CALDECOTT IMPROVEMENT PROJECT

GEOTECHNICAL BASELINE REPORT

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1 Introduction

1.1 General

This Geotechnical Baseline Report (GBR) has been prepared for the Fourth Bore of the Caldecott Tunnel (Bore No. 4), which is part of the Caldecott Improvement Project. The Caldecott Improvement Project has been undertaken by the California State Department of Transportation (Caltrans) in association with the Contra Costa Transportation Authority (CCTA), and includes construction of Bore No. 4 and associated cross passages, a new Operations, Maintenance and Control Building (OMC), improvements on State Route 24 (SR 24) leading to the Caldecott Tunnels, new electrical sub-stations, and noise barriers. This GBR is only applicable to the mined length of Bore No. 4 and associated cross passage connections to Bore No. 3.

This GBR summarizes the geotechnical basis for the design of Bore No. 4 and seven cross passages between Bore No. 4 and Bore No. 3. Specifically this report includes: a project description; interpretations of the geological and geotechnical data obtained for Bore No. 4 and cross passages; descriptions of ground classes, which are defined by anticipated ground conditions and behaviors; descriptions of groundwater conditions; construction considerations; and summaries of relevant previous tunneling experience.

This GBR provides supplementary geological and geotechnical information used to develop ground classes, and summarizes geotechnical and construction considerations that form the basis of the project design and Contract. This information is intended to enhance the Contractor's understanding of key project elements described in the Contract Documents. In order to distinguish baselines from supplementary information, baselines are identified as such throughout this report.

1.2 Purpose and Limitations

For purpose and limitations of the GBR see section "Geotechnical Baseline Report" of the Special Provisions of the Caldecott Improvement Project Contract Documents.

1.3 Basis for Geological Descriptions

This report uses the USBR (1998) system terminology to describe rock mass characteristics for fracture and bedding density, degree of weathering, intact rock strength, hardness and discontinuity characteristics (type, shape, aperture and roughness). USBR terms for describing rock mass characteristics within this report are defined in Figure 1.1. Rock mass structure and discontinuity surface conditions are also described using terminology based on the Geological Strength Index (GSI) chart reproduced in Figure 1.2 (Marinos and Hoek, 2005).

1.4 Investigations and Reports

A summary of the field investigations and all geologic and geotechnical data collected for Bore No. 4 are presented in the GDR. The GDR and other information, as referenced herein, were relied upon during the preparation of the GBR.

2 Project Description

2.1 Project Location

Bore No. 4 is located north of the existing Caldecott Tunnel on SR 24 between SR 13 in Oakland and Gateway Boulevard in Orinda (Figure 2.1). The existing Caldecott Tunnels connect Oakland and Orinda through the Berkeley Hills. The project area is situated at the eastern margin of the San Francisco Bay Region (SFBR).

Portal No. 1 (west portal) is about 1.2 km (0.75 mi) northeast of the intersection of SR 13 and SR 24. The Portal No. 1 site is bounded by Caldecott Lane and Old Tunnel Road on the north side and by the existing Bore No. 3 exiting lanes on the south side.

Portal No. 2 (east portal) is located about 0.6 km (0.37 mi) southwest from the Fish Ranch Road exit on SR 24. The Portal No. 2 site is bounded by Fish Ranch Road on the west side and the existing Bore No. 3 approaching lanes on the east side.

2.2 Project Elements

Bore No. 4 consists of a two-lane tunnel north of the existing Bore No. 3 that will connect to SR 24 on either end. The project elements covered by this report include:

- The mined tunnel portion of Bore No. 4, which is 990.4 m (3249.2 ft) long and has a horseshoe shape with excavated dimensions of approximately 15 m (49.2 ft) in width and 11.0 to 12.3 m (36.1 to 40.3 ft) in height. Cut-and-cover portions of Bore No. 4 are not addressed in this report.
- Seven cross passages between Bore No. 4 and the existing Bore No. 3.

The alignment of Bore No. 4 and the locations of the cross passages are shown in the Plans. Bore No. 4 includes jet fans, lighting, fire protection, and operation and control systems.

The Bore No. 4 roadway clearance envelope is 5.1 m (16.7 ft) high. The travel way includes two traffic lanes that are 3.6 m (11.8 ft) wide and two shoulders that are 3 m (9.8 ft) and 0.6 m (2.0 ft) wide. A 1-m-wide (3.3-ft-wide) emergency walkway is located adjacent to the south shoulder; and a curb is provided adjacent to the north shoulder.

The horseshoe-shaped cross passages are 32.7 to 44.1 m (107 to 145 ft) long. The excavated dimensions of the cross passages will be about 4.2 m (13.8 ft) wide and 4.7 m (15.4 ft) high.

The design and construction of Bore No. 4 and cross passages is based on the philosophy of the sequential excavation method (SEM). Depending on ground conditions along the alignment, the initial support system will include shotcrete, rock dowels, lattice girders, spiles, and grouted steel pipes in various combinations as specified in the contract documents. The final lining of Bore No. 4 is cast-in-place reinforced concrete lining, and the final lining within the cross passages is reinforced shotcrete lining. A waterproofing membrane and drainage system is placed between the initial and final linings in Bore No. 4 and the cross passages.

2.3 Site Access

Construction of Bore No. 4 can be performed from both Portal No. 1 and Portal No. 2. SR 24 will provide primary access to both of these portal sites. For access to Portal No. 1, the westbound traffic on SR 24 will use the Caldecott Lane exit, located adjacent to the staging area; whereas, the eastbound traffic will use the Broadway exit. Access to Portal No. 2 from westbound SR 24 will be via Fish Ranch Road; whereas, the eastbound traffic will use the Old Tunnel Road exit.

3 Geologic Setting

3.1 Regional Geology and Seismicity

The project is located in the Oakland-Berkeley (East Bay) Hills of the San Francisco Bay Area, which is a part of the Coast Ranges geomorphic province of California. The project area topography consists of ridges and intervening valleys that trend northwest consistent with the orientation of the Hayward and Calaveras faults that bound the East Bay Hills.

The East Bay Hills are divided into several structural provinces and stratigraphic assemblages based on fault boundaries (Graymer, 2000). The Caldecott Tunnels lie within the easterly assemblage of the Hayward fault zone province which consists of a sequence of sedimentary and volcanic rocks that accumulated in the interval between about 16 and 8.4 Ma (middle and late Miocene). The basal rocks of these Tertiary deposits consist of deep marine basin sediments of the Monterey Group (represented by the Sobrante Formation and the Claremont Formation at this locale) that are about 13 to 16 million years old. These rocks are overlain unconformably by an interbedded sequence of terrestrial sediments (Orinda Formation) and volcanic rocks (Moraga Formation) that range in age from 10.5 to 8.4 million years old. The Tertiary rocks have been folded into large-amplitude, northwest-trending folds (i.e., the Siesta syncline and Glorietta anticline) that are cut by north-trending strike-slip faults.

The San Francisco Bay Region, which is crossed by four major faults (San Gregorio, San Andreas, Hayward, and Calaveras), is considered one of the more seismically active regions of the world. The active Hayward fault, which lies 1.4 km (0.9 mi) to the west of the Caldecott Tunnels, is the closest major fault to the project area. The southern segment of the Hayward fault produced the 1868 "Haywards" earthquake of estimated magnitude 6.8 that was accompanied by 30 to 35 km of surface faulting. No active[1], or potentially active, faults have been mapped within the project area.

Refer to the GDR for a more detailed discussion of the regional geology and seismicity of the project area.

[1] Based on the State of California Geological Survey definitions of an active fault as one that has documented Holocene (11,000 years to present) displacement, and a potentially active fault as one that has documented Quaternary (1.5 million years to present) displacement.

3.2 Topography and Surface Conditions

Bore No. 4 is aligned approximately perpendicular to the ridgeline of the East Bay Hills, which marks the crest of the ground surface profile along the tunnel alignment. The ridgeline trends northwest with the slopes extending downward to the northeast and the southwest. Cover above the tunnel varies from 7.3 m (24 ft) near the portals to 165 m (541 ft) at the ridge.

The northeast and southwest facing slopes rise to a ridgeline crest elevation of 425 m. The slopes in the project vicinity are typically inclined at 2- to 3-horizontal to 1-vertical (2H:1V to 3H:1V); however, the slope inclinations in a few areas vary from 1.5H:1V to 4H:1V. The southwest facing slope extends from the crest down to Portal No. 1 which is at an elevation of 235 m. The horizontal distance from Portal No. 1 to the crest is approximately 555 m (1820ft). The northeast facing slope extends from the crest down to Portal No. 2, which is at an elevation of 280 m. The horizontal distance from Portal No. 2 to the crest is approximately 470 m (1542 ft).

The roads above the alignment of Bore No. 4 include Grizzly Peak Boulevard, Bay Forest Drive, Tunnel Road, and Fish Ranch Road. Grizzly Peak Boulevard crosses the Bore No. 4 alignment near the ridgeline of the East Bay Hills. Bay Forest Drive and the Tunnel Road cross the alignment on the southwest facing slope. Fish Ranch Road crosses the alignment on the northeast facing slope.

Residences are located on the slopes above and on either side of the tunnel alignment, the closest being approximately 70 m (203 ft) above the tunnel crown. The greatest number of residences is located on Bay Forest Drive with significant numbers also located on Tunnel Road and Grizzly Peak Boulevard. The closest residences to Portal No. 1 are within a condominium complex, located approximately 130 m (427 ft) from the mined portal, and 22 m (72 ft) from the edge of the proposed construction staging area. The area of the Portal No. 2 site is sparsely populated, but there are some isolated residences west of the portal to the north and south.

Most slope surfaces are covered by grassland, scrub, and forest composed primarily of native trees and shrubs. Hazardous fire conditions occur and heavy precipitation events will generate surface runoff water carrying slope wash and debris to the portal areas.

3.3 Major Geologic Formations and Regional Structures

The geology of the alignment is characterized by northwest-striking, moderately to steeply-dipping beds of marine and non-marine sedimentary rocks of the Middle to Late Miocene age. The western end of the alignment traverses marine shale and sandstone of the Sobrante Formation (Radbruch 1969). The “middle” section of the alignment traverses chert, shale, and sandstone of the Claremont Formation. The eastern end of the alignment traverses non-marine claystone, siltstone, sandstone, and conglomerate of the Orinda Formation. The geologic profile in Figure 3.1 shows the estimated distribution of these geologic formations along the alignment.

The Middle Miocene Sobrante Formation, which is the oldest formation of the Monterey Group, is composed of marine siltstone and shale, with fine-grained sandstone, that has minor occurrences of glauconite (i.e., in these occurrences the mineral glauconite is found in relative abundance), and minor occurrences of limestone. The completion report for the Bay Area Rapid Transit (BART) tunnels (Bechtel, 1968) reported that rocks that correlate with the Sobrante Formation are complexly faulted and folded with individual beds generally highly contorted and lenticular.

The Middle Miocene Claremont Formation stratigraphically and conformably overlies the Sobrante Formation. The Claremont Formation generally consists of steeply-dipping, alternation of thin (< 10 cm [4 in]) beds of chert and siliceous shale. Continuous reaches of sandstone beds/dikes are also common. Occasionally, the formation contains clay shale, porcelanite, limestone, and dolomite beds (Page, 1950).

The non-marine Middle to Late Miocene Orinda Formation stratigraphically overlies the Claremont Formation along a slightly angular unconformity along which “some slippage has taken place” (Page 1950). The Orinda Formation consists of “poorly consolidated mudstone and sandstone, with conglomerate at intervals” (Page, 1950).

The regional geological structure of the project area (and the East Bay Hills, in general) has been characterized by previous investigators as part of the western, and overturned at some locales, limb of a broad, northwest-trending syncline (the Siesta Valley Syncline), the axis of which lies east of the project area. The overturned nature of this syncline at the project site is characterized by the relationship of the Claremont and Orinda Formations, with rocks of the younger Orinda Formation dipping southward and beneath the older, overlying rocks of the Claremont Formation; however, some of the units near the western end of the Caldecott

Tunnels (i.e., the Sobrante Formation and basal units of the Claremont Formation) do not appear to have been overturned since the bedding is predominantly dipping to the north.

Refer to the GDR for a more detailed discussion of the major geologic formations and regional structure.

3.4 Geologic Units

The three major geologic formations along the alignment identified in Section 3.3 were subdivided into seven distinct geologic units by Page (1950) during the excavation of Bores Nos. 1 and 2 as shown in Figure 3.1. The Sobrante Formation is subdivided into the First Shale (Tsf), Portal Sandstone (Tsp), and Shaly Sandstone (Tss) geologic units; the Claremont Formation is subdivided into the Preliminary Chert (Tcp), Second Sandstone (Tcs), and Claremont Chert and Shale (Tc) geologic units; and the Orinda Formation (Tor) is treated as one geologic unit that includes claystone, siltstone, sandstone, and conglomerate. Detailed descriptions of these geologic units are presented in Section 4.

3.5 Faults

Four major faults were identified along the tunnel alignment. In addition, three minor fault systems and other structural features will be encountered within the tunnel excavation. These are summarized below and discussed in detail in Section 4.

3.5.1 <u>Major Faults</u>

Four major faults were identified along the tunnel alignment. These faults are all inactive and define contacts between different geologic units as shown in Figure 3.1. The faults strike northwesterly, nearly perpendicular to the tunnel alignment. The location and orientations of the four major faults along the alignment are presented in Table 3.1. A change in lithology and/or orientation of bedding occurs on either side of the fault contacts. The rock adjacent to the fault contacts include: very intensely fractured rock zones that may also be severely weathered; slickensided shear planes; shear zones with disintegrated rock, clay gouge and breccia; inclusions of lithologically different blocks or beds from across the fault contact; and a progressive increase in fracturing as the fault contact is approached. These rock conditions associated with the major faults cannot always be clearly distinguished from the widespread disturbance caused by regional folding and faulting. However the rock conditions adjacent to the fault contacts described above will extend from 1.5 m (5 ft) to at least 26 m (85 ft) beyond the fault contact. Characteristics specific to each major fault are described in Section 4.

3.5.2 Minor Faults

Three minor fault systems are expected within the Claremont and the Orinda Formations based on observations by Page (1950) during the construction of Bores Nos. 1 and 2. The oldest of the three minor fault systems are bedding-parallel faults (Page, 1950). In the Claremont Formation these bedding-parallel faults consist of 1.3 to 15 cm (0.5 to 6 in) of plastic gray gouge that are spaced from 1.5 to 30 m apart (5 to 100 ft) (Page, 1950). These bedding-parallel faults are expected anywhere within the Claremont Formation.

In the Orinda Formation these bedding-parallel faults occur as ill-defined shear zones 30 to 150 cm (1 to 5 ft) wide (Page, 1950). These shear zones occur generally in the claystone layers where the rock “is sheared into slickensided lenticular plates” (Page, 1950). Twelve of these features were encountered in Bores No. 1 and 2 (Page, 1950). The claystone and siltstone of the Orinda Formation observed in the project borings contain shear zones where the rock exhibits pervasive, weakly healed, hairline slickensided discrete shears. The discrete shears are healed with calcite, or filled with clay, and some have polished surfaces. Where healed, the discrete shears can appear to be part of the intact rock fabric. These shear zones have been observed forming polished lenticular surfaces in the broken rock core and a pattern of short, vein-like, interconnected (anastomosing), and healed discrete shears on the exterior of the rock core. These shear zones observed in the project borings are interpreted to be the bedding-parallel faults identified by Page (1950).

The bedding-parallel faults are offset by small north- to northwest-trending thrusts which dip 35 degrees to 45 degrees to the northeast and southwest, forming a conjugate set (Page, 1950). These thrusts are then offset by nearly-vertical left-lateral faults that strike east-west, which are well developed in the Claremont Formation (Page, 1950).

3.5.3 Other Faults, Very Intensely Fractured Rock, and Shear Zones

Less prominent faults, very intensely fractured rock zones, and shear zones (in addition to the major and minor faults described above) occur within the rock along the alignment due to the tectonic setting of the project site. These structural features are unique to each rock mass type, and are discussed in Section 4.

3.6 Bedding

Bedding in the geologic units west of Fault 2 is predominantly northeast dipping whereas bedding in the units east of Fault 2 is predominantly overturned and southwest dipping. West of Fault 2, the bedding in the Sobrante Formation and in the Preliminary Chert geologic unit of the Claremont Formation dips predominantly northeast at 45 to 85 degrees. Bedding attitudes in the Shaly Sandstone unit are not systematic due to faulting and folding. In places within the First Shale, Portal Sandstone and Shaly Sandstone, bedding is overturned and dips to the southwest. At the scale of the project site, bedding orientations in the Preliminary Chert are bimodal and will generally dip to the northeast or southwest. However, bedding in the Preliminary Chert will also exhibit tight folding at the scale of the tunnel, the trend of which can be in any direction.

East of Fault 2, bedding orientations in the Second Sandstone, Claremont Chert and Shale, and Orinda Formation are overturned and predominantly dip 50 to 75 degrees to the southwest. At some locations, the Orinda Formation bedding varies from vertical to dipping steeply toward the northeast. At the scale of the project site, the overall bedding attitudes of the chert and shale beds of the Claremont Formation are generally uniform. However, these beds will be tightly folded and convoluted at the scale of the tunnel, as observed in road cuts in the area.

3.7 Joints

There is considerable scatter in joint orientation measurements. Systematic joint sets are generally poorly defined and randomly oriented joints will be encountered in all geologic units. The average orientations of joint sets are listed in Table 3.2 by geologic unit. Further details on the joint characteristics are included in Section 4.

3.8 Dikes and Sills

Intrusive sandstone dikes and sills (referred to hereafter as sandstone dikes) and both hydrothermally-altered and unaltered igneous dikes and sills (referred to hereafter as igneous dikes) occur along the tunnel alignment and contribute to the overall structural complexity and relative weakness within the rock mass.

Sandstone dikes are differentiated from sandstone beds by their irregular shapes, inclusions of parent rock, and cross cutting relationships with surrounding beds. Page (1950) indicates that the sandstone dikes can have “limitless” shapes, but tabular shaped dikes will tend to strike parallel with the surrounding bedding but dip discordantly across the bedding. A few of the dikes encountered in the existing tunnels strike northeast, parallel to the tunnel alignment. The sandstone dikes are generally well indurated, slightly weathered to fresh, and relatively strong, but the surrounding parent rock mass is often weaker due to crushing or the presence of clay minerals.

According to Page (1950) the thickness of sandstone dikes in Bore Nos. 1 and 2 ranged from “a fraction of an inch to at least 25 m (82 ft)” and “some probably exceeded 60 m (200 ft) in length[2].” Sandstone beds or dikes or a combination of both were observed 21 times in borings drilled during site investigations for this project within the Claremont Chert and Shale geologic unit. These occurrences ranged from 0.3 m to 18.9 m (1 to 62 ft) in length along the borings. One sandstone dike occurrence was observed on a surface outcrop within the Second Sandstone geologic unit. For baseline purposes, sandstone dikes will occur in the Shaly Sandstone, Preliminary Chert, Second Sandstone, and Claremont Chert and Shale, and a maximum of 50 sandstone dikes between 0.3 m and 26 m (1 ft to 85 ft) in thickness should be anticipated within these geologic units.

Based on observations in Boring N5 and from experience in the existing Caldecott Tunnels, igneous dikes will exhibit strengths ranging from soft clay to friable to strong rock. The igneous dikes rock will be severely weathered to fresh and very intensely to slightly fractured. Page (1950) observed that the irregular shapes of the igneous dikes result in a wide range of orientations, “but statistically the prevailing strike is east-west, and the ‘preferred’ dip is very steeply southward.” The igneous dikes are commonly emplaced along pre-existing faults and intensely fractured zones.

The construction records from Bore Nos. 1 and 2 indicate that the largest igneous dike was 6.4 m (21 ft) wide and 123 m (405 ft) long[3], although most dikes were only 0.3 to 3 m (1 to 10 ft) wide. Igneous dikes were encountered in the Second Sandstone and in the Orinda

[2] This observation is understood to mean the dike was encountered along 60 m (200 ft) of the tunnel.
[3] Per Page (1950). This observation is understood to mean the dike was encountered along 123 m (405 ft) of the tunnel.

Formation in Bore Nos. 1 and 2 (Page, 1950). Radbruch (1964) reported that igneous dikes in Bore No. 3 were less common and smaller than those observed in Bore Nos. 1 and 2. Igneous dikes have also been mapped in the Orinda Formation highway cuts near Portal No. 2. Igneous dikes have been encountered in the Claremont Formation, as well as in the First Shale and the Shaly Sandstone geologic units in borings and test pits used for site investigation along the project alignment. Very few severely-altered igneous dikes were positively identified in the test borings along the Bore No. 4 alignment, but several soft clayey zones were encountered.

The igneous dikes will occur in all of the geologic units along the alignment, but tunneling experience in the existing Caldecott tunnels indicates that the dikes will be encountered most frequently in the Claremont Chert and Shale. For baseline purposes, up to 15 igneous dikes exceeding 0.3 m (1 ft) in width should be anticipated along the tunnel alignment.

3.9 In Situ Stress

The major principal stress acts vertically and its magnitude is proportional to the depth below ground surface and the unit weight of the overlying rock mass. The ratio of average horizontal in situ stress in any direction to vertical stress (K_o) is expected to vary from 0.4 to 1.0 along the alignment.

3.10 Contaminated Geologic Materials

3.10.1 Toxic and Combustible Gas

Occurrences of methane, carbon dioxide and hydrogen sulfide gases were encountered within the Claremont and Orinda Formations during construction of the Claremont Tunnel, Berkeley Hills BART Tunnel, and the existing Caldecott Tunnels located near the Bore No. 4 alignment. These occurrences included: measurements of trace levels of gas concentration in Bore No.3; an occurrence of a gas flare during welding in the Claremont Formation during construction of Bore No. 3; traces of methane, carbon dioxide and hydrogen sulfide and one dangerous occurrence of methane in Bores No. 1 and 2 (Page, 1950); and two fires in the Orinda Formation reach of the Claremont Tunnel, one of which lasted for 30 days due to the "oil-soaked rock" conditions according to Young (1929). The occurrence of volatile organic compounds, combustible gases (methane with oxygen), and toxic gases (hydrogen sulfide and carbon monoxide) in the Claremont and Orinda Formations is also confirmed by field tests of core samples using a photoionization detector (PID) and a combustible gas indicator (CGI).

Based on the above information, it is assumed that toxic and flammable gasses will occur along the Bore No. 4 alignment. Bore No. 4 has been classified as “Gassy with Special Conditions” by Cal/OSHA.

3.10.2 Liquid Hydrocarbons

The Claremont Formation is one of the major petroleum sources in California. Test borings N4 and N5 along the Bore No. 4 alignment show occurrences of hydrocarbons. The petroleum hydrocarbons found in core samples are naturally occurring.

Limited testing of the core material for total petroleum hydrocarbons quantified as diesel (TPHd) and total petroleum hydrocarbons quantified as motor oil (TPHmo) showed that TPHd was detected in all (12) samples at concentrations ranging from 1.3 to 1000 mg/kg, while TPHmo was detected in 7 of 12 samples at concentrations ranging from 50 to 2600 mg/kg. The highest concentrations of hydrocarbons were found in two samples collected from the Claremont Chert and Shale where petroleum was also visible. The samples were not tested in the laboratory for volatile organic compounds (VOCs); however boring logs from borings N4 and N5 include a description of hydrocarbon odors encountered during drilling.

During the construction of the Claremont Tunnel, the Berkeley Hills BART Tunnel, and the existing Caldecott Tunnels, oil seepage and asphaltic deposits were encountered within the Portal Sandstone and Second Sandstone geologic units as well as in the Claremont and Orinda Formations. Page (1950) reported that asphalt, hydrocarbons and lignite (coal) were encountered at locations in the Orinda Formation in the first and second bores. Radbruch (1964) noted “bituminous material” near the Orinda Formation contact with the Claremont Formation in Bore No. 3. For baseline purposes, liquid hydrocarbon seepage through fractures, shear zones and faults, and deposits, will be encountered in any of the geologic units along the Bore No. 4 alignment. Section 6.1 presents additional information related to disposal of excavated material containing naturally occurring hydrocarbons.

3.10.3 Heavy Metals

Testing of heavy metals was performed on core samples and the results were compared to total threshold limit concentrations (TTLC), soluble threshold limit concentrations (STLC) and toxicity characteristic leaching procedure (TCLP). Concentrations of metals did not exceed the TTLC, 10 times the STLC or 20 times the TCLP for any of the samples analyzed.

3.11 Seismic Hazards

As described in Section 3.1, the Bore No. 4 alignment is located near several active faults that could cause strong ground shaking in the project area. The magnitude of ground shaking will vary with the seismic event return period.

The initial support of Bore No. 4 has been designed for block loading corresponding to a Construction Evaluation Earthquake (CEE) with a return period of 100 years. The permanent facilities for the project are designed to meet criteria for both a Functional Evaluation Earthquake (FEE), which has a mean return period of 300 years and a Safety Evaluation Earthquake (SEE), which has a mean return period of 1500 years. Peak ground accelerations at the ground surface associated with the CEE, FEE and SEE events are 0.42g, 0.72g and 1.2g respectively.

4 Ground Characterization

This section describes characteristics of rock masses with similar lithology and rock mass properties identified during the design phase, which are called Rock Mass Types (RMTs). This information constitutes one criterion for selection of support categories during construction. During design, RMT characteristics, along with in situ conditions such as stress level, were used to evaluate RMT rock mass behaviors, which is the basis of classification of RMTs into ground classes and support categories as described later in Sections 5. This section also summarizes the expected hydrogeologic conditions along the alignment.

4.1 Geologic Units and Rock Mass Types

The seven geologic units described in Section 3 that occur along the alignment were further divided into 18 RMTs during the design phase. The sections that follow describe the range of rock mass characteristics within each geologic unit and its associated RMTs. These descriptions are to be used as part of the support selection process during construction.

Overall RMT rock mass descriptions are provided using the GSI system terminology (Figure 1.2). These GSI descriptions correspond to a rock mass volume (related to the tunnel span) that controls overall rock mass behaviors at the scale of the tunnel. Variability of rock mass conditions within the overall RMT GSI descriptions are provided using the USBR system terminology (Figure 1.1). It is noted that descriptions of strength, hardness and weathering applied to the intact rock for each RMT are stated as such.

The rock mass conditions associated with major faults, minor faults, or other faults, very intensely fractured rock zones, or shear zones discussed in Section 3.5 that will be encountered along the tunnel alignment were considered in the development of the RMTs. The ground conditions around the major faults are described in separate sections below to enhance the Contractor's understanding of these features. Because the major faults are contacts between different geologic units having distinct lithologies, there are separate RMTs for each side of the contact, and therefore, there are two RMTs associated with each major fault. These RMTs include the ground conditions which exist immediately adjacent to the fault contact. It is also noted that igneous dikes, described in Section 3.8, may occur in any RMT and sandstone dikes occur in specific geologic units defined in Section 3.8.

Each RMT has distinct geological or geotechnical characteristics. The profile in Figure 4.1 shows the estimated extent of the geologic units and component predominant RMTs along the alignment but the actual limits and distribution of the geologic units and predominant RMTs along the tunnel will vary from what is estimated in Figure 4.1. The actual limits of the predominant RMTs are to be determined during construction as a part of the support selection process.

Some RMT characteristics and properties are summarized in Table 4.1 to enhance the Contractor's understanding of RMTs and to define properties used in design evaluations of support requirements. The rock mass strength parameters for each RMT presented in Table 4.1 are based on the Hoek-Brown criterion (2002). Young's modulus of elasticity values for the intact rock are based on laboratory tests. Rock mass deformation modulus estimates are based on empirical methods (Hoek and Diederichs, 2006), analytical models (Rafael and Goodman, 1979), measurements of intact rock modulus, and field test results from bore jacking tests, pressuremeter tests and seismic surveys.

The following sections describe the geologic units, associated RMTs and major faults in sequence along the alignment from west to east. Table 3.2 summarizes bedding and joint orientations.

4.1.1 Sobrante Formation

4.1.1.1 *First Shale (Tsf)*

The First Shale is a gray to brown to black silty to clayey shale with occurrences of sandstone, siltstone, claystone, argillite, limestone, and igneous dikes.

Bedding in the First Shale is predominantly northwest striking and moderately to steeply dipping to the east-northeast. Steep southwest and shallow east dips are also found at outcrops near Portal No. 1. The southwest and east dips indicate bedding is folded, overturned, and/or faulted. The shale has planar bedding laminations 2 to 6 mm (0.1 to 0.25 in) thick. Joint attitudes in the First Shale are random except for two joint sets: a bedding parallel set and a closely spaced impersistent joint set that corresponds to a moderately-steep north dipping foliation. Joints that are continuous through the very intensely fractured rock zones in the First Shale are open (≤3 mm [0.1 in]) to tight, planar to irregular to wavy, and polished to slightly rough, some are coated with thin (< 2 mm

[0.08 in]) clay films and others are filled with clay. Table 3.2 summarizes bedding and joint orientations.

Systematic discrete faults and discrete shears in the First Shale tend to dip moderately to steeply to the east-northeast and are often parallel or sub-parallel to bedding. Discrete shears are open to tight, planar, and polished to smooth. Discrete shear fractures within approximately 1 to 2 m (3.3 to 6.6 ft) of the Fault 1 contact are slickensided.

The First Shale geologic unit comprises a single RMT (Figure 4.1) and has the following rock mass characteristics:

- Disintegrated to blocky/disturbed/seamy structure with very poor to fair discontinuity surface conditions using the GSI terminology.
- This RMT typically consists of very intensely fractured rock zones 1.5 m to 15 m (0.5 to 50 ft) wide. The rock fragments in some zones of very intensely fractured rock are bound by a clayey silt (ML) matrix. These zones of very intensely fractured rock bound by a clayey silt matrix occur primarily as small irregular pockets, but may also occur as planar features, 0.5 cm to 2.5 m (0.25 in to 8 ft) wide. Less than 25% of this RMT by volume is intensely to moderately fractured.
- Friable to strong intact rock strength.
- Soft to moderately hard intact rock.
- Severely weathered to fresh intact rock.

Ground conditions in the First Shale associated with Fault 1 are consistent with conditions to be encountered further to the west of this contact at the scale of the tunnel width, and are thus included in the Tsf RMT.

4.1.1.2 ***Fault 1***

Fault 1 is an abrupt fault contact between the First Shale and the Portal Sandstone geologic units (Figure 4.1). A 1 m (3 ft) wide zone of very intensely fractured, severely weathered rock that is sub-parallel to bedding, and discrete shears that are slickensided occur in the First Shale adjacent to the fault contact. Discrete shears that are slickensided and/or coated with clay and very intensely fractured blocks or beds of shale also occur within the Portal Sandstone adjacent to the fault contact. These ground conditions associated with Fault 1 are included in the Tsf RMT described above and the Tsp RMT described below.

4.1.1.3 *Portal Sandstone (Tsp)*

The Portal Sandstone consists of gray and light blue-gray fine- to medium-grained sandstone and silty fine sandstone, and becomes increasingly silty and shaly to the east.

Bedding in the Portal Sandstone is generally massive or indistinct and generally steeply dipping to the northeast and with minor occurrences of overturned (i.e., southwest-dipping) bedding. Some isolated blocks or beds of shale have been incorporated into the Portal Sandstone near Fault 1. Three joint sets were identified in the Portal Sandstone: shallow dipping to the west-northwest, moderately steeply dipping to the north-northeast and steeply dipping to the west, although randomly oriented fractures are also common. Joints in the Portal Sandstone are predominantly slightly weathered, open to tight, planar, and smooth to moderately rough. Joints are predominantly clean or have calcite infillings or oxide coatings. Minor sandy infillings and clay infilled joints also occur in the Portal Sandstone, with clay infilled joints being the least common type. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Portal Sandstone are filled to tight, planar, polished to slightly rough, and less than 40% are filled with clay or clay gouge gouge up to 50 mm (2 in) thick. Discrete shears near the Fault 1 contact are slickensided and/or coated with clay.

The Portal Sandstone geologic unit comprises a single RMT (Figure 4.1) and has the following rock mass characteristics:

- Blocky/disturbed/seamy rock mass structure and poor to fair discontinuity surface conditions.
- Intensely to moderately fractured typically. Less than 10% of this RMT by volume consists of very intensely fractured rock zones 0.15 to 2.1 m (0.5 to 7 ft) wide.
- Weak to very strong intact rock strength.
- Moderately hard intact rock.
- Slightly weathered to fresh intact rock.

Ground conditions in the Portal Sandstone associated with Fault 1 are consistent with conditions to be encountered further to the east of this contact at the scale of the tunnel width, and are thus included in the Tsp RMT.

4.1.1.4 *Shaly Sandstone (Tss)*

The Shaly Sandstone consists of silty fine sandstone and shale that varies in color from gray to brown. The contact between the Shaly Sandstone and Portal Sandstone is gradational and as such, the Shaly Sandstone also contains interbeds of the light blue-gray sandstone that comprises the Portal Sandstone. In some cases, the contact between the gray silty fine sandstone and the light blue-gray sandstone is sheared. The silty-sandstone has minor occurrences of interbedded shale. A shale bed approximately 4 m (13 ft) thick occurs near the contact with the Preliminary Chert. There are minor occurrences of limestone.

The bedding orientation in the Shaly Sandstone is scattered, but generally dips steeply to the east-northeast, with some beds dipping steeply to the southwest. Joint orientations in the Shaly Sandstone are scattered, with randomly oriented joints occurring in nearly all orientations. However, three relatively well defined joint sets were identified: shallow dipping to the west-northwest, moderately steeply dipping to the north-northeast and steeply dipping to the west. Joints within the Shaly Sandstone geologic unit predominantly have planar joint surfaces that are slightly weathered and smooth to slightly rough. Infilled joints are predominantly sandy with a minor clay fraction. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Shaly Sandstone are filled to tight, planar to irregular, smooth to moderately rough, and less than 50% are filled with clay or calcite.

Two distinct Rock Mass Types are anticipated in the Shaly Sandstone geologic unit: Tss-1 and Tss-2 (Figure 4.1).

The Tss-1 RMT has the following rock mass characteristics:

- Blocky/disturbed/seamy to very blocky rock mass structure and poor to fair discontinuity surface conditions using the GSI terminology.
- Intensely to slightly fractured typically. Less than 20% of this RMT by volume consists of very intensely fractured rock zones 0.3 to 5 m (1 to 18 ft) wide with fractures typically healed with calcite. These very intensely fractured rock zones also contain fractures that are not tight or healed. Less than 10% of the very intensely fractured rock zones are less than 1 m (3.3 ft) wide and bound by a clay matrix.
- Weak to very strong intact rock strength.
- Moderately hard to hard intact rock.
- Slightly weathered to fresh intact rock.

The Tss-2 RMT has the following rock mass characteristics:

- Disintegrated rock mass structure and poor to fair discontinuity surface conditions using the GSI terminology.
- Intensely to moderately fractured typically. Up to 40% of this RMT by volume consists of very intensely fractured rock zones 1 to 5 m (3.3 to 18 ft) wide with fractures typically healed with calcite. These very intensely fractured rock zones also contain fractures that are not tight or healed. Less than 10% of the very intensely fractured rock zone are bound by a clayey matrix and are up to 2 m (6.5 ft) wide, but generally they are less than 0.6 m (2 ft) wide.
- Weak to very strong intact rock strength.
- Low hardness to hard intact rock.
- Slightly weathered to fresh intact rock.

4.1.2 Claremont Formation

4.1.2.1 *Preliminary Chert (Tcp)*

The Preliminary Chert consists of shale, siliceous shale (cherty shale), laminated siltstone and chert that vary in color from gray to brown. This geologic unit also contains a few beds or dikes of sandstone. Bedding thickness ranges from a few millimeters to several centimeters and is fissile in the shale and chert.

Bedding in the Preliminary Chert has a bimodal distribution, with beds dipping moderately to steeply to the northeast and steeply to the southwest. Joint orientations in the Preliminary Chert are scattered, but two moderately well-defined joint sets occur: one dips steeply to the south, and the other dips moderately to the southeast. Joints observed in outcrop and in near surface core recoveries of the Preliminary Chert are predominantly moderately weathered, planar and smooth to slightly rough with minor occurrences of clay infillings. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Preliminary Chert are filled, planar to wavy, rough, and less than 25% are brecciated.

The Preliminary Chert geologic unit comprises a single Rock Mass Type (Figure 4.1), and has the following rock mass characteristics:

- Disintegrated to blocky/disturbed/seamy and poor to fair discontinuity surface conditions using the GSI terminology.

- This RMT typically consists of very intensely fractured rock zones 0.15 to 1 m (0.5 to 3.3 ft) wide except for a 9 to 15 m (30 to 50 ft) wide zone adjacent to Fault 2. Up to 50% of these very intensely fractured rock zones have weak intact rock strength, soft intact rock hardness, and are severely weathered. Less than 40% of this RMT by volume is intensely to moderately fractured.
- Moderately strong to strong intact rock strength.
- Low hardness to hard intact rock.
- Slightly weathered to fresh intact rock.

Ground conditions in the Preliminary Chert associated with Fault 2 are consistent with conditions to be encountered further to the west of this contact at the scale of the tunnel width, and are thus included in the Tcp RMT.

4.1.2.2 *Fault 2*

Fault 2 is an abrupt fault contact between the Preliminary Chert and the Second Sandstone geologic units (Figure 4.1) and also marks a change in the overall geologic structure of the alignment, as it separates predominantly northeast-dipping strata on the west from predominantly southwest-dipping strata on the east.

Both the Preliminary Chert and Second Sandstone are more intensely fractured near the fault contact. The rock is continuously very intensely fractured over a zone of 9 to 15 m (30 to 50 ft) within the Preliminary Chert geologic unit adjacent to the fault contact. Moderately to intensely fractured sandstone interbedded with intensely to very intensely fractured chert and shale occurs over a zone approximately 16 m (53 ft) wide within the Second Sandstone geologic unit adjacent to the fault contact. The very intensely fractured interbeds of chert and shale in the Second Sandstone geologic unit are up to 4.25 m (14 ft) thick, disintegrated, sheared and contain lean clay gouge. The ground conditions associated with Fault 2 are included in the Tcp RMT described above and the Tcs-3 RMT described below.

4.1.2.3 *Second Sandstone (Tcs)*

The Second Sandstone consists of fine to medium grained sandstone and silty sandstone with minor occurrences of interbeds of shale and siliceous shale that varies in color from gray to brown to orange. Angular, elongate shale inclusions occur in this unit, as do sandstone dikes.

The appearance of the Second Sandstone intact rock is similar to that of the Portal Sandstone, but its average strength is lower.

The bedding planes of the sandstone in the Second Sandstone are indistinct to faintly defined. There is considerable scatter in the bedding orientations; however, bedding in the Second Sandstone is predominantly dipping moderately to the southwest. Joint orientations in the Second Sandstone are scattered, with two weakly to moderately-well defined joint sets that both dip steeply to the northwest. The joints are predominantly slightly weathered, planar to wavy, and smooth to slightly rough. Less than 30% of the joints are either infilled with sand, or have surface staining. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Second Sandstone are filled, planar to wavy, and polished to rough.

Three Rock Mass Types are anticipated within the Second Sandstone geologic unit along the alignment: Tcs-1, Tcs-2 and Tcs-3 (Figure 4.1).

The Tcs-1 RMT has the following rock mass characteristics:

- 90% or more of this RMT by volume has a blocky rock mass structure with fair to good discontinuity surface conditions using the GSI terminology. Other characteristics of this blocky rock mass are:
  - Moderately to slightly fractured typically.
  - Weak to strong intact rock strength.
  - Soft to moderately hard intact rock.
  - Slightly weathered to fresh intact rock.
- Less than 10% of this RMT by volume has a blocky/disturbed/seamy rock mass structure with poor to fair discontinuity surface conditions, using the GSI terminology, affecting tunnel scale reaches greater than 15 m (50 ft) wide. Less than 10% of the block/disturbed/seamy rock mass is very intensely to intensely fractured rock that occurs in zones 0.3 to 1 m (1 to 3.3 ft) wide. The rock within these zones has the same intact rock properties described above for the blocky Tcs-1 RMT rock mass. Very intensely fractured rock occurs in shear zones less than 0.5 m (1.5 ft) wide, with discrete shears that are filled with gouge, breccia or sand, planar to irregular, and polished to rough.

The Tcs-2 RMT includes ground conditions in the Second Sandstone associated with Fault 3 and has the following rock mass characteristics:

- Blocky/disturbed/seamy to very blocky rock mass structure with poor to fair discontinuity surface conditions using the GSI terminology.
- Intensely to slightly fractured typically. Less than 10% of this RMT by volume consists of very intensely fractured rock zones 0.3 to 1m (1 to 3.3 ft) wide. A 1 m (3.3 ft) wide zone of very intensely fractured rock occurs adjacent to the Fault 3 contact.
- Weak to moderately strong intact rock strength.
- Soft to moderately hard intact rock.
- Slightly weathered to fresh intact rock.

The Tcs-3 RMT differs from Tcs-1 and Tcs-2 because the sandstone includes beds of chert and shale. This RMT includes ground conditions in the Second Sandstone associated with Fault 2 and has the following rock mass characteristics:

- Disintegrated to blocky/disturbed/seamy rock mass structure with poor to fair discontinuity surface conditions using the GSI terminology.
- Intensely to moderately fractured typically. Less than 20% of this RMT by volume consists of very intensely fractured chert and shale beds 1.5 to 4.25 m (5 to 14 ft) wide. Some of the very intensely fractured rock zones of shale are bound in a clay matrix. Up to 70% of these very intensely fractured rock occurs in shear zones 1.5 m to 2 m (1.5 ft to 3.3 ft) wide, with discrete shears that are filled, planar to irregular, and polished to smooth.
- Friable to moderately strong intact rock strength.
- Low hardness to hard intact rock.
- Slightly weathered to fresh intact rock typically. Severely weathered to fresh intact rock near fault 2.

Ground conditions in the Second Sandstone associated with Faults 2 and 3 are consistent with conditions in the Tcs-3 and Tcs-2 RMTs respectively at the scale of the tunnel width, and are thus included in these RMTs.

4.1.2.4 *Fault 3*

Fault 3 is an abrupt fault contact between the Second Sandstone and the Claremont Chert and Shale geologic units (Figure 4.1). A 1 m (3 ft) wide zone of very intensely fractured rock occurs in the Second Sandstone adjacent to the fault contact and approximately 8 m (27 ft) of continuously and very intensely fractured chert, shale and sandstone, with up to 1 m (3 ft) of clay gouge and breccia occurs in the Claremont Chert and Shale adjacent to the fault contact.

The Fault 3 contact is within the western part of a 183 m wide (600 ft wide) disturbed zone observed in Bores No. 1 and No. 2, described as being highly fractured with contorted bedding that is cut by irregularly shaped sandstone and altered igneous dikes (Page, 1950). Approximately 122 m (400 ft) of this zone was observed in Boring N-4 for Bore No. 4. In Boring N-4, the Second Sandstone becomes progressively more fractured close to the fault contact, and contains very intensely fractured rock zones up to 1 m (3.3 ft) wide. These conditions are included in the Tcs-2 RMT described above.

In the Claremont Chert and Shale an approximately 18 m wide (60 ft wide) moderately to intensely fractured sandstone bed or dike occurs east of the 8 m (27 ft) wide very intensely fractured rock zone adjacent to the fault contact. To the east of this sandstone bed or dike is moderately to intensely fractured siliceous shale, followed by more moderately to intensely fractured sandstone beds and/or dikes, and intensely to very intensely fractured siliceous shale, chert and shale, and sandstone. These ground conditions in the Claremont Chert and Shale are included in RMTs Tc-4a, Tc-4b and Tc-5a described below.

4.1.2.5 *Claremont Chert and Shale (Tc)*

Chert, siliceous shale (cherty shale), shale, and siltstone that vary in color from dusky red to gray, and brown are the predominant rock types in the Claremont Chert and Shale. The unit includes sandstone beds and probable sandstone dikes near the Fault 3 contact, limestone, dolomite, and igneous dikes which are frequently altered, weakened and softened.

The lithology proportions vary along the alignment within this unit. Except for the eastern 50 m (165 ft) of the Claremont Chert and Shale near Fault 4, the unit is composed of thin, sharply defined layers of cherty material alternating with shale. The thickness of the cherty beds ranges from less than 25 mm to 15 cm (1 to 6 in), but on average are 25 to 50 mm (1 to 2 in) thick. The interbeds of less siliceous shale tend to be thinner than the cherty beds and are estimated to average about 12 mm (0.5 in) thick. In contrast, the rocks within the eastern 50 m (165 ft) of the unit are predominantly dark brown, dark gray and black shale/claystone and siltstone, and are thinly bedded with local interbeds of cherty shale and sandstone. Page (1950) also reported the presence of lenticular beds and “stubby lenses” of dolomite up to about 30 cm (12 in) thick, with carbonate-filled fractures.

Bedding within the Claremont Chert and Shale generally dips steeply to the southwest, but will vary due to tightly folded beds that can be contorted. There is a bimodal distribution of bedding, as many beds were found to have shallow to steep dips to the northeast. The chert and cherty shale tends to separate along bedding and break into gravel-sized blocks due to cross-fracturing perpendicular to bedding.

Joint orientations in the Claremont Chert and Shale are primarily random with some moderate to weakly-defined joints dipping to the northeast and southeast. Joints in the Claremont Chert and Shale are predominantly slightly weathered, planar and smooth. Clay infilled joints occur throughout this geologic unit with variable frequency and thickness. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Claremont Chert and Shale are filled to tight, planar to wavy, polished to rough. Less than 30% of the discrete shears are filled with clay up to 10 cm (4 in) thick; less than 10% if the discrete shears are filled with gouge; and less than 30% of the discrete shears are brecciated. The occurrence of sandstone dikes, altered igneous dikes, very intensely fractured rock zones, minor systematic faults described in Section 3.5.2, and tightly folded beds contribute to complex rock mass structures within the Claremont Chert and Shale, resulting in several RMTs being defined to represent the range of conditions.

Seven Rock Mass Types have been defined for the Claremont Chert and Shale geologic unit: Tc-1, Tc-2, Tc-3, Tc-4a, Tc-4b, Tc-5a and Tc-5b (Figure 4.1).

The Tc-1 RMT is composed of chert and shale, and has the following characteristics:

- Very blocky rock mass structure and fair discontinuity surface conditions using the GSI terminology.
- Intensely to slightly fractured typically. Less than 10% of this RMT by volume is very intensely fractured in zones 0.3 to 1 m (1 to 3.3 ft) wide that contain clay.
- Moderately strong to very strong intact rock strength.
- Moderately hard to hard intact rock.
- Slightly weathered to fresh intact rock.

The Tc-2 RMT is composed of chert and shale, and has the following characteristics:

- Blocky/disturbed/seamy rock mass structure and poor to fair discontinuity surface conditions using the GSI terminology.

- Intensely to slightly fractured typically. Less than 25% of this RMT by volume consists of very intensely fractured rock zones 0.3 to 2 m (1 to 6.6 ft) wide. Less than 35% of the very intensely fractured rock zones contain breccia and less than 35% of the very intensely fractured rock zones contain discontinuities filled with clay up to 15 cm (6 in) thick.
- Friable to very strong intact rock strength.
- Soft to hard intact rock.
- Slightly weathered to fresh intact rock.

The Tc-3 RMT occurs in the eastern portion of the Claremont Chert and Shale immediately west of the Fault 4 contact. The Tc-3 RMT contains thinly bedded shale/claystone and siltstone, as well as minor occurrences of cherty shale and sandstone. This RMT has the following characteristics:

- Very blocky rock mass structure and fair discontinuity surface conditions using the GSI terminology.
- Intensely to slightly fractured typically. Less than 10% of this RMT by volume consists of very intensely fractured rock zones 0.3 to 1 m (1 to 3.3 ft) wide.
- Friable to very strong intact rock strength.
- Soft to hard intact rock.
- Slightly weathered to fresh intact rock.

The Tc-4a and Tc-4b RMTs are composed of chert and shale but the Tc-4a RMT includes sandstone beds and dikes, while the Tc-4b RMT does not. These RMTs include ground conditions in the Claremont Chert and Shale associated with Fault 3 and have the following rock mass characteristics:

- Disintegrated to blocky/disturbed/seamy rock mass structure and poor to fair discontinuity surface conditions using the GSI terminology.
- Intensely to slightly fractured typically. Less than 25% of these RMTs by volume consist of very intensely fractured rock zones 0.3 to 5 m (1 to 16 ft) wide.
- Weak to very strong intact rock strength.
- Soft to hard intact rock.
- Slightly weathered to fresh intact rock.

The Tc-5a RMT occurs anywhere within the Claremont Chert and Shale geologic unit (except within the Tc-3 RMT). The Tc-5a RMT consists of chert and shale with clay-filled discrete shears, and altered igneous dikes. This RMT includes ground conditions in the Claremont Chert and Shale associated with Fault 3 and has the following characteristics:

- Disintegrated rock mass structure and very poor to poor discontinuity surface conditions using the GSI terminology.
- This RMT typically consists of very intensely fractured rock zones 1 to 13 m (3.3 to 42 ft) wide. Less than 30% of this RMT by volume consists of intensely to moderately fractured rock.
- Weak to very strong intact rock strength.
- Soft to hard intact rock.
- Severely weathered to fresh intact rock.

The Tc-5b RMT occurs within the Tc-3 RMT and includes ground conditions associated with Fault 4. The Tc-5b RMT consists of siltstone, shale, cherty shale, sandstone and claystone with clay-filled discrete shears, and altered igneous dikes, and has the following characteristics:

- Blocky/disturbed/seamy rock mass structure and very poor to poor discontinuity surface conditions using the GSI terminology.
- This RMT typically consists of very intensely fractured rock. Less than 30% of this RMT by volume consists of intensely to moderately fractured rock.
- Weak to very strong intact rock strength.
- Soft to hard intact rock.
- Severely weathered to fresh intact rock.

Ground conditions in the Claremont Chert and Shale associated with Fault 3 are consistent with conditions in the Tc-4a, Tc-4b, Tc-5a RMTs at the scale of the tunnel width, and are thus included in these RMTs. Ground conditions associated with Fault 4 are consistent with conditions in the Tc-5b RMT at the scale of the tunnel width, and are thus included in this RMT.

4.1.2.6 *Fault 4*

Fault 4 occurs at the contact between the Claremont and Orinda Formations (Figure 4.1), and is also marked by a slight change in the dip of bedding. This fault contact may be difficult to identify during construction because it occurs between RMTs that share lithologies of similar character, i.e. shale and siltstone to the west versus claystone and siltstone to the east. In Bore Nos. 1 and 2, Page (1950) identified the contact between the two geologic units by the presence of a thick conglomerate bed at the base of the Orinda Formation, but this may not exist in Bore No. 4 due to lateral discontinuity. However, the relative location of the tunnel heading with respect to Fault 4 can be determined during construction by the occurrence of either conglomerate beds that occur only in the Orinda Formation, or shale beds that occur only in the Claremont Chert and Shale.

The Claremont Chert and Shale is intensely fractured over a 3 m (10 ft) zone adjacent to the fault contact. The Orinda Formation adjacent to the fault contact is moderately to slightly fractured, with a narrow zone (less than 0.5 m [1.5 ft] wide) of very intensely fractured and brecciated rock. Many hairline polished fractures occur in the area of the fault on either side of the fault contact. These ground conditions associated with Fault 4 are included in the Tc-5b RMT described above and the Tor-2 RMT described below.

4.1.3 Orinda Formation (Tor)

The Orinda Formation consists of interbedded bluish gray and greenish gray conglomerate, sandstone, and siltstone, and grayish red claystone. Claystone and siltstone are estimated to make up 55 percent of the Orinda Formation by volume along the alignment of Bore No. 4. The percentages of conglomerate and sandstone are approximately 25 percent and 20 percent, respectively by volume.

Bedding in the Orinda Formation is lenticular and ranges in thickness from about 3 cm to 30 m (0.1 to 98 ft). Bedding contacts are gradational to abrupt. Abrupt bedding planes will be tight, and predominantly dip steeply to the southwest. Joint orientations in the Orinda Formation are predominantly scattered with two joint sets: one steeply dipping to the west-northwest, and one shallow dipping to the east-southeast. Joint surfaces are predominantly slightly weathered and planar. Less than 25% of the joint are coated or filled with clay. Table 3.2 summarizes bedding and joint orientations. Discrete shears in the Orinda Formation are open to filled, planar to wavy, smooth to stepped, and less than 10% have gouge or breccia.

Three Rock Mass Types are anticipated within the Orinda Formation: Tor-1, Tor-2 and Tor-3 (Figure 4.1).

The Tor-1 RMT has the following rock mass characteristics:

- 60% of this RMT by volume has a blocky to massive rock mass structure with fair discontinuity surface conditions using the GSI terminology. Other characteristics of this blocky to massive rock mass are:
  - Moderately to very slightly fractured.
  - Weak to strong intact rock strength typically. Friable intact rock strength for less than 15% of the blocky to massive rock mass in the Tor-1 RMT by volume.
  - Low hardness to moderately hard intact rock typically. Soft for less than 15% of the blocky to massive rock mass in the Tor-1 RMT by volume. Hard for less than 15% of the blocky to massive rock mass in the Tor-1 RMT by volume.
  - Slightly weathered to fresh intact rock.
- 40% of this RMT by volume consists of zones of blocky/disturbed/seamy rock mass structure with poor to fair discontinuity surface conditions, using the GSI terminology, affecting tunnel scale reaches greater than 15 m (50 ft) wide. These zones have the same intact rock properties described above, but the following fracturing and shear zone characteristics:
  - Less than 25% of the blocky/disturbed/seamy rock mass in the Tor-1 RMT by volume consists of very intensely fractured rock zones 0.3 to 1.5 m (1 ft to 5.5 ft) wide. Less than 15% of the very intensely fractured rock zones in the blocky/disturbed/seamy rock mass in the Tor-1 RMT by volume occurs in shear zones less than 0.5 m (1.5 ft) wide, with discrete shears that are filled with clay, clayey silt and gouge, planar to irregular, and polished to rough.
  - Up to 65% of the blocky/disturbed/seamy rock mass in the Tor-1 RMT by volume consists of zones of pervasive healed, slickensided discrete shears in the claystone/siltstone less than 2 m (6.6 ft) wide.

The Tor-2 RMT includes ground conditions associated with Fault 4 and has the following rock mass characteristics:

- 65% of this RMT by volume consists of very blocky rock mass structure with poor to fair discontinuity surface conditions using the GSI terminology. Other characteristics of this very blocky rock mass are:
  - Intensely to slightly fractured typically. Very slightly fractured rock makes up less than 15% of the very blocky rock mass in the Tor-2 RMT by volume.
  - Weak to moderately strong intact rock strength typically. Friable intact rock strength makes up less than 15% of the very blocky rock mass in the Tor-2

RMT by volume. Strong intact rock strength makes up less than 25% of the very blocky rock mass in the Tor-2 RMT by volume.
    - Soft to hard intact rock.
    - Slightly weathered to fresh intact rock.
- 35% of this RMT by volume consists of zones of blocky/disturbed/seamy rock mass structure with poor to fair discontinuity surface conditions, using the GSI terminology, affecting tunnel scale reaches greater than 15 m (50 ft) wide. . The rock mass conditions in zones of blocky/disturbed/seamy rock mass in the Tor-2 RMT are are more adverse than those in zones of blocky/disturbed/seamy rock mass in the Tor-1 RMT due to the more adverse typical rock mass conditions in the Tor-2 RMT. These zones have the same intact rock properties described above, but the following fracturing and shear zone characteristics:
    - A narrow zone (less than 0.5 m [1.5 ft] wide) of very intensely fractured and brecciated rock, and hairline polished fractures occurs adjacent to the Fault 4 contact.
    - Less than 30% of the blocky/disturbed/seamy rock mass in the Tor-2 RMT by volume consists of very intensely fractured rock zones 0.3 to 1 m (1 ft to 3.3 ft) wide.
    - Up to 70% of the blocky/disturbed/seamy rock mass in the Tor-2 RMT by volume consists of zones of pervasive healed, slickensided discrete shears in the claystone/siltstone less than 1.5 m (5.5 ft) wide.

The Tor-3 RMT has the following rock mass characteristics:

- Blocky/disturbed/seamy rock mass structure with poor to fair discontinuity surface conditions using the GSI terminology.
- Moderately to very slightly fractured typically. Less than 10% of this RMT by volume consists of very intensely fractured rock zones 0.3 to 1.8 m (1 ft to 6 ft) wide. Less than 20% of the very intensely fractured rock zones occur in shear zones less than 0.5 m (1 ft) wide, with discrete shears that are open to filled, planar to irregular, polished to rough.
- Friable to strong intact rock strength.
- Soft to hard intact rock.
- Moderately weathered to fresh intact rock.

Ground conditions in the Orinda Formation associated with Fault 4 are consistent with conditions in the Tor-2 RMTs at the scale of the tunnel width, and are thus included in this RMT.

4.2 Hydrogeology

This section presents baselines on hydrogeological conditions along the tunnel alignment.

The overall groundwater level along the alignment will range from the tunnel crown elevation to 35 m (115 ft) above the tunnel crown with seasonal fluctuations of 2 to 4 m (6.5 to 13 ft). Figure 3.1 shows the overall groundwater level along the alignment. Variations and offsets in groundwater level are also expected along the alignment due to groundwater barriers created by shear zones and faults as suggested in Figure 3.1.

Within the Sobrante and Claremont Formations, the overall groundwater level will range from 0 to 35 m (0 to 115 ft) above the tunnel crown: zero at Portal No. 1 and the maximum under the crest of the hill in the Claremont Chert and Shale. Within the Orinda Formation, the overall groundwater level will range from the tunnel crown level at Portal No. 2 to 12 m (40 ft) above the tunnel crown except for elevated groundwater levels associated with layers of conglomerate and sandstone close to the contact of the Orinda and Claremont Formations as shown in Figure 3.1. In these conglomerate and sandstone layers the groundwater will be up to 58 m (191 ft) above the tunnel crown.

Hydraulic conductivities will range between $2x10^{-6}$ to $2x10^{-3}$ cm/sec ($6x10^{-3}$ to 6 ft/day) based on results from valid packer tests. At larger scales (100 to 400 m [330 to 1300 ft]) geologic features such as shear zones and faults will decrease the hydraulic conductivity to $5x10^{-6}$ to $1x10^{-4}$ cm/sec ($1x10^{-2}$ to $3x10^{-1}$ ft/day) based on back-analyses of measured inflows into Bore No. 3. The hydraulic conductivity in fractured rock masses adjacent to faults and shear zones will be up to $1x10^{-2}$ cm/sec (30 ft/day).

5 Anticipated Tunnel Ground Conditions

5.1 Ground Classes

The various RMTs described in Section 4 have been grouped into four major ground classes, and three sub-type ground classes, based on the similarity of their anticipated predominant and secondary ground behaviors in the tunnel opening. Table 5.1 summarizes this grouping. This section identifies the predominant RMTs within each ground class, discusses predominant and secondary behavior for each ground class, and baselines key rock mass properties.

Each ground class requires a unique combination of excavation sequence and initial support elements, collectively referred to as a support category. Ground classes and support categories have a one-to-one ground class relation (i.e., Ground Class 1a corresponds to Support Category IA). The estimated occurrence of ground classes along the alignment, based on available geologic and geotechnical information, is provided in the Plans.

Along portions of the tunnel, more than one ground class will occur within the cross-section of the tunnel. Categorization of the ground within these reaches of the tunnel is discussed in Section 5.2.5.

5.2 Ground Class Characterization

The following sections describe ground classes based on the predominant rock mass types and anticipated rock mass behaviors that were identified during the design phase. The ground classes are to be determined during construction by: (1) identifying the component predominant RMT, or rock masses with similar characteristics; and (2) identifying the behaviors described in this section. In most cases, no one single rock mass characteristic, i.e. lithology, fracture spacing and orientation, etc., or behavior mode will provide a definitive identification of ground class. Therefore, consideration of all the rock mass characteristics described in Section 4, rock mass properties described in Section 5.3, along with behaviors described in this section, is required for assessment of the ground class. If conditions arise where the behavior and rock mass conditions imply different ground classes, the ground class associated with behavior will be used.

Predominant and secondary behaviors expected within each of the ground classes for an unsupported tunnel excavated to the full cross-section limits, and the identified RMTs assigned to each ground class, are summarized in Table 5.1. The glossary includes descriptions of the behaviors and how the behaviors would be manifested in an unsupported tunnel excavation.

The predominant behaviors are the behaviors that dominate the global behavior of the tunnel excavation throughout the majority of the ground class and control the major support category requirements. The predominant behaviors anticipated along the alignment are block failures, deep seated shear failure and crown instability due to low cover. Secondary behaviors are those behaviors that do not control the global behavior but still must be controlled to maintain stability of the tunnel during tunnel mining. The secondary behaviors can occur either locally or throughout the ground class. The secondary behaviors include: raveling, shallow shear failure, slaking/softening and swelling.

Rock mass behavior is determined by both the geomechanical properties and in situ conditions such as cover, groundwater conditions, joint orientations relative to the tunnel, and other factors. Therefore, rock masses can occur in more than one ground class depending on their behaviors under different in-situ conditions as shown in Table 5.1 and as defined in this section. For example, RMT Tor-2 occurs in both Ground Class 2a and Ground Class 3a because, as ground cover and in situ stresses increase, the primary ground behavior for Tor-2 changes from block failure to deep shear failure.

Because the support categories as designed will control the behavior of the ground, major manifestations of some of the behavior types will not be visible within the supported tunnel. Therefore, assessment of anticipated behaviors by experienced SEM engineers, as well as observations of the unsupported tunnel perimeter and tunnel face during mining, and interpretations of measured tunnel convergence obtained from the monitoring program, are key elements for identifying rock mass characteristics and ground behavior modes and, therefore, ground class. Personnel experienced in SEM tunneling are responsible for mapping and identifying ground conditions and observing or anticipating ground behaviors that both comprise the classification of the ground and the support selection process.

5.2.1 Ground Class 1

Ground conditions within Ground Class 1 will typically have a blocky to massive structure, and fair to good discontinuity surface conditions, in terms of the GSI terminology. The predominant ground behavior of Ground Class 1 is block failure (Figure 5.1 (a)). Ground Class 1 is divided into two subtypes, Ground Class 1a and 1b. The difference between Ground Class 1a and 1b is that Ground Class 1b could consistently exhibit block failures within the face while in Ground Class 1a block failures within the face will be localized behavior.

Classification of encountered ground conditions into the Ground Class 1 subtypes during construction is to be based on rock mass characteristics and anticipated behaviors consistent with the descriptions below. Ground conditions predicted based on results of site investigation performed during the design phase, that classify into these subtypes is as follows:

Ground Class 1a

- Tcs-1 (Second Sandstone)

Ground Class 1b

- Tor-1 (Orinda Formation).

Detailed descriptions of these RMTs are provided in Section 4. Further descriptions of Ground Class 1 behaviors are provided in the following paragraphs.

Discontinuity orientations within Ground Class 1 exhibit significant scatter so that rock block shapes, sizes, and locations will be variable. Block failure could occur prior to support application along the tunnel perimeter of the unsupported top heading and bench, as well as at the unsupported face in both the Tor-1 and Tcs-1 RMTs where adverse combinations of discontinuity orientations occur at a particular location.

Secondary behavior in Ground Class 1a (Tcs-1) RMT, outside of very intensely to intensely fractured zones and shear zones, is limited to slaking within occurrences of silty sandstone strata, where slake durability is expected to be very low (see Table 5.3). Secondary behaviors in Ground Class 1b (Tor-1), outside of very intensely fractured zones and shear zones, include slaking (with very low to low slake durability, Table 5.3), softening, and swelling, which are all associated with the claystones and siltstones of the Orinda Formation. Slaking along the sidewalls and crown or on the tunnel face could occur if the layer of sealing shotcrete is not applied immediately following excavation. Swelling could occur at the top heading and bench inverts and at other locations along the tunnel perimeter where seepage inflows occur and where water is not channeled away from swell prone materials. Softening will result in poor invert conditions. Softening and swelling behaviors may not be visible at excavated surfaces prior to initial support application.

Ground behavior within shear zones, and very intensely to intensely fractured zones that are a part of Ground Class 1a (Tcs-1) includes raveling (Figure 5.1 (b)) in addition to other secondary behaviors noted above. Ground behaviors within rock mass associated with shear zones and very intensely fractured zones that are part of Ground Class 1b (Tor-1) include raveling (Figure 5.1 (b)) and shallow shear failure (Figure 5.1 (c)) in addition to the other secondary behaviors noted above. See Section 4 for characterization of shear zones and intensely to very intensely fractured zones within Ground Class 1 RMTs. Raveling could occur anywhere on the unsupported tunnel face or around the perimeter of the unsupported top heading and bench. Shallow shear failures could occur within the rock mass adjacent to the tunnel perimeter. Shallow shear failures may not be visible within the tunnel excavation but could be identified by the deformations measured by the tunnel instrumentation and monitoring program as well as by assessments of anticipated behavior.

The occurrence of adverse discontinuity orientations and surface conditions in Ground Class 1 could define unstable blocks that require immediate support after excavation.

5.2.2 Ground Class 2

Ground conditions within Ground Class 2 will have a disintegrated to very blocky structure, and poor to fair discontinuity surface conditions, in terms of the GSI terminology. The predominant ground behavior within the Ground Class 2 is block failure similar to Ground Class 1. However, the fracture density within Ground Class 2 is higher than Ground Class 1 and, therefore, the block sizes will be smaller in Ground Class 2. Ground Class 2 is divided into two sub-types, Ground Class 2a and 2b. The sub-division of Ground Class 2 into these sub-types is due to the more extensive zones of intensely to very intensely fractured rock, and associated raveling behavior, within Ground Class 2b. In contrast, these conditions and behaviors occur only locally in Ground Class 2a.

Classification of encountered ground conditions into the Ground Class 2 subtypes during construction is to be based on rock mass characteristics and anticipated behaviors consistent with the descriptions below. Ground conditions predicted are based on results of site investigation performed during the design phase that classify into these subtypes is as follows:

Ground Class 2a

- Tor-2 (Orinda Formation)
  (anticipated between Station 114+70 and Station 114+35)

Ground Class 2b

- Tsp (Portal Sandstone)
- Tss-1 (Shaly Sandstone)
- Tcs-2 (Second Sandstone)
- Tc-1, Tc-2, Tc-3, Tc-4a and Tc-4b (Claremont Chert and Shale)
- Tor-3 (Orinda Formation)
  (anticipated between Station 116+69 and Station 117+14)

Detailed descriptions of these RMTs are provided in Section 4. Further descriptions of Ground Class 2 behaviors are provided in the following paragraphs.

Discontinuity orientations within the Ground Class 2 RMTs exhibit significant scatter so that rock block shapes, sizes, and locations will be variable. Block failure could occur prior to support installation along the tunnel perimeter of the unsupported top heading and bench, as well as at the unsupported face where adverse combinations of discontinuity orientations occur at a particular location.

Secondary behaviors in Ground Class 2 include raveling, shallow shear failure, slaking, softening and swelling. The occurrence of these secondary behaviors by the identified component RMTs will be as follows:

- Raveling: Tsp, Tss-1, Tcs-2, Tc-1, Tc-2, Tc-3, Tc-4a, Tc-4b, Tor-2 (within shear zones or very intensely fractured rock zones) and Tor-3 (within shear zones or very intensely fractured rock zones)
- Shallow shear failure: Tc-1, Tc-2, Tc-3, Tc-4a, Tc-4b, Tor-2 and Tor-3
- Slaking and softening: Tss-1, Tc-3 and Tcs-2 (no softening), Tor-2 and Tor-3
- Swelling: Tc-3, Tor-2 and Tor-3

Raveling could occur prior to support application anywhere on the unsupported tunnel face or around the perimeter of the unsupported top heading and bench at locations with very intense fracture density, including discrete shears. Shallow shear failures could occur within the rock mass adjacent to the tunnel perimeter and will tend to occur in association with adversely oriented discontinuities or sheared or very intensely fractured zones. Shallow shear failures may not be visible within the tunnel excavation but could be identified by the deformations measured by the tunnel instrumentation and monitoring program as well as by assessments of anticipated behavior. Slaking and softening are expected to occur within the siltstones and claystones of the Orinda Formation (where slake durability will be very low to low, Table 5.3), as well as within claystone, siltstone and silty sandstone in other Ground Class 2 RMTs (where slake durability will be very low to low, Table 5.3). Slaking along the sidewalls and crown or on the tunnel face could occur if the initial layer of shotcrete is not applied immediately following excavation. Softening will result in poor invert conditions. Swelling could occur at the top heading and bench inverts and at other locations along the tunnel perimeter where seepage inflows occur and where water is not channeled away from swelling prone materials. Softening and swelling behaviors may not be visible at excavated surfaces prior to initial support application.

The occurrence of adverse discontinuity orientations and surface conditions in Ground Class 2 will produce unstable blocks that require immediate support after excavation. Raveling ground conditions will exhibit negligible stand up time after excavation.

5.2.3 Ground Class 3

Ground conditions within Ground Class 3 will have a disintegrated to very blocky structure, and very poor to fair discontinuity surface conditions, in terms of the GSI terminology. The predominant ground behavior that will occur in Ground Class 3 is deep shear failure (Figure 5.1 (d)). Ground Class 3 is divided into two sub-types, Ground Class 3a and 3b. The sub-division of Ground Class 3 into these sub-types is based on the higher degree of overstressing related to deep shear failure behavior in Ground Class 3b relative to Ground Class 3a. Classification of encountered ground conditions into these Ground Class 3 subtypes during construction is to be based on rock mass characteristics and anticipated behaviors consistent with the descriptions below. Ground conditions predicted are based on results of site investigation performed during the design phase that classify into these subtypes is as follows:

Ground Class 3a

- Tss-2 (Shaly Sandstone)
- Tcp (Preliminary Chert)
- Tcs-3 (Second Sandstone)
- Tc-5a, Tc-5b (Claremont Chert and Shale)
- Tor-2 (Orinda Formation)

(anticipated between Station 114+35 approximately Station 114+00)

- Tor-3 (Orinda Formation)
  (anticipated between Station 114+70 and Station 116+69)

Ground Class 3b

- Tc-5a, Tc-5b (Claremont Chert and Shale) with a continuous extent of clayey fault gouge or soft altered igneous dike(s) [approximate dimensions greater than 7.6 m (25 ft)] in an orientation that exacerbates the deep shear failure behavior of the rock mass around the tunnel.

Detailed descriptions of these RMTs are provided in Section 4. Further descriptions of Ground Class 3 behaviors are provided in the following paragraphs.

Deep shear failure may not be visible within the short unsupported section of tunnel and will be identified by the deformations measured by the tunnel instrumentation program as well as by assessments of anticipated behavior.

Secondary ground behaviors in Ground Class 3a are block failures, raveling, slaking, softening, and swelling. The occurrence these secondary behaviors by RMT will be as follows:

- Block failure: Tcp, Tcs-3, Tor-2 and Tor-3
- Raveling: All Ground Class 3a RMTs (only within shear zones or very intensely fractured rock zones in Tor-2 and Tor-3)
- Slaking and softening: Tss-2, Tcs-3 (no softening), Tc-5a, Tc-5b, Tor-2 and Tor-3
- Swelling: Tc-5b, Tor-2 and Tor-3

Discontinuity orientations within Ground Class 3a exhibit significant scatter so that rock block shapes, sizes, and locations will be variable. Block failure could occur along the tunnel perimeter of the unsupported top heading and bench, as well as at the unsupported face. Raveling could occur anywhere on the unsupported tunnel face or around the perimeter of the unsupported top heading and bench. Slaking and softening are expected to occur the in the siltstones and claystones of the Orinda Formation (where slake durability will be very low to low, Table 5.3) and in occurrences of claystone, siltstone and silty sandstone in other Ground Class 3a RMTs (where slake durability will be very low to low, Table 5.3). Softening will result in poor invert conditions. Swelling could occur at the top heading and bench inverts, and at other locations along the tunnel perimeter where seepage inflows occur and where water is not channeled away from swelling prone materials. Softening and swelling behaviors may not be visible at excavated surfaces prior to initial support application.

Secondary ground behaviors in Ground Class 3b consist of raveling, slaking, swelling and softening. The occurrence of these secondary behaviors by the identified component RMTs will be as follows:

- Raveling: Tc-5a and Tc-5b
- Slaking and softening: Tc-5a and Tc-5b
- Swelling: Tc-5b

Raveling will occur anywhere on the unsupported tunnel face or around the perimeter of the unsupported top heading and bench. Slaking and softening are expected in occurrences of claystone, siltstone and silty sandstone in Ground Class 3b RMTs (where slake durability will be very low to low, Table 5.3). Softening will result in poor invert conditions. Swelling could occur at the top heading and bench inverts, and at other locations along the tunnel perimeter where seepage inflows occur and where water is not channeled away from swelling prone materials. Softening and swelling behaviors may not be visible at excavated surfaces prior to initial support application.

Raveling ground conditions in Ground Class 3 will exhibit negligible stand-up time after excavation. The occurrence of adverse discontinuity orientations and surface conditions in the Tor-2 RMT will produce unstable blocks that require immediate support after excavation.

5.2.4 Ground Class 4

Ground conditions within Ground Class 4 will have a disintegrated structure, and very poor to fair discontinuity surface conditions, in terms of the GSI terminology. The predominant ground behavior in the Ground Class 4 Tsf RMT consists of crown instability due to low cover (Figure 5.1 (e)). Classification of encountered ground conditions into Ground Class 4 during construction is to be based on rock mass characteristics and anticipated behaviors consistent with the descriptions below. Ground conditions predicted based on results of site investigation performed during the design phase that classify into Ground Class 4 are as follows:

Ground Class 4

- Tsf (First Shale)at Portal No. 1

Detailed descriptions of these RMTs are provided in Section 4. Further descriptions of Ground Class 4 behaviors are provided in the following paragraphs.

Crown instability will occur near the west portal as a result of the low cover and limited arching capacity of the ground above the crown. Crown instability will be aggravated by occurrences of clayey, very intensely fractured rock zones. Instability above the crown may not be visible at excavated surfaces prior to initial support application.

Secondary behaviors in Ground Class 4 include raveling, shallow shear failure, slaking and softening. Raveling will occur anywhere on the tunnel face or around the perimeter of the top heading and bench. Shallow shear failures could occur within the rock mass adjacent to the tunnel perimeter and will aggravated by occurrences of clayey, very intensely fractured rock zones. Shallow shear failures may not be visible within the tunnel excavation but could be identified by the deformations measured by the tunnel instrumentation and monitoring program as well as by assessments of anticipated behavior. Raveling and shear failures could progress to the ground surface in areas of low cover within Ground Class 4 in an unsupported tunnel. Slaking and softening can occur anywhere along the excavated surface. Slake durability in the First Shale will be very low to low (see Table 5.3). Softening will result in poor invert conditions. Softening may not be visible at excavated surfaces prior to initial support application.

Negligible stand up time after the excavation is anticipated due to the pervasiveness of raveling conditions throughout Ground Class 4.

5.2.5 Multiple Ground Class ~~Sections~~ Conditions

Where more than one ground class occurs within the tunnel ~~cross section~~ top heading, bench, and invert over one or more advance lengths, the regions of different ground class will likely exhibit different behaviors. Where the global behavior of the overall tunnel excavation is controlled primarily by a particular ground class, it would be appropriate to categorize the ground over these advance lengths according to the controlling behavior and associated ground class. However, where the behavior associated with a particular ground class is localized and does not control the global behavior of the overall tunnel excavation, it will not be appropriate to categorize the length of tunnel to the ground class corresponding to the local behavior.

5.3 Ground Class Properties

This section discusses ground class properties. The expected distribution of Rock Quality Designation (RQD) by ground class is shown in Figure 5.2. Histograms showing the distribution of RQD by RMTs within ground classes are shown in Figures 5.3 to 5.6.

The Unconfined Compressive Strength (UCS) of intact rock was evaluated using Point Load Index converted to estimates of UCS and laboratory UCS tests. In Ground Class 4, additional ISRM field index tests were performed on hand samples of the closely fractured shale to evaluate intact rock strength since this material was not suitable for UCS or PLI testing. Histograms of measured UCS values for the RMTs where sufficient data is available are grouped by ground class and presented in Figures 5.7 to 5.10. Table 5.2 presents the baselines for UCS for each RMT. The predicted upper bound of UCS presented in Table 5.2 for some RMT have been adjusted to account for the expected range of rock strengths and, therefore, do not correlate exactly with histogram data presented in Figures 5.7 to 5.10. For baseline purposes, the Contractor should assume the percent of data value shown in Figures 5.7 to 5.10 for the histogram's maximum UCS interval applies to UCS values ranging from the the maximum UCS interval values shown in Figures 5.7 to 5.10, up to the upper bound baseline UCS value in Table 5.2.

The Cerchar Abrasivity Index (CAI) baseline ranges in Table 5.2 were established based on test results and comparison of published CAI values for lithologies expected along the alignment. CAI values by RMT are presented in Figure 5.11. The maximum baseline values of CAI for the igneous dikes, and the conglomerate of the Orinda Formation (Tor-1, 2, and 3) are presented separately from the maximum baseline values of CAI for the RMTs. The maximum expected CAI values for the RMTs are based on the measured values. The maximum expected CAI values for igneous dikes are based on published values (Plinninger et al., 2003). The occurrence of the igneous dikes is discussed in Section 3.8. The maximum expected CAI values for the conglomerates are controlled by test results performed on clasts within the conglomerate. The maximum occurrence of conglomerate is discussed in Section 4.1.3.

Slake Durability Index baseline ranges in Table 5.2 were established based on testing of selected rock samples. Table 5.3 summarizes the classification of slake potential. Observations of slaking behavior in the Orinda Formation made during construction of Bore No. 3 were also considered in establishing the baselines. Variations of slake durability within each of the Ground Classes is described in Section 5.2.

6 Mined Tunnel Construction Considerations

6.1 Selection of Support

Support measures include standard support measures and additional support measures. Standard support measures are defined in four major support categories, and three variant support categories, each of which correspond to one of the ground classes defined in Section 5. Thus, Support Category IA is to be used with reaches of Ground Class 1a, Support Category IIA is to be used with Ground Class 2a and so on. The estimated occurrence of ground classes and support categories along the alignment, based on available geologic and geotechnical information, is provided in the Plans. Some reaches of the tunnel will encounter more than one ground class within the tunnel section. Additional support measures are supplementary to the standard support measures. Additional support measures are required for addressing observed or measured local ground conditions or behaviors. These additional support measures will be installed when measured convergence exceeds warning levels or when specific ground conditions or support system behaviors are observed as defined on the Plans and in the sections below.

Support category selection during construction requires evaluation of the ground class based on ground characteristics and behaviors as discussed in Section 5. Personnel experienced in SEM tunneling are responsible for selecting the appropriate support category based on the ground conditions and observed or anticipated behaviors. Approval of support selection by the Engineer, which is specified in “Tunnel Excavation and Support” of these Special Provisions, will be based on an independent assessment by the Engineer of ground conditions and observed or anticipated behaviors.

As discussed in Section 5, the support categories as designed will control the behavior of the ground, and as such, some behaviors will not be visible within the supported tunnel. Therefore, selection of both standard and additional support will require characterization and anticipation of rock mass conditions and behaviors during construction through probe drilling, observation of encountered rock mass conditions and visible behaviors, predictions of rock mass behaviors described in Section 5, and measurement and synthesis of previous ground behavior in similar rock mass conditions to determine the appropriate Ground Class and associated Support Category.

Where more than one ground class occurs within the tunnel top heading, bench, and invert over one or more advance lengths, ~~section for a particular reach of the runnel~~ support selection will be based on the global behavior of the overall tunnel excavation in the reach of multiple ground classes. Where the behavior is localized, additional support will be used to control local behavior. This is explained further below.

Within reaches of the tunnel where more than one ground class occurs in the tunnel ~~cross section~~top heading, bench, and invert, the global behavior of the tunnel excavation will control the selection of the appropriate support category. For example, where Ground Class 3a occurs within the crown area of the tunnel, and Ground Class 2a occurs near the invert of the top heading, the appropriate support category within the top heading would be Support Category IIIA because the ground conditions within the crown area of the tunnel will control the predominant behavior – deep seated shear failure, as well as one of the key secondary behaviors – raveling in these ground conditions.

In the case where there is a local occurrence of a more adverse ground class within the top heading, bench, and invert ~~a particular tunnel section~~ and the local occurrence does not control the global behavior of the tunnel excavation, the support category corresponding to the more favorable ground class augmented by additional support measures would be appropriate. For example, where there is a minor occurrence of Ground Class 3a in the haunch area of the tunnel and Ground Class 2b elsewhere, it would be appropriate to utilize Support Category IIB augmented by local spiling in the area where Ground Class 3a occurs.

6.2 Excavation and Support

6.2.1 Excavation Sequence

The mined tunnel excavation and support will be performed using a top heading and bench sequence. Alternative excavation sequences of top heading and bench, and bench cuts, are allowed but are subject to restrictions on lags and distance behind the bench cuts within which support installation must be completed.

6.2.2 Excavation Methods

Feasible excavation methods suited to SEM construction include use of a road header, an excavator or backhoe with a cutter head attachment, and drill-and-blast methods. Based on an evaluation of ground characteristics, excavation by road header will be feasible for the majority of Bore No. 4 and the cross passages, provided that a road header with sufficient weight and cutterhead power is employed. The remaining reaches can be excavated by drilling and blasting. The selection of specific excavation methods shall be the responsibility of the Contractor.

The selected excavation methods will have to address several key ground condition considerations:

- Variation of UCS and fracture spacing;
- Occurrence of altered very intensely fractured fault and shear zones;
- Abrasivity of intact rock, clasts in conglomerate, and igneous dikes; and
- Mixed ground conditions.

6.2.3 Pre-excavation Probe and Drain Holes

Three systematic probe holes are required ahead of the top heading face for the full length of the tunnel. Drilling records and drill cuttings from these probe holes will be used to assess ground conditions ahead of the face. These assessments are to be used, along with other information, to make determinations of changes in ground class and to evaluate the extent of thick clayey shear zones or altered igneous dikes in Tc-5a or Tc-5b RMTs required for identification of Ground Class 3b. Where required, additional probe holes will be used to assess changing distributions of materials ahead of the face.

For designated sections of the tunnel, drain holes will be required ahead of the top heading to control the impact of groundwater on various ground behaviors. These impacts include aggravation of (1) block and shear failure behaviors due to hydrostatic pressure; (2) raveling due to seepage forces; and (3) slaking, softening and swelling due to availability of moisture. The drain holes will also be required where high groundwater inflows are encountered.

Probe and drain holes will be subject to caving in some of the ground conditions that are anticipated along the tunnel. The Contractor should review all rock mass data and descriptions for consideration of caving in the selection of the drilling equipment.

6.2.4 Initial Support

The anticipated behaviors described in Section 5 are controlled by the application of various standard and additional support measures in the tunnel section shown in the Plans. Table 6.1 summarizes the ground behavior anticipated for each ground class and identifies the support elements that will control the behavior.

Pre-support will be required when advancing the top heading to control raveling, crown instability due to low cover, and block failure within the top heading advance length. Section 5 identifies the Ground Classes and associated rock masses where these behaviors are anticipated. Pre-support may also be required as an additional support measure locally as shown on the Plans. Pre-support required as standard support includes spiles (drill and grout or self-drilling as required in ground that caves when drilling) and a pipe canopy. The Contractor should review the rock mass data and descriptions to determine which ground conditions require self-drilling spiles. The pipe canopy is only required in the Ground Class 4 Tsf RMT at Portal No. 1, and adjacent to Portal No. 2 in the Ground Class 2b Tor-3 RMT due to potentially higher loading of pre-support at these low cover locations. Pre-support that can be used as an additional support measure consists of spiling only (drill and grout as well as self-drilling).

Face support is required to control block failure, raveling, slaking and shallow shear failure behaviors at the tunnel face. Section 5 identifies the ground classes and associated rock masses where these behaviors are expected. Face support may also be required as an additional support measure locally as shown on the Plans. The predominant bedding orientations along the tunnel (see Table 3.2) relative to the driving direction will influence the extent of block failure behavior at the face, and associated support requirements. However, as discussed in Section 4, the bedding can include tight folds and, therefore, face stability conditions will be variable along the tunnel. Similarly, face stability conditions due to joints will be variable due to the scatter in joint orientations described in Sections 3 and 4. Standard support measures to control anticipated face behaviors include face dowels, fiber reinforced shotcrete, and a ~~sloping~~ face supporting core of unexcavated ground, which acts as a buttress. Installation of face dowels will have to utilize measures to address caving hole conditions as required by ground conditions. All of these support measures can be used to control the anticipated face behaviors, except for raveling and slaking, which require sealing shotcrete. Alternative supports using face dowels and shotcrete, or a ~~sloping~~ face supporting core, may be used to control behaviors at the face in Support Category II, as shown on the

Plans. Face support that can be used as an additional support measure consists of face dowels and fiber reinforced shotcrete.

Shotcrete thickness requirements increase proceeding from Support Category I to IV, corresponding to changes in ground class behaviors. For example, the thickness of the shotcrete lining increases from 203 mm (8 in.) in Support Category I, to 245 mm (10 in.) thick in Support Category II, due to the additional load associated with shallow shear failure and raveling associated loosening loads in Ground Class 2. Similarly, the shotcrete lining thickness required for support of Ground Class 3 increases to 304 mm (12 in) due to the additional load associated with deep shear failure behavior. Furthermore, an invert arch is required in the top heading and invert of Support Category IIIB to control lateral movements associated with deep shear failure behavior in more extensive occurrences of Ground Class 3b material. The shotcrete lining thickness requirement in Support Category IV is in consideration of loading by the slope to the north of the alignment at Portal No. 1.

Rock dowel spacing decreases proceeding from Support Category I (1.8 m) to Support Category III (1.5 m) in response to changes in predominant behavior from block failure in Ground Class 1 to deep shear failure and raveling in Ground Class 3. Rock dowels are not required in Support Category IV. Rock dowels will be drill and grout and will be self drilling as required in ground that caves when drilling. The Contractor is responsible for determining the rock mass conditions that will require self-drilling dowel.

Lattice girders are required in all ground classes that will exhibit raveling behavior for support of spiles. Lattice girders will also contribute to stabilization of blocks within the advance length.

The behaviors of slaking, softening, and swelling are aggravated by fluctuations in moisture. A mud mat, as well as face and perimeter sealing shotcrete, are critical to control these behaviors. A mud mat is required to be installed in reaches of siltstone, mudstone, claystone and shale within the Tor-1, Tor-2, Tor-3 and Tc-3 RMTs, where softening and/or swelling behaviors are expected. Additionally, groundwater inflows and construction water must be controlled to mitigate these behaviors. Probe holes and possible drain holes will also mitigate softening and swelling.

For the center bench cut option shown on the Plans for Support Categories IA, IB, IIA, and IIB, the side berms are a critical element of support. Water control measures are required to ensure water does not pond along the sides of the top heading either before or during benching operations.

6.2.5 Final Lining Types

Invert and pavement heave after completion of construction is addressed by application of final lining types appropriate to the swell potential of potentially swelling ground reaches along the alignment. Potentially swelling ground is expected to occur in the Orinda Formation RMTs, as well as within the Tc-3 and Tc-5b RMTs of the Claremont Chert and Shale geologic unit. The selection of the appropriate final lining type will be made during construction as the tunnel excavation is advanced through the reach of potentially swelling ground. This decision will be made by the Engineer based on tunnel mapping and test results on grab and core samples taken from the top heading. The Contractor is required to obtain test samples, perform testing and provide the information necessary for the Engineer to select the appropriate final lining type in sufficient time to accommodate the Contractor's construction schedule.

6.3 Groundwater Inflows and Control

Groundwater will flow into the tunnel through the face prior to installation of supports; and also through radial rock dowel boreholes, cracks in the shotcrete lining, weep holes drilled through the shotcrete lining, radial drain holes, and drain holes installed ahead of the tunnel face. Discharge of tunnel inflows will be assisted by gravity due to the tunnel grade on the Portal No. 1 heading. Tunnel inflows will tend to collect at the face on the Portal No. 2 heading and will need to be pumped out.

Baselines for inflow estimates are based on past experience during construction of the existing Caldecott Tunnels and inflow measurements made after completion of construction. The baseline for maximum flush inflow within 30 m (100 ft) of the top heading excavation face is 3.5 L/sec (55 gpm) away from faults or shear zones and 7 L/sec (110 gpm) at faults or shear zones. For baseline purposes, two flush flow events will produce up to 3.5 L/sec (55 gpm), and one flush flow event will produce up to 7 L/sec (110 gpm). Flush flows will decrease to steady state inflow levels behind the tunnel heading within one week. The baseline for maximum steady state groundwater inflow from the full length of Bore No. 4, including the cross passages, is 6.0 L/sec (95 gpm). The steady state inflows from each tunnel heading will be lower than this baseline inflow for the full length of Bore No. 4 and will depend on the length of the headings. The baseline for the maximum inflow during construction, which includes both flush flows at the heading and sustained inflows behind the heading, is 12 L/sec (190 gpm). The maximum inflow levels will drop to steady state inflow levels within one week.

6.4 Instrumentation and Monitoring

Tunnel instrumentation data will be required to verify support performance. The instrumentation data will also be used to determine where additional support measures are needed.

The tunnel monitoring instruments will be used to measure displacements of the shotcrete lining at points around the perimeter of the tunnel, and to measure ground movements within the rock mass adjacent to the tunnel excavation including the rock pillar between Bore Nos. 3 and 4 near the portals.

At the Portal No. 1 area, the slope to the north of the alignment will be monitored during construction using data from surface settlement points and inclinometers.

Groundwater inflows into the tunnels are expected to be variable and will need to be measured for comparison with baseline inflows. The Portal No. 1 heading will be driven upgrade and the total groundwater inflow can be measured and monitored at Portal No. 1 using a weir. The Portal No. 2 heading will be driven downgrade and groundwater will be collected and pumped back to Portal No. 2. In this case, the total groundwater inflows can be measured by a flow meter on the pump discharge line. In addition to monitoring groundwater inflows, construction water inflows supplied to the heading will need to be monitored and subtracted from the total measured tunnel inflows to determine net inflow.

6.5 Water Treatment and Disposal

Treatment plants sizing will have to consider the predicted 12 L/sec (190 gpm) maximum inflow from the full length of Bore No. 4 and cross passages, as well as construction water. ~~Contaminant types and levels are described~~An assessment of existing groundwater quality is provided in the Conceptual Design Report for the ~~Temporary Non-Stormwater Treatment System~~ Storm Water Run-on Bypass and Temporary Treatment System for Tunnel Excavation, which is included in the "Project Information" of the Special Provisions.

6.6 Disposal of Excavated Materials

Excavation of Bore No. 4 and cross passages will generate approximately 210,000 m^3 (275,000 yd^3) of excavated material (muck). The estimated muck volume is based on the excavation line shown in the Plans and a bulking factor of 1.4. The estimated quantity of muck also includes face-sealing shotcrete and mud mat where applicable, and a 30% allowance for shotcrete rebound and overspray. The estimated volume of contaminated excavated material is approximately 37,000 m^3, which is approximately 20% of the estimated volume of excavated materials only, including a 1.4 bulking factor. See “Disposal of Excavated Materials” of the Special Provisions for a definition of contaminated excavated material.

7 Cross Passage Construction Considerations

7.1 Ground Class Descriptions

Seven cross passages will be constructed between Bore No. 4 and the existing Bore No. 3 as shown in the Plans. The rock mass types and ground classes defined in Sections 4 and 5, respectively, apply to the cross passages as well as the main tunnel. The ground behaviors described in Section 5 also apply to the cross passages, but due to the differing size and orientation of the cross passages relative to the main tunnel, the cross passage support categories do not have a one-to-one relationship to the ground classes.

7.2 Selection of Support

Initial ground support within the cross passages consists of standard support measures defined by three support categories. Cross Passage Support Category I is to be used on all reaches of Ground Class 1; Support Category II is to be used on all reaches of Ground Class 2 and Ground Class 3a; and Support Category III is to be used on all reaches of Ground Class 3b. Cross passages are not expected within reaches of Ground Class 4. Additional support measures are required for the occurrence of observed ground conditions and behaviors, or if tunnel lining convergence exceeds warning levels. Alarm levels of tunnel lining convergence will require immediate stoppage of excavation and implementation of contingency measures.

Selection of support categories during construction requires comparison and matching of encountered ground conditions and behaviors to rock mass descriptions and behaviors for each ground class. Where a mixed ground condition occurs in a particular reach of a cross passage, support selection will be based on the global behavior of the cross passage excavation in the reach. Where the behavior is localized, additional support will be used to control the local behavior.

Characterization of encountered ground conditions is to be performed in terms of the descriptions of the ground classes using observations of ground conditions and behaviors during tunnel excavation, observations and mapping at the cross passage heading and face, and results from the monitoring and instrumentation work described later in this Section. A preliminary assessment of support requirements for the cross passages is presented in the Plans.

7.3 Excavation and Support

7.3.1 Excavation Sequence and Methods

Cross passage construction may start after the closest excavation face of Bore No. 4 has been advanced the minimum specified distance from the cross passage and after the initial shotcrete lining adjacent to the cross passage has attained its minimum required strength.

Cross passages will be excavated full face within Support Categories I and II. Support Category III will be excavated in a top heading and invert sequence.

Refer to Section 6 for feasible excavation methods.

7.3.2 Pre-excavation Probe and Drain Holes

Systematic probe holes and drain holes will not be required within the cross passages. Instead, experience from the excavation of Bore No. 4 is to be used for assessment of ground conditions ahead of the face. Probe holes will only be required if unexpected ground conditions are encountered, and drain holes will be required at locations of high groundwater inflow.

7.3.3 Initial Support

Initial support requirements have been designed to address the behaviors described in Section 5. Three support categories were developed to address the anticipated ground behaviors in all seven cross passages. Support requirements increase proceeding from Support Category I to III, corresponding to changes in behaviors for different Ground Classes.

All cross passages, except for cross passage CP-2, are expected to require the same support category along their full length. The majority of cross passage CP-2 is expected to be in Ground Class 1a, but the south end is expected to be in Ground Class 3a. Application of cross passage support categories during construction shall be determined based on the actual ground conditions and behaviors encountered.

Pre-support consisting of drill and grout spiles and self-drill and grout spiles will be required when advancing the excavation in ground that exhibits raveling behavior. Pre-support is only required as a standard support measure within Cross Passage Support Category III. Pre-support may also be used as an additional support measure as required by ground conditions and behavior.

Face support requirements are designed to prevent general shear failure of the ground ahead of the face, stabilize blocks that could form at the face, and control raveling and slaking ground behaviors. Standard face support measures to address these behaviors include 50 mm (2 in) face sealing fiber reinforced shotcrete within all Support Category II and III cross passages. For Support Category I, face support is required on as needed bases within the Tor-1 RMT and will consist of a 50 mm (2 in.) thick layer of fiber reinforced shotcrete (additional support). Face support, as additional support, may be required in all Cross Passage support categories.

Block failure behavior in Ground Class 1a and 1b is addressed by systematic rock dowels and 125 mm (5 in) thick fiber reinforced shotcrete lining. These measures are adequate for the predominant ground behaviors within Ground Class 1a and 1b. The deep shear failure behavior within Ground Class 3a requires increasing the shotcrete lining thickness to 200 mm (8 in) for Support Category II. Spiles are required as additional support to control raveling behavior where it occurs within Support Category II. For Support Category III the increase of fiber reinforced shotcrete lining thickness to 250 mm is needed due to the higher ground cover and 250 mm thick invert arch are required to control lateral movements in Ground Class 3b. Raveling behavior in Ground Class 3b is addressed by means of systematic spilings.

A 50 mm (2 in) thick sealing shotcrete on the cross passage sidewalls and crown is essential to control secondary behaviors of slaking, softening and swelling in all support categories. During excavation and initial lining construction a 100 mm (4 in) thick mud mat is required to be installed in reaches of siltstone, mudstone, claystone and shale within Tor-1, Tor-2, Tor-3 and Tc-3 RMT, where softening and/or swelling behaviors are expected. Construction water and ground water will also have to be collected and handled to control these secondary behaviors.

7.3.4 Final Cross Passage Invert

Swelling ground is expected to be encountered within cross passages CP-6 and CP-7. During construction, invert protection in reaches of swelling ground will be provided by the mud mat in Support Categories I and II, unless long-term treatment is applied immediately. Long term treatment for swelling ground with respect to long term behavior will be addressed by application of an invert arch as an additional measure.

The decision to apply an invert arch for long-term swelling behavior will be made using swelling potential assessments in Bore No. 4 at the cross passage locations. This decision will be made by the Engineer as described in Section 6.2.5.

7.4 Groundwater Inflows and Control

Groundwater will flow by gravity from the heading of cross passages CP-1 through CP-6 to Bore No. 4 as these cross passages are driven from Bore No. 4 towards Bore No. 3. In contrast, inflows from cross passage CP-7 will tend to collect at the face and will need to be pumped out. This is due to the lower elevation of Bore No. 3 in comparison to Bore No. 4 at the location of CP-7. Measures are required to prevent the accumulation of groundwater in the cross passages to prevent softening of the invert, particularly in cross passages CP-6 and CP-7.

Baselines for inflow estimates are based on past experience during construction of the existing Caldecott Tunnels and inflow measurements made after completion of construction. Water ingress into the cross passages will occur from isolated pockets of water mostly within the Claremont formation, at the contact of Sobrante and Claremont formations, and within the Orinda Formation. It is expected that close proximity of Bore No. 4 and Bore No. 3 will significantly lower the ground water flush flows for the cross passages. The baseline for maximum flush inflow at the cross passages is 2.8 L/sec (44 gpm). This flush inflow is expected to decrease to steady state inflows within one week. Steady state inflows from the cross passages will be less than 1 L/sec (15 gpm).

Groundwater steady state inflows from the cross passages are included in the baselines described in Section 6.3.

7.5 Instrumentation and Monitoring

Cross passages will be instrumented to monitor displacements of the shotcrete lining around the tunnel perimeter similar to Bore No. 4 as described in Section 6.4.

8 Previous Tunnel Experience

This section provides information on previous tunneling in geologic conditions similar to those that will be encountered during Bore No. 4 construction. Table 8.1 summarizes tunnel geometries, excavation method, initial support systems, final linings, and adverse ground conditions encountered during previous tunneling projects. While previous tunnel experience is important for understanding the behaviors of similar geologic materials, it is noted that the applicability of past experience may be limited by differences in excavation and support methods, among other factors, as ground behaviors and support requirements are dependent on excavation and support methods.

8.1 Caldecott Bore Nos. 1 and 2

Caldecott Bore Nos. 1 and 2 run parallel to the proposed Bore No. 4 and are offset to the southeast approximately 100 m (328 ft). The tunnels of Bore Nos. 1 and 2 merge at the portals and are 30.5 m (100 ft) apart elsewhere. The first two bores are horseshoe shaped and have excavated dimensions of approximately 11 m (36 ft) wide and 10.4 m (34 ft) high. The lengths excavated were approximately 914 m (3,000 ft). The construction of these tunnels began in 1934 and was completed in 1937.

Construction records from 1934 to 1937 are the basis for the following observations. The tunnels cross the Sobrante, Claremont, and Orinda formations. The geologic conditions varied from "poorly consolidated to highly fractured brittle sedimentary rocks with near vertical bedding." This observation from inspection reports is interpreted to indicate rocks along the alignment were weak to moderately strong with closely spaced fractures in many locations following the USBR terminology shown in Figure 2.1. Occasionally faults and dikes were encountered during excavation. The tunnel excavation used a series of drifts around a central core. A timber arch was constructed within these drifts to support for the full tunnel section. The number of drifts and their extent changed along the tunnel. The core of rock remaining in the center of each bore was removed in successive stages after serving as support for the drifts and providing support for the tunnel face. During construction, inspection reports describe the ground condition as highly variable within the Claremont formation. Running ground was encountered occasionally within the Sobrante and Claremont formations, requiring heavy timber supports and breast boarding. The Orinda formation became "soft, plastic and unstable" when wet. Water running along the invert was "soaked up by the mudstone, which softened and tended to slough into the drifts". The timbers of the first two bores showed "a good deal of strain" in areas of wet mudstone. We interpret this to mean that slaking and softening, and possibly swelling, were common behaviors within the Orinda formation when wet.

Two cave-ins occurred during the construction of the 2nd Bore. The first cave-in occurred during replacement of timbers to allow for the full thickness of concrete lining. The cave-in occurred in the Preliminary Chert at its contact with the Second Sandstone. The cave-in extended to the ground surface 30 m (100 ft) above the tunnel, resulting in a sink hole developing at the surface.

The second cave-in occurred in Bore No. 2 under the highest point of the hill. According to Page (1950), the cave-in was caused by the weakness of a hydrothermally altered igneous dike 7.6 to 335 cm (3 in to 11 ft) wide, which occurred in a fault zone.

Gas and oil occurrences in the tunnels required safety modifications to equipment and routine gas tests after each round of blasting. One occurrence of methane was detected; however the inspection reports state that it was quickly dissipated. The ground was damp in most of the tunnel during the excavation, but occasionally yielded a groundwater flow of up to 15.8 L/sec (250 gpm). This flow of water fell to 1.6 L/sec (25 gpm) after 5 days.

The final lining was placed as the tunnel heading was being advanced. No specifics on the lag between the heading advance and the final lining placement are available, but the lag was 30 m (100 ft) in at least one situation. The final lining consists of a concrete arch 0.9 m (3 ft) thick above the springline, and thickened below the springline to 1.9 m (6.25 ft) at the footing elevation.

8.2 Caldecott Bore No. 3

Caldecott Bore No. 3 is a horseshoe shaped tunnel that runs parallel to the proposed 4th bore and is offset to the southeast approximately 32 m (105 ft). The excavated dimensions of Bore No. 3 are 14.3 m (47 ft) wide and 12.2 m (40 ft) high. The total excavation length is 975 m (3,200 ft).

The geologic setting and conditions encountered in Bore No. 3 were very close to those in Bore Nos. 1 and 2, except for the comparatively lower incidence of igneous dikes in Bore

No. 3. Bore No. 3 was built using advancement of top heading wall plate drifts followed by a top heading and bench excavation sequence. Wall plate drifts were carried ahead of the main tunnel excavation to install wall plates to support the top heading steel ribs. A crown drift was also used at the west portal area. The top heading drive from the west portal used a breast board jumbo and extended 614 m (2,015 ft). A shield was used on the top heading drive from the east portal to excavate the remaining 392 m (1285 ft). The top heading was completed from portal to portal prior to bench excavation. Benching was preceded by drilling of 0.6-m-diameter (2-ft-diameter) holes to the bottom of the footing grade, in which concrete pilasters were constructed to support the top heading wall plates.

Construction records from 1961 to 1964 are the basis for the following observations. During construction, the Resident Engineer described the ground conditions within the Sobrante formation as “badly fractured, wet and unstable material”. We interpret the term “badly fractured” to be consistent with the very close to moderate fracture spacing observed in borings drilled for Bore No. 4 within the Sobrante Formation, and the term “unstable material” to correspond to shallow or deep shear failure, raveling and block failure behaviors anticipated in the Sobrante Formation. The Claremont formation was characterized by numerous “sandstone dikes, slip-outs, and heavy ground conditions”, however portions of the Second Sandstone were reported to exhibit “excellent drill and shoot conditions” that did not require any timber support in the wall plate drifts. We interpret the term “slip-outs” to refer to shallow shear failure or block failure behaviors anticipated in the Claremont Formation. The Orinda formation was described as generally “blocky”, however the Orinda mudstones “deteriorated rapidly in water”. The wall plate drift from the east portal encountered “knee deep mud” at Sta. 231+36 in the Orinda Formation. We interpret the term “deteriorated rapidly in water” and “knee deep mud” to refer to slaking and softening behaviors. A large conglomerate block at the tunnel face failed along a softened mud seam.

Ground water inflow was described by McCarry[4] as “not a major issue” during the construction of Bore No. 3. He recalled that the average sustained inflows throughout construction were approximately 1.9 L/sec (30 gpm). Daily reports during construction indicate that isolated sustained flows of 1.6 to 3.2 L/sec (25 to 50 gpm) were encountered during the right drift excavation in the Claremont formation, and the groundwater was described as “raining hard overhead” in some locations within the Sobrante formation.

[4] Dennis McCarry (Resident Engineer), interview by Michael Capuzzi, November 1, 2004.

The final lining was constructed using forms supported on a hauling frame advanced on tracks. The final lining operations were concurrent with excavation of the bench. The lag between benching operations and final lining installation averaged 122 to 152 m (400 to 500 ft). The final lining is 0.9 m (3 ft) thick above springline and increases to 1.8 m (6 ft) thick at the footing elevation. The initial support steel ribs and pilasters are incorporated into the final lining.

8.3 Berkeley Hills BART Tunnel

The BART tunnels are horseshoe shaped tunnels excavated about 6.4 m (21 ft) wide and 6.4 m (21 ft) high. Conventional full face excavation methods used typical round lengths of 1.2 m (4 ft). The initial support was provided by 20-cm-wide (8-in-wide) flange steel sets at 0.6 to 1.2 m (2 to 4 ft) spacing and invert struts as required. The BART Geological Report (Bechtel, 1968) states that in the Portal Sandstone, crown bars and breast boards were used at the heading along with steel sets and invert struts used to support the tunnel section. The final lining is 46-cm-thick (18-in-thick) reinforced concrete. Typical tunnel reinforcement consisted of transverse and longitudinal No. 9 bars on 30 cm (12 in) centers placed on the intrados.

Construction records from 1965 to 1967 are the basis for the following observations. The BART Tunnel encountered all three of the formations found along the Bore 4 alignment. According to the BART geologic maps, the First Shale was “closely sheared in many places but blocky in others.” We interpret this to mean the First Shale is closely to very closely fractured, with minor occurrences of very intensely fractured clayey zones as well as sandstone, siltstone, claystone and argillite blocks. The First Shale was described as “moderately soft to hard” when dry, and exhibited slaking behavior when wet. We interpret this to mean the First Shale has a weak strength and low to moderate hardness in terms of the USBR terminology. The Portal Sandstone was described as “gray, friable to well cemented, predominantly fine-grained, and blocky.” The Portal Sandstone was “moderately hard” with scattered sheared interbeds of shale. We interpret this to mean the Portal Sandstone had low to moderate hardness in terms of USBR terminology. Blasting within the Portal Sandstone typically required 0.2 to 0.9 kg (0.5 to 2.0 lbs) of explosives per cubic yard of material. The Shaly Sandstone was described as “slabby, with fractures spaced at [2.54 to 91 cm] 1 inch to 3 feet, and generally breaks along shear surfaces that are highly polished.” This observed range of fracture spacing is consistent with the ground class to which the Shaly Sandstone belongs. We interpret “slabbing” behavior to correspond to slaking and softening. The

Second Sandstone was described as "moderately hard with shale interbeds and igneous dikes, with fractures spaced at [2.54 to 61 cm] 1 inch to 2 feet." The BART tunnel also encountered "thinly bedded chert that was hard and closely fractured" with numerous igneous dikes. We interpret the term "hard" here to be consistent with the low to moderate hardness (per the USBR terminology) observed in the Preliminary Chert and Claremont Chert and Shale. We also interpret the terms "thinly bedded" and "closely fractured" to be consistent with USBR terminology. Approximately 15 m (50 ft) of the Berkeley Hills BART tunnels was constructed in faulted and sheared ground within the Orinda Formation east of the fault contact with the Claremont Formation. This required split spacing of the steel sets.

8.4 Claremont Tunnel

The Claremont Tunnel is a 5.6-km-long (3.5-mi-long) horseshoe-shaped tunnel located north of the BART Tunnels, with a finished diameter of 2.7 m (9 ft). The Claremont Tunnel encountered the Claremont and Orinda Formations in common with Bore No. 4. Initial support used on the Claremont Tunnel through the Claremont and Orinda formations consists of timber sets, ranging in size from 20 x 20 cm to 30 x 30 cm at 1.8 m spacing (8 x 8 in to 12 x 12 in at 6 ft).

Construction records from 1926 to 1929 are the basis for the following observations. The reach of the Claremont Tunnel through the Orinda Formation consisted of "fair to poor rock conditions", and included "swelling, slaking, and squeezing" ground conditions. We interpret the historic report of "squeezing" to be attributable to radial convergence of the tunnel perimeter due to shallow shear failure and swelling behavior. One specific location in the Orinda formation about 12 m (40 ft) wide was described as "exceedingly bad swelling ground", indicating the possibility for a minor occurrence of material with a high swell potential. The average advance rate was approximately 215 meters per month (705 feet per month) in the Orinda formation. The advance rate in the Claremont formation was between 60 and 185 meters per month (197 and 607 feet per month), indicating more difficult ground. Although groundwater inflows were not measured during construction of the Claremont Tunnel, heavy or unusual flows were noted during tunnel construction. However, no unusual or heavy groundwater inflows were noted in the Claremont or Orinda formations. Inspection reports note oil seepages and gas occurrences within the Orinda formation. They also note 2 oil and gas fires in the Orinda Formation; one was noted as burning for 2 hours, while the other was noted as burning for 30 days.

The final concrete lining thickness over timber support is about 10 cm (4 in) in the Claremont and Orinda formations. Reinforcement was only used at two locations throughout the Claremont and Orinda Formations.

Systematic contact grouting, lining repairs and lining invert replacement were recently performed within reaches of poor quality ground along the Claremont Tunnel. This work was performed during two periods: November 2005 to February 2006, and November 2006 to February 2007. The upgrade work done within the Orinda Formation consisted of reinforcing the structural integrity of the lining by grouting and by installing supplemental lining in the areas of swelling ground. The areas associated with swelling ground within the Orinda Formation were identified by cracks in the lining that did not yield significant quantities of water.

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GLOSSARY

Abrasivity: Characteristic of rock which contributes to the wearing down of surfaces that are in frictional contact with the rock.

Alteration: Any change in the mineralogic composition of a rock brought about by physical or chemical means, esp. by the action of hydrothermal solutions. See Hydrothermal alteration.

Anastomosing: Branching and recombining to form a netlike pattern.

Argillite: A compact rock derived from mudstone or shale, more highly indurated than either of those rocks. It lacks the fissility of shale or the cleavage of slate. It is regarded as product of weak metamorphism.

Bed: A distinct layer of sediment or sedimentary rock.

Bedding plane: A surface that separates each layer from those above or below in sedimentary or stratified rocks. It usually records a change in depositional circumstances by grain size, composition, color, or other features. The rock may tend to split or break readily along bedding planes.

Benching: Excavation of large area in stages by benches.

Bimodal distribution: A continuous probability distribution with two different modes.

Blocky (GSI): A rock mass with well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets.

Blocky/Disturbed/Seamy (GSI): A folded rock mass with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity.

Cave-in: Failure of tunnel by caving.

Chert: A hard, dense microcrystalline or cryptocrystalline sedimentary rock, consisting chiefly of interlocking crystals of quartz less than about 30 μm (0.001 in) in diameter; it may contain amorphous silica (opal).

Clast: An individual constituent, block, grain, or fragment of a detrital sediment or sedimentary rock, produced by the physical disintegration of a larger rock mass. Also the harder rock blocks or fragments within the softer matrix of conglomerates.

Claystone: Non-fissile, fine-grained rock consisting of compacted particles, at least two-thirds of which are less than about 0.004 mm (0.0002 in) in size. In this report, the term claystone includes rocks classified in the field as mudstone or claystone.

Clayey: In accordance with the USCS soil classification, containing more than 12% clay particles (less than 0.004 mm [0.0002 in] in size).

Coarse (grained): Grain size of 3.18 mm (0.125 in) and greater.

Conglomerate: Sedimentary rock made of at least 20% rock fragments greater than 2 mm (0.08 in) in size in a finer-grained matrix.

Construction water: Water collected at sump due to construction activities including drilling, dust control, concrete mix, equipment wash, and leakage from water supply and drainage. Construction water does not include groundwater.

Contorted bedding: Refer to "convoluted bedding".

Convoluted bedding: Intricately crumpled or folded bedding at the scale of the tunnel face.

Cross passage: Smaller size tunnel connection between two parallel or semi-parallel tunnels.

Dike: A tabular body of rock that cuts across the structure of adjacent rocks or massive rocks.

Discontinuity: A general term for any mechanical break or fracture in a rock mass having zero to low tensile strength. It is the collective term for most types of joints, weak bedding planes, foliation planes, fractures, faults, and discrete shears.

Discontinuity Surface Conditions (GSI): Quality of the discontinuity surfaces within a rock mass.

- **Very Good:** Very rough, fresh unweathered surfaces.
- **Good:** Rough, slightly weathered, iron stained surfaces.
- **Fair:** Smooth, moderately weathered and altered surfaces.
- **Poor:** Slickensided, highly weathered surfaces with compact coatings or fillings or angular fragments.
- **Very Poor:** Slickensided, highly weathered surfaces with soft clay coatings or fillings.

Discrete Shear: A fracture that along which one part of a rock has moved past an adjacent part but magnitude of movement cannot be determined.

Disintegrated (GSI): A poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces.

Dolomite: A sedimentary rock of which more than 50% by weight consists of the mineral dolomite. Most dolomite is associated, and often interbedded, with limestone.

Fault: A fracture or fracture zone along which there has been apparent displacement of the sides relative to one another parallel to the fracture. The evidence for such displacement can be juxtaposed rock types, brecciation and/or gouge and slickensides.

Fault zone: An area with multiple sub-parallel faults, or a tabular band of finite width containing brittle, very intensely fractured rock and gouge.

Fine (grained): Grain particles not visible to just barely visible with the naked eye.

Fissile: Capable of being easily split along closely spaced planes.

Flush flow: Initial tunnel inflow occurring over a 30-m-long (98-ft-long) heading section of the tunnel; the amount of water to be expected can vary significantly depending on the permeability of and storage of water in the encountered rock mass.

Foliation: A general term for a planar arrangement of textural or structural features in any type of rock. Discontinuities parallel to foliation are referred to as foliation joints or discrete shears depending on the nature of the discontinuities.

Fracture: Any break in rock along which no significant movement has occurred.

Friable: Said of a rock specimen that is easily crumbled by hand, e.g., a poorly cemented sandstone.

GSI: See "Geological Strength Index."

Geological Overbreak: see section "Tunnel Excavation and Support" of the Special Provisions.

Geological Strength Index (GSI): Rock mass classification system based on rock mass structure and the quality of the discontinuity surface conditions as described by Hoek and Marinos, 2000.

Geologic Unit: Rock mass classification according to similar lithology.

Glauconite: A green mineral, closely related to mica, that is essentially hydrous potassium iron silica. It is an indication of very slow sedimentation.

Gouge: A soil-like material composed of very intensely fractured and pulverized rock resulting from fault movement. Composed of varying combinations of clay, silt, sand, and gravel, but typically a clayey gravel or gravelly clay. Composition depends on parent rock, amount of movement, and degree of alteration or weathering.

Ground behavior: Reactions or phenomena of the tunnel ground mass as it is excavated and exposed including the following behaviors modified from "Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation," Draft English Translation, 2004, Austrian Society for Geomechanics.

Behavior	Description of failure modes and manifestations in an unsupported tunnel
Block failures	Discontinuity-controlled, gravity-induced failure of rock blocks that manifest as falling and sliding of blocks.
Raveling	Progressive, discontinuity controlled failure of small rock blocks within the general rock mass at or near the excavation surface. Raveling is manifested as successive fallout of small rock blocks, and can ultimately result in a significant void beyond the tunnel perimeter.
Shallow shear failure	Shallow shear failures result from overstressing of the ground within 0.25D to 0.5D of the tunnel perimeter (D=tunnel diameter), and may be enhanced by the potential for discontinuity and gravity-controlled failure modes. Shallow shear failure is manifested by moderate inward movement of the tunnel perimeter, including invert heave, and possibly by movement of rock into the tunnel opening along discontinuities.
Deep shear failures	Deep-seated shear failures result from overstressing of the ground beyond 0.25D to 0.5D from the tunnel perimeter (D=tunnel diameter). Deep-seated shear failure manifests as large radial convergence of the tunnel perimeter, including invert heave.
Slaking/softening	Slaking is the deterioration and breakdown of intact rock upon exposure by excavation and manifests as slabbing of material from the crown and sidewalls. The severity of this behavior (see Table 5.3) is assessed on the basis of slake durability tests performed according to ASTM Test Method 4644. Softening, which is dependent on wetting and exposure by excavation, is the reduction of intact rock strength at the invert or elsewhere and manifests as the development of a muddy or unstable invert or sloughing along segments of the tunnel perimeter elsewhere.
Swelling	Swelling occurs due to absorption of water by clay minerals in rock upon excavation-induced unloading. Swelling manifests as movement of the ground into the tunnel opening or additional tunnel support loading. Swelling of rock at the excavation boundary contributes to softening.
Crown instability due to low cover	Excessive crown geological overbreak and chimney-type failure will occur due to lack of confinement under low cover reaches at portals that manifest as block fallout and raveling above the crown.

Heading: see section “Tunnel Excavation and Support” of the Special Provisions.

Hydrothermal alteration: Alteration of rocks or minerals by the reaction of hydrothermal (hot) water with pre-existing solid phases.

Intact or Massive (GSI): Intact rock specimens or massive in situ rock with few widely spaced discontinuities.

Interbedded: Layer of rock lying between or alternating with layers of a different kind of rock.

Invert arch: Concaved, arch-shaped invert designed to accommodate uplift pressure or displacement in the tunnel invert.

Joint: A discontinuity such as a fracture or parting in a rock exhibiting no evidence of shear displacement.

Joint set: A group of joints which have similar dip and dip direction within a region or area

Laminated/Sheared (GSI): Lack of blockiness due to close spacing of weak schistosity or shear planes.

Lithology: The description of rocks on the basis of physical characteristics such as mineralogic composition and grain size. The rock description may be qualified by color or structure.

Medium (grained): Grain particles barely visible to easily visible with naked eye. Grain size up to 3.18 mm (0.125 in).

Multiple Ground Class Section: Occurrence of a combination of ground classes within the same tunnel section or face.

Muck: Material generated during tunnel construction activities including rock, soil, or gouge; by-products of tunneling construction operations such as wasted, damaged, or unused construction materials; and inert materials such as residue from blasting products.

Mudmat: An artificial layer of granular material that replaces or is placed over swelling or softening material to provide a stable and durable work surface.

Mudstone: A very fine-grained, non-fissile sedimentary rock in which the proportions of clay and silt are approximately equal.

Outcrop: Part of a geologic formation or structure that appears at the surface of the earth.

Persistence: Continuous length of a joint through a rock mass.

Porcelanite: A dense, siliceous rock having the texture, dull luster, and general appearance of unglazed porcelain. It is less hard, dense, and vitreous than chert. The term has been used for an impure chert, for a baked clay or shale found in the roof or floor of a burned-out coal seam, and for a fine-grained acidic tuff compacted by secondary silica.

Probe hole: A drilled hole within ground to be excavated to characterize the ground in advance and predict ground behavior.

Pre-support: see section “Tunnel Excavation and Support” of the Special Provisions.

Raveling: Refer to “ground behavior.”

Reach: A single continuous portion of tunnel alignment.

Rock: Aggregate, consisting of mineral components, developed from natural processes.

Rock mass: Part of the earth's crust, composed of intact rock, discontinuities, soil-like discontinuity infillings, and voids filled with liquids or gases.

Rock Mass Structure (GSI): Refers to the overall arrangement, degree of interlocking, and shape of rock blocks formed by discontinuities in a rock mass at the scale of the tunnel diameter. Refer to “Intact or Massive,” “Blocky,” “Very Blocky,” “Blocky/Distubed/Seamy,” “Disintegrated,” and “Laminated/Sheared.”

Rock Mass Type (RMT): Rock mass classification according to similar geological and geotechnical characteristics.

Sandstone: A medium-grained, clastic sedimentary rock composed predominantly of sand sized mineral grains. The grains are commonly cemented with silica, iron oxide or calcium carbonate.

Sandstone dike: A tabular or irregularly shaped intrusive sandstone body that cuts across the rock structure.

Sandstone sill: a tabular or irregularly shaped sandstone body that has intruded along the rock structure.

Shale: Sedimentary rock derived from finely laminated (bedded) mud; is fissile. Particles in shale are commonly clay minerals mixed with tiny grains of quartz eroded from pre-existing rocks.

Shear(ed): Deformation resulting from the sliding movement of one body past another.

Shear zone: Tabular region of sheared rock or tabular region containing closely spaced (see Figure 1) discrete shears.

Siliceous: Containing abundant silica.

Sill: A tabular volcanic intrusion that parallels the planar structure of the surrounding rocks.

Siltstone: Sedimentary rock lacking fissility in which the mud fraction is over two-thirds silt (0.004 to 0.062 mm [0.00016 to 0.0024 in]).

Silty: In accordance with the USCS soil classification, containing more than 12% silt particles (0.1 to 0.004 mm [0.0039 to 0.00016 in] in size).

Slabbing: Failure of excavated rock surface in slabs or flat pieces.

Slaking: Refer to "ground behavior."

Slickensides: Scratches or grooves on a discontinuity surface which formed by shear displacement along the discontinuity.

~~Sloping~~ Face supporting core: A berm of unexcavated rock or soil with unsupported slopes against the tunnel face in order to stabilize the tunnel face without installing face support.

Sloughing: Rock coming loose and detaching from the excavation boundary, can be aggravated by exposure to water..

Softening: Refer to "ground behavior."

Squeezing: Plastically extruding ground into the tunnel without visible fracturing or loss of continuity, not related to change in ground water condition. Also, ductile, plastic yield and flow due to overstress.

Steady state inflow: Condition where a constant magnitude of tunnel inflow is reached following the lowering of groundwater levels such that the rate of recharge to the surrounding rock mass is equal to the tunnel inflow. Seasonal fluctuations in groundwater recharge may cause changes to the inflow once the steady state condition is reached.

Strike: The direction or trend of a bedding plane or fault as it intersects the horizontal.

Strike-slip fault: General term for a vertical or nearly vertical fault which has experienced horizontal displacement parallel to the fault strike, producing lateral relative motion of the rock on either side.

Structure: A geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks.

Swelling: Refer to "ground behavior."

Tectonic: Of or relating to forces in the earth's crust.

Thrust fault: Fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.

Unconformable: Description of strata that do not succeed underlying rocks in immediate order of age or in parallel position.

Very Blocky (GSI): Interlocked, partially disturbed rock mass with multi-faceted angular blocks formed by 4 or more discontinuity sets.

ABBREVIATIONS

BART	Bay Area Rapid Transit
Cal/OSHA	California Occupational Safety and Health Administration
Caltrans	California State Department of Transportation
CCTA	Contra Costa Transportation Authority
CEE	Construction Evaluation Earthquake
cfm	cubic feet per minute
CG	Combustible Gas Indicator
cm	centimeter(s)
FEE	Functional Evaluation Earthquake
ft	feet
ft/s	feet per second
ft^3	cubic feet
GBR	Geotechnical Baseline Report
GDR	Geotechnical Data Report
GPa	Giga Pascal
gpm	gallon(s) per minute
GSI	Geological Strength Index
in	inch(es)
ISRM	International Society of Rock Mechanics
km	kilometer(s)
kN	kilo-Newton
kN/m^3	kilo-Newton per cubic meter
kPa	kilo-Pascal
ksf	kip(s) per square foot
ksi	kip(s) per square inch
L/min	Liter per minute
L/sec	Liter per second
lbs	Pounds
m	meter(s)
m/s	meter(s) per second
m^3	cubic meter(s)
m^3/min	cubic meter(s) per minute
Ma	Mega-annum or Mega year

mi	mile(s)
MN	Mega Newton
mm	millimeter(s)
MPa	Mega Pascal
NATM	New Austrian Tunneling Method
OMC	Operations, Maintenance and Control
pcf	pound(s) per cubic feet
PID	Photoionization Detector
PLI	Point Load Index
psi	pound(s) per square inch
RMT	Rock Mass Type
RQD	Rock Quality Designation
SC	Support Category
SEE	Safety Evaluation Earthquake
SEM	Sequential Excavation Method
SFBR	San Francisco Bay Region
SR	State Route
Tc	Chert and Shale
Tcp	Preliminary Chert
Tcs	Second Sandstone
Tor	Orinda Formation
Tsf	First Shale
Tsp	Portal Sandstone
Tss	Shaly Sandstone
UCS	Unconfined Compressive Strength
USBR	United States Bureau of Reclamation
yd^3	cubic yard(s)

TABLES

Table 3.1 Major Faults

Fault Zone No.	Location	Approximate Fault Contact Station	Fault Dip
1	First Shale/Portal Sandstone contact	107+75	30° to 45° NE across bedding
2	Preliminary Chert/Second Sandstone contact	109+34	90° NE
3	Second Sandstone/Claremont Chert and Shale contact	110+57	85° SW across bedding
4	Claremont Chert and Shale/Orinda Formation contact	114+00	80° SW along bedding

*Major faults strike sub-perpendicular to the tunnel alignment. See Section 4 for geologic descriptions of faults

Table 3.2 Average Joint Set and Bedding Orientation

Geologic Unit	Set	Dip	Dip Direction
First Shale	J1 J2 B1	84° 54° 45°	55° 340° 80°
Portal Sandstone Shaly Sandstone	J1 J2 J3 B1	10° 69° 78° 78°	290° 23° 270° 53°
Preliminary Chert	J1 J2 B1 B2	72° 38° 73° 47°	191° 142° 53° 212°
Second Sandstone	J1 J2 B1	71° 64° 47°	339° 300° 220
Claremont Chert & Shale	J1 J2 B1, S1 S2 S3 S4	84° 62° 64° 40° 40° 90°	146° 67° 227° 155° 335° 0°
Orinda Formation	J1 J2 B1, S1 S2 S3 S4	80° 6° 84° 40° 40° 90°	295° 102° 215° 155° 335° 0°

Key: J – Joint Set
B – Bedding
S – Shear

Randomly oriented joints occur in all geologic units.

Table 4.1 Rock Mass Type Data

Rock Mass Type			Tsf	Tsp	Tss-1	Tss-2	Tcp	Tcs-1	Tcs-2	Tcs-3	Tc-1
Lithology/Structure			Disintegrated to blocky/disturbed/seamy silty-shale with clayey shears	Blocky/disturbed/seamy sandstone	blocky/disturbed/seamy to very blocky silty-sandstone sandstone	Disintegrated sandstone with clay joint fillings	Disintegrated to Blocky/disturbed/seamy chert and shale	Blocky sandstone	blocky/disturbed/seamy to very blocky sandstone	Disintegrated to blocky/disturbed/seamy sandstone with local beds of very intensely fractured cherty shale	Very blocky chert and shale with few clay fillings
Average Measured Unit Weight			22.8 kN/m^3 (145 pcf)	25.2 kN/m^3 (160 pcf)	25.2 kN/m^3 (160 pcf)	25.2 kN/m^3 (160 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)
Seismic Velocity		P-wave	811 to 2760 m/s (2,660 to 9,050 ft/s)[1]	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured
		S-Wave	457 to 732 m/s (1,500 to 2,400 ft/s)[1]	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured
Intact Rock	UCS[3]	Range	2.8 to 40.1 MPa (400 to 5,810 psi)	17.0 to 158 MPa (2,465 to 22,912 psi)	10.8 to 127 MPa (1,566 to 18,410 psi)	10.8 to 127 MPa (1,566 to 18,410 psi)[3a]	17.2 to 110 MPa (2,500 to 15,990 psi)[3b]	8.1 to 38.3 MPa (1,175 to 5,554 psi)	10.5 to 27.5 MPa (1,523 to 3,988 psi)	7.5 to 15.9 MPa (1,088 to 2,306 psi)	20.1 to 116.3 MPa (2,915 to 16,864 psi)
	Estimated m_i	Range	6 to 8	15 to 19	14 to 18	14 to 18	6 to 9	15 to 19	15 to 19	13 to 17	7 to 9
	Young's Modulus[4]	Measured Range[4]	3.1 to 9.5 GPa (445 to 1,380 ksi)	12.4 to 23.7 GPa (1,800 to 3,440 ksi)	4.4 to 17.3 GPa (635 to 2,510 ksi)	3.9 to 8.4 GPa (560 to 1,220 ksi)	6.2 to 34.5 GPa (910 to 5,000 ksi)	1.9 to 9.4 GPa (280 to 1,360 ksi)	1.9 to 9.4 GPa (280 to 1,360 ksi)	1.9 to 9.4 GPa (280 to 1,360 ksi)	1.9 to 9.4 GPa (280 to 1,360 ksi)
		Design	1.2 GPa (180 ksi)	12.8 GPa (1,850 ksi)	8.1 GPa (1,180 ksi)	8.1 GPa (1,180 ksi)	22.8 GPa (3,300 ksi)	4.5 GPa (650 ksi)	4.5 GPa (650 ksi)	4.5 GPa (650 ksi)	22.8 GPa (3,300 ksi)
Rock Mass Properties	GSI	Range	23 to 30	30 to 38	30 to 53	21 to 27	23 to 35	45 to 63	40 to 45	25 to 50	40 to 50
		Mean	26	34	38	24	28	56	42	35	45
	Estimated Deformation Modulus[5]	Lower Bound to Mean	240 to 410 MPa (35 to 60 ksi)	1,380 to 2,070 MPa (200 to 300 ksi)	690 to 1,380 MPa (100 to 200 ksi)	410 to 830 MPa (60 to 120 ksi)	690 to 1,380 MPa (100 to 200 ksi)	1,030 to 2,070 MPa (150 to 300 ksi)	690 to 1,030 MPa (100 to 150 ksi)	345 to 690 MPa (50 to 100 ksi)	3,100 to 4,480 MPa (450 to 650 ksi)
	Estimated Poisson Ratio		0.25 to 0.35	0.2 to 0.3	0.2 to 0.3	0.25 to 0.35	0.25 to 0.35	0.2 to 0.3	0.2 to 0.3	0.25 to 0.35	0.2 to 0.3
Joints	Measured Density		very intensely to intensely fractured	very intensely to moderately fractured	very intensely to slightly fractured	very intensely to moderately fractured	very intensely to moderately fractured	very intensely to slightly fractured	intensely to slightly fractured	very intensely to moderately fractured	very intensely to slightly fractured
	Estimated Shear Strength	Peak	27° to 32°	27° to 35°	25° to 29°	25° to 29°	24° to 29°	29° to 33°	29° to 33°	29° to 33°	22° to 26°
		Residual	16° to 25°	25° to 30°	23° to 26°	23° to 26°	23° to 27°	28° to 31°	28° to 31°	28° to 31°	22° to 25°
Estimated Bedding Shear Strength		Peak	30° to 35°	39° to 42°	31° to 36°	31° to 36°	22° to 25°	35° to 40°	35° to 40°	35° to 40°	23° to 26°
		Residual	25° to 32°	32° to 35°	29° to 33°	29° to 33°	20° to 23°	32° to 35°	32° to 35°	32° to 35°	22° to 25°
Measured Slake Durability of Intact Rock (no. of tests)			22 to 69 (5)	20 to 96 (3)	0 to 96 (4)		Not Measured	sandstone: 4 to 71 (5) cherty shale (only Tcs-3): 91 (1)			12 to 99 (7)
Swelling	Measured Free Swelling Strain	Range	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured
	Measured Max. Swelling Pressure	Range	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured
	Potentially Swelling Lithologies		None	None	None	None	None	None	None	None	None

Table 4.1 (Continued) Rock Mass Type Data

Rock Mass Type			Tc-2	Tc-3	Tc-4a	Tc-4b	Tc-5a	Tc-5b	Tor-1	Tor-2	Tor-3
Lithology/Structure			Blocky/disturbed/seamy chert and shale with few clay fillings	Very blocky shale, siltstone, sandstone and claystone	Disintegrated to blocky/disturbed/seamy chert and shale with weak sandstone dikes	Disintegrated to blocky/disturbed/seamy chert and shale	Disintegrated chert and shale with thick, local clayey shears or moderately to severely altered dikes	Blocky/disturbed/seamy shale, siltstone, sandstone and claystone with thick, clayey shears or moderately to severely altered dikes	Blocky to massive interbedded mudstone, siltstone, sandstone, and conglomerate with local shears and slickensided or clayey joints	Very blocky interbedded mudstone, siltstone, sandstone, and conglomerate with local shears and slickensided or clayey joints	Blocky/disturbed/seamy interbedded mudstone, siltstone, sandstone, and conglomerate with local slickensided or clayey joints
Average Measured Unit Weight			24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.4 kN/m^3 (155 pcf)	24.2 kN/m^3 (154 pcf)	24.2 kN/m^3 (154 pcf)	24.2 kN/m^3 (154 pcf)
Seismic Velocity		P-wave	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	1,430 to 4,270 m/s (4,700 to 14,000 ft/s)[2]
		S-Wave	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	Not Measured	640 to 1420 m/s (2,100 to 4,650 ft/s)[2]
Intact Rock	UCS[3]	Range	21.7 to 145 MPa (3,147 to 20,995 psi)	3.8 to 114 MPa (551 to 16,467 psi)	3.9 to 103.1 MPa (566 to 14,950 psi)[3c]	17.2 to 103.1 MPa (2,500 to 14,950 psi)[3d]	17.2 to 103.1 MPa (2,500 to 14,950 psi)[3d]	3.8 to 114 MPa (551 to 16,467 psi)[3e]	0.7 to 39.3 MPa (102 to 5,699 psi)	1.0 to 90.6 MPa (145 to 13,140 psi)	1.1 to 21.1 MPa (160 to 3,060 psi)
	Estimated m_i	Range	7 to 9	6 to 8	11 to 13	7 to 9	7 to 9	6 to 8	6 to 9	6 to 9	6 to 9
	Young's Modulus[4]	Measured Range	6.2 to 34.5 GPa (910 to 5,000 ksi)	3.5 to 9.6 GPa (510 to 1,390 ksi)	-	6.2 to 34.5 GPa (910 to 5,000 ksi)	6.2 to 34.5 GPa (910 to 5,000 ksi)	3.5 to 9.6 GPa (510 to 1,390 ksi)	0.4 to 9.4 GPa (60 to 1,358 ksi)	0.4 to 9.4 GPa (60 to 1,358 ksi)	0.4 to 9.4 GPa (60 to 1,358 ksi)
		Design	22.8 GPa (3,300 ksi)	6.1 GPa (880 ksi)	10.3 GPa (1,500 ksi)	22.8 GPa (3,300 ksi)	22.8 GPa (3,300 ksi)	-	2.4 GPa (350 ksi)	2.4 GPa (350 ksi)	1.6 GPa (225 ksi)
Rock Mass Properties	GSI	Range	30 to 42	41 to 46	28 to 40	28 to 36	15 to 30	20 to 28	50 to 69	35 to 52	40 to 61
		Mean	36	45	33	33	22	24	58	45	47
	Estimated Deformation Modulus[5]	Lower Bound to Mean	1,380 to 2,410 MPa (200 to 350 ksi)	1,380 to 2,070 MPa (200 to 300 ksi)	1,030 to 1,380 MPa (150 to 200 ksi)	1,380 to 2,070 MPa (200 to 300 ksi)	345 to 690 MPa (50 to 100 ksi)	345 to 690 MPa (50 to 100 ksi)	1,030 to 1,380 MPa (150 to 200 ksi)	345 to 1,030 MPa (50 to 150 ksi)	310 to 690 MPa (45 to 100 ksi)
	Estimated Poisson Ratio		0.25 to 0.35	0.2 to 0.3	0.25 to 0.3	0.25 to 0.3	0.2 to 0.3	0.2 to 0.3	0.2 to 0.3	0.2 to 0.3	0.25 to 0.35
Joints	Measured Density		very intensely to slightly fractured	very intensely to slightly fractured	very intensely to slightly fractured	very intensely to slightly fractured	very intensely to moderately fractured	very intensely to moderately fractured	very intensely to very slightly fractured	very intensely to very slightly fractured	very intensely to very slightly fractured
	Estimated Shear Strength	Peak	22° to 26°	22° to 26°	22° to 26°	22° to 26°	22° to 26°	22° to 26°	22° to 29°	22° to 29°	22° to 29°
		Residual	22° to 25°	22° to 25°	22° to 25°	22° to 25°	22° to 25°	22° to 25°	20° to 26°	20° to 26°	20° to 26°
Estimated Bedding Shear Strength		Peak	23° to 26°	23° to 26°	23° to 26°	23° to 26°	23° to 26°	23° to 26°	27° to 34°	27° to 34°	27° to 34°
		Residual	22° to 25°	22° to 25°	22° to 25°	22° to 25°	22° to 25°	22° to 25°	25° to 30°	25° to 30°	25° to 30°
Measured Slake Durability of Intact Rock (no. of tests)			12 to 99 (7)						claystone/siltstone: 1 to 48 (7) claystone/siltstone mixed with sandstone: 1 to 86 (7) sandstone/conglomerate: 41 to 82 (5)		
Swelling	Measured Free Swelling Strain	Range	Not Measured	0.3 to 13.7 %	Not Measured	Not Measured	Not Measured	0.3 to 13.7 %	1.8 to 12.2 %	1.8 to 12.2 %	1.8 to 12.2 %
	Measured Max. Swelling Pressure	Range	Not Measured	14 to 781 kPa (2 to 113 psi)	Not Measured	Not Measured	Not Measured	14 to 781 kPa (2 to 113 psi)	22 to 941 kPa (3 to 136 psi)	22 to 941 kPa (3 to 136 psi)	22 to 941 kPa (3 to 136 psi)
	Potentially Swelling Lithologies		None	shale, siltstone, sandstone w/ high clay content	None	None	None	shale, siltstone, sandstone w/ high clay content	claystone, siltstone, sandstone w/ high clay content		

Notes:

1. Range of seismic velocity increasing over depth 0 to 9.8m (0 to 32 ft) below ground surface.
2. Range of seismic velocity increasing over depth 0 to 45.7m (0 to 150) ft below ground surface.
3. UCS range is the measured range from UCS tests and PLI tests unless noted as follows: 3a. The UCS range for Tss-1 and Tss-2 are estimated to be the same due to their similar lithologies; 3b. Lower bound of UCS range for Tcp is based on field index tests; 3c. The measured UCS range for sandstone dikes is 3.9 to 34.4 MPa (566 to 4995 psi); 3d. The lower bound of the UCS range is estimated from field index tests; 3e. UCS range for Tc-5b is estimated from test results from Tc-3.
4. The range shown for intact rock Young's modulus are estimates of unloading/reloading modulus, not the modulus from the virgin compression. Refer to Geotechnical Data Report for virgin loading modulus.
5. Range shown for the estimated rock mass deformation modulus reflect lower bound and mean values used in design.

Table 5.1 Ground Behaviors in Tunnel Section

Anticipated Ground Behaviors	Rock Mass Type Shaded by Ground Class																					
	Tsf	Tsp	Tss-1	Tss-2	Tcp	Tcs-1	Tcs-2	Tcs-3	Tc-1	Tc-2	Tc-3	Tc-4a	Tc-4b	Tc-5a		Tc-5b		Tor-1	Tor-2		Tor-3	
Block Failure		P	P		S	P	P	S	P	P	P	P	P					P	P	S	P	S
Raveling	S	S	S	S	S	S*	S	S	S	S	S	S	S	S	S	S	S	S*	S*	S*	S	S*
Shallow shear failure	S								S	S	S	S	S					S*	S		S	
Deep shear failure				P	P			P						P	P	P	P			P		P
Slaking/ softening	S		S	S		S	S	S			S			S	S	S	S	S	S	S	S	S
Swelling											S					S	S	S	S	S	S	S
Crown instability due to low cover	P																					

* in association with very intensely to intensely fractured rock zones and shear zones

Legend

Predominant Behavior P

Secondary Behavior S

Ground Class 1a

Ground Class 1b

Ground Class 2a

Ground Class 2b

Ground Class 3a

Ground Class 3b

Ground Class 4

Table 5.2 Engineering Properties of Ground Classes1

Ground Class		Ground Class 1	Ground Class 2	Ground Class 3	Ground Class 4
UCS (Intact Rock)	Baseline	Tcs-1 8.1 to 38.3 MPa (1,175 to 5,554 psi) Tor-1 0.7 to 96.5 MPa (102 to 14,000 psi)[2]	Tor-2 1.0 to 96.5 MPa (145 to 14,000 psi)[2] Tsp 17.0 to 158 MPa (2,465 to 22,912 psi) Tss-1 10.8 to 127 MPa (1,566 to 18,410 psi) Tcs-2 10.5 to 27.5 MPa (1,523 to 3,988 psi) Tc-1 20.1 to 158.6 MPa (2,915 to 23,000 psi)[3] Tc-2 21.7 to 158.6 MPa (3,147 to 23,000 psi)[3] Tc-3 3.8 to 114 MPa (551 to 16,467 psi) Tc-4a 3.9 to 158.6 MPa (566 to 23,000 psi)[3] Tc-4b 17.2 to 158.6 MPa (2,500 to 23,000 psi)[3] Tor-3 1.1 to 96.5 MPa (160 to 14,000 psi)[2]	Tss-2 10.8 to 127 MPa (1,566 to 18,410 psi) Tcp 17.2 to 158.6 MPa (2,500 to 23,000 psi)[3] Tcs-3 7.5 to 15.9 MPa (1,088 to 2,306 psi) Tc-5a 17.2 to 158.6 MPa (2,500 to 23,000 psi)[3] Tc-5b 3.8 to 114 MPa (551 to 16,467 psi) Tor-2 1.0 to 96.5 MPa (145 to 14,000 psi)[2] Tor-3 1.1 to 96.5 MPa (160 to 14,000 psi)[2]	Tsf 2.8 to 40.1 MPa (400 to 5,810 psi)
CAI	RMT Baseline Max.	Tcs-1: 1.0 Tor-1: 0.8	Tor-2: 0.8 Tsp: 1.2 Tss-1: 1.1 Tcs-2: 1.0 Tc-1: 3.0 Tc-2: 3.0 Tc-3: 3.0 Tc-4a: 3.0 Tc-4b: 3.0 Tor-3: 0.8	Tss-2: 1.1 Tcp: 1.4 Tcs-3: 1.4 Tc-5a: 3.0 Tc-5b: 3.0 Tor-2: 0.8 Tor-3: 0.8	Tsf: 1.6
	[Igneous dikes][4] (Orinda Conglomerate)[5]	[3.4] (6.3)	[3.4] (6.3)	[3.4] (6.3)	[3.4]

Table 5.2 (continued)

Ground Class		Ground Class 1	Ground Class 2	Ground Class 3	Ground Class 4
Slake Durability	Range	Tcs-1: 0-71 Tor-1: 0-86	Tor-2: 0-86 Tsp: 90-100[6] Tss-1: 0-96 Tcs-2: 0-71 Tc-1: 60-100[6] Tc-2: 60-100[6] Tc-3: 60-85[6] Tc-4a: 10-100 Tc-4b: 60-100[6] Tor-3: 0-86	Tss-2: 0-96 Tcp: 10-100 Tcs-3: 0-91 Tc-5a: 10-100 Tc-5b: 10-85 Tor-2: 0-86 Tor-3: 0-86	Tsf: 20-70

1. Ground Class baseline range is from minimum to maximum of RMT values shown.
2. Upper bound baseline for the intact rock UCS is based on the highest measured value within the Orinda Formation. The specific Orinda Formation RMT from which this baseline is made, however, is not part of this Ground Class.
3. Upper bound baseline for the intact rock UCS is based on the highest measured value within the Claremont Chert and Shale geologic unit. The specific Claremont Chert and Shale RMT from which this baseline is made is not part of this Ground Class.
4. Values only for isolated occurrences of igneous dikes.
5. Values only for Orinda Formation conglomerate.
6. Slake durability within clayey very intensely fractured zones will be less than 30.

Table 5.3 Slake Durability Classification (after Gamble, 1971)

Slake Durability Class	Slake Durability Index
Very high	>98
High	95-98
Medium-High	85-95
Medium	60-85
Low	30-60
Very Low	<30

Table 6.1 Initial Support Elements by Ground Behavior and Support Category

Ground Behavior	Support Category				
	I	II	IIIA	IIIB	IV
Block Failure	Rock dowels and shotcrete	Rock dowels, lattice girders, spiling (Support Category IIB only) and shotcrete	Rock dowels, lattice girders, spiling and shotcrete		
Raveling	Spiling	Lattice girders, shotcrete and spiling	Lattice girders, shotcrete and spiling	Lattice girders, shotcrete and spiling	Lattice girders, shotcrete and pipe canopy
Shallow shear failure		Lattice girders, rock dowels and shotcrete			Lattice girders, shotcrete and pipe canopy
Deep shear failure			Rock dowels and shotcrete (including footing widening)	Rock dowels and shotcrete (including invert arch)	
Slaking	Shotcrete	Shotcrete	Shotcrete	Shotcrete	Shotcrete
Softening	Shotcrete (mud mat required in Orinda Formation, Tc-3 RMT, and elsewhere as needed)	Shotcrete (mud mat required in Orinda Formation, Tc-3 RMT, and elsewhere as needed)	Shotcrete (mud mat required in Orinda Formation, Tc-3 RMT, and elsewhere as needed)	Shotcrete (mud mat required in Orinda Formation, Tc-3 RMT, and elsewhere as needed)	Shotcrete
Swelling	Shotcrete	Shotcrete	Shotcrete	Shotcrete	
Crown instability due to low cover					Lattice girders, pipe canopy and shotcrete

Table 8.1 Previous Tunnel Experiences Summary

Existing Tunnels		**Caldecott Bore Nos. 1 & 2**	**Caldecott Bore No. 3**	**Berkeley Hills Bart Tunnel**	**Claremont Tunnel**
Year Completed		1937	1964	1968	1929
L=Length W=Excavated Width H=Excavated Height		L 914 m (3000 ft) W 11 m (36 ft) H 10.4 m (34 ft)	L 975 m (3200 ft) W 14.3 m (47 ft) H 12.2 m (40 ft)	L 4.9 km (3.1 mi) W 6.4 m (21 ft) H 6.4 m (21 ft)	L 5.6 km (3.5 mi) W 3.7 m (12 ft) H 3.7 m (12 ft) 2.7 m (9 ft) finished diameter.
Excavation Sequence/Method		Stacked drifts. Drill-and-blast.	Top heading and bench excavation sequence. Air spades and jack hammers to drill-and-blast.	Full face drill-and-blast excavation with 1.2 m (4 ft) round length	Full face drill-and-blast excavation with 1.2 to 1.8 m (4 to 6 ft) round length
Initial Support		15.2cm x 30.4 cm (6"x12") to 30.4cm x 30.4cm (12"x12") timber sets and 7.6cm x 30.4xm (3"x12") laggings.	Combination of steel sets with timber lagging, wall plates, and concrete pilasters. Timber sets for crown and wall plate drifts.	20-cm (8-in) wide flange steel sets at 0.6 to 1.2 m (2 to 4 ft) spacing. Invert struts as required.	20.3cm x 30.4xm (8"x8") to 30.4cm x 30.4cm (12"x12") timber sets on 1.8m (6 ft) centers.
Final Lining		0.9 to 1.9-m (3 to 6.25-ft) thick reinforced concrete.	0.9 to 1.8-m (3 to 6-ft) thick reinforced concrete.	46-cm (18-in) thick reinforced concrete.	Cast-in-place concrete with 10.2 cm (4 in) thickness over timber sets; local reinforcement.
Face Support		Rock core	Breast board jumbo and shield	Breast boarding as required.	None
Pre-Support		Spiling	Spiling	Crown bars	None
Ground Behavior and Construction Incidents	Sobrante Formation	Unstable slopes and high lateral loads at west portal; Weak Tss causing heavy loads; Sloughing of wet, soft, very intensely fractured ground required breast boarding; One dangerous occurrence of methane was detected and quickly dissipated. No information is available as to which formation this occurred in.	Steel sets at 2 ft spacing in Tsp due to variable ground conditions; Tsp described as "bad ground" and cave-in occurred on a wall plate drift in Tsp; Wet broken and badly fractured unstable materials encountered;	Complexly faulted and folded with individual beds highly contorted and lenticular; Tsf closely sheared in many places but blocky in others, moderately soft to hard when dry but slaky when wet; Tsp moderately hard with scattered sheared interbeds of shale; Tss was slabby with fractures spaced 1 in to 3 ft and breaks along polished shear surfaces.	Not encountered
	Claremont Formation	Breast boarding and spiling required in Tcp for running ground; Wet, granulated chert and shale intrusions in sandstone contributed to occasional ground slips and running ground requiring immediate support; Considerable pressure on timber sets in Tcs; First cave-in and sink hole at Tcp and Tcs contact in Bore 2; Running ground at small faults, dikes and elsewhere as well in Tc; Gradual loading stresses developed in Tc; Water weakened igneous dikes; Very intensely fractured Tc containing pockets of water flowed into tunnel up to 30 cubic yards of running ground with inflow of 80 gpm.; Ground instability promoted by sandstone and igneous dikes; Second cave-in under crest of hill in Bore 2 at location of igneous dike. Traces of CH_4, Co2 and H_2S were found; One dangerous occurrence of methane was detected and quickly dissipated. No information is available as to which formation this occurred in.	Excellent drill and shoot condition in Second Sandstone; Sandstone dikes, slip outs and heavy ground conditions in Tc; Heavy ground conditions in Tc required breast boarding and steel sets at 2 ft spacing. Void about 3-m (10-ft) high, 10.7-m (35-ft) long and 4.6-m (15-ft) wide formed above shield; Air quality monitored in Tc due to concerns regarding presence of hazardous gas.	Tcs moderately hard with shale interbeds and igneous dikes. Fracture spacing in Tcs was 1 in to 2 ft Tc chert hard, brittle and highly fractured; Tc shale interbeds generally less than 2.5-cm (1-in) thick, sheared and ranges from soft to hard; Tc marked by frequent occurrences of sandstone and igneous dikes generally parallel to bedding but also cross bedding; Sandstone dike material blocky with average fracture spacing of 3 in and generally well cemented – described as "ravelly";	Bad ground encountered at the contact with Wildcat fault; Progress improved 61 m (200 ft) to 183 m (600 ft) going east of Wildcat fault.
	Orinda Formation	Vulnerable to slaking when exposed to air; Mudstone is prone to slaking/softening when wet; Conglomerate beds feed water to adjacent beds; Timber showed considerable strain in areas of wet mudstone; Water on invert softened mudstone on walls and caused sloughing; One dangerous occurrence of methane was detected and quickly dissipated. No information is available as to which formation this occurred in.	East portal wall plate drift encountered "knee deep mud;" Ground surface crack developed on Fish Ranch Road during top heading drive; Conglomerate block failure at face along wet clay seams fatally injured miner; Wall plate failure near east portal.	Siltstone soft to moderately hard, slakes, decomposes in water, massive to thinly bedded with sandstone; Sandstone moderately hard, moderately well cemented; Conglomerate friable to well cemented, and massive with only scattered fractures; Conglomerate contains gravel up to 12 in in diameter.	Fair to poor ground conditions including swelling clays prone to slaking and squeezing, and easily eroded sands and clays. Locations of exceedingly bad swelling ground Oil and gas occurrences and two fires, one burning for two hours, the other for 30 days. Petroleum from Claremont formation accumulated at basal part of Orinda formation. Local collapse during accidental flooding from San Pablo Creek
Groundwater Inflow	Sobrante Formation	Damp to isolated yield of 1 to 150 gpm;	No major problems reported.	Negligible to 5 gpm during construction	Not available
	Claremont Formation	Generally flows less than 50 gpm and fell to nothing after about 48 hours; Isolated inflow of 250 gpm fell to 25 gpm in 5 days;	Sustained inflow was about 30 gpm during construction. Seepage at contact of Tsf and Tsp described as "raining hard." Right drift experienced inflows of 25 to 50 gpm in Tc.		No notable inflows during 1929 construction. Nine minor inflow occurrences during 1966 upgrade
	Orinda Formation	Damp to isolated yield of 1 to 150 gpm except for some parts.			No notable inflows.

FIGURES

KEY TO TERMS USED TO DESCRIBE THE PHYSICAL CONDITION OF ROCK CORE[1]

FRACTURE SPACING	SPACING/CORE RECOVERY LENGTHS	FRACTURE DENSITY[2]
(VC) Very closely spaced (crushed)	Less than 30 mm (<0.1 ft)	Very intensely
(Cl) Closely spaced	30 to 100 mm (0.1 ft to 0.3 ft)	Intensely
(Mo) Moderately spaced	100 to 300 mm (0.3 ft to 1.0 ft)	Moderately
(Wi) Widely spaced	300 mm to 1 m (1.0 ft to 3.0 ft)	Slightly
(VW) Very widely spaced	1 to 3 m (3.0 ft to 10.0 ft)	Very Slightly
(Ex) Extremely wide	Greater than 3 m (>10 ft)	Unfractured

BEDDING OR FLOW TEXTURE	THICKNESS/SPACING
(La) Laminated	Less than 10 mm (<0.03 ft (3/8 in))
(VTn) Very thinly bedded	10 to 30 mm (0.03 (3/8 in) to 0.1 ft)
(Tn) Thinly bedded	30 to 100 mm (0.1 to 0.3 ft)
(Mo) Moderately bedded	100 to 300 mm (0.3 to 1 ft)
(Tk) Thickly bedded	300 mm to 1 m (1.0 to 3.0 ft)
(VTk) Very thickly bedded	1 to 3 m (3.0 to 10.0 ft)
(Ma) Massive	Greater than 3 m (>10 ft)

ROCK HARDNESS	
(So) Soft	can be grooved or gouged easily with a knife, can be scratched with fingernail
(Lo) Low Hardness	can be grooved 1/16 inch (2 mm) deep with a knife with moderate or heavy pressure
(Mo) Moderately Hard	can be scratched with a knife with light or moderate pressure
(Ha) Hard	can be scratched with a knife with difficulty
(VH) Very Hard	cannot be scratched with a knife

ROCK STRENGTH	
(Fr) Friable	breaks with light to moderate manual pressure
(We) Weak	core or fragment breaks with light hammer blow or heavy manual pressure
(Mo) Moderately Strong	core or fragment breaks with moderate hammer blow
(St) Strong	heavy hammer blow required to break specimen
(VS) Very Strong	core or fragment breaks only with repeated heavy hammer blows
(Ex) Extremely Strong	core or fragment can only be chipped with repeated heavy hammer blows

RELATIVE WEATHERING			
	DECOMPOSITION	DISCOLORATION	FRACTURES
(Fr) Fresh	Unaltered; cleavage surfaces glistening	No discoloration	No stains or coatings
(Sl) Slight	No megascopic alteration of minerals; no grain separations	Slight and localized	Few stains on fracture surfaces
(Mo) Moderate	Slight alternation of minerals; cleavage surfaces lusterless/stained; partial separation of grains visible	Moderate discoloration, usually throughout	Thin coatings or stains
(Se) Severe	Moderate to complete alteration of minerals; feldspars to clay, etc.; rock is friable	Discolored throughout	Extensively coated with oxides, carbonates, or clay

KEY TO TERMS USED TO DESCRIBE DISCONTINUITES[1]

DISCONTINUITY TYPE (and dip inclination)
(Be) Bedding plane
(Fo) Foliation
(Me) Mechanical break (dip angle not recorded)
(Jo) Joint
(Sh) Shear or Fault
(Ve) Vein

SURFACE SHAPE
(Ir) Irregular
(Pl) Planar
(Wa) Wavy or undulating

APERTURE	
(Ti) Tight	No visible separation
(Op) Open	Amount of separation, staining or coatings on fracture surfaces, and fracture surface moisture conditions may be noted
(He) Healed	Degree of healing, (i.e., partial or complete), thickness and mineralogy/hardness may be noted
(Fi) Filled	Degree of filling, (i.e., partial or complete), thickness and type of filling may be noted

ROUGHNESS (note presence of slickensides or striations)	
(St) Stepped	Near normal steps and ridges occur on fracture surface
(Ro) Rough	Large, angular asperities can be seen
(Mo) Moderately rough	Asperities are clearly visible and fracture surface feels abrasive
(Sl) Slightly rough	Small asperities on the fracture surface visible and can be felt
(Sm) Smooth	No asperities, smooth to touch
(Po) Polished	Extremely smooth and shiny

Notes:

1. Based on US Bureau of Reclamation, 1998, Engineering Geology Field Manual, Second Edition, Vol.1.
2. Fracture density refers to the range of core recovery lengths for a given run and excludes mechanical breaks.

Figure 1.1 Rock Mass Description Definitions

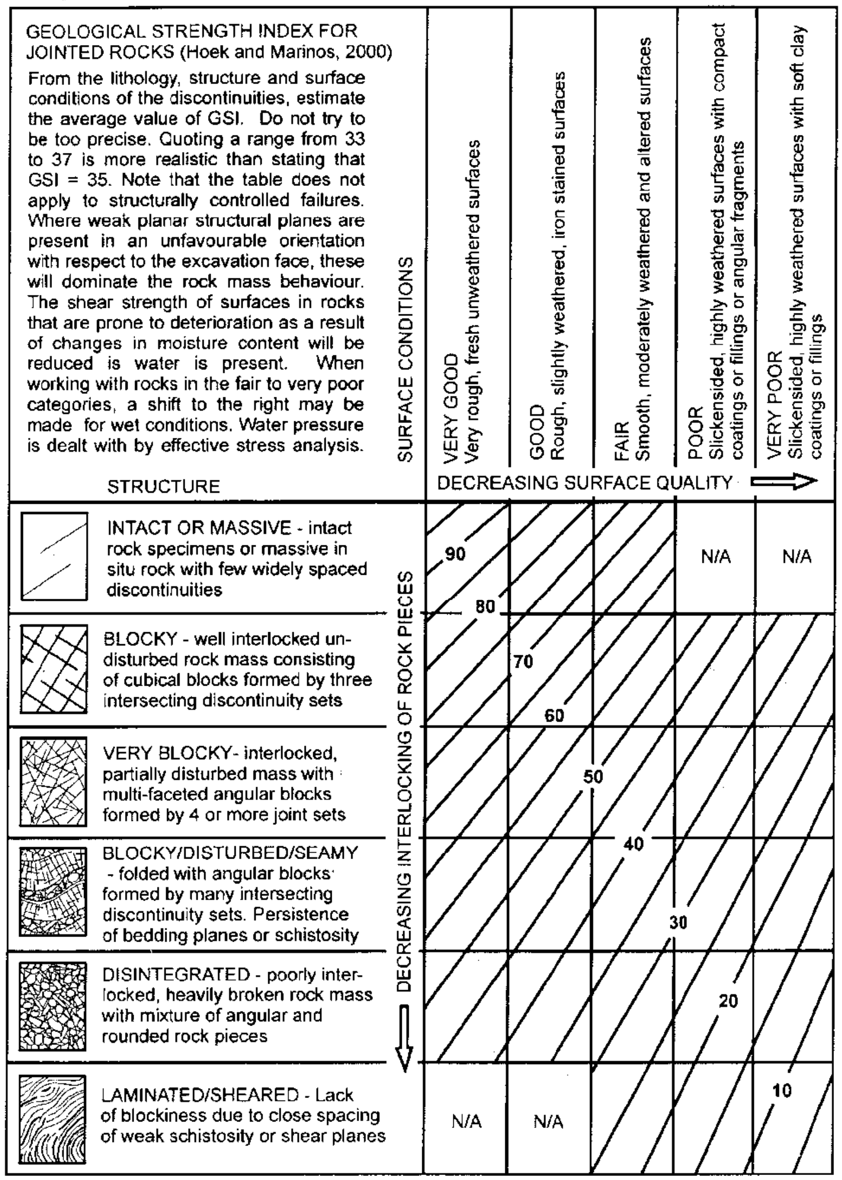


Figure 1.2 Geological Strength Index (GSI) System (Marinos et al., 2005)

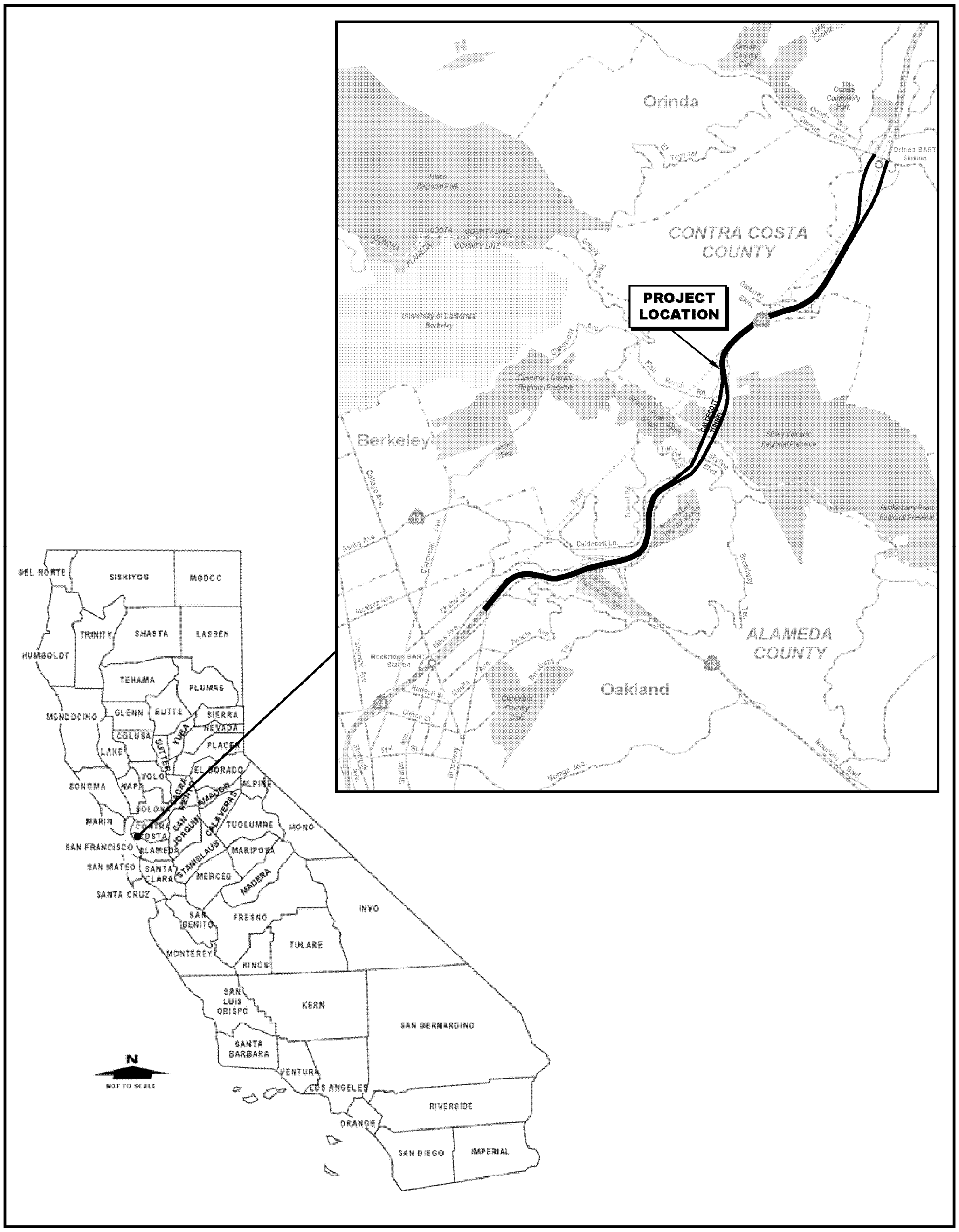


Figure 2.1 Project Site Location Map

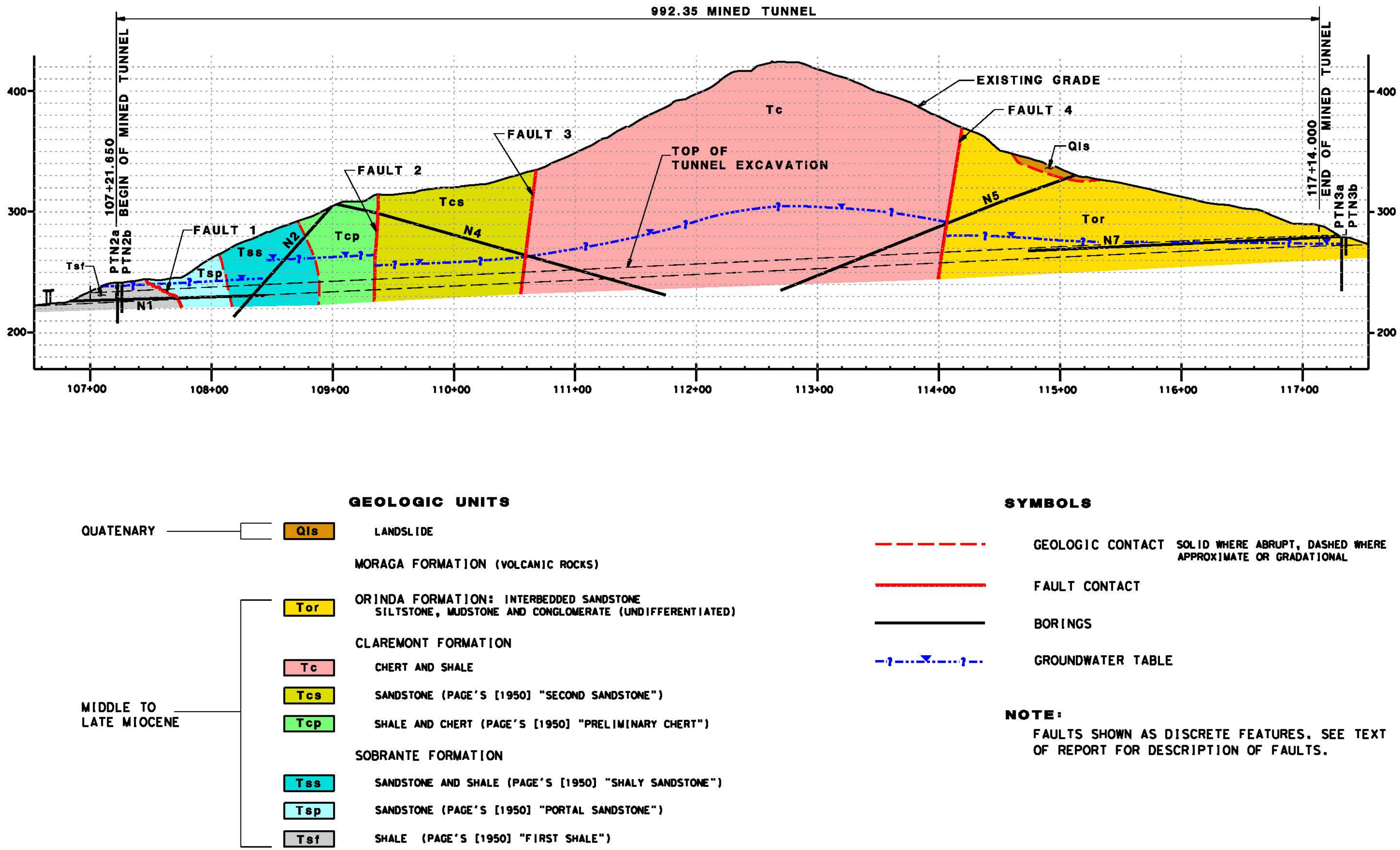


Figure 3.1 Geologic Profile

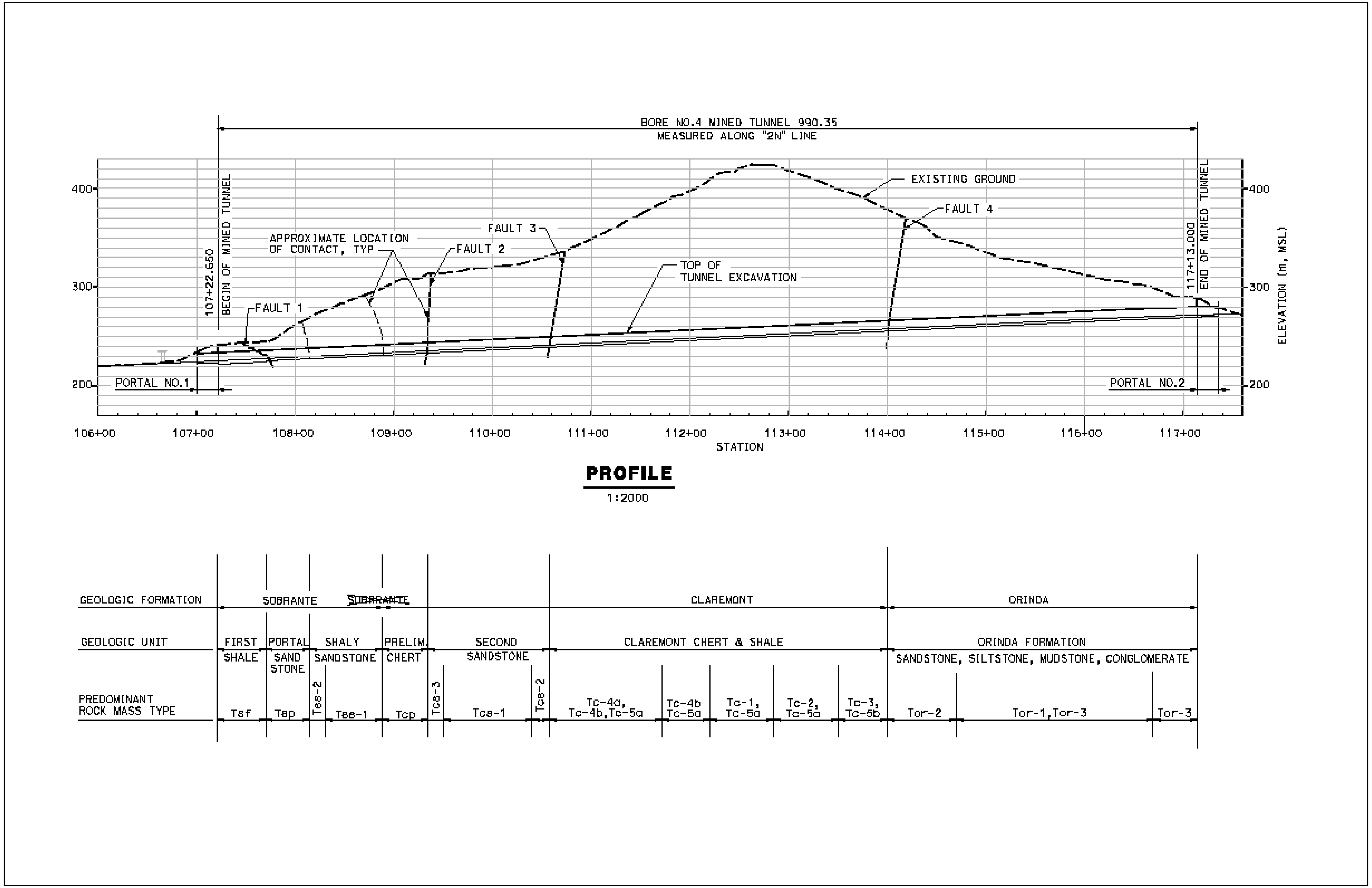
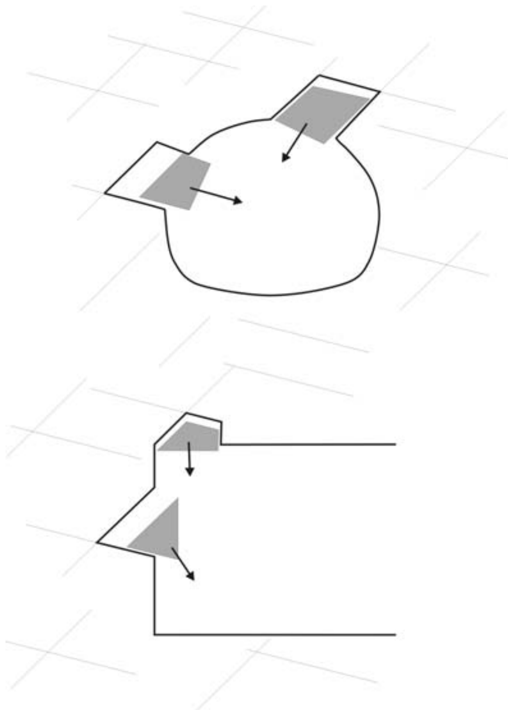
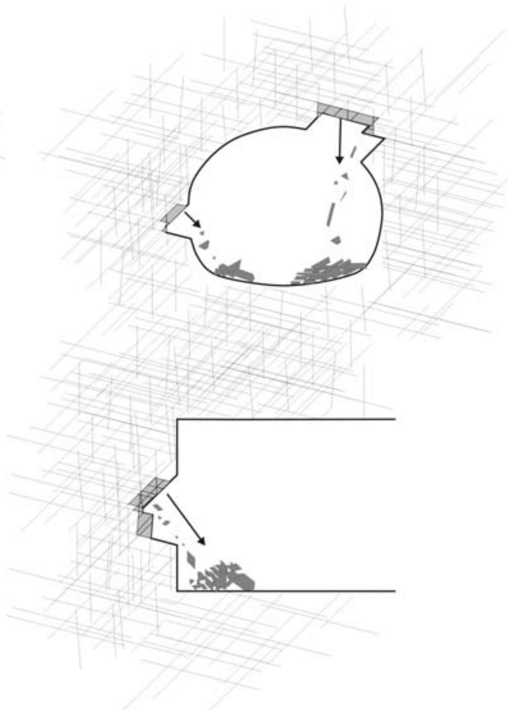


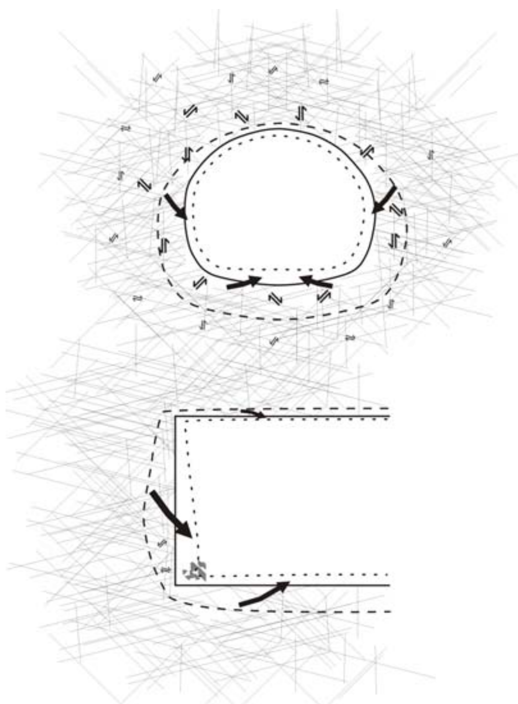
Figure 4.1 Estimated Distribution of Geologic Formations, Geologic Units and Predominant Rock Mass Types



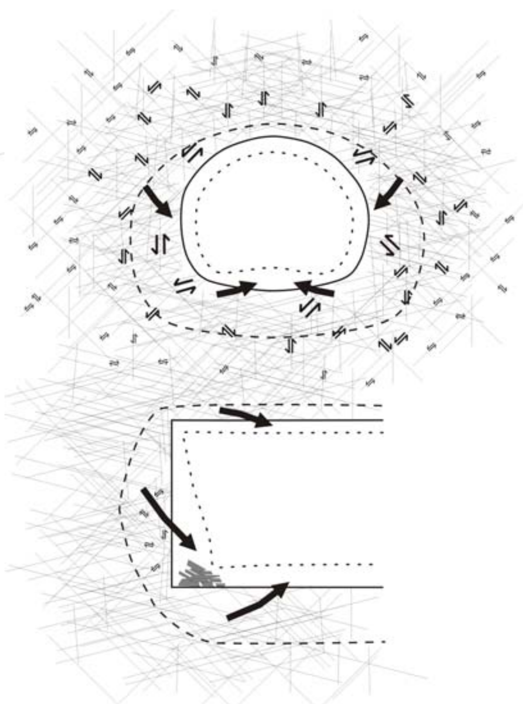
(a) Block Failure



(b) Raveling

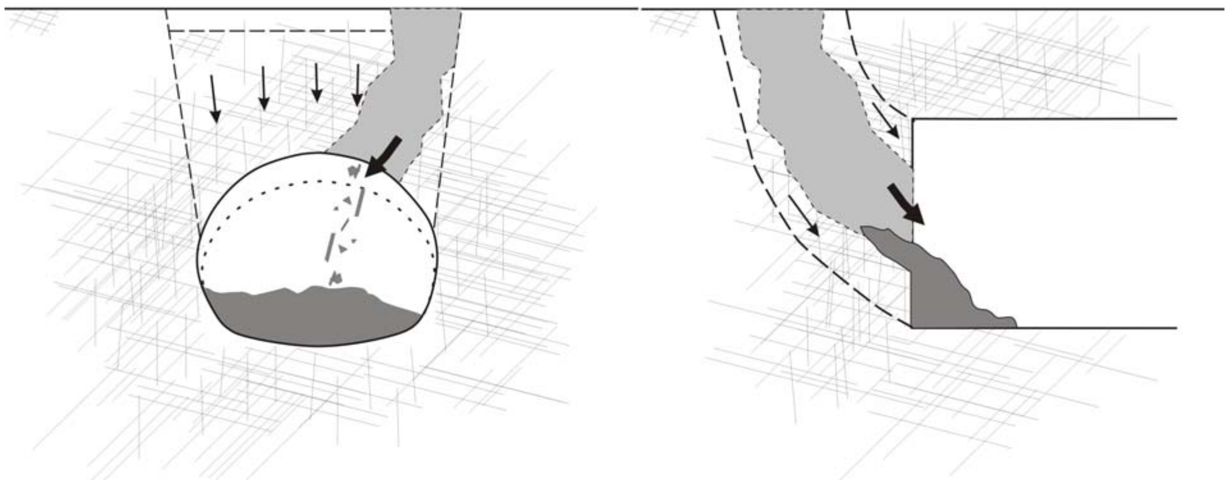


(c) Shallow shear failure



(d) Deep shear failure

Figure 5.1 Schematics of ground behaviors (refer to glossary for descriptions)



(e) Crown instability due to low cover

Figure 5.1 (continued) Schematics of ground behaviors (refer to glossary for descriptions)

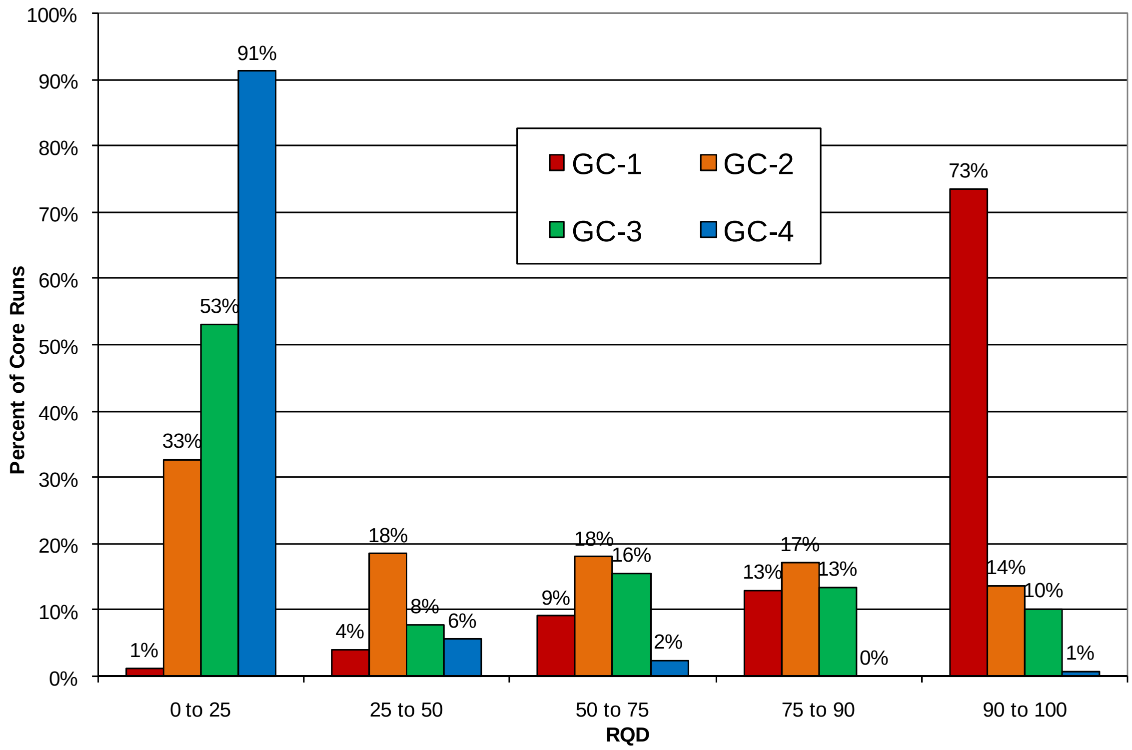


Figure 5.2 Histogram of RQD Values

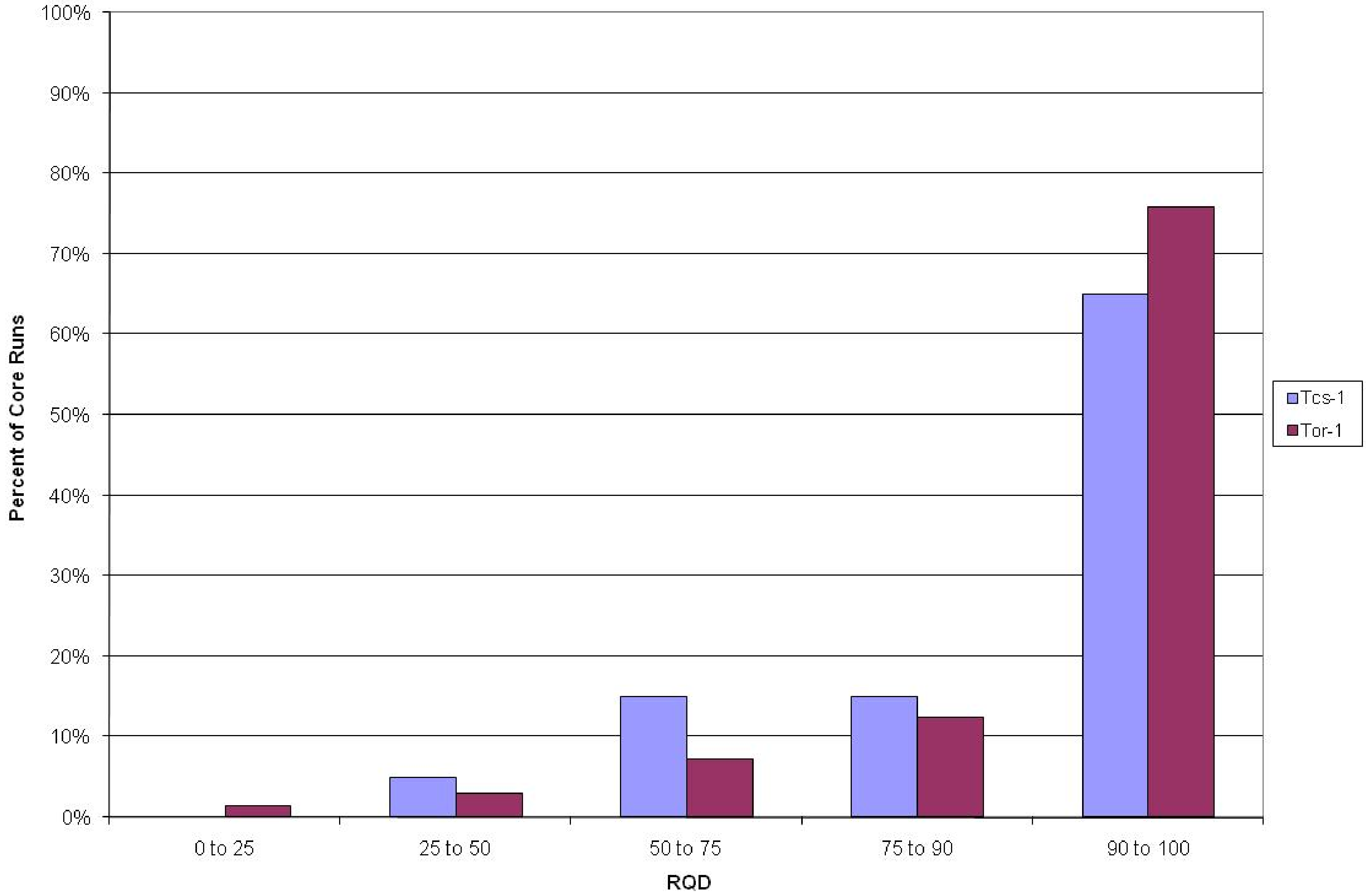


Figure 5.3 Histogram of RQD Values in Ground Class 1

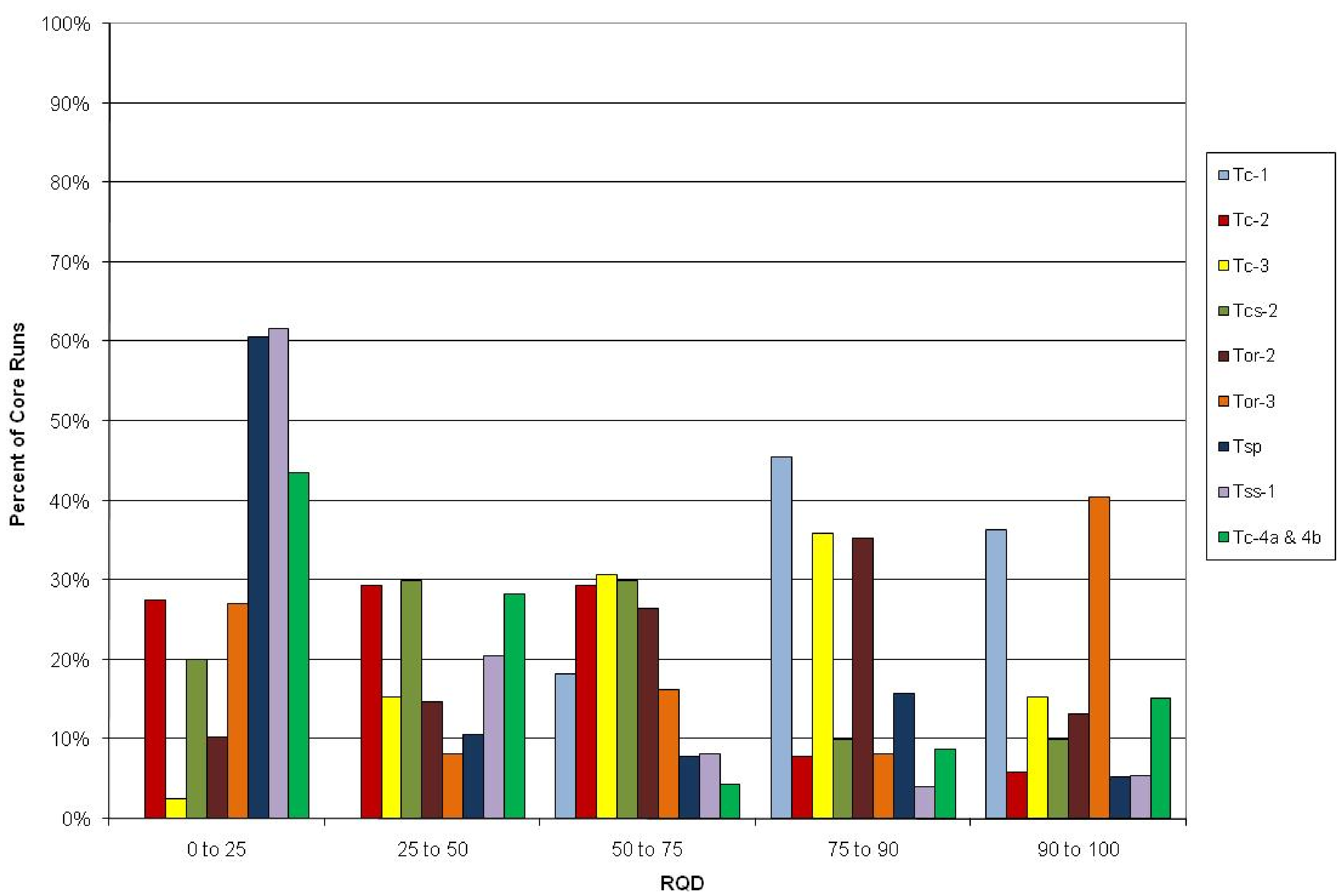


Figure 5.4 Histogram of RQD Values in Ground Class 2

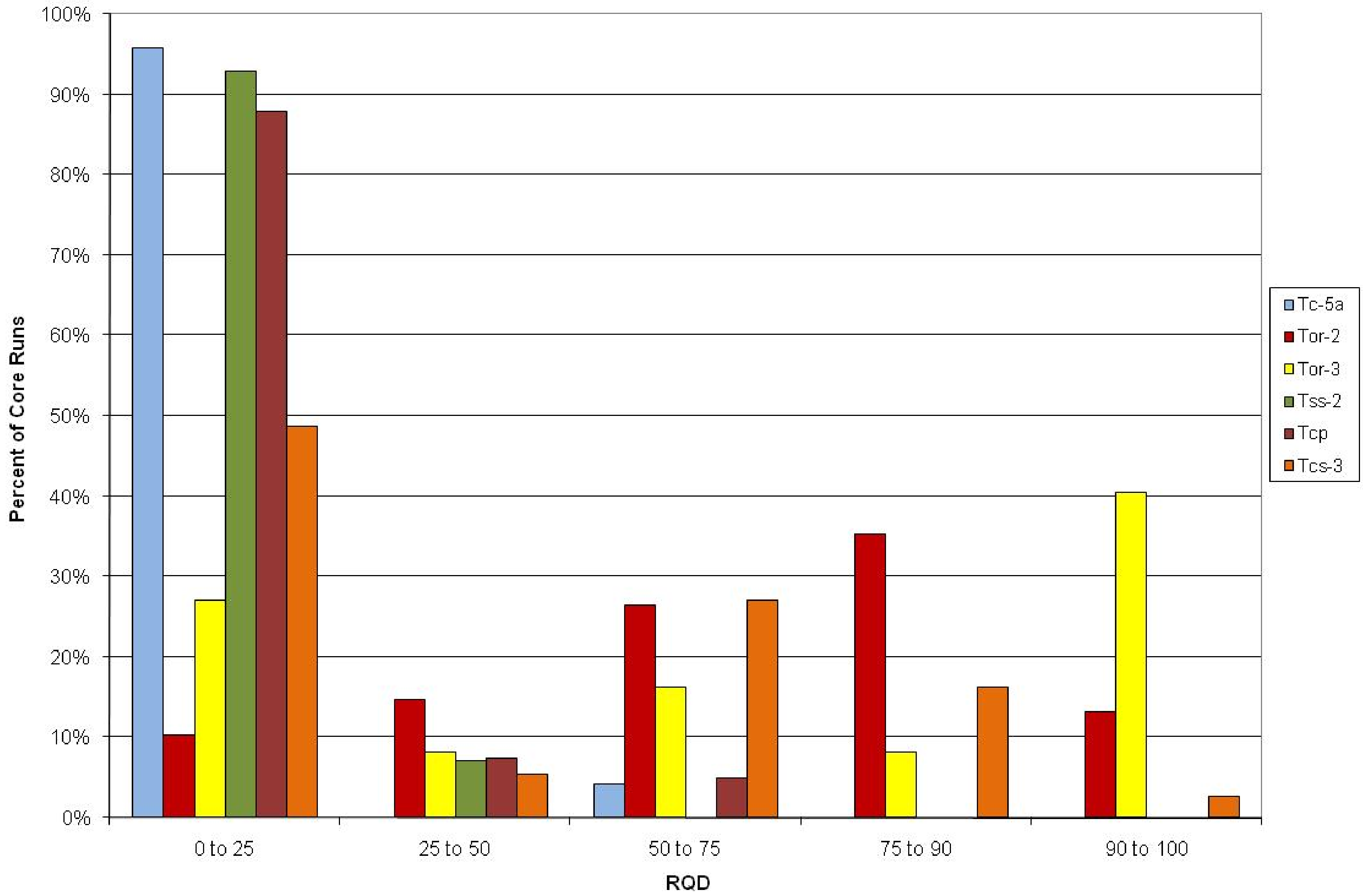


Figure 5.5 Histogram of RQD Values in Ground Class 3

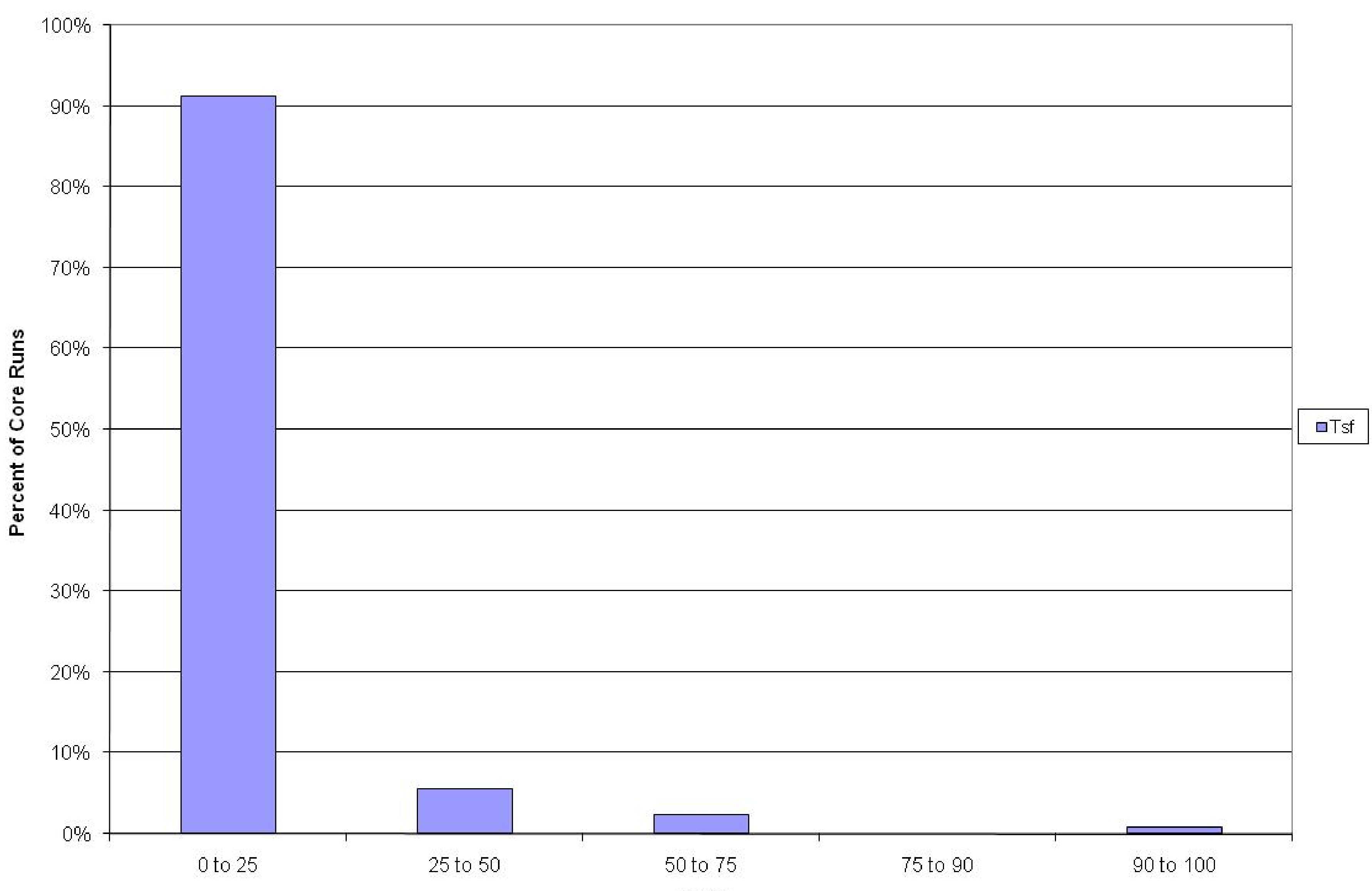
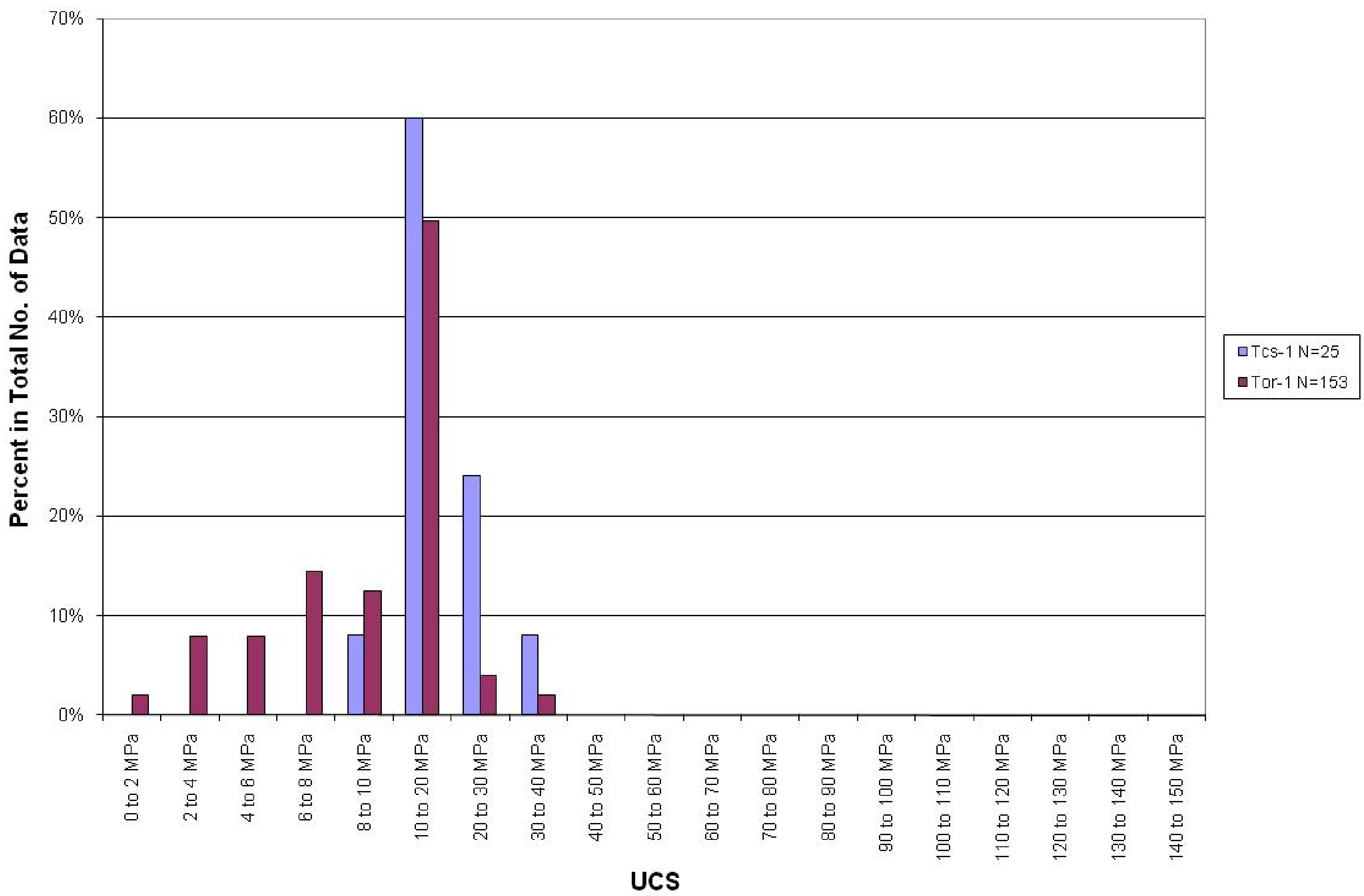


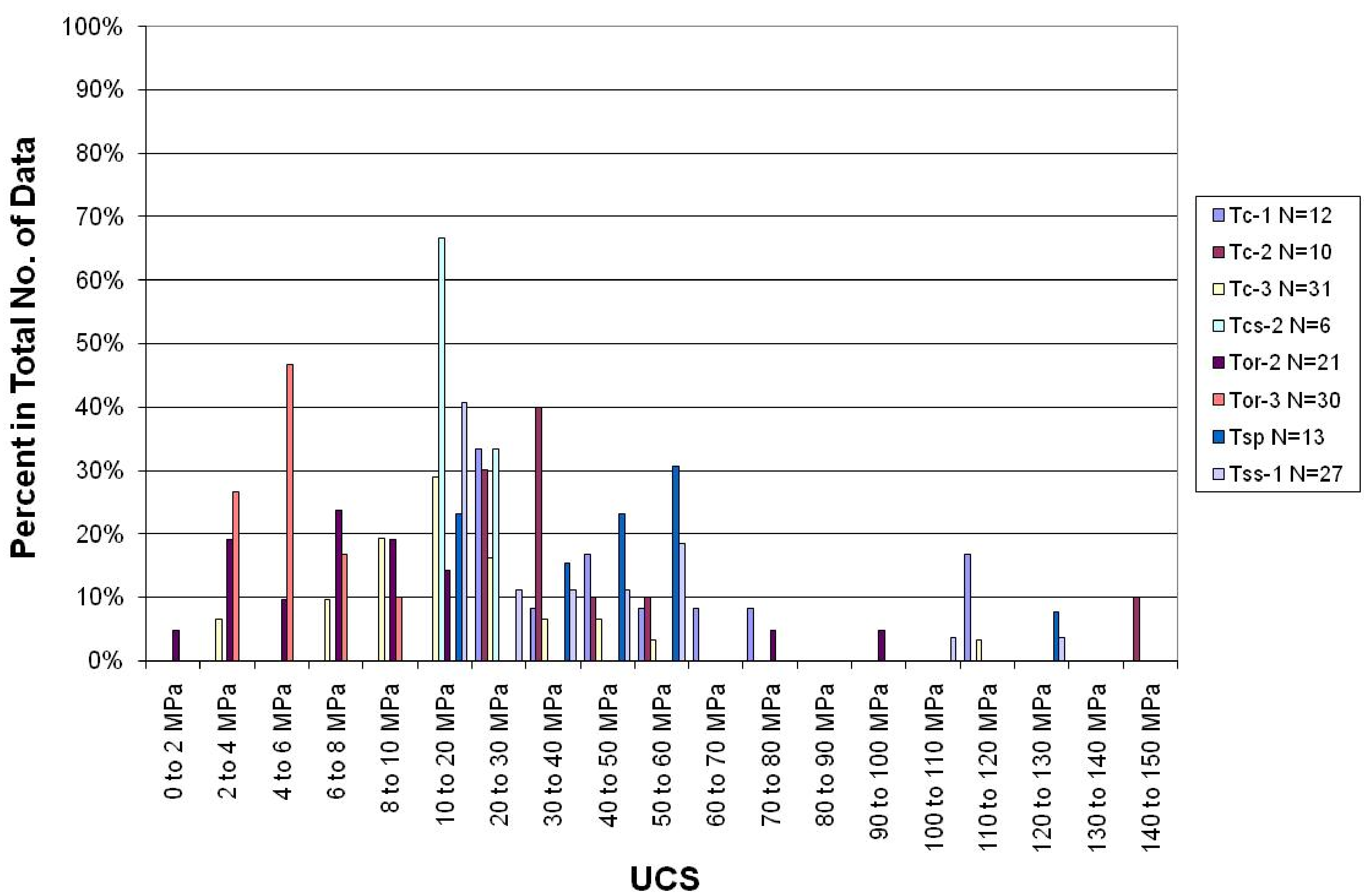
Figure 5.6 Histogram of RQD Values in Ground Class 4



Notes:

1. See Table 4.1 for measured UCS ranges for each Rock Mass Type.
2. See Table 5.2 for baselines. The baseline maximum for Ground Class 1 is higher than the measured strengths shown for these RMTs.
3. N= number of samples.
4. Horizontal scale intervals are 2MPa below 10 MPa, and are 10 MPa above 10 MPa

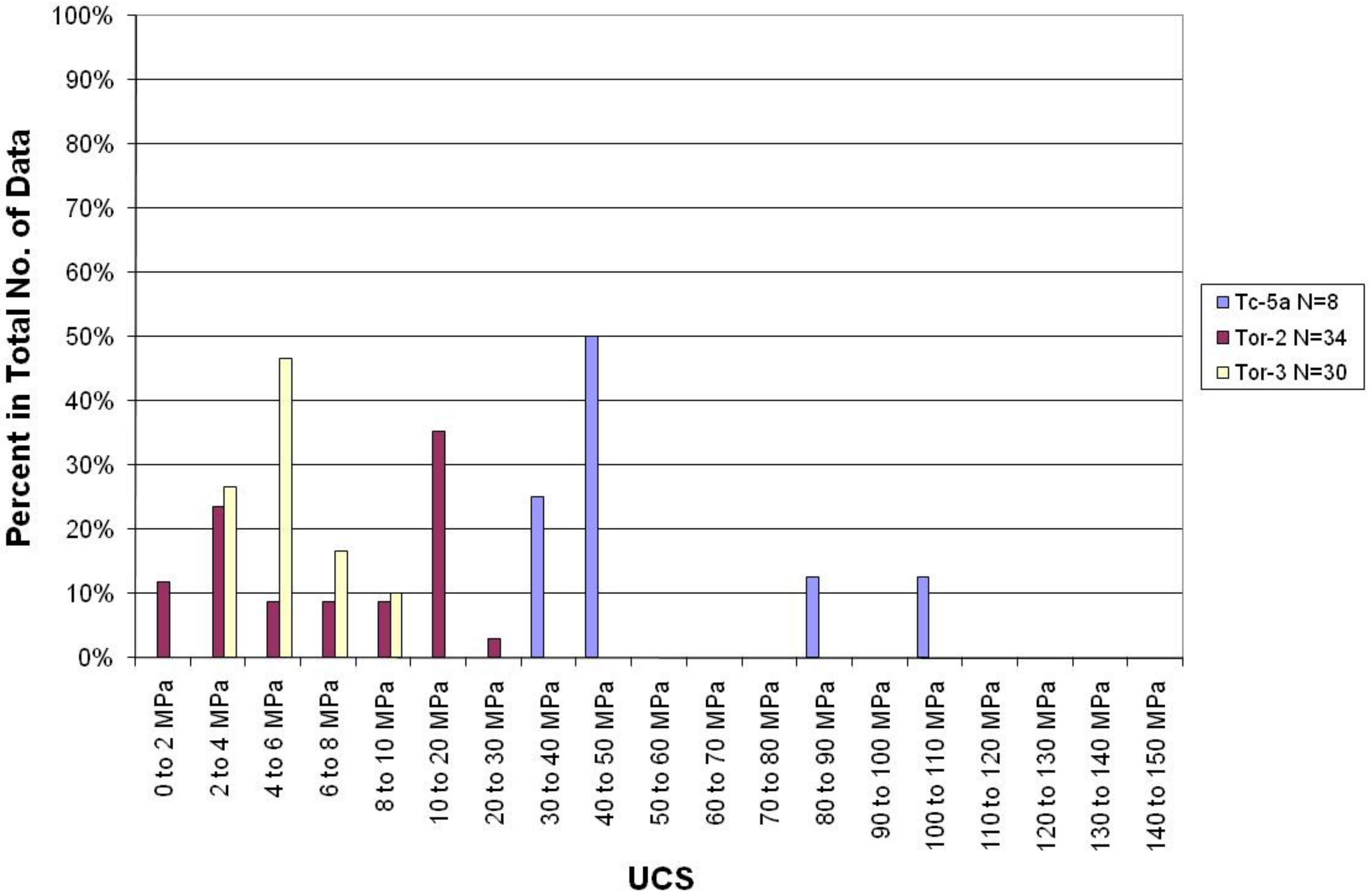
Figure 5.7 Histogram of Uniaxial Compressive Strength Measurements in Ground Class 1



Notes:

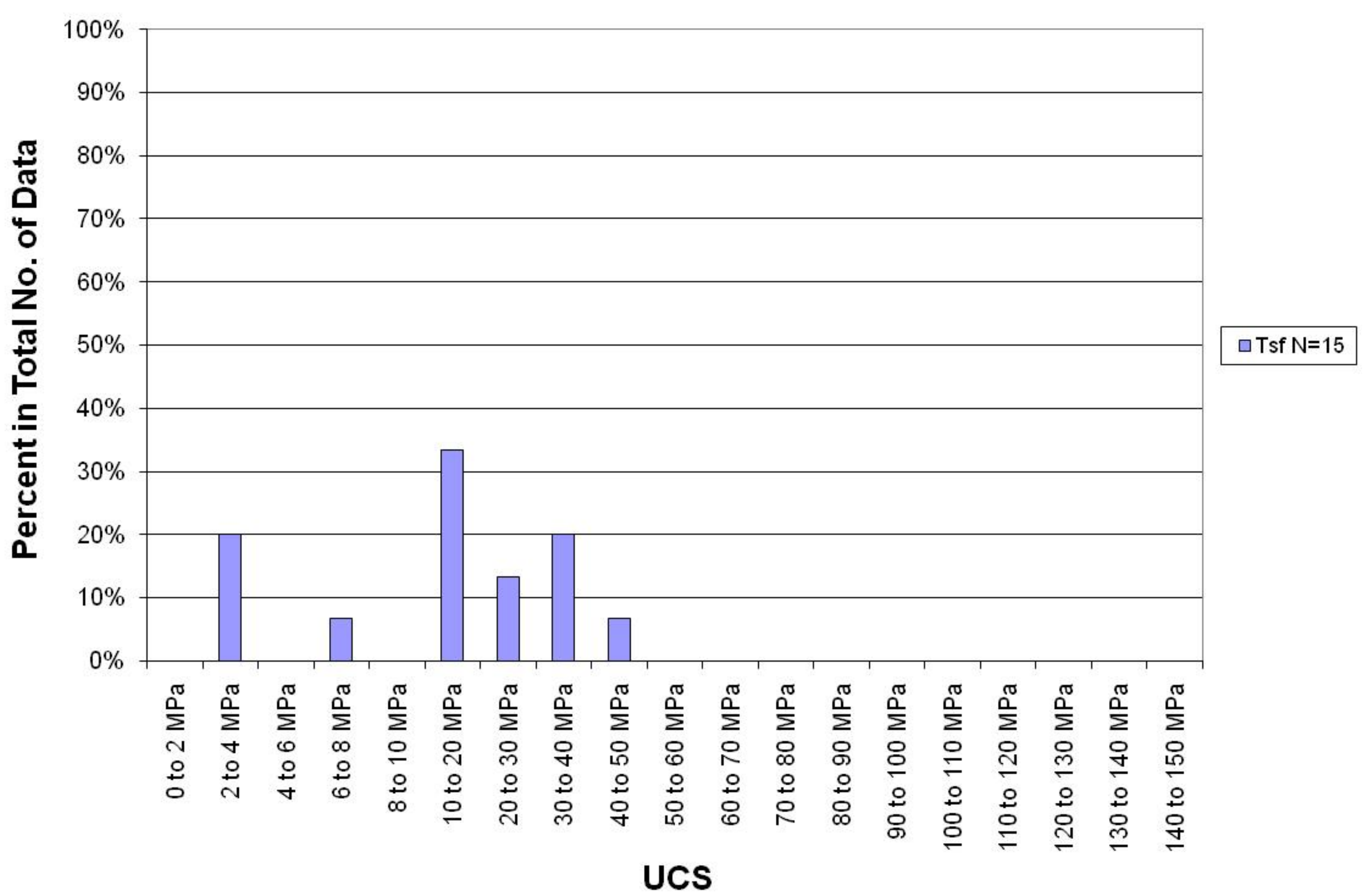
1. See Table 4.1 for measured UCS ranges for each Rock Mass Type.
2. No measurement made for Tc-4a and Tc-4b. UCS distributions for these RMT's will be similar to histograms shown for Tc-1 and Tc-2 except for sandstone dikes in Tc-4a. See Notes to Figure 4 for measured range of UCS of sandstone dikes.
3. See Table 5.2 for baselines.
4. N= number of samples.
5. Horizontal scale intervals are 2MPa below 10 MPa, and are 10 MPa above 10 MPa

Figure 5.8 Histogram of Uniaxial Compressive Strength Measurements in Ground Class 2



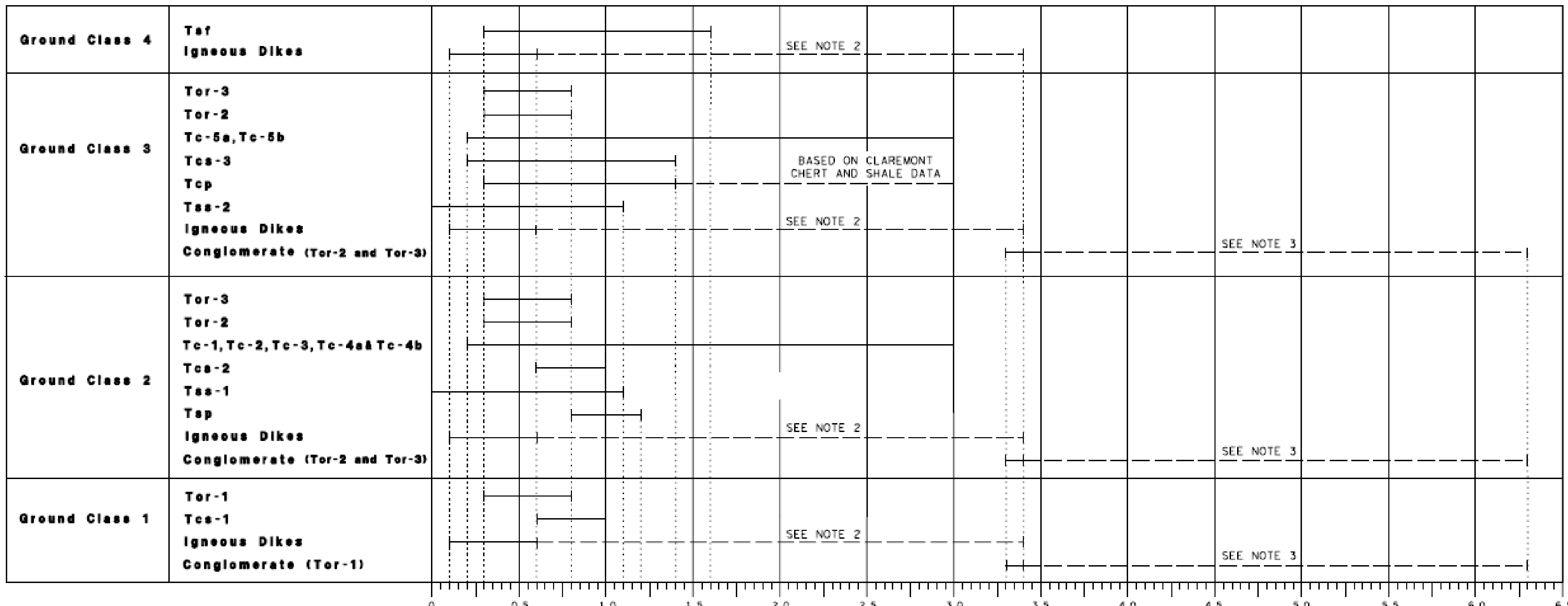
Notes:
1. See Table 4.1 for measured UCS ranges for each Rock Mass Type.
2. No measurement made for Tss-2. UCS distribution for this RMT will be similar to histogram shown for Tss-1 in GC 2.
3. Tcp is not included in the histogram due to insufficient data. Four UCS measurements were made in Tcp ranging 35.2 to 110.3 MPa (5111 to 15990 psi) with average of 63.9 MPa (9272 psi).
4. Tcs-3 is not included in the histogram due to insufficient data. Two UCS measurements were made as 7.5 MPa (1090 psi) and 15.9 MPa (2309 psi) averaging 11.7 MPa (1700 psi). UCS distribution within chert beds in this RMT will be similar to histograms shown for Tc-1 and Tc-2 in GC 2.
5. No measurements made for Tc-5b. Refer to Table 5.2 for baselines in this RMT.
6. See Table 5.2 for baselines. The baseline maximum for Ground Class 3 is higher than the measured strengths shown for these RMTs.
7. N= number of samples.
8. Horizontal scale intervals are 2MPa below 10 MPa, and are 10 MPa above 10 MPa

Figure 5.9 Histogram of Uniaxial Compressive Strength Measurements in Ground Class 3



Notes:
1. See Table 4.1 for measured UCS ranges for each Rock Mass Type.
2. See Table 5.2 for baselines.
3. N= number of samples.
4. Horizontal scale intervals are 2MPa below 10 MPa, and are 10 MPa above 10 MPa

Figure 5.10 Histogram of Uniaxial Compressive Strength Measurements in Ground Class 4



NOTES:

1. BASELINES ARE SUMMARIZED IN TABLE 5.3.
2. MAXIMUM EXPECTED VALUES FOR IGNEOUS DIKES BASED ON PUBLISHED VALUES FOR UNALTERED IGNEOUS DIKES (PLINNINGER ET AL.,2003) BECAUSE TEST SAMPLES AVAILABLE FROM CORE MAY NOT REPRESENT UNALTERED DIKES.
3. MAXIMUM EXPECTED VALUES FOR CONGLOMERATES CORRESPOND TO CLASTS WITHIN THE ORINDA FORMATION CONGLOMERATE. SEE SECTION 4.1.3 FOR OCCURRENCES OF CONGLOMERATE WITHIN THE ORINDA FORMATION.

|———| = MEASUREMENTS

|— — — —| = MAXIMUM EXPECTED

Figure 5.11 CAI Values by RMT