

B-3

## Phase II Bedrock Hydrogeologic Investigation

**REPORT ON**

**EAGLE PROJECT**

**PHASE II BEDROCK HYDROGEOLOGIC INVESTIGATION**

*Submitted to:*

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## TABLE OF CONTENTS

| <b><u>SECTION</u></b>                                                   | <b><u>PAGE</u></b> |
|-------------------------------------------------------------------------|--------------------|
| <b>LIST OF TABLES .....</b>                                             | <b>iii</b>         |
| <b>LIST OF FIGURES .....</b>                                            | <b>iii</b>         |
| <b>LIST OF APPENDICES .....</b>                                         | <b>vi</b>          |
| <b>1.0 INTRODUCTION .....</b>                                           | <b>1</b>           |
| 1.1 Objectives .....                                                    | 1                  |
| 1.2 Report Format .....                                                 | 1                  |
| 1.3 Background and Approach .....                                       | 2                  |
| <b>2.0 GEOLOGY .....</b>                                                | <b>4</b>           |
| 2.1 Quaternary Geology of the Project Area .....                        | 4                  |
| 2.2 General Bedrock Geology – Yellow Dog Plains, Marquette County, MI.. | 4                  |
| <b>3.0 BOREHOLE INFORMATION.....</b>                                    | <b>6</b>           |
| <b>4.0 GROUTED-IN PIEZOMETERS .....</b>                                 | <b>8</b>           |
| 4.1 Selection of Intervals for Monitoring Within the Bedrock.....       | 8                  |
| 4.2 Piezometer Installation.....                                        | 8                  |
| <b>5.0 EQUIPMENT FOR HYDRAULIC TESTING .....</b>                        | <b>10</b>          |
| 5.1 Surface Equipment.....                                              | 10                 |
| 5.2 Downhole Equipment .....                                            | 11                 |
| <b>6.0 ANALYSIS METHODOLOGY .....</b>                                   | <b>13</b>          |
| 6.1 Measurement of Hydraulic Heads .....                                | 13                 |
| 6.2 Computations of Water Levels from Pressure Data .....               | 13                 |
| 6.3 Water Level Changes.....                                            | 13                 |
| 6.4 Testing Approach.....                                               | 14                 |
| 6.5 Defining a Response to Testing at Observation Zones.....            | 14                 |
| 6.6 Distances Between Source and Observation Zones.....                 | 15                 |
| 6.7 Analysis Approach.....                                              | 15                 |
| 6.7.1 Pressure Derivative Data.....                                     | 16                 |
| 6.7.2 Transmissivity Normalized Plots.....                              | 16                 |
| 6.7.3 Diffusivity .....                                                 | 17                 |
| 6.8 Analysis Software .....                                             | 18                 |
| <b>7.0 HYDRAULIC TESTING – BOREHOLE 05EA-107 .....</b>                  | <b>20</b>          |
| 7.1 Scan Tests .....                                                    | 20                 |
| 7.1.1 Objectives and Test Approach.....                                 | 20                 |
| 7.1.2 Measured Data .....                                               | 20                 |
| 7.1.3 Analysis for Hydraulic Parameters .....                           | 20                 |
| 7.2 Consecutive Slug Test #1.....                                       | 21                 |
| 7.2.1 Objectives and Test Approach.....                                 | 21                 |
| 7.2.2 Measured Data .....                                               | 21                 |
| 7.3 Consecutive Slug Test #2.....                                       | 22                 |
| 7.3.1 Objectives and Test Approach.....                                 | 22                 |
| 7.3.2 Measured Data .....                                               | 22                 |
| <b>8.0 HYDRAULIC TESTING – BOREHOLE 04EA-084 .....</b>                  | <b>24</b>          |

|             |                                                           |           |
|-------------|-----------------------------------------------------------|-----------|
| 8.1         | Objectives and Test Approach .....                        | 24        |
| 8.2         | Measured Data .....                                       | 24        |
| 8.3         | Analysis for Hydraulic Parameters .....                   | 26        |
| <b>9.0</b>  | <b>WATER QUALITY RESULTS .....</b>                        | <b>29</b> |
| 9.1         | Sample Methods.....                                       | 29        |
| 9.1.1       | Borehole 05EA-107 .....                                   | 29        |
| 9.1.2       | Borehole 04EA-084 .....                                   | 30        |
| 9.2         | Chemistry Results .....                                   | 30        |
| 9.2.1       | Results and Quality Control/Quality Assurance .....       | 32        |
| 9.2.2       | Groundwater Characterization.....                         | 36        |
| 9.2.3       | Discussion of Water Quality Results .....                 | 37        |
| <b>10.0</b> | <b>ASSESSMENT FOR VERTICAL GRADIENTS.....</b>             | <b>39</b> |
| 10.1        | Static Formation Pressure and Groundwater Potential ..... | 39        |
| 10.2        | Groundwater Density Profile .....                         | 40        |
| 10.3        | Freshwater and Environmental Head Profiles .....          | 41        |
| 10.4        | Discussion of Vertical Hydraulic Gradients .....          | 42        |
| <b>11.0</b> | <b>SUMMARY AND CONCLUSIONS .....</b>                      | <b>43</b> |
| <b>12.0</b> | <b>CLOSURE .....</b>                                      | <b>45</b> |
| <b>13.0</b> | <b>REFERENCES.....</b>                                    | <b>46</b> |

### LIST OF TABLES

|            |                                                                                                                                       |
|------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Table 3.1  | Boreholes/Monitoring Wells Used in Phase 1 and Phase II Investigations; Orientation and Geometry                                      |
| Table 3.2  | Boreholes/Monitoring Wells Used in Phase 1 and Phase II Investigations; Function and Geology                                          |
| Table 4.1  | Downhole Piezometer Summary                                                                                                           |
| Table 6.1  | Source and Observation Zone Coordinates and Distances Between Source and Observation Zones                                            |
| Table 6.2  | Flow Models Available in SAPHIR                                                                                                       |
| Table 7.1  | Analysis Results for Scan Tests in Borehole 05EA-107                                                                                  |
| Table 7.2  | Summary of Measured Responses During 05EA-107 Consecutive Slug Test #1                                                                |
| Table 7.3  | Summary of Measured Responses During 05EA-107 Consecutive Slug Test #2                                                                |
| Table 8.1  | Summary of Measured Responses During Borehole 04EA-084 Pumping Test                                                                   |
| Table 8.2  | Borehole 04EA-084 Pumping Test, Estimates of Hydraulic Parameters for Select Zones Using Radial Composite and Homogeneous Flow Models |
| Table 8.3  | Borehole 04EA-084 Pumping Test, Estimates of Hydraulic Parameters for Source Zone using Fracture Model                                |
| Table 9.1  | Sample Information and Field Parameters                                                                                               |
| Table 9.2  | Groundwater Analyses Summary Table                                                                                                    |
| Table 9.3  | Analytical Results for QA/QC Samples                                                                                                  |
| Table 9.4  | QA/QC Checks for Borehole Data.                                                                                                       |
| Table 10.1 | Summary of Total Dissolved Solids and Groundwater Density Data                                                                        |
| Table 10.2 | Summary of Freshwater Heads and Environmental Heads                                                                                   |

### LIST OF FIGURES

|            |                                                                                                                                                                     |
|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Figure 3.1 | Borehole Traces With 3-D Detail                                                                                                                                     |
| Figure 4.1 | Borehole YD02-20; Grouted-in Piezometers                                                                                                                            |
| Figure 4.2 | Borehole 04EA-074; Grouted-in Piezometers                                                                                                                           |
| Figure 4.3 | Borehole 04EA-077; Grouted-in Piezometers                                                                                                                           |
| Figure 5.1 | Borehole 04EA-084 Downhole Tool Schematic                                                                                                                           |
| Figure 6.1 | Borehole YD02-20; Tidal Effects                                                                                                                                     |
| Figure 6.2 | Borehole 04EA-074; Tidal Effects                                                                                                                                    |
| Figure 6.3 | Borehole 04EA-077; Tidal Effects                                                                                                                                    |
| Figure 6.4 | Example for Illustration; Log-Log Plot of Hydraulic Test Data; Diagnosis of Flow Model with Semi-Log Derivative Data (also referred to as Pressure Derivative Data) |
| Figure 6.5 | Example for Illustration; Analysis of Slug Test Using Deconvolution Method                                                                                          |
| Figure 6.6 | Example for Illustration; Transmissivity Normalized Plot of the Slug Test Shown in Figure 6.5                                                                       |
| Figure 6.7 | Example for Illustration; Transmissivity Normalized Plot (pressure derivative data only) for a Pumping and Observation Well Response                                |
| Figure 7.1 | Borehole 05EA-107; 21.33 m to 38.03 m; Slug Test Data                                                                                                               |
| Figure 7.2 | Borehole 05EA-107; 36.54 m to 53.24 m; Slug Test Data                                                                                                               |
| Figure 7.3 | Borehole 05EA-107; 51.63 m to 68.34 m; Slug Test Data                                                                                                               |
| Figure 7.4 | Borehole 05EA-107; 66.96 m to 83.67 m; Slug Test Data                                                                                                               |
| Figure 7.5 | Borehole 05EA-107; 82.11 m to 98.82 m; Slug Test Data                                                                                                               |

|              |                                                                                                     |
|--------------|-----------------------------------------------------------------------------------------------------|
| Figure 7.6   | Borehole 05EA-107; 97.52 m to 114.22 m; Slug Test Data                                              |
| Figure 7.7A  | Borehole 05EA-107; 21.33 m to 38.03 m; Slug Test Analysis; Cooper Method                            |
| Figure 7.7B  | Borehole 05EA-107; 21.33 m to 38.03 m; Slug Test Analysis; Deconvolution Method                     |
| Figure 7.8A  | Borehole 05EA-107; 36.54 m to 53.24 m; Slug Test Analysis; Cooper Method                            |
| Figure 7.8B  | Borehole 05EA-107; 36.54 m to 53.24 m; Slug Test Analysis; Deconvolution Method                     |
| Figure 7.9A  | Borehole 05EA-107; 51.63 m to 68.34 m; Slug Test Analysis; Cooper Method                            |
| Figure 7.9B  | Borehole 05EA-107; 51.63 m to 68.34 m; Slug Test Analysis; Deconvolution Method                     |
| Figure 7.10A | Borehole 05EA-107; 66.96 m to 83.67 m; Slug Test Analysis; Cooper Method                            |
| Figure 7.10B | Borehole 05EA-107; 66.96 m to 83.67 m; Slug Test Analysis; Deconvolution Method                     |
| Figure 7.11A | Borehole 05EA-107; 82.11 m to 98.2 m; Slug Test Analysis; Cooper Method                             |
| Figure 7.11B | Borehole 05EA-107; 82.11 m to 98.82 m; Slug Test Analysis; Deconvolution Method                     |
| Figure 7.12A | Borehole 05EA-107; 97.52 m to 114.22 m; Slug Test Analysis; Cooper Method                           |
| Figure 7.12B | Borehole 05EA-107; 97.52 m to 114.22 m; Slug Test Analysis; Deconvolution Method                    |
| Figure 7.13  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1                                    |
| Figure 7.14  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; QAL-023                           |
| Figure 7.15  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; QAL-043                           |
| Figure 7.16  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; QAL-044                           |
| Figure 7.17  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; YD02-20 Upper Bedrock Piezometer  |
| Figure 7.18  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; YD02-20 Lower Bedrock Piezometer  |
| Figure 7.19  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; 04EA-074 Upper Bedrock Piezometer |
| Figure 7.20  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; 04EA-074 Lower Bedrock Piezometer |
| Figure 7.21  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; 04EA-077 Upper Bedrock Piezometer |
| Figure 7.22  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; 04EA-077 Lower Bedrock Piezometer |
| Figure 7.23  | Borehole 05EA-107; 97.52 m to 114.22 m; Consecutive Slug Test #1; Non-Responding Observation Zones  |
| Figure 7.24  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2                                     |
| Figure 7.25  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; QAL-023                            |
| Figure 7.26  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; QAL-043                            |
| Figure 7.27  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; QAL-044                            |
| Figure 7.28  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; YD02-20 Upper Bedrock Piezometer   |
| Figure 7.29  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; YD02-20 Lower Piezometer           |
| Figure 7.30  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; 04EA-074 Upper Bedrock Piezometer  |

|              |                                                                                                                                                                          |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Figure 7.31  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; 04EA-074 Lower Bedrock Piezometer                                                                       |
| Figure 7.32  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; 04EA-077 Upper Piezometer                                                                               |
| Figure 7.33  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; 04EA-077 Lower Bedrock Piezometer                                                                       |
| Figure 7.34  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; Responding Observation Zones                                                                            |
| Figure 7.35  | Borehole 05EA-107; 18.20 m to 34.90 m; Consecutive Slug Test #2; Non-Responding Observation Zones                                                                        |
| Figure 8.1   | Aerial View of Boreholes Used in 04EA-084 Pumping Test and Drawdown Measured at End of Pumping                                                                           |
| Figure 8.2   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test                                                                                                                    |
| Figure 8.3   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; QAL-023                                                                                                           |
| Figure 8.4   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; QAL-043                                                                                                           |
| Figure 8.5   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; QAL-044                                                                                                           |
| Figure 8.6   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; YD02-20 Upper Bedrock Piezometer                                                                                  |
| Figure 8.7   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; YD02-20 Lower Bedrock Piezometer                                                                                  |
| Figure 8.8   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; 04EA-074 Upper Bedrock Piezometer                                                                                 |
| Figure 8.9   | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; 04EA-074 Lower Bedrock Piezometer                                                                                 |
| Figure 8.10  | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; 04EA-077 Upper Bedrock Piezometer                                                                                 |
| Figure 8.11  | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; 04EA-077 Lower Bedrock Piezometer                                                                                 |
| Figure 8.12  | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; Responding Observation Zones                                                                                      |
| Figure 8.13  | Borehole 04EA-084; 249.05 m to 302.08 m; Pumping Test; Non-Responding Observation Zones                                                                                  |
| Figure 8.14A | TNP Plot; Conceptual Model for 04EA-084 Pumping Test Response; Early Time – Vertical (to Sub-Vertical) Water Conductive Feature Dominates Formation Response             |
| Figure 8.14B | TNP Plot; Conceptual Model for 04EA-084 Pumping Test Response; Matrix/Background Fracture Network in Good Hydraulic Communication with Vertical Water Conductive Feature |
| Figure 8.14C | TNP Plot; Conceptual Model for 04EA-084 Pumping Test Response; Matrix/Background Fracture Network in Poor Hydraulic Communication with Vertical Water Conductive Feature |
| Figure 8.15A | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Recovery Data; Radial Composite Flow Model; Constant Rate Log-Log Analysis                                            |
| Figure 8.15B | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Radial Composite Flow Model; Match to Entire Simulation                                                               |

|              |                                                                                                                                                                                                                           |
|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Figure 8.16A | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Recovery Data; Radial Composite Flow Model; Constant Rate Log-Log Analysis; Alternative Analysis to Assess Sensitivity of Parameters                                   |
| Figure 8.16B | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Recovery Data; Radial Composite Flow Model; Match to Entire Simulation; Alternative Analysis to Assess Sensitivity of Parameters                                       |
| Figure 8.17  | Borehole 04EA-084 Pumping Test; Borehole 04EA-074 Lower Bedrock Piezometer; Recovery Data; Constant Rate Log-Log Analysis                                                                                                 |
| Figure 8.18  | Borehole 04EA-084 Pumping Test; Borehole 04EA-077 Lower Bedrock Piezometer; Recovery Data, Constant Rate Log-Log Analysis                                                                                                 |
| Figure 8.19A | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Recovery Data; Fracture Connected to Wellbore Model; Constant Rate Log-Log Analysis                                                                                    |
| Figure 8.19B | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Match to Entire Simulation; Fracture Connected to Wellbore Model                                                                                                       |
| Figure 8.19C | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Numerical Grid Used to Simulate Pumping Test; 3-D View; Fracture Connected to Wellbore - Half-Length of 160 m                                                          |
| Figure 8.19D | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; Numerical Grid Used to Simulate Pumping Test; 2-D View of Grid: Fracture Connected to Wellbore – Half-Length of 160 m                                                  |
| Figure 8.19E | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; 3-D View; 7 Hours After Start of Pumping; Flow in Fracture Dominates Response Resulting in One-Dimensional Flow; Fracture Connected to Wellbore – Half-Length of 160 m |
| Figure 8.19F | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; 2-D View; 7 Hours After Start of Pumping; Flow in Fracture Dominates Response Resulting in One-Dimensional Flow; Fracture Connected to Wellbore – Half-Length of 160 m |
| Figure 8.19G | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; 3-D View; Fracture Connected to Wellbore Model; Proximal to End of Pumping; Flow in Matrix/Background Fracture Network Dominates Response Resulting in Radial Flow     |
| Figure 8.19H | Borehole 04EA-084 Pumping Test; Borehole 04EA-084; 2-D View; Fracture Connected to Wellbore Model; Proximal to End of Pumping; Flow in Matrix/Background Fracture Network Dominates Response Resulting in Radial Flow     |
| Figure 9.1   | Piper Diagram for Selected Groundwater Samples                                                                                                                                                                            |
| Figure 9.2   | Stiff Diagrams for Borehole 04EA-084 and 05EA-107 Water Samples                                                                                                                                                           |
| Figure 10.1  | Monitoring Data Expressed as Freshwater Head Versus Time                                                                                                                                                                  |
| Figure 10.2  | Interpreted Density Versus Elevation Profile                                                                                                                                                                              |
| Figure 10.3  | Freshwater Head and Environmental Head Versus Elevation                                                                                                                                                                   |
| Figure 10.4  | Regression on Environmental Head Versus Elevation                                                                                                                                                                         |

## LIST OF APPENDICES

|            |                                              |
|------------|----------------------------------------------|
| Appendix A | Grouted-in Piezometer Procedures             |
| Appendix B | Pumping Test Procedure                       |
| Appendix C | Logbooks                                     |
| Appendix D | Parameters Measured During Water Sampling    |
| Appendix E | Water Quality Results from Laboratories      |
| Appendix F | Calibration Certificates for Instrumentation |

## **1.0 INTRODUCTION**

### ***1.1 Objectives***

On behalf of Kennecott Eagle Minerals Company (Kennecott), Golder Associates Inc. (Golder) completed Phase II of the bedrock hydrogeologic characterization in September and October 2005 at the Eagle Project (Project) in Michigan's Upper Peninsula. The basis for the Phase II work is documented in a Golder work plan (Golder, 2005a) and the overall objective was to collect additional hydrogeologic data to assist in the ongoing mine planning and environmental impact assessments. This report presents the data that was collected during the investigation and the interpretation of the data.

### ***1.2 Report Format***

This report has the following format:

- Section 1 discusses report format, background and approach.
- Section 2 provides the geologic setting.
- Section 3 presents pertinent information for boreholes used in the investigation.
- Section 4 discusses installation of grouted-in piezometers that were used to monitor pore pressures in the bedrock during testing.
- Section 5 overviews the equipment used during hydraulic testing.
- Section 6 describes data processing, testing approach, interpretation methodology and analysis software.
- Section 7 presents the results for estimates of hydraulic parameters from the testing performed in borehole 05EA-107.
- Section 8 presents the results for estimates of hydraulic parameters from the testing performed in borehole 04EA-084.
- Section 9 describes water quality sample results for water samples collected during testing in boreholes 05EA-107 and 04EA-084.
- Section 10 discusses the analysis for vertical gradients.
- Section 11 presents the summary and conclusions.
- Section 12 contains the references.

The figures and appendices are presented after the main body of the report.

The depths are presented as measured along borehole in units of meters (m) unless referenced to true vertical depth (mTVD).

### **1.3 Background and Approach**

The Phase I bedrock investigation focused on flow logging and packer tests to determine the spatial distribution of local scale hydraulic properties and to locate enhanced zones of hydraulic conductivity for characterization in future investigations (Golder, 2005b). Emphasis was placed on obtaining discrete data so the fractures with flow (water conductive features) could be correlated with geology, structure and depth to better understand the controlling factors. A conceptual model was developed based on the collected information and interpretation of the data. The hydraulic conductivity values estimates were relatively low and two hydrostratigraphic units were defined as follows:

- The Upper Bedrock hydrostratigraphic unit (top of bedrock to 90 mTVD or approximately 345 m elevation) is estimated to contain a relatively moderate to low hydraulic conductivity. The higher hydraulic conductivity estimated for the Upper Bedrock versus the Lower Bedrock hydrostratigraphic unit may be attributed to more conductive features due to unloading from past glacier events and weathering in general.
- The Lower Bedrock hydrostratigraphic unit (>90 mTVD or approximately >345 m MSL) is estimated to contain a very low hydraulic conductivity range of values, which is consistent with properties expected for the Precambrian rocks. The packer testing and flow logging identified localized zones of enhanced hydraulic conductivity that are sparsely distributed in the Lower Bedrock (one water conductive feature every 173 m; Golder, 2005b). The two identified water conductive features were within the orebody but not correlated with a specific structure as defined in the Eagle Project Geotechnical Study (Golder, 2006).

For the Phase II investigation, the main focus of this report, emphasis was placed on the following:

- Collection of additional hydraulic data to expand the data base;
- Characterization of water quality characteristics with depth;
- Evaluation of the degree of hydraulic communication between the alluvium sediments and the bedrock groundwater systems; and
- Characterization of large scale hydraulic properties and connectivity of a water conductive feature in the Lower Bedrock identified in the Phase I investigation.

As a first step, piezometers were installed to provide a monitoring network within the bedrock to allow for characterization of the three dimensional response to hydraulic testing (Chapter 4) and to establish hydraulic vertical gradients (Chapter 10). Hydraulic testing was then performed in exploration boreholes and monitoring was performed in both the bedrock and within the

alluvium. Packers were used to isolate test sections and examine hydrogeological characteristics of discrete borehole intervals (the test equipment is described in Chapter 5).

Due to the relatively high fracture intensity observed in the core from borehole 05EA-107 based on visual evaluation (personal communication, KMC, September 2005), which is primarily within the Upper Bedrock hydrostratigraphic unit, this borehole was selected for testing to evaluate local scale properties (Chapter 7). Additionally, water samples were collected at relatively shallow and intermediate depths compared to the proposed mining (Chapter 9).

The bottom portion of borehole 04EA-084 was isolated with a packer that encompassed a water conductive feature (257.54 to 260.29 m) identified in the Phase 1 investigation (Golder, 2005b), to characterize its large scale hydraulic properties (Chapter 8) and its water quality properties (Chapter 9). This water conductive feature showed the largest flow anomaly during Phase I that infers this feature contains the highest localized hydraulic conductivity of the six boreholes with flow logging records.

## **2.0 GEOLOGY**

### **2.1 *Quaternary Geology of the Project Area***

Regional geologic maps for the Project Area show that the site is covered with a surficial deposit of unconsolidated, Quaternary glacial outwash and post-glacial Quaternary deposits. Details for the Quaternary Geology of the Project Area can be found in the Eagle Project Environmental Baseline Study Hydrology Report Volume 1 (North Jackson Company, 2005).

### **2.2 *General Bedrock Geology – Yellow Dog Plains, Marquette County, MI***

The Yellow Dog Plains in northern Marquette County is composed of Precambrian rocks covered by glacial Quaternary and post-glacial Quaternary sediments. The bedrock beneath the plains is mostly metasedimentary rocks of the Michigamme Formation, part of the Marquette Range Supergroup of Proterozoic age rocks (roughly 2 billion years old). These metasedimentary rocks are contained in an east-west trending structural trough known informally as the Baraga Basin (Klasner, et al., 1979). This trough is flanked on the north, south, and east by gneiss and greenstone Archean basement rocks, older than 2.5 billion years. Because of the extensive Quaternary deposit cover on the plains, very little exposure of the Michigamme Formation exists in this area. The Archean basement rocks have numerous outcrop exposures surrounding the Baraga Basin.

The Michigamme Formation beneath the Yellow Dog Plains consists of fine-grained clastic rocks, largely black slate and argillite as shown by core drilling (Klasner, et al., 1979). These rocks were deformed and metamorphosed to the greenschist facies about 1.9 billion years ago, during the Penokean orogenic event.

Emplaced into the Michigamme Formation are east to west-trending diabase dikes of early Keweenaw age, intruded about 1.1 billion years ago. The Yellow Dog Peridotite is present in the central Yellow Dog Plains, and is known from two outcrops located in T50N, R29W, Section 11 and 12, along one of these dike trends. The Eagle nickel mineralization prospect is located within the Peridotite near the outcrop located in Section 11. The Peridotite is generally undeformed and only moderately serpentinized (Klasner, et al., 1979). The higher grade

mineralization either post dates or is syn-deformation. The deformation event is best characterized as a WNW-ESE trending dextral shear couple with evidence of dilation. The event may have been responsible for the location of, and controls the shape of, the intrusive units including the massive and semi-massive sulfide mineralization. Major structures could exist on the edges or contacts of the earlier intrusions, including gabbros, pyroxenites, and peridotites containing disseminated sulfides.

### 3.0 BOREHOLE INFORMATION

The majority of the bedrock boreholes (5) used in the Phase I and Phase II investigations are collared at the surface in the north side of the crown (Figure 3.1). These boreholes provided coverage of the hanging wall side of the crown, center of the orebody and the footwall at depth. Of the remaining boreholes, two are collared at the surface along the east side of the deposit, one borehole is collared at the footwall of the deposit, and one is collared in the area of the proposed decline and portal ramp (Figure 3.1). The boreholes were cased through the overburden. Rock composition was similar in both the hanging wall and footwall. The majority of the boreholes encountered the three major geologic units at the site – Siltstone, Peridotite and Orebody. The borehole azimuths varied between 0 and 180 degrees, the inclination varied between -56 and -90 degrees and the maximum TVD is 347 m. In comparison, the current mine plan proposes a maximum true vertical depth for mining of 289 mTVD. In addition, three monitoring wells completed in the overlying Quarternary deposits were used in the investigation. The pertinent borehole and monitoring well information is provided in Tables 3.1 and 3.2.

**Table 3.1. Boreholes/Monitoring Wells Used in Phase 1 and Phase II Investigations;  
Orientation and Geometry**

| Borehole | Collar Location         | Azimuth (degrees) | Inclination (degrees) | Casing Depth (m) | Screen Interval (m) | Total Measured Depth (m) | Total True Vertical Depth (mTVD) |
|----------|-------------------------|-------------------|-----------------------|------------------|---------------------|--------------------------|----------------------------------|
| 04EA-047 | Crown                   | 180               | -78                   | 12.8             | n/a                 | 268.22                   | 262.36                           |
| 04EA-054 | Crown                   | 180               | -75                   | 12.8             | n/a                 | 323.09                   | 323.10                           |
| 04EA-073 | Eastern Zone            | 180               | -75                   | 14.9             | n/a                 | 266.4                    | 255.96                           |
| 04EA-074 | Footwall                | 0                 | -56                   | 27.4             | n/a                 | 381                      | 295.17                           |
| 04EA-077 | Eastern Zone            | 180               | -70                   | 21.3             | n/a                 | 256.03                   | 240.57                           |
| 04EA-083 | Crown                   | 180               | -83                   | 13.7             | n/a                 | 239.88                   | 238.07                           |
| 04EA-084 | Crown                   | 100               | -60                   | 13.7             | n/a                 | 302.05                   | 261.60                           |
| 05EA-107 | Crown                   | 0                 | -87                   | 15.2             | n/a                 | 117.5                    | 109.78                           |
| YD02-20  | Decline and Portal Ramp | 0                 | -90                   | 6.1              | n/a                 | 346.6                    | 346.6                            |
| QAL-023  | North Side of Crown     | 0                 | -90                   | n/a              | 8.23-9.75           | 11.28                    | 11.28                            |
| QAL-043  | North Side of Crown     | 0                 | -90                   | n/a              | 9.14-10.67          | 11.89                    | 11.89                            |
| QAL-044  | North Side of Crown     | 0                 | -90                   | n/a              | 10.67-12.19         | 17.37                    | 17.37                            |

**Table 3.2. Boreholes/Monitoring Wells Used in Phase I and Phase II Investigations;  
Function and Geology**

| Borehole                                      | Function in Hydrogeologic Investigation                  |                                                                   | Geology   |            |         |
|-----------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------|-----------|------------|---------|
|                                               | Phase I Investigation                                    | Phase II Investigation                                            | Siltstone | Peridotite | Orebody |
| <b>Boreholes Completed in Bedrock</b>         |                                                          |                                                                   |           |            |         |
| 04EA-047                                      | flow logging, hydraulic tests for small scale properties | not used                                                          | X         | X          | X       |
| 04EA-054                                      | flow logging                                             | not used                                                          | X         | X          | X       |
| 04EA-073                                      | flow logging, hydraulic tests for small scale properties | not used                                                          | X         | X          | X       |
| 04EA-074                                      | not used                                                 | grouted-in piezometers, monitoring in bedrock                     | X         | X          | X       |
| 04EA-077                                      | flow logging                                             | grouted-in piezometers, monitoring in bedrock                     | X         | X          | X       |
| 04EA-083                                      | flow logging, hydraulic tests for small scale properties | not used                                                          | X         | X          | X       |
| 04EA-084                                      | flow logging, hydraulic tests for small scale properties | water quality samples, hydraulic tests for large scale properties | X         | X          | X       |
| 05EA-107                                      | not used                                                 | water quality samples, hydraulic tests for small scale properties | X         | NA         | X       |
| YD02-20                                       | not used                                                 | grouted-in piezometers, monitoring in bedrock                     | X         | X          | NA      |
| <b>Monitoring Wells Completed in Alluvium</b> |                                                          |                                                                   |           |            |         |
| QAL-023                                       | monitoring in alluvium                                   | monitoring in alluvium                                            | NA        | NA         | NA      |
| QAL-043                                       | not used                                                 | monitoring in alluvium                                            | NA        | NA         | NA      |
| QAL-044                                       | not used                                                 | monitoring in alluvium                                            | NA        | NA         | NA      |

## **4.0 GROUTED-IN PIEZOMETERS**

### ***4.1 Selection of Intervals for Monitoring Within the Bedrock***

Three boreholes were selected for installation of piezometers to measure the drawdown response to hydraulic testing and primarily for the proposed pumping test in Borehole 04EA-084. The monitoring zone distances were selected to provide an approximate logarithmic spacing between observation and pumping zone, restricted to within 300 m of the pumping zone, which was the predicted cone of influence (Golder, 2005b). Also, the relative directions from Borehole 04EA-084 were varied to allow for spatial distribution of responses. In addition, within each borehole selected for grouted-in piezometer installation, one piezometer was installed in the Upper Bedrock hydrostratigraphic unit and one piezometer was installed in the Lower Bedrock hydrostratigraphic unit. Further, the depth for the Lower Bedrock piezometer in borehole 04EA-077 was selected in vicinity of the depth of a flow anomaly identified in the Phase I investigation (Golder, 2005b).

### ***4.2 Piezometer Installation***

The procedure used for piezometer installation is provided in Appendix A and the logbook for the actual installation is provided in Appendix C. A summary of the installation is described below.

Prior to lowering the piezometer into the borehole, drill rods were lowered to the bottom of each hole and freshwater was circulated to ensure no bridges in the annular space. Once the borehole was flushed, two piezometers were lowered into the borehole on 24 mm inside diameter schedule 80 PVC pipe. Each pipe segment was measured to provide accurate installation depths. Both piezometers were taped to the PVC pipe at the target depth as the PVC pipe was lowered to the base of the borehole. The electrical cable was taped to the PVC pipe every 2 m to prevent damage to the cable.

Once communication was verified, a cement and bentonite grout was tremied through the PVC pipe and up to the surface. The grout mixture consisted of 1 part cement, 2.5 parts water and 0.3 parts bentonite to produce a pumpable, yet low hydraulically conductive grout. The procedure is consistent with the guidelines provided in Mickelson and Green (2003).

Schematic for the installations are provided in Figures 4.1 to 4.3.

## 4.2 Instrumentation

The piezometers are of the vibrating wire type to measure pressure. In addition, each instrument contains a thermistor that measures temperature. The calibration certificates for the instruments are provided in Appendix F. Each piezometer was connected to a Geokon single channel data logger with 8000 arrays of memory. Additional information on the Geokon single channel data logger is provided in Section 5.1. At the time of installation, the piezometer was zeroed to read 0 kPa at the surface. Hence, the piezometers read gauge pressure. Table 4.1 provides a summary of the instruments.

**Table 4.1. Downhole Piezometer Summary**

| Borehole ID |       | Measured<br>Piezometer<br>Depth | True Vertical<br>Transducer<br>Depth | Piezometer<br>Serial Number | Datalogger<br>Serial Number | Piezometer Pressure<br>Range |
|-------------|-------|---------------------------------|--------------------------------------|-----------------------------|-----------------------------|------------------------------|
|             |       | (m)                             | (mTVD)                               |                             |                             | (kPa)                        |
| YD02-20     | Upper | 23.38                           | 23.38                                | 05-10383                    | 3563                        | 350                          |
|             | Lower | 244.45                          | 244.40                               | 05-8438                     | 3579                        | 3000                         |
| 04EA-074    | Upper | 30.45                           | 25.22                                | 05-10384                    | 3580                        | 350                          |
|             | Lower | 240.76                          | 192.00                               | 05-8437                     | 3564                        | 3000                         |
| 04EA-077    | Upper | 49.14                           | 46.34                                | 05-9447                     | 3578                        | 700                          |
|             | Lower | 192.45                          | 182.46                               | 05-7644                     | 3565                        | 2000                         |

Note: mTVD – meters true vertical depth resulting from borehole inclination.

## **5.0 EQUIPMENT FOR HYDRAULIC TESTING**

The essential components and specifications that were considered in the design of the equipment are listed below:

- a packer system that would be flexible to allow both single and straddle packer configurations;
- robust packers with pressure differential rating greater than 6 MPa (megapascals) with maximum expected differential pressure of 3 MPa;
- downhole equipment that would fit inside the nominal 76 mm diameter exploration boreholes;
- a pumping system that could be adapted to the packer string and capable of producing water from discrete intervals at relatively low rates under a relatively large total dynamic head as low transmissivity intervals were expected; and
- surface readout to allow for real time analysis to optimize the test duration.

The equipment performed within specifications and no damage was detected to the packer elements based on inspections at the surface.

### **5.1 *Surface Equipment***

The testing data acquisition and control was performed by a Geokon <sup>TM</sup> Model 8001 single channel data logger. The data was automatically recorded on the hard disk of the acquisition computer while the test was in progress. Geokon LogWare software was the user interface for programming, communicating and downloading data from the data logger. Data arrays are produced in comma delineated ASCII text, which can be easily imported into spreadsheet programs.

The packers were inflated from the surface through a 6 mm diameter nylon line (17 MPa pressure rating) using compressed nitrogen. Packer pressure showed no variation during the test to confirm that there was no measurable packer leakage during the test.

Water was discharged from BTW rods (56 mm outside diameter, 46 mm inside diameter) to a holding tank. The flow rate was checked throughout the test using a calibrated 20 Liter container.

## **5.2 Downhole Equipment**

The downhole equipment used for testing in borehole 04EA-084 consisted of the following main components:

- packers;
- transducer; and
- pump system.

A schematic for the downhole tools used for testing in borehole 04EA-084 is provided in Figure 5.1, shown in a single packer configuration. The packer was lowered to test depth on BTW rods. Packers were manufactured by Baski Inc. <sup>TM</sup> and specifications are listed below:

- un-inflated diameter of 61 mm
- constructed on 19 mm diameter, schedule 80 stainless steel mandrel;
- length of 1 m;
- rated for borehole diameters up to 114 mm; and
- a pressure differential rating of 6.2 MPa for 72 mm diameter borehole.

A vibrating wire piezometer was located in a gauge carrier above the interval for testing performed in borehole 04EA-084. Geokon<sup>TM</sup> manufactures the piezometer with an operating range of 750 psi (see Appendix F for calibration certificates). The piezometer was ported to the test interval to monitor pressure conditions between the packers.

A progressive cavity pumping system manufactured by Wetherford<sup>TM</sup>, model Geremia 14.25-200IM, was used to produce water from the selected interval in borehole 04EA-084. This type of pump, common in the oil industry, was selected due to its ability to produce moderate to low rates under relatively large dynamic head conditions from small diameter boreholes. The pump, generally referred to as stator, was located in the test string above the packers and rated for a maximum lift capacity of 1000 m and flowrate of 5 L/100 revolutions per minute (rpm). A helical shaped rotor was lowered through the BTW rods on 16 mm diameter pony rods as the pump was lowered (Figure 5.1). Once on depth, the pony rods were rotated using the top drive of the core rig. As the rotor turns eccentrically in the stator, a series of sealed cavities form between the stator and rotor surface to move fluid from the intake of the pump to the surface. The discharge rate is proportional to the rotational speed of the rotor and the differential pressure across the stator.

In borehole 05EA-107, a simpler downhole tool was used for testing than described above, which was more suited for the test objectives and the hydraulic conditions. The tools were originally set-up to perform series of fixed-interval overlapping tests with a double packer tool. Prior to packer inflation, a piezometer was lowered inside the BTW rods to below the stabilized water level for each slug test (discussed in Section 7) and subsequently removed prior to moving the tools to the next interval. Two intervals were also selected for collection of representative water samples. As the test interval transmissivity was relatively low, the method selected for purging water from the interval was through a series of consecutive slug tests. The method of slug removal was to evacuate fluid from the borehole using an air compressor connected to a flexible line that was lowered to below the water table.

## **6.0 ANALYSIS METHODOLOGY**

### **6.1 *Measurement of Hydraulic Heads***

The hydraulic head changes during testing were monitored with piezometers of the strain gauge type. For alluvium monitoring zones, the piezometers were installed in an open monitoring well and vented to the surface to compensate for barometric pressure changes. All piezometers were calibrated by the manufacture and the calibration certificates are included in Appendix F.

### **6.2 *Computations of Water Levels from Pressure Data***

The pressure readings were converted to hydraulic head by assuming a freshwater pressure gradient of 9.81 kPa/m. No correction was applied for the variation in the water density with depth. Based on the measured water quality, the estimated error due to density variation is estimated to be 0.31 m or less (see Section 10). True vertical depths were calculated by interpolating between measured vertical depths obtained from borehole traces. The borehole trace data was provided by Kennecott.

### **6.3 *Water Level Changes***

In addition to responses to hydraulic testing, natural groundwater pressure fluctuations due to earth tides, i.e. pressure changes due to gravitational forces of the moon on the rock mass, and atmospheric pressure variations were recorded, commonly referred to as background head fluctuations. The earth tide effects were greater in the lower piezometers versus the upper piezometers with the magnitude of the regular cyclic variation on the order of 10 cm or less (Figures 6.1 to 6.3). Superimposed on the tidal effects were atmospheric effects which were irregular in occurrence (see Figure 7.35, approximately 64 hours elapsed time) and result in head changes up to 15 cm. In addition to earth tide and atmospheric effects, the alluvium wells were responding to precipitation events. For example, Figure 7.35 shows the water level rising in the alluvium wells at about 64 hours elapsed time while the atmospheric pressure was decreasing and water was being removed from borehole 05EA-107. No barometric correction was applied to the zones that were selected for analysis as the much larger response to testing (see Figure 8.12 for an example) minimized the influence of background head changes.

## **6.4 Testing Approach**

The testing approach was dictated by the test objectives and relative order of magnitude for the test interval transmissivity. To develop profiles for discrete hydraulic properties along the borehole, the approach was to perform a series of fixed-interval packer tests along the length of the open hole section. Due to the relatively low transmissivity conditions at the Project site, the following testing sequence was selected:

- Packer Inflation: nominal 5 minutes
- Partial-Equilibration Period: nominal 25 minutes
- Slug Withdrawal: nominal 90 minutes

To evaluate relatively large scale properties, the following sequence was selected:

- Packer Inflation: nominal 30 minutes
- Pumping Period: nominal 7 days
- Recovery Period: nominal 7 days

In addition, water samples were collected from shallow to intermediate depths by the performance of consecutive slug tests. This approach was selected versus pumping as the smaller available hydraulic head from the shallower depths limited the maximum continuous pumping rate that was below the lower limit of the pumping equipment.

During the testing program, monitoring was performed in three observation wells completed in the Quaternary deposits and from six grouted-in piezometers installed in the bedrock.

## **6.5 Defining a Response to Testing at Observation Zones**

For select observation zones, the magnitude of response to hydraulic testing may be similar to the magnitude of response due to background head fluctuations. Therefore, the following criteria were established to define a response to hydraulic testing:

- trend in head changes similar to the production zone; and
- a similar lag time between, start of pumping and first measured response to pumping, and start of recovery and first measured response to recovery.

## 6.6 Distances Between Source and Observation Zones

The distances between the source (active test zone) and observation zones are shown in Table 6.1.

**Table 6.1. Source and Observation Zone Coordinates and Distances Between Source and Observation Zones**

| Borehole ID | Borehole Inclination | Coordinates of Center of Test Interval or Piezometer |            |         | Distance From Center of Test Interval to Piezometer Sensor or Mid-Point of Screen Interval (m) |                 |                       |
|-------------|----------------------|------------------------------------------------------|------------|---------|------------------------------------------------------------------------------------------------|-----------------|-----------------------|
|             |                      | X                                                    | Y          | Z       |                                                                                                |                 |                       |
|             | (Degrees)            | (m)                                                  | (m)        | (m MSL) | 05EA-107 Test 1                                                                                | 05EA-107 Test 2 | 04EA-084 Pumping Test |
| 04EA-084    | -60                  | 431580.22                                            | 5177562.60 | 191.76  | --                                                                                             | --              | --                    |
| QAL-023     | -90                  | 431441.65                                            | 5177593.25 | 414.19  | 118.07                                                                                         | 79.07           | 263.85                |
| QAL-043     | -90                  | 431542.93                                            | 5177588.97 | 418.04  | 95.68                                                                                          | 26.90           | 230.84                |
| QAL-044     | -90                  | 431587.25                                            | 5177623.38 | 417.36  | 118.69                                                                                         | 77.94           | 233.75                |
| YD02-20     | Shallow              | 431717.78                                            | 5177577.60 | 418.82  | 219.75                                                                                         | 198.67          | 265.90                |
|             | Deep                 |                                                      |            | 197.80  | 236.26                                                                                         | 286.33          | 138.51                |
| 04EA-074    | Shallow              | 431472.15                                            | 5177428.57 | 412.53  | 190.75                                                                                         | 165.12          | 279.97                |
|             | Deep                 |                                                      |            | 245.75  | 95.68                                                                                          | 166.50          | 114.25                |
| 04EA-077    | Shallow              | 431590.49                                            | 5177608.20 | 388.63  | 96.64                                                                                          | 75.61           | 202.34                |
|             | Deep                 |                                                      |            | 252.51  | 106.00                                                                                         | 169.43          | 61.72                 |

Note: m MSL – meters above mean sea level.

The measuring points were selected as follows:

- monitoring wells completed in the Quaternary deposits: mid-point of the screen;
- grouted-in piezometers: sensor position; and
- test intervals isolated with packers: mid-point of test interval.

## 6.7 Analysis Approach

The approach to analysis of individual responses is summarized as follows:

- select most appropriate input parameters;
- determine the most appropriate flow model; and
- perform type curve analysis

The most appropriate flow model was selected by reviewing the available geologic information and by evaluating the formation response using the pressure derivative data in log-log coordinates (see subsection 6.7.1).

The approach for analysis of observation zones also includes the following steps:

- viewing data on transmissivity normalized plots (see subsection 6.7.2); and
- computation of diffusivity (see subsection 6.7.3)

Recent advances that were used in the analyses to improve accuracy are discussed in the subsections below.

### **6.7.1 Pressure Derivative Data**

The introduction of the semi-log pressure derivative (Bourdet et al., 1983) plotted in log-log scale together with the pressure change (generally referred to as pressure derivative data) was a significant advancement in the analysis of constant rate tests (see Figure 6.4 for an example). This method of viewing the data may be extended to slug test through deconvolution (Perez et al.; see Figure 6.5 for an example). The advantage of the pressure derivative data is that it is able to display separate characteristics and thus help identify different flow regimes that govern the transient pressure response. The use of the pressure derivative as a diagnostic tool is shown in Figure 6.4 and summarized as follows:

- Slopes are used to identify flow regimes. For example: a) a positive unit slope denotes a closed system (no-flow boundary), b) a positive half slope infers linear flow, c) a flat derivative (slope of zero) indicates radial flow, d) a negative half slope is consistent with spherical flow, and e) a negative unit slope indicates a constant pressure boundary.
- The vertical position of the semi-log derivative during infinite acting radial flow period is used to determine transmissivity.
- Humps in the semi-log derivative are used to identify phase segregation effects in the borehole or changes in storativity away from the wellbore: a) downward humps in the derivative reflect an increase in storativity (e.g. dual porosity model) and b) upward humps reflect a decrease in storativity.

In summary, the pressure derivative data reduces the non-uniqueness in the solution that improves the diagnostic and quantitative analysis of slug and constant-rate pumping tests (Spane and Wurstner, 1993).

### **6.7.2 Transmissivity Normalized Plots**

A useful diagnostic tool to evaluate multiple formation responses on a single plot is the transmissivity normalized plot or TNP Plot (Enachescu et al., 2004). The TNP Plot displays the derivative data that is normalized by the pumping rate. For the radial flow regime, transmissivity

is the y-equivalent value, and therefore, transmissivity can be read directly from the plot. The plot is used to directly compare formation models and relative transmissivity for multiple zones. Viewing the data on single plots assists in the development of the conceptual model for the overall response and assists in reducing the non-uniqueness in the solution. For examples, the following figures have been provided:

- Figure 6.5: shows the deconvolution analysis for a slug test;
- Figure 6.6: shows the same analysis as above but plotted in transmissivity normalized coordinates; and
- Figure 6.7: shows a direct comparison of a pumping zone and observation zone on a transmissivity normalized plot.

### 6.7.3 Diffusivity

In homogeneous formations, the individual observation zones are analyzed based on the assumption that the total measured drawdown at the observation interval is due to uniformly distributed radial flow towards the well. However, the flow in heterogeneous formations is not uniformly distributed. Hence, lower transmissivity regions yield less and consequently show a lower drawdown than observations zones in higher-transmissivity regions. A separate analysis would then yield an erroneously high transmissivity value if the total pumping rate was used in the analysis (National Research Council, 1997).

To assist in deciding which monitoring zones are poorly connected to the pumping zone, diffusivity (transmissivity (T) divided by storativity (S)) can be computed from measured data (Bradley et al., 2000). The diffusivity (T/S) is computed by rearrangement of the distance equation below for pressure transients:

$$d = A\sqrt{\frac{T}{S}t_s} \quad (\text{STRELTSOVA 1988})$$

The length of the flowpaths (d) is assumed to be linear distance between source and observation zones. In reality, the flowpaths may be tortuous and therefore the distance could be greater. The time factor ( $t_s$ ) is the lag between the start of pumping and the first measured response in the observation zone. The coefficient 'A' is a constant dependent on the definition for the radius of

investigation. The 'A' constant used in the analyses is 2, corresponding to a dimensionless drawdown of approximately 0.3.

Once the diffusivity values are computed, the zones that show relatively low diffusivities would not be analyzed with the measured pumping rate as would result in an erroneously high transmissivity. As discussed above, the low drawdown would be due to a small percent of the total pumping rate influencing the region in the vicinity of the observation zone.

In summary, the computation of diffusivity assists in the conceptual understanding in the overall responses by allowing a quantitative method to evaluate the relative degree of hydraulic communication between the source and observation zones which is essential for heterogeneous formations.

## **6.8 Analysis Software**

Two software packages were used for type curve analysis and described below.

FlowDim (version 2.14) was used for slug test analysis. FlowDim is a Golder in-house software that has been verified in assessment of potential nuclear repository investigations in Europe (NAGRA, 2001). All test types may be analyzed including constant rate, constant head and slug phases. Two step superposition is available – recovery following a constant rate period. In addition, the software includes the deconvolution approach to analysis of slug data (Chakrabarty and Enachescu, 1997). Flow models include homogeneous, composite and double porosity.

Constant rate analyses were also performed with the software package SAPHIR that is distributed by KAPPA ENGINEERING. This is an oil field industry standard analytical tool that contains full superposition (can accommodate multiple rate changes) and contains multiple flow models as summarized in Table 6.2.

**Table 6.2. Flow Models Available in SAPHIR**

|                         |                                                                       |
|-------------------------|-----------------------------------------------------------------------|
| <b>Near Well Bore</b>   | Line Source                                                           |
|                         | Wellbore Storage and Skin                                             |
|                         | Partial Penetration                                                   |
|                         | Fracture Connected to Borehole                                        |
| <b>Formation</b>        | Homogeneous                                                           |
|                         | Double Porosity                                                       |
|                         | Double Permeability                                                   |
|                         | Composite (source well only)                                          |
| <b>Outer Boundaries</b> | Infinite in Aerial Extent                                             |
|                         | Single Boundary<br>(no flow or constant pressure)                     |
|                         | Two Boundaries<br>(any combination of no flow or constant pressure)   |
|                         | Three Boundaries<br>(any combination of no flow or constant pressure) |
|                         | Closed System                                                         |

SAPHIR also includes a numerical model module for complex flow geometries.

## 7.0 HYDRAULIC TESTING – BOREHOLE 05EA-107

### 7.1 Scan Tests

#### 7.1.1 Objectives and Test Approach

A series of overlapping, fixed-interval tests (Scan Tests) were performed to develop a profile of hydraulic properties with depth. Due to the relatively low interval transmissivity, slug tests were performed to evaluate the local scale hydraulic properties. At completion of testing, the higher transmissivity intervals were selected for longer duration withdrawal tests to obtain representative water samples (see Sections 7.2 and 7.3).

#### 7.1.2 Measured Data

The measured test data is shown in Figures 7.1 to 7.6.

#### 7.1.3 Analysis for Hydraulic Parameters

Each test was analyzed with two approaches. The Cooper et al. (1967) method, referred to as Cooper, is traditional method that was developed for confined aquifers. In addition, the deconvolution match using the same set of parameters is also provided. The analyses are shown in Figures 7.7 to 7.12 and the results are summarized in Table 7.1.

**Table 7.1. Analysis Results for Scan Tests in Borehole 05EA-107**

| Top<br>[m] | Bottom<br>[m] | Interval<br>[m] | Analysis Method          | Flow Model  | Transmissivity<br>[m <sup>2</sup> /s] | Hydraulic<br>Conductivity<br>[m/s] | Figure |
|------------|---------------|-----------------|--------------------------|-------------|---------------------------------------|------------------------------------|--------|
| 21.34      | 38.04         | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $7.9 \times 10^{-07}$                 | $4.7 \times 10^{-08}$              | 7.7    |
| 36.55      | 53.25         | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $4.2 \times 10^{-08}$                 | $2.5 \times 10^{-09}$              | 7.8    |
| 51.63      | 68.34         | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $2.8 \times 10^{-08}$                 | $1.7 \times 10^{-09}$              | 7.9    |
| 66.96      | 83.67         | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $5.4 \times 10^{-07}$                 | $3.2 \times 10^{-08}$              | 7.10   |
| 82.11      | 98.82         | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $2.2 \times 10^{-07}$                 | $1.3 \times 10^{-08}$              | 7.11   |
| 97.54      | 114.24        | 16.70           | Cooper,<br>Deconvolution | Homogeneous | $1.5 \times 10^{-06}$                 | $8.9 \times 10^{-08}$              | 7.12   |

The geometric mean hydraulic conductivity is  $1.4 \times 10^{-08}$  m/s.

## 7.2 Consecutive Slug Test #1

### 7.2.1 Objectives and Test Approach

Consecutive Slug Test #1 was completed within the Lower Bedrock unit from 97.34 mTVD to 113.99 mTVD. The primary objective of the test was to obtain a representative water sample. As the interval transmissivity was relatively low, fluid was produced from the interval by a series of consecutive slug tests. The water quality sample is discussed in Section 9.

### 7.2.2 Measured Data

The annotated plot of the source zone data is shown in Figure 7.13 and the observation zone responses are shown in Figures 7.14 to 7.22. A summary of responses is provided in Table 7.2.

**Table 7.2. Summary of Measured Responses during 05EA-107 Consecutive Slug Test #1**

| Borehole                 | Elevation for Midpoint of Packer Interval, Well Screen or Piezometer Sensor [m MSL] | Distance to Pumping Interval [m] | Final Drawdown [m]     | Lag Time Between Start of Pumping and Measured Response [minutes] | Diffusivity [m <sup>2</sup> /s] | Figure |
|--------------------------|-------------------------------------------------------------------------------------|----------------------------------|------------------------|-------------------------------------------------------------------|---------------------------------|--------|
| <b>Source Zone</b>       |                                                                                     |                                  |                        |                                                                   |                                 |        |
| 05EA-107                 | 325.34                                                                              | 0                                | 16 to 20               | N/A                                                               | N/A                             | 7.13   |
| <b>Observation Zones</b> |                                                                                     |                                  |                        |                                                                   |                                 |        |
| QAL-023                  | 414.19                                                                              | 118.07                           | No Detectable Response | N/A                                                               | N/A                             | 7.14   |
| QAL-043                  | 418.04                                                                              | 95.68                            | No Detectable Response | N/A                                                               | N/A                             | 7.15   |
| QAL-044                  | 417.36                                                                              | 118.69                           | No Detectable Response | N/A                                                               | N/A                             | 7.16   |
| YD02-20                  | 418.82                                                                              | 219.75                           | No Detectable Response | N/A                                                               | N/A                             | 7.17   |
| YD02-20                  | 197.80                                                                              | 236.26                           | No Detectable Response | N/A                                                               | N/A                             | 7.18   |
| 04EA-074                 | 412.53                                                                              | 190.75                           | No Detectable Response | N/A                                                               | N/A                             | 7.19   |
| 04EA-074                 | 245.75                                                                              | 95.68                            | No Detectable Response | N/A                                                               | N/A                             | 7.20   |
| 04EA-077                 | 388.63                                                                              | 96.64                            | No Detectable Response | N/A                                                               | N/A                             | 7.21   |
| 04EA-077                 | 252.51                                                                              | 106.00                           | No Detectable Response | N/A                                                               | N/A                             | 7.22   |

$$\text{Diffusivity} = \text{distance}^2 \text{ (m)} / 4 * \text{lag time (seconds)}$$

No responses to the testing were observed at the observation zones. A composite plot of the non-responding observation zone data is provided in Figure 7.23. Some of the monitoring zones show a drawdown trend starting during the middle portion of the test but appears to be correlated to a

decrease in barometric effects at approximately 58 hours elapsed time. The barometric effects were superimposed on the diurnal fluctuations related to tidal effects.

## 7.3 Consecutive Slug Test #2

### 7.3.1 Objectives and Test Approach

Consecutive Slug Test #2 was completed within the Upper Bedrock unit from 18.17 mTVD to 34.90 mTVD. The primary objective of the test was to obtain a representative water sample. As the interval transmissivity was relatively low, fluid was produced from the interval by a series of slug tests. The water quality sample is discussed in Section 9.

### 7.3.2 Measured Data

The annotated plot of the source zone data is shown in Figure 7.24 and the observation zone responses are shown in Figures 7.25 to 7.33. A summary of responses is provided in Table 7.3.

**Table 7.3. Summary of Measured Responses During 05EA-107 Consecutive Slug Test #2**

| Borehole                 | Elevation for Midpoint of Packer Interval, Well Screen or Piezometer Sensor [m MSL] | Distance to Pumping Interval [m] | Final Drawdown [m]     | Lag Time Between Start of Pumping and Measured Response [minutes] | Diffusivity [m <sup>2</sup> /s] | Figure |
|--------------------------|-------------------------------------------------------------------------------------|----------------------------------|------------------------|-------------------------------------------------------------------|---------------------------------|--------|
| <b>Source Zone</b>       |                                                                                     |                                  |                        |                                                                   |                                 |        |
| 05EA-107                 | 404.49                                                                              | 0.00                             | 10 to 12               | N/A                                                               | N/A                             | 7.24   |
| <b>Observation Zones</b> |                                                                                     |                                  |                        |                                                                   |                                 |        |
| QAL-023                  | 414.19                                                                              | 79.07                            | 0.025                  | 1804                                                              | 1.44x10 <sup>-02</sup>          | 7.25   |
| QAL-043                  | 418.04                                                                              | 26.90                            | No Detectable Response | N/A                                                               | N/A                             | 7.26   |
| QAL-044                  | 417.36                                                                              | 77.94                            | No Detectable Response | N/A                                                               | N/A                             | 7.27   |
| YD02-20                  | 418.82                                                                              | 198.67                           | No Detectable Response | N/A                                                               | N/A                             | 7.28   |
| YD02-20                  | 197.80                                                                              | 286.33                           | No Detectable Response | N/A                                                               | N/A                             | 7.29   |
| 04EA-074                 | 412.53                                                                              | 165.12                           | No Detectable Response | N/A                                                               | N/A                             | 7.30   |
| 04EA-074                 | 245.75                                                                              | 166.50                           | No Detectable Response | N/A                                                               | N/A                             | 7.31   |
| 04EA-077                 | 388.63                                                                              | 75.61                            | No Detectable Response | N/A                                                               | N/A                             | 7.32   |
| 04EA-077                 | 252.51                                                                              | 169.43                           | No Detectable Response | N/A                                                               | N/A                             | 7.33   |

Diffusivity = distance<sup>2</sup> (m)/4\*lag time (seconds)

Composite plots of responding and non-responding observation zone data are provided in Figures 7.34 and 7.35, respectively. The piezometer installed in monitoring well QAL-23 was the only

detectable response to the test. At about 60 hours elapsed time, this piezometer started to show a similar response as the source well but at a subdued drawdown. As the lag time was 30 hours between the start of the slug tests and the first measured response, and considering the relatively small distance between top of test interval and the alluvium (about 4 m), the response is consistent with a relatively low hydraulic conductivity of the formation which attenuated the vertical propagation of the pressure transients.

## 8.0 HYDRAULIC TESTING – BOREHOLE 04EA-084

### 8.1 Objectives and Test Approach

The primary objective of the test was to evaluate relatively large scale formation response for a water conductive feature in the Lower Bedrock and to obtain a water sample that represents the water quality at a relatively deep depth with respect to the proposed mining. To meet the objectives, a nominal seven day constant rate pumping test and a nominal seven day recovery test was performed. The water quality sample is discussed in Section 9.

### 8.2 Measured Data

The source and observation zones are shown on Figure 8.1 along with the measured drawdown at the end of pumping. The annotated plot of the active test zone data is provided in Figure 8.2 and the observation zone responses are shown in Figures 8.3 to 8.11. A summary of responses is provided in Table 8.1.

**Table 8.1. Summary of Measured Responses During Borehole 04EA-084 Pumping Test**

| Borehole                 | Elevation for Midpoint of Packer Interval, Well Screen or Piezometer Sensor [m MSL] | Distance to Pumping Interval [m] | Final Drawdown [m]     | Lag Time Between Start of Pumping and Measured Response [minutes] | Diffusivity [m <sup>2</sup> /s] | Figure |
|--------------------------|-------------------------------------------------------------------------------------|----------------------------------|------------------------|-------------------------------------------------------------------|---------------------------------|--------|
| <b>Source Zone</b>       |                                                                                     |                                  |                        |                                                                   |                                 |        |
| 04EA-084                 | 191.76                                                                              | 0                                | 195                    | 0                                                                 | N/A                             | 8.2    |
| <b>Observation Zones</b> |                                                                                     |                                  |                        |                                                                   |                                 |        |
| QAL-023                  | 414.19                                                                              | 263.85                           | No Detectable Response | N/A                                                               | N/A                             | 8.3    |
| QAL-043                  | 418.04                                                                              | 230.84                           | No Detectable Response | N/A                                                               | N/A                             | 8.4    |
| QAL-044                  | 417.36                                                                              | 233.75                           | No Detectable Response | N/A                                                               | N/A                             | 8.5    |
| YD02-20                  | 418.82                                                                              | 265.90                           | No Detectable Response | N/A                                                               | N/A                             | 8.6    |
| YD02-20                  | 197.80                                                                              | 138.51                           | 0.77                   | 2079                                                              | 3.8x10 <sup>-02</sup>           | 8.7    |
| 04EA-074                 | 412.53                                                                              | 279.97                           | No Detectable Response | N/A                                                               | N/A                             | 8.8    |
| 04EA-074                 | 245.75                                                                              | 114.25                           | 83.18                  | 9                                                                 | 6.04                            | 8.9    |
| 04EA-077                 | 388.63                                                                              | 202.34                           | 0.39                   | 789                                                               | 0.21                            | 8.10   |
| 04EA-077                 | 252.51                                                                              | 61.72                            | 91.08                  | 10.02                                                             | 1.58                            | 8.11   |

Diffusivity = distance<sup>2</sup> (m)/4\*lag time (seconds)

Composite plots of responding and non-responding observation zone data are provided in Figures 8.12 and 8.13, respectively.

All monitoring zones within 203 m of the pumping interval showed a response to pumping. Conversely, the monitoring zones greater than 230 m from the pumping interval showed no measurable responses to pumping, which include all the alluvium wells. Therefore, based on the measurements from the monitoring network, the radius of influence can be constrained between 203 and 230 m.

The four responding observation zones can be divided into two general groups based on the magnitude of the diffusivity. Two of the zones, located 54 m (04EA-074 Lower Bedrock Piezometer) and 61 m (04EA-077 Lower Bedrock Piezometer) above the pumping interval, showed good hydraulic communication to the pumping interval based on relatively high diffusivity values ( $>1 \text{ m}^2/\text{s}$ ). In the two remaining zones, poor hydraulic communication was observed to the pumping interval based on the relatively low diffusivity values ( $<1 \text{ m}^2/\text{s}$ ). The zones in poor communication to the pumping well can be summarized as follows:

- YD02-20 Lower Bedrock Piezometer, located at a similar elevation as the pumping interval and to the east; and
- 04EA-077 Upper Bedrock Piezometer, located 197 m higher in elevation than the pumping interval.

The water conductive feature isolated during the test is considered an extended wellbore as the head decrease in the feature is expected to be relatively instantaneous followed by a slower recharge from the lower hydraulic conductivity matrix. The higher diffusivities were measured in the Lower Bedrock Piezometers in boreholes 04EA-077 and 04EA-074, aligned in an approximate south-west and north-east orientation, suggests these monitoring points are relatively proximal to the water conductive feature. Lower diffusivities measured in the other two responding monitoring points are attributed to attenuation of pressure transients by the matrix away from the water conductive feature.

### 8.3 Analysis for Hydraulic Parameters

The analysis was started by the development of a conceptual model for the measured responses based on the drawdown and the measured diffusivity. As a first step, the recovery derivative data for the source zone and all the responding zones were plotted on a TNP (Transmissivity Normalized) Plot (Figure 8.14) and the evaluation is summarized below:

- **Figure 8.14A – Fracture Response:** The pressure derivative data from the pumping well shows a hump in the early time data (initial 200 seconds) due to wellbore storage and skin effects, followed by a short period of radial flow (200 to 400 seconds) with an equivalent transmissivity of  $2 \times 10^{-06} \text{ m}^2/\text{s}$  and then dominated by positive half slope (400 seconds to 60,000 seconds). The positive half slope is characteristic for one-dimensional flow that occurs in a vertical to sub-vertical feature such as a fracture or fracture system. This response is likely responsible for the flow anomaly that was observed to be intersecting the borehole between 257.54 m and 260.29 m based on previous testing and geophysical logging (Golder, 2005b). In late time, the pressure derivative data starts to flatten out (100,000 seconds) and attributed to recharge from the bulk of the rock mass.
- **Figure 8.14B – Matrix/Background Fracture Network in Good Hydraulic Communication to Vertical Fracture:** The pressure derivative data from the pumping well and two responding observation zones with diffusivity values  $>1 \text{ m}^2/\text{s}$  show a leveling off with an equivalent transmissivity of approximately  $2 \times 10^{-07} \text{ m}^2/\text{s}$ . This response is attributed to recharge of the matrix/background fracture network to the vertical fracture connected to borehole 04EA-084. In this scenario, as the drawdown is propagated in the single vertical fracture, a pressure gradient is created between the water conductive feature and the matrix/background fracture network comprising the bulk of the rock mass. For a single water conductive feature that is poorly connected to other water conductive features, the recharge from the matrix/background fracture network will eventually equal the total pumping rate and the flow regime changes from one-dimensional in the vertical fracture (positive half slope in pressure derivative data) to radial flow (leveling off of the pressure derivative data) within the matrix/background fracture network.
- **Figure 8.14C - Matrix/Background Fracture Network in Poor Hydraulic Communication to Vertical Fracture:** In late time, the zones that are in poor communication with the 04EA-084 test interval, as indicated by the relatively low diffusivity, start to respond. The poor hydraulic communication may be attributed to a relatively large distance to the water conductive feature controlling flow to the borehole. As mentioned above, due to the relatively low yield from the zones in vicinity of these monitoring points, applying the entire pumping rate to the individual analyses results in an erroneously high transmissivity value.

Based on the diagnosis above, the approach was to analyze the pumping test interval and those zones that appear to be in good hydraulic communication based on relatively high diffusivity values; thereby allowing accurate analysis using the measured pumping rate. In the analysis of the pumping well, the flow model was simplified to a radial composite model with early time data representative for the vertical feature properties and the late time response representative for the matrix/background fracture network. Two analyses were performed (Figures 8.15 and 8.16) to assess the degree to which parameters could be varied while maintaining the quality of the match. In the analysis of the responding monitoring zones (Figures 8.17 and 8.18) with relatively high diffusivity, a homogenous model was used with the derived transmissivity representative for the matrix/background fracture network.

The analyses results are shown in Figures 8.15 to 8.18 and summarized in Table 8.2.

**Table 8.2. Borehole 04EA-084 Pumping Test, Estimates of Hydraulic Parameters for Select Zones using Radial Composite and Homogeneous Flow Models**

| Zone                      | Local Scale                     | Discontinuity Radius | Regional Scale                            | Storativity           | Figure |
|---------------------------|---------------------------------|----------------------|-------------------------------------------|-----------------------|--------|
|                           | Vertical Feature Transmissivity |                      | Matrix/Background Fracture Transmissivity |                       |        |
|                           | [m <sup>2</sup> /s]             |                      | [m <sup>2</sup> /s]                       |                       |        |
| 04EA-084                  | 2.5x10 <sup>-06</sup>           | 88                   | 2.1x10 <sup>-07</sup>                     | n/a                   | 8.15   |
| 04EA-084                  | 3.7x10 <sup>-06</sup>           | 135                  | 2.8x10 <sup>-07</sup>                     | n/a                   | 8.16   |
| 04EA-074 Lower Piezometer | not intersected by borehole     | Not Applicable       | 2.6x10 <sup>-07</sup>                     | 2.5x10 <sup>-06</sup> | 8.17   |
| 04EA-077 Lower Piezometer | not intersected by borehole     | Not Applicable       | 1.3x10 <sup>-07</sup>                     | 1.6x10 <sup>-05</sup> | 8.18   |

The local scale transmissivity of 2.5x10<sup>-06</sup> m<sup>2</sup>/s to 3.7x10<sup>-06</sup> m<sup>2</sup>/s is considered representative for the early time properties of the water conductive feature connected to the wellbore. This result is consistent with results from the 2004 field investigation (Golder, 2005b) with a transmissivity of 3.1x10<sup>-06</sup> m<sup>2</sup>/s derived from the packer test that isolated the same feature.

The transmissivity derived from the late time data in the analysis of the pumping well and the transmissivity derived from the responding observation zones with diffusivities greater than 1 m<sup>2</sup>/s shows a variation between 1.3x10<sup>-07</sup> and 2.8x10<sup>-07</sup> m<sup>2</sup>/s and considered to representative for the matrix/background fracture network.

Additional analyses were performed on the pumping well data using fracture model to match the early time response (Figures 8.19A to 8.19 H) and the results are shown in Table 8.3.

**Table 8.3. Borehole 04EA-084 Pumping Test, Estimates of Hydraulic Parameters for Source Zone using Fracture Model**

| Zone     | Local Scale             | Fracture Transmissivity | Regional Scale                            | Storativity | Figure |
|----------|-------------------------|-------------------------|-------------------------------------------|-------------|--------|
|          | Half-Length of Fracture |                         | Matrix/Background Fracture Transmissivity |             |        |
|          | [m]                     |                         | [m <sup>2</sup> /s]                       |             |        |
| 04EA-084 | 160                     | 2.0x10 <sup>-06</sup>   | 2.2x10 <sup>-07</sup>                     | n/a         | 8.19   |

Figures 8.17C to 8.17H show snapshots of the animated three-dimensional (3-D) and two-dimensional (2-D) views of the drawdown for selected times using the parameters matched in the type curve analysis as summarized in Table 8.3.

The half-length of 160 m (total length of 320 m) matched in the analysis is sensitive to the assumed storativity. A storativity of 1x10<sup>-06</sup> was assumed in the analysis and compares with 2.6x10<sup>-06</sup> and 1.6x10<sup>-05</sup> storativity values estimated from the analysis of the observation zones. Assuming a storativity value of 1x10<sup>-05</sup>, the half length would be expected to be reduced by a factor of 0.3 based on the inverse relationship between distance and storativity (see subsection 6.7.3), resulting in a fracture half-length of 48 m (96 m total length).

## **9.0 WATER QUALITY RESULTS**

### **9.1 *Sample Methods***

Pumping tests were performed in two boreholes, 04EA-084 and 05EA-107. Field parameters and water quality samples were collected during each pumping test. Specifics for the pumping test, as well as for data and sample collection, are provided in the following sections.

#### **9.1.1 Borehole 05EA-107**

A straddle packer tool was used to isolate two select discrete intervals for sampling. Purging was completed by performing consecutive slug tests by air-lifting the column of water inside the BTW rods then allowing the formation to recover for approximately 30 minutes before repeating. A sample from each slug test was analyzed for field parameters including pH, temperature, conductivity, turbidity, total dissolved solids, and salinity. Field parameters collected during purging are provided in Appendix D. No odors, such as hydrogen sulfide, were noted during purging. Field parameter instrumentation was calibrated daily. The average volumetric flow rates for the 18.20 to 34.90 m interval and 97.52 to 114.22 m interval were 0.6 Liters per minute (L/min) and 0.7 L/min, respectively.

Once the target purge volume was reached, a low-flow submersible pump was lowered down the BTW rods to provide a steady flow rate of approximately 0.5 L/min for sample collection. One groundwater sample was collected from the 18.20 to 34.90 m interval after purging 1,410 liters, or 12 system volumes. The minimum criteria for purging are three system volumes and stabilization of field parameters. One groundwater sample was also collected from the 97.52 to 114.22 m interval after purging 1,590 liters, or 6 system volumes. One system volume consists of the volume of the isolated borehole interval plus the volume of the rods. Samples were collected in laboratory supplied bottles, filtered when appropriate for dissolved constituents, and preserved with ice, with the exception of the mercury sample, which did not require preservation. Samples were delivered to the laboratory following appropriate chain-of-custody protocol.

Field parameters collected at the time of sampling are provided in Table 9.1.

**Table 9.1. Sample Information and Field Parameters**

| Borehole | Sample Interval  | Volume Purged | Temp.   | pH   | Conductivity | Salinity | TDS    | Turbidity |
|----------|------------------|---------------|---------|------|--------------|----------|--------|-----------|
|          | (m)              | (L)           | (deg C) |      | (uS/cm)      | (0/00)   | (mg/L) | (NTU)     |
| 05EA-107 | 18.20 to 34.90   | 1410          | 9.4     | 7.57 | 359          | 0.2      | 168    | 18.5      |
|          | 97.52 to 114.22  | 1590          | 12.3    | 7.52 | 599          | 0.3      | 287    | 56.0      |
| 04EA-084 | 249.05 to 302.08 | 16480         | 9.4     | 8.25 | 4980         | 2.6      | 2540   | 5.92      |
|          |                  | 41960         | 10.4    | 8.42 | 5980         | 3.1      | 3060   | 2.35      |
|          |                  | 66750         | 8.5     | 8.10 | 5590         | 2.9      | 2840   | 2.35      |

### 9.1.2 Borehole 04EA-084

A single packer tool was used to isolate the lower portion of the borehole from 249.05 to 302.08 m (215.23 m to 168.27 m MSL). Purging and sampling was completed with a progressive cavity pumping system (Figure 5.1) positioned inline directly above the packer at approximately 249 m below ground surface along the borehole. No odors, such as hydrogen sulfide, were noted during purging. Field parameters and flow rates were collected every hour and are provided in Appendix D. All field parameter instrumentation was calibrated daily.

Water samples were collected after 16,480 liters (21 system volumes), 41,960 liters (54 system volumes), and 66,750 liters (86 system volumes) had been purged at an average rate of approximately 6 L/min. Field parameters measured at the time of sample collection are provided in Table 9.2. A blind duplicate and field blank sample were collected after 86 system volumes were purged. The field blank was collected by pouring laboratory grade de-ionized water through a new inline filter for dissolved metals analysis. Samples were collected in laboratory supplied bottles, filtered when appropriate for dissolved constituents, and delivered to the laboratory following chain-of-custody protocol in coolers preserved with ice, with the exception of mercury, which did not require preservation.

## 9.2 Chemistry Results

Water quality sample analytical laboratory sheets are provided in Appendix E. Groundwater analytical data is summarized in Table 9.2.

[illegible]

Notes:  
 "U" Mercury sample results below the method detection limit (MDL) were reported at the MDL.  
 "J" Mercury result is an estimate. See notes in laboratory reports in Attachment B.  
 "NA" Not Analyzed.

## **9.2.1 Results and Quality Control/Quality Assurance**

To ensure representative data, Golder collected additional samples for Quality Assurance and Quality Control (QA/QC) and performed standard QA/QC checks on the data. Based on these QA/QC processes, the data are considered valid; specifics for the QA/QC analyses are provided in the following sections.

### **9.2.1.1 Blind Duplicates, Field Blanks, and Historical Samples**

Samples for QA/QC included a blind duplicate for the 04EA-084 (86 system volume) sample and a field blank. Analytical results for QA/QC samples are provided in Table 9.3. Results from the blind duplicate are generally within 10% of those from the standard sample. Exceptions to this include dissolved silver, total and dissolved mercury, and total and dissolved selenium due to very low concentrations. For the metals, variations in analytical results at these relatively low concentrations are not unusual due to analytical accuracy and precision at low concentrations.

The field blank was analyzed for dissolved metals. Metals detected in the field blank included boron, mercury, silver, and sodium. Boron and sodium concentrations were an order of magnitude lower than those detected in borehole samples and may be the result of detergent contamination. Silver and mercury detections were of the same order of magnitude measured in the samples. This may indicate some carryover or contamination by these metals between samples. However, concentrations of silver and mercury were relatively low in both the field blank and the borehole samples, near 1 µg/L for silver and 0.1 to 3.5 ng/L for mercury.

In addition to the above QA/QC checks, samples from borehole 04EA-084 were compared to past results for borehole 04EA-084 groundwater, as sampled in September of 2004 (Golder, 2005b). Analytical results for the September 2004 sample are also provided on Table 9.3. Some variation is observed, in particular that the September 2004 sample has a lower total dissolved solids. However, this variation was attributed to contamination from drilling fluid (Golder 2005b). The more efficient pumping system used in the 2005 investigation allowed for higher and more sustained production rates. Dissolved iron is an order of magnitude lower in the September 2004 sample. Drilling fluids kept at the surface and then injected into the reducing aquifer (discussed below in Section 9.2.2) may have not only diluted iron concentrations but also resulted in

Table 9.3. Analytical Results for QA/QC Samples

| Sample Location                     |              | 04EA-084        | Blind Duplicate | 04EA-084    | Field Blank     |
|-------------------------------------|--------------|-----------------|-----------------|-------------|-----------------|
| Sample Date and Time                |              | 9/29/05 - 08:00 | 9/29/05 - 08:00 | 9/8/2004    | 9/29/05 - 08:00 |
| <b>Dissolved Metals</b>             | <b>Units</b> |                 |                 |             |                 |
| Aluminum                            | ug/L         | < 50            | < 50            | <100        | < 50            |
| Antimony                            | ug/L         | < 5             | < 5             | <5          | < 5             |
| Arsenic                             | ug/L         | <b>19</b>       | <b>23</b>       | <b>6.8</b>  | < 2             |
| Barium                              | ug/L         | < 20            | < 20            | <20         | < 20            |
| Beryllium                           | ug/L         | < 1             | < 1             | <1          | < 1             |
| Boron                               | ug/L         | <b>5900</b>     | <b>5800</b>     | <b>6800</b> | <b>110</b>      |
| Cadmium                             | ug/L         | < 5             | < 5             | <5          | < 0.5           |
| Calcium                             | mg/L         | <b>76</b>       | <b>75</b>       | <b>31</b>   | < 0.5           |
| Chromium                            | ug/L         | < 5             | < 5             | <5          | < 5             |
| Cobalt                              | ug/L         | < 10            | < 10            | <10         | < 10            |
| Copper                              | ug/L         | < 5             | < 5             | <5          | < 5             |
| Iron                                | ug/L         | <b>1800</b>     | <b>1600</b>     | <b>190</b>  | < 20            |
| Lead                                | ug/L         | < 1             | < 1             | <1          | < 1             |
| Lithium                             | ug/L         | <b>130</b>      | <b>140</b>      | <b>49</b>   | < 8             |
| Magnesium                           | mg/L         | <b>61</b>       | <b>61</b>       | <b>22</b>   | < 0.5           |
| Manganese                           | ug/L         | <b>68</b>       | <b>67</b>       | <b>220</b>  | < 20            |
| Molybdenum                          | ug/L         | < 10            | < 10            | <b>53</b>   | < 10            |
| Mercury                             | ng/L         | <b>0.21</b>     | 0.1 U           | NA          | 0.1 U           |
| Nickel                              | ug/L         | < 25            | < 25            | <b>59</b>   | < 25            |
| Selenium                            | ug/L         | <b>17</b>       | <b>21</b>       | <b>7.3</b>  | < 1             |
| Silver                              | ug/L         | <b>0.46</b>     | <b>1.1</b>      | <1          | <b>1.3</b>      |
| Sodium                              | mg/L         | <b>970</b>      | <b>960</b>      | <b>360</b>  | <b>0.77</b>     |
| Strontium                           | ug/L         | <b>4800</b>     | <b>4700</b>     | NA          | < 50            |
| Zinc                                | ug/L         | <b>19</b>       | <b>19</b>       | <b>88</b>   | < 10            |
| Potassium                           | mg/L         | <b>9.2</b>      | <b>9.3</b>      | <b>12</b>   | < 0.5           |
| <b>Total Metals</b>                 | <b>Units</b> |                 |                 |             |                 |
| Aluminum                            | ug/L         | < 50            | <b>67</b>       | NA          | NA              |
| Antimony                            | ug/L         | < 5             | < 5             | NA          | NA              |
| Arsenic                             | ug/L         | <b>18</b>       | <b>18</b>       | NA          | NA              |
| Barium                              | ug/L         | < 100           | < 100           | NA          | NA              |
| Beryllium                           | ug/L         | < 1             | < 1             | NA          | NA              |
| Boron                               | ug/L         | <b>5000</b>     | <b>5600</b>     | NA          | NA              |
| Cadmium                             | ug/L         | < 5             | < 5             | NA          | NA              |
| Calcium                             | mg/L         | <b>72</b>       | <b>81</b>       | NA          | NA              |
| Chromium                            | ug/L         | < 5             | < 5             | NA          | NA              |
| Cobalt                              | ug/L         | < 10            | < 10            | NA          | NA              |
| Copper                              | ug/L         | < 5             | < 5             | NA          | NA              |
| Iron                                | ug/L         | <b>2600</b>     | <b>2900</b>     | NA          | NA              |
| Lead                                | ug/L         | < 1             | < 1             | NA          | NA              |
| Lithium                             | ug/L         | <b>120</b>      | <b>130</b>      | NA          | NA              |
| Magnesium                           | mg/L         | <b>61</b>       | <b>65</b>       | NA          | NA              |
| Manganese                           | ug/L         | <b>68</b>       | <b>73</b>       | NA          | NA              |
| Molybdenum                          | ug/L         | < 10            | < 10            | NA          | NA              |
| Mercury                             | ng/L         | <b>0.66 J</b>   | <b>0.27</b>     | <b>89.1</b> | NA              |
| Nickel                              | ug/L         | < 25            | < 25            | NA          | NA              |
| Selenium                            | ug/L         | <b>3.6</b>      | <b>7.7</b>      | NA          | NA              |
| Silver                              | ug/L         | < 1             | < 1             | NA          | NA              |
| Sodium                              | mg/L         | <b>1200</b>     | <b>1200</b>     | NA          | NA              |
| Strontium                           | ug/L         | <b>4700</b>     | <b>5100</b>     | NA          | NA              |
| Zinc                                | ug/L         | <b>39</b>       | <b>40</b>       | NA          | NA              |
| Potassium                           | mg/L         | <b>8.5</b>      | <b>9</b>        | NA          | NA              |
| <b>Physical/Chemical Parameters</b> | <b>Units</b> |                 |                 |             |                 |
| Alkalinity, Bicarbonate             | mg/L         | <b>37</b>       | <b>38</b>       | <b>62</b>   | NA              |
| Alkalinity, Carbonate               | mg/L         | <b>2.9</b>      | < 2             | <2          | NA              |
| Alkalinity, Total                   | mg/L         | <b>40</b>       | <b>38</b>       | NA          | NA              |
| Chloride                            | mg/L         | <b>2010</b>     | <b>2020</b>     | <b>676</b>  | NA              |
| Fluoride                            | mg/L         | <b>1</b>        | <b>0.99</b>     | <b>0.53</b> | NA              |
| Nitrogen, Ammonia                   | mg/L         | <b>0.26</b>     | <b>0.27</b>     | NA          | NA              |
| Nitrogen, Nitrate                   | mg/L         | < 0.05          | < 0.05          | NA          | NA              |
| Phosphorus, Total                   | mg/L         | <b>0.0148</b>   | <b>0.0136</b>   | NA          | NA              |
| Residue, Dissolved                  | mg/L         | <b>3560</b>     | <b>3690</b>     | <b>1590</b> | NA              |
| Sulfate                             | mg/L         | < 5             | < 5             | <5          | NA              |
| Sulfide                             | mg/L         | < 1             | < 1             | NA          | NA              |
| Tritium                             | TU           | < 0.71          | < 0.83          | <b>9.2</b>  | NA              |

Notes:

"U" Mercury sample results below the method detection limit (MDL) were reported at the MDL

"J" Mercury result is an estimate. See notes in laboratory reports in Attachment B

NA Not Analyzed

Detected analytes are shown **BOLD**

precipitation of iron due to changing redox conditions, affecting the earlier sample. Other causes for the higher iron in the recent sample, such as microbial activity or changing redox conditions due to sampling method, are possible; however, given that dissolved iron concentrations are below 3mg/L, examination of these causes are beyond the scope of this document. In summary, all of the 04EA-084 groundwater samples have similar chemistry, as shown by the Piper diagram in Figure 9.1 (discussed further in Section 9.2.3).

### 9.2.1.2 Additional QA/QC Checks

Samples collected were also examined for internal consistency as a part of the QA/QC process, including anion-cation balance, alkalinity values, and comparing calculated to measured values for total dissolved solids (TDS) and electrical conductivity (EC). These results are provided in Table 9.4. The difference between the milliequivalents of anions and cations is less than 5% for the 04EA-084 borehole samples. For the 05EA-107 (97.52 to 114.22 m interval) sample, the difference is less than 10%. For the 05EA-107 (18.20 to 34.90 m interval) the difference was significant, greater than 40%. However, this discrepancy may be due to a low reported bicarbonate alkalinity for this sample (discussed further below). In all borehole samples, the measured TDS is generally similar to the calculated TDS. The measured EC is consistently higher than the calculated EC for all samples. Given how consistently this result is returned, it may be due to a calibration error in the instrument that resulted in consistently higher readings.

**Table 9.4. QA/QC Checks for Borehole Data**

| Sample Location                      |       | 05EA-107                 | 05EA-107                | 04EA-084                 | 04EA-084                 | Blind Duplicate          |
|--------------------------------------|-------|--------------------------|-------------------------|--------------------------|--------------------------|--------------------------|
| Sample Interval Depth Along Borehole |       | 18.20 to 34.90 m         | 97.52 to 114.22 m       | 249.05 to 302.8 m        | 249.05 to 302.8 m        | 04EA-084                 |
| Sample Date and Time                 |       | 9/20/05 - 09:15          | 9/18/05 - 11:40         | 9/23/05 - 11:50          | 9/29/05 - 08:00          | 9/29/05 - 08:00          |
| Volume Purged Prior to Sampling      |       | 12 System Volumes Purged | 6 System Volumes Purged | 21 System Volumes Purged | 86 System Volumes Purged | 86 System Volumes Purged |
| Anions                               | meq/L | 0.724                    | 4.28                    | 56.5                     | 57.4                     | 57.7                     |
| Cations                              | meq/L | 1.76                     | 4.91                    | 59.6                     | 53.1                     | 52.6                     |
| Difference                           | %     | 41.6                     | 6.9                     | 2.7                      | 3.9                      | 4.6                      |
| Measured TDS                         | mg/L  | 76                       | 278                     | 3979                     | 3551                     | 3691                     |
| Calculated TDS                       | mg/L  | 78                       | 286                     | 3282                     | 3172                     | 3179                     |
| Measured EC                          | uS/cm | 359                      | 599                     | 4980                     | 5590                     | na                       |
| Calculated EC                        | uS/cm | 72                       | 298                     | 3225                     | 3053                     | na                       |

Notes - 1) Anion and cation equivalents, calculated TDS, and calculated EC determined using AqQA. 1/2 detection limit used for non-detect analytes. 2) System volume = sample interval volume plus volume of the rods used to lower the packers.

As a part of the QA/QC process several discrepancies with the data were noted and clarified by Golder and the analytical laboratory Trimatrix Laboratories Inc. (Trimatrix). These included clarifying chloride values that were previously only reported to two significant digits and resolving a total alkalinity value for the sample from 04EA-084 (86 system volumes) which was high due to a calculation error. These revised data are included in Table 9.2. For several trace metals, dissolved concentrations were higher than total concentrations, most notably for arsenic and selenium. Causes for these minor discrepancies include standard analytical error, potentially incomplete digestion of total, or matrix interferences.

A discrepancy exists in the reported alkalinity values for sample 05EA-107 (18.20 to 34.90 m interval). Generally, the sum of the bicarbonate and carbonate alkalinity is expected to approach the value for total alkalinity (exceptions to this exist, particularly if large concentrations of organic compounds exist in the water). In sample 05EA-107 (18.20 to 34.90 m interval), the total alkalinity is twice as much as the sum of the bicarbonate and carbonate alkalinities. It is possible that the bicarbonate or carbonate alkalinity value for 05EA-107 (18.20 to 34.90 m interval) is too low. Increasing the bicarbonate concentration to match the total alkalinity improves the charge balance discrepancy described above.

As a part of the QA/QC process, concerns about the non-detection of sulfur species, including sulfate and sulfide, were addressed by Golder and Trimatrix. Most natural waters contain at least some sulfur in the form of sulfate or sulfide. In the groundwater from boreholes 04EA-084 and 05EA-107, sulfate concentrations are below the reporting detection limit of 5 mg/L. Closer examination by the laboratory indicated that sulfate was detected in two of the samples, though at concentrations below the detection limit of 5 mg/L (2.5 mg/L in 05EA-107 (18.20 to 34.90 m) and 0.21 mg/L in the blind duplicate for 04EA-084 (86 system volumes)). A sulfate concentration below the detection limit was also reported for a previous sample from 04EA-084 (Golder, 2005b). These factors indicate that sulfate concentrations in the groundwater sampled are generally lower than the detection analytical laboratory detection limit for sulfate.

Both boreholes have reducing conditions, based on the detectable ammonia concentrations, so sulfur in the groundwater may also be present completely or partially as sulfide. However, no detections of sulfide were measured in any of the analytical samples.

In summary, these factors indicate that sulfate, and perhaps sulfide, is present in the groundwater at relatively low concentrations, generally below the detection limits for sulfate and sulfide, or is present in low concentrations of sulfide that could be removed from the groundwater by the purging method.

## **9.2.2 Groundwater Characterization**

Analytical chemistry data for the borehole samples are plotted on Piper diagrams and Stiff diagrams in order to characterize the water chemistry, as shown in Figures 9.1 and 9.2. Both types of diagrams provide a graphical representation of the data that allows a determination of water type and potential mixing trends.

Groundwater samples from the various depths along the borehole 04EA-084 were relatively similar. All samples plot in a similar location on the Piper diagram and have similar Stiff diagram shapes. Groundwater in borehole 04EA-084 (215.23 m to 168.27 m MSL) is characterized as a sodium-chloride type water, as shown by the Piper diagram. The TDS concentrations are between 3,500 and 4,000 mg/L, classifying the waters as moderately saline (Hem, 1985) or brackish (Freeze and Cherry, 1979). The water is alkaline, with pH values between 8.1 and 8.4. The water is also reducing, as demonstrated by the measurable concentrations of ammonia.

The borehole 05EA-107 groundwater sample from the 97.52 to 114.22 m interval is also sodium-chloride type water, though it does not plot with the samples from 04EA-084 on the Piper diagram (Figure 9.1). In addition, this sample also has a lower TDS than the 04EA-084 samples (278 mg/L), which is also shown graphically by the Stiff diagram in Figure 9.2. Groundwater from this interval is slightly alkaline with pH values near 7.5 and contains nitrogen as ammonia, indicating reducing conditions.

The borehole 05EA-107 groundwater sample from the 18.20 to 34.90 m interval is a sodium-bicarbonate water, as shown on the Piper diagram (Figure 9.1). This sample has a relatively low TDS (76 mg/L) and is slightly alkaline (pH values near 7.5). Groundwater at this interval is also reducing given the nitrogen was measured as ammonia in this sample.

Groundwater samples from boreholes 04EA-054A, 04EA-054B, 04EA-054E, and 04EA-084 collected in 2004 (Golder 2005) are also plotted on the Piper diagram in Figure 9.1 for reference. These water types vary from calcium-chloride to sodium-bicarbonate to sodium-chloride.

In addition, average water chemistry data for the Quaternary deposit are plotted on the Piper diagram. Average chemistry data were calculated for QAL001A, QAL001D, QAL003A, and QAL003B using the spring snowmelt runoff, summer baseflow, fall rain runoff, winter baseflow, and spring snowmelt runoff analyses. The Quaternary deposit groundwater is of calcium-bicarbonate type water with relatively low TDS concentrations. Specific chemistry data for these samples and further discussion of Quaternary groundwater are provided in the Eagle Project environmental baseline hydrology report (North Jackson Company, 2005).

### **9.2.3 Discussion of Water Quality Results**

Groundwater sampled from 04EA-084 is consistent with bedrock water quality of a sodium-chloride type that is moderately saline with TDS concentrations between 3,500 and 4,000 mg/L. This water quality is consistent with previous sampling events and remains consistent throughout the pumping test. No major changes in water quality are observed between the samples collected after pumping 21, 54, and 86 system volumes (Table 9.2). Field parameters collected throughout the pumping test support this, with very little change in measured pH, EC, or TDS throughout the course of the test (Appendix D). Reducing, sodium-chloride type water with high TDS is consistent with deep, bedrock aquifer systems (e.g. Nordstrom et. Al., 1989; Pyne, 1995).

Groundwater sampled from 05EA-107 has overall lower TDS concentrations that decrease at the shallower interval. The sample collected at the shallower 18.20 to 34.90 m interval has similar anion chemistry to the Quaternary deposits, falling between the bedrock and Quaternary deposit chemistry with respect to anions and cations, as shown on the Piper diagram in Figure 9.1. The anion-cation signatures indicate that at this shallow interval the groundwater may be influenced by both bedrock and Quaternary deposit groundwater. Combined with the lower TDS of both bedrock borehole samples, these factors indicate that some water from the Quaternary deposit may influence or dilute the TDS concentrations at both depths, though the specific mechanism of influence this cannot be determined using chemistry alone.

Tritium results from all samples during the current study were less than one tritium unit (TU; Table 9.2). Water with TU values around one is considered to have been groundwater since before 1953, as the source of the water has not been in contact with the atmosphere since this time. Water with TU values near ten or greater is considered to be modern groundwater that has been in contact with atmospheric precipitation since 1953. A previous tritium result for groundwater from borehole 04EA-084, collected in September 2004, had a higher tritium value (9.2 TU; Table 9.3). However, it was suspected that water in the borehole at this time may have been contaminated by drilling fluids, which would have been previously in contact in the atmosphere and have a much higher tritium value (Golder, 2005b). The current results indicate that groundwater in 04EA-084 and 05EA-107, have sub-modern groundwater sources (Freeze and Cherry, 1979).

All groundwater samples collected in the study have relatively high boron concentrations. However, this is considered consistent with the local geology and geochemical conditions in the Lake Superior area Precambrian materials, as discussed in Golder 2005.

## **10.0 ASSESSMENT FOR VERTICAL GRADIENTS**

### ***10.1 Static Formation Pressure and Groundwater Potential***

The “*static formation pressure*” is defined as the undisturbed *in situ* groundwater pressure. Groundwater head is a measure of the potential, derived from the static formation pressure that determines the magnitude and direction of groundwater flow. In groundwater of variable density, the potential for horizontal flow is assessed using freshwater head, and the potential for vertical flow is assessed using environmental head (Luszczynski, 1961).

Freshwater head is the level, relative to a given datum, of a column of freshwater required to balance the static formation pressure at a given measurement point. The environmental water head is calculated by subtracting the pressure of the column of groundwater of variable density, between the measurement point and the depth above which the groundwater is fresh, from the static formation pressure, and expressing the remaining pressure as meters of freshwater, relative to a given datum.

In order to calculate the environmental water head it is necessary to determine both the static formation pressure and the groundwater density profile. The static formation pressures have been selected from stable periods of the pressure data recorded by six grouted-in piezometers installed within the bedrock (04EA-074, 04EA-077 and YD02-20), and three piezometers suspended in the well screen of the Quaternary boreholes (QAL-023, QAL-043, QAL-044).

Figure 10.1 shows the monitoring data from all nine piezometers expressed as freshwater head. It can be seen from Figure 10.1 that while the bedrock pressure response showed fluctuations due to earth tides and atmospheric pressure changes, the average pressure was relatively stable. All groundwater pressure responses in the bedrock showed a small decrease between September 4 and September 14, 2005. However, this trend appears to have reversed during the final day of monitoring and is not considered to be significant. Only the final day of monitoring data is available for the Lower Bedrock Piezometer in borehole 04EA-074. The pressure responses recorded in the Quaternary wells showed some unidentified variation, although the variation was consistently less than the equivalent of 0.05 m of head, and therefore is not considered significant.

## 10.2 Groundwater Density Profile

The groundwater density profile has been estimated based on the total dissolved solids (TDS) recorded in three samples taken from bedrock boreholes 05EA-107 and 05EA-084. Three groundwater samples were acquired from depths between 26.5 mTVD and 241.0 mTVD. These samples were analyzed for a variety of parameters. The results of the total dissolved solids (TDS) analyses have been used here to estimate the groundwater density profile. The TDS, measured in milligrams per liter (mg/L), is summarized in Table 10.1.

The TDS measurements range from 76 mg/L to 3,990 mg/L. For comparison purposes, water is generally considered moderately saline, or “brackish” if the TDS is between 3,000 mg/L and 10,000 mg/L, and saline when the TDS is greater than 10,000 mg/L. Seawater has a TDS of about 33,000 mg/L. It can therefore be seen that even the highest TDS is almost one tenth that of seawater. It might therefore be expected that the variation in groundwater density will have limited influence on the groundwater heads.

The groundwater density has been calculated using the following equation, referenced from the Handbook of Physics and Chemistry 67<sup>th</sup> Edition:

$$\text{Density (kg/m}^3\text{) at 20C} = 1000.1 + [6.4535 \times 10^{-4} \times \text{TDS (mg/L)}]$$

**Table 10.1. Summary of Total Dissolved Solids and Groundwater Density Data**

| Borehole Identity | Test Interval Top Elevation (m MSL) | Test Interval Bottom Elevation (m MSL) | Total Dissolved Solids (mg/L) | Density (kg/m <sup>3</sup> ) |
|-------------------|-------------------------------------|----------------------------------------|-------------------------------|------------------------------|
| 05EA-107          | 412.83                              | 396.10                                 | 76                            | 1000.15                      |
| 05EA-107          | 333.48                              | 316.78                                 | 278                           | 1000.28                      |
| 04EA-084          | 215.23                              | 168.27                                 | 3990                          | 1002.67                      |

The calculated groundwater densities (see Table 10.1) are presented against elevation in Figure 10.2. It is assumed that the groundwater density does not vary consistently and significantly in the horizontal direction across the site, and therefore the data can be presented on a single vertical profile. This is reasonable given the size of the site and knowledge of the geochemistry. When a linear regression is drawn through the two deeper data points it intercepts the freshwater density at approximately 95 mTVD (335 m MSL). This is consistent with the previously proposed

conceptual model, which categories bedrock above 90 mTVD as moderate to low hydraulic conductivity, and bedrock below 90 mTVD as low hydraulic conductivity. Low hydraulic conductivity bedrock would be expected to have older groundwater and corresponding higher TDS.

### 10.3 Freshwater and Environmental Head Profiles

Table 10.2 summarizes the freshwater heads and environmental heads calculated for each monitoring location. The heads calculated in the Quaternary boreholes correspond to the screened intervals, and those in the bedrock correspond to the locations where the piezometers were grouted in the borehole.

Since the groundwater is fresh above 335 m MSL (approximately 95 mTVD), the freshwater heads and environmental heads are identical above this depth. The largest difference between the freshwater head and environmental head, 0.31 m, was observed for the Lower Bedrock Piezometer in borehole YD02-20.

**Table 10.2. Summary of Freshwater Heads and Environmental Heads**

| Monitoring Zone Identity | Top of Screen (m MSL) | Bottom of Screen (m MSL) | Gauge Depth (m MSL) | Freshwater Head (m MSL) | Environmental Water Head (m MSL) |
|--------------------------|-----------------------|--------------------------|---------------------|-------------------------|----------------------------------|
| QAL-023                  | 423.98                | 422.45                   | 422.49              | 431.55                  | 431.55                           |
| QAL-043                  | 424.28                | 422.76                   | 422.76              | 431.70                  | 431.70                           |
| QAL-044                  | 424.28                | 422.76                   | 428.26              | 431.63                  | 431.63                           |
| 04EA-077 Upper           | -                     | -                        | 388.6               | 431.15                  | 431.15                           |
| YD02-20 Upper            | -                     | -                        | 418.9               | 431.96                  | 431.96                           |
| 04EA-074 Upper           | -                     | -                        | 412.5               | 432.40                  | 432.40                           |
| 04EA-077 Lower           | -                     | -                        | 252.5               | 432.20                  | 432.09                           |
| YD02-20 Lower            | -                     | -                        | 197.9               | 430.24                  | 429.93                           |
| 04EA-074 Lower           | -                     | -                        | 245.8               | 432.55                  | 432.40                           |

Figure 10.3 shows the freshwater heads and environmental heads against depth. It should be noted that due to the large elevation range on the vertical axis and the small head range on the horizontal axis, this chart exaggerates apparent hydraulic gradients. The maximum difference in environmental heads measured over the 220 m depth range is about 2.5 m, and all lie between approximately 432.4 m MSL to 429.9 m MSL. The three heads in the Quaternary boreholes are

consistent and lie within the range 431.55 m MSL to 431.7 m MSL. As shown in Figure 10.3, comparison of the heads determined from the upper and lower gauges in the three bedrock boreholes reveals small hydraulic gradients with different trends, as summarized below.

- Borehole 04EA-074: no vertical hydraulic gradient
- Borehole 04EA-077: -0.007 (upward) vertical hydraulic gradient
- Borehole YD02-20: 0.009 (downward) vertical hydraulic gradient

#### ***10.4 Discussion of Vertical Hydraulic Gradients***

The vertical hydraulic gradients presented in the previous section are both small and apparently contradictory. No vertical gradient was observed in 04EA-074, a small apparent upward gradient was estimated in 04EA-077, and a small apparent downward gradient in YD02-20.

The significance of these apparent variations should be assessed in terms of the overall uncertainty and the environmental heads. Potential significant sources of uncertainty include:

- Gauge accuracy (manufacturers quoted accuracy is +/- 0.1%);
- Gauge depth (depends on accuracy of installation and borehole survey);
- Pressure variations (due to long term recovery trend, atmospheric variations and earth tides); and,
- Groundwater density profile (groundwater density could increase more rapidly below 335 m MSL, than indicated by the regression line shown in Figure 2).

Figure 10.4 places the apparent vertical hydraulic gradient in perspective by showing the environmental heads against elevation, with a reduced exaggeration on the horizontal axis (i.e., the head axis). As for groundwater density, it is assumed that the heads do not vary consistently and significantly in the horizontal direction across the site, and therefore the data can be presented on a single vertical profile. Figure 10.4 also shows the linear regression line on the head data, together with the 95% confidence limits on the regression. The results from individual monitoring zones suggest that small local variations in the environmental head occur above and below the general trend with depth. While this apparent range will include real variation and uncertainty, this pattern is consistent with the conceptual model of poorly connected fractured bedrock. Nevertheless, it is concluded that the overall trend indicates a negligible average vertical gradient.

## 11.0 SUMMARY AND CONCLUSIONS

The test objectives for the 2005 Phase II bedrock hydrogeological investigation at the Eagle Project were achieved and summarized as follows:

- performed additional testing to increase the data base for hydraulic properties;
- collected representative water samples;
- assessed the degree of hydraulic communication between the alluvium sediments and the bedrock groundwater systems; and
- evaluated of the large scale response of a flow anomaly identified in the Lower Bedrock hydrostratigraphic unit.

The summary and results are as follows:

- Majority of the Scan Tests in borehole 05EA-107 were performed in the Upper Bedrock hydrostratigraphic unit. The geometric mean hydraulic conductivity from these tests of  $1.4 \times 10^{-08}$  m/s shows good consistency with the geometric mean value of  $2 \times 10^{-08}$  m/s for the Upper Bedrock hydrostratigraphic unit based on the Phase I investigation (Golder, 2005b).
- The bottom portion of borehole 04EA-084 was isolated with a packer with the majority of flow controlled by a water conductive feature. This water conductive feature showed the largest flow anomaly (257.54 to 260.29 m) of the six boreholes with flow logging records and analysis of the short duration test performed in 2004 resulted in an estimated transmissivity of  $3.1 \times 10^{-06}$  m<sup>2</sup>/s (Golder, 2005b). A seven day pumping test and a seven day recovery test was performed to assess the large-scale properties for the water conductive feature.
- Based on the analysis of the source zone data from the borehole 04EA-084 Pumping Test, the estimates for local transmissivity matched to early time data shows a range between  $2.0 \times 10^{-06}$  and  $3.7 \times 10^{-06}$  m<sup>2</sup>/s while the relatively large scale transmissivity derived from the late time data shows a variation between  $2.1 \times 10^{-07}$  and  $2.8 \times 10^{-07}$  m<sup>2</sup>/s. The decrease in transmissivity away from the well is attributed to transition from flow in a water conductive feature in early time to flow in a lower transmissivity matrix/background fracture network in late time. The decrease in transmissivity indicates that the water conductive feature is limited in extent and poorly connected to other water conductive features. Analysis for estimates of the length of the water conductive feature and sensitivity analysis shows an estimated range between 96 and 320 m.
- Based on the analysis of two of the four responding observation zone data from the borehole 04EA-084 Pumping Test, the estimates for transmissivity vary between  $1.3 \times 10^{-07}$  and  $2.6 \times 10^{-07}$  m<sup>2</sup>/s, consistent with the values derived from the late time data from the analysis of the source zone. From the time match, storativity values of  $2.5 \times 10^{-06}$  and  $1.6 \times 10^{-05}$  were derived from the analyses. The remaining two responding zones were poorly connected to the source zone, based on the low diffusivity estimates, and no analysis was performed. No responses to the pumping test were detected in the Quarternary deposits monitoring wells.

- Three water samples were collected from a relatively shallow depth, an intermediate depth and a relatively deep depth with respect to the proposed mining. Prior to sampling, a minimum of six system volumes were removed from the intervals and field parameters were relatively stable at the time of sampling. The shallow water sample is characterized as a sodium -bicarbonate water while the intermediate and deep samples are characterized as a sodium-chloride type water. The TDS increases with depth. For the relatively deep sample collected from the bottom of borehole 04EA-084, the TDS concentrations showed a variation between 3,500 and 4,000 mg/L, which is considered moderately saline, and was relatively stable throughout the pumping test.
- In order to calculate the environmental water head to evaluate vertical gradients at the Project site it was necessary to determine both the static formation pressure and the groundwater density profile. Regression on the two deep samples intercepts the freshwater density/salinity line at about 95 mTVD. The more saline water with depth indicates poorer hydraulic communication between the alluvium aquifer and the deeper bedrock and attributed to decreasing hydraulic conductivity with depth, consistent with the conceptual model for the site. The analyses concluded that the overall trend indicates a negligible average vertical gradient for the Project site.
- The alluvium wells that were monitored during testing in the bedrock showed no response to testing with one exception. A subdued and delayed response was observed in one alluvium well during Consecutive Slug Test #2. As the lag time was 30 hours between the start of the test in the bedrock and the first measured response, and considering the relatively small distance between the top of the test interval and the alluvium (about 4 m), the response is consistent with a relatively low hydraulic conductivity bedrock that attenuates the vertical propagation of the pressure transients. In addition, the water conductive feature isolated for testing in Borehole 04EA-84 shows distinct differences in water quality (higher TDS in particular) compared to the alluvium and confirms the poor hydraulic communication with the alluvium sediments. Overall, as the bedrock contains relatively low hydraulic conductivity, and lower than the alluvium sediments, the relatively poor hydraulic communication between the alluvium and the bedrock groundwater systems is attributed to the relatively low hydraulic conductivity of the bedrock.

## 12.0 CLOSURE

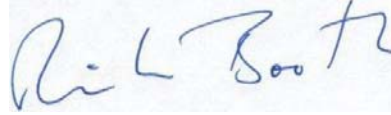
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Report prepared by:

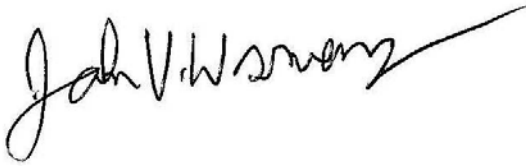


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