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1 Introduction

The goal of the Mill Valley to Corte Madera Bike and Pedestrian Corridor Study is to conduct the geotechnical investigations necessary to develop conceptual tunnel rehabilitation recommendations and a conceptual cost estimate for the Alto Tunnel (Figure 1). This abandoned and partially collapsed railroad tunnel is located in southeast Marin County, running parallel and just to the west of Highway 101. The North Portal is located in Corte Madera and the South Portal is in Mill Valley. Rehabilitating the tunnel and adding bike path extensions will directly connect existing bike and walk paths in and between the two cities. The following subtasks were undertaken by the Jacobs Associates team as a part of this study:

- Review of existing data, including published and unpublished geologic maps and geotechnical reports, as well as review of the Alto Tunnel Scoping Study prepared by Jacobs Associates in 2001.
- Geologic field reconnaissance above the tunnel, including mapping of portals and approaches to the portals, to gather data on rock properties such as joint orientations and rock mass classifications.
- Completion of geomechanical interpretation of the anticipated rock mass conditions at the tunnel elevation.
2 Desktop Investigation

2.1 Regional Geology

The Alto Tunnel project site is located in the Southern Coast Ranges of the greater Coast Ranges Geomorphic Province of California. The Coast Ranges are characterized by northwest-trending mountain ranges and intervening valleys, the orientations of which are strongly controlled by the structural fabric of the bedrock geology. These mountain ranges and intervening valleys are controlled by folds and faults that resulted from the collision of the Pacific and North American plates and subsequent strike-slip faulting along the San Andreas fault zone. The bedrock underlying the site is the Franciscan Complex, which consists of rocks that are typically strongly deformed (faulted, fractured, and folded), due primarily to ancient tectonic processes and, to a lesser degree, activity associated with the San Andreas fault system. The Jurassic-Cretaceous (65 to 205 million years ago) Franciscan Complex consists mainly of marine-deposited sedimentary and volcanic rocks in close association with bodies of serpentinite. Following deposition, the Franciscan Complex rocks were regionally uplifted and, in the process, extensively folded and faulted. The uplift and faulting in the Bay Area occurred in several episodes during the late Tertiary period. The result was a series of northwest-trending valleys and mountain ranges, including the Berkeley Hills, the San Francisco Peninsula, the Marin Headlands, and the intervening San Francisco Bay.

In the Southern Coast Ranges, Franciscan bedrock generally consists of three predominant rock types: sandstone (sometimes referred to as greywacke), shale, and mélange. The sandstones and shales are highly variable in degree of fracturing, strength, hardness, and weathering. The mélange unit is characterized by a chaotic, heterogeneous mixture of small-to-large (i.e., from boulder size up to miles in dimension) masses of different rock types—including greywacke, shale, claystone, greenstone, chert, and various metamorphic rocks, plus exotic high-grade metamorphic rocks and serpentinite—surrounded by a mélange matrix of pervasively crushed and sheared mudstone (argillite) and lithic sandstone. The Alto Tunnel lies completely within mélange (fsr) rock of the Franciscan Complex, within units of sandstone and undifferentiated mélange (Figure 2).

Although treated as a single terrain, the mélange unit is actually the result of the tectonic mixing of rocks derived from several terrains:

- The rocks that would form the sheared matrix from an unnamed and almost completely disrupted terrain;
- The chert, greenstone, greywacke, and metamorphic blocks from accreted Franciscan Complex terrains; and
- The serpentinite from the Coast Range ophiolite.

Blocks and resistant masses have survived the extensive shearing evident in the mélange’s matrix and range in abundance from less than 1% to 50% or more of the rock mass. The degree of shearing in the unit ranges from gouge to unsheared rock, with resistant masses consisting of relatively unsheared and sheared matrix. Severely sheared shale is abundant in areas where blocks are abundant. Fresh, relatively unsheared rock is hard, the larger resistant masses are pervasively fractured, and blocks are commonly tough and relatively unfractured (Blake et al., 2000). This mixture of rock materials exhibits a range of characteristics, including massive, closely jointed, completely crushed, and conditions resembling soft
clay. The greywacke sandstone is grayish green where fresh, weathering to brown, commonly medium-to-coarse grained, and locally veined with quartz and carbonate. The main consequence of this geologic mixture, especially as it pertains to the prediction of ground conditions, is that the Franciscan Complex typically lacks spatial continuity and, therefore, exhibits frequent and abrupt variations in geomechanical characteristics.

The Coast Ranges are located within a region of high seismic activity dominated by a zone of major, northwest-trending active strike-slip faults associated with the San Andreas fault system, which forms the boundary between the North American and Pacific tectonic plates. The San Andreas fault system consists of numerous active, major strike-slip faults. From east to west, these are the Calaveras, Hayward, San Andreas, and San Gregorio-Hosgri faults. This zone of faulting has been the source of numerous moderate- to large-magnitude historical earthquakes that have caused strong ground shaking in the project area, including the 1906 Richter magnitude (M) 8.3 San Francisco earthquake and the 1989 M 6.9 Loma Prieta earthquake (both on the San Andreas fault), and the 1868 M 7.0 (estimated) Hayward fault earthquake. None of these faults cross the project alignment. The closest of these to the project area are the San Andreas and Hayward faults, located about 10 km west and 18 km east, respectively.

2.2 Franciscan Complex Units

The following are three of the units found in the Franciscan Complex that were observed along the tunnel alignment and are most likely to comprise the tunnel excavation envelope.

2.2.1 Sandstone

The sandstone is a greywacke, grayish green where fresh, weathering to brown, commonly medium-to-coarse grained, consisting of fine-to-coarse grains of quartz, feldspar, and clay, with some lithic clasts. The sandstone has mineralization, clay, and iron-oxide staining along fractures, as well as healed fractures, and contains calcite and silica veins. The laminated original depositional fabric is occasionally preserved but can be deformed. The sandstone contains chert inclusions and zones of interbedding with shale, siltstone, and mudstone (in some cases with up to 30% mudstone interbeds). Sandstone blocks vary from strong intact blocks to crushed sandstone without clay or sandstone fragments in a clay matrix that is friable and plastic.

2.2.2 Mudstone/Claystone/Shale

Mudstone/claystone/shale is a clay-size-grained laminated rock that occurs either as a separate unit or interbedded with sandstone. Shale has fissile laminations, while laminations in mudstone and claystone are nonfissile. The fractures in the mudstone/claystone/shale have iron-oxide staining, contain clay, and are occasionally polished. Where the mudstone is interbedded with sandstone, very closely spaced fractures follow the mudstone, often associated with clay along fracture surfaces. The mudstone/claystone/shale is frequently associated with shear zones, where it is crushed or occurs as a more competent rock mass containing crushed zones.

2.2.3 Mélange Matrix
The matrix of the Franciscan Complex varies from a weak rock to a soil and typically consists of sand-to-gravel-sized clasts of the lithologies comprising the rock blocks confined in the mélange matrix, surrounded by a sheared and deformed clay, serpentine, or tale matrix. The rock-like mélange matrix resembles a conglomerate and can range from massive to blocky/disturbed (Table 1). The soil matrix ranges from a dense, silty, clayey, angular-to-subangular gravel to a soft-to-hard, silty clay containing angular-to-subangular gravel. The clayey soil matrix and the rock matrix are frequently intermixed and mineralized, and weather to clay. The matrix contains healed fractures, fractures with polished or iron-oxide-stained surfaces, or fractures filled with calcite.

2.3 Cal Park Hill Tunnel

The Cal Park Hill Tunnel (Figures 1 and 2) is a railway tunnel built in 1886 and widened in 1924. It is currently being rehabilitated for use as a pedestrian and bike pathway and a commuter rail transportation corridor by the County of Marin. The tunnel was constructed in Franciscan Complex rocks composed of sandstone, shale, and mélange matrix units. It is anticipated that the rock mass behavior in the Alto Tunnel will be similar to that observed during rehabilitation of the Cal Park Hill Tunnel, taking into account the smaller dimension of the Alto Tunnel and differences in rock mass degradation between the two tunnels arising from weathering of the tunnel envelope, ground instability in areas of fallen or severely damaged timber sets, and effects of tunnel collapse at the portals.
3 Geotechnical Investigation

3.1 Field Reconnaissance

Field reconnaissance was undertaken during three visits to the tunnel site, including access to the Marin Municipal Water District (MMWD) tunnel shafts in which pictures and videos were taken of the tunnel wall conditions on July 9 and 23, 2008, and two visits to the tunnel portals and tunnel alignment on January 20, 2009 (Figure 3).

3.2 MMWD Shaft Investigation

The MMWD North and South shafts were opened for access to the MMWD water pipeline (Figure 3), which is parallel to the Alto Tunnel. No entry was permitted, but one photograph and several videos were taken by lowering a digital camera into the shaft. Figure 4 shows the conditions of the MMWD pipeline tunnel at the South Shaft. The timber support beams are intact and have not been deformed since their placement, suggesting that the support was sufficient for the rock mass and overburden conditions encountered. No direct view of the rock mass was possible, but inferences can be made based on the condition of the support. The support consists of timber square sets, which in one location at least are additionally supported by a steel column (screw jack). No inference can be made as to rock type, since no rock surface was visible from the shaft. Where observations were possible, it can be surmised that the tunnel is stable at the shafts and adjacent tunnel sections.

3.3 Tunnel Portal and Alignment Investigation

The north and south tunnel portals were visited to assess the general condition of the portal areas, measure the railroad right-of-way area for portal access and rescue turn-around areas, and assess the geomechanical conditions of the rock outcrops. The tunnel alignment was investigated at the surface along 60–70% of its projected length to locate rock outcrops in proximity to the tunnel and assess the rock mass conditions.

3.3.1 North Portal

The north portal (Figure 3) is accessible on foot and was investigated to determine the condition of any rock outcrops in the proximity of the portal, measure the dimensions of the pathway right-of-way, and determine the condition of the slopes on either side of the portal (Figure 5).

The slope on the east side of the portal, beginning approximately 40 ft north of the portal, contains a 2:1 rock slope stabilized by shotcrete, with a 2:1 vegetated rubble and soil slope at the base (Figure 6). This slope consists of sandstone with 8-in.-wide beds, fractured along the bedding planes (Figure 7), with a dip and dip-direction of 65/310. The fractures in the sandstone are spaced 1–2 in. parallel to the bedding planes and 2–4 in. across the bedding planes. The sandstone also contains 4-in.-wide shale or siltstone interbeds, spaced 5–10 ft apart, which are fractured parallel to bedding. The fractures in the shale/siltstone are spaced 0.5–1.5 in. parallel to the bedding planes and 1–2 in. across the bedding planes. The slope on the east side of the portal within the first 40 ft to the north of the portal is a nearly vertical rock slope stabilized by shotcrete, which shallows near the top where it is vegetated with residual soil overlying the rock (Figure 8). This nearly vertical east wall forms the side of a rock outcrop that encroaches on the pathway right-of-way, narrowing the right-of-way with respect to the slopes to the north of the outcrop.
(Figures 5 and 9). The shotcrete contains holes and vugs through which sandstone and residual soil are visible. One hole adjacent to the portal begins 8 ft above the ground surface and travels between the shotcrete and the slope rock down to the ground surface (Figure 10). This slope consists of massive sandstone with fractures 1–2 ft apart, crossed with 4-in.-wide zones of fractures 0.5–1.5 in. apart.

The slope on the west side of the portal, beginning approximately 40 ft north of the portal, contains a 1:1 vegetated residual soil slope on which no rock outcrops are visible. The slope on the east side of the portal within the first 40 ft to the north of the portal is a 2:1 rock slope stabilized by shotcrete, which shallows near the top to 1:1, where it is vegetated with residual soil overlying the rock (Figure 11). The shotcrete is sufficiently pervasive to prevent a thorough investigation of the rock mass conditions; however, a small hole in the shotcrete adjacent to the portal is underlain by sandstone. A second hole in the concrete permitted the removal of several pieces of intact siltstone (Figure 12). The holes in the shotcrete are insufficient to identify bedding in either the sandstone or siltstone; however, the siltstone was found to contain fractures spaced 3–5 in. apart. Additional holes in the shotcrete show that shotcrete was applied to soil, and in some cases bushes were seen to grow out of the holes, which are up to 15 in. wide × 10 in. high.

The slope above the portal slopes at 2:1 and consists of vegetated residual soil. No rock outcrops were found within 75–100 ft to the south of the portal above the tunnel alignment.

A previous investigation of the north portal (Jacobs Associates, 2001) included entry into the tunnel up to the lean concrete bulkhead. Conditions in the tunnel are described in the Jacobs Associates (2001) report, The tunnel was found to be lined from the portal to the bulkhead with concrete and shotcrete; therefore, no rock was visible (Figure 13).

3.3.2 Tunnel Alignment

The tunnel alignment at ground surface was visually inspected, where access was possible, to locate all rock outcrops above and adjacent to the tunnel alignment within approximately 250 ft horizontally from the tunnel’s surface projection. South of the north tunnel portal private properties prevent access to the tunnel alignment for approximately 500 ft. Within the vicinity of the MMWD north shaft (Figure 3), the tunnel alignment is accessible, but the area consists of vegetated residual soil and boulder fill at the base of the slope adjacent to Corte Madera Avenue.

No outcrops were found south of the north portal to Road Cut 1 on the west side of Corte Madera Avenue (Figure 3). Road Cut 1 consists of sandstone and associated sandstone residual soil (Figure 14). The sandstone in this location contains highly fractured zones with nearly disintegrated rock (Figure 14, left) and zones with fractures spaced 1–3 in. apart (Figure 14, right).

Road Cut 2, on the west side of Camino Alto (Figure 3), consists of sandstone and associated sandstone residual soil. Major fractures, which are considered to be continuous joints with a thin mineral coating, are spaced approximately 4–8 in. apart, and are oriented with dip and dip-direction: 70/010, 60/040, 80/210. The similarity between the first two orientations suggests that these fractures are parallel to bedding planes. Minor, discontinuous joints are spaced 1–2 in. × 1.5–3.0 in. × 2–4 in. apart (Figure 15, left), creating nearly rectangular blocks (Figure 15, right).

The sandstone outcrop in the Alto Bowl is assumed to be in situ bedrock rather than a displaced rock block. It contains continuous fractures 1–3 ft apart (Figure 16, left), oriented with dip and dip-direction of
70/010 and 50/054. It also contains zones of calcite- or quartz-healed fractures 1–4 in. apart (Figure 16, right).

A rock outcrop consisting of highly deformed sandstone and chert clasts in a solid matrix (Figure 17) was named Mélange Matrix Rock Outcrop 1. The outcrop is 2 × 4 ft and does not contain any visible fractures.

A group of outcrops consisting of highly deformed chert clasts in a solid matrix (Figure 18) was named Mélange Matrix Rock Outcrop 2. These outcrops range from 6 × 6 in. to 2 × 2 ft and do not contain any visible fractures.

A small 2 × 2 ft sandstone outcrop is located approximately 100 ft of the south tunnel portal and does not contain any visible fractures.

The areas between the outcrops described above are vegetated either with grasses or native vegetation consisting of shrubs (including poison oak) and blackberry brambles. These areas are covered either with residual soil or fill, and additional rock outcrops above the tunnel alignment were not encountered.

### 3.3.3 South Portal

The south portal area (Figure 3) is accessible on foot and was investigated to determine the condition of any rock outcrops in the proximity of the portal. A stream flows from Underhill Road downslope towards the south portal, deviating to the east of the portal, and flowing south through a very vegetated, marshy area (Figure 19). The south portal was covered with fill following the portal collapse (Jacobs Associates, 2001) and is not visible (Figure 20). A piece of concrete is visible through the fill and could be the exposed east corner of the portal structure (Figure 19).

The fill pile is bounded on the northeast by a nearly vertical sandstone outcrop 15-ft high with conjugate fractures 8–12 in. apart (Figure 21, left), oriented with dip and dip-direction of 50/080 and 85/210. The outcrop contains two shaley shear zones 1-to-2-ft wide and 10-ft wide (Figure 21, right), the lower of which is oriented with dip and dip-direction of 35/330, and pinches out to the east and west.

The fill pile is bounded to the west and northwest by 1:1 to 2:1 vegetated slopes on which no rock outcrops could be found.
4 Anticipated Geomechanical Conditions

Based on the information gathered during the site investigations and on an analysis of previous studies, the following are the anticipated geomechanical conditions that are likely to be found within the tunnel area. Stand-up time refers to the minimum length of time the tunnel is anticipated to remain stable without any support. During tunnel rehabilitation, immediate resupport of the tunnel envelope will be required if there is a short stand-up time so that the tunnel does not collapse. This also implies that if the sets have degraded, most likely due to rotting, and can no longer provide support to the rock, the tunnel in the sections with short stand-up time will collapse unless they are rehabilitated. Rock toughness and abrasivity refer to rock properties that are unfavorable to excavation because they provide greater resistance to excavation (in the case of tough rocks) and cause higher equipment wear (in the case of abrasive rocks). Both of these characteristics would require laboratory testing to determine the magnitude of excavation resistance (usually based on intact rock strength) and abrasivity to aid in selecting the most appropriate excavation methodology.

4.1 North Portal

At the north portal, very blocky to blocky (Table 1) sandstone and shale are anticipated to comprise the slopes adjacent to the portal. The sandstone to the east of the portal is typically blocky, with stand-up time of several hours to several days, and will be tough and abrasive. The residual soil sitting at the top of the slopes is stabilized by shotcrete and vegetation but can be removed with excavating equipment, such as an excavator and hydraulic hammer.

4.2 Tunnel Alignment

Investigation of the MMWD North and South shafts exposed the tunnel support to visual inspection. Inferences can be made regarding the rock mass conditions based on an analysis of the existing support. The analysis suggests that the rock mass is very blocky (Table 1) in the best case and disintegrated in the worst case. This inference is based on the assumption that rock support was installed in reaction to the rock mass conditions encountered, and not as a uniform support system along the whole length of tunnel. This rock mass type is subject to instability—leading to block gravity fall in the best case to running ground and piping to surface in the worst case—arising from the combination of rock mass conditions and low overburden (approximately 10 ft). A deeper tunnel (such as the Alto Tunnel) would be less susceptible to these failure mechanisms due to the confinement provided at greater depth if the rock is very blocky.

An analysis of the as-built conditions (Figure 22) has allowed the geological conditions to be inferred by relating the timber set spacing to the ground condition (Table 2). The field investigation and examination of the as-built drawings has led to the following conclusions regarding the likely rock mass to be encountered at the tunnel depth from south to north along the tunnel alignment (Figure 20), as follows:

- From the south portal, Station 255+89, to Station 259+00, variable conditions changing at 20-to-25-ft intervals ranging from disintegrated to very blocky sandstone or mélange matrix. This zone coincides with a known cave-in, and pea gravel backfill is used to support the remaining rock.
• From Station 259+00 to 260+50, variable conditions changing at 30-to-50 ft intervals, ranging from very blocky to blocky sandstone. This area coincides with a minor cave-in.
• From Station 260+50 to 261+75, variable conditions changing at 20-to-50 ft intervals, ranging from blocky to massive sandstone or mélange matrix.
• From Station 261+75 to 262+80, variable conditions changing at 20-ft intervals, ranging from disintegrated to blocky/disturbed sandstone or mélange matrix. This area coincides with a minor cave-in.
• From Station 262+80 to 263+75, constant conditions of blocky to massive sandstone.
• From Station 263+75 to 265+80, variable conditions changing at 20-to-25 ft intervals, ranging from very blocky to blocky sandstone. This area coincides with a minor cave-in.
• From Station 265+80 to 270+20, constant conditions of blocky to massive sandstone.
• From Station 270+70 to 271+75, variable conditions changing at 20-ft intervals, ranging from blocky/disturbed to very blocky sandstone or mélange matrix.
• From Station 271+75 to the north portal, Station 277+62, the area is built in blocky to very blocky sandstone and shale. This area coincides with a >100-ft-long concrete bulkhead (Jacobs Associates, 2001).

In the massive and blocky rock masses, stable ground conditions are expected, with stand-up time exceeding one day, and tough and highly abrasive conditions. In the very blocky rock mass, stand-up time will be less than one day, and tough and abrasive conditions are also possible, especially in the sandstone. Discontinuity orientations and spacing in the blocky and very blocky rock masses create the potential for rock block and wedge failure that will cause rock several cubic feet in volume to fall into the tunnel when exposed by the removal of the timber sets. In the blocky/disturbed rock mass, raveling is anticipated with stand-up time less than 6 hr with the removal of the timber sets. In the disintegrated rock mass, running is expected in cohesionless material with no stand-up time upon removal of the timber sets, and sloughing and slabbing are anticipated in cohesive material with stand-up time of less than 1 hr upon removal of the timber sets.

4.3 South Portal

The existence of a sandstone outcrop to the northeast of the south portal suggests that sandstone may underlay the residual soil and fill in the portal area. This sandstone outcrop is blocky to massive and will be tough and abrasive. The close timber spacing in the southernmost section of the tunnel suggests that the rock mass at tunnel depth is blocky/disturbed. As a result, sandstone rock mass ranging from blocky/disturbed to massive is to be expected at the portal below the residual soil and fill. Mélange matrix is also likely in this area, although no interpretations can be made regarding the rock mass conditions without further investigation.

The fill and residual will be removed with excavation equipment, such as an excavator and hydraulic hammer, but stability of the material will allow a stand-up time of only a few hours until solid rock is encountered. If no solid rock is encountered, the very block to blocky/disturbed rock will have a stand-up time of only a few hours.
5 Conclusions

A desktop investigation of existing documentation and geological maps was conducted, which was complemented by a field investigation of the engineering geological conditions at both portals and along the tunnel alignment. These investigations show that most of the tunnel is in sandstone and some shale (especially to the north), and rock-like mélange matrix (especially to the south). The rock mass conditions comprise a wide spectrum—from disintegrated rock with no stand-up time to massive rock with long stand-up time and tough and abrasive excavation conditions. The majority of the rock is very blocky to blocky, with a stand-up time of several hours to several days, but in which block and wedge failure are likely upon the removal of the timber sets. Some minor cave-ins were mapped in the late 1970s, and a major cave-in was backfilled in 1982. The north portal is surrounded by very blocky to blocky sandstone and shale rock slopes overlaid by vegetated residual soil at the top. The south portal is covered with rock and soil fill, but it is surrounded by very blocky to blocky sandstone, and potentially mélange matrix.
6 References


# 7 Revision Log

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<td>4/19/09</td>
<td>Issued for discussion with TAP</td>
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<td>C</td>
<td>7/31/09</td>
<td>Issued for project team review</td>
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### Table 1. Descriptions of rock mass structure

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<thead>
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<th>Structure</th>
<th>Description</th>
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<tr>
<td>Massive</td>
<td>Intact in situ rock with few widely spaced discontinuities.</td>
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<tr>
<td>Blocky</td>
<td>Well-interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets.</td>
</tr>
<tr>
<td>Very Blocky</td>
<td>Interlocked, partially disturbed mass with multifaceted angular blocks formed by 4 or more joint sets.</td>
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<tr>
<td>Blocky/Disturbed</td>
<td>Folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity.</td>
</tr>
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<td>Disintegrated</td>
<td>Poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces.</td>
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<tr>
<td>Laminated</td>
<td>Lack of blockiness due to close spacing of weak schistosity.</td>
</tr>
<tr>
<td>Sheared</td>
<td>Lack of blockiness due to close spacing of shear planes.</td>
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After Marinos et al. (2005).

### Table 2. Relation of timber spacing to rock mass structure

<table>
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<th>Timber Set Spacing (in.)</th>
<th>Rock Mass Classification (per Table 1)</th>
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<td>&gt;72</td>
<td>Massive</td>
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<td>Blocky</td>
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<td>&lt;24</td>
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Figure 16. Tunnel Alignment: Condition of rock mass in sandstone above tunnel in rock outcrop in Alto Bowl

Figure 17. Tunnel Alignment: Mélange Matrix Outcrop 1 above tunnel
Figure 18. Tunnel Alignment: Mélange Matrix Outcrop 2 above tunnel
Figure 19. South Portal: Schematic of south portal area south of Underhill Road
Figure 20. South Portal: Typical condition of rock fill at south portal

Figure 21. South Portal: Sandstone outcrop above tunnel portal
Figure 22. Tunnel Alignment: Condition of rock mass in tunnel inferred from installed support