BOREHOLE LOGGING AS AN EXPLORATION TOOL FOR TUNNEL DESIGN

Mario Carnevale, Hager GeoScience, Inc., Woburn, MA
Jutta L. Hager, Hager GeoScience, Inc., Woburn, MA

Abstract

Hager GeoScience, Inc. has just completed mapping a 17.6-mile-long deep-rock water supply tunnel outside Boston, Massachusetts. The exploration phase included drilling a series of boreholes from the surface through the proposed tunnel alignment and collecting rock core; the core was logged and lithology and structure, including fractures, described. No oriented core was taken or geophysical borehole logging performed. Thus, fractures and other discontinuities could not be completely characterized from the borehole descriptions, and the orientation of fracture sets that might produce problems during tunnel construction could not be determined.

We have used our tunnel mapping data to show how geophysical borehole logging during the preliminary investigation could have benefited design of this tunnel and can benefit the design of future tunnels as well. Geophysical borehole logging, particularly acoustic televiewer (ATV), would have better enabled the contractor to predict which fracture sets might be of concern. Acoustic televiewer logging is more accurate and less expensive than oriented core, and can be performed in a borehole as small as 3 inches.

Introduction

Since January 1997, Hager GeoScience, Inc. (HGI) has been mapping the 17.6-mile MetroWest Water Supply Tunnel (MWWST) and shafts outside Boston, Massachusetts. With the mapping task complete, we have now used the tunnel mapping data to review the geologic exploration model. The goals of this review were threefold: 1) to determine the strength and weakness of the model; 2) to understand the differences between actual and predicted geologic conditions; and 3) to show how geophysical borehole logging during the preliminary investigation could have benefited design of the MWWST and, by extension, could benefit the design of future tunnels as well.

The preliminary investigation included surface geophysical surveys, mapping of bedrock outcrops, and 37 deep rock borings through the projected tunnel alignment. Each boring was cored and the rock core logged by project geologists. Selected samples were also thin sectioned and petrographic analysis performed. No oriented core was taken, nor was geophysical borehole logging performed.

The exploration model stressed a regional geologic framework, with an emphasis on major regional structural boundaries. However, many of the features actually mapped in the tunnel belong to fracture sets not identified as such or stressed in the exploration model. Thus, while lithologic descriptions were generally accurate and major regional structural boundaries were identified, to a large extent, the structural predictions were “hit or miss.”

Figure 1 shows a cross section of the MWWST alignment and shaft locations.

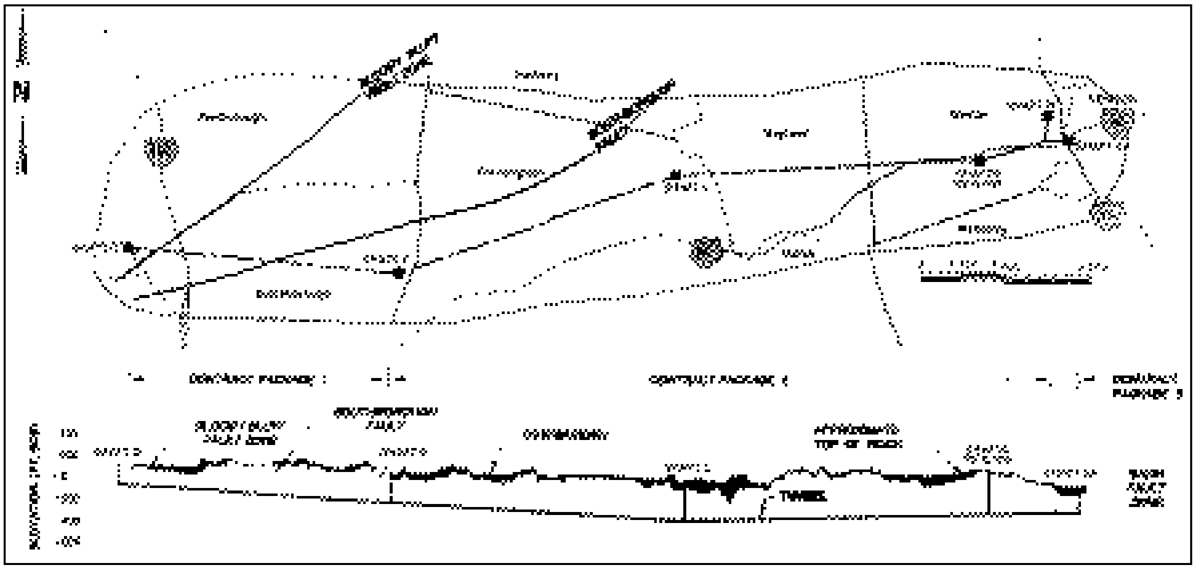


Figure 1. Map cross section of MWWST alignment and shaft locations (GZA GeoEnvironmental, Inc., 1995).

Figure 2 shows the exploration model cross section for the tunnel alignment between Shafts D and E (top) and the corresponding tunnel features map (bottom).

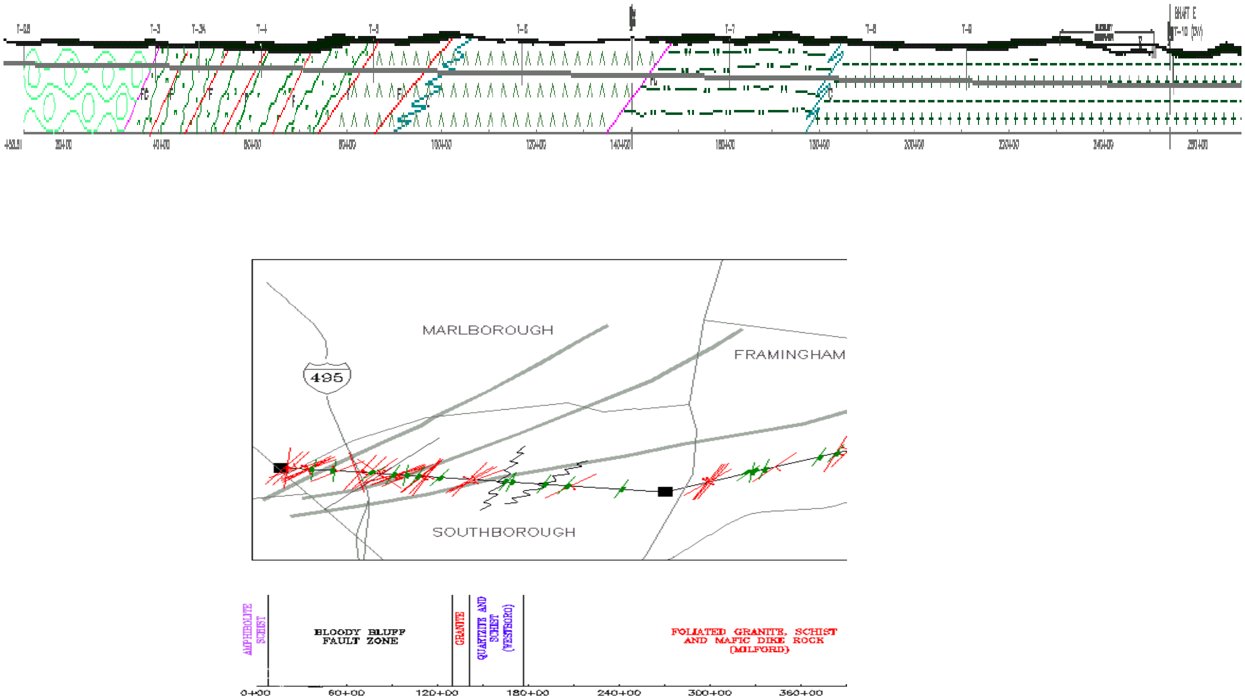


Figure 2. (Top) Exploration model cross section for interval between Shafts D and E. (Bottom) Features mapped for that segment of the tunnel. Fractures are shown in red; dikes in green; contacts as zig-zag lines.

Geologic maps of eastern Massachusetts show three prominent fault zones along the MWWST alignment from east to west: the Boston Basin Margin Fault, the Southborough Fault, and the Bloody Bluff Fault Zone, the latter two features between Shafts D and E. The exploration model cross section (Figure 2) shows these and other discontinuities as west-dipping features. However, east-dipping features delineated during tunnel mapping often had greater impact on the project construction and budget. Figure 3 shows the effect of younger, east-dipping fracture sets intersecting the older west-dipping fractures in the tunnel. The result in this case is a rubble zone approximately 100 feet long marking the eastern margin of the Bloody Bluff Fault Zone between Shafts D and E.

Figure 3. Photograph of Bloody Bluff Fault interval showing how the intersection of younger east-dipping fractures with older fractures has produced cobble-sized rubble requiring support of ring steel and wire mesh.

Potential Contributions of Borehole Logging

The contrast between features as mapped in the tunnel versus as compared to their orientation as inferred from existing geologic data and boring logs highlights the potential value of geophysical borehole logging in early stages of this type of project. Only 10 exploratory borings were drilled across the two broad fault zones anticipated to be encountered along the tunnel alignment between Shafts D and E, a distance of almost 5 miles. Numerous contacts were mapped and steeply dipping fracture surfaces noted on the boring logs. However, minimal information was obtained about the orientations of mapped structures. Table 1 shows the type of detailed information that could have been obtained had acoustic televiewer (ATV) log data been obtained from some of the MetroWest borings.

Table 1. Example Table Showing Typical Structural Information from ATV Logs

Boring ID	**Depth**	**Elev.**	**Strike**	**Dip Angle**	**Apparent Aperture (in)**	**Weathering**	**Spacing (ft)**	**Set #**
B-01	58.11	94.56	286.0	74.65	0.00	heavily weathered	4	3
B-01	60.49	92.18	56.4	16.45	4.80	heavily weathered	5	1
B-01	61.11	91.56	263.5	82.39	0.00	heavily weathered	4	4
B-01	62.28	90.39	85.9	19.84	10.80	heavily weathered	5	1
B-01	63.06	89.61	59.1	83.92	0.00	heavily weathered	20	5
B-01	65.41	87.26	0.0	0	4.80	heavily weathered	5	1
B-01	66.36	86.31	311.5	46.39	4.80	heavily weathered	4	3
B-01	74.08	78.59	264.8	74.51	0.00	fresh	4	4
B-01	75.59	77.08	78.1	31.94	3.60	slightly weathered	5	1
B-01	80.47	72.2	76.0	33.27	3.60	slightly weathered	5	1
B-01	85.98	66.69	0.0	0	6.00	heavily weathered	5	1
B-01	88.62	64.05	51.8	81.82	0.00	fresh	20	5
B-01	94.13	58.54	211.0	27.7	4.80	Moderately weathered	4	4

Strike and dip information entered on a table like the one above can be used to generate rose diagrams and stereonets showing the orientations of bedrock discontinuities encountered in individual borings, or summarizing bedrock discontinuities over a larger region. Figures 4 and 5 show the rose diagram and stereonet, respectively, created from the ATV information in Table 1.

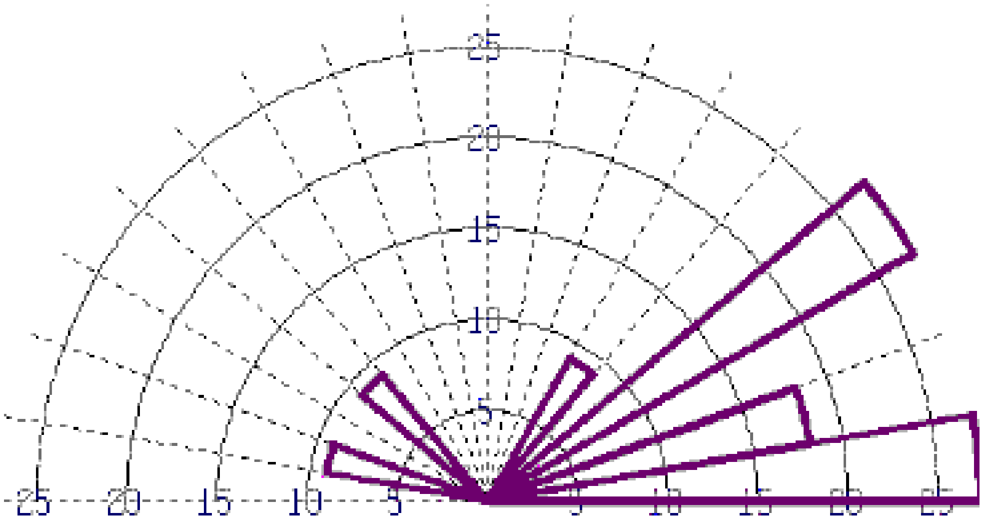
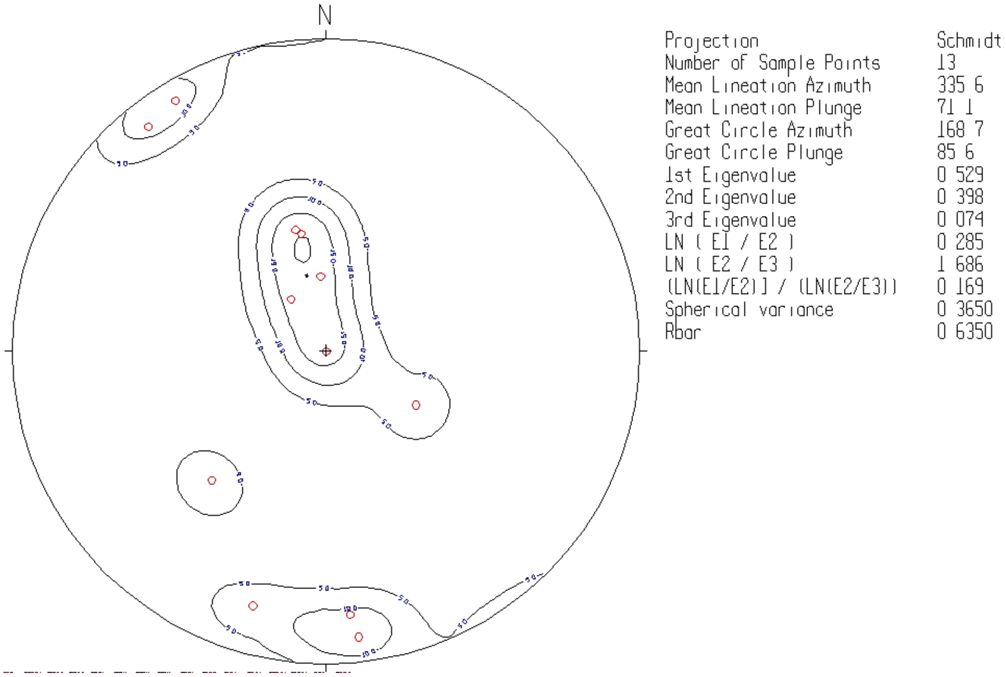


Figure 4. Rose diagram showing fracture orientations for boring B-01 from ATV data.



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Projection                      Schmidt
Number of Sample Points         13
Mean Lineation Azimuth          335 6
Mean Lineation Plunge           71 1
Great Circle Azimuth            168 7
Great Circle Plunge             85 6
1st Eigenvalue                  0 529
2nd Eigenvalue                  0 398
3rd Eigenvalue                  0 074
LN ( E1 / E2 )                  0 285
LN ( E2 / E3 )                  1 686
(LN(E1/E2)) / (LN(E2/E3))       0 169
Spherical variance              0 3650
Rbar                            0 6350
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Figure 5. Stereonet showing fracture orientations for boring B-01 from ATV data.

The rose diagram for Boring B-1 (Figure 4) shows that the major strike direction of fractures is to the east-northeast, with a subsidiary northwest orientation. The stereonet plot in Figure 5 further shows that the fracture population is composed of at least three subsets with different orientations: One set is nearly horizontal and the other two dip steeply to the northwest and southeast.

It is possible to extrapolate from the point ATV data to the regional level by visually integrating these summary data plots into regional interpretation maps such as the one in Figure 6 below. This figure combines rose diagrams and stereonets from the ATV logs for an entire suite of borings with interpreted lineaments from a photolineament study, a bedrock contour map developed from surface geophysical surveys, and structural interpretations based on regional geological and geophysical investigations. Summarizing all the information on one map also makes it easier to detect data inconsistencies and/or errors.

CONCLUSIONS

Information obtained during the exploration phase for tunnels drives the nature of contract documents and estimates of rock quality and boreability. Critical to the realistic assessment of tunnel mining is the orientation of and relationship between fractures and faults along the alignment. Obtaining this structural information from the acoustic televiewer logging of borings during this exploratory phase of the project is well worth the relatively small additional cost and effort involved.

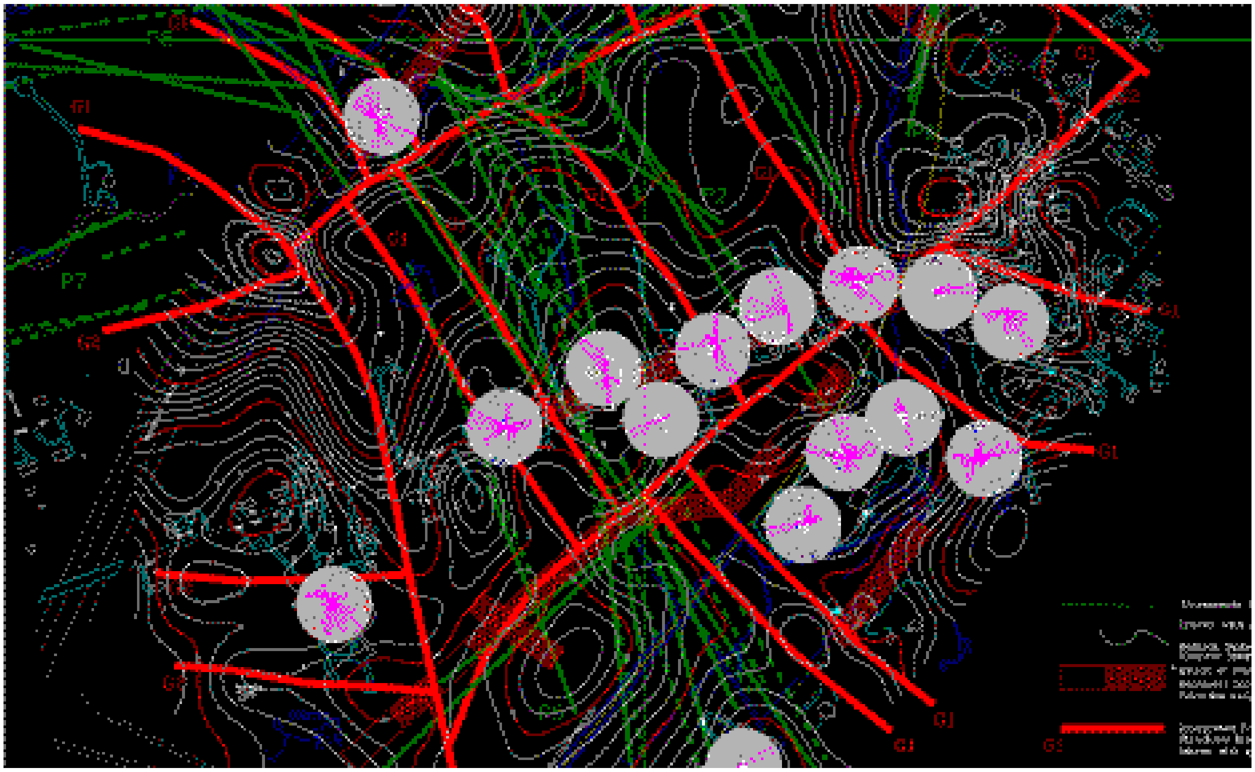

Figure 6. Regional interpretation map incorporating ATV fracture orientation data with data from other geophysical and geological sources.

References

1. GZA GeoEnvironmental (1995), "Geotechnical Data Report, MetroWest Water Supply Tunnel Construction Packages 1, 2, and 3," December, IX volumes.