressure should be considered in design Instrumentation is essential
High (Heavy) squeezing	Rock mass or soil with a stress to strength ratio greater than 5	<ul style="list-style-type: none"> Inadequate stand-up time to install support Rate of closure is more rapid than moderate squeezing ground with a closure magnitude > 5% Excavation deforms irregularly resulting in irregular cross-section 	<ul style="list-style-type: none"> Initial support should be installed as early as possible to reduce the rate of closure or to limit closure Tunnel excavation diameter should be increased to allow for acceptable closure Invert support should be installed as early as possible to mobilize support capacity TBM steering may be difficult Instrumentation is essential

Ground Condition Description	Potential Materials	Excavation Behavior	Design and Construction Considerations
Swelling	Rock mass or soil with expansive clay minerals that have natural moisture contents near or less than their liquid limit	<ul style="list-style-type: none"> Expansive clays absorb water and expand volumetrically resulting in some degree of tunnel closure or swelling pressure where support is placed in advance of swelling 	<ul style="list-style-type: none"> Tunnel excavation diameter should be increased to allow for expected swelling Measures should be made to limit moisture being absorbed by swelling clay during and following construction Tunnel closure should be measured
Running	Decomposed to highly weathered, very intensely fractured to earthlike unsaturated rock mass or cohesionless soil or soil-like material	<ul style="list-style-type: none"> Blocks, grains or particles fall or "run" into tunnel from the face, invert, crown or walls 	<ul style="list-style-type: none"> Forepoling, grouting or other ground improvements may be necessary to stabilize ground and reduce the risk of mining-in-place Excavated volumes and advance should be monitored closely
Flowing	Decomposed to highly weathered, very intensely fractured to earthlike saturated rock mass or cohesionless soil or soil-like material, usually under water pressure	<ul style="list-style-type: none"> Mixture of rock or soil and water material flows into tunnel like a viscous fluid from the face, invert, crown or walls 	<ul style="list-style-type: none"> Forepoling, grouting or other ground improvements may be necessary to stabilize ground and reduce the risk of mining-in-place Dewatering ahead of excavation to reduce water pressure Excavated volumes and advance should be monitored closely
Rock bursting, Slabbing, Spalling	Unfractured to very slightly fractured, hard rock mass under moderate to high stress	<ul style="list-style-type: none"> Portions of massive, unsupported rock explode, elastically deform rapidly, or pop from unsupported areas of the face, invert, crown or walls 	<ul style="list-style-type: none"> Rock anchors installed in portions of tunnel where slabbing is evident or where there is a delay before installing support Micro-seismic monitoring essential

Source: Singh et al., 1999.

6.8 Fault Zones

Three wide fault zones intersect the tunnel alignments as illustrated in the drawings in Appendix A. These wide fault zones are San Gabriel fault, Sierra Madre fault (north), and the Sierra Madre fault (south). The wide fault intersections consist of multiple smaller faults and several wide fault gouge zones consisting of clay and silt gouge, rock flour and crushed rock. Adjacent to the fault gouge are zones of crushed and sheared rock, weathered rock and highly fractured and jointed rock. Joint infillings may be clay and silt as well as crushed rock with some healed by carbonate. The degree of jointing and fractured rock usually decreases away from the fault gouge zone until the rock mass escapes the imprint of deformation and weathering associated with the fault zone. This is usually a few hundred feet of transition to intact rock mass. Other smaller faults also intersect the tunnel alignments to differing degrees as shown on the drawings (Appendix A). The

smaller fault zones are similar to the wide fault zones in appearance with a narrower core of fault gouge and narrower zones of sheared and brecciated rock adjacent to the gouge zone. Primarily the difference between faults is the width of the fault zone in the rock mass as it intersects the tunnel. The width can appear wider than the actual fault width if the tunnel intersects the fault at a small angle. For evaluating feasibility of tunnel construction, three fault widths (I, II, and III) have been labeled on the drawings (Appendix A) to distinguish those faults to be considered for construction feasibility as follows.

I – Fault width that is <20 feet (<10 feet on either side of gouge zone). Fault width Category I is not expected to cause difficulties for mining or TBM operation except for limited wedge or block failures resulting from the fault and joint intersection geometries. Small increases of groundwater flow should be anticipated along the fault with the potential for the fault causing a groundwater barrier in the host rock.

II – Fault width that is approximately 20 to 100 feet (10 to 50 feet on either side of gouge zone), and is usually one fault strand of a named fault (e.g. Transmission Line fault and Lone Tree fault). Category II width faults will result in noticeable increases in groundwater flow and will likely result in a groundwater barrier in the host rock. Some convergence of the tunnel may be expected but will be of limited extent.

III – Fault width that is approximately 100 to 200 feet (50 to 100 feet on either side of gouge zone), and contains substantial gouge zone(s). A single named fault (e.g. San Gabriel fault) may have multiple fault strands in this category that when combined are an additive width. Fault width Category III will be most challenging for mining and for TBM operation. Tunnel wall convergence should be expected accompanied by high groundwater flows into an open tunnel adjacent to the fault zone. Depending on the depth below ground, high groundwater pressures may occur at the tunnel depth. Other likely ground conditions may include running ground and flowing ground. The anticipated ground conditions will be the most challenging of the three fault width categories.

6.9 Summary of Tunneling Conditions

A summary of the tunneling conditions for each of the proposed alternative alignments within ANF is presented in Table 6-9.

Table 6-9 Angeles National Forest Tunneling Conditions Summary

Tunneling Condition Description	SR14 Alignment	E1 Alignment	E2 Alignment
Total All Tunnel Lengths for Entire Project (mi)	24.27	23.32	22.6
Number of All Portals	Ten	Four	Six
ANF Tunnel Lengths (mi)	7.22	18.75	18.79
Number of Narrow-Width Faults (I) / Net Width (ANF)*	Nine / 180 Feet Net Width	Three / 60 Feet Net Width	Six / 120 Feet Net Width
Number of Medium-Width Faults (II) / Net Width (ANF)*	Two / 200 Feet Net Width	None / 00 Feet Net Width	One / 100 Feet Net Width
Number of Wide Faults (III) / Net Width (ANF)*	Four / 800 Feet Net Width	Four / 800 Feet Net Width	Thirteen / 2,600 Feet Net Width

Tunneling Condition Description	SR14 Alignment	E1 Alignment	E2 Alignment
Total Width of Gouge, Crushed and Sheared Rock Zones (ANF)	1,180 Feet	860 Feet	2,820 Feet
Maximum Distance between Sierra Madre fault zone traces (north and south segments)	2.85 Miles	2.75 Miles	1.45 Miles
Maximum Distance between San Gabriel fault zone traces	1.2 Miles	0.4 Miles	1.2 Miles
Approximate Overburden at San Gabriel Fault	1,600 Feet	700 Feet	1,700 Feet
Maximum Overburden	2,060 Feet	2,060 Feet	2,650 Feet
Tunnel Length with pressures above 25 Bar and less than 35 bar	0.6 Miles	2.6 Miles	2.1 Miles
Tunnel Length with pressures above 35 Bar	1.0 Mile	4.3 Miles	4.5 Miles
Known Springs, Wells in ANF, and HSRA Monitoring Points Within One Mile	Two Inactive Wells No Springs ALT-B2 and ALT-B3	One Active Well Three Springs E1-B1, E1-B2, and FS-B1	Three Inactive Wells One Active Well Nine Springs FS-B1 and C-1

*Narrow-Width Faults assumed to be less than 20 feet of gouge, sheared and crushed rock (Category I); Medium-Width Faults assumed to be 20 to 100 feet of gouge, sheared and crushed rock (Category II); Wide Faults assumed to be 100 to 200 feet of gouge, sheared and crushed rock (Category III). Net width is the sum of widths of individual fault widths.

tunnels
guaranteed
to leak

7 TUNNEL FEASIBILITY EVALUATION

During the selection and evaluation of potential tunnel alignments through the Angeles National Forest, major conditions affecting tunnel feasibility were identified and discussed between the Regional Consultant (RC) and HSRA (Authority). Many of the conditions have been documented to varying degrees in historical southern California projects that have encountered adverse conditions affecting tunnel design and construction methods, and impacts to groundwater, surface water and habitats. All of the concepts and criteria discussed in this study are preliminary and for feasibility level assessments. More detailed geotechnical investigations and engineering evaluations will be required to establish design parameters, construction methodology, and mitigation measures for the selected alignment.

7.1 ANF Feasibility Assumptions

During the initial stages of the feasibility evaluation, the Authority developed several design guidelines as Technical Memoranda (TM) to be used in the feasibility evaluations. These TMs provided guidelines concerning the location of the ANF tunnel alignment and profile, intersections with Hazardous faults, potential water pressures, avoidance of environmental constraints, and adverse ground conditions.

The key criteria and assumptions considered in the ANF tunnel alignments feasibility evaluation include the following:

- Watertight tunnel linings designs have been successfully constructed to withstand 25 bar of sustained groundwater pressure (approximately 360 psi or 850 feet of hydraulic head);
- Both drained and undrained tunnel lining designs are possible;
- Unless the lining design and construction technology can be improved, it is likely that groundwater leakage cannot be prevented along the entire reach of any of the ANF tunnels; and
- Fault displacements can be accommodated by design for specified displacement magnitude and slip direction.

7.2 Tunnel Design and Construction Constraints

The feasibility of tunnel design, excavation and support is largely governed by the ground conditions, and groundwater pressures and inflows during tunnel construction and/or operation. Typically, in long tunnels, using TBM and a pre-cast concrete lining system is the most economical because of cost and schedule. However, in most tunneling projects, appurtenant tunnel components (i.e., cross passages, utility chambers, etc.) are constructed using a variety of methods (e.g., drill and blast, mechanized mining using a shield and roadheader, etc.) and support systems (e.g., shotcrete and rockbolts, steel sets, truss systems, etc.).

7.2.1 Ground Conditions

The ANF tunnels will encounter a wide spectrum of ground conditions ranging from soft ground to hard rock conditions. The ground conditions are governed by the geologic units (i.e., lithology or alluvial sediments), geologic structures, in-situ stress, groundwater conditions, rock mass conditions, and excavation methods. With respect to the feasibility of the ANF tunnels, the most adverse ground conditions are likely zones of heavy (high) squeezing in proximity to faults where the rock mass surrounding the tunnel "squeezes" causing tunnel closure (convergence) of 5 percent or more. In such conditions, it may be necessary to install temporary reinforcing to maintain safety and control the rate of closure, and allow some degree of deformation to occur before installing the final support. The excavation diameter within these zones should carefully consider the ground load and tolerable deformation for the tunnel lining system.

The ground conditions should be carefully considered in the TBM selection and design. Based on the anticipated ground conditions, the more adverse ground conditions (i.e., squeezing, high groundwater pressure) will likely require a TBM that can operate in closed-mode [e.g., an Earth Pressure Balance (EPB) TBM, Slurry TBM, or Crossover TBM]. Such TBM technologies have been successfully used to mine tunnels subjected to groundwater pressures as high as 11 to 15

bar (Hallandsås Tunnel, Sweden and Lake Mead Tunnel, Nevada). To avoid the risks of the TBM becoming frozen (entrapped), the TBM and lining system should be designed such that the thrust necessary to overcome shield friction from squeezing ground can be accommodated.

7.2.2 Groundwater Pressures

The maximum groundwater head (pressure) of about 850 feet (25 bar) assumed for the conceptual tunnel lining is considered state-of-the-art for a watertight, precast, segmental lining for the proposed tunnel diameter. Therefore, development and testing of lining systems for pressures greater than 25 bar (360 psi) and a watertight lining requirement is needed to mitigate groundwater impacts. Based on conceptual design considerations, the TBM-excavated tunnels would be lined with a one-pass system, consisting of bolted and gasketed precast concrete segments with the capability to resist approximately 25 bar of groundwater pressure; the concrete segments would have an effective hydraulic conductivity of approximately 1×10^{-8} centimeter per second (cm/sec). As a result, where the external groundwater pressure is 25 bar or less, inflows into the completed tunnel are considered negligible.

Where groundwater pressure exceeds 25 bar, it is assumed that the lining would leak, or be designed to leak, to the extent that the maximum external water pressure would be limited to 25 bar or less.

7.2.3 Groundwater Flow Potential

Drainage of groundwater from the rock mass into the tunnels can occur during construction, and also after the tunnels are completed if the lining is not watertight. The amount of drainage that occurs during construction will be dependent on the hydraulic conductivity of the rock mass, depth of the tunnel relative to the groundwater level (i.e. pressure) above the tunnel, and the construction methods used. The extent to which water drains from the rock mass following construction will be dependent on the ability of the tunnel's final lining system to resist the hydrostatic pressure. However, a small amount of leakage is inevitable for most lining systems.

At tunnel depths within the ANF, the rock mass generally has a low to very low hydraulic conductivity. The shallow zones have moderate to low hydraulic conductivity. Therefore, groundwater flow through the rock mass is generally expected to occur at a slower rate at depth than near the ground surface. This condition could be favorable in terms of limiting the potential effects that tunnel construction could have on water resources in the vicinity of the project. However, locally, more intensely fractured zones may have higher hydraulic conductivity and allow more rapid water flows through the affected rock. This is assumed to occur in association with fault zones.

Fault, shear, or fracture zones that are present in the rock mass typically have higher conductivity than the general rock mass. Where crossed by the tunnels, such fracture zones could introduce relatively high water flows into the tunnels, causing significant hazards and/or difficulty during construction. Under the assumption that a TBM will be used to excavate the tunnels, inflows may come from the heading area (the zone around the TBM ahead of where the tunnel lining is installed) and through the completed tunnel lining.

The main method for mitigating tunnel flooding is through probing and pre-excavation grouting. According to the Tunnel Safety Orders of the CCR, Cal-OSHA requires a minimum of 20 feet of tested ground ahead of the excavation face in tunnels where there is a likelihood for dangerous accumulations of water, gas or mud within 200 feet of the working area. If the ANF Tunnel Alignments are constructed using TBMs that apply a positive face pressure, tunnel flooding is prevented so long as the TBM operating pressure is greater than the groundwater pressure in the vicinity of the excavation. Additional precautions may be necessary (e.g., using compressed air) during TBM intervention (mandatory access to the TBM cutterhead) or maintenance when the tunnel is not being advanced for prolonged periods of time and groundwater pressures begin to recover. Once the tunnel is completed, the cast in place or gasketed tunnel lining system is designed to prevent leakage through the lining system.

7.2.4 Gassy Ground Mitigation

Once a preferred tunnel alignment has been selected and a preliminary investigation is completed, the CCR Subchapter 20 Article 8 require a tunnel classification be obtained from Cal/OSHA with respect to flammable gas or vapors. Depending upon the Cal/OSHA classification, various gas monitoring and ventilation methods may be required during tunnel construction and operation. Based on the limited data available at this time, the potential for gassy ground within the ANF may exist. The risk for gassy ground is higher for tunnel lengths within or overlying Modelo Formation, which is known as a source of gas, and oil within southern California. However, conventional tunneling methods and ventilation systems appear to be feasible to mitigate gas and ventilate the tunnels during construction and operations.

7.2.5 Corrosive Groundwater Mitigation

Based on the limited groundwater chemistry tests from samples of groundwater within the ANF, the potential for corrosive ground and groundwater exists. Corrosive ground and groundwater can be mitigated by the use of corrosion resistant concrete mix and admixtures. As more information and data is collected for the selected tunnel alignment, project-specific designs would need to consider the effects of corrosion on the tunnel structures and components.

8 SUMMARY AND PRELIMINARY CONCLUSIONS

Following is a summary of the geotechnical feasibility evaluation of the ANF Tunnel Alignments through the San Gabriel Mountains, preliminary findings, and conclusions. The significant tunneling and ground conditions are summarized in Table 6-9 (Section 6.9 of this report).

Based on the results from a limited field investigation, the geologic and hydrogeologic conditions along the tunnel alignments present significant design and construction challenges.

Design and construction challenges within the ANF could be overcome with adequate site characterization and proper planning and design. Specifically, the major challenges are:

- Squeezing ground will be encountered, affecting TBM performance and possibly forcing TBM rescues.
- Active fault zones intersect the tunnel alignments resulting in the need for special designs for tunnel linings and enlarged tunnel sections to accommodate fault displacement for track realignment.
- High groundwater pressures on the tunnel lining system would require a thickened and high strength concrete lining system and TBMs with closed-mode capability.
- High groundwater flows and pressures will be encountered at faults and sheared rock zones. Release of pressures during construction may be necessary.

8.1 Ground Conditions

Squeezing ground conditions are expected to occur in the deeper sections of tunnel and in proximity to wide fault zones that are intersected by tunnel. In order to overcome the squeezing ground conditions, geologic investigations must thoroughly evaluate ground conditions within lengths of tunnel with high overburdens and at major fault zone crossings (e.g., width Category III). An enlarged bore and/or construction methods may need to be compatible with or capable of overcoming or avoiding squeezing pressures. In some cases, ground improvement may be feasible to stabilize squeezing ground ahead of tunnel excavation. It is not expected that squeezing ground poses a feasibility risk if anticipated and planned for in advance. Future design and construction planning should include contingencies for conducting TBM rescues in the event that one becomes frozen (entrapped).

Tunnels crossing active faults are subject to fault displacement causing offset of the tunnel structure below ground due to relative displacement across a fault or fault zone. Fault displacements can be accommodated by design for specified displacement magnitude and slip direction. These include use of enlarged tunnel sections and/or fault chambers. Restoration of a tunnel would require realignment or smoothing of the offset of the tunnel and repair of the lining system. For high-speed train projects, the track realignment would require track straightening or curvature restoration within the tunnel diameter (or chamber) to allow the train to maintain required speed for the project.

8.2 Hydrologic and Hydrogeologic Conditions

The hydrologic and hydrogeologic conditions along and adjacent to the tunnel corridor pose two major feasibility challenges as follows: 1) impacts on the groundwater and surface water resources are undesirable and would require mitigation; and 2) groundwater pressures greater than 25 bar pose challenges to tunnel excavation and support.

Tunneling will tend to provide a conduit for groundwater to drain into the excavation as the advancing tunnel intersects fractures and faults within the crystalline rock terrain below the ANF. Based on the general understanding of the groundwater system within the crystalline bedrock from the limited geotechnical investigation, the near surface water resources appear to respond more rapidly to annual precipitation and will likely respond to tunnel construction within the shallow groundwater zones along the tunnel alignments. The magnitude of potential impacts to shallow groundwater resources and surface water would depend upon the total volume of groundwater that flows into the tunnel during construction and the potential rate of recharge due to precipitation. Since the deeper rock zones generally exhibit lower hydraulic conductivity than

shallower zones, recharge from shallow zones vertically downward will likely exceed the rate of drainage/leakage from rock mass surrounding the tunnel lining.

The groundwater encountered at the deeper tunnel profiles (e.g., below 1,000 ft depth) tends to respond slower to water drainage due to the generally tighter rock fractures and resultant lower hydraulic conductivities. It also appears that rock at greater depths contains confined zones of groundwater that occur in pockets or zones (compartmentalized) of more fractured rock separated by less fractured rock. This results in confined aquifers being isolated from the shallow resources by zones of very low hydraulic conductivity rock. Tunneling in these deeper sections are not expected to influence the shallower groundwater systems or surface water resources.

In portions of tunnels where groundwater pressure is less than 25 bar, tunnel lining designs could eliminate water leakage into the tunnel once tunnel construction is completed. Thus the shallow groundwater, which is most susceptible to impacts of water draining into the tunnel, would be isolated from the tunnel effects by design of the tunnel lining. The tunnel lining would be watertight and the groundwater system would begin to recover rapidly to pre-tunnel conditions.

In zones of tunnels where the groundwater pressure is greater than the assumed limit of 25 bar, the tunnel lining system will need to be designed to reduce the external hydrostatic pressures by allowing controlled drainage of water from around the tunnel lining. The continuous drainage of water will need to be controlled to balance the maximum pressure on the tunnel lining system versus the minimum amount of water drainage needed to maintain the design pressure. The amount of water drainage for pressure relief purposes will need to be evaluated along all tunnel sections affected by groundwater pressures over 25 bar. The rate of groundwater losses can be minimized by grouting the native rock to lower its hydraulic conductivity immediately around the tunnel lining. This will accomplish two objectives: 1) Will maintain a lower recharge rate in the grouted zone in contact with the tunnel lining while allowing a higher recharge rate outside the grouted zone; and 2) Will minimize losses of water into the tunnel with minimal impact on the bedrock groundwater system.

Although a groundwater pressure of 25 bar is the current state-of-the-art for a watertight tunnel lining, development and testing of a lining system that can withstand higher pressures is possible and the actual maximum design pressure is unknown. Specific design concepts may be developed to increase the maximum design pressure applicable to this project including the use of new gasket technologies and/or double gasket tunnel lining segments. Alternatively, the use of a two-pass lining system incorporating an impermeable membrane between the interim and final lining is an option for preventing water entry into the tunnel and increasing the tunnel lining strength. Some tunnel sections may need the use of two-pass lining systems especially for enlarged fault chamber sections and at tunnel crossovers.

In summary, anticipated hydrologic and hydrogeologic conditions may be mitigated by use of special design and construction considerations as follows:

- Pre-excavation grouting of the rock ahead of the tunnel excavation can reduce or prevent groundwater drainage into the tunnel. Reducing inflow into the tunnel during construction will reduce the hydrologic and hydrogeologic impacts to the ANF.
- A segmental, precast, concrete lining with bolted and gasketed joints could control groundwater inflows to the tunnel during and after excavation up to certain pressures, as discussed above.
- Although less effective in protecting groundwater and surface water resources, a lining system that allows enough leakage to reduce groundwater pressures on the lining system may be considered as an alternative in specific areas of a final tunnel alignment provided that impacts to water resources do not occur or can be mitigated.

9 REFERENCES

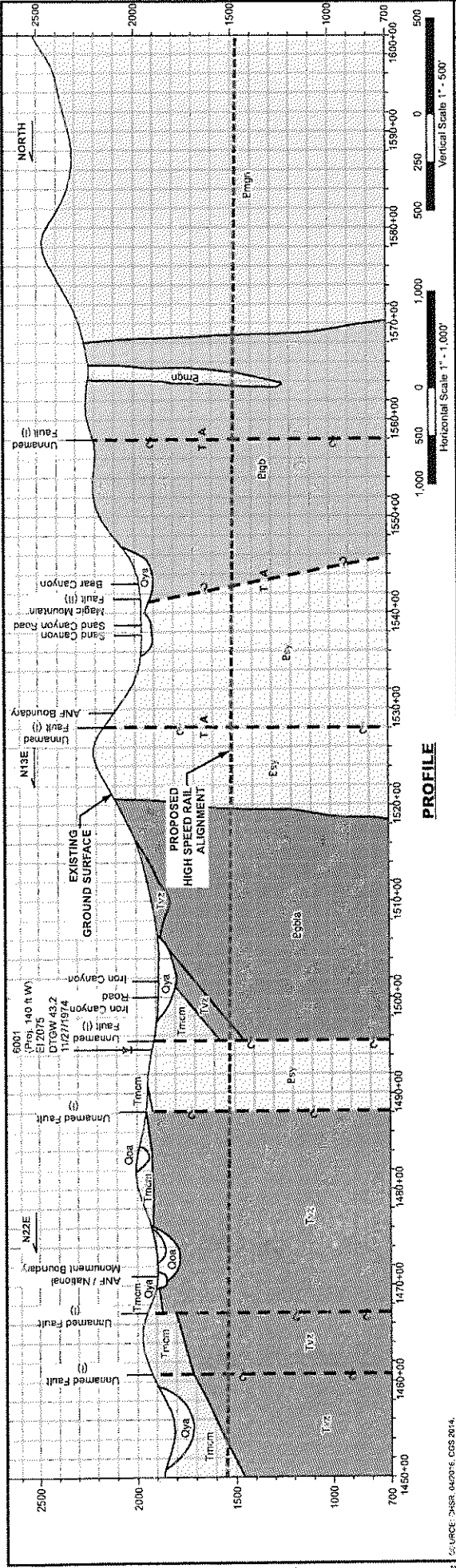
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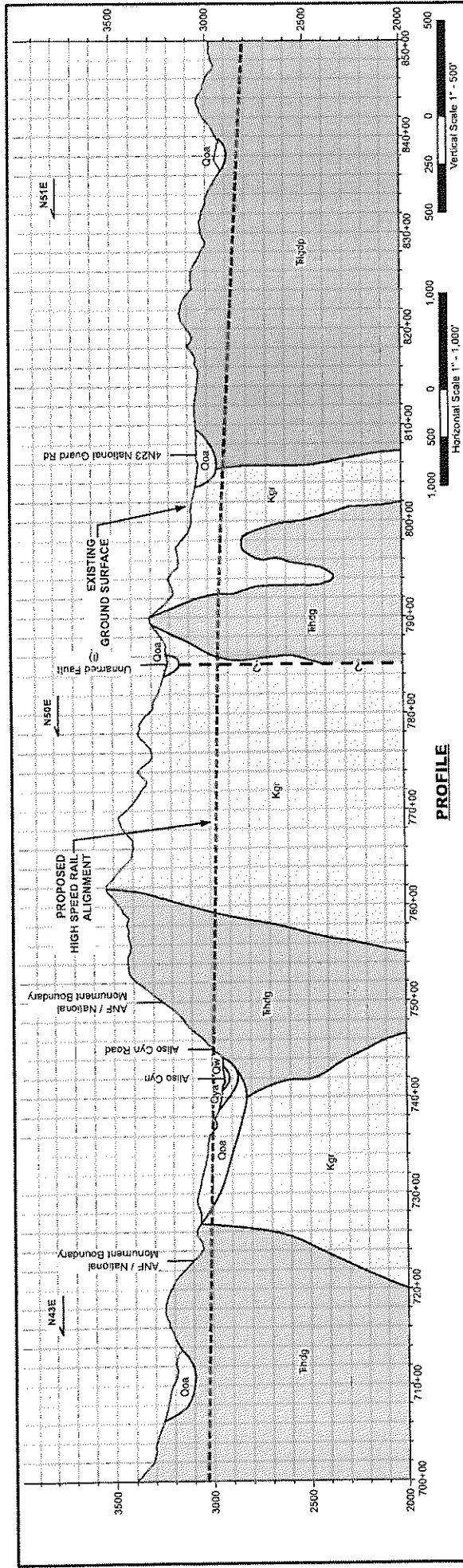
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APPENDIX A

GEOLOGIC PROFILES AND ANTICIPATED TUNNEL CONDITIONS



TBM 28' ID		TBM ETD 31.5' ID			
Tunnel Information					
Formation		Vasquez Formation (Tvz)		Anorthosite-gabbro complex - syenite (Psy)	
Lithology		coarse sandstone, conglomerate and interbedded andesite-basalt		gabbro with numerous inclusions of anorthosite	
Fracturing / Bedding / Structure		thickly bedded breccia, interbedded		strongly layered	
Key Features / Geologic Hazards		conglomeratic, mega-breccia, high abrasiveness		high abrasiveness	
Hydraulic Conductivity (Lugeon)		Low to High (0.01-50)		Very Low to Moderate (<0.01-5)	
Groundwater Head (bar)		Moderate (5-10)		High (10-25)	
Intact Rock Strength (MPa)		Soft to Hard (1-100)		Mod. Soft to Hard (5-100)	
RMR, GSI		Very Poor to Fair (0-60)		Poor to Good (21-80)	
Q		Ext. Poor to Fair (0.004-10)		Very Poor to Good (0.1-40)	
In-Situ Stress				Moderate	
Ground Condition		Moderate Squeezing, Swelling		Mild to Mod. Squeezing	
				Non to Mild Squeezing	



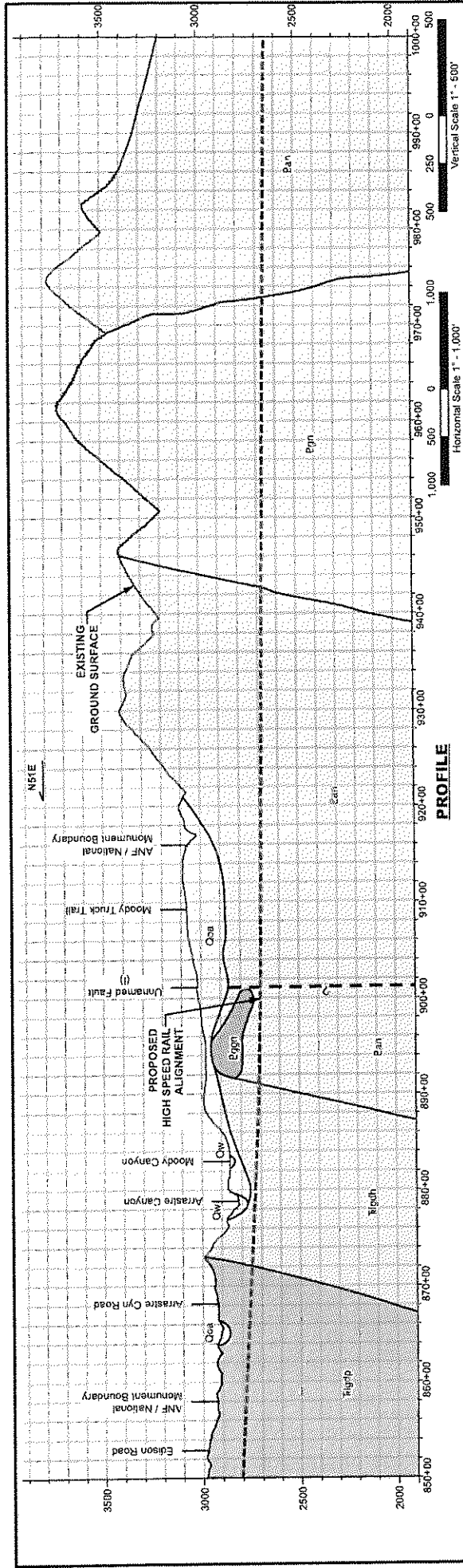
SOURCE: CHSR, 04/2014; CGS 2014.

PROFILE

Tunnel Information		Mined 28' ID		Mined 28' ID	
Formation	Mount Lowe intrusive suite - hornblende diorite gabbro (TRhdg)	Mount Lowe intrusive suite - hornblende diorite gabbro (TRhdg)	Granitic Rocks (Kgr)	Granitic Rocks (Kgr)	Mount Lowe intrusive suite - porphyritic facies (TRhdg)
Lithology	hornblende diorite gabbro	hornblende diorite gabbro	quartz monzonite, granodiorite, tonalite, quartz diorite and diorite	quartz monzonite, granodiorite, tonalite, quartz diorite and diorite	Orthoclase phenocrysts in matrix of plagioclase and subordinate quartz, localized garnet
Fracturing / Bedding / Structure	massive to locally foliated	massive to locally foliated	N/A	N/A	N/A
Key Features / Geologic Hazards	high abrasiveness	high abrasiveness	high to extreme abrasiveness	high abrasiveness	localized garnet, high to extreme abrasiveness
Hydraulic Conductivity (Lugeon)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)	Low (<5)
Groundwater Head (bar)	Low (<5)	Low (<5)	Low (<5)	Low (<5)	Low (<5)
Intact Rock Strength (MPa)	Mod. Soft to Hard (5-100)	N/A	Mod. Soft to Very Hard (5-250)	Mod. Soft to Very Hard (5-250)	Mod. Soft to Very Hard (5-250)
RMR, GSI	Poor to Good (21-80)	N/A	Poor to Good (21-80)	Poor to Good (21-80)	Poor to Good (21-80)
Q	Very Poor to Good (0.1-40)	N/A	Very Poor to Good (0.1-40)	Very Poor to Good (0.1-40)	Very Poor to Good (0.1-40)
In-Situ Stress	Low to Moderate	Low	Low to Moderate	Low to Moderate	Low to Moderate
Ground Condition	Non to Mild Squeezing	Running	Non to Mild Squeezing	Non to Mild Squeezing	Non Squeezing



CALIFORNIA HIGH-SPEED RAIL PROJECT SECTION
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E1 GEOLOGIC PROFILE AND
ANTICIPATED TUNNEL CONDITIONS
STATION 700+00 TO 850+00



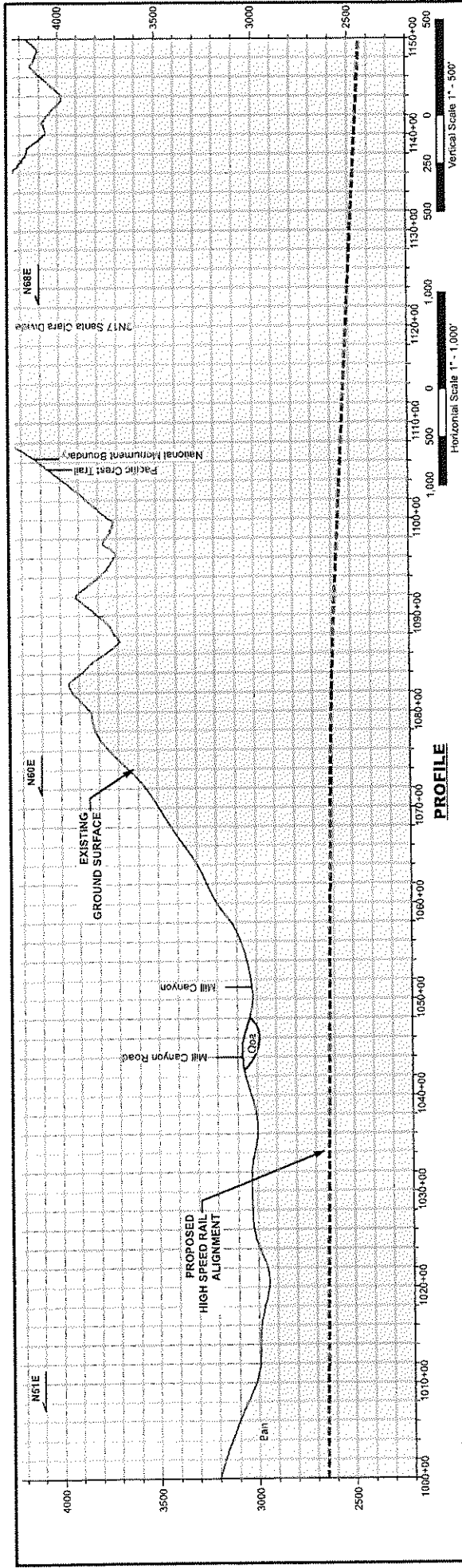
SOURCE: CHSR, AUGUST 2014, C&S 2014.

Tunnel Information		TBM 28" ID	
Formation	Mount Lowe intrusive suite - porphyritic facies (TRgpp)	Anorthositic-gabbro complex - anorthositic (Pan)	Anorthositic-gabbro complex - anorthositic (Pan)
Lithology	Orthoclase phenocrysts in matrix of plagioclase and subordinate quartz; localized garnet	anorthositic, more than 90% plagioclase, less than 10% mafic minerals, occasional quartz dikes	gneiss, biotite-rich and quartz-feldspar-rich lenses
Fracturing / Bedding / Structure	---	massive, pervasively sheared, shattered, brecciated. Layering rare, but sparse layering is present	foliated, banded layers generally ~1-in thick, sheared
Key Features / Geologic Hazards	localized garnet, high to extreme abrasiveness	quartz dikes, high to extreme abrasiveness	foliation and banding, extreme abrasiveness
Hydraulic Conductivity (Lugeon)	---	Very Low to Moderate (<0.01-5)	---
Groundwater Head (bar)	Low (<5)	Moderate (5-10)	High (10-25)
Intact Rock Strength (MPa)	Mod. Soft to Very Hard (5-250)	---	Mod. Hard to Ext. Hard (25->250)
RMR, GSI	Poor to Good (21-30)	---	Fair to Good (41-60)
Q	Very Poor to Good (0.1-40)	---	Poor to Good (1-40)
In-Situ Stress	Low to Moderate	Moderate	Moderate to High
Ground Condition	Non Squeezing	Non to Mild Squeezing	Moderate



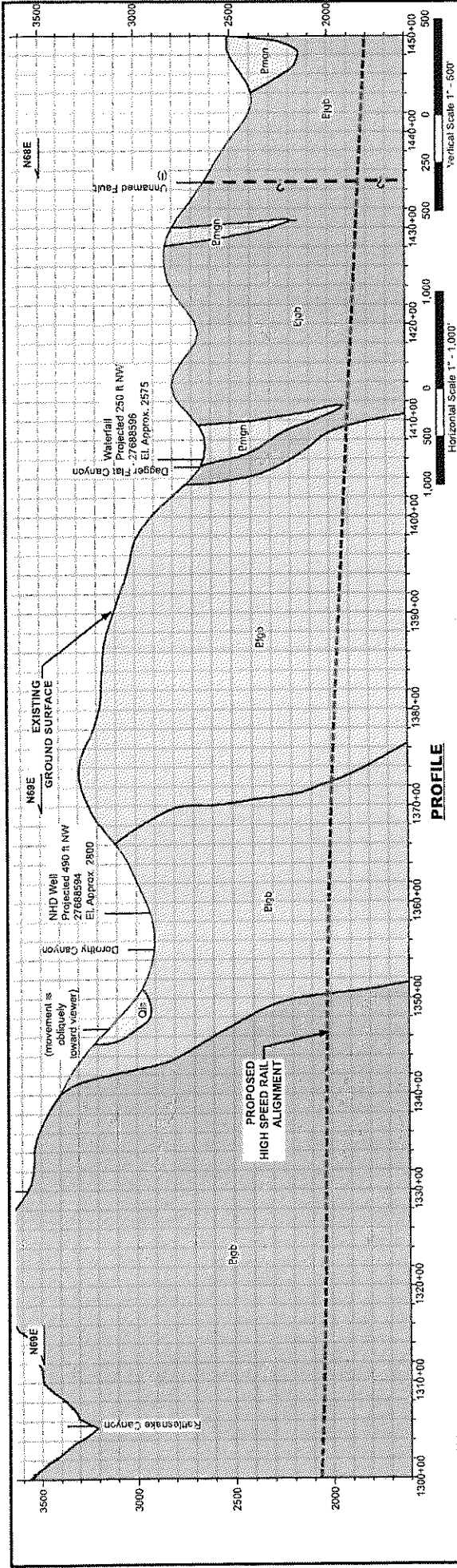
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E1 GEOLOGIC PROFILE AND
ANTICIPATED TUNNEL CONDITIONS
STATION 850+00 TO 1000+00

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3 of 8



SOURCE: CHSR, 642714, GSE 2014

Tunnel Information		TBM 28' ID	
Formation		Anorthositic-gabbro complex - anorthositic (Pan)	
Lithology		anorthositic, more than 90% plagioclase, less than 10% mafic minerals, occasional quartz dikes	
Fracturing / Bedding / Structure		massive, pervasively sheared, shaltered, brecciated. Layering rare, but sparse layering is present	
Key Features / Geologic Hazards		quartz dikes, high to extreme abrasiveness	
Hydraulic Conductivity (Lugeon)		Very Low to Moderate (<0.01-5)	
Groundwater Head (bar)		High (10-25)	High (10-25)
Intact Rock Strength (MPa)		Moderate (5-10)	Ext. High (>35)
RMIR, GSI		Fair to Good (41-50)	Poor to Good (21-80)
Q		Poor to Good (1-40)	Very Poor to Good (0.1-40)
In-Situ Stress		High	
Ground Condition		Non Squeezing	
In-Situ Stress		Non to Mild Squeezing	
Ground Condition		Mild to Moderate Squeezing, Spalling, Slabbing, Rock Bursting	
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NOT FOR CONSTRUCTION		CALIFORNIA HIGH-SPEED RAIL AUTHORITY PALMDALE TO BURBANK PROJECT SECTION E1 GEOLOGIC PROFILE AND ANTICIPATED TUNNEL CONDITIONS STATION 1000+00 TO 1150+00	
DATE		4 of 8	



SOURCE: CHER, 04/03/14, CCS 2014.

Tunnel Information		TBM 28 ID		Mined ETD 32 ID	
Formation	Anorthositic-gabbro complex - joutonic gabbro (Pgjo)	Anorthositic-gabbro complex - ferro-gabbro (Pgfb)	Anorthositic-gabbro complex - joutonic gabbro (Pgjo)	Anorthositic-gabbro complex - joutonic gabbro (Pgjo)	Anorthositic-gabbro complex - joutonic gabbro (Pgjo)
Lithology	joutonic gabbro with antiperthitic andesine	gabbro, leucogabbro and anorthositic	ferro-gabbro, mostly ferro-magnesian minerals with lesser feldspars	joutonic gabbro with antiperthitic andesine	joutonic gabbro with antiperthitic andesine
Fracturing / Bedding / Structure	compositionally layered	heterogeneous layering, 1 cm-1 dm layers, differing only in Plagioclase composition	---	compositionally layered	compositionally layered
Key Features / Geologic Hazards	high abrasiveness	high to extreme abrasiveness	contains magnetite-ilmenite, high abrasiveness	high abrasiveness	high abrasiveness
Hydraulic Conductivity (Lugeon)					
Groundwater Head (bar)					
Intact Rock Strength (MPa)					
RMR, GSI					
Q					
In-Situ Stress					
Ground Condition					

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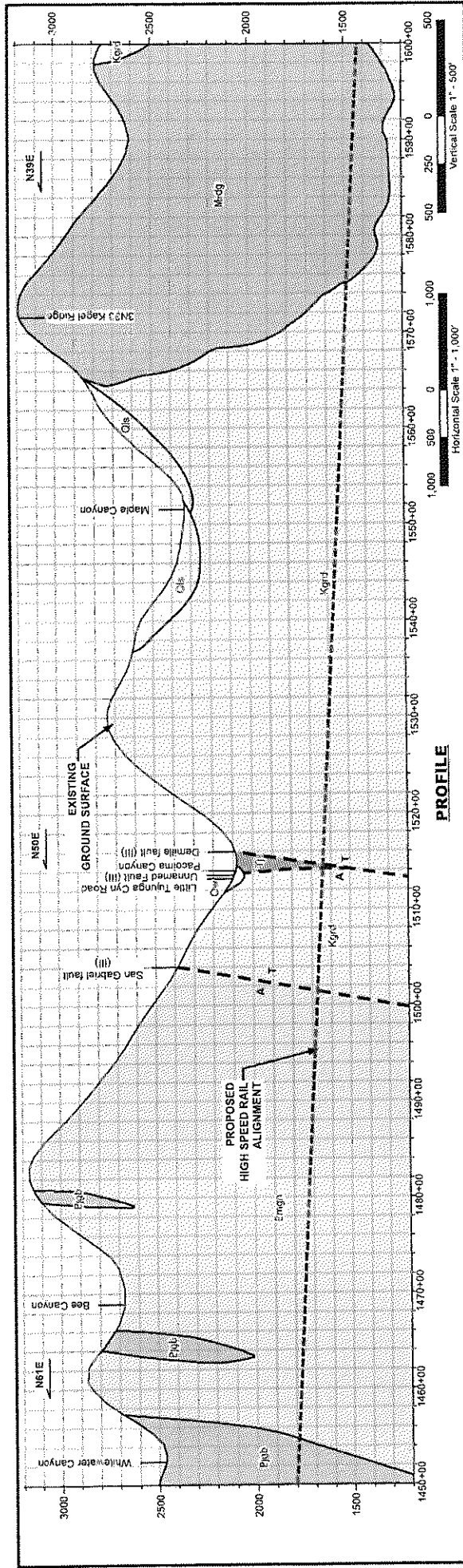
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ANTICIPATED TUNNEL CONDITIONS
STATION 1300+00 TO 1450+00

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REVISIONS

NO.	DATE	DESCRIPTION
1	04/03/14	ISSUED FOR REVIEW
2	04/03/14	ISSUED FOR REVIEW
3	04/03/14	ISSUED FOR REVIEW
4	04/03/14	ISSUED FOR REVIEW
5	04/03/14	ISSUED FOR REVIEW
6	04/03/14	ISSUED FOR REVIEW
7	04/03/14	ISSUED FOR REVIEW
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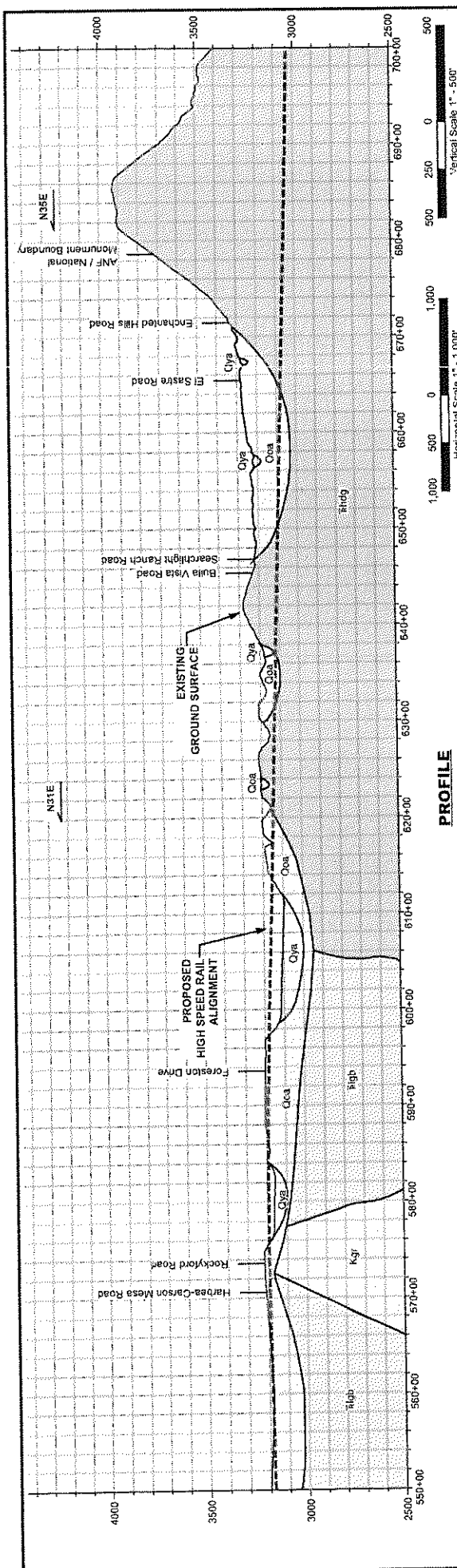
SOURCE: CH&M, D-1016, 2-25-2014.

Tunnel Information		Mined ETD 32' ID		TBM ETD 36' ID	
Formation		Mendocino gneiss (Pmgn)		Granodiorite (Kgnd)	
Lithology		layered migmatitic felsic gneiss and mafic granitite		granodiorite with quartz diorite and granite	Diabase gneiss (Hc-gg)
Fracturing / Bedding / Structure		compositionally layered, large scale foliations, fracturing and jointing		mostly massive, gneissoid near contacts with older rocks	gneiss, including metadiorites, hornblende diorite and amphibolite and diorite schists, foliated gneiss, hornblende diorites are massive
Key Features / Geologic Hazards		extreme abrasiveness		large inclusions and pendants of gneiss and Placerita metasediments, extreme abrasiveness	high abrasiveness
Hydraulic Conductivity (Luggeon)					
Groundwater Head (bar)		High (10-25)	Very High (25-35)	High (10-25)	Very High (25-35)
Intact Rock Strength (MPa)		Mod. Soft to Very Hard (5-250)	Soft to Hard (1-100)	Soft to Very Hard (1-250)	Ext. High (>35)
RMR, GSI		Poor to Good (21-60)	Very Poor to Fair (0-60)	Poor to Good (21-60)	Very High (25-35)
Q		Very Poor to Good (0.1-40)	Ext. Poor to Poor (0.004-4)	Very Poor to Good (0.1-40)	High (10-25)
In-Situ Stress		Moderate to High	Moderate to High (Tectonic)	Moderate to High	
Ground Condition		Mild to Moderate Squeezing	Moderate to Heavy Squeezing, Spalling, Slabbing, Rock Bursting	Mild to Moderate Squeezing, Spalling, Slabbing, Rock Bursting	



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STATION 1450+00 TO 1600+00



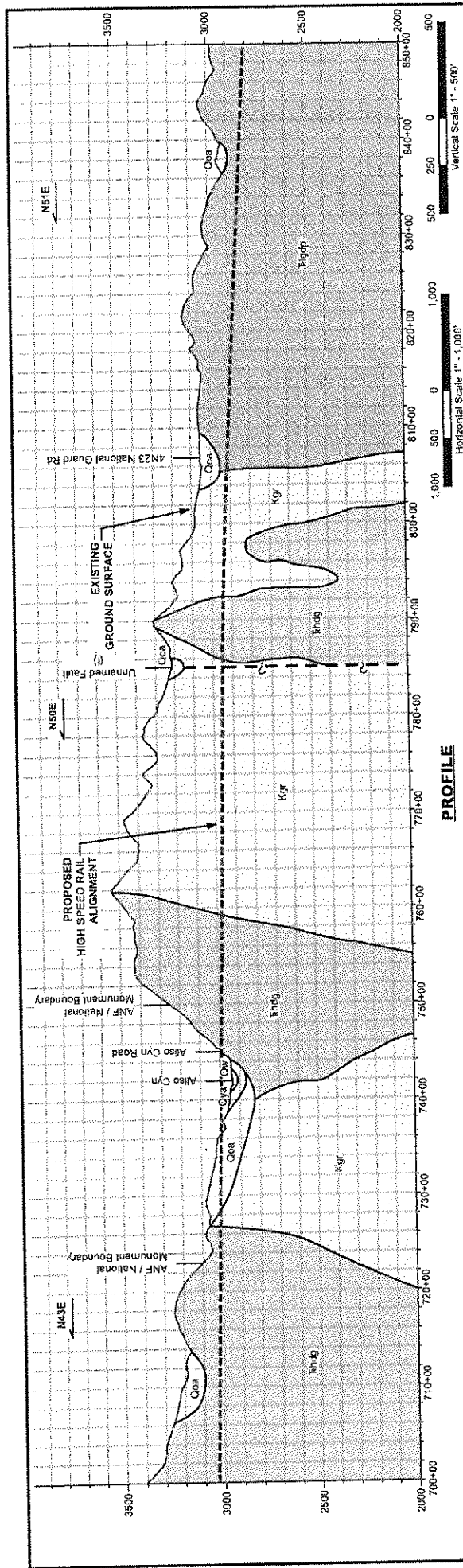
SOURCE: CBR, 6-2014; CGS 2014.

Tunnel Information		Mined 28 ID	
Formation	Old alluvium, undivided (Qoa)	Old alluvium, undivided (Qoa)	Mount Lowe intrusive suite - hornblende diorite gabbro (Rthg)
Lithology	silt, sand, gravel, cobbles and boulders	silt, sand, gravel, cobbles and boulders	hornblende diorite gabbro
Fracturing / Bedding / Structure	N/A	N/A	massive to locally foliated
Key Features / Geologic Hazards	unconsolidated to moderately indurated, conglomeratic (some boulders), medium to high abrasiveness	unconsolidated to moderately indurated, conglomeratic (some boulders), medium to high abrasiveness	high abrasiveness
Hydraulic Conductivity (Lupeol)			Very Low to Moderate (<0.01-5)
Groundwater Head (bar)			Moderate (5-10)
Intact Rock Strength (MPa)	N/A	N/A	Mod. Soft to Hard (5-100)
RMR, GSI	N/A	N/A	Poor to Good (21-60)
Q	N/A	N/A	Very Poor to Good (0.1-40)
In-Situ Stress			Low to Moderate
Ground Condition			Non to Mild Squeezing

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E2 GEOLOGIC PROFILE AND
ANTICIPATED TUNNEL CONDITIONS
STATION 550+00 TO 700+00

1 of 8



SOURCE: CH2M HILL, 2009; CDS 2014.

Tunnel Information		Mined 28' ID	
Formation	Mount Lowe intrusive suite - hornblende diorite gabbro (Trdg)	Granitic Rocks (Kgr)	Mount Lowe intrusive suite - porphyritic facies (TRgdp)
Lithology	hornblende diorite gabbro	hornblende diorite gabbro	Orthoclase phenocrysts in matrix of plagioclase and subordinate quartz; localized garnet
Fracturing / Bedding / Structures	massive to locally foliated	massive to locally foliated	---
Key Features / Geologic Hazards	high abrasiveness	high to extreme abrasiveness	localized garnet, high to extreme abrasiveness
Hydraulic Conductivity (Lugeon)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)	---
Groundwater Head (bar)	Low (<5)	Low (<5)	Low (-5)
Intact Rock Strength (MPa)	Mod. Soft to Hard (5-100)	Mod. Soft to Very Hard (5-250)	---
RMR, GSI	Poor to Good (21-60)	Poor to Good (21-80)	---
Q	Very Poor to Good (0.1-40)	Very Poor to Good (0.1-40)	---
In-Situ Stress	Low to Moderate	Low to Moderate	---
Ground Condition	Non to Mild Squeezing	Non to Mild Squeezing	Non Squeezing

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STATION 700+00 TO 850+00

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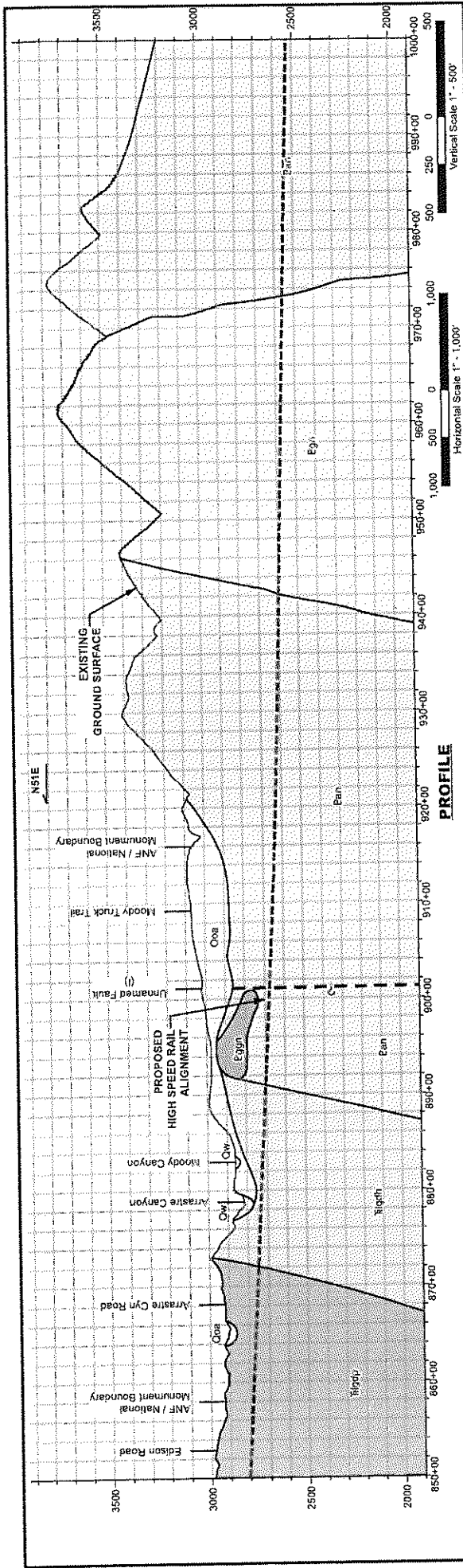
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SHEET NO: 2 of 8



SOURCE: CHSR, 6-2016; CGS 2014.

Tunnel Information		Mined 28' ID		TBM 28' ID	
Formation	Mount Lowe intrusive suite - porphyritic facies (T1Rigdp)	Mount Lowe intrusive suite - orthoclase-hornblende facies (T1Rigdp)	Anorthosite-gabbro complex - anorthosite (Pan)	Gneiss (Pgnt)	Anorthosite-gabbro complex - anorthosite (Pan)
Lithology	Orthoclase phenocrysts in matrix of plagioclase and subordinate quartz; localized garnet	hornblende diolite	anorthosite, more than 90% plagioclase, less than 10% mafic minerals, occasional quartz dikes	gneiss, biotite-rich and quartz-feldspar-rich lenses	anorthosite, more than 90% plagioclase, less than 10% mafic minerals, occasional quartz dikes
Fracturing / Bedding / Structure	---	---	massive, pervasively sheared, shattered, brecciated. Layering rare, but sparse layering is present	foliated, banded layers generally ~1-in thick, sheared	massive, pervasively sheared, shattered, brecciated. Layering rare, but sparse layering is present
Key Features / Geologic Hazards	localized garnet, high to extreme abrasiveness	high abrasiveness	quartz dikes, high to extreme abrasiveness	foliation and banding, extreme abrasiveness	quartz dikes, high to extreme abrasiveness
Hydraulic Conductivity (Lugeon)	Low (<5)	Moderate (5-10)	High (10-25)	Very Low to Moderate (<0.01-5)	
Groundwater Head (bar)	Mod. Soft to Very Hard (5-250)	Poor to Good (21-80)	Poor to Good (41-80)	Mod. Hard to Ext. Hard (25-250)	
Intact Rock Strength (MPa)	Very Poor to Good (0.1-40)	Poor to Good (21-80)	Poor to Good (41-80)	Poor to Good (1-40)	
RMR, GSI	Low to Moderate	Moderate	Moderate	Moderate to High	
In-Situ Stress	Non Squeezing	Non Squeezing	Non Squeezing	Non Squeezing	
Ground Condition	Non Squeezing	Non Squeezing	Non Squeezing	Non Squeezing	

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PALMDALE TO BURBANK PROJECT SECTION
E2 GEOLOGIC PROFILE AND
ANTICIPATED TUNNEL CONDITIONS
STATION 850+00 TO 1000+00

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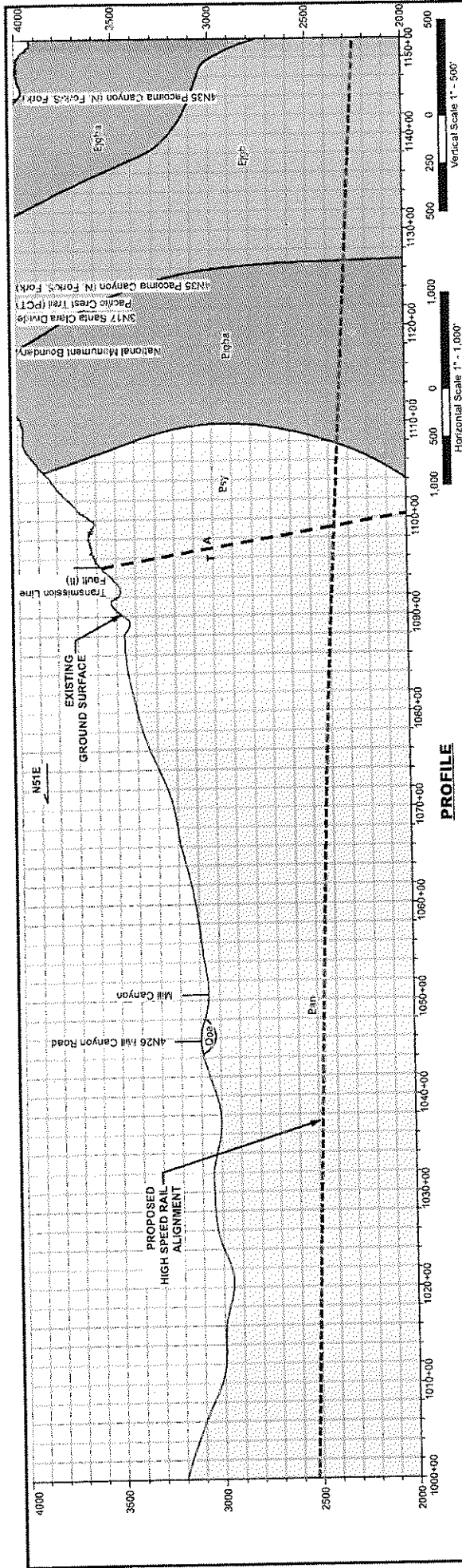
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PROJECT: CALHSR E2

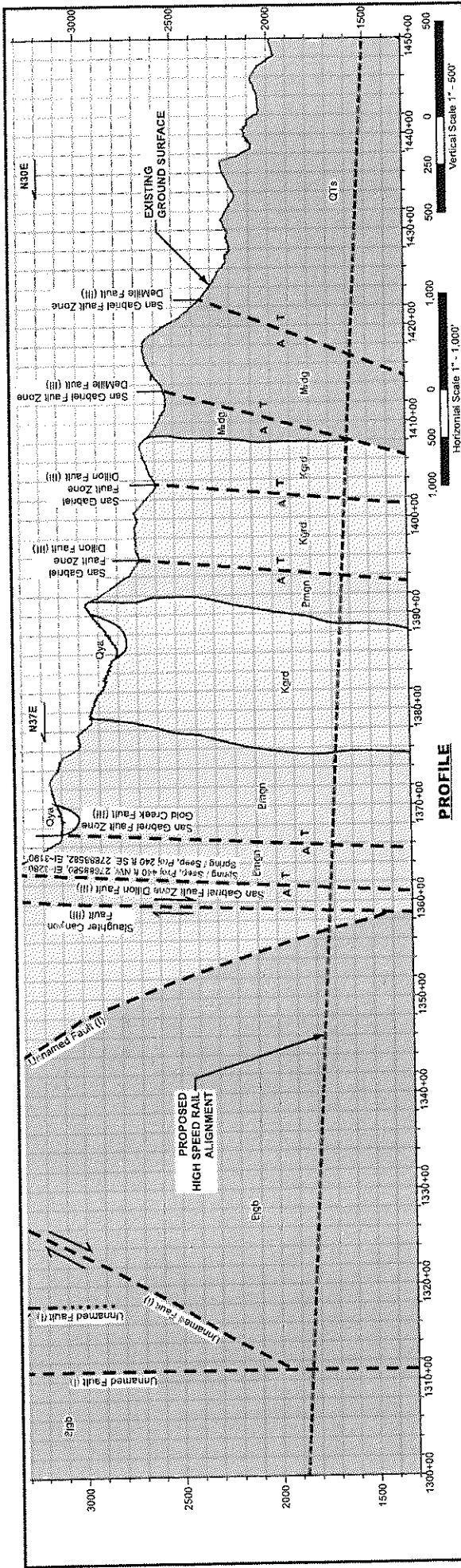
3 of 8



SOURCE: CERRI, 04/20/14, CERRI 2014.

TBM 26 (D)	
Tunnel Information	
Formation	Anorthosite-gabbro complex - anorthosite (Pan)
Lithology	anorthosite, more than 90% plagioclase, less than 10% mafic minerals, occasional quartz dikes
Fracturing / Bedding / Structure	massive, pervasively sheared, shattered brecciated. Layering rare, but sparse layering is present
Key Features / Geologic Hazards	quartz dikes, high to extreme abrasiveness
Hydraulic Conductivity (Lugeon)	
Groundwater Head (bar)	
Intact Rock Strength (MPa)	
RMR, GSI	
Q	
In-Situ Stress	
Ground Condition	

Very Low to Moderate (<0.0+5)	
Very High (25-35)	
Ext. High (>35)	
Soft to Very Hard (1-250)	
Mod. Soft to Very Hard (5-250)	
Poor to Good (21-80)	
Very Poor to Good (0.1-40)	
High (Tectonic)	
High	
Mild to Moderate Squeezing	
Non to Mild Squeezing	
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PALMDALE TO BURBANK PROJECT SECTION	
E2 GEOLOGIC PROFILE AND	
ANTICIPATED TUNNEL CONDITIONS	
STATION 1000+00 TO 1150+00	
A3	
4 of 8	



SOURCE: CHER, INC. 2014, 2015

TBM ETD 32' ID									
Tunnel Information	Formation	Lithology	Fracturing / Bedding / Structure	Key Features / Geologic Hazards	Hydraulic Conductivity (Luqeon)	Groundwater Head (bar)	Intact Rock Strength (MPa)	RMR, GSI	Q
	Auriferous-gabbro complex - jolunite gabbro (Pgbb)	basaltic gabbro with antiperthitic andesite compositionally layered		high abrasiveness			Mod. Soft to Very Hard (5-250)	Good (21-80)	Very Poor to Good (0.1-40)
							Ext. High (>35)		
							Very Low to Moderate (<0.01-5)		
							Very Soft to Hard (1<-100)		
							Poor to Fair (21-60)		
							Ext. Poor to Fair (0.004-10)		
							High to Very High (Tectonic)		
							Mod. to Heavy Squeezing, Swelling, Rock Bursting, Spalling, Slabbing		
							Mod. Squeezing, Swelling, Rock Bursting, Spalling, Slabbing		
							Mild to Mod. Squeezing, Ravelling, Flowing		

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E2 GEOLOGIC PROFILE AND
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STATION 1300+00 TO 1450+00

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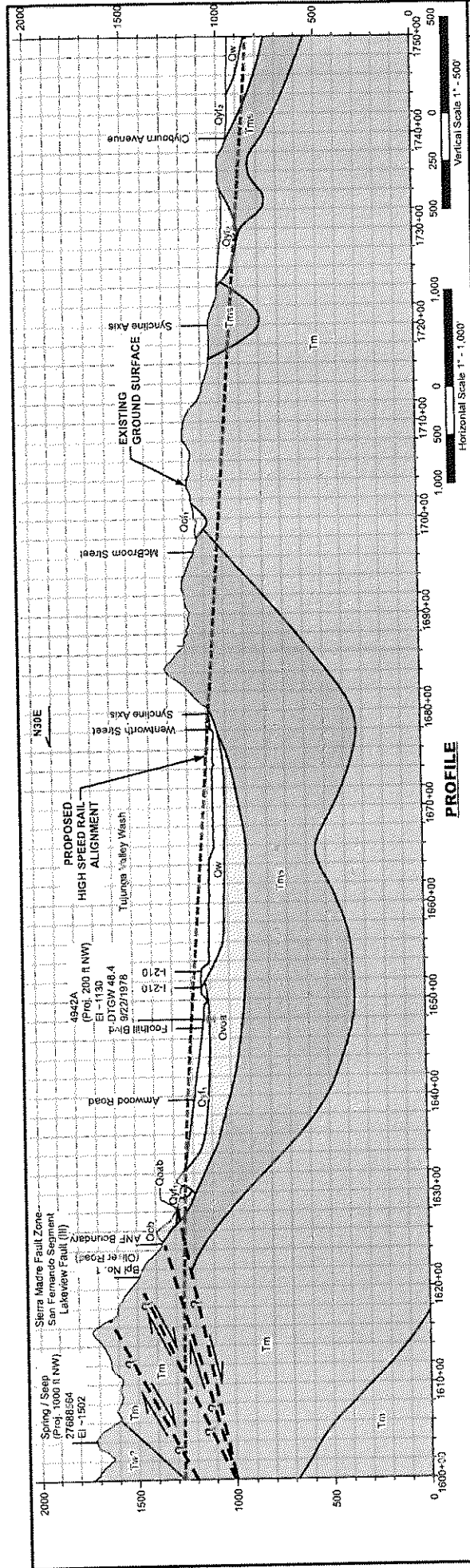
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SCALE: 1" = 1,000'

6 of 8



TBM ETD 32' ID		SEM ETD 33' 5" ID	
Tunnel Information	Modelo Formation, undivided (Tms)	Modelo Formation, undivided (Tms)	Modelo Formation, undivided (Tms)
Formation	Modelo Formation, undivided (Tms)	Modelo Formation, undivided (Tms)	Modelo Formation, undivided (Tms)
Lithology	mudstone, diatomaceous clay shale or siltstone with very fine to coarse-grained sandstone	sandstone and conglomerate	sandstone and conglomerate
Fracturing / Bedding / Structure	thin bedded, interbedded, sheared along bedding	thin bedded, interbedded, sheared along bedding	thin bedded, interbedded, sheared along bedding
Key Features / Geologic Hazards	sheared along bedding, potential gassy ground, low to medium abrasiveness	sheared along bedding, potential gassy ground, low to medium abrasiveness	sheared along bedding, potential gassy ground, low to medium abrasiveness
Hydraulic Conductivity (Lugeon)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)	Very Low to Moderate (<0.01-5)
Groundwater Head (bar)	Moderate (5-10)	Low (<5)	Low (<5)
Intact Rock Strength (MPa)	Very Soft to Mod. Hard (1-50)	Very Soft to Mod. Hard (1-50)	Very Soft to Mod. Hard (1-50)
RMR, GSI	Very Poor to Fair (0-60)	Very Poor to Fair (0-60)	Very Poor to Fair (0-60)
Q	Ext. Poor to Poor (0.004-4)	Ext. Poor to Poor (0.004-4)	Ext. Poor to Poor (0.004-4)
In-Situ Stress	Moderate (Tectonic)	Low	Low
Ground Condition	Firm, Ravelling, Swelling	Firm, Ravelling, Swelling	Firm, Ravelling, Swelling

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PALMDALE TO BURBANK PROJECT SECTION
E2 GEOLOGIC PROFILE AND
ANTICIPATED TUNNEL CONDITIONS
STATION 1600+00 TO 1750+00

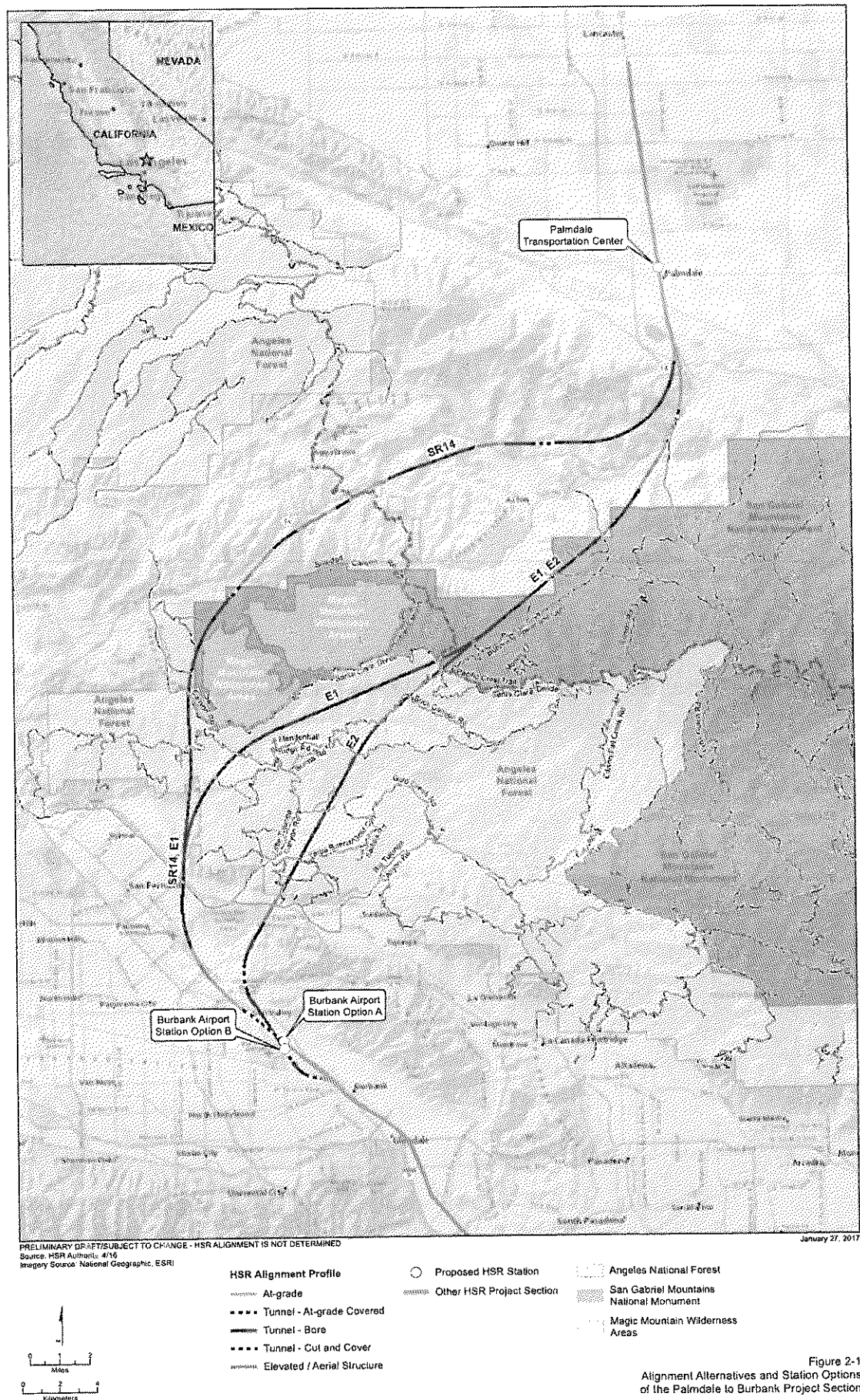
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REVISIONS

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FIGURES

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
PALMDALE TO BURBANK PROJECT SECTION



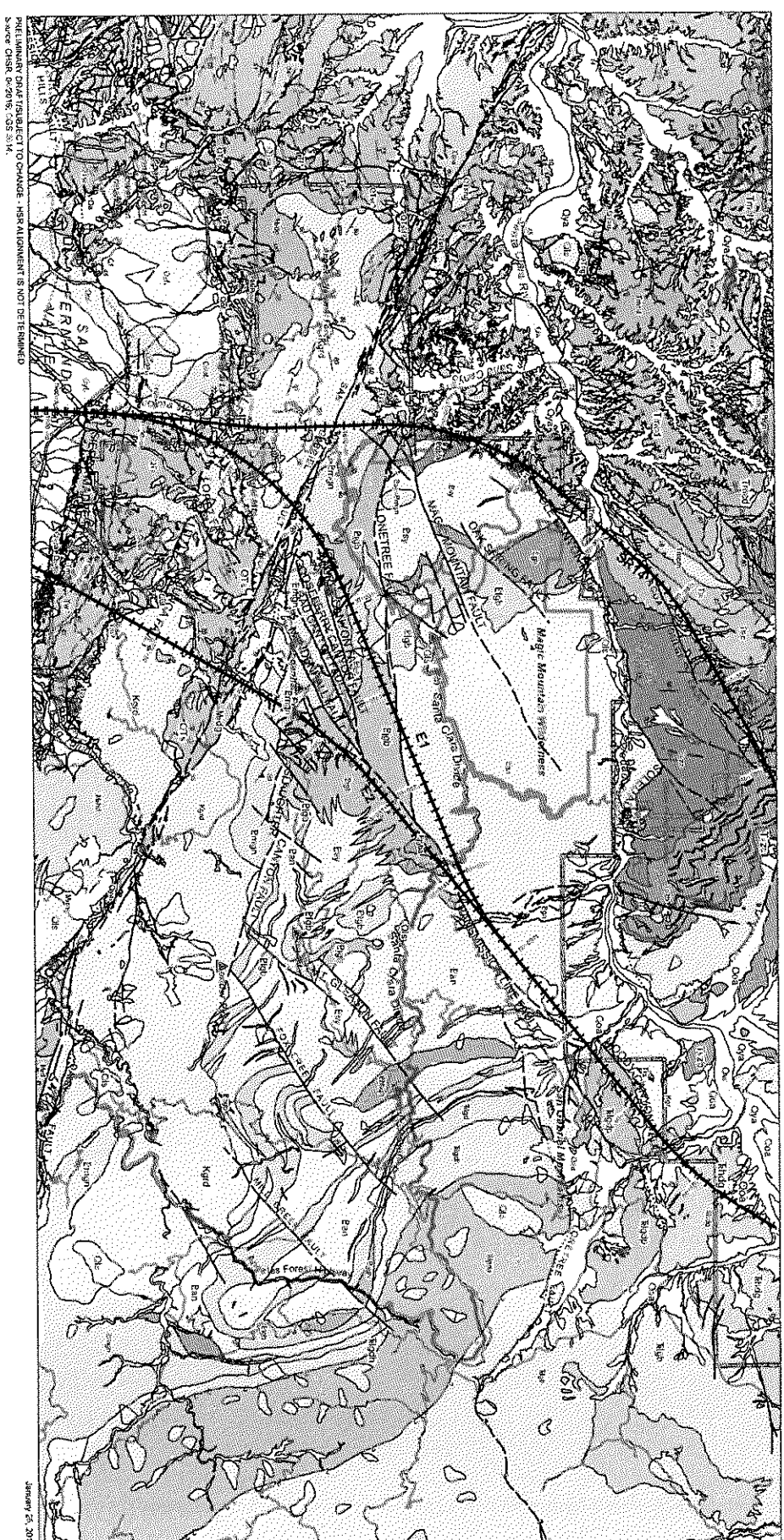


Figure 5-1 Geologic Map

CALIFORNIA HIGH-SPEED RAIL AUTHORITY PALMDALE TO BURBANK PROJECT SECTION

	Artificial fill (Holocene)			Gneiss (Proterozoic)
	Wash deposits (Holocene)			Undivided (early Miocene to Oligocene)
	Landslide deposits (Only selected, larger landslides shown) (Holocene)			Andesitic volcanic rocks (early Miocene to late Oligocene)
	Young alluvium, undivided (Holocene)			Sedimentary rocks (early Miocene to late Oligocene)
	Young alluvial fan deposits, Unit 2 (Holocene and late Pleistocene)	San Gabriel Mountains and Eastern Santa Monica Mountains		
	Old alluvium, undivided (late to middle Pleistocene)			Juncal Formation. Turbidly current and submarine fan deposits, including sandstone, conglomeratic sandstone, conglomerate and siltstone (late early Eocene)
	Old alluvial fan deposits, Unit 2 (late Pleistocene)			Granitic Rocks. Includes a variety of plutonic rocks, chiefly quartz diorite (late Cretaceous)
	Old alluvial fan deposits, Unit 1 (late Pleistocene)			Granodiorite with quartz diorite and granite, commonly gneissoid near contacts with older rocks. Locally carries large inclusions and pendants of gneiss and Placencia metasediments (Cretaceous)
	Very old alluvium, undivided (middle to early Pleistocene)			Diorite gneiss (early to middle Mesozoic)
	Very old alluvial fan deposits, undivided (middle to early Pleistocene)	Mount Lowe Intrusive Suite		
	Pacoima Formation (Ventura Basin)	A compositionally layered pluton (Triassic)		
	Funglomerate or sedimentary breccia (middle Pleistocene)			Biotite-orthoclase facies
	Saugus Formation (Ventura Basin)			Porphyritic facies
	Predominantly non-marine sandstone, conglomerate and siltstone (late Pleistocene)			Orthoclase-hornblende facies
	QTs Undivided			Hornblende diorite gabbro
	Towlesy Formation	Anorthosite-gabbro complex of Oakeshott (1958) (Proterozoic)		
	Turbidly current deposits of interbedded sandstone, conglomerate, sandy siltstone and mudstone (early Pliocene to late Miocene)	Unit is composed of sub-units mapped and described by Carter (1980a) including:		
	Tw Undivided			Anorthosite
	Modele Formation			Syenite
	Mudstone, diatomaceous clay shale or siltstone with interbeds of sandstone (late to middle Miocene)			Ferro-gabbro
	Tm Undivided			Leuogabbro
	Mint Canyon Formation			Jolunitic gabbro
	Non-marine fluvial and lacustrine sedimentary breccia, conglomerate, sandstone, siltstone and mudstone (late to middle Miocene)			Jolunitic-norite gabbro-diorite
	Tmcd Undivided			Gabbroic to anorthositic gneiss
	Lacustrine deltaic (freset) facies			Gabbro
	Lacustrine and lake-marginal fluvial facies			Anorthositic inclusion-rich gabbro
	Lacustrine and lake-marginal fluvial facies			Anorthositic inclusion-rich gabbro
	Tick Canyon Formation			
	Fluvial and lacustrine sedimentary sandstone, siltstone, claystone and conglomerates (middle to early Miocene)			
	Ttic Conglomerate			

Source: CHSR, MORTIS, C-5, 2014, November 2016.

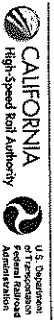


Figure 5-2 Geologic Map Explanation

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
PALMDALE TO BURBANK PROJECT SECTION

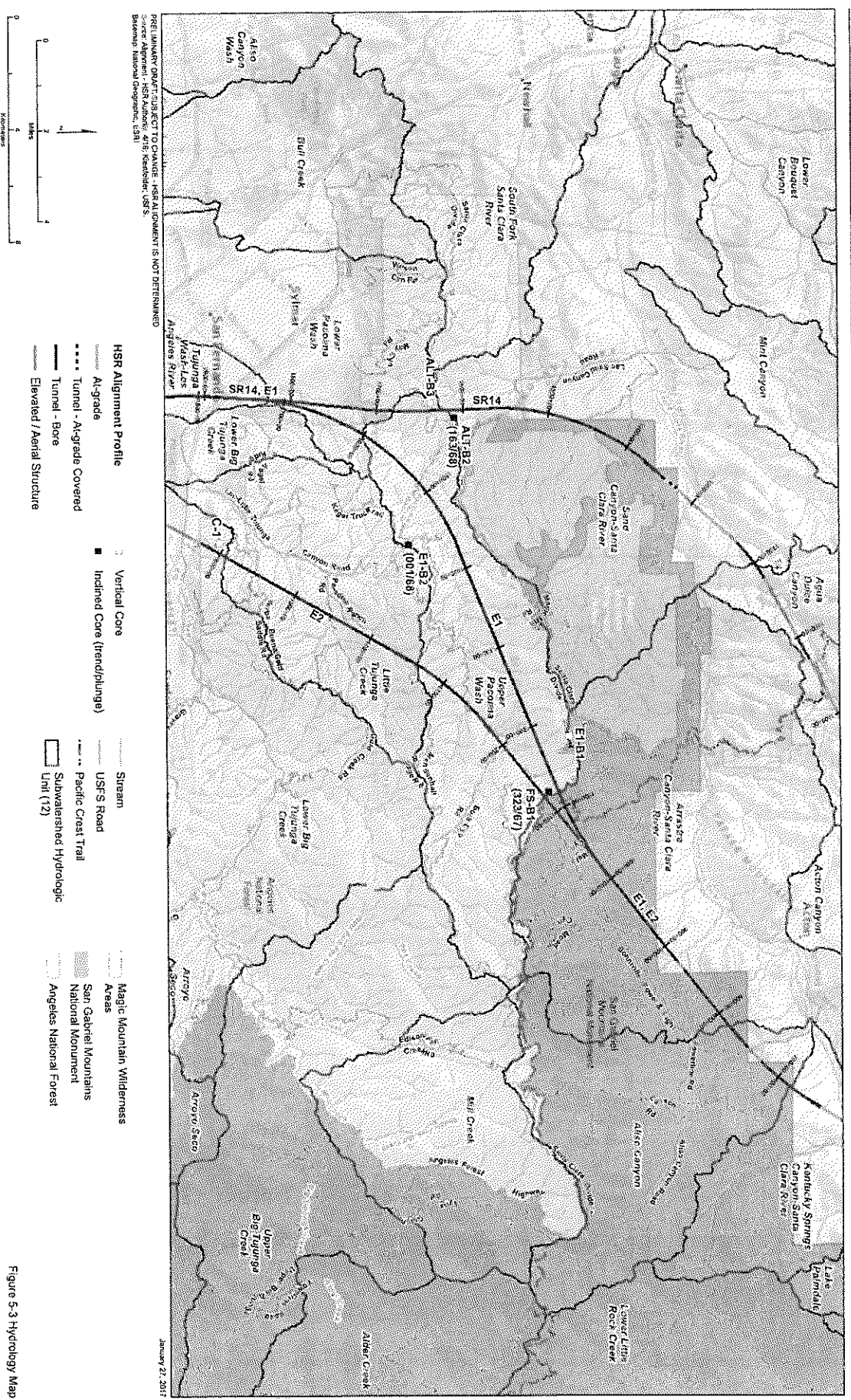
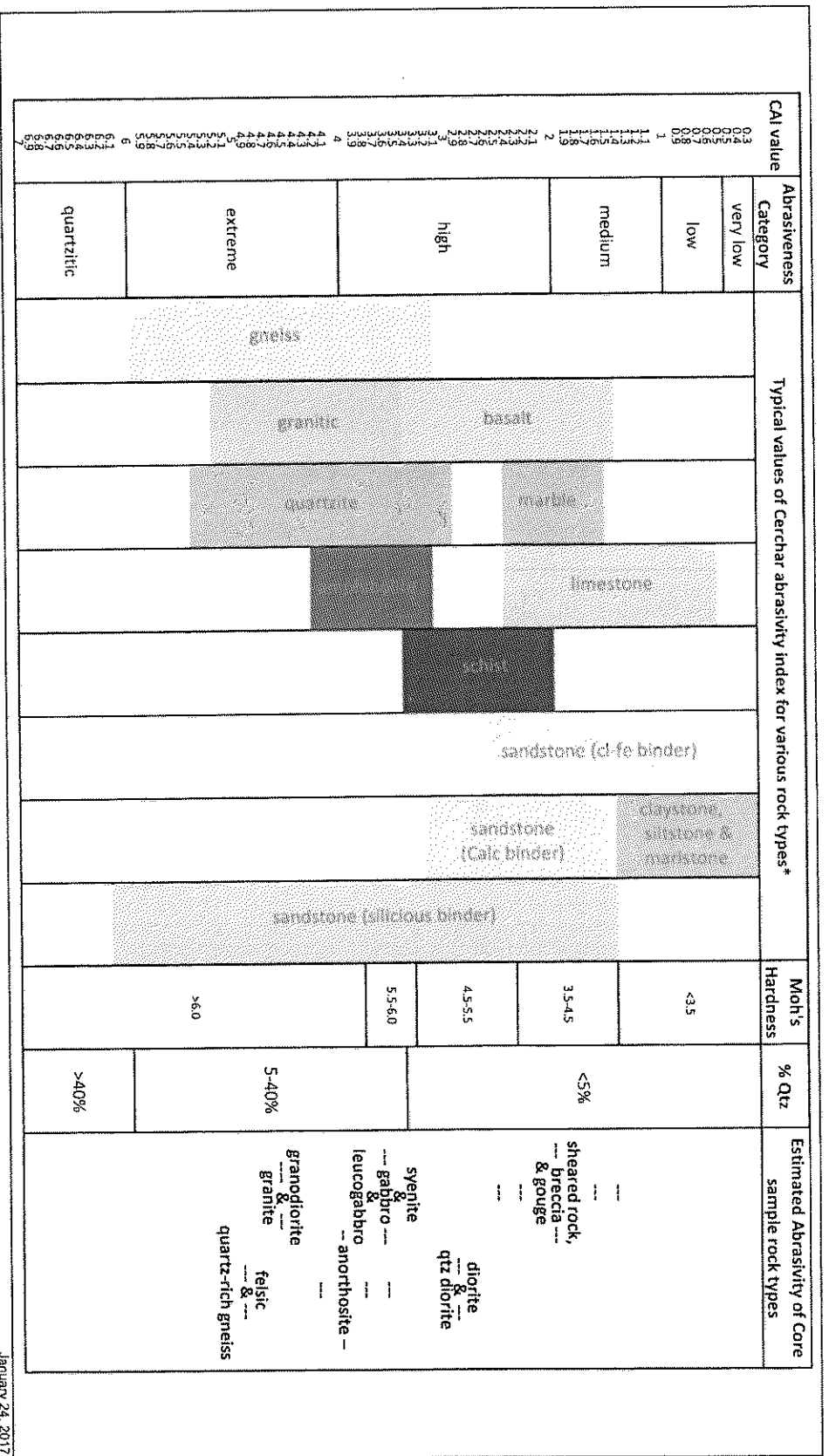


Figure 5-3 Hydrology Map

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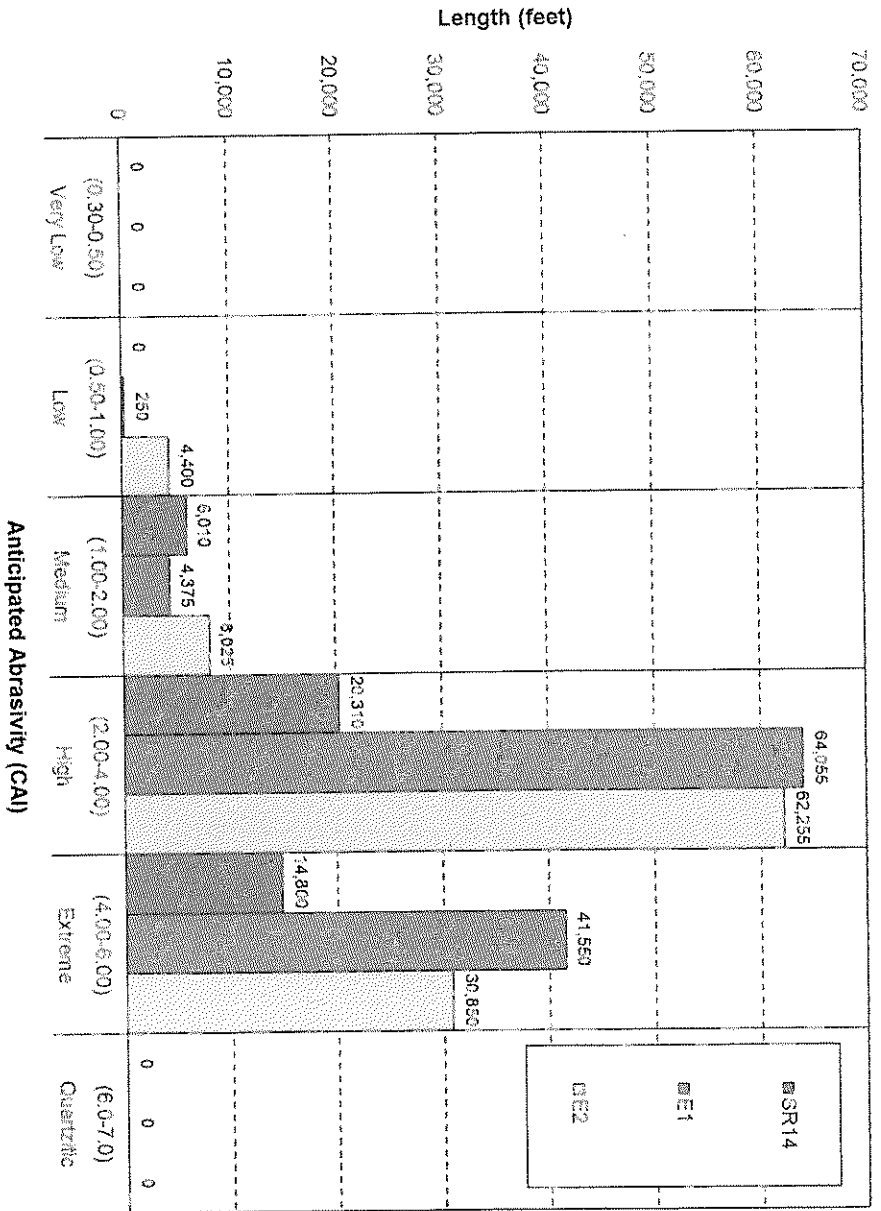


Adapted from:
Zhang, 2016; and
Pinninger et al., 2003.

January 24, 2017

Figure 6-1
Abrasivity correlations

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
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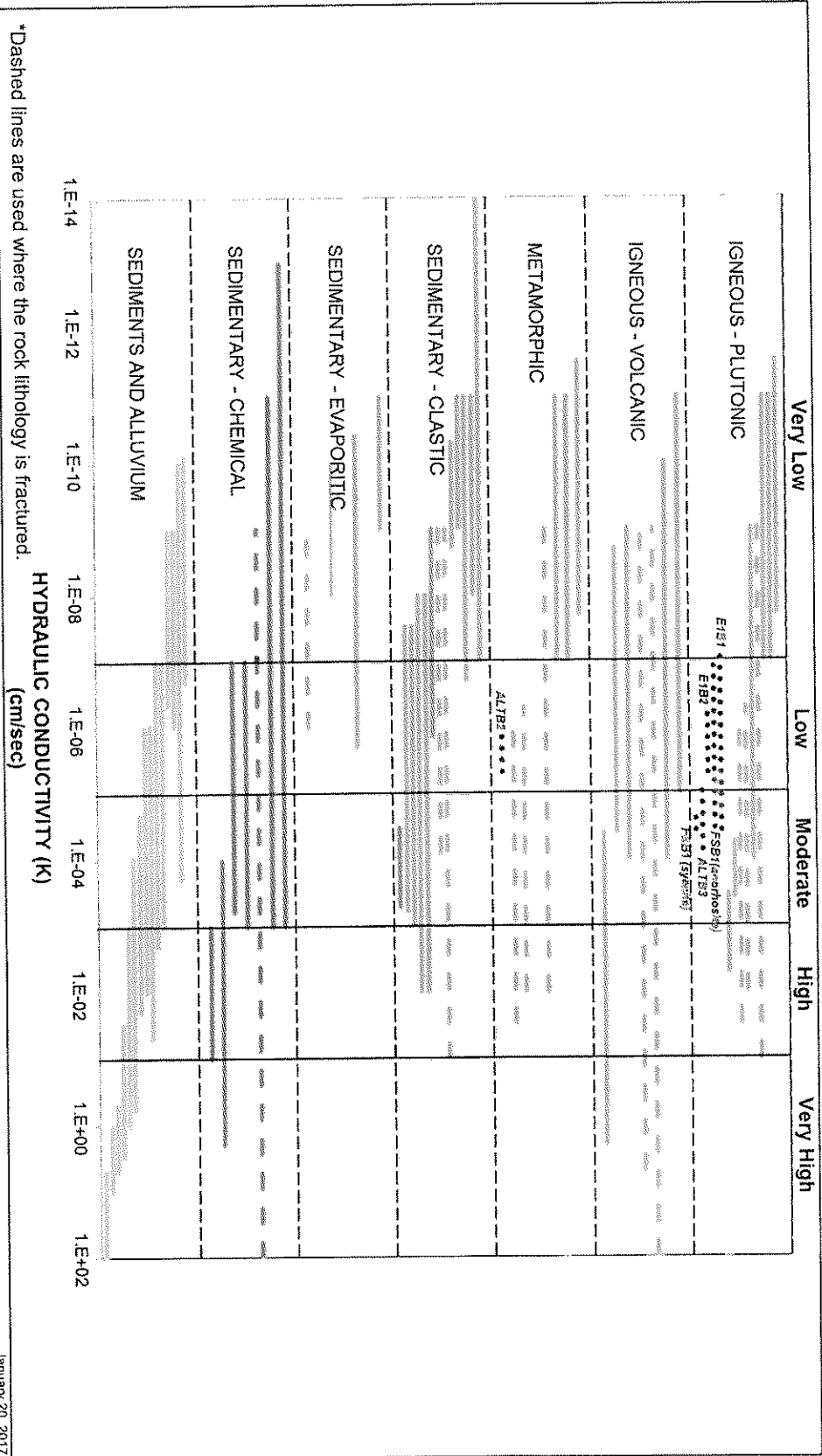
Anticipated Abrasivity (CAI)

January 23, 2017

Tunnel Alignment	Stationing	Very Low		Low		Medium		High		Extreme		Quartzitic	
		Length (feet)	%	Length (feet)	%	Length (feet)	%	Length (feet)	%	Length (feet)	%	Length (feet)	%
SR14	1330+00 1750+00	41,120	0	0	0.0	6,010	14.6	20,310	49.4	14,800	36.0	0	0.0
E1	638+80 1750+00	110,230	0	250	0.2	4,375	4.0	64,055	58.1	41,560	37.7	0	0.0
E2	638+80 1750+00	105,530	0	4,400	4.2	8,025	7.6	62,255	59.0	30,850	29.2	0	0.0

Figure 6-2
Summary of
anticipated abrasivity

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
PALMDALE TO BURBANK PROJECT SECTION



Sources:
Domenico and Schwartz, 1990;
Freeze and Cherry, 1979;
Goodman, 1988;
Ishenwood, 1978;
Jaeger and Cook, 2007, and
USBR, 1998.

Figure 6-3
Hydraulic conductivity
correlations

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
PALMDALE TO BURBANK PROJECT SECTION

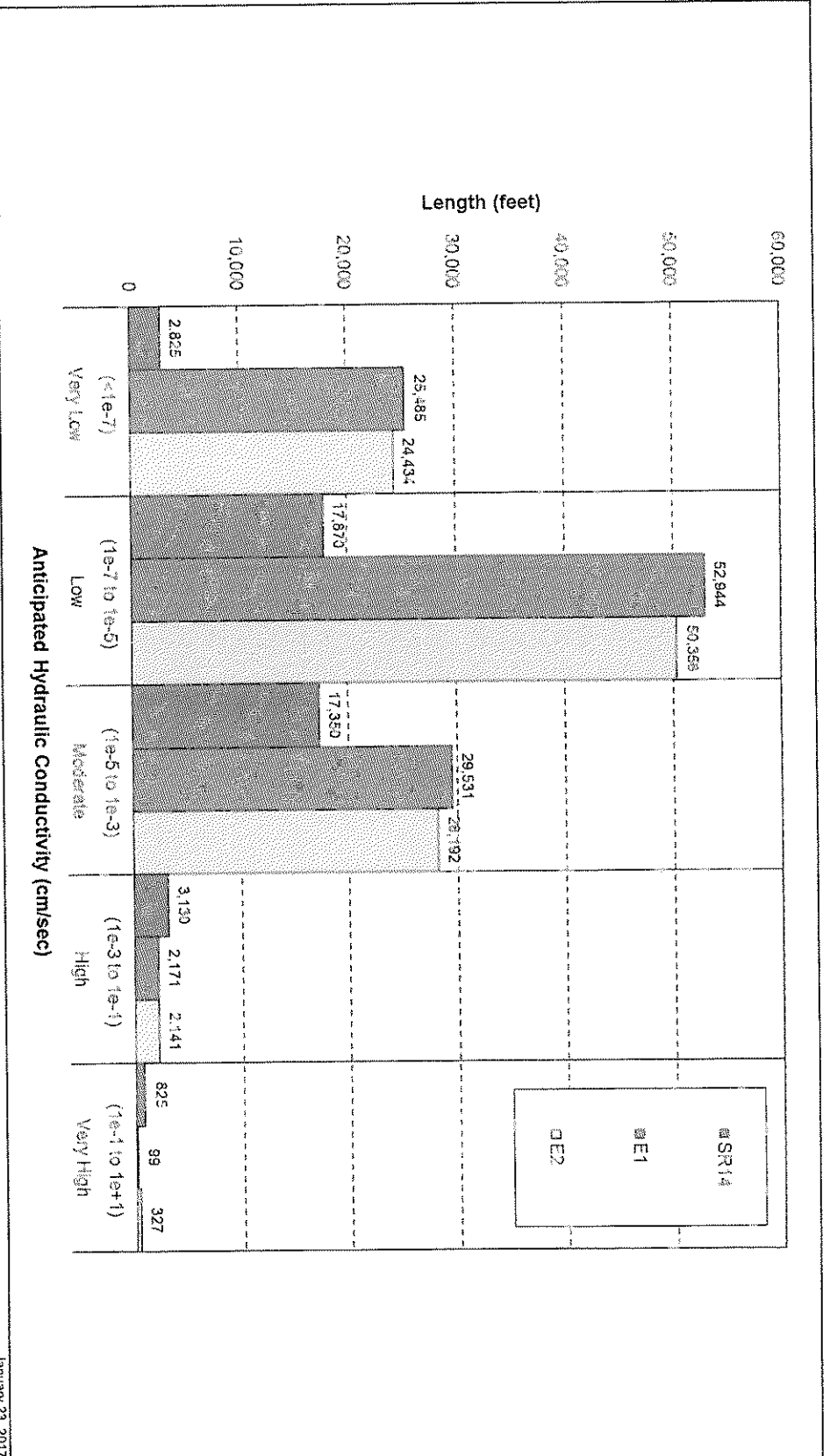


Figure 6-4
Summary of anticipated
hydraulic conductivity

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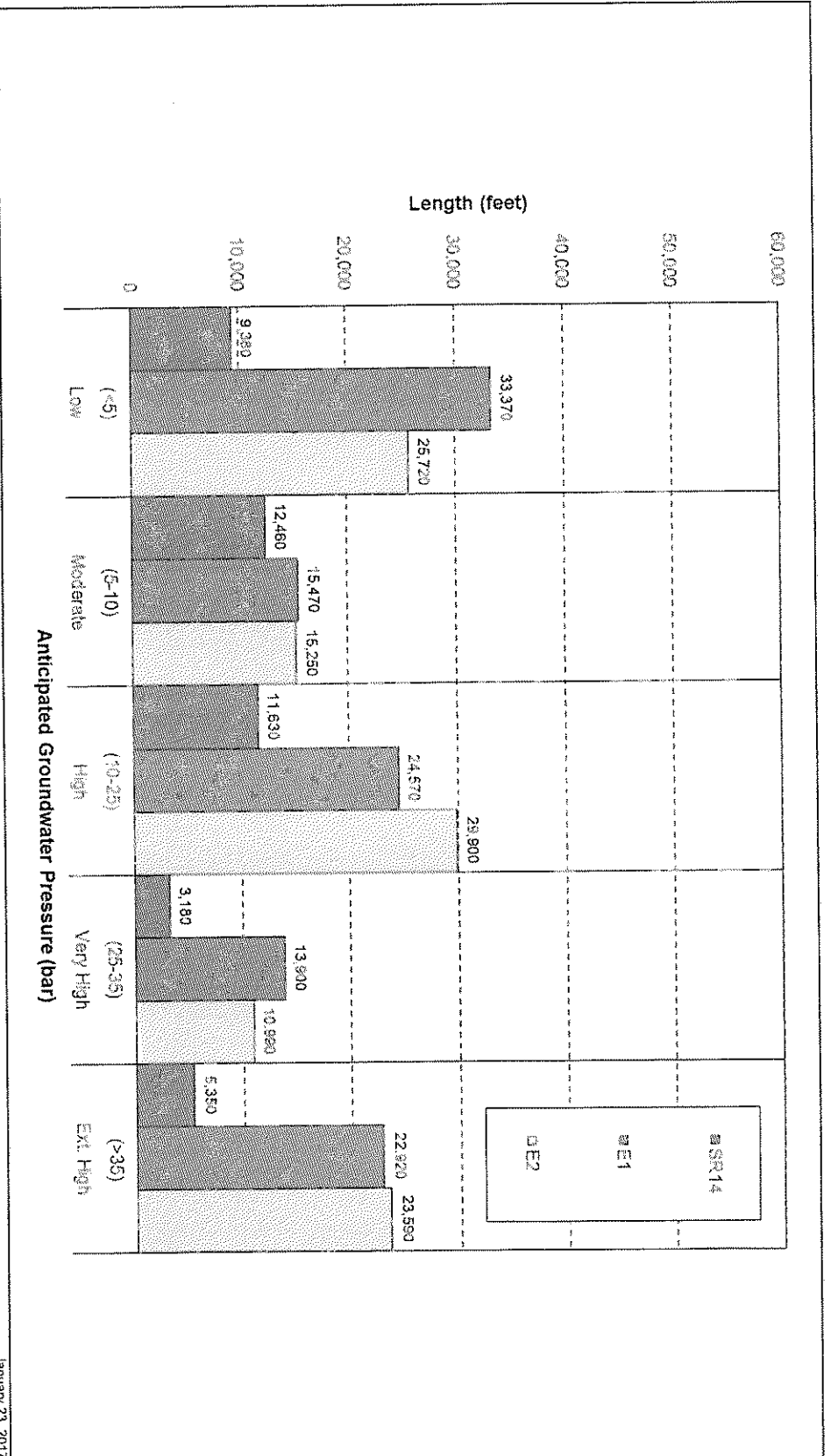


Figure 6-5
Summary of anticipated
groundwater pressure

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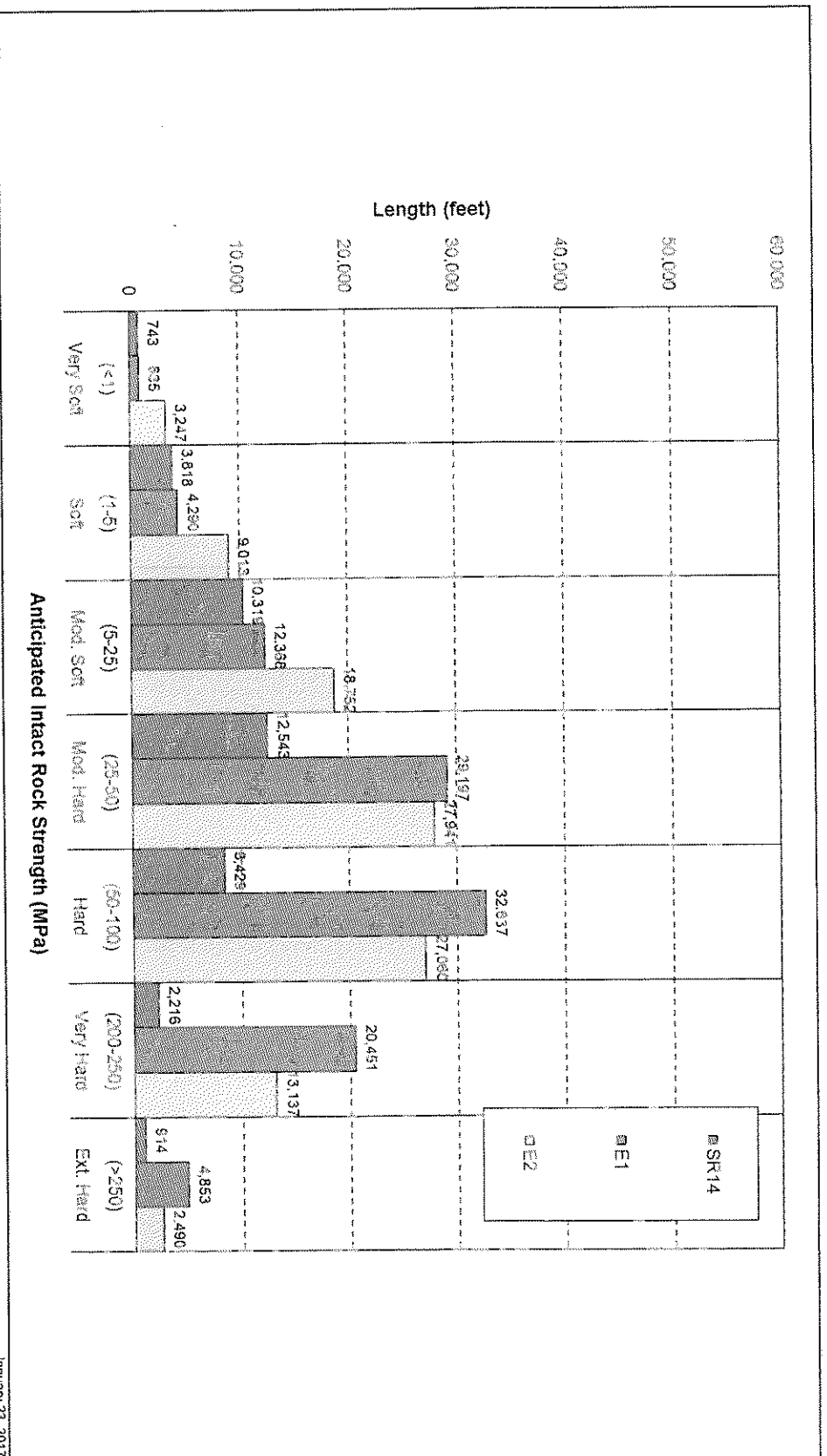


Figure 6-6
Summary of anticipated
intact rock strength

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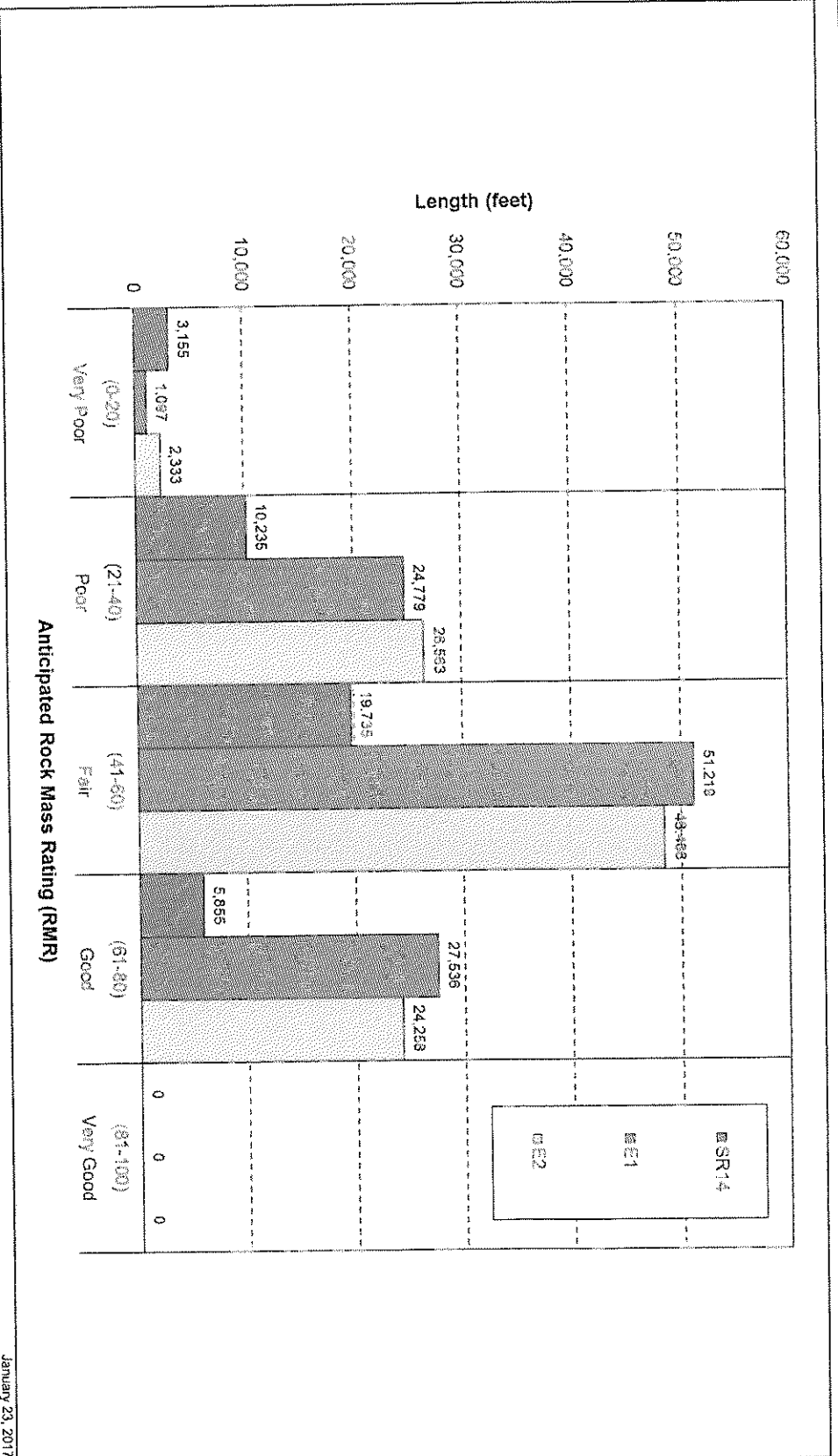
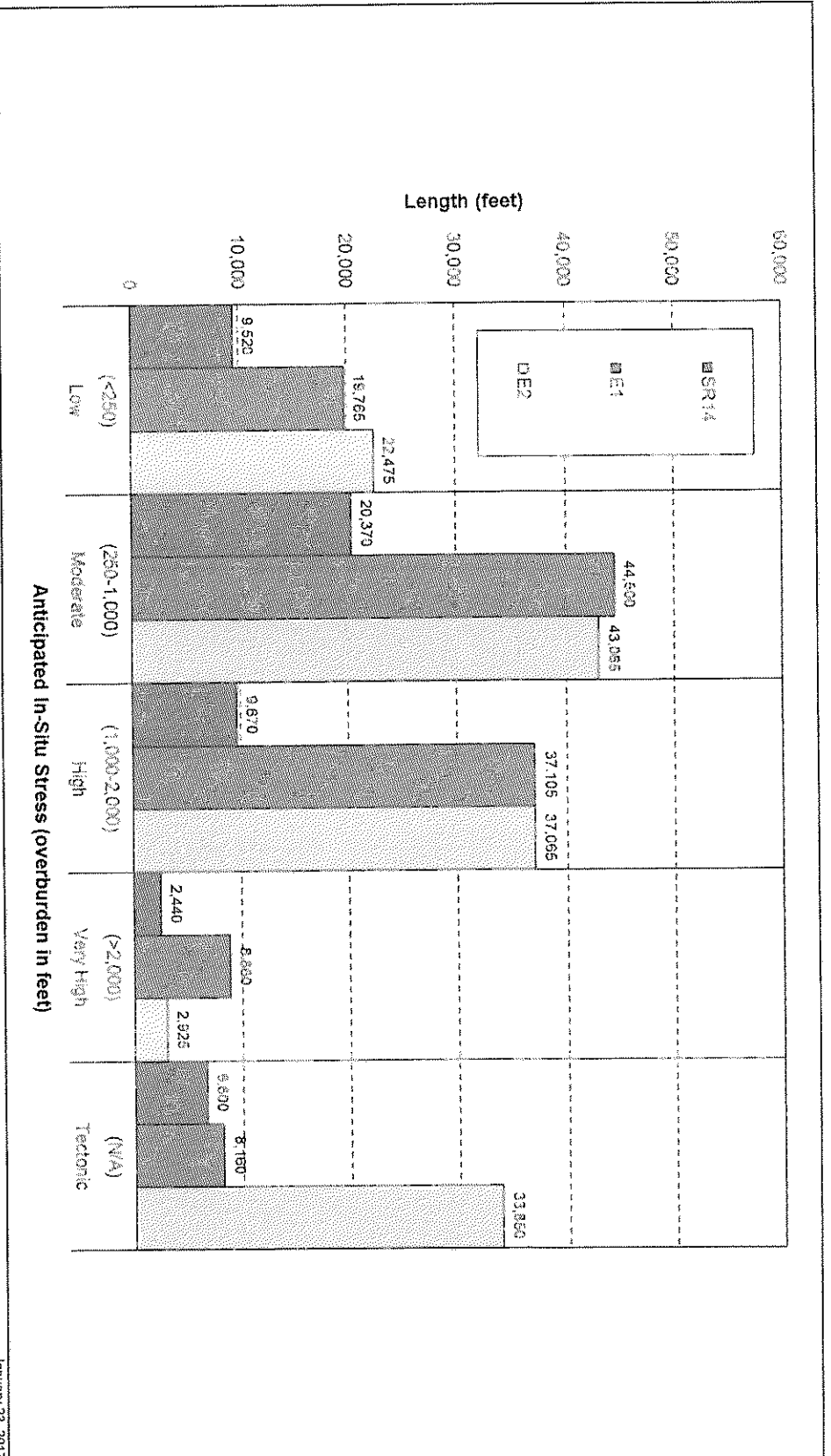


Figure 6-7
Summary of anticipated
rock mass conditions

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
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Tunnel Alignment	Stationing	Low		Moderate		High		Very High		Tectonic		
		Length feet	Length %	Length feet	Length %	Length feet	Length %	Length feet	Length %	Length feet	Length %	
SR14	1330+00 1750+00	42,000	9.520	22.7	20,370	48.5	9,670	23.0	2,440	5.8	6,600	15.7
E1	638+80 1750+00	110,230	19,765	17.9	44,500	40.4	37,105	33.7	8,860	8.0	8,160	7.4
E2	638+80 1750+00	105,530	22,475	21.3	43,065	40.8	37,065	35.1	2,925	2.8	33,850	32.1

Tectonic stress is not exclusive to a single range or magnitude of In-situ stress.

*Tectonic stress is not exclusive to a single range or magnitude of in-situ stress.

Figure 6-8
Summary of anticipated
in-situ stress

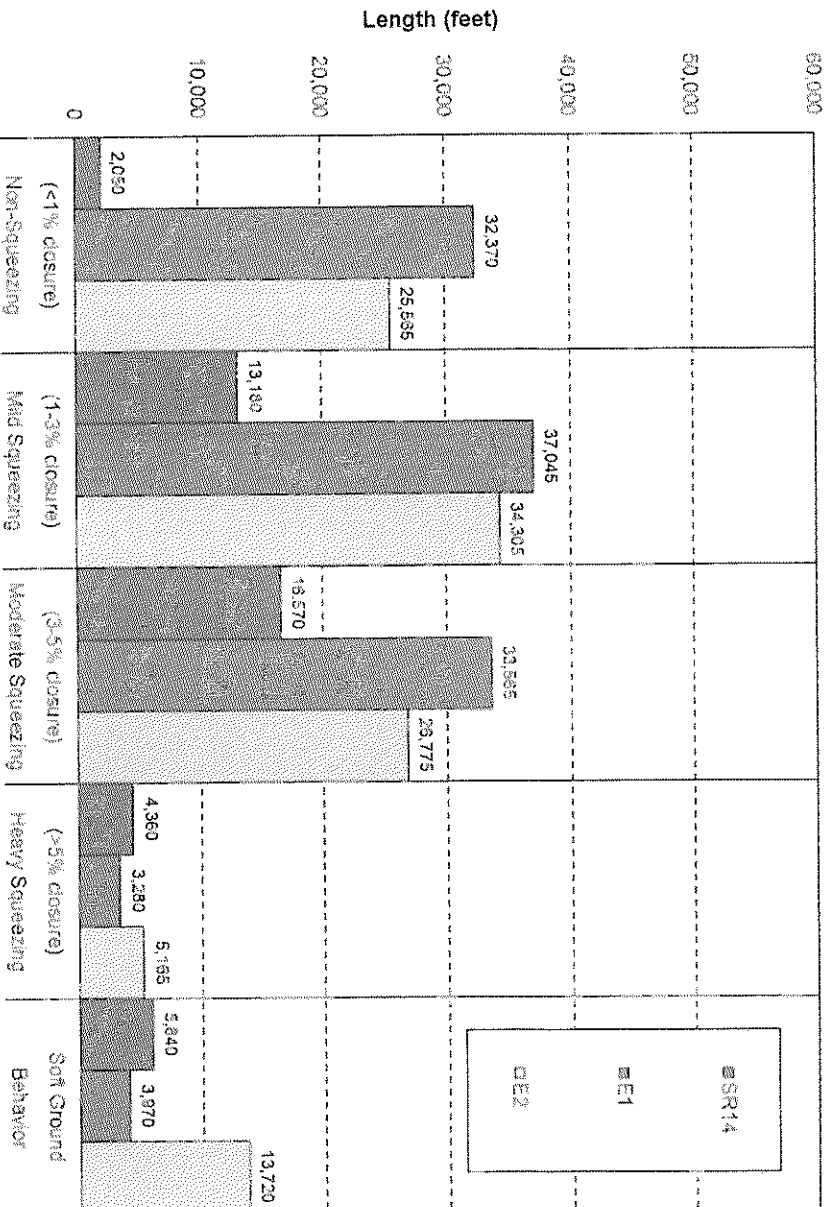


CALIFORNIA
High-Speed Rail Authority



U.S. Department
of Transportation
Federal Railroad
Administration

CALIFORNIA HIGH-SPEED RAIL AUTHORITY
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Anticipated Ground Conditions

January 23, 2017

Tunnel Alignment	Stationing	Non-Squeezing		Mild Squeezing		Moderate Squeezing		Heavy Squeezing		Soft Ground		
		Length feet	%	Length feet	%	Length feet	%	Length feet	%	Length feet	%	
SR14	1330+00 1750+00	42,000	2,050	4.9	13,180	31.4	16,570	39.5	4,360	10.4	5,840	13.9
E1	638+80 1750+00	110,230	32,370	29.4	37,045	33.6	33,565	30.4	3,280	3.0	3,970	3.6
E2	638+80 1750+00	105,530	25,565	24.2	34,305	32.5	26,775	25.4	5,165	4.9	13,720	13.0

*Soft Ground Behavior includes: Firm, Ravelling, Running, or Flowing Ground

Figure 6-9
Summary of anticipated
ground conditions