Evaluation of the Reflooded Mine Solute Transport Model Developed for the Proposed Crandon Mine, Forest County, Wisconsin

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Prepared through the cooperation of the

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Wisconsin Geological and Natural History Survey
Open-File Report 2004-28 ◆ 2005

Published by and available from

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Section 1
Introduction

1.1 Background

Crandon Mining Company, later renamed Nicolet Minerals Company (NMC), submitted a Mine Permit Application in 1995 (updated in 1998) for the proposed Crandon zinc-copper mine, in which the plans for development, operation, closure, and long-term maintenance of the proposed mine facilities were presented (Foth & Van Dyke, 1995/1998). Figure 1 shows the location of the site. Figures 2 and 3 show the location of the Crandon Formation zinc and copper ore deposits that would be mined. Wisconsin Statutes and Administrative Codes require that a metallic mine be designed, operated, and closed in a manner that will protect Wisconsin's groundwater resources. In consideration of this requirement, a number of features were incorporated into the mine design to be protective of groundwater resources, including the following: passive hydraulic control to allow groundwater to circulate freely through the mine drifts to promote mixing and to minimize concentrations of solutes; removal of oxidized-acidic backfill at the end of mining; cleaning of open access workings; and accelerated reflooding of the mine to minimize oxidation of sulfide minerals (Foth & Van Dyke, 2000).

An initial analysis of solute transport from the reflooded mine following closure of the proposed mine was conducted by HSI GeoTrans, Inc. (GeoTrans, 1998, 1999). In response to the WDNR's review of this analysis, GeoTrans developed a three-dimensional numerical contaminant transport model of the reflooded mine (hereinafter called the applicant's model), which included a detailed representation of the proposed mine configuration in a simplified geologic setting (GeoTrans, 2000). The model included the processes of advection, dispersion, and diffusion, along with sensitivity testing, using a porous media approximation of flow within the bedrock. It was used to estimate the future effects of solute transport from the reflooded mine on groundwater in the area. Results were presented as relative concentrations of a generic solute, calculated for a 10,000-year time period into the future, with special attention given to concentrations at the Design Management Zone (DMZ) compliance boundary. NMC's analysis indicated that concentrations generally increased with depth below the surface, with highest concentrations occurring in the moderately weathered, weakly weathered, and unweathered bedrock units. In the uppermost units, the sandy outwash and till and the strongly weathered bedrock, concentrations were substantially lower.

Source concentrations that were derived from laboratory leaching studies of five separate sources within the mine area were multiplied by the relative concentrations produced by the model to calculate concentrations of a number of inorganic constituents at the DMZ. These concentrations were then compared with Wisconsin's Chapter NR 140 Preventive Action Limits (PALs) for groundwater. PAL concentrations are target levels lower than the NR 140 Enforcement Standards (ESs). NMC's analysis indicated that the concentrations of all of the chemical parameters would be below the PAL at the DMZ in the glacial outwash, till, and strongly weathered bedrock. However, NMC reported that for the deeper bedrock units, concentrations of nitrate-nitrite and cobalt would be above PALs, but below ESs. The concentration of one constituent, sulfate, was calculated to be above the ES at the DMZ in the deeper bedrock units.

The Technical Working Group (TWG), composed of hydrogeologists and hydrologists from the WDNR, the United States Geological Survey (USGS), the Wisconsin Geological and Natural History Survey (WGNHS), and RMT, Inc., was convened by the WDNR to evaluate the applicant's model of reflooded mine solute transport. In August 2001, May 2002, and August 2002, RMT, Inc. (RMT), delivered technical memoranda to the Wisconsin Department of Natural Resources (WDNR) that reviewed aspects of the model that GeoTrans prepared for NMC (RMT, 2001, 2002a, 2002b). The reports evaluated the applicant's model and included a number of additional sensitivity tests beyond those originally conducted by GeoTrans (2000). While GeoTrans used the MODFLOWT transport code (Duffield and others, 1998) for its simulations, RMT converted the transport model to the MT3DMS code (Zheng and Wang, 1999) for further sensitivity testing and evaluation. Selected results from these reports, plus additional testing conducted since August 2002, are presented in the following sections of this report.

1.2 Purpose

The purpose of this investigation is to evaluate the appropriateness and validity of the NMC reflooded mine groundwater flow and transport model, to make revisions where deemed appropriate and necessary, and to use the revised model to evaluate the effect of the proposed reflooded mine on groundwater. Specific factors that have been identified as warranting evaluation include the following: (1) the mechanism by which the mine-related source is introduced into the simulated groundwater system; (2) the hydraulic control system design (closed versus open workings); (3) the simulated hydraulic conductivity of the bedrock; (4) the numeric solver; (5) whether the reflooded mine model, when adapted to current conditions, appropriately and adequately represents the existing groundwater system; and (6) whether the presence of the open mine workings would cause deep, ambient groundwater of presumed low existing quality (not affected by mining) to move upward and potentially affect the quality of shallow groundwater. The evaluation includes testing the sensitivity of the model results to various parameter values or conditions. The NMC (applicant) model was not calibrated to tracer tests at the site and there is no historical contamination that can be used for transport model calibration. As such, the applicant's model includes a substantial degree of uncertainty, with respect to contaminant transport (see Mehl and Hill, 2001, and Hunt and Zheng, 1999). Lacking calibration targets, it is appropriate to incorporate a range of representative values for key parameters into the model, to try to encompass some of the uncertainty associated with the lack of calibration targets.

This report does not present any conclusions regarding whether the proposed mine, following reflooding, would comply with applicable groundwater quality standards. Results from waste characterization evaluations of the source materials could be factored in with the results of the "final" model runs presented here, to evaluate whether the proposed mine would comply with groundwater standards. Conclusions regarding compliance with applicable groundwater quality standards were intended to be presented in the draft Environmental Impact Statement; however, in the final stages of this evaluation, the proposed mine property was sold and the permit application was withdrawn. In the interest of sharing the information that this extensive evaluation has yielded, we have documented the results in this report.

Section 2
Applicant's Conceptual Model of Reflooded Mine Flow and Transport

2.1 Hydrogeologic Conditions

The conceptual model for the reflooded mine was described in Appendix B of Addendum No. 1 to the Mine Permit Application (FVD, 2000), prepared on behalf of NMC by GeoTrans (2000). The zinc ore and copper ore that would be mined are part of the Crandon deposit, which extends from the top of the bedrock (at a depth of approximately 100 feet below ground surface) to a depth of about 2,100 feet below ground surface (see Figure 3). In general, the hydraulic conductivity of the bedrock is thought to decrease with depth, from the strongly weathered bedrock near the surface to the moderately weathered bedrock, the weakly weathered bedrock, and the unweathered bedrock at depth. The upper 100 feet of the bedrock, called the crown pillar, are strongly weathered with relatively high permeability, and would not be mined. A weathered zone of bedrock that is immediately adjacent to the Crandon deposit has a higher permeability than the surrounding bedrock in the upper portion of the bedrock. Overlying the bedrock is glacial sediment composed of till and permeable outwash units. The uppermost unit (the outwash) is apparently unsaturated over the ore body itself, but the water table occurs within the outwash elsewhere in the area.

The horizontal heterogeneity of hydraulic conductivity was assumed by NMC to be relatively unimportant to the groundwater flow system and the transport of contaminants in the immediate vicinity of the reflooded mine. This differs from the horizontal heterogeneity in hydraulic conductivity that has been built into the regional flow model for the area (GeoTrans, 1998, 1999; Krohelski, 2003). For example, the hanging wall and foot wall bedrock have hydraulic conductivity values that differ by approximately an order of magnitude in the regional flow model, whereas the reflooded mine model assumes that, outside of the immediate vicinity of the Crandon Formation itself, the hydraulic conductivity is uniform horizontally.

Groundwater flow in the glacial sediment is through the pores between the grains of sediment. In the bedrock, groundwater flow is primarily through fractures. However, it is assumed that groundwater flow in the fractured bedrock can be approximated by a porous medium. This approximation is commonly made in models with fractured bedrock where the scale of the model domain is large (thousands of feet).

The plan for the mine itself includes placement of low-permeability paste backfill into the mined-out portions of the bedrock. The base of the crown pillar that overlies the mined portion of the bedrock would be sealed with low-permeability grout; however, the hydraulic conductivity of the grout is assumed to increase over time due to weathering of the grout, and eventually attain a value that is approximately 20 times higher than the value estimated by NMC's consultant (TRC) in a technical memorandum on the long-term durability of the proposed grout (TRC, 2000). The proposed design also calls for the mine drifts, shafts, and spiraling ramps, which lie immediately outside the ore body, to remain open to the top of the bedrock. This approach is designed to allow groundwater to circulate freely through the open workings outside of the paste backfill, along the entire length and vertical extent of the mine. Figure 3 shows the configuration of the hanging wall open workings surrounding the paste backfill on the east end of the ore body (footwall workings would only be developed for the western half of the mine).

2.2 Source Material and Solute Transport

Following closure of the mine, groundwater will flow back into the mine, filling the void spaces in the fractured bedrock and open mine workings, and will re-establish a groundwater flow system. Chemical reactions both during and following mining will cause sulfate and various other constituents to dissolve from the paste backfill, the wall rock of the mine workings, and the base of the crown pillar and enter the groundwater. The processes of advection, dispersion, and diffusion will transport the solutes from the high concentrations in the pores of the paste backfill and in the water at the margins of the workings and crown pillar to the surrounding groundwater. The solutes will then migrate with the groundwater laterally through the open workings of the mine, through the bedrock, and (to a degree) up into the till and outwash. The groundwater and solutes from the mine will migrate under the influence of the prevailing hydraulic gradients, toward the DMZ boundary and beyond. Advection, dispersion, and diffusion will transport the solutes along with the groundwater. Chemical and biological reactions, and sorption, although likely of significance to many metallic constituents, are assumed to be unimportant for the purposes of this model. Because many of these reactions would likely reduce the concentrations (of metals in particular), this assumption of nonreactive chemical behavior during transport is generally thought to be conservative.

A generic solute was used to represent all of the solutes of interest. Compared to the source concentration (assumed equal to 1.0), the relative concentrations of the generic solute at various locations, depths, and times, can then be calculated for each source zone. Concentrations were evaluated over a 10,000-year time period. Special attention was given to the concentrations at the DMZ compliance boundary.

Section 3
Summary of Model Design

3.1 Reflooded Mine Groundwater Flow Model

3.1.1 Model Codes

The MODFLOWT code (Duffield et al., 1998) was used by GeoTrans to simulate groundwater flow and solute transport from the reflooded mine. The MODFLOWT code incorporates the widely-used MODFLOW code (Harbaugh and McDonald, 1996) to solve the equations of groundwater flow and to simulate the groundwater velocity field. It is further described later in this section of this report.

MODFLOW was also used to solve the groundwater flow portion of the solute transport model in the WDNR simulations that are presented later in this report. The Groundwater Vistas graphical design system for MODFLOW and MT3DMS (Rumbaugh and Rumbaugh, 2002) was used by the WDNR TWG to facilitate evaluation of the model design, revise parameters and boundary conditions, and to graphically display model results.

3.1.2 Domain and Grid

The model domain chosen by GeoTrans was 7,875 feet east-west, and 3,375 feet north-south, centered on the mine (Figure 4). The mine extent was approximated as a rectangle 300 feet north-south and 5,025 feet east-west. Vertically, the model domain extended 1137.5 feet below ground to the elevation of 462.5 feet above mean sea level, and thus included only the upper half of the mine. The model domain did not include the lower half of the mine in order to improve model run efficiency, and because GeoTrans believed that exclusion of the lower half of the mine and groundwater system would not significantly affect the results. This assumption was tested by GeoTrans, and they concluded that this simplification was justified (GeoTrans, 2000).

A finite-difference grid that included 106 rows, 226 columns, and 26 layers, was constructed by GeoTrans. Most nodes were 37.5 feet square horizontally; in the vicinity of the edge of the mine, node width was progressively decreased to a minimum value of 1.5 feet, to provide a better simulation of transport from the mine. Vertically, the model layers were of constant thickness over the horizontal extent of the model domain. The individual layer thickness values varied between 25 and 85 feet.

The geologic complexity present in the regional model of the area was greatly simplified for the applicant's reflooded mine model (GeoTrans, 2000). Model layers were assigned a uniform thickness. The top two layers represented outwash and till/saprolite, respectively; layers 3 through 5, the crown pillar and strongly weathered bedrock; and layers 6-26, the moderately weathered to unweathered bedrock units with the backfilled stopes and open workings of the mine.

For the simulations that are part of the current investigation and are reported here, the model domain and layering used by GeoTrans in their simulations have been retained. Except for a limited number of sensitivity tests, the model grid was unchanged from the GeoTrans grid.

3.1.3 Boundary Conditions

The boundary conditions were set by GeoTrans as constant head around the perimeter of the model, for all layers. The constant head values were approximated based on the head distribution from the regional flow model, and were assigned to be uniform over depth (no vertical gradient). The effect of vertical gradients and more accurate head assignments from the regional model was tested, and is discussed later in this report. A no-flow boundary condition was set at the bottom of the model; flow to or from the lower half of the mine was not included in the simulations because GeoTrans (2000) showed that exclusion of the lower portion of the mine did not affect simulation results significantly. Recharge was uniformly set at 10 inches per year over the model domain, which is essentially the same value (rounded to the nearest inch) used in the WDNR regional groundwater flow model (Krohelski, 2003). No surface water features were incorporated into the model.

3.1.4 Hydraulic Conductivity

Hydraulic conductivity values for various model hydrostratigraphic units were varied by model case. The values used by GeoTrans in their "expected case" model are listed as "NMC case" in the second column, and are approximated from the values used in the applicant's regional flow model (GeoTrans, 2000). For comparison, Table 1 columns 2 and 3 present High End Case and Low End Case hydraulic conductivity values that are generalized from the High End and Low End Case WDNR regional groundwater flow models (Krohelski, 2003). After sensitivity testing (discussed in Section 6), the High End K values were adopted for use in the WDNR reflooded mine model (called the "reflood high K" model), as discussed in Section 8. Although both the applicant's and WDNR's regional flow models have substantial heterogeneity of hydraulic conductivity in the model domain, for simplicity a uniform value of K was selected for each layer outside of the mine.

Consistent with the approach taken in the regional groundwater flow model, hydraulic conductivities were assigned to five geologic strata: outwash, till/saprolite, strongly weathered bedrock, moderately weathered bedrock, and weakly-weathered to unweathered bedrock. With the exception of a weathered zone immediately adjacent to the mine, each model layer was assigned a uniform hydraulic conductivity value for the native geologic deposits (see Table 1 for values). In the upper portion of the bedrock, the weathered zone adjacent to the mine was simulated to include effects of accelerated weathering in the mine vicinity, due to oxidation of pyrite-rich bedrock.

GeoTrans simulated complex, large shifts in hydraulic conductivity values in areas of drifts, shafts, backfill, and crown pillar. The paste backfill, grouted crown pillar, and open mine workings were all assigned individual values. Table 1 presents the hydraulic conductivity values assigned by GeoTrans to the various mine features. During sensitivity testing, the effects of changes in the hydraulic conductivity values and anisotropy of K in various hydrostratigraphic units were tested, as discussed later in this report.

3.2 Reflooded Mine Transport Model

3.2.1 Model Codes (MODFLOWT, MT3DMS)

The MODFLOWT code (Duffield et al., 1998) was used by GeoTrans to simulate solute transport from the reflooded mine. The transport portion of the MODFLOWT code uses an implicit finite-difference discretization approach to solving the partial differential equations of solute transport. It can incorporate the processes of advection, dispersion, diffusion, sorption, and decay of a single chemical species. In the approach taken by GeoTrans for the applicant's Crandon reflooded mine model, a generic nonreacting chemical constituent was simulated.

The MT3DMS code (Zheng and Wang, 1999) was used in most of the simulations that are presented in this report. The MT3DMS code was used because it is one of the most widely-used transport codes, it is well tested, it can simulate complex hydrogeologic conditions in three dimensions, and it has the ability to use a variety of numerical solution approaches. The use of a different transport code also provided a test of the effect of transport code choice on results.

The MT3DMS code offers a variety of solution technique choices for the transport portion of the model, including both implicit and explicit finite-difference methods, the third-order total-variation-diminishing (TVD) method, and Eulerian-Lagrangian methods, including the method-of-characteristics (MOC) and modified/hybrid MOC approaches. Various solution approaches were tested during the evaluation of the model. However, outside of the tests of the solution techniques themselves (summarized later in this report), all other simulations reported in this evaluation were conducted using the implicit finite-difference approach.

3.2.2 Boundary and Initial Conditions, and Contaminant Source Representation

Five separate sources of contaminants for the reflooded mine model were identified by the applicant. The sources included one "continuous" source (continuous release from the unoxidized and oxidized-neutral *paste backfill*) and four "instantaneous" sources (instantaneous release from the unoxidized and oxidized-neutral *paste backfill*, the *acidic oxidized paste* at the margin of the paste backfill, the base of the *crown pillar*, and the *wall rock of the mine workings*). A continuous source is assumed to maintain a constant concentration over time, adding mass into the groundwater at a rate necessary to maintain the concentration assigned to it. Instantaneous sources are assumed to release all of the contaminant mass directly into the groundwater at the start of the simulation, with no continuing release from the source; thus, the concentrations at the source diminish over time.

A generic contaminant is simulated for each source, and as groundwater flows through the source zone, contaminant mass is transported into the surrounding model domain. An initial nominal concentration of 1.0 (unitless) is assigned to groundwater within each source material for the generic constituent, and the resulting concentrations derived from the model results are a fraction of the initial concentration.

Each source has a distinct, representative concentration for each chemical constituent of interest based on laboratory leaching tests on parent materials. These laboratory leaching tests have been conducted concurrently with the model simulations. Because each source and each chemical constituent will have a unique concentration assigned to it, each source material is simulated separately. The laboratory-derived concentrations that are representative of each source material can then be multiplied by the relative concentrations to obtain "actual" (not relative) predicted concentrations in the groundwater throughout the model domain that are contributed by each individual source.

A central assumption in the applicant's model is that the concentrations from each individual source are additive. Under this assumption, the "actual" predicted concentrations from each source can be added together at each point in space ("superposed"), to derive the total predicted concentrations. Those concentrations for the applicant's simulations have been summarized in Section 9 of Addendum No. 1 to the Mine Permit Application (Foth & Van Dyke, 2000).

The assumption that the concentrations from separate sources are additive is consistent with the assumption that the constituents of concern are chemically non-reactive. Both of these assumptions are generally considered to be conservative (i.e., tend to yield higher predicted concentrations), and they have been retained for the WDNR "final" model simulations that are reported here. However, only the relative concentrations of the generic constituent are reported here: the actual predicted concentrations for individual constituents were to be reported in a subsequent publication using the finalized waste characterization results that were being developed through a separate WDNR review process.

Mass is added only in the designated source zones, within the mine. Recharge was assigned a zero concentration. Mass enters the model by advection into the groundwater system when groundwater flows through each of the source zones. However, for the paste backfill source, the hydraulic conductivity of the source nodes is low enough (at 3e-4 ft/d) that a significant amount of contaminant mass is also apparently transported into the groundwater system of the model through transverse dispersion/diffusion as groundwater flows past the paste backfill through the highly permeable open workings of the mine drifts and shafts (Smith, 2000a, 2000b). This effect was evaluated during sensitivity testing, presented in Section 6.

The concentration value of the source nodes is unitless; for any individual constituent, the relative concentration computed by the model at each cell can be multiplied by the actual concentration of the constituent at the source to derive estimated concentrations across the model domain. Initial concentrations were set at zero everywhere in the model domain except in the source zone that was being simulated, where the (constant) concentrations were set equal to "1." Constant head nodes in areas of groundwater outflow at the edges of the model domain acted as sinks of contaminant mass.

3.2.3 Conservative Transport Behavior

Conservative chemical behavior was assumed for dissolved chemical constituents in the applicant's transport model. Sorption or chemical reactions were not considered. GeoTrans adopted this simplified approach, arguing that it is conservative in that most chemical processes would serve to decrease concentrations along groundwater flow paths.

This chemically conservative assumption was also adopted in the simulations that are reported here. Although nonconservative chemical behavior (such as sorption, dissolution/precipitation) is potentially important for certain constituents, more realistic simulation of the behavior of multiple constituents is complex and is beyond the scope of this investigation.

Section 4
Applicant's Expected Case Simulation

GeoTrans (2000) constructed an "Expected Case" groundwater flow and transport model as discussed in Subsection 3.1.4, with parameters that were based on the best engineering judgment of GeoTrans, Foth &Van Dyke, and NMC's other consultants (L. Smith, 2000; SRK, 2000; TRC, 2000). According to GeoTrans (2000), the applicant and its consultants selected hydraulic and transport parameters such as hydraulic conductivity, porosity, dispersivity, and diffusion coefficients based on their assessment of values that were representative of site and project conditions. Constant head boundary values were assigned around each side of the model for all layers, and were interpolated from the regional flow model simulations. The GeoTrans model is discussed thoroughly in Appendix C of Addendum 1 to the Mine Permit Application (GeoTrans, 2000). A brief summary of the model results is presented here.

Maximum concentrations of a generic contaminant at the DMZ at 10,000 years were simulated, relative to a source concentration set at 1.0, using the applicant's "Expected Case" model inputs. A 10,000-year time period was selected because it is long enough to allow concentrations to approach equilibrium and reach an approximate maximum value at the DMZ in the low-permeability bedrock. Results are presented in Table 2 for the applicants' MODFLOWT simulation (item 1, the MODFLOWT results) and for a simulation using MT3DMS with the same hydraulic parameters as the applicant (item 2, the "NMC case" results). Table 2 presents the maximum concentration at the DMZ for layers representing major geologic units in the model: Layer 2 (till/saprolite); Layer 3 (strongly weathered bedrock); Layer 7 (moderately weathered bedrock); Layer 12 (weakly weathered/unweathered bedrock); and Layer 26 (base of model, in weakly weathered/unweathered bedrock). When more than one model layer comprised a geologic unit, the model layer with the highest concentration was selected for presentation of results.

The simulated heads and velocity vectors for layer 7, moderately weathered bedrock, indicate groundwater flow from the east to west, with gradients that are generally consistent with measured values and with the regional flow model (Fig. 5). Although Figure 5 shows output from the MT3DMS simulation, the results from the applicant's MODFLOWT simulation are virtually identical. The groundwater flow paths through the mine, under base case conditions and with open mine workings, are complex (Fig. 6). The open workings serve as important conduits for groundwater flow. Flow is downward in the eastern (upgradient) end of the model domain, and upward in the western (downgradient) end of the model domain. The NMC case simulated model plume concentrations after a 10,000-year period were lowest in the glacial aquifer, were higher in the strongly weathered bedrock, and were highest in the unweathered bedrock (Fig. 7).

As shown in Table 2 (see Item 1, MODFLOWT expected case (Rfl147) run results), the applicant's simulation resulted in maximum relative concentrations of 0.028 in the till/saprolite, and 0.032 in the strongly weathered bedrock. These units lie near the surface, and have more potential to be utilized for drinking water and to affect surface waters. Deeper in the bedrock, concentrations are higher at the DMZ, reaching relative concentrations at 10,000 years of up to 0.22, 0.26, and 0.35 in the moderately weathered bedrock, the weakly weathered bedrock, and the unweathered bedrock units, respectively. The time to achieve equilibrium (and maximum) values at the DMZ increases dramatically with depth, due to decreasing permeability of the bedrock with depth. In the three upper layers, the model predicted that maximum concentrations would be achieved within approximately 200 years; in layers 7, 12, and 26, maximum concentrations were approached at approximately 2,000 years, 8,000 years, and 10,000 years, respectively (GeoTrans, 2000).

Section 5
Limitations of Applicant's Submitted Model

It is important to understand the limitations of the NMC reflooded mine model, so that findings and conclusions that are based on the model results can be evaluated appropriately.

The NMC model was always intended to be substantially simplified in its representation of the hydrogeologic system (GeoTrans, 2000). Compared to the regional flow model that has been constructed and calibrated to site conditions, the reflooded mine model has much less detail with respect to the uppermost glacial sediment; four layers in the regional flow model have been combined into two layers in the reflooded mine model. In the bedrock, lateral heterogeneity in hydraulic conductivity (K) has been replaced with a representative homogeneous K value in each layer, for all of the domain that is outside of the mine and the adjacent weathered zone. Also in the bedrock units, the regional model includes significantly different K values for the hanging wall and the foot wall based on field data on K from pumping tests; in contrast, the K values for the reflooded mine model are uniform within each layer, outside of the mine zone. These simplifications may result in projections of solute transport that are slower in some areas, faster in others, and with less spreading of the plume, than if the lateral heterogeneities of the regional flow model were incorporated.

The K values for a number of the layers in the bedrock are at the low end of the range of K values used in both the applicant's and the WDNR's regional flow models, which results in lower groundwater velocities and slower plume migration than would otherwise be the case. The effect of lower K values on plume migration has been tested and is described in detail in Section 6.

Isotropic K conditions are assumed for the bedrock in the NMC model. However, in both the applicant's and the WDNR's regional groundwater flow models, anisotropic conditions for the bedrock are incorporated, with K values in the east-west direction equal to 10 times the K values in the north-south direction in each weathering horizon except for strongly weathered bedrock. The geologic strata at the site have been tilted nearly vertical, with the fabric of the rock oriented east-west (the "strike" in geologic terms). Groundwater flow in an easterly or westerly direction would occur along the fabric, whereas flow to the north or south would cross the fabric. Fractures in the bedrock usually occur preferentially along fabric, because they typically represent planes of weakness. The hydraulic conductivity perpendicular to fabric is commonly assumed to be 1/10 that which is parallel to fabric. An assumption of isotropic conditions in the NMC model may underestimate the velocity of groundwater flow and plume migration in the east-west direction, and overestimate velocity and plume migration in the north-south direction. This situation has been tested and is described in detail in Section 6.

The NMC model assumes that the bedrock acts like a porous medium with respect to groundwater flow. On a small scale, this assumption could significantly limit the accuracy of contaminant transport projections, such as in the source zone (paste backfill and adjacent areas). However, simulation of flow through individual fractures requires a substantial knowledge of the characteristics of the fractures, including number, orientation, spacing, aperture, etc. Such detailed knowledge of the fracture system does not exist for the Crandon site. As the scale of the site being simulated increases, groundwater flow through fractured bedrock can tend to resemble flow through porous media. There may be a significant anisotropy of K due to fracture orientation, with higher K in the direction of fracture orientation. Because of lack of sufficient information on the fractures and difficulties with modeling fracture flow in general, an assumption of an equivalent porous medium is made for most sites in fractured bedrock. It is uncertain how much the porous medium assumption limits the accuracy of projections made for contaminant transport at this site.

The vertical extent of the model has been limited to a depth of 1,200 feet below ground surface, whereas the mine is designed to extend to a depth of approximately 2,300 feet. This limitation on the extent of the mine was made in order to reduce the number of nodes and increase computational efficiency, since the model runs were requiring approximately 15 hours of execution time (GeoTrans, 2000). The transition from moderately weathered bedrock to weakly weathered and unweathered bedrock occurs at a depth of approximately 250 feet; therefore, the mine extends about 2,000 feet into the zone of weakly weathered/unweathered bedrock. GeoTrans tested the effect of removing the lower portion of the mine from consideration in the model, and found the effect to be minor, as is discussed in Section 6.3.1 of the GeoTrans (2000) report.

The applicant's reflooded mine model has not been calibrated to groundwater flow conditions at the site, because it represents future, not current, conditions with a stress (the reflooded mine) that potentially has a profound effect on the groundwater flow system. Normally, the effects of stresses (such as pumping) on groundwater systems are simulated by first calibrating a model to existing conditions, superimposing a historical stress (such as a drought, or substantial pumping) on the system, and evaluating the response of the model compared to the measured response. For the reflooded mine model, this step was not done; rather, the reflooded mine model was fashioned after the regional model (which was calibrated to pumping test results), albeit with a much simplified depiction of the hydrogeologic system. Furthermore, the NMC reflooded mine model has incorporated K values for some layers that are lower than or equal to the end of the range of values used in the regional model, rather than a more representative average value, as discussed above. The effect of using different K values for the bedrock that are closer to those in the regional model is discussed in detail later in this report.

The transport portion of the model has not been calibrated to existing conditions, such as the migration of a tracer plume in the groundwater, since no such information exists and because initial conditions for the model are based upon estimated project conditions. Under existing conditions, it would be possible to simulate concentrations of a tracer in the groundwater system, which could help constrain some of the transport parameters to a reasonable range of values. Because this was not done and because actual conditions at the end of the project can only be estimated, the transport portion of the NMC model has substantial uncertainty. In an attempt to test the transport portion of the reflooded mine model, we revised the regional flow model to incorporate solute transport under existing flow conditions (prior to mining). The reflooded mine model was then revised as well to attempt to simulate transport under existing pre-mining groundwater flow conditions, so that the results of the revised models could be compared. These results are discussed later in this report (Section 7).

No sensitivity tests were reported by NMC on instantaneous source simulations, from the paste backfill, acidic paste, crown pillar or mine workings wall rock. It was apparently assumed that results with these sources would be sensitive to the same parameters as with continuous source paste backfill.

Section 6
Sensitivity of Results to Model Parameters

This section presents results of simulations that test the sensitivity of the reflooded mine model to various parameters. In Appendix B to Addendum No. 1 to the Mine Permit Application, GeoTrans (2000) discussed the sensitivity of the reflooded mine model to a number of factors, including hydraulic parameters (*e.g.*, K of the outwash, till, bedrock, crown pillar, and paste backfill; porosity; dispersivity), simplifying assumptions (*e.g.*, model depth, ore width, K of open workings); and simulation methods (*e.g.*, tighter grid, shorter time steps). Some of the factors that GeoTrans found changed the model concentrations most are as follows:

- Increased K of the bedrock
- Increased K of the paste backfill
- Decreased or increased K of the outwash
- Decreased K of the open workings
- Tighter model grid around the edge of the mine

With this information as a starting point, the WDNR's Technical Working Group (TWG) recommended a number of simulations to do the following:

- To evaluate the setup of, and inputs to, the December 2000 reflooded mine groundwater flow and transport model constructed for NMC by GeoTrans
- To test the sensitivity of the results to model code, hydrologic parameters, solvers, boundary conditions, source term, and mine design

The simulations presented here were intended to go beyond those conducted previously by GeoTrans (2000). The following discussion highlights selected results of the simulations that were judged to be most important to the understanding of flow and transport of contaminants from the reflooded Crandon mine.

6.1 Model Code (ModflowT versus MT3DMS)

The ModflowT code (Duffield et al., 1998) was used by GeoTrans to simulate groundwater flow and transport in and around the reflooded mine. For most simulations presented here, the WDNR used Modflow (Harbaugh and McDonald, 1996) to simulate flow and MT3DMS (Zheng and Wang, 1999) to simulate transport, with the same parameters and boundary conditions that were used by GeoTrans. As expected, the two models simulated nearly identical groundwater flow fields (RMT, 2001).

Implicit finite-difference methods were applied in the applicant's ModflowT model and the WDNR's MT3DMS model, along with central-in-time and central-in-space weighting in the transport simulation. However, the two models differed in their solvers. The applicant used an Orthomin solver with Partial Factorization Method 1 in their ModflowT model , whereas the Generalized Conjugate Gradient solver, with the modified Choleski method was applied most frequently in the WDNR's MT3DMS model . Other solvers were also applied to the WDNR's MT3DMS model during sensitivity testing, as discussed below.

The MT3DMS code was modified for this project by the developer of the code, Dr. Chunmiao Zheng of the University of Alabama, to allow for nonuniform values of vertical dispersivity and diffusion to be specified within a layer. This allowed for the substantially different vertical dispersivity and diffusion coefficient values associated with the mine and the surrounding bedrock to be fully incorporated, as they were in the ModflowT simulations.

As shown in Table 2, items 1 and 2, the results of the MT3DMS solution were similar, in general, to that of the ModflowT solution, but differed in some of the details. Table 2 presents the maximum concentrations at the DMZ for model layers 2, 3, 7, 12, and 26. These layers represent the different hydrostratigraphic units, as was presented by GeoTrans in their report. These model layers were chosen by GeoTrans because they typically contained the highest maximum concentrations at the DMZ for the specific unit they represent. This was also typically the case with the simulations that are presented in this report.

Nearly identical maximum concentrations were exhibited for layers 7 and 12, but lower maximum concentrations were present in the MT3DMS solution for layers 2 and 26 (Table 2). Substantially higher maximum concentrations were present in layer 3 in the MT3DMS solution. However, the shape and magnitude of the concentration plume using the two different model codes is quite similar.

The reason for the difference in maximum concentrations at the DMZ (Table 2) between the ModflowT solution and the MT3DMS solution, is unclear at this time. Communications with the originator of the ModflowT code, Mr. Glenn Duffield, were not successful in resolving this issue. It appears that the solver approaches for the transport equations may be different enough to result in the observed differences in simulated concentrations. It may also be that the transport of mass from the source nodes in the paste backfill to the surrounding open workings is handled differently by the two models, causing the difference in results. However, because MT3DMS has been used for other aspects of the review of this project, and is more widely used and tested, MT3DMS was used for further testing and evaluation of the reflooded mine.

6.2 Numeric Solver for the Fate and Transport Model (Implicit FD vs. TVD)

The effect of the mathematical solution method, or solver on the results of the fate and transport model was investigated, by comparing results using the Total-Variation-Diminishing (TVD) solver with those using the implicit finite-difference (FD) method. GeoTrans used the ModflowT program (which uses the Orthomin partial factorization method) for the applicant's fate and transport simulations of the reflooded mine (GeoTrans, 2000), and a comparison of the results from the ModflowT code versus the MT3DMS code with an implicit FD solver is discussed above.

The TVD solver, which is one of the solvers featured in MT3DMS, has several advantages over other solution techniques. Its ability to conserve mass, suppress oscillations, and minimize numerical dispersion while preserving concentration "peaks" may well represent the "best compromise between the standard finite-difference method and particle tracking methods based on Langrangian or mixed Eulerian-Lagrangian methods" (Zheng and Wang, 1999). Because of its advantages, the TVD method is judged to be the most accurate solution method available for use with the MT3DMS code. Comparing the results derived using the TVD solver to those derived using implicit FD methods is useful in evaluating how accurate the finite-difference solution results may be. If the results compare closely, we have greater confidence in the numerical accuracy of the results of MT3DMS simulations using finite-difference methods.

One disadvantage of the TVD solver is that it requires substantially more computational time for each simulated time step, rendering it impractical to use for most reflooded mine simulations. Therefore, results from the TVD solver version of MT3DMS were compared over relatively short time periods to the results from the implicit finite-difference methods that were used for the bulk of the MT3DMS simulations reported here. In a prolonged simulation, a model run using the TVD solver was conducted over a 61-year runtime period, requiring over 3 months of computer time (with a 1 GHz processor and 512 megabytes of memory). A comparison of mass in the aquifer over the course of the 61-year test period indicates that the TVD solver yielded contaminant mass values that were consistently higher than with implicit FD methods, but by less than 4 percent (Table 3). The close correspondence of results from the two solvers evident over the 61-year test period suggests that the results may also be representative of longer times as well. This evaluation suggests that the MT3DMS simulations conducted using implicit FD methods are likely to be reasonably numerically accurate.

6.3 Anisotropy of Hydraulic Conductivity

This simulation adds anisotropy to the bedrock hydraulic conductivity (K) of the NMC case run. As in the regional flow model, the reflooded mine model horizontal hydraulic conductivity (K_x) values in the east-west direction are set to be higher than the vertical (K_z) hydraulic conductivity value by a factor of 3.16 (i.e., $K_x = 3.16K_z$). K_y values (north-south direction) are set to be one-tenth the value of K_x(i.e., $K_y = 0.1K_x$), and thus are also lower than the K_z values. These ratios are the ones used in the applicant's and the WDNR's regional groundwater flow models. As shown in Table 4 (run 758b), the higher K_x values result in substantially higher maximum concentrations at the DMZ in the strongly weathered bedrock, the weakly weathered bedrock, and the deeper layers at an intermediate time step of 453 years. The 453-year time step was selected for comparison of results because other runs showed that the plume typically reaches nearly steady-state concentrations by this time, allowing for a shorter and more efficient simulation to test the sensitivity.

6.4 High End Case K from Regional Model (Isotropic Conditions)

A comparison of model runs 401 (the NMC case run, using NMC aquifer parameters) and 757 (High End Case K) shows the effect of a higher value of K (equal to the geometric mean Kz value for the corresponding layer(s) in the WDNR High-End Case regional model) on model results (Table 4). As compared to NMC case run results after 453 years, for run 757, the total mass in the aquifer is approximately 50 percent higher and the maximum concentrations at the DMZ are about twice as high for Layers 2 (glacial aquifer) and 7 (moderately weathered (MW)bedrock). In addition, the total mass outflux is about three times as high, and maximum concentrations deeper in the bedrock (Layers 12 and 26) are much higher after 453 years in run 757 than in the NMC case run. These higher concentrations are the result of the higher K values in the bedrock facilitating more rapid transport to and beyond the DMZ compared to the NMC Case run.

6.5 High End Case K from Regional Model (Anisotropic Conditions)

This run evaluates the effect of adding anisotropy to the bedrock in a manner consistent with that of the regional model, along with High End Case K values from the WDNR regional flow model. Kz is set equal to the geometric mean Kz value from the WDNR High End Case regional model. Anisotropy ratios are the same as in the applicant's and WDNR's regional flow model, with Kx = 3.16 Kz, Ky equal to 0.1 K_x (except for strongly weathered bedrock, Layer 3, which remains isotropic). Compared to run 757, the effect of anisotropy at 453 years is to focus the plume into a more narrow region oriented east-west (compare plume maps shown in Figure 8). At 453 years, the mass outflux from the aquifer is approximately the same as in run 757 (isotropic conditions), but the mass in the aquifer is somewhat less under anisotropic conditions, as the plume is narrower (Table 4). Maximum concentrations in runs 757 and 755b at the DMZ after 453 years are approximately the same in most of the layers shown in Table 4, except in Layer 3 (strongly weathered bedrock), where the maximum concentration is twice as high in run 755b.

In addition, comparing the results from run 755b at 453 years (Table 4) to the results at 10,000 years (Table 5) indicates that plume concentrations have largely reached steady state at the DMZ by 453 years. The only change in concentration in any of the reported layers is in layer 26 in the deep bedrock, where it increases by about 20 percent from 453 years to 10,000 years. The near steady-state nature of the simulation at 453 years is also supported by a comparison of both the total mass in the aquifer and the mass outflux from the model at 453 years and 10,000 years; the total mass in the model domain is nearly identical.

6.6 Hydraulic Conductivity from the WDNR Low End Case Regional Flow Model (Anisotropic Conditions)

The effect of K values from the WDNR low end regional flow model that are marginally higher than NMC Case values was tested in this run (run 754b). Anisotropic conditions were simulated, consistent with the WDNR regional Low End Case flow model. The K_z values for each layer were set equal to the geometric mean K_z value for the corresponding layer(s) in the WDNR Low End regional model. K_x values were 3.16 times the K_z values, and K_y values were 1/10 the K_x values. Table 1 shows the WDNR Low End Case regional model K values used for this run. As shown in Table 4, the mass in the aquifer, the total mass outflux through the boundaries of the model, and the maximum concentrations at the DMZ after 453 years, are generally similar, but differ in some respects, for this run and for run 758b (with NMC Case K values and anisotropic conditions). Compared to NMC Case run results after 10,000 years, this run shows substantially higher concentrqtions in the strongly weathered bedrock, but about 50 percent lower maximum concentrations in the deeper bedrock layers (Table 5). Based upon a comparison at both times of the total mass in the aquifer, and the deep bedrock concentrations at the two times, the plume has not reached full development at 453 years in this scenario.

6.7 Closed Workings, NMC Case K Values, Low End K of Grouted Crown Pillar

The NMC Reflooded Mine Management Plan (Foth and VanDyke, 2000) has as a central feature a system of open mine workings, whereby the mine shafts, drifts, and crosscuts would be left open following closure of the mine. This section evaluates the effect of a substantially different design strategy, where the drifts, shafts, and crosscuts of the mine would be sealed off in places with a low-permeability backfill.

Model run 725 (Table 5) simulated a “closed workings” condition, with the workings sealed off with low-permeability backfill ($3x10^{-4}$ ft/d, equal to the K of the paste backfill) and with the grouted crown pillar simulated as intact (K reduced by a factor of 10 from the NMC case model). The model was highly sensitive to these changes: compared to the NMC case run, there was a 10-fold decrease in maximum concentrations at the DMZ at shallow depths (glacial sediment and strongly weathered bedrock). Maximum concentrations at the DMZ were approximately equal to those of the NMC case run at mid-depths, and 3-fold higher concentrations were obtained at deep depths (Table 5). Figure 9 shows three-dimensional block diagrams that portray the growth of the contaminant plume over time in three dimensions, for the open workings (NMC case) and closed workings scenarios. The figure shows that the open workings scenario results in higher concentrations and a larger contaminant plume in the upper portion of the groundwater system as compared to the closed workings scenario.

These results indicate that sealing off the mine shafts, drifts, and crosscuts, and leaving the grout in the crown pillar intact would substantially reduce concentrations in the near-surface layers. At substantial depths in the bedrock, concentrations would increase; however, analysis of the concentrations over time indicates that the increased concentrations at depth would take several thousand years to occur. By "closing off" the mine workings with low-permeability backfill, the circulation of groundwater from deep to shallow depths would be greatly reduced, limiting the transport of contaminant mass from the mine toward the shallow groundwater.

6.8 Closed Mine Workings, WDNR Regional Model High End K Values

Model run 756 also simulates a "closed workings" condition, similar to run 725 discussed above, with WDNR High End K values from the regional model (Tables 4 and 5). Anisotropic conditions like those in the WDNR High End Case regional model are assigned (see the description for run 755b above).

The results from this simulation show substantial similarity to those in run 725 using NMC Case K values, except that, in this run, maximum concentrations at the DMZ at 10,000 years are somewhat lower at shallow to mid-depths (strongly-weathered bedrock, moderately-weathered bedrock, and weakly-weathered bedrock). As compared to the NMC Case run, the closed workings run using High End K values again results in an approximate 10-fold decrease in maximum concentrations at the DMZ at shallow depths (glacial sediment and strongly weathered bedrock). The maximum concentrations at the DMZ at 10,000 years were approximately equal to those in the NMC case run at mid-depths and were higher by two to three times in the deep bedrock. Because the deep bedrock K values are higher in this run as compared to the NMC case run, the plume in the deep bedrock arrives at the DMZ earlier and yields higher concentrations at the 453-year time frame in the deep bedrock. As compared to run 755b, run 756 yields half the mass outflux at 453 years, and about a 60 percent decrease in mass outflux at 10,000 years.

6.9 Paste Backfill Source Term Investigation

The "source term," or the mechanism by which the contaminant enters the model, was investigated in order to better understand how source material enters the simulated groundwater system from the paste backfill, and to evaluate whether the modeling approach is a reasonable representation of the expected situation. A mass flux rate is not explicitly assigned in the NMC model for the paste backfill. In the continuous source situation, mass enters the groundwater system in the NMC model from the constant concentration cells that are assigned to the paste backfill area of the closed mine, by advection, dispersion, and diffusion. Simulations were conducted to identify which process or processes are most important for the introduction of mass into the groundwater system.

6.9.1 Advective Flux from the Source

The importance of advective flux was tested in model run 707 (Table 6), in which it was attempted to set advection from the constant concentration source to near zero by reducing the hydraulic conductivity (K) of the paste backfill nodes from 3e-4 ft/d to an extremely low value (3e-8 ft/d). Because of the way in which MODFLOW calculates flow between nodes, setting the K of the paste alone to a very low value does not eliminate advective flow; the K of the adjacent bedrock nodes must also be set low. When the hydraulic conductivity of the 35 feet of bedrock that fringe the paste backfill were also assigned an extremely low K value (model run 720) and advective flow was effectively diminished, there was a substantial (84%) decrease in mass in the aquifer (Table 6). Part of this substantial decrease in mass in the aquifer is from a decrease in dispersivity as well as advection, because dispersivity is also effectively decreased if the velocity is decreased. The following section shows that eliminating dispersivity alone has a substantial, but smaller, effect on mass transfer.

In a modification of the preceding simulation, model run 721 tested whether advection through the open mine workings would be the dominant mechanism for the release of mass from the constant concentration nodes if the K of the open workings was left high, and the K of the other nodes that make up the paste backfill and fringe of the paste were assigned an extremely low value. The simulation also showed a substantial (79 percent) decrease in mass in the aquifer, compared to the NMC Case run (Table 6). This indicates that the advective mass flux from the paste backfill to the open workings alone is not the major pathway. Rather, it shows that advective transport outward along the entire edge of the paste backfill (not only along the open workings) is the primary mechanism by which contaminant mass enters the groundwater system.

6.9.2 Dispersive Flux from the Source

The relative importance of dispersive flux of mass from the source nodes was tested in several simulations, in which the longitudinal, transverse horizontal, and transverse vertical dispersivity were individually set to zero from the values assigned by GeoTrans (50 feet for longitudinal dispersivity, and 0.5 to 5 feet for transverse horizontal and vertical dispersivity). In run 710 in Table 6, the model failed to converge with all dispersivity (longitudinal, transverse horizontal, and transverse vertical) parameters set to zero, indicating that dispersivity plays an important role in the numerical stability of the model.

The model was also computationally sensitive to eliminating longitudinal dispersivity alone. Setting it equal to zero also resulted in nonconvergence (model run 713).

The model showed a moderate to high sensitivity to transverse horizontal dispersivity. When the transverse horizontal dispersivity was set to zero, there was a 13 percent decrease in the overall contaminant mass in the aquifer (model run 717, see Table 6). There was a 42 percent increase in contaminant mass in the aquifer when the transverse horizontal dispersivity was increased from 5 feet to 50 feet (model run 723).

The elimination of vertical dispersivity from the model had a moderate effect on contaminant mass in the aquifer. Setting the vertical dispersivity to zero in the paste backfill and surrounding fringe nodes resulted in a 20 percent decrease in contaminant mass in the aquifer (model run 716). Setting the vertical dispersivity equal to zero in all of the nodes (bedrock and paste) in Layers 6-26 resulted in a somewhat larger decrease in contaminant mass in the aquifer (27 percent; see model run 711 in Table 3).

6.9.3 Diffusive Flux from the Source

Model runs that tested the importance of diffusive flux in transporting mass into the aquifer indicate that diffusive flux is not an important mechanism for transport in this system. In the first run (model run 709), setting diffusion to zero resulted in only a 1 percent decrease in contaminant mass in the aquifer. Increasing the diffusion coefficient from the value used in the NMC Case (1.6e-4 ft/d) to a value that is at the upper end of the reasonable range of diffusion coefficients (5.7e-4 ft/d, Freeze and Cherry, 1979) resulted in a 3 percent increase in mass in the aquifer (model run 722 in Table 6).

Section 7
Comparison of Reflooded Mine Model to Regional Model

7.1 Groundwater Flow

The reflooded mine model as constructed by NMC was not calibrated against any existing aquifer conditions because no mine is in place currently, and thus there is no equivalent condition that can be used for calibration. There is no published record that NMC attempted to calibrate the reflooded mine model to pre-mine conditions. In an effort to evaluate how well the reflooded mine model represents the hydrogeologic conditions surrounding the mine, we have attempted to revise the reflooded mine model to simulate pre-mine conditions, and to compare the results to those obtained by the WDNR regional groundwater flow model. Changes to the original NMC model have been kept at the minimum judged necessary to adequately represent current conditions, with the understanding that the NMC reflooded mine model has always been intended to be a substantially simplified version of reality.

We simulated groundwater flow and solute transport in both the reflooded mine model and in a sub-domain of the WDNR regional model. The WDNR regional flow model has been calibrated to existing hydrologic conditions (Krohelski, 2003), and by comparing the reflooded mine model results to the WDNR regional model results, it is hoped that this would provide a limited means with which to evaluate the representativeness of the reflooded mine model for the area surrounding the mine. The WDNR regional model was revised for this purpose to simulate contaminant transport in a much smaller model domain that matched the domain of the NMC reflooded mine model (Figure 4). These revisions are described in Appendix A of this report. As with the reflooded mine model, the regional model was assigned constant head values for all of the nodes at the edge of the model domain.

Limited revisions were made to the NMC reflooded mine model to simulate pre-mine conditions. All mine-related engineering features (such as drifts, shafts, and crosscuts) were eliminated from the model. The hydraulic conductivity (K) of the ore body in the model was revised to match local-average K values used in the WDNR regional flow model; the K values for the ore in the regional model are relatively high compared to surrounding bedrock and are much higher than the paste backfill K in the post-mine simulations. K values for the ore from both the Low End and High End Case WDNR regional models were used in two separate simulations. The K was changed in the reflooded mine model to equal the geometric mean of the bedrock K for the sub-domain in each layer of the WDNR regional flow model for both the

HighEnd and LowEnd Case models. The details of these changes are documented in Appendix A.

There are obvious differences in the geometry of the regional model versus the reflooded mine model. The regional model has more layers representing the unconsolidated sediment that comprises the uppermost geologic units. For example, the top three layers in the regional model are represented by a single layer (Layer 1) in the reflooded mine model. Deeper in the bedrock, the reflooded mine model has more layers than the regional model, and a single layer in the regional model is represented by up to five layers in the reflooded mine model. Also, all of the layer top and bottom elevations are variable in the regional model, but are simplified to constant, uniform values for each layer in the reflooded mine model.

The saturated thickness in the outwash (Layer 1) in the reflooded mine model is uniformly set at 25 feet. In the regional model, an analysis of 25 randomly-selected points indicated that the average saturated thickness (and related transmissivity) of the outwash is similar (approximately 29 feet), but the saturated thickness is highly variable from point to point, ranging from 0 to approximately 100 feet.

Differences in the saturated thickness between the reflooded mine model and the regional flow model become more pronounced in the second layer. For the Pre- to Early Wisconsin till/massive saprolite unit (Layer 2 in the reflooded mine model, Layer 4 in the regional model), the saturated thickness in the reflooded mine model is 25 feet, compared to an average value of approximately 65 feet in the regional model. For deeper (bedrock) geologic units, the entire thickness of the unit is saturated, and the reflooded mine model and regional model represent the deeper layers similarly.

The average transmissivity in the regional model for the predominantly outwash units in Layers 1-3 is approximately 2,000 ft^2/d, based on 25 randomly-selected locations; the transmissivity of the outwash in the reflooded mine model is uniformly 1,000 ft^2/d. Since the average thickness of the outwash in both models is similar, this implies that the K of the outwash in the reflooded mine model is somewhat lower than the average K of the outwash in the regional model. The average transmissivity for the Pre- to Early Wisconsin till/massive saprolite (Layer 4) in the regional model is approximately 194 ft^2/d in the HighEnd Case model, and 130 ft^2/d in the Low End Case model, based on 25 randomly-selected locations. The transmissivity of the till in the reflooded mine model is lower, with a uniform value of 50 ft/d.

Despite the aforementioned differences in the aquifer properties, the resulting head distributions for the reflooded mine model and the regional model are similar, as shown on Figures 10 and 11, for groundwater in the upper glacial drift and the shallow bedrock, respectively. This is likely a result of the control that the constant head nodes that bound the model domain exert on the overall head distribution. In the following subsection, mass flux results, which may be more important indicators of comparability, are discussed.

7.2 Solute Transport

Solute transport modeling was conducted with the revised reflooded mine model, under pre-mine conditions. The results were compared to corresponding results from the WDNR High End Case and Low End Case regional sub-domain models (modified for transport conditions) as another test of comparability of the reflooded mine model to the WDNR regional model. The MT3DMS solute transport code that was applied previously to the reflooded mine model (RMT, 2001) was used for both the reflooded mine model and the WDNR regional sub-domain model simulations. In both the regional sub-domain High End Case and Low End Case models and the WDNR reflooded mine model, constant concentration nodes were set in the copper/zinc ore area to represent groundwater with high solute concentrations in the zone in and around the ore. Groundwater sampling in this zone has found water with higher concentrations of dissolved solids (Dames & Moore, 1978). The ore zone was simulated with constant concentration nodes, set at a concentration of 1.0, so that the way in which the two models moved the solute mass out into the surrounding groundwater system could be compared. A 600-year period of comparison was chosen for computational efficiency, because concentrations along the core of the plume approach long-term steady-state values within that time period.

7.2.1 High End Case Model Comparison

A comparison of the MT3DMS transport model results from the reflooded mine model and the regional sub-domain transport model, with constant concentration source terms in the ore, yielded the following information for the High End Case K model. Shallow groundwater concentrations in the reflooded mine model were generally higher by at least a factor of 3 in the uppermost layer (outwash) compared to the equivalent layers in regional sub-domain model (Figure 12). This is largely because the transmissivity of the outwash in the WDNR revised reflooded mine model is half that of the regional sub-domain model, as discussed above, and therefore the source concentrations are diluted to a lesser degree. Moreover, a substantial number of nodes in the upper three layers are unsaturated in the regional sub-domain model, especially over the mine, and this impedes the transport of mass into the upper three layers. In Layer 2 of the reflooded mine model (till and massive saprolite), contoured concentrations appear to be slightly higher than in the equivalent layer in the regional model, Layer 4. The magnitude of concentrations in all of the bedrock layers of the reflooded mine model compares closely to the magnitude of the concentrations in equivalent layers in the regional model (see, for example, the comparison of the results in the upper bedrock in Figure 13).

The mass in the individual reflooded mine model model layers ranges from less than half to over twice that in the regional model, with the greatest differences occurring in the upper layers (Table 7). The overall mass in the reflooded mine model model is only slightly different (lower by 3 percent) than the overall mass in the regional model.

7.2.2 Low End Case Model Comparison

For the Low End Case model, using K values from the WDNR Low End Case regional model, concentrations in the outwash and till (Layers 1 and 2) in the reflooded mine model are higher than in the regional sub-domain model, by approximately 3 to 10 times. Concentrations in the uppermost bedrock layer (reflooded mine model Layer 3) are somewhat higher than in the regional model, but are more comparable than in the outwash and till layers. Deeper bedrock layers (reflooded mine model Layers 4-26) have concentrations that compare relatively closely to concentrations in the regional model.

For the Low End Case, the mass in Layer 1 (outwash) in the reflooded mine model is approximately five times that in the regional model (see Table 7). The greater mass in the reflooded mine model is likely caused by the higher transmissivity of the outwash and till/saprolite in the regional sub-domain model as described above, which causes more dilution of the source concentrations. The lower concentrations in the regional sub-domain model are also at least in part a result of the large number of inactive nodes over the mine in the regional model, where the outwash material is located above the water table. The total mass in most of the other layers compares favorably between the reflooded mine model and the regional model, with an overall 3 percent greater mass in the reflooded mine model than in the regional model.

Section 8
Revisions to the Applicant's Model

Evaluation of the appropriateness and sensitivity of the reflooded mine model to various parameters, boundary conditions, and solvers, indicates that certain revisions to the NMC reflooded mine model would be more representative or effective at simulating the effect of the reflooded mine on groundwater flow and contaminant transport. The following revisions to the NMC reflooded mine model have been adopted into the "final" WDNR model.

8.1 MT3DMS Transport Code

The MT3DMS code is selected for use because, while it yields results that are similar to those of the MODFLOWT code used by the applicant, it is a more widely used and well tested code that has been used for other aspects of this overall project. Use of the MT3DMS code brings some consistency with the other evaluations.

8.2 High End Case Hydraulic Conductivity From the Regional Model

The K values that are derived from the WDNR High End Case regional flow model are considered to be more representative of the actual conditions in the vicinity of the mine than the values used in the NMC model. The WDNR regional flow model has been calibrated against regional groundwater head values and long-term pumping tests, using both High End Case and Low End Case K values, as discussed in Section 7. In the NMC reflooded mine model, the K values for a number of the bedrock layers are lower than those of the WDNR High End Case regional model, and they are at the low end of the range of values in the WDNR Low End Case model. K values derived form the WDNR High End Case model are selected for subsequent simulations because, in a comparison of pre-mining conditions, there was a somewhat closer correlation between contaminant mass results in the WDNR sub-domain model and the WDNR reflooded mine model using the High End Case K values than with the Low End Case K values (RMT, 2002a). The High End Case K values tend to be more conservative than the Low End Case K values, in that they result in higher simulated concentrations and more mass transfer to the DMZ. A representative Kz (vertical hydraulic conductivity) value for each layer was calculated from the geometric mean of all regional model Kz values in the domain of the reflooded mine model.

8.3 Anisotropic Hydraulic Conductivity Conditions

Anisotropic conditions, similar to those in the regional flow model, have been selected for the revised reflooded mine model. Anisotropic conditions are an important part of the regional flow model that has been calibrated to site conditions. Sensitivity testing (discussed in Section 6) has shown that the results of the reflooded mine model are sensitive to anisotropy, which causes the resultant plume to be more narrowly focused and with higher concentrations arriving at the DMZ earlier in the core of the plume. Kx (horizontal hydraulic conductivity values in the north-south direction) was set at 3.16 times the value of Kz. Ky (horizontal hydraulic conductivity values in the east-west direction) was set at 1/10 the value of Kz, as in the regional flow model.

8.4 Open and Closed Mine Workings Scenarios

Sensitivity testing (Section 6) showed that compared to the open mine workings scenario used in the NMC model, a low K ("closed") workings scenario resulted in substantially lower concentrations at the DMZ in the shallow groundwater in the outwash and strongly weathered bedrock. The closed workings scenario resulted in concentrations in the deep bedrock that would eventually rise to higher values than in the open workings scenario, but over considerable time. To consider a broad range of results from potential designs, both the open workings and the closed workings scenarios are included in the final model simulations.

8.5 Range of Paste K Values

The NMC model assumed a hydraulic conductivity value for the paste backfill of 2.8E-4 ft/d (1e-7 cm/s), based on laboratory testing of a single sample (Geo Trans, 2000). However, a review of the paste backfill testing results, and comparison to other published results from similar mine sites, was conducted for the WDNR by Mine System Designa firm specializing in the design of paste and backfill. Mine System Design (2003) concluded that the 2.8e-4 ft/d value chosen for the paste backfill was at the extreme low end of reasonable values, based on his review, and that a value of 1.1e-2 ft/d (4 e-6 cm/s) was more representative (Mine System Design, 2003). In consideration of these findings, the 2.8e-4 ft/d value used by NMC for the paste backfill was selected as a low end K value for the paste backfill, and a 1.1e-2 ft/d value was selected for use in the high end simulation.

8.6 Range of Transverse Dispersivity Values

Sensitivity testing has shown that the model results are sensitive to the values used for transverse dispersivity in both the horizontal and vertical directions. A case is made that the values of transverse dispersivity are reasonable, based on the scale of the model domain (L. Smith, 2000). However, there is no site-specific evidence to support the values selected by NMC for either the transverse vertical dispersivity (0.5 foot) or transverse horizontal dispersivity (5 feet). For this reason, reasonable high end Case and low end values were selected for the WDNR "final model" runs, based on a review of literature values, sensitivity testing, and professional judgment. The reasonable low end dispersivity values selected for the final model runs are 0.5 foot for both the transverse horizontal and vertical dispersivity. For both the high end transverse horizontal and vertical dispersivity, a value of 5 feet was selected.

Section 9
"Final" WDNR Model Results

This section presents the results for the "final" WDNR model runs, which include the five different sources, under four different scenarios. The five sources were identified and incorporated into the applicant's model (GeoTrans, 2000) and have been described in detail in Subsection 3.2.2.

Each source is assigned an initial concentration of 1.0 (unitless) for a generic contaminant. The five sources are as follows:

- Continuous source paste backfill
- Instantaneous source paste backfill
- Instantaneous source acidic paste
- Instantaneous source crown pillar
- Instantaneous source wall rock workings

For each source, there are four final modeling scenarios as follows:

- Open workings, high end K paste and dispersivity
- Open workings, low end K paste and dispersivity
- Closed workings, high end K paste and dispersivity
- Closed workings low end K paste and dispersivity

Each of the five sources is simulated independently, under each of the four scenarios, for a total of twenty simulations. The results of these simulations are discussed below.

The Environmental Impact Statement that was to be prepared for this proposed mine would have combined the relative concentrations obtained from these simulations with waste analysis initial concentrations of individual constituents, for the five sources. The applicant's assumption that the concentrations from the five sources are additive will be retained in this analysis. Superposed concentrations for each constituent in the groundwater will then be derived, for each of the four scenarios.

9.1 Continuous Source Paste Backfill

Results for the continuous source paste backfill are presented on Table 8 and Figures 14, 15, 16, and 17. For high end K paste and dispersivity conditions, a comparison of open workings results (run 789) versus closed workings results (run 800) shows that closed workings would result in substantially lower maximum concentrations at the DMZ in the shallow groundwater (outwash, strongly weathered bedrock) by nearly an order of magnitude (Figures 14 and 15).

Conversely, maximum concentrations in the deeper bedrock would be higher under closed workings conditions than under the open workings scenario.

Similarly, under high end K paste/low end dispersivity conditions, there would be substantially lower concentrations in the shallow groundwater and somewhat higher concentrations in the deeper groundwater under closed workings conditions compared to open workings conditions. This is shown on Table 8, results for run 810 versus run 801 and on Figures 16 and 17.

A comparison of high end K paste and dispersivity versus low end K paste and dispersivity (runs 789 versus 810, and 800 versus 801) indicates that the high end K paste and dispersivity scenario results in maximum concentrations at the DMZ that are up to four times higher, especially in the shallow groundwater (Table 8).

9.2 Instantaneous Source Paste Backfill

Table 9 shows the model results for four scenarios for the instantaneous source paste backfill. As with all instantaneous release source simulations, concentrations at the DMZ change over time. They differ from the continuous source paste backfill simulations in that they do not approach steady-state concentrations, but instead reach a maximum at some point in time and then decrease. The time to reach a maximum concentration at the DMZ varies with the conditions simulated (e.g., open versus closed workings), but in general, the maximum concentrations in shallow groundwater at the DMZ are reached with a few tens of years under open working conditions, and a few hundred to thousands of years under closed workings conditions. In deeper groundwater, maximum concentrations at the DMZ are reached in several hundred to several thousand years.

Results for the model runs simulating the instantaneous release from the paste backfill (Table 9) indicate that relative concentrations are somewhat lower, and in some cases substantially lower, than those for the continuous release paste backfill source (Table 8). However, they are not directly comparable. These are relative concentrations, which must be aggregated with the other individual source concentrations (i.e., continuous source paste, and instantaneous source paste, acidic paste, crown pillar, and wall rock from the open workings) using the separate source concentrations developed outside of this work, in the waste characterization analysis.

A comparison of maximum concentrations at the DMZ under open versus closed workings conditions indicates a similar pattern to that described for the continuous source paste. Substantially lower concentrations in shallow groundwater result from model runs 806 and 815 in Table 9 (closed workings conditions) compared to those in open conditions (model runs 802 and 811). Somewhat higher concentrations were evident in the deep groundwater under closed conditions compared to open conditions.

High end paste K and dispersivity conditions resulted in three to over 100 times higher maximum concentrations at the DMZ, compared to the low end paste K and dispersivity conditions. This finding is evident in the maximum concentrations reported for runs 802 and 811 versus those for runs 806 and 815 in Table 9.

9.3 Instantaneous Source Acidic Paste

The relative concentrations simulated for the acidic paste instantaneous source (Table 10) are substantially lower than for either the continuous source paste backfill (Table 8) or the instantaneous source paste backfill (Table 9). This indicates that the relatively small mass of acidic paste would contribute a small total mass into the surrounding groundwater, resulting in lower concentrations relative to the source. However, without incorporating the "actual" initial source concentration, it is not possible to make direct comparisons of the relative importance of each source.

Maximum concentrations in shallow groundwater at the DMZ under closed workings conditions are generally lower by 100 times or more, compared to open workings conditions. This can be seen in Table 10 by comparing the results from run 803 to run 807, and run 812 to run 816. In deeper groundwater, maximum concentrations at the DMZ are also generally lower, by up to 6 times, compared to those under open workings conditions.

High end paste K and dispersivity conditions result in somewhat higher maximum concentrations at the DMZ compared to low end paste K and dispersivity conditions, although the difference is generally 50 percent or less. This is evident by comparing results from run 803 to run 812, and run 807 to run 816 in Table 10.

Generally, the time to reach a maximum concentration at the DMZ ranges from a few tens to a few hundred years in the shallow groundwater , under both open and closed workings conditions (see Table 10). For deeper groundwater, the time to reach maximum concentration at the DMZ ranges from a few tens of years under open conditions to a few hundreds to thousands of years under closed workings conditions.

9.4 Instantaneous Source Crown Pillar

The relative concentrations simulated for the crown pillar instantaneous source (Table 11) are lower than either the continuous source paste backfill (Table 8) or the instantaneous source paste backfill (Table 9), but somewhat higher than those with the acidic paste source (Table 10). This indicates that the relatively small volume of the crown pillar would contribute a relatively small total contaminant mass into the surrounding groundwater, resulting in lower concentrations, relative to the source. However, without incorporating the "actual" initial source concentrations, it is not possible to make direct comparisons.

Maximum concentrations at the DMZ are generally highest in the shallow groundwater, with concentrations in the deeper groundwater ranging from about ten to a thousand times lower than in shallow groundwater. Maximum concentrations in shallow groundwater at the DMZ under closed workings conditions are somewhat lower (up to 40%) than those in the open workings scenario, in the shallow groundwater. This can be seen in Table 11 by comparing the results from run 804 to run 808, and run 813 to run 817. Although maximum concentrations in the deeper groundwater are higher under closed conditions than under open conditions, the relative concentrations are generally very low in both cases.

High end K paste and dispersivity conditions result in somewhat higher maximum concentrations at the DMZ (compared to low end conditions), although the difference is generally 50 percent or less. This is evident by comparing results from run 804 to run 813, and run 808 to run 817.

The time to reach a maximum concentration at the DMZ ranges from a few tens of years in the shallow groundwater, to a few hundred years in the deep groundwater, under both open and closed workings scenarios. Unlike other instantaneous sources, the time to reach maximum concentration at the DMZ is not consistently higher under closed workings conditions than under open workings conditions, for the instantaneous source crown pillar.

9.5 Instantaneous Source Mine Workings Wall Rock

Table 12 presents the maximum concentrations at the DMZ over time, for the instantaneous source mine workings wall rock. Some of the relative concentrations simulated for the crown pillar source are lower and some are higher than either the continuous source paste backfill (Table 8) or the instantaneous source paste backfill (Table 9). The relative concentrations are again somewhat higher than those with the acidic paste source (Table 10) or the Crown Pillar source (Table 11). However, direct comparisons are not possible without incorporating the "actual" initial source concentrations.

Maximum concentrations at the DMZ are much lower in the shallow groundwater than in the deeper groundwater, as a result of dilution of concentrations in the shallow groundwater with relatively substantial shallow, regional groundwater flow. Maximum concentrations in the deeper groundwater range from about ten to a thousand times higher than shallow groundwater concentrations.

Maximum concentrations in shallow groundwater at the DMZ under closed workings conditions are substantially lower (by up to 100 times or more) than those in the open workings scenario. This can be seen in Table 12 by comparing the results from run 805 to run 809, and run 814 to run 818. Maximum concentrations in the deeper groundwater are also lower, by 50 percent to about 10 times, under closed conditions than under open conditions.

High end K paste and dispersivity conditions result in relatively similar maximum concentrations at the DMZ as compared to low end K paste and dispersivity conditions, with the difference being generally 30 percent or less under open conditions. Under closed workings conditions, the maximum concentrations are low in the shallow groundwater under both high end K paste and dispersivity conditions and low end K paste and dispersivity conditions. In deeper groundwater under open workings conditions, maximum concentrations at the DMZ are similar under both high end K paste and dispersivity and low end K paste and dispersivity scenarios. Under closed workings conditions, maximum concentrations at the DMZ can be up to several times higher in high end K paste and dispersivity conditions. This is evident by comparing results from run 805 to run 814, and run 809 to run 818 in Table 12.

The time to reach a maximum concentration at the DMZ ranges from a few tens of years in the shallow groundwater, to a few hundred years in the deep groundwater, under both open and closed workings scenarios. Under low-K paste and open workings conditions, the time to reach maximum DMZ concentrations is about ten times longer than under high-K paste/open workings conditions.

Section 10
Limitations of "Final" WDNR Model Results

All models are simplifications of reality (Anderson and Woessner, 1992), and must be evaluated for how representative the results may be. The "final" reflooded mine model is simplified in a number of areas that must be kept in mind when considering the results and implications. Section 5 discusses the limitations of the applicant's submitted model in some detail.

The "final" WDNR model has adopted much of the applicant's model design, and thus is subject to many of the same limitations discussed in Section 5. The geologic complexity of the glacial sediment has been greatly simplified by assuming homogeneous conditions within layers, and reducing the number of layers that represent shallow geologic strata in the reflooded mine model compared to the regional flow model for the project; similarly, the substantial differences between the hydraulic characteristics of the bedrock in the foot wall versus the hanging wall are not included in the reflooded mine model (GeoTrans, 2000; Krohelski, 2003). Instead the model assumes homogeneous conditions within each layer outside the mine zone. However, as reported in Section 7, a comparison of contaminant transport results from the reflooded mine model to a modified regional model indicate that the simplifications of the geologic complexity in the reflooded mine model may not cause dramatically different results, especially with the deeper bedrock units. It is likely that, as with the applicant's model, these simplifications in the "final" WDNR model may result in projections of contaminant transport that are slower in some areas and faster in others, and with less spreading of the plume, than if the lateral heterogeneities of the regional flow model were incorporated.

The assumption that the fractured bedrock can be represented by an equivalent porous medium also imposes limitations on the results. Fractures tend to substantially affect contaminant velocity/travel time, and the volume into which source contaminants mix with surrounding groundwater. The dispersivity parameter is used to approximate spreading that might be caused by a fracture network, an approach that is shared by most contaminant transport models of fractured bedrock. Without building an entirely new model that incorporates discrete fracture flow, it is not possible to quantify the magnitude of these limitations. There is an absence of detailed site-specific data needed for a fracture-flow model, which would diminish the usefulness of such a model for this site. This limitation is common to most models that simulate contaminant transport in fractured bedrock.

The flow and transport portions of the "final" WDNR model have not been calibrated to existing conditions, because it represents future (not existing) conditions with a closed mine in place at the site. However, as discussed in Section 7, the reflooded mine model and the regional flow models were modified so that the reflooded mine model could simulate existing conditions, and the regional model could simulate solute transport. A comparison of the results from the two models indicated that the reflooded mine model results were generally comparable to those of the regional model, which has been calibrated to existing flow conditions. However, there are no tracer test or contaminant data from the site to use for calibrating the transport model. The results of the "final" WDNR model are limited by an absence of a thorough calibration to both flow and transport.

The assumption that the generic contaminant being simulated is chemically conservative is probably a substantial limitation for many constituents. However, it is likely a conservative approximation, in that many of the contaminants of interest may be attenuated by sorption or chemical reactions in the natural environment.

Finally, the range in results in the "final" WDNR model runs is limited by uncertainty as to whether the full range of important parameters has been incorporated into the model. While there are abundant hydraulic parameter data for the shallow unconsolidated sediment, there are relatively few data for the hydraulic conductivity or hydraulic heads in the intermediate and deep bedrock. Contaminant transport parameter data, for such parameters as fracture dispersion, have not been tested at the site in shallow or deep strata, which may constitute a substantial limitation to the results.

Section 11
Conclusions and Implications

- Results from the reflooded mine model are highly sensitive to:
  - the hydraulic conductivity of the bedrock,
  - dispersivity, and
  - the condition of the mine workings (open versus closed)
- No sensitivity tests were reported by NMC on instantaneous source simulations, from the paste backfill, acidic paste, crown pillar or mine workings wall rock. A limited number of sensitivity tests on instantaneous sources are reported here, for high and low end K paste and dispersivity, and for open versus closed mine workings. It is assumed that results with these sources would be sensitive to the same parameters as with continuous source paste backfill.
- The K values of the bedrock in the NMC model are lower than K values in the WDNR Low End Case regional flow model by up to 7 times, and are up to 50 times lower than the K values in the WDNR High End Case regional flow model. There is no justification given for the K values used in the NMC model.
- Final model results presented here utilize the High End Case K values from the WDNR regional flow model, because, in simulations of pre-mine conditions, the reflooded mine model more closely matched results from the modified regional model when High End Case K values were used.
- Paste backfill K values in the NMC model are thought to represent the extreme low end of the range of reasonable values. "Final" WDNR model results presented here utilize these low K values for the paste for the low end simulation, but also utilize paste K values that are 40 times higher in a high end simulation based on an evaluation of paste backfill at this and other sites (Mine Systems Design, 2003).
- "Final" WDNR model simulations are presented for four scenarios:
  - high paste K and dispersivity values, open mine workings conditions
  - high paste K and dispersivity values, closed mine workings conditions
  - low paste K and dispersivity values, under open mine workings conditions
  - low paste K and dispersivity values, under closed mine workings conditions
- The results indicate that maximum concentrations at the DMZ would be approximately two to five times higher under the high end paste K and dispersivity conditions as compared to low end conditions.
- Closed mine workings conditions result in maximum concentrations at the DMZ that are two to 9 times lower than open mine workings conditions in the groundwater from the glacial sediments and the shallow bedrock. Concentrations in the deep bedrock would be

higher under closed conditions than under open conditions, but the plume would take much longer to arrive at the DMZ, and the mass flux would be lower.

- The transport models discussed here have not been calibrated to existing (pre-mine) conditions, which limits the usefulness of these analyses. However, an attempt to compare results of the reflooded mine model (modified to represent existing conditions) to the regional flow model (modified) indicate that the reflooded mine model results are comparable to those of the modified regional flow model, which has been calibrated to existing flow (but not transport) conditions.
- The "final" WDNR model is also limited by a simplification of the geologic complexity that exists at the site. Significant uncertainty in the actual flow and transport parameters due to lack of data, especially in the fractures and K of the deeper bedrock, limits the accuracy of the model to an unknown degree.
- Results of the final model runs presented here could be combined with results from the waste characterization analysis on source materials, to evaluate whether the proposed mine would comply with applicable groundwater quality standards. Conclusions regarding compliance with groundwater quality standards were to be presented in the draft Environmental Impact Statement, but this process was terminated when the mine was sold and the mine permit application was withdrawn.

Section 12
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Table 1
Simulated Hydraulic Conductivity Values for Geologic Formations

HYDROSTRATIGRAPHIC UNIT		NMC EXPECTED CASE[1] REFLOOD MODEL (ft/d)			DNR REFLOOD HIGH K[2] (ft/d)			DNR REFLOOD LOW K[3] (ft/d)		
		Kz	Kx	Ky	Kz	Kx	Ky	Kz	Kx	Ky
Outwash (Layer 1)		4	40	40	4	40	40	4	40	40
Early Wisconsin Till/Massive Saprolite (Layer 2)		.075	2	2	.6	3	3	.075	2	2
Strongly-Weathered (SW) Bedrock (Layer 3)	HW	.1	.1	.1	.1	.32	.032	.077	.24	.024
	FW	.1	.1	.1	.1	.32	.032	.077	.24	.024
Moderately-Weathered (MW) Bedrock (Layers 4-7)	HW	.02	.02	.02	.07	.22	.022	.014	.044	.0044
	FW	.02	.02	.02	.07	.22	.022	.014	.044	.0044
Weakly-Weathered/Unweathered (WW/UW) Bedrock (Layers 8-26)	HW	.001	.001	.001	.05-.01	.17-.03	.017-.003	.0067 - .001	.021 - .0031	.0021 - .00031
	FW	.001	.001	.001	.05-.01	.17-.03	.017-.003	.0067 - .001	.021 - .0031	.0021 - .00031
Crown Pillar (Layers 3-4)[4]		8	8	8	8	8	8	8	8	8
Grouted Crown Pillar (Layer 5)[5]		.3	.3	.3	.3	.3	.3	.3	.3	.3
Backfill (Layers 6-26)[5]		.0003	.0003	.0003	.0003	.0003	.0003	.0003	.003	.0003
Open Workings[5]		500	500	500	500	500	500	500	500	500
Ore (Pre-Mine) (Layers 6-26)[6]		--	--	--	.88-.09	2.8-.28	.28-.03	1.1-.95	3.4-2.9	.34-.29

Notes:
(1) Expected Case conditions from GeoTrans model, also adopted here as NMC case model.
(2) Values used by WDNR in High End Case K regional model.
(3) Geometric means of values used by WDNR in Low End CaseLow End Case K regional model.
(4) Layers 3-5 in pre-mine simulations.
(5) Not present in pre-mine simulations.
(6) Only present in pre-mine simulations.
The geometric mean of the hydraulic conductivity values for the hanging wall and the foot wall from the WDNR High End Case.
K regional model were used to determine a representative value for Kz for the WDNR reflood High End Case K simulation.
For MW, WW, and UW bedrock, Kx = 3.162(Kz), and Ky = Kz/3.162.

Table 2
Comparison of MODFLOWT to MT3DMS Results

(at t=10,000 years)

MODEL SIMULATIONS/MODEL RUN	TOTAL MASS IN AQUIFER (kg)[1,2]	TOTAL MASS % DIFFERENT FROM MT3DMS - NMC CASE		MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1]				
				GLACIAL AQUIFER LAYER 2	STRONGLY WEATHERED BEDROCK LAYER 3	MODERATELY WEATHERED BEDROCK LAYER 7	WEAKLY WEATHERED BEDROCK LAYER 12	UNWEATHERED BEDROCK LAYER 26
MODFLOWT – NMC Expected Case parameters –isotropic (Rfl147)	*521*	*+22*		*0.028*	*0.032*	*0.22*	*0.26*	*0.35*
MT3DMS – NMC Case - NMC parameters, isotropic (401)	**425**	**0**		**0.021**	**0.059**	**0.21**	**0.27**	**0.25**

Notes:
[1] Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.
[2] Total mass includes only the mass outside of the mine body. Since no sorption is included in any simulation, all mass is dissolved.

Table 3
Solver Effect on Model Results - TVD vs. Finite Difference

Time		Mass – TVD Solver (mg/L x ft^3)	Mass - FD Solver (mg/L x ft^3)	Δ (%)
(Days)	(Years)			
601	1.6	2.85×10^5	2.77×10^5	2.9
673	1.8	3.08×10^5	3.01×10^5	2.3
1,597	4.4	5.71×10^5	5.56×10^5	2.7
2,964	8.1	8.97×10^5	8.72×10^5	2.9
4,991	14	1.32×10^6	1.28×10^6	3.1
7,632	21	1.80×10^6	1.75×10^6	2.9
7,990	22	1.86×10^6	1.80×10^6	3.2
11,899	33	2.45×10^6	2.39×10^6	2.5
12,423	34	2.53×10^6	2.46×10^6	2.8
18,213	50	3.23×10^6	3.16×10^6	2.1
18,991	52	3.31×10^6	3.25×10^6	1.9
22,218	61	3.62×10^6	3.57×10^6	1.4

Table 4
Sensitivity of Contaminant Mass and Concentrations to Hydraulic Conductivity, Anisotropy, and Closed Versus Open Workings Design – Results at 453 years

MODEL SIMULATIONS/MODEL RUN	TOTAL MASS IN AQUIFER (kg)[(1),2)]	TOTAL MASS % DIFFERENT FROM NMC CASE	TOTAL MASS OUTFLUX OVER 453 YRS (kg)[(3)]	MAXIMUM DMZ - BOUNDARY CONCENTRATIONS (mg/L)[(1)] (at t=453 Years).				
				GLACIAL AQUIFER LAYER 2	STRONGLY WEATHERED BEDROCK LAYER 3	MODERATELY WEATHERED BEDROCK LAYER 7	WEAKLY WEATHERED BEDROCK LAYER 12	UNWEATHERED BEDROCK LAYER 26
NMC Case - NMC bedrock K (isotropic) (401)	**246**	**0**	**699**	**0.021**	**0.054**	**0.13**	**1.4E-04**	**4.1E-04**
NMC bedrock Kz; Anisotropic (Kx=3.16Kz; Ky=Kz/3.16; Layer 3 isotropic) (758b)	210	-15	657	0.023	0.088	0.27	0.095	0.082
Low End Case bedrock K (anisotropic, except Layer 3 (754b)	211	-14	596	0.020	0.082	0.21	0.15	0.075
Low End Case bedrock K (anisotropic), match regional model T value in Layer 1 (752c)	189	-23	656	0.016	0.076	0.16	0.13	0.063
High End Case bedrock K=Kz (isotropic) (757)	354	+44	1840	0.048	0.070	0.21	0.28	0.16
High End Case bedrock K (anisotropic, except Layer 3) (755b)	280	+14	1910	0.050	0.14	0.26	0.23	0.15
Closed works, NMC reflood K values (isotropic) (725)	116	-53	142	0.002	0.01	0.11	1.3E-04	2.6E-09
Closed works, High End Case K values (anisotropic) (756)	373	+52	934	0.002	0.0068	0.13	0.52	0.73

Notes:
(1) Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.
(2) Total mass in groundwater includes only the mass outside of the mine body. Since no sorption is included in any simulation, all mass is dissolved.
(3) Total mass outflux refers to flux out the boundary of the model domain.
(4) At the 453 year time period summarized here, the plume has not reached steady state at all depths in the bedrock, in any of the simulations presented in this table.

Table 5
Sensitivity of Contaminant Mass and Concentrations to Hydraulic Conductivity, Anisotropy, and Closed Versus Open Workings Design – Results at 10,000 years

MODEL SIMULATIONS/MODEL RUN	TOTAL MASS IN AQUIFER (kg)[1,2]	TOTAL MASS % DIFFERENT FROM NMC CASE	TOTAL MASS OUTFLUX OVER 10,000 YEARS (kg)[3]	MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1] (at t=10,000 Years)				
				GLACIAL AQUIFER LAYER 2	STRONGLY WEATHERED BEDROCK LAYER 3	MODERATELY WEATHERED BEDROCK LAYER 7	WEAKLY WEATHERED BEDROCK LAYER 12	UNWEATHERED BEDROCK LAYER 26
MODFLOWT – NMC Expected Case parameters – isotropic (Rfl147)	*521*	*+22*	Not available	*0.028*	*0.032*	*0.22*	*0.26*	*0.35*
MT3DMS – NMC Case - NMC parameters, isotropic (401)	**425**	**0**	**13,855**	**0.021**	**0.059**	**0.21**	**0.27**	**0.25**
Low End CaseLow End Case regional K, anisotropic, except Layer 3 (754b)	262	-38	11,928	0.020	0.085	0.22	0.18	0.12
Low End CaseLow End Case regional K, anisotropic, match T in L1 (752c)	225	-47	13,282	0.017	0.083	0.16	0.14	0.10
High End Case regional K, anisotropic, except Layer 3 (755b)	283	-33	40,800	0.05	0.14	0.26	0.23	0.18
Closed workings, NMC K values, isotropic (725)	615	+45	1,320	0.0023	0.015	0.21	0.76	0.84
Closed workings, High End Case Regional K, anisotropic (756)	493	+16	16,717	0.0021	0.0069	0.13	0.53	0.85

Notes:
(1) Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.
(2) Total mass in groundwater includes only the mass outside of the mine body. Since no sorption is included in any simulation, all mass is dissolved.
(3) Total mass outflux refers to flux out the boundary of the model domain.

Table 6
Sensitivity of Contaminant Mass and Concentrations to Source Term, Boundary Conditions, and Model Parameters

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1] (at t=10,000 Years)								
ITEM NO.	MODEL SIMULATIONS/MODEL RUN	TOTAL MASS IN AQUIFER (kg)[1,2]	TOTAL MASS % DIFFERENT FROM NMC CASE	GLACIAL AQUIFER LAYER 2	STRONGLY WEATHERED BEDROCK LAYER 3	MODERATELY WEATHERED BEDROCK LAYER 7	WEAKLY WEATHERED BEDROCK LAYER 12	UNWEATHERED BEDROCK LAYER 26
1	*MODFLOWT – NMC Expected Case parameters(Rfl147)*	*521*	*22*	*0.028*	*0.032*	*0.22*	*0.26*	*0.35*
2	**MT3DMS – NMC case run (401)**	**425**	**0**	**0.021**	**0.059**	**0.21**	**0.27**	**0.25**
3	Decrease K of paste (no advection) (707)	419	-1	0.020	0.055	0.19	0.52 (L22)	0.37
4	Decrease K of paste and fringe (no advect.) (720)	69	-84	0.0003	0.001	0.007	0.012	0.01
5	Decr. K of paste and backfill; crosscuts open (721)	92	-79	0.0017	0.0088	0.041	0.045	0.05
6	Tran hor. Dispersivity = 0 in mine, fringe (717)	371	-13	0.020	0.053	0.18	0.23	0.22
7	Increase trans. hor. dispersivity to 50 ft (723)	604	+42	0.018	0.062	0.28	0.33	0.34
8	All dispersion = 0 (710)	NA[3]	NA[3]	NA[3]	NA[3]	NA[3]	NA[3]	NA[3]
9	Vert. Dispersivity = 0 in mine, fringe (716)	340	-20	0.015	0.041	0.15	0.23	0.23
10	Vert. Dispersivity = 0 Layers 6-26 (711)	309	-27	0.021	0.036	0.18	0.28	0.44
11	Longitudinal dispersion = 0 Layers 1-26 (713)	<<425[3]	NA[3]	NA[3]	NA[3]	NA[3]	NA[3]	NA[3]
12	Diffusion = 0 in paste backfill (709)	422	-1	0.021	0.060	0.21	0.26	0.25
13	Increase diffusion everywhere by 3.5x (722)	439	+3	0.022	0.059	0.21	0.27	0.25
14	Add HFB (same K), thick = 0.75 ft (728)	425	0	0.021	0.059	0.21	0.27	0.25
15	Regional model heads as boundaries (712)	394	-7	0.024	0.061	0.21	0.27	0.24
16	Set Recharge = 0 over mine (729)	380	-11	0.028	0.064	0.21	0.24	0.24
17	Set Recharge = 50 percent everywhere (730)	376	-12	0.037	0.077	0.21	0.24	0.24
18	Close open works, Low End CaseLow End Case K of grouted CP (725)	615	+45	0.0023	0.015	0.21	0.76	0.84

Notes:
(1) Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.
(2) Total mass in groundwater includes only the mass outside of the mine body. Since no sorption is included in any simulation, all mass is dissolved.
(3) Simulation did not converge.

Table 7
Distribution of Mass by Layer, Regional Inset Model vs. Reflooded Mine Model

High End Case K Model Run 739b (t=200 yr.)					
Regional Model Layer	Equivalent Reflooded mine model Layer	Geologic Unit	Regional Model Mass (high end) (200 yr.) (mg/L x ft^3)	Equivalent Mass (mg/L x ft^3)	Ratio Reflooded Mass /WDNR (high end) Mass (mg/L x ft^3)
1			1.19E+02		
2			6.74E+04		
3	1	Outwash	6.46E+05	9.71E+05	1.36
4	2	Till	3.48E+06	1.89E+06	0.54
5	3	SW Bedrock	8.99E+06	3.33E+06	0.37
6	6	MW Bedrock	4.45E+06	1.02E+07	2.29
7	8-9	WW/UW Bedrock	1.60E+07	1.15E+07	0.72
8	10-12	WW/UW Bedrock	1.56E+07	2.51E+07	1.61
9	13-16	WW/UW Bedrock	3.46E+07	3.23E+07	0.93
10	17-20	WW/UW Bedrock	3.27E+07	3.22E+07	0.99
11	21-26	WW/UW Bedrock	4.92E+07	4.59E+07	0.93
Total			**1.66E+08**	**1.63E+08**	**0.99**

Low End CaseLow End Case K Model Run 740 (t=600 yr.)					
Regional Model Layer	Equivalent Reflooded Model Layer	Geologic Unit	Regional Model Mass (low end) (600/yr.) (mg/L x ft^3)	Equivalent Reflooded Model Mass (mg/L x ft^3)	Ratio Reflooded Mass /WDNR (low end) Mass (mg/L x ft^3)
1			1.63E+02		
2			2.41E+04		
3	1	Outwash	3.04E+05	1.78E+06	5.4
4	2	Till	2.87E+06	3.67E+06	1.28
5	3	SW Bedrock	6.49E+06	5.24E+06	0.81
6	6	MW Bedrock	4.55E+06	1.22E+07	2.67
7	8-9	WW/UW Bedrock	1.61E+07	1.15E+07	0.72
8	10-12	WW/UW Bedrock	1.58E+07	2.52E+07	1.59
9	13-16	WW/UW Bedrock	3.56E+07	3.23E+07	0.91
10	17-20	WW/UW Bedrock	3.36E+07	3.21E+07	0.96
11	21-26	WW/UW Bedrock	4.93E+07	4.55E+07	0.92
Total			**1.65E+08**	**1.69E+08**	**1.03**

Table 8
Final Model Results - Continuous Source Paste Backfill

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1] (at t=10,000 Years)							
ITEM NO.	MODEL SIMULATIONS/MODEL RUN		GLACIAL AQUIFER LAYER 2	STRONGLY WEATHERED BEDROCK LAYER 3	MODERATELY WEATHERED BEDROCK LAYER 7	WEAKLY WEATHERED BEDROCK LAYER 12	UNWEATHERED BEDROCK LAYER 26
1	NMC Expected Case parameters - open mine workings	(401)	0.021	0.059	0.21	0.27	0.25
2	High End Case K bedrock – High End Case K paste – open mine workings	(789)	0.097	0.12	0.36	0.33	0.25
3	High End Case K bedrock – High End Case K paste – closed mine workings	(800)	0.012	0.017	0.17	0.68	0.95
4	High End Case K bedrock – Low End CaseLow End Case K paste – open mine workings	(810)	0.022	0.042	0.091	0.10	0.15
5	High End Case K bedrock – Low End CaseLow End Case K paste – closed mine workings	(801)	0.0044	0.0046	0.013	0.50	0.88

Notes:
[1] Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.

Table 9
Final Model Results - Instantaneous Source Paste Backfill

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[(1)]							
ITEM NO.	MODEL SIMULATIONS/MODEL RUN	RUN NO.	GLACIAL AQUIFER LAYER 2 (TIME, YRS)*	STRONGLY WEATHERED BEDROCK LAYER 3 (TIME, YRS)*	MODERATELY WEATHERED BEDROCK LAYER 7 (TIME, YRS)*	WEAKLY WEATHERED BEDROCK LAYER 12 (TIME, YRS)*	UNWEATHERED BEDROCK LAYER 26 (TIME, YRS)*
1	NMC Expected Case parameters- open mine workings	**(760)**	**0.0071** (33)	**0.015** (352)	**0.073** (352)	**0.16** (3,350)	**0.16** (652)
2	High End Case K bedrock – High End K paste - open mine workings	**(802)**	**0.046** (75)	**0.053** (75)	**0.17** (169)	**0.17** (169)	**0.17** (113)
3	High End Case K bedrock – High End K paste –closed mine workings	**(806)**	**0.016** (88)	**0.017** (108)	**0.10** (96)	**0.47** (77)	**0.85** (1,627)
4	High End Case K bedrock – Low End K paste - open mine workings	**(811)**	**0.0085** (75)	**0.015** (352)	**0.052** (252)	**0.068** (352)	**0.10** (75)
5	High End Case K bedrock – Low End K paste - closed mine workings	**(815)**	**3.9E-04** (2,151)	**3.9E-04** (2,248)	**0.0047** (169)	**0.34** (50)	**0.76** (752)

Notes:
* Time is the number of years at which maximum concentration was achieved, at any point along the DMZ.
[(1)] Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.

Table 10
Final Model Results - Instantaneous Source Acidic Paste Backfill

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1]							
ITEM NO.	**MODEL SIMULATIONS/MODEL RUN**	**RUN NO.**	**GLACIAL AQUIFER LAYER 2 (TIME, YRS)***	**STRONGLY WEATHERED BEDROCK LAYER 3 (TIME, YRS)***	**MODERATELY WEATHERED BEDROCK LAYER 7 (TIME, YRS)***	**WEAKLY WEATHERED BEDROCK LAYER 12 (TIME, YRS)***	**UNWEATHERED BEDROCK LAYER 26 (TIME, YRS)***
1	NMC Expected Case parameters - open mine workings	**(761)**	**1.1E-04**	**1.5E-04**	**5.6E-04**	**5.8E-04**	**4.1E-04**
			(50)	(352)	(552)	(3,950)	(852)
2	High End Case K bedrock – High End K paste - open mine workings	**(803)**	**3.5E-04**	**5.3E-04**	**2.7E-03**	**2.7E-03**	**1.8E-03**
			(50)	(50)	(33)	(33)	(75)
3	High End Case K bedrock – High End K paste -closed mine workings	**(807)**	**1.6E-06**	**5.0E-06**	**1.6E-04**	**1.0E-03**	**1.2E-03**
			(169)	(169)	(113)	(113)	(652)
4	High End Case K bedrock – Low End K paste - open mine workings	**(812)**	**2.8E-04**	**3.4E-04**	**1.8E-03**	**1.9E-03**	**1.8E-03**
			(33)	(75)	(33)	(33)	(75)
5	High End Case K bedrock – Low End K paste -closed mine workings	**(816)**	**9.6E-08**	**2.0E-07**	**2.3E-04**	**3.0E-04**	**9.8E-04**
			(33)	(113)	(50)	(452)	(1,851)

Notes:
* Time is the number of years at which maximum concentration was achieved, at any point along the DMZ.
[1] Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.

Table 11
Final Model Results - Instantaneous Source Crown Pillar

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1]							
ITEM NO.	MODEL SIMULATIONS/MODEL RUN	RUN NO.	GLACIAL AQUIFER LAYER 2 (TIME, YRS)*	STRONGLY WEATHERED BEDROCK LAYER 3 (TIME, YRS)*	MODERATELY WEATHERED BEDROCK LAYER 7 (TIME, YRS)*	WEAKLY WEATHERED BEDROCK LAYER 12 (TIME, YRS)*	UNWEATHERED BEDROCK LAYER 26 (TIME, YRS)*
1	NMC Expected Case parameters - open mine workings	**(762)**	**0.0046**	**0.0017**	**0.0014**	**4.30E-04**	**2.10E-04**
			(21)	(75)	(352)	(3,350)	(2,651)
2	High End Case K bedrock – High End K paste - open mine workings	**(804)**	**4.3E-03**	**2.9E-03**	**1.1E-03**	**3.3E-04**	**1.1E-04**
			(13)	(33)	(50)	(113)	(75)
3	High End Case K bedrock – High End K paste – closed mine workings	**(808)**	**3.3E-03**	**2.6E-03**	**0.010**	**5.8E-03**	**7.3E-06**
			(21)	(33)	(33)	(33)	(252)
4	High End Case K bedrock – Low End K paste – open mine workings	**(813)**	**6.6E-03**	**3.0E-03**	**1.1E-03**	**5.4E-04**	**8.7E-05**
			(21)	(50)	(75)	(113)	(366)
5	High End Case K bedrock – Low End K paste - closed mine workings	**(817)**	**3.9E-03**	**2.4E-03**	**0.047**	**0.056**	**1.3E-08**
			(33)	(50)	(50)	(33)	(302)

Notes:
* Time is the number of years at which maximum concentration was achieved, at any point along the DMZ.
(1) Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.

Table 12
Final Model Results - Instantaneous Source, Wall Rock of Open Workings

MAXIMUM DMZ – BOUNDARY CONCENTRATIONS (mg/L)[1]								
ITEM NO.	MODEL SIMULATIONS/MODEL RUN	RUN NO.	GLACIAL AQUIFER LAYER 2 (TIME, YRS)*	STRONGLY WEATHERED BEDROCK LAYER 3 (TIME, YRS)*	MODERATELY WEATHERED BEDROCK LAYER 7 (TIME, YRS)*	WEAKLY WEATHERED BEDROCK LAYER 12 (TIME, YRS)*	UNWEATHERED BEDROCK LAYER 26 (TIME, YRS)*
1	NMC Expected Case parameters - open mine workings	**(763)**	**0.032**	**0.054**	**0.20**	**0.12**	**0.17**
			(33)	(352)	(352)	(3,350)	(652)
2	High End Case K bedrock – High End K paste – open mine workings	**(805)**	**0.076**	**0.096**	**0.62**	**0.73**	**0.56**
			(33)	(33)	(33)	(21)	(50)
3	High End Case K bedrock – High End K paste - closed mine workings	**(809)**	**4.6E-04**	**1.6E-03**	**0.048**	**0.21**	**0.34**
			(113)	(113)	(75)	(75)	(452)
4	High End Case K bedrock – Low End K paste – open mine workings	**(814)**	**0.068**	**0.10**	**0.830**	**0.880**	**0.59**
			(265)	(954)	(265)	(257)	(918)
5	High End Case K bedrock – Low End K paste – closed mine workings	**(818)**	**5.8E-05**	**8.0E-05**	**4.3E-03**	**0.068**	**0.23**
			(50)	(452)	(33)	(113)	(652)

Notes:
* Time is the number of years at which maximum concentration was achieved, at any point along the DMZ.
[1] Concentrations and total mass in groundwater calculated based on an assumed constant concentration of source nodes equal to 1.0 mg/L.

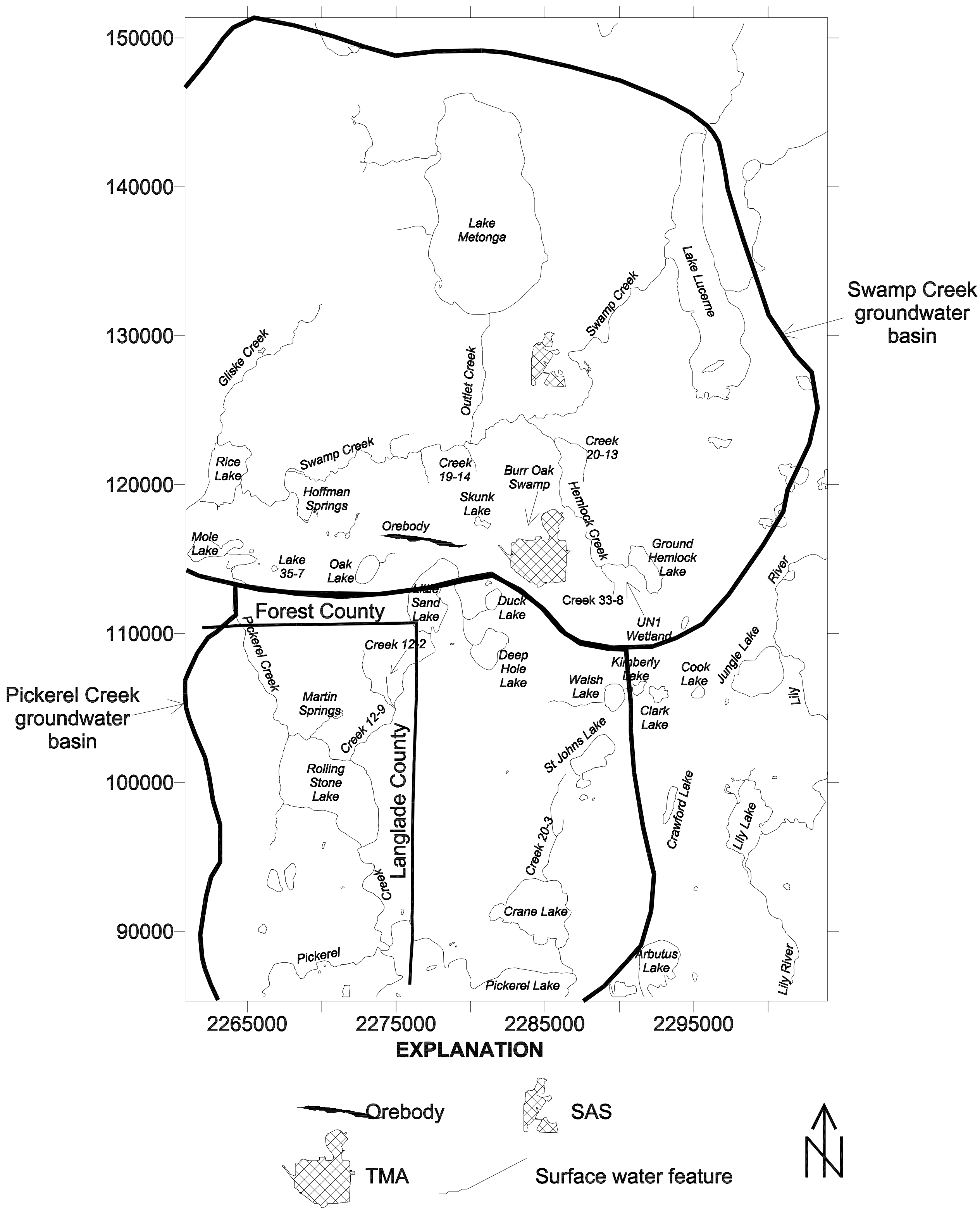
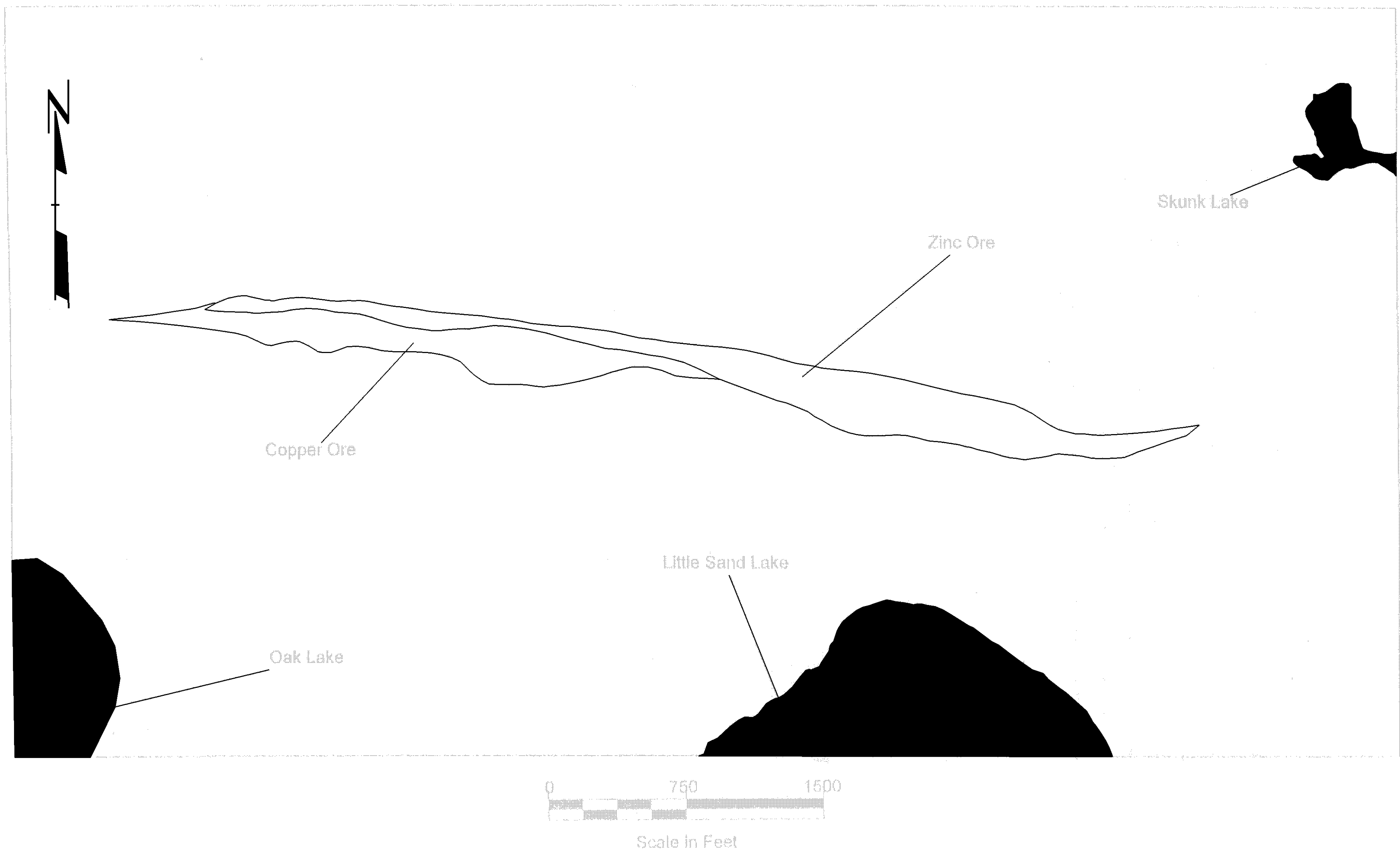
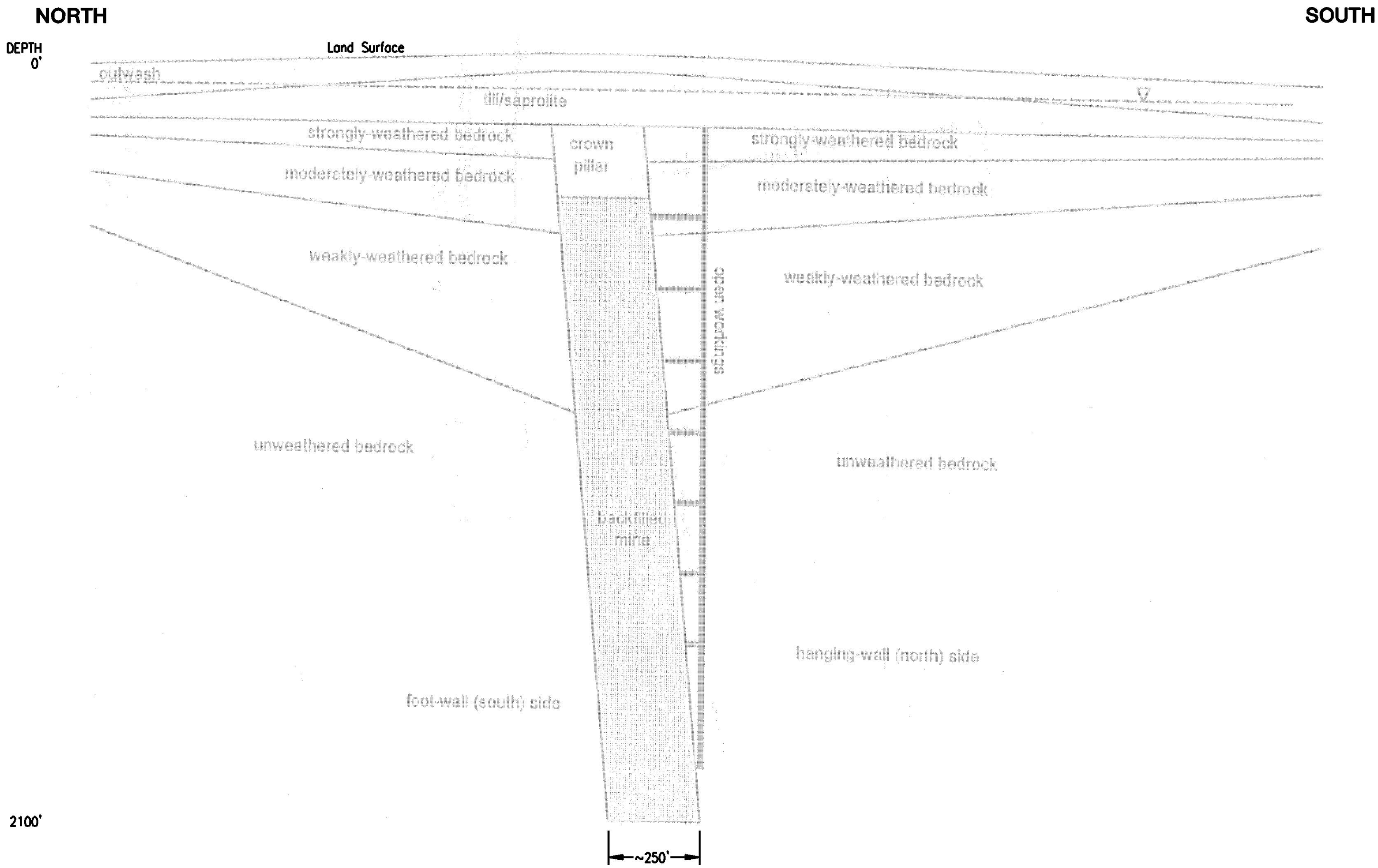


Figure 1. Crandon area base map and Swamp and Pickerel Creek groundwater basins. Map coordinates are State Plane North, in feet, (Modified from Foth and Van Dyke, EIR, 1995). Boundary of groundwater basins are based on GFLOW model (Kelson and others, 2002) particle tracking from Cty M for the Swamp Creek basin and Hwy 55 for Pickerel Creek basin. [Abbreviations: TMA, Tailings Management Area; SAS, Soil Adsorption Site]



RMT®	ZINC AND COPPER ORE AT SUBCROP, PLAN VIEW	DRAWN BY:	MEYERHOFER
		APPROVED BY:	
		PROJECT NO.	5436.01
	FIGURE 2	FILE NO.	54360101.DWG
	(ADAPTED FROM GEOTRANS, 2000)	DATE:	APRIL 2004



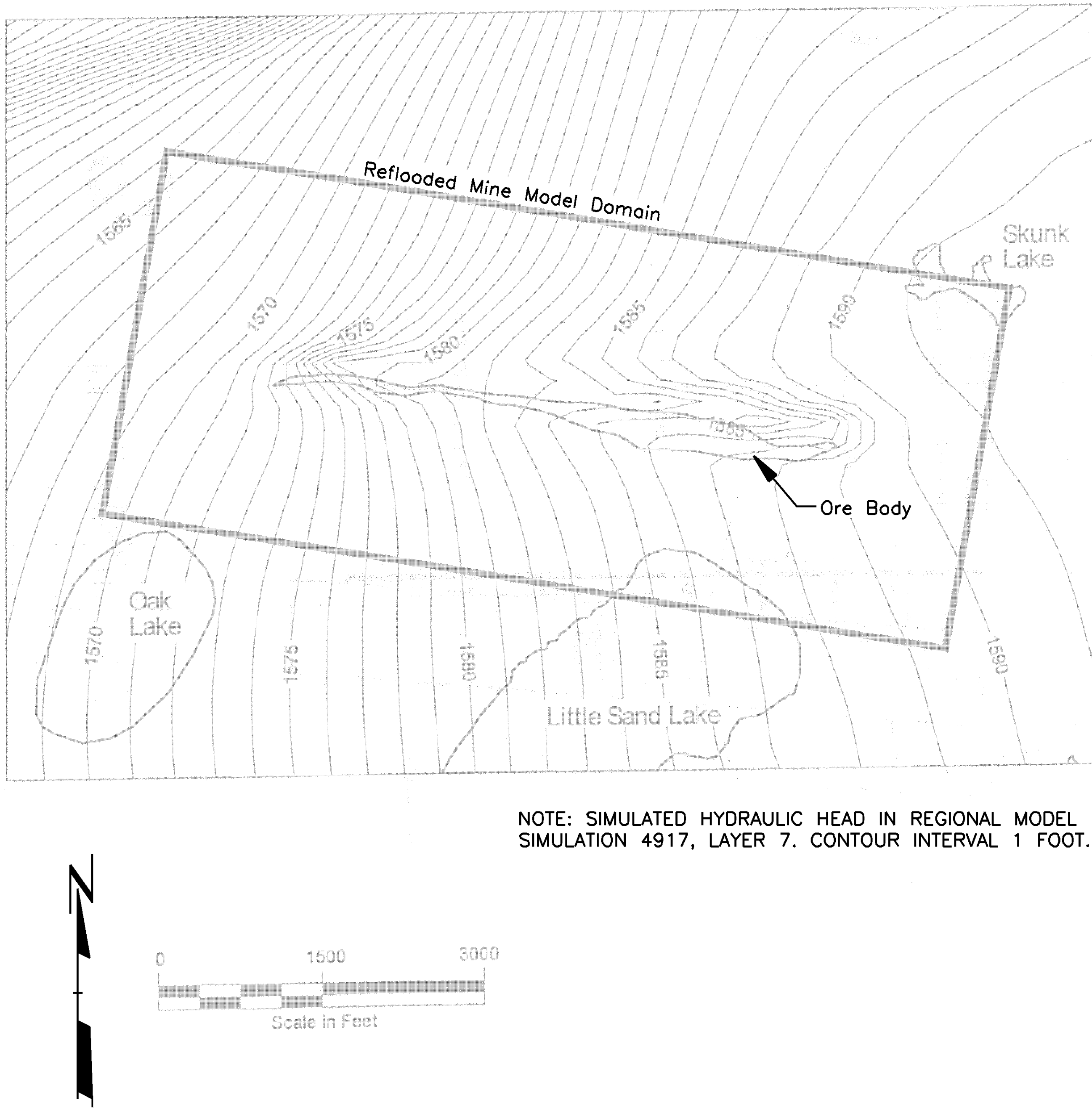
RMT®

CONCEPTUAL NORTH-SOUTH CROSS SECTION ON EAST END OF ORE BODY SHOWING HYDROGEOLOGIC UNITS AND HANGING WALL WORKINGS

FIGURE 3

(ADAPTED FROM GEOTRANS, 2000)

DRAWN BY:	MEYERHOFER
APPROVED BY:	
PROJECT NO.	5436.01
FILE NO.	54360102.DWG
DATE:	APRIL 2004



NOTE: SIMULATED HYDRAULIC HEAD IN REGIONAL MODEL SIMULATION 4917, LAYER 7. CONTOUR INTERVAL 1 FOOT.

RMT®

REFLOODED MINE MODEL DOMAIN AND REGIONAL GROUNDWATER FLOW SIMULATED HYDRAULIC HEAD

FIGURE 4

(ADAPTED FROM GEOTRANS, 2000)

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APPROVED BY:	
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FILE NO.	54360103.DWG
DATE:	APRIL 2004

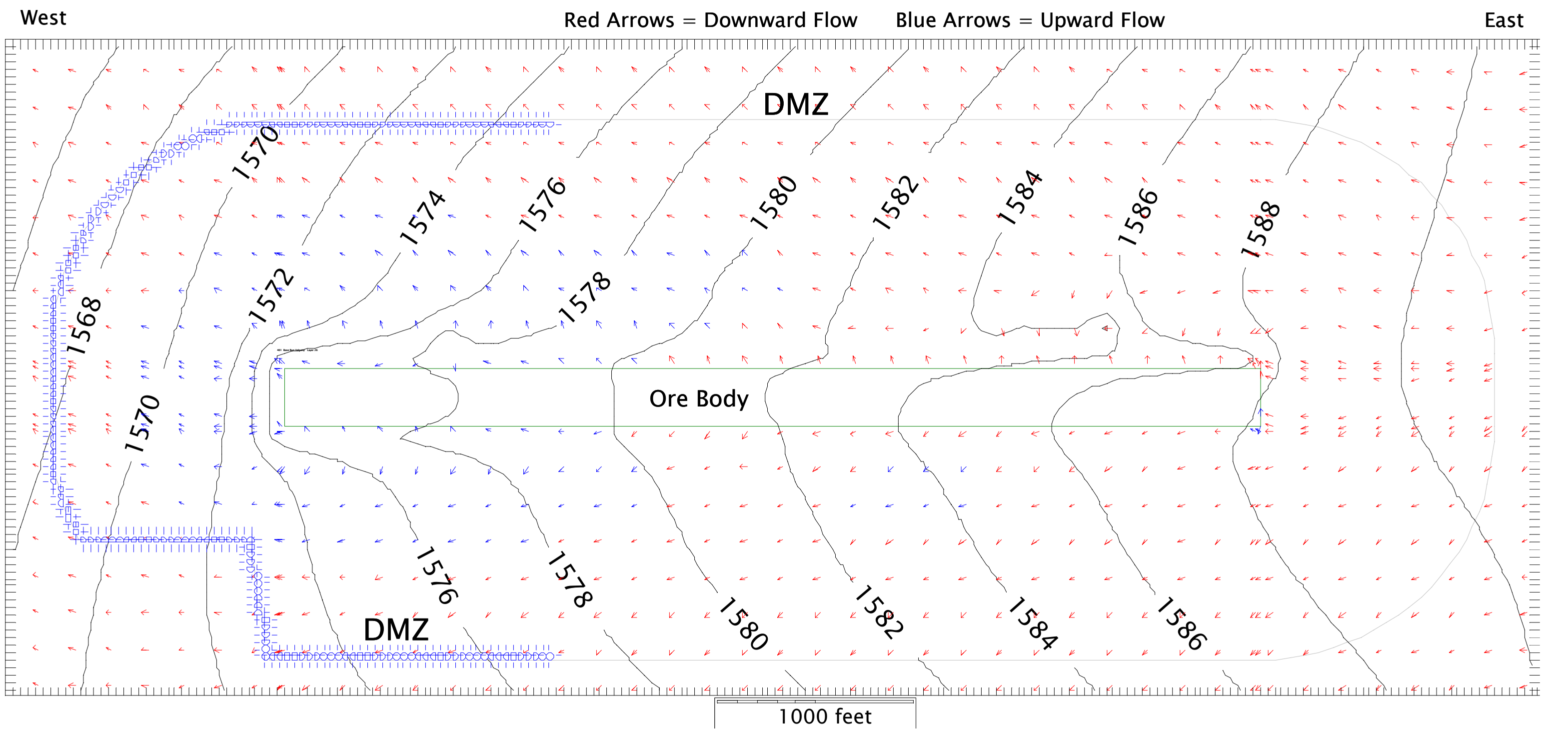


Figure 5. NMC Case (Run 401) Simulated Heads and Velocity Vectors, Layer 7, MW Bedrock.

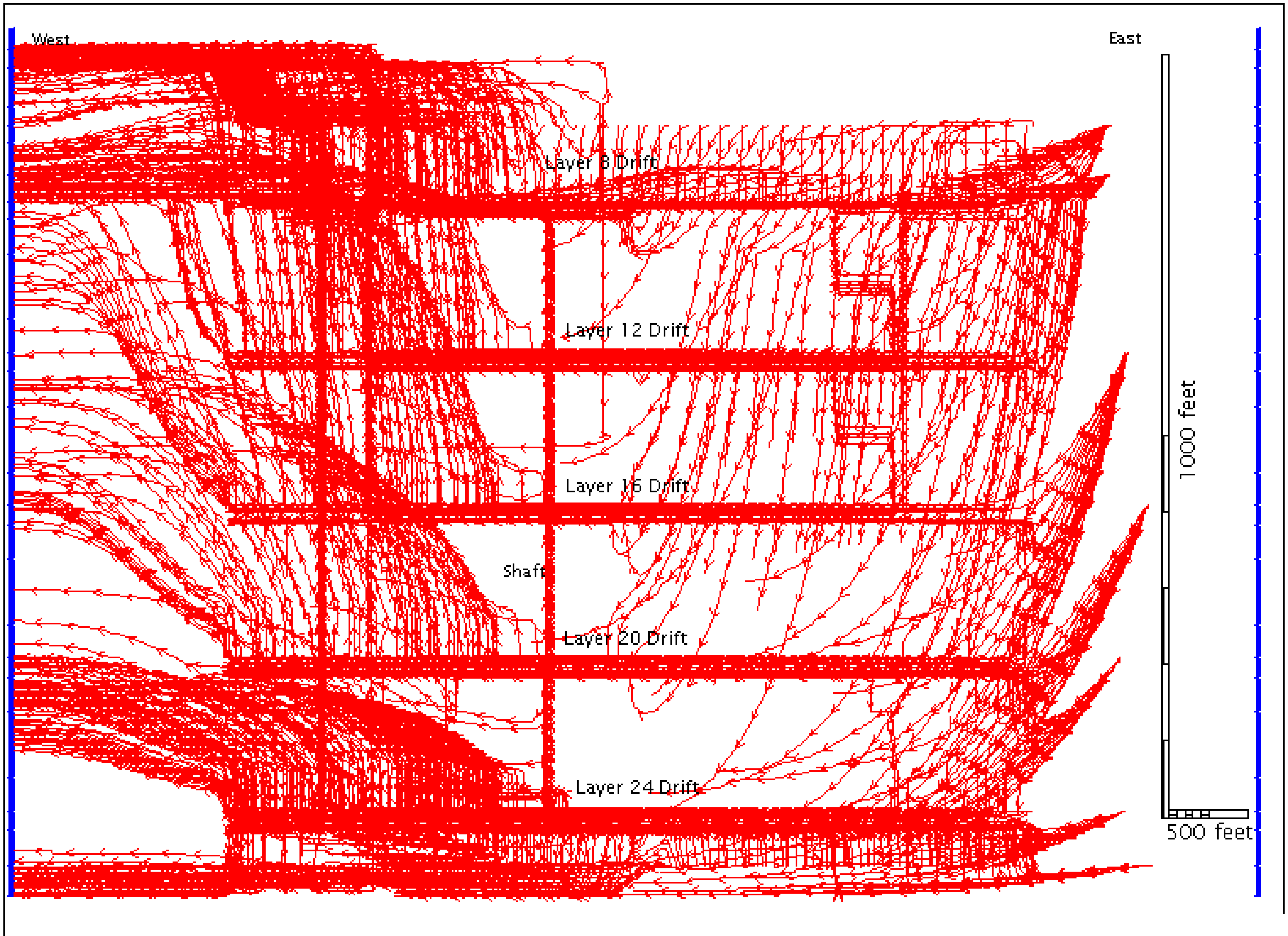


Figure 6. NMC Case (Run 401) Particle Tracks, East-West Cross Section Through South End of Mine.

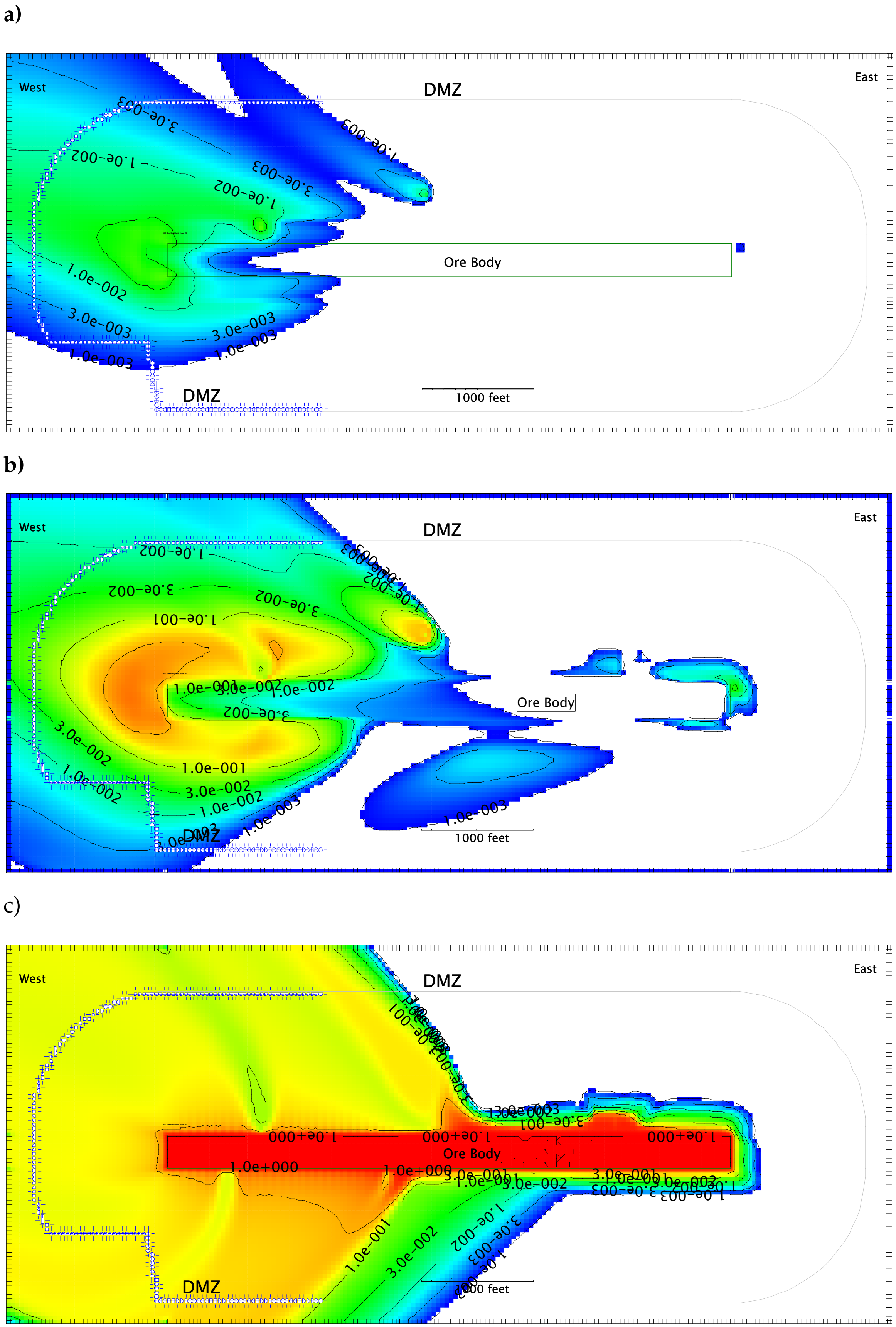
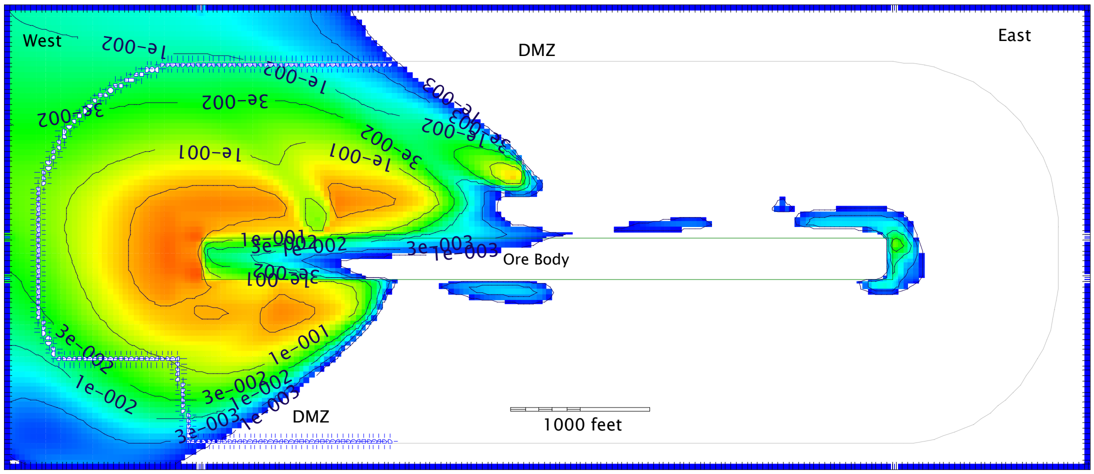


Figure 7. NMC Case Concentrations in the Glacial Aquifer (a), Strongly-Weathered Bedrock (b), and Unweathered Bedrock (c) at 10,000 Years.

a)



b)

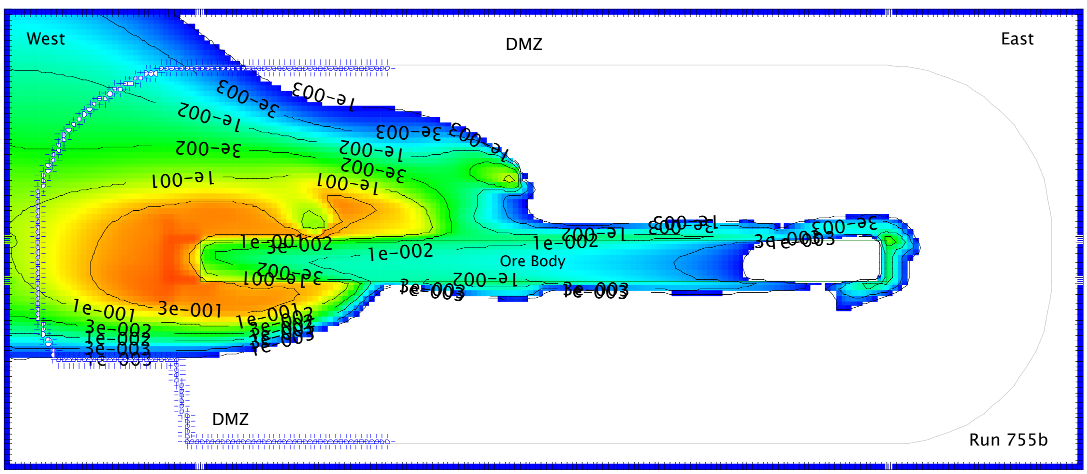


Figure 8. Concentrations in Strongly-Weathered Bedrock at 453 Years, High-End Case Regional Model K Values: Isotropic (a) versus Anisotropic (b) Conditions.

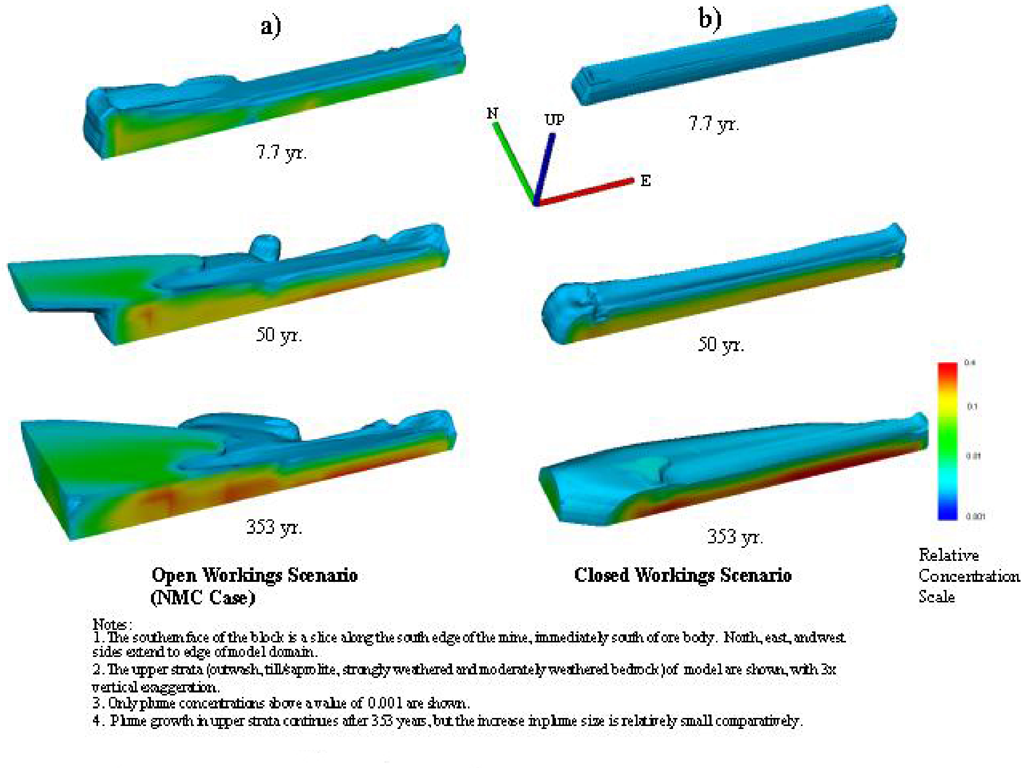
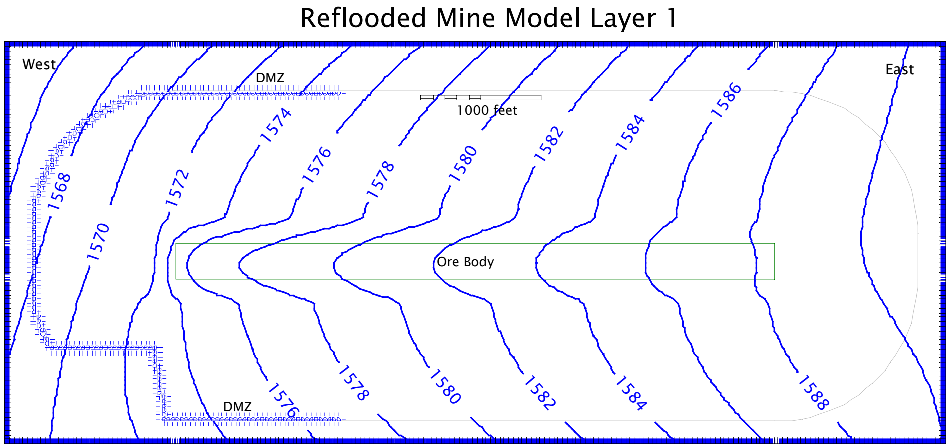


Figure 9. Block Diagram of Plume Growth Over Time - Open vs. Closed Workings Scenarios.

a)



b)

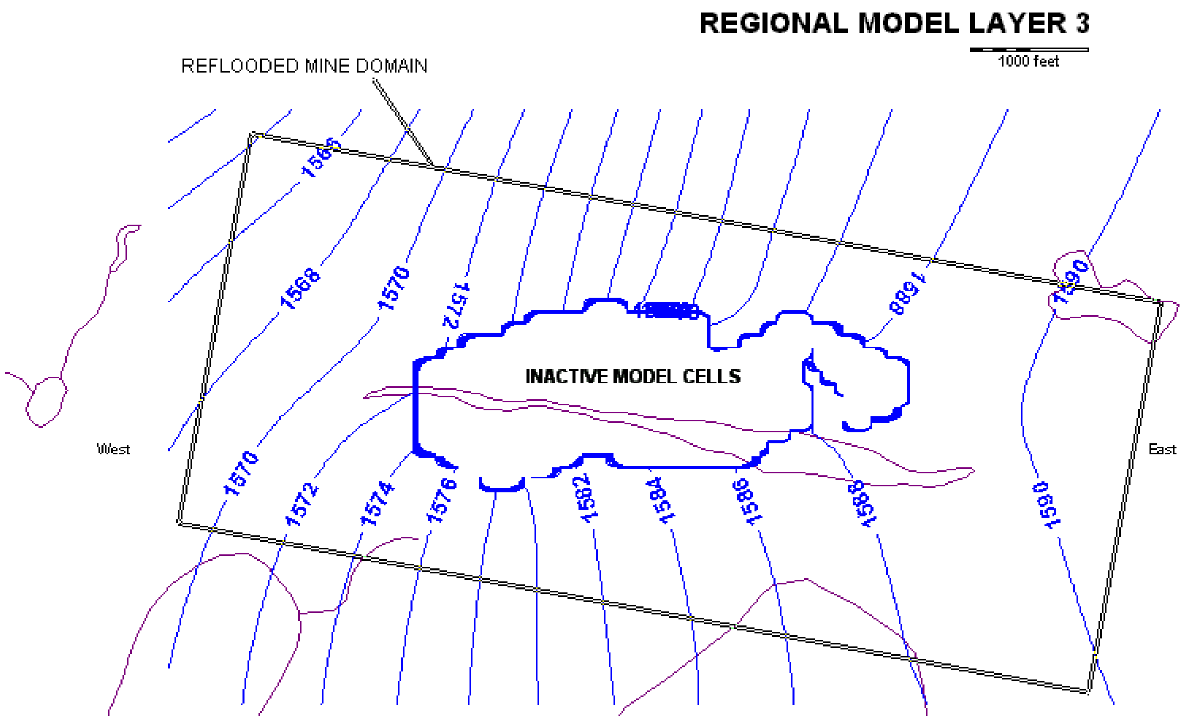
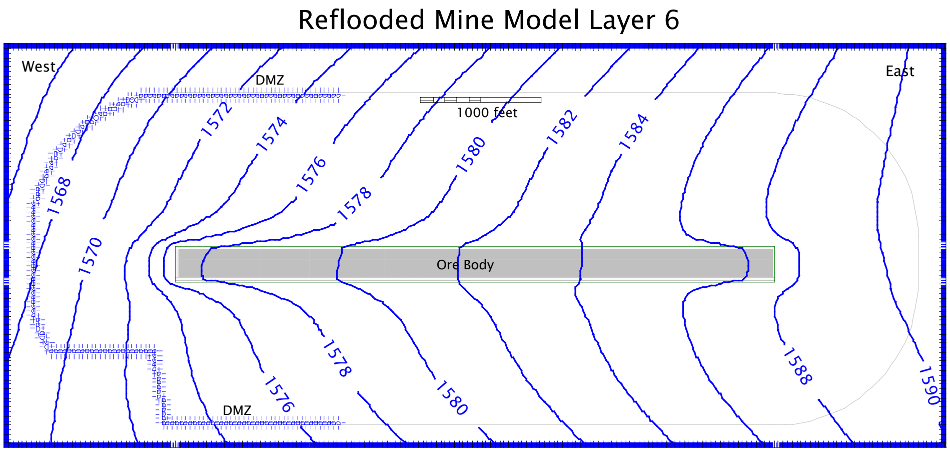


Figure 10. Pre-Mine Hydraulic Head Distribution in Outwash, a) Reflooded Mine Model and b) Regional Model

a)



b)

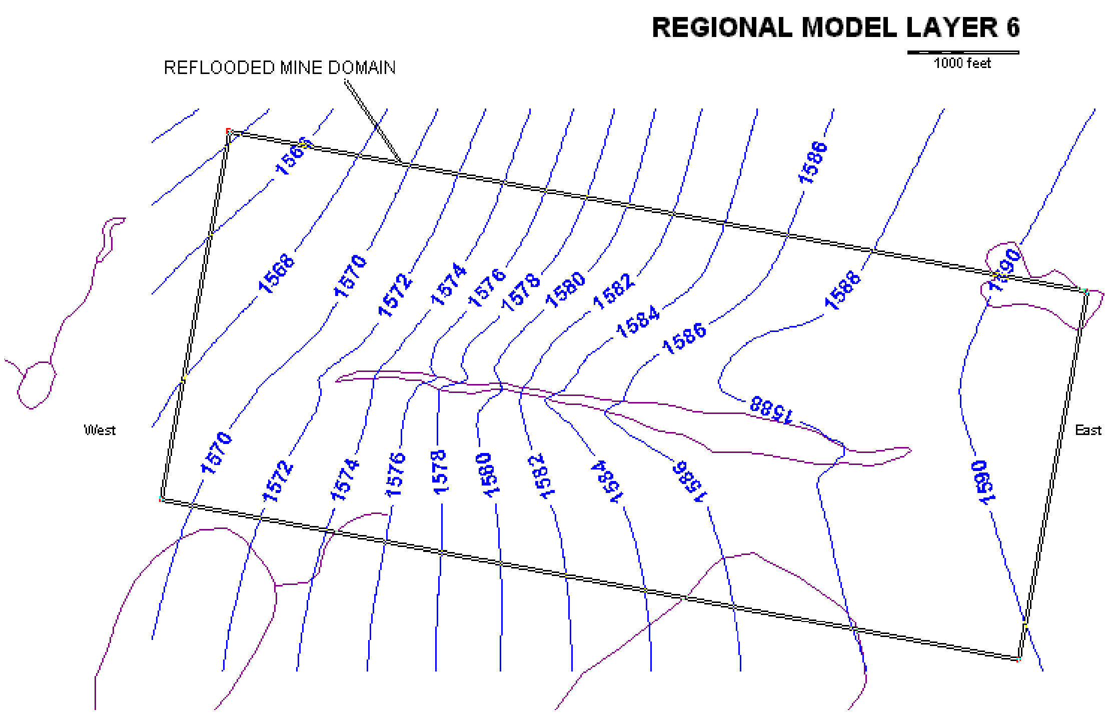
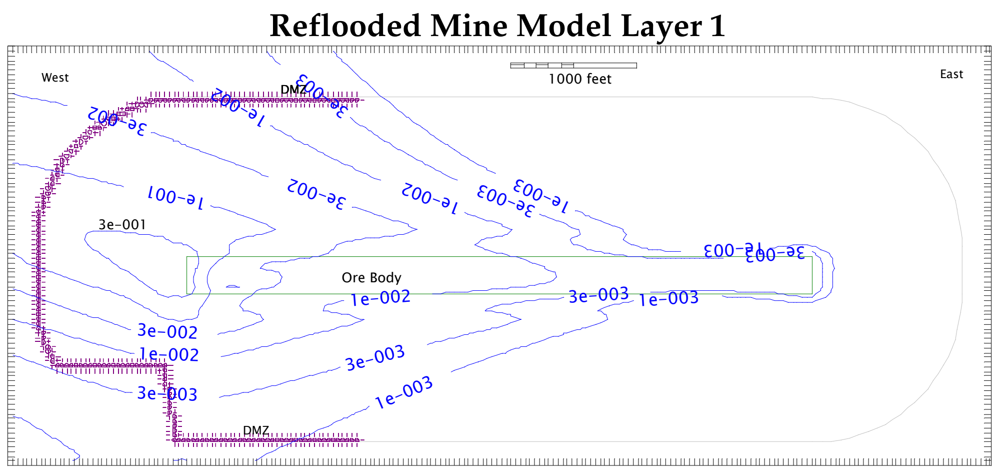


Figure 11. Pre-Mine Hydraulic Head Distribution in Shallow Bedrock, a) Reflooded Mine Model and b) Regional Model.

a)



b)

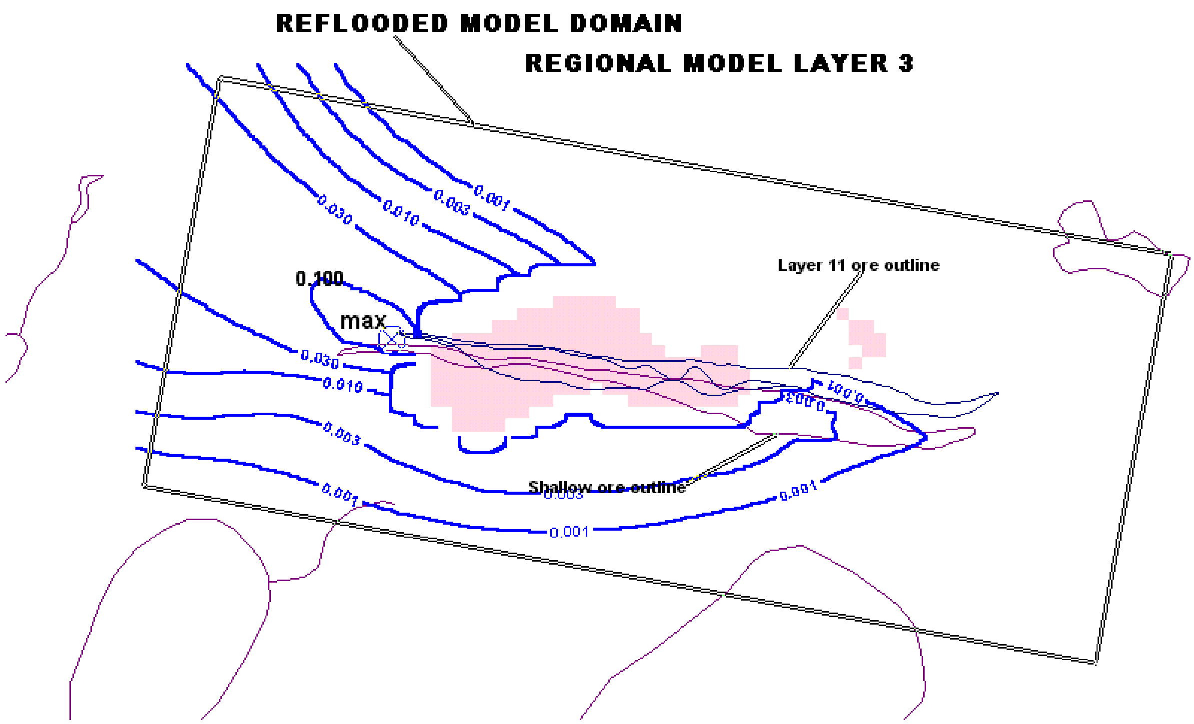
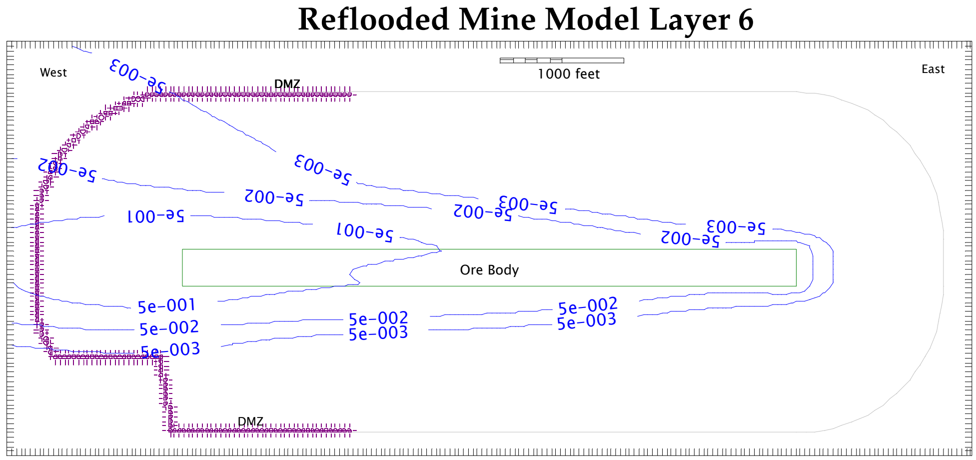


Figure 12. Pre-Mine Solute Concentrations in Outwash: a) Reflooded Mine Model and b) Regional Model.

a)



b)

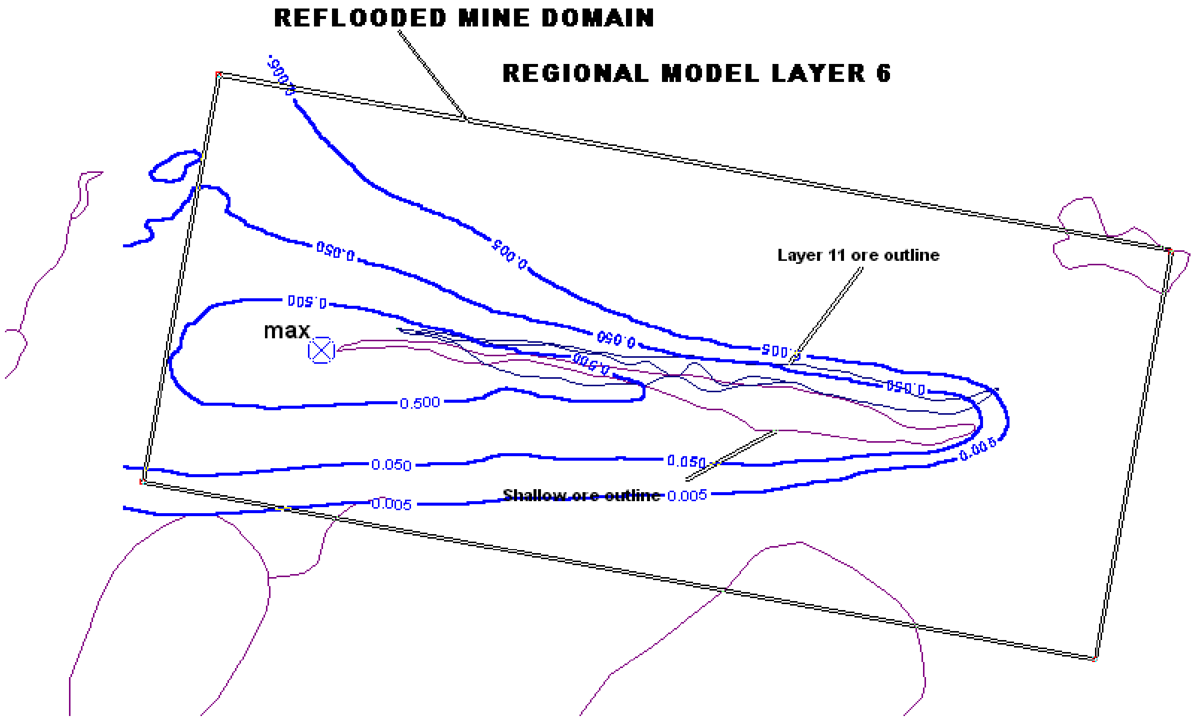


Figure 13. Pre-Mine Solute Concentrations in Shallow Bedrock: a) Reflooded Mine Model and b) Regional Model.

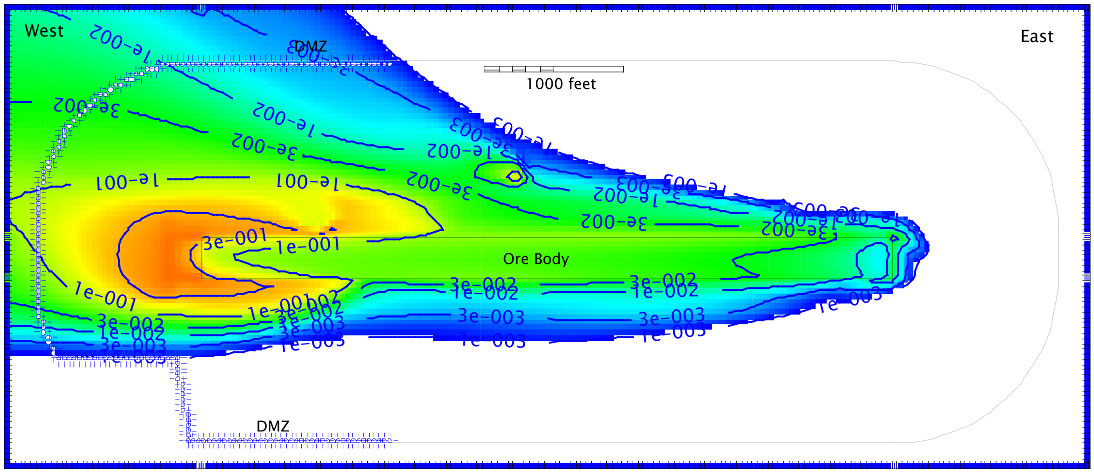


Figure 14. Final Model Results – Concentrations in Strongly-Weathered Bedrock at 10,000 years, High-End K Paste and Dispersivity, Open Mine Workings

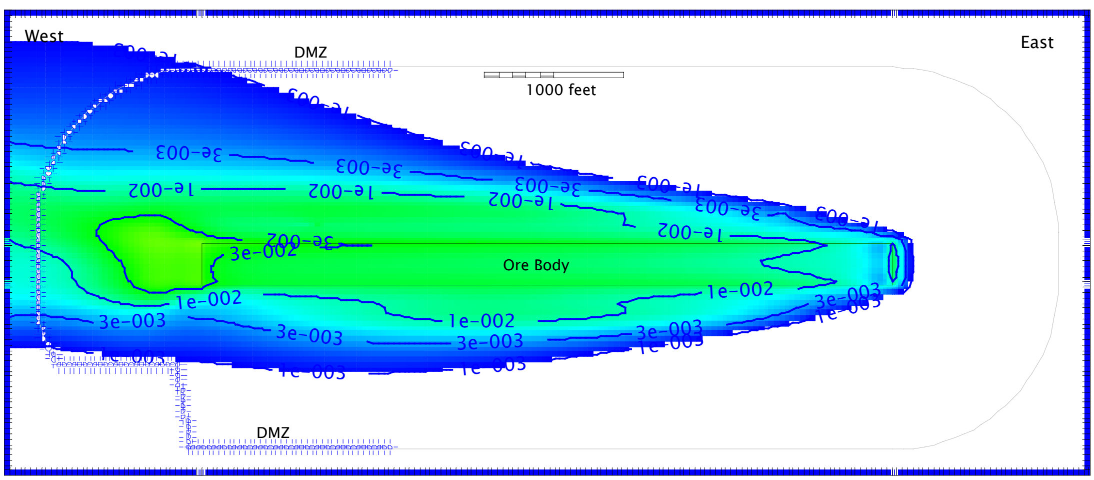


Figure 15. Final Model Results – Concentrations in Strongly-Weathered Bedrock at 10,000 years, High-End K Paste and Dispersivity, Closed Mine Workings

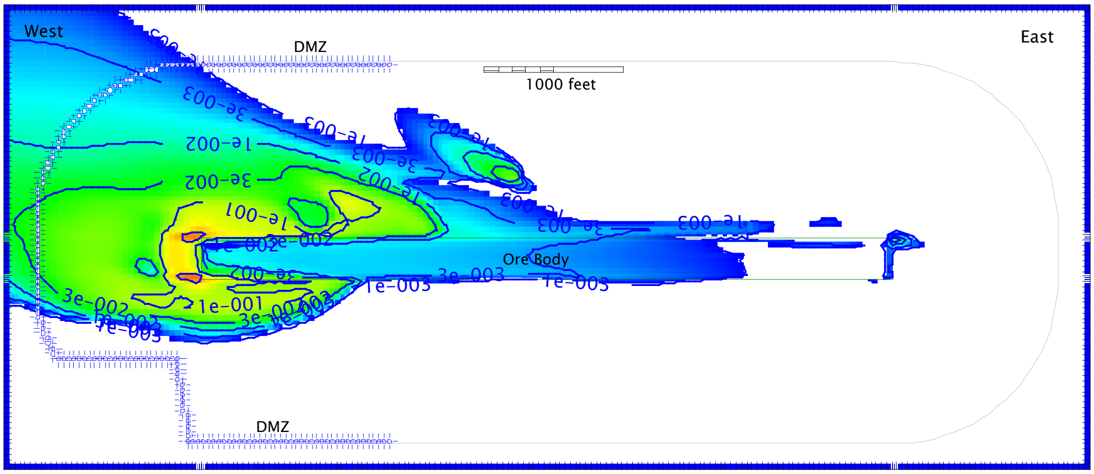


Figure 16. Final Model Results – Concentrations in Strongly-Weathered Bedrock at 10,000 years, Low-End K Paste and Dispersivity, Open Mine Workings

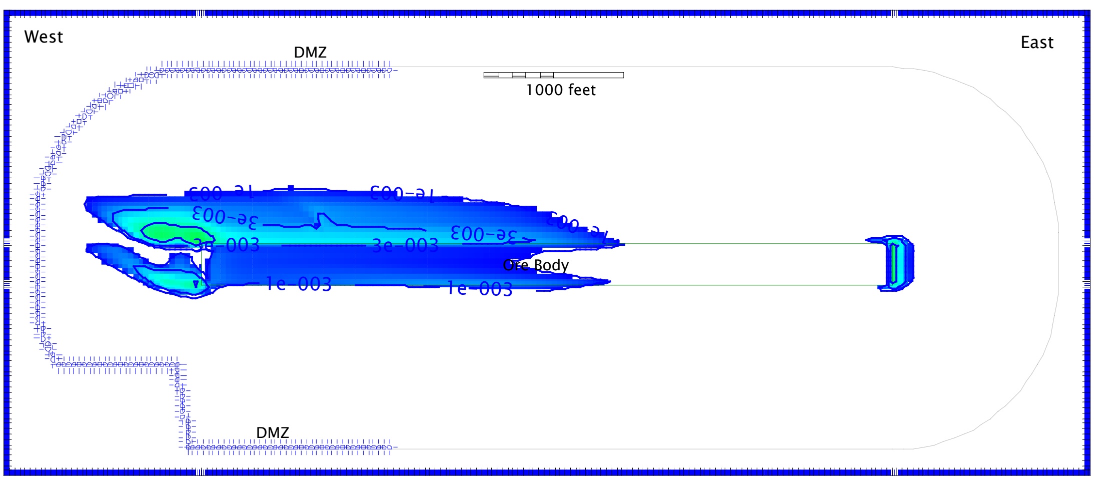


Figure 17. Final Model Results – Concentrations in Strongly-Weathered Bedrock at 10,000 years, Low-End K Paste and Dispersivity, Closed Mine Workings

Appendix A. Memorandum

To: Chris Carlson WDNR, Galen Kenoyer RMT
From: Daniel Feinstein USGS
Date: 15 September 2003
Subject: Crandon: Regional MODFLOW MT3D Transport Model for Reflooded Mine Analysis

Introduction

This memo documents the adaptation of the Crandon regional flow model as a transport model for the reflooded mine problem. The ultimate purpose of this work is to compare results of this regional reflooded mine to the inset reflooded mine model that has been used for a series of exploratory and sensitivity simulations by consultants for the mining company and by consultants for the WDNR. The inset transport model adds much finer resolution to the area of concern and, therefore, is appropriate for targeted study of the consequences of reflooding the proposed Crandon mine. However, because it is an inset model, it does not exactly duplicate the flow field from the regional model that is, for the purposes of the WDNR project review, the base representation of groundwater flow in the project area. Therefore, the WDNR requested a comparison of the transport results for a coarse-gridded regional model that preserves the standard flow field with the transport results from the fine-gridded inset model to determine if the inset model is an appropriate tool. These issues are discussed in greater detail in the reports that present the WDNR version of the inset model.

It is important to emphasize that the comparison between the regional and inset model can only be performed for an artificial scenario that uses the original ore body as the contaminant source but simulates the pre-mine condition in terms of the flow field. The regional model does not support the resolution to include the particular features of the mine (e.g., the exact configuration of drifts) that will influence the spread of the paste contaminants upon reflooding after mining operations cease. Therefore, the inset model was modified to eliminate these features so that the comparison could be carried out.

Descriptions of changes to the inset model and the further step of comparing the inset and regional results are presented in the body of the WDNR reports on the reflooded mine problem. This memo is limited to an account of the construction and application of the regional flow model to transport (herein referred to as the "regional transport model"). It has three parts:

- Explanation of changes to the regional MODFLOW model needed to support a transport simulation;
- Explanation of construction of the MT3D regional transport model;
- Presentation of the results of the MT3D regional transport model;

Modification of regional MODFLOW model

There are two versions of the regional flow model: High End and Low End. Therefore, there are also two versions of the transport model linked to the flow model. The *high-end* version of the transport model is linked to the flow simulation UC-78, the base high-end, pre-mine, steady-state simulation of regional flow. The *low-end* version of the transport model is linked to the flow simulation UC-8, the base low-end, pre-mine, steady-state simulation of regional flow. These base simulations are discussed in detail in J.T. Krohelski [editor], 2005, Evaluation of Groundwater Flow Models Used to Simulate the Effects of Proposed Mining on the Ground-water–Surface Water System in the Vicinity of Crandon, Forest County, Wisconsin, Wisconsin Geological and Natural History Survey Open-File Report 2004-26.

In order to link to the MT3D transport code, both UC-78 and UC-8 required modification. MT3D does not support either the STREAM or LAKE packages in MODFLOW. However, from the standpoint of the transport, there is no loss in converting these elements into the RIVER package, which MT3D does support. The reason is that MT3D only requires the velocity flow field and discharge boundaries from MODFLOW. It is possible to convert the STREAM and LAKE packages to the RIVER package without changing the velocity field while preserving the discharge boundaries needed to properly simulate the fate of contaminants. The conversion consists of transferring the location, stage and conductance information from one MODFLOW package to another. In all cases the model layer occupied by the surface-water element, an output of the original model runs, were explicitly included as an input of the modified runs. Surface-water elements not in connection with groundwater according to the base runs were eliminated from the modified runs. The name of the modified runs was UC-78MLS and UC-8MLS.

In order to insure that the modified UC-78 and UC-8 runs produced the same head, flux and velocity output as the original runs, two changes were made to the input:

1) the starting head matrices in UC-78MLS and UC-8MLS corresponded to the output from UC-78 and UC-8, respectively.
2) the SIP solver routine consisted of one time step with the acceleration parameter set to 0.001.

Even though the modified models are substantively equivalent to the original models, whenever numerical methods are applied to the finite-difference equations some changes in the solution occur. The low acceleration parameter applied to the solver ensured that the new solutions deviated negligibly from the old. Examination of the mass-balance terms as well as head output demonstrated the equivalence of the original and modified output for both the *high-end* and *low-end* versions. The flux file outputs from the modified runs were then input to the MT3D transport runs.

<u>Construction of the regional MT3D transport model</u>

The purpose of constructing a regional transport model was to compare it to the inset transport model. In order to have a comparable flow field, it is important to make the other aspects of the regional transport model as similar to the inset transport model as possible. With respect to the choice of parameter values, the regional and inset runs used in the comparison shared the following inputs:

<u>Dispersivity</u>	**Longitudinal** *(ft)*	**Transverse Horizontal** *(ft)*	**Transverse Vertical** *(ft)*	**Diffusion** *(ft^2/day)*
Unconsolidated Material (regional model layers 1-4)	50	5	0.5	1.6×10^{-4}
Bedrock (regional model layers 5-13)	50	5	5	1.6×10^{-4}

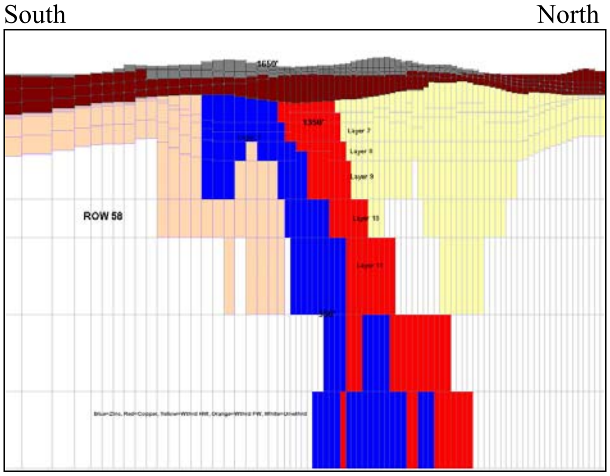
Porosity	Non-ore	Ore
Unconsolidated Material (regional model layers 1-4)	0.1	n/a
Strongly-Weathered Bedrock (regional model layer 5)	0.05	0.1
Moderately-Weathered Bedrock (regional model layer 6)	0.01	0.1
Weakly-Weathered Bedrock (regional model layers 7-13	0.003	0.1

Both the regional and inset model runs used in the comparison applied the "implicit upstream finite-difference" solver option in MT3DMS. The maximum transport time step was 10 days.

The inset model grid is rotated with respect to the regional model. Moreover, the source term in the inset model is a parallelepiped block (5025' x 300' x 1137.5' = 17.15×10^8 ft^3) that approximates the volume of the ore body backfilled with paste, while the ore body in the regional model has a more complicated configuration that changes with depth and is different for the *high-end* and *low-end* versions of the model. The following figures show the ore body configuration for the two versions of the regional model along an east-west cross section:

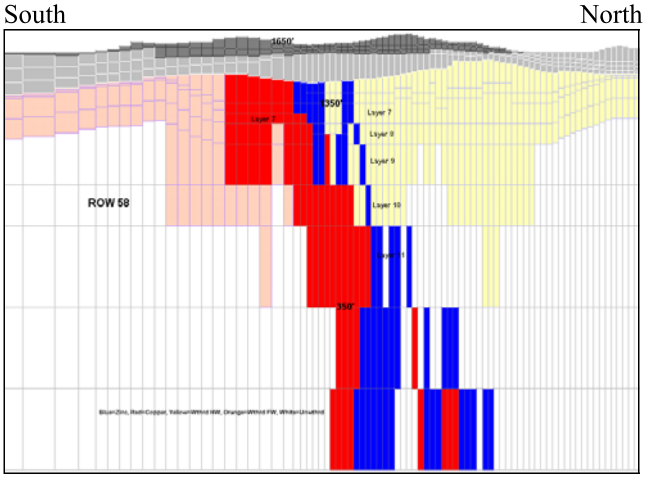
High End (blue=copper, red=zinc, yellow=hanging wall, orange=footwall, white=unweathered):

South North



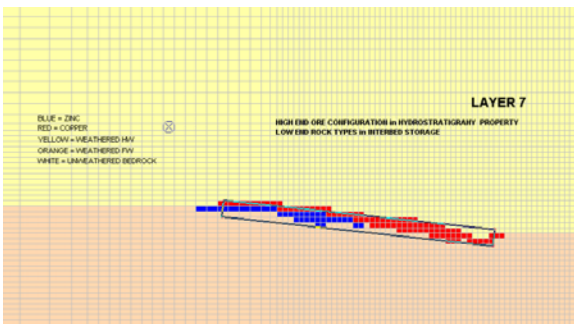
Low End (blue=copper, red=zinc, yellow=hanging wall, orange=footwall, white=unweathered):

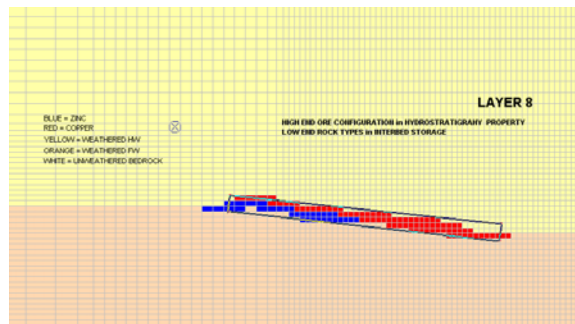
South North

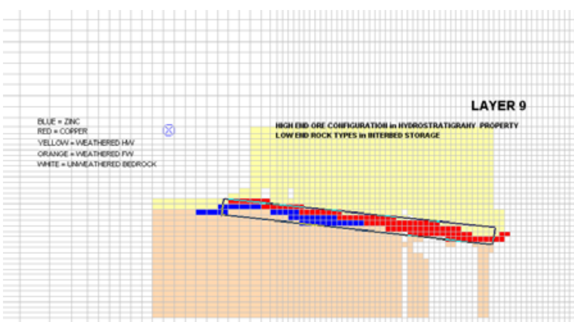


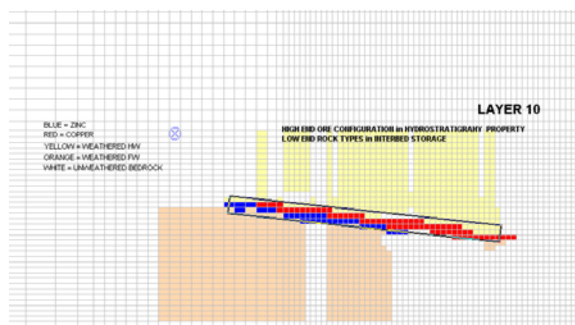
To facilitate the comparison, the paste-backfill source area in the regional model was not identified directly with the ore body, but instead was assumed to be a parallelogram in each layer of the regional model, with the parallelograms offset with depth to account for the dip of the ore body. The following series of plan-view figures show the relation between the ore body and source parallelepipeds by layer for the *high-end* and *low-end* versions of the regional model. The parallelepipeds superimposed on the ore body all have areas equal to 5025’ x 300’, but their thicknesses vary as a function of layer thickness. They are rotated 6 degrees clockwise relative to the eastern direction of the model grid. Note that the top of the source body is layer 7, corresponding to the top of the ore body, but the bottom of the source body does not correspond to the bottom of the ore body (layer 13), but rather corresponds to the bottom of the inset model (layer 11).[1]

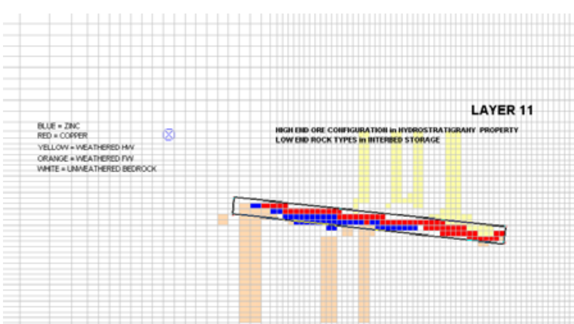
High End (blue=copper, red=zinc, yellow=hanging wall, orange=footwall, white=unweathered):





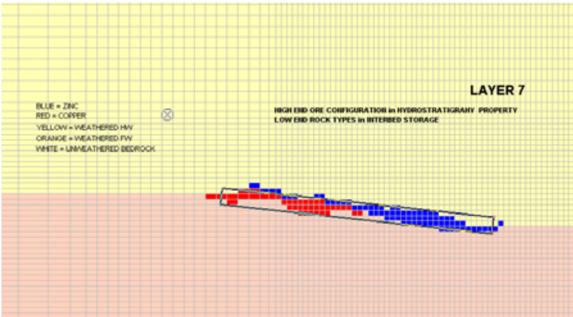


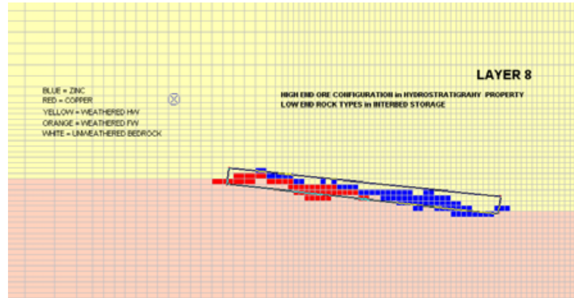


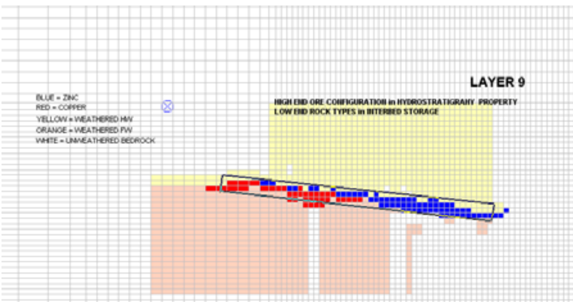


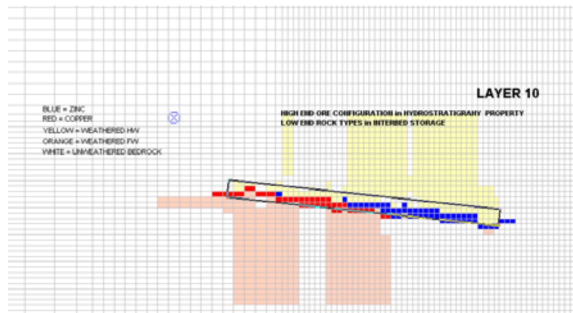
[1] The bottom of the inset model falls between the top and bottom of layer 11 in the regional model. For this reason, mass calculations presented later in this memo only take account of part of the contribution of layer 11 in the regional model.

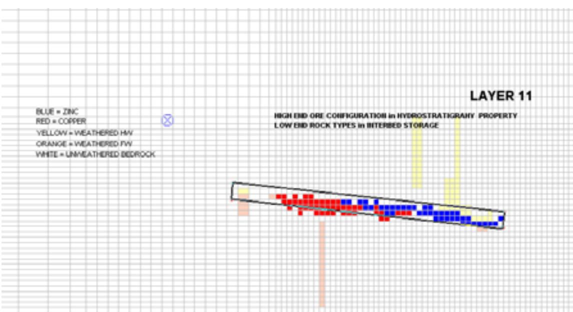
Low End (blue=copper, red=zinc, yellow=hanging wall, orange=footwall, white=unweathered):











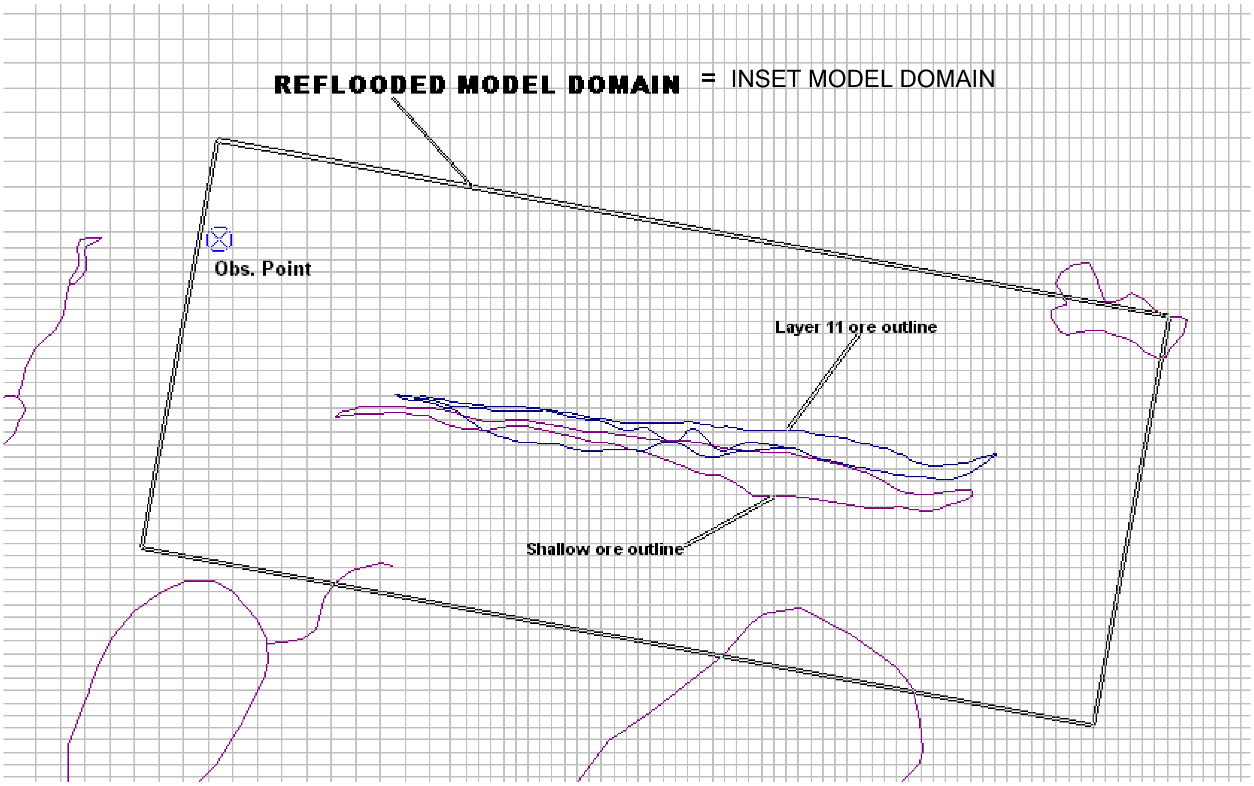
The stacked set of parallelepipeds is the same for the *high-end* and *low-end* regional model versions and, when summed together, are virtually equal to the 17.15×10^8 ft^3 volume in the inset model. It is interesting to compare this volume with the volume of actual ore body (subject to filling by paste) in the two versions of the regional model:

	High-end	*Low-end*
Zinc	13.0 x10^8	9.6 x10^8
Copper	6.6 x10^8	6.5 x10^8
TOTAL	19.6 x10^8	16.1 x10^8

In both the inset and regional models, no distinction is made between the zinc and copper portions of the source body. Instead the entire source block (a single 1137.5 ft thick parallelepiped in the inset model, a series of parallelepipeds of varying thickness offset by layer in the regional model) is assigned a single relative concentration equal to 1.0.

Results of regional MT3D transport model

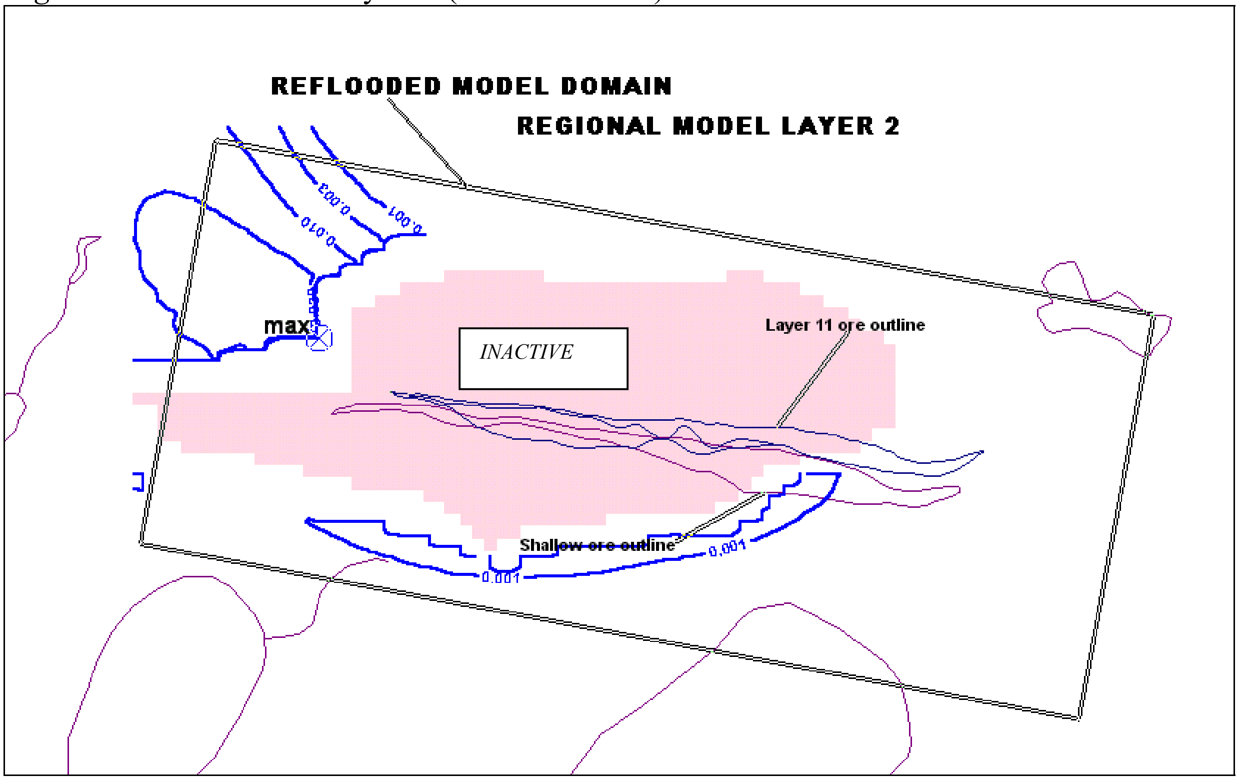
The MT3D transport calculations were restricted in the regional model to an area that closely approximates the full extent of the inset model:

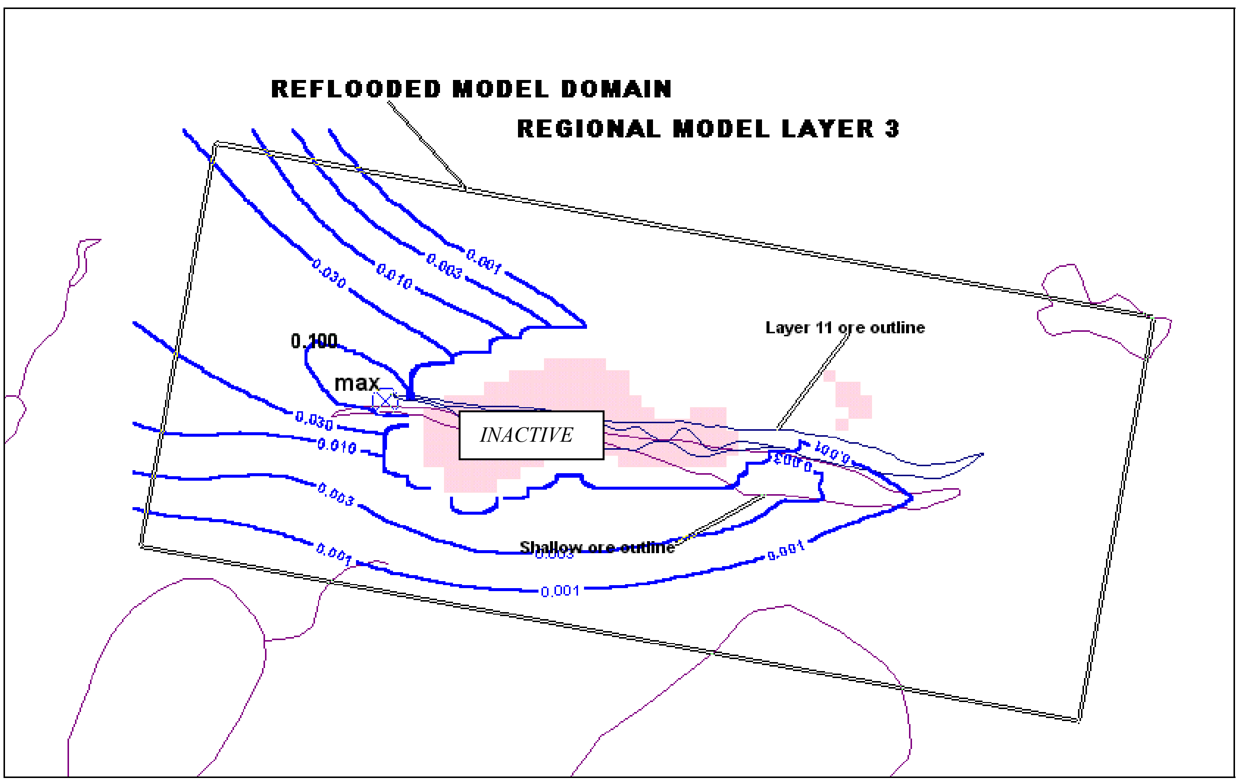


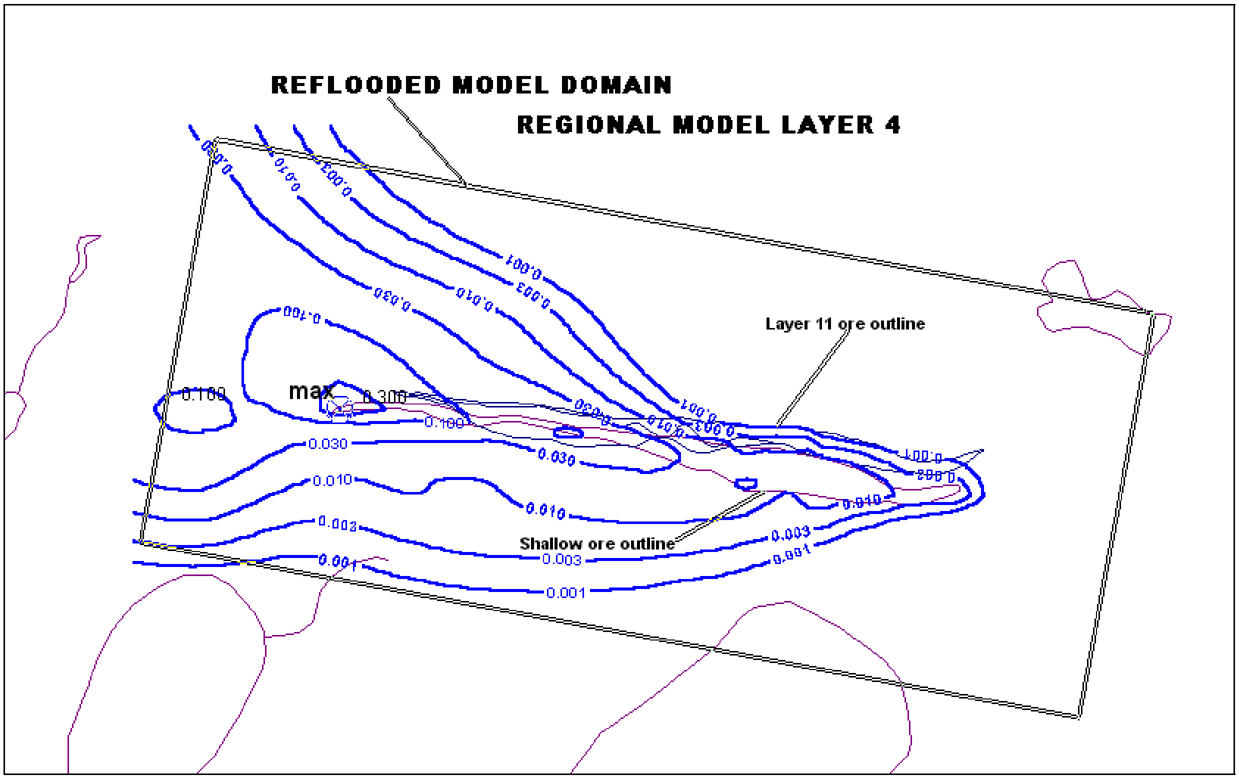
The outlines of the shallow ore body and the deep ore body (corresponding to layer 11 in the regional model) are shown for reference.

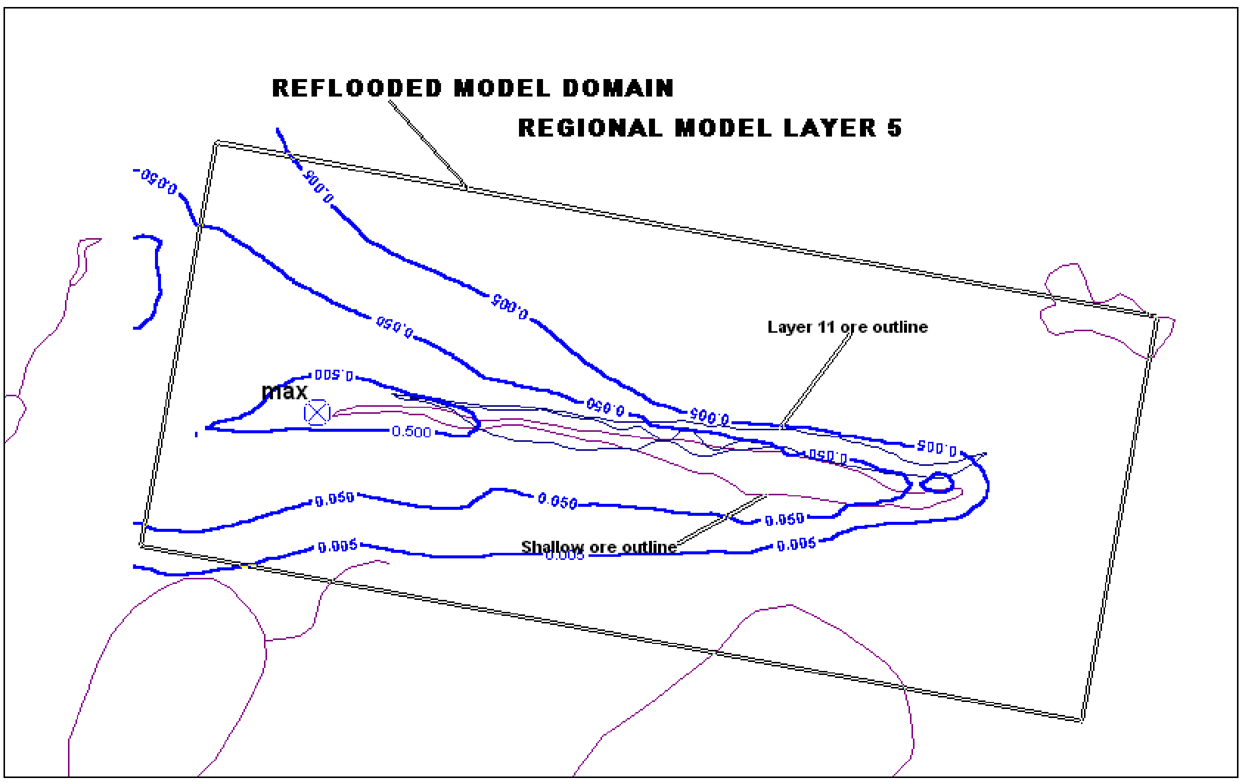
The following set of figures show the relative concentration results by regional model layer after 200 years of transport simulation. The contours represent the spread of contamination from the ore body assumed to have a relative concentration of 1.0 throughout the source body in layers 7 through 11. The contour interval is logarithmic. Recall that layers 2 through 4 represent the unconsolidated material (layer 1 is largely inactive over the transport domain in the regional model) layers 5 and 6 represent the strongly- and moderately-weathered bedrock plus ore body and the deeper layers represent the weakly-weathered bedrock plus ore body. The node with the maximum concentration in a layer (outside the source body, if present) is noted in each plot. Pink zones represent inactive areas where unconsolidated material in a layer is largely absent. Yellow zones represent the source body in regional model layers 7 through 11.

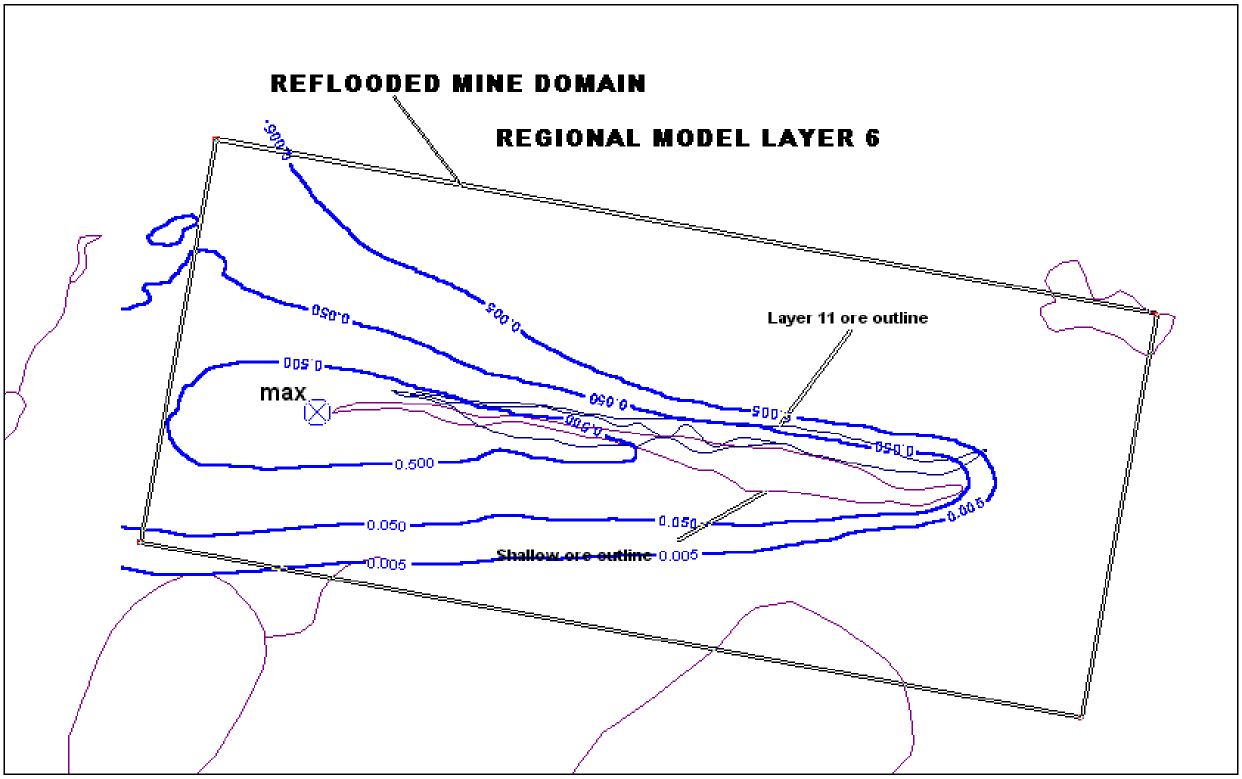
High-End Results after 200 years (run MT3D5-78):

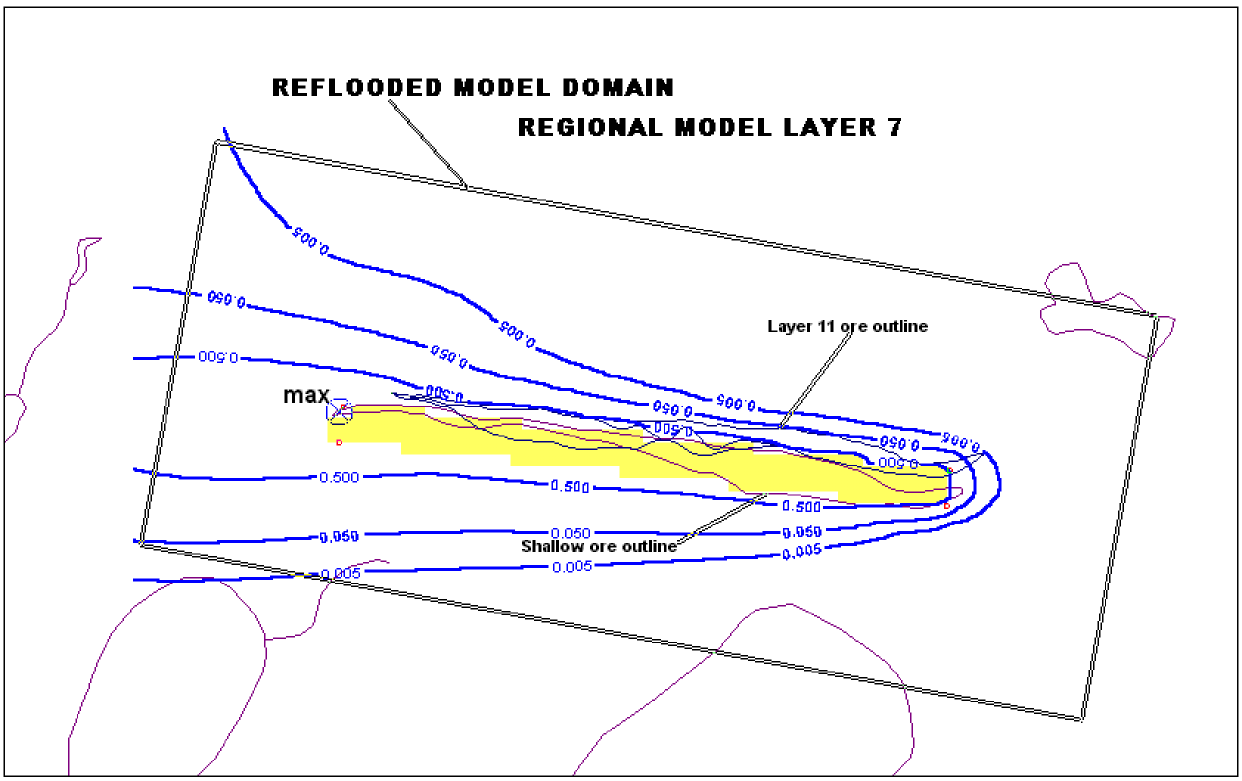


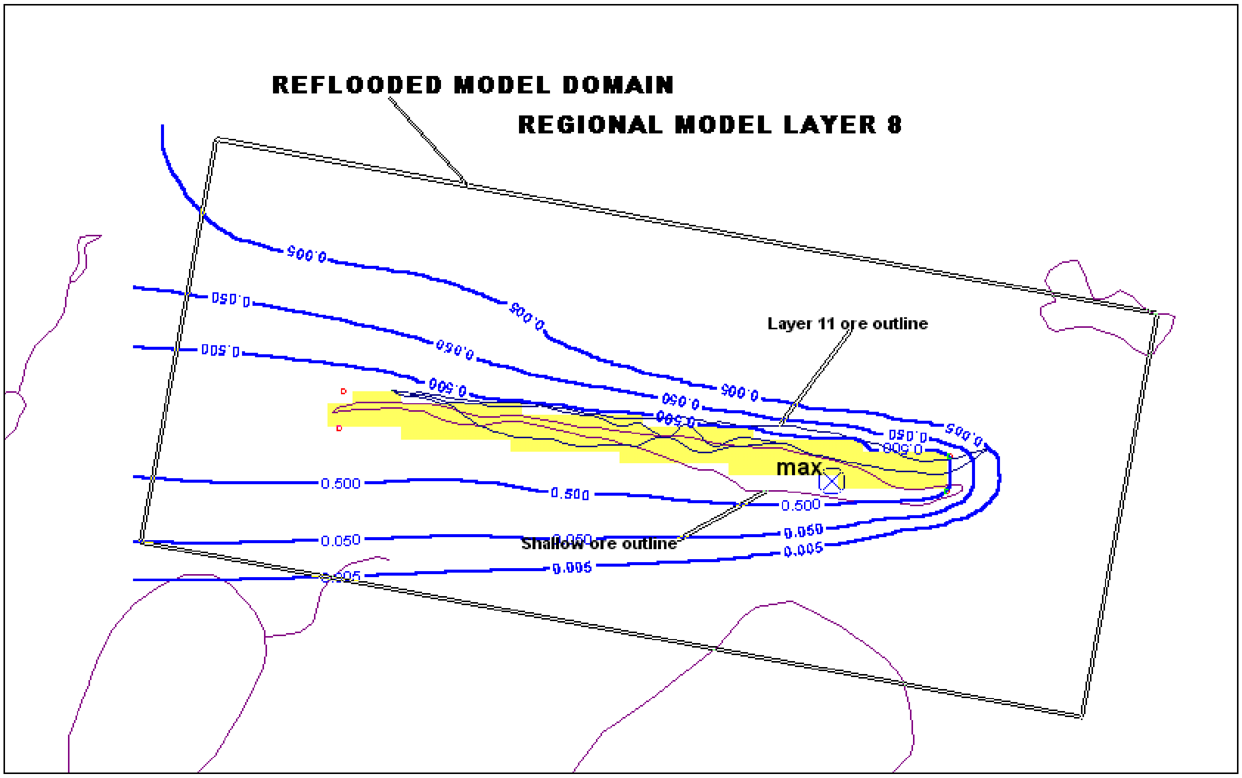


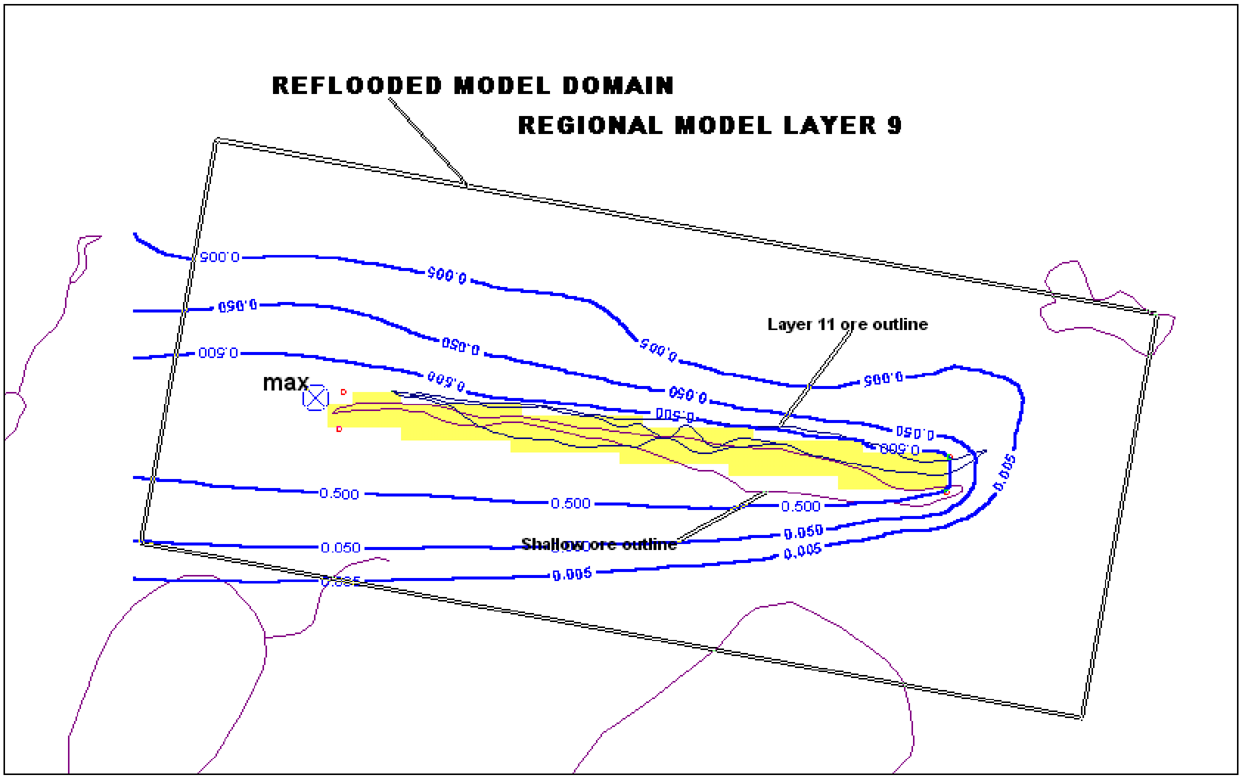

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 4
Layer 11 ore outline
max
0.100
0.300
0.030
0.010
0.003
0.001
Shallow ore outline

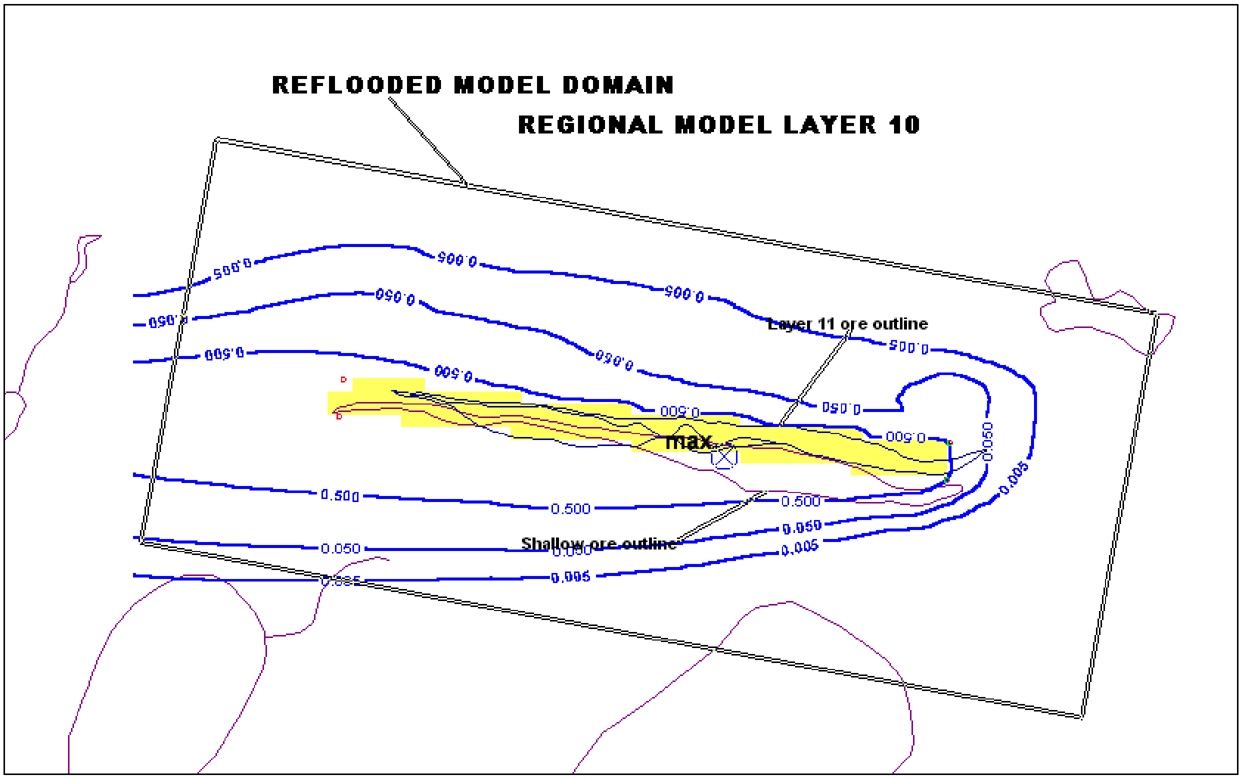

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 5
Layer 11 ore outline
max
0.500
0.050
0.005
Shallow ore outline

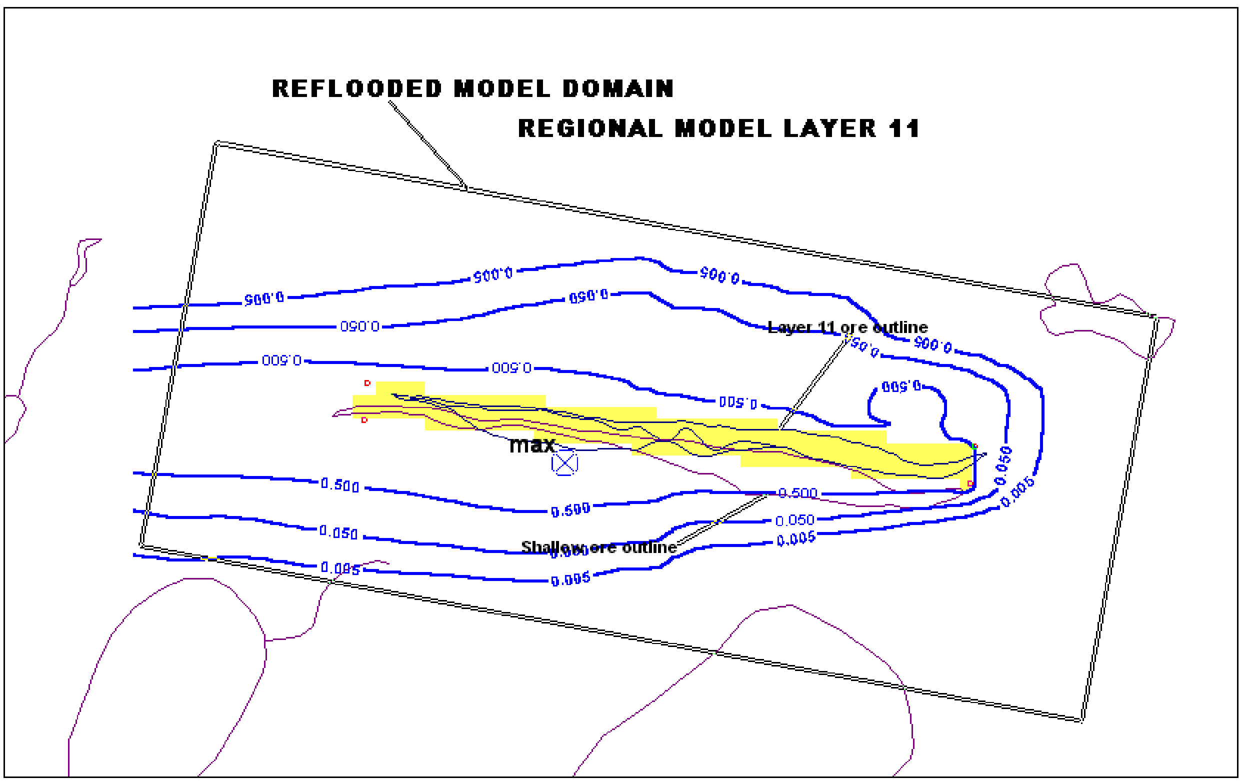

REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 6
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500


REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 7
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500

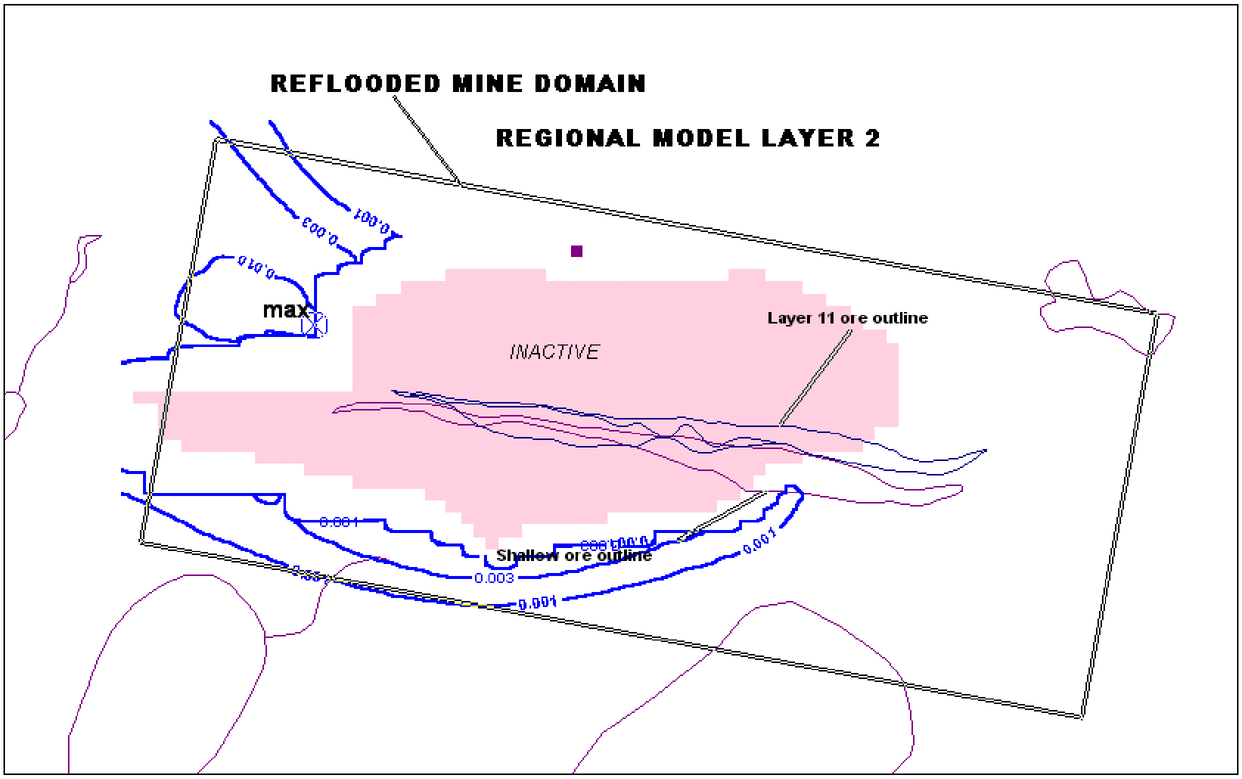

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 8
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500

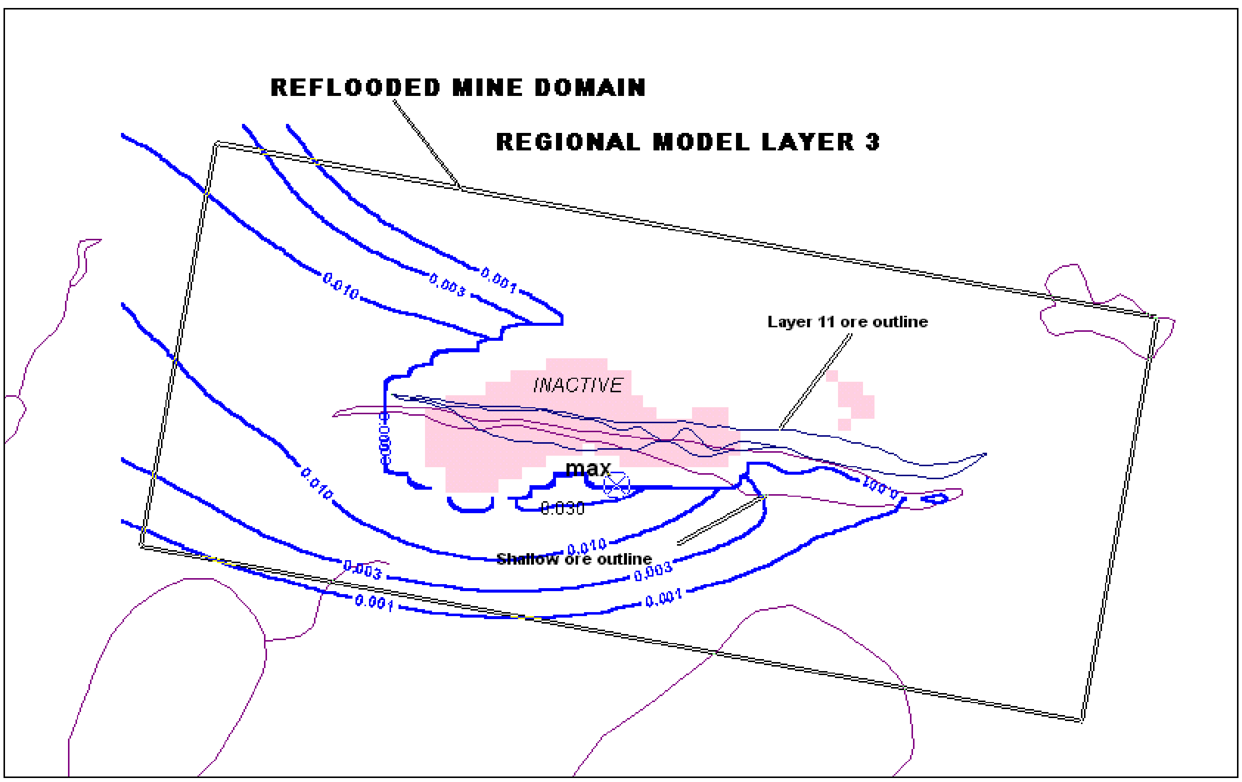

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 9
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500

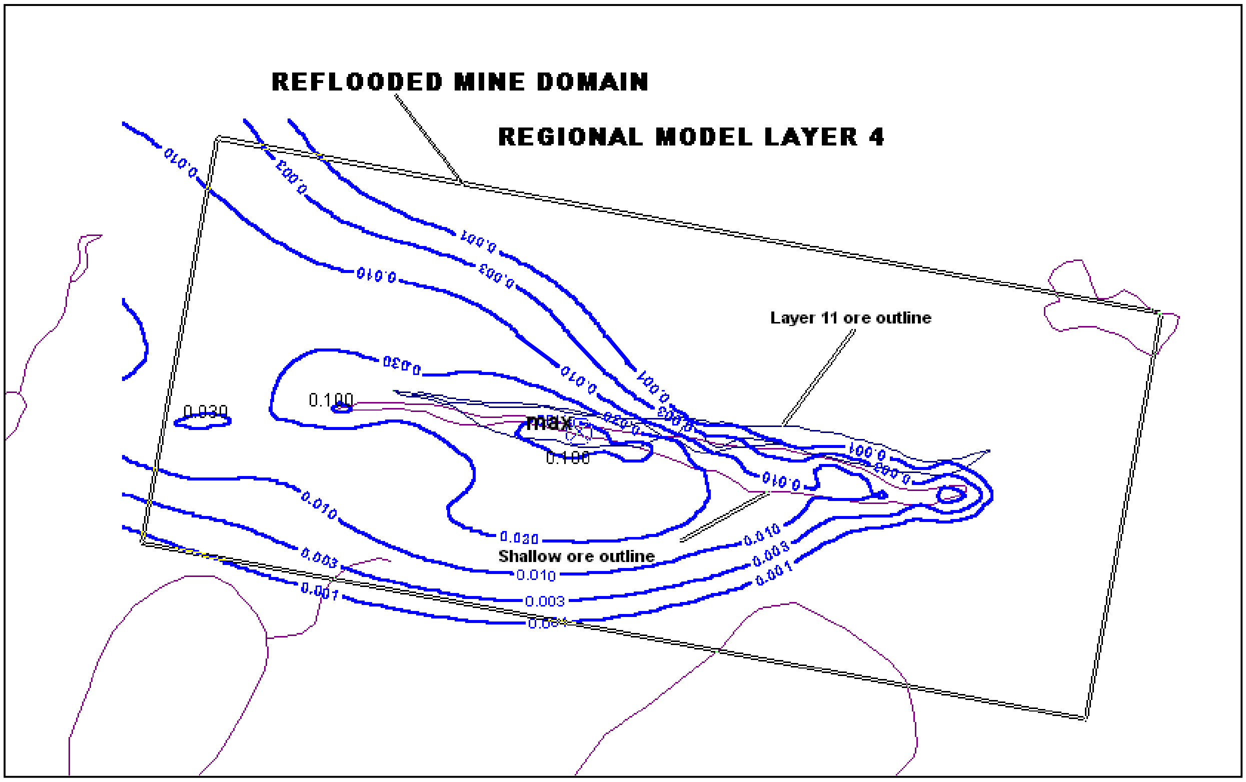

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 10
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500

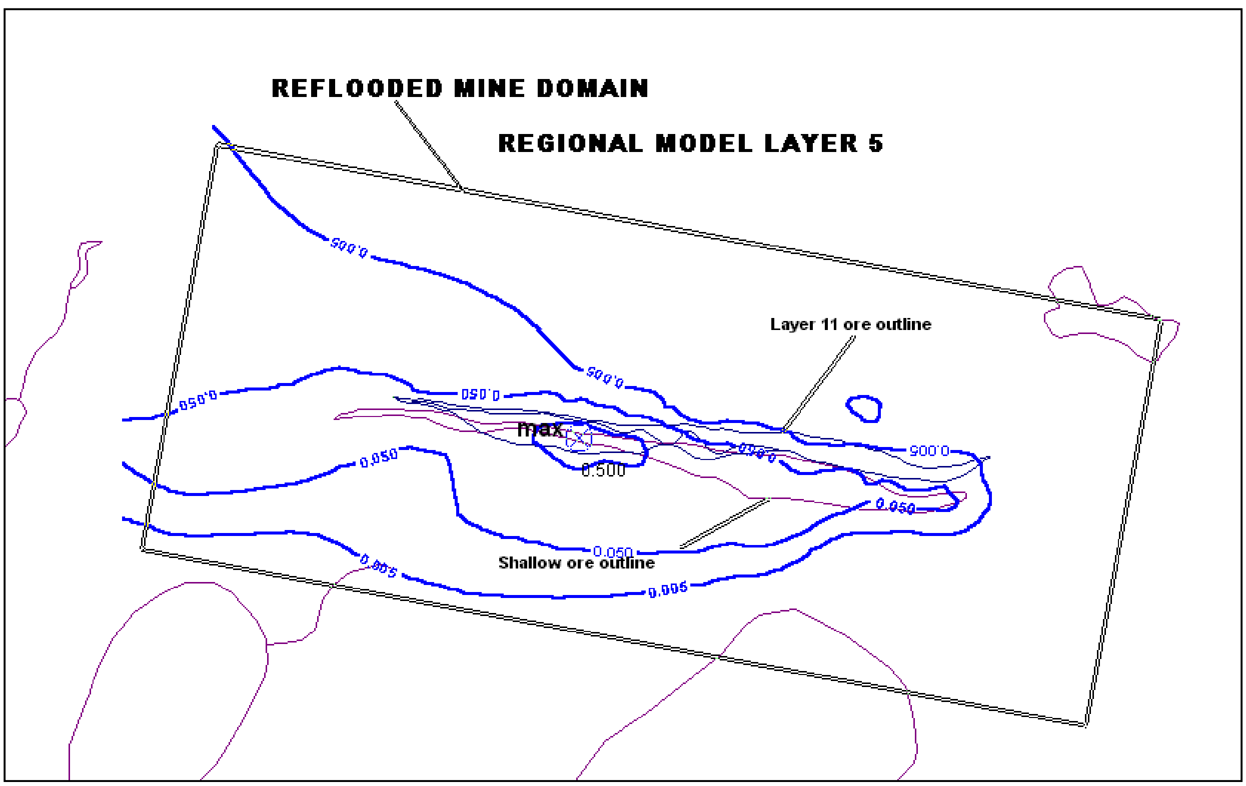

REFLOODED MODEL DOMAIN
REGIONAL MODEL LAYER 11
Layer 11 ore outline
max
Shallow ore outline
0.005
0.050
0.500

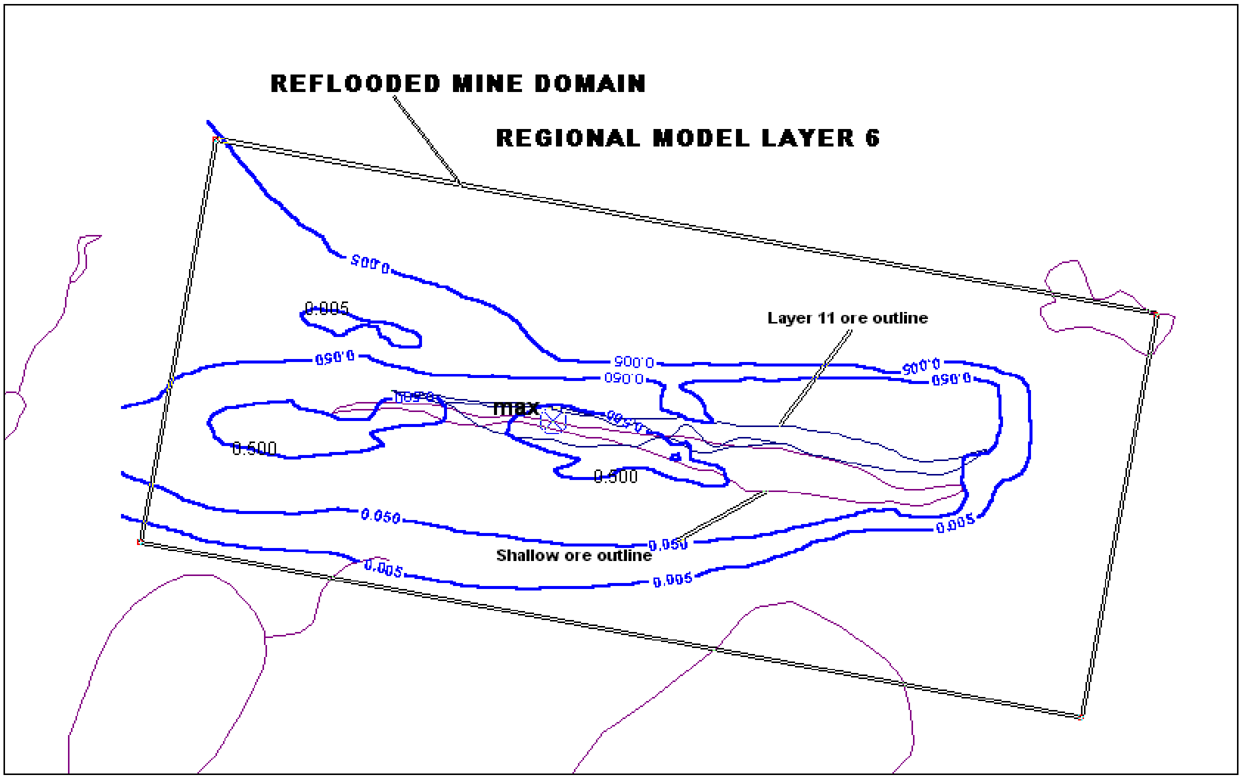
Low-End Results after 200 years (run MT3D5-8):

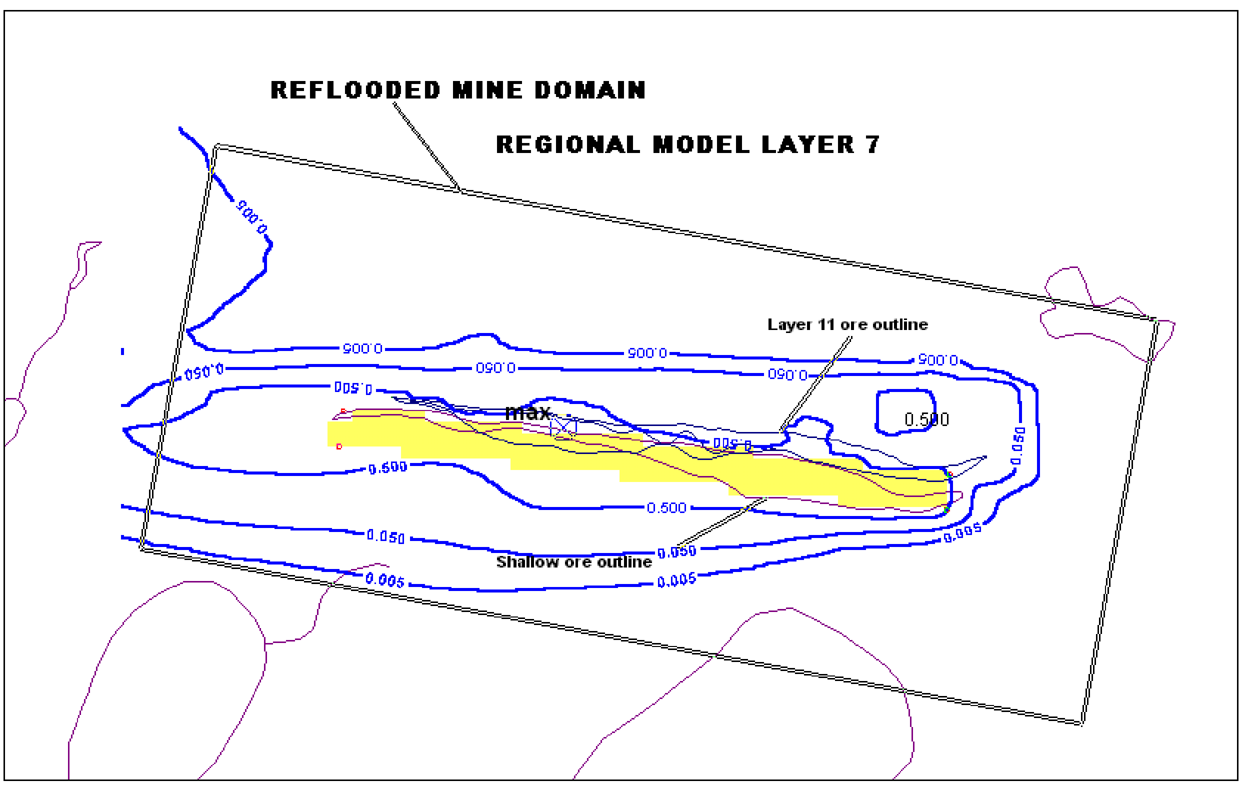


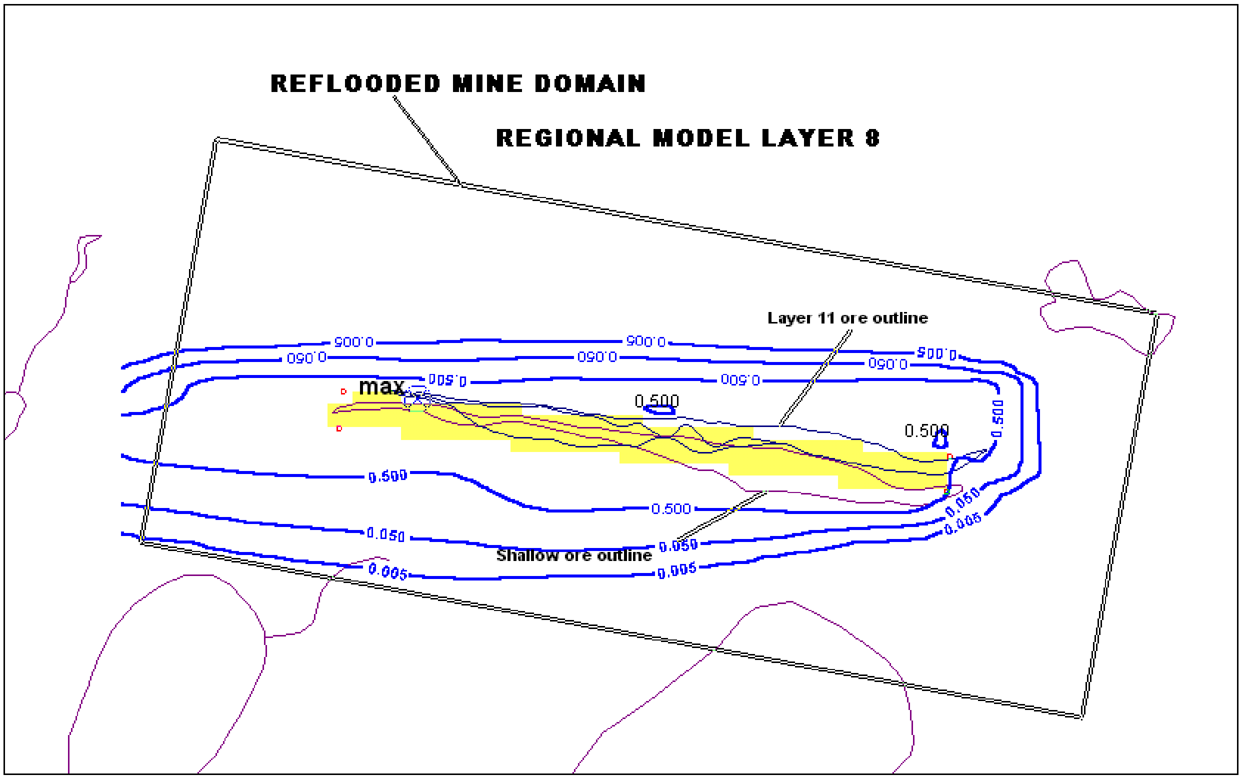


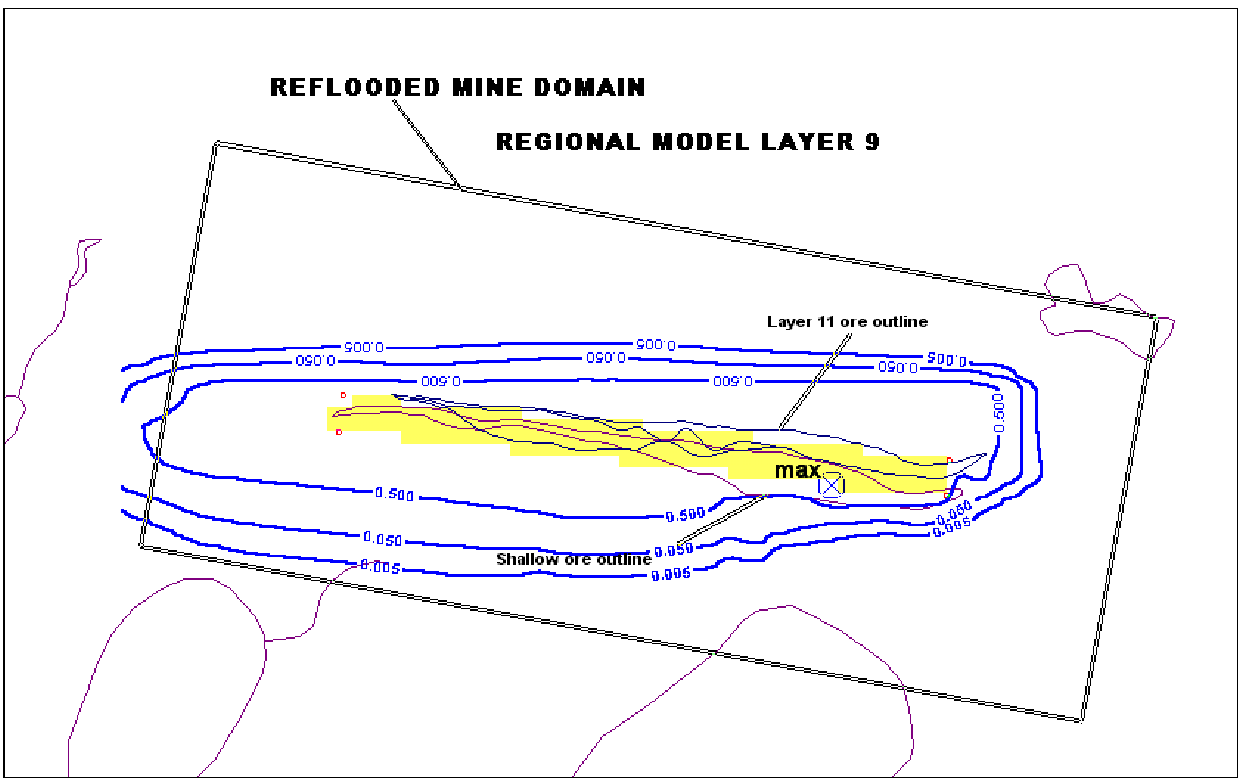

REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 4
Layer 11 ore outline
Shallow ore outline
max
0.010
0.003
0.001
0.030
0.100
0.010
0.003
0.001

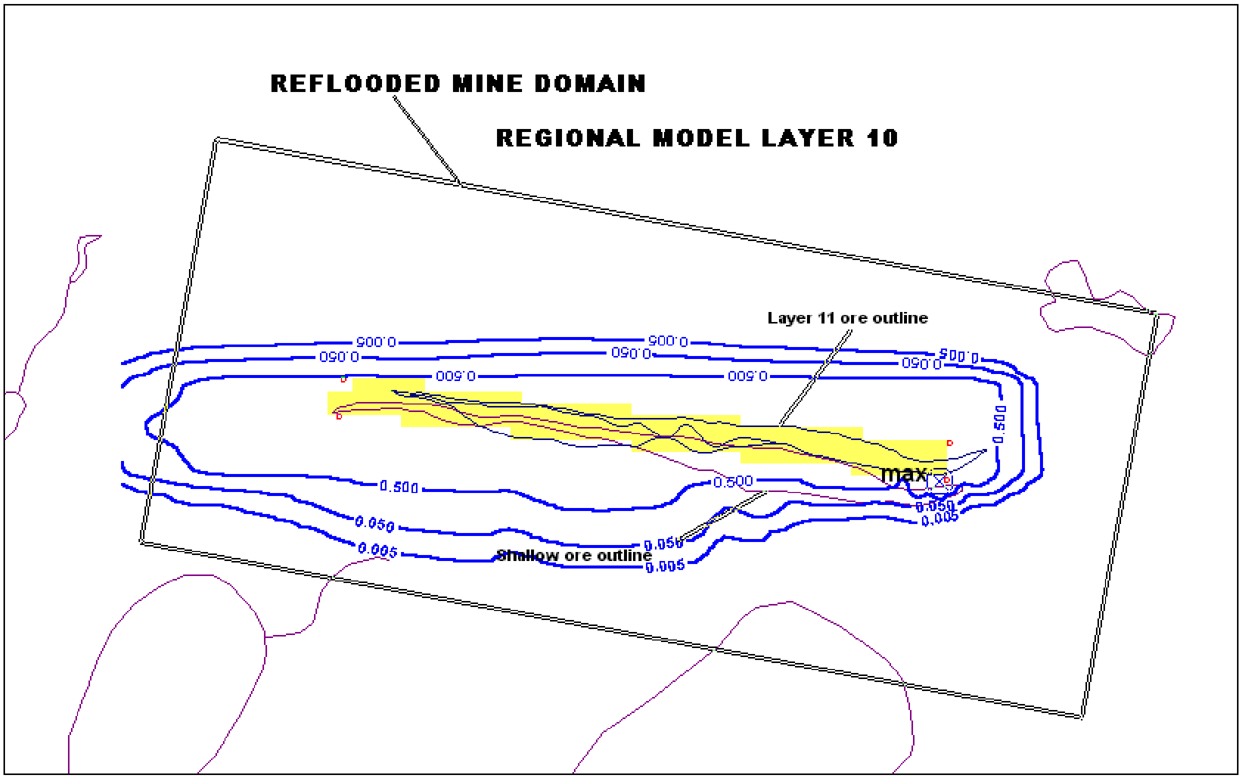

REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 5
Layer 11 ore outline
Shallow ore outline
max
0.500
0.050
0.005

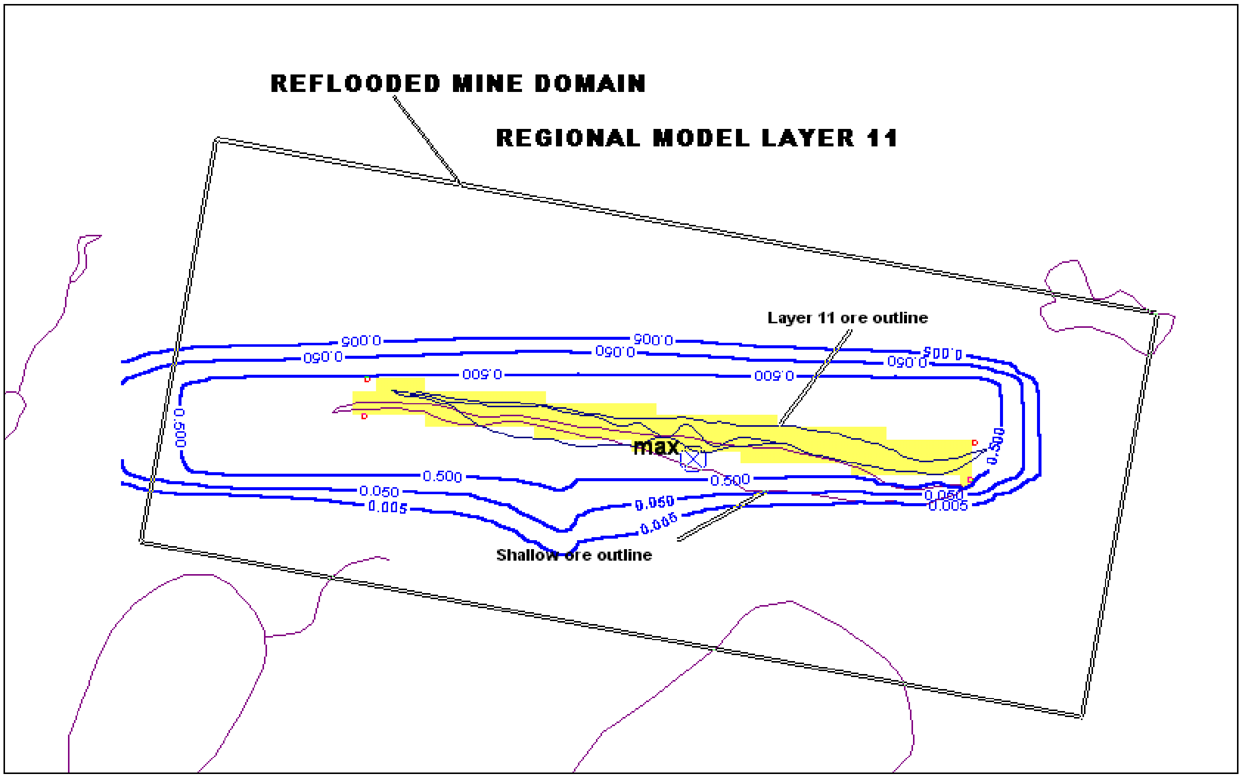

REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 6
0.005
Layer 11 ore outline
0.050
0.500
max
0.500
0.050
0.005
Shallow ore outline


REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 7
0.005
Layer 11 ore outline
0.050
0.500
max
0.500
0.050
0.005
Shallow ore outline


REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 8
Layer 11 ore outline
max
0.500
0.005
0.050
Shallow ore outline


REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 9
Layer 11 ore outline
max
0.500
0.050
0.005
Shallow ore outline


REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 10
Layer 11 ore outline
0.005
0.050
0.500
max
Shallow ore outline


REFLOODED MINE DOMAIN
REGIONAL MODEL LAYER 11
Layer 11 ore outline
0.005
0.050
0.500
max
Shallow ore outline

Another way to evaluate the spatial output of the regional transport model is to tabulate the percent of mass in each layer after 200 years of transport. Recall that layers 1-4 are glacial material, layers 5 and 6 are strongly- and moderately-weathered bedrock respectively with no ore body source, layers 7 through 11 are weakly-weathered bedrock with the ore body source, and layers 12 and 13 are weakly-weathered bedrock assumed to be without an ore body source and outside the transport domain. The ore body parallelepipeds in the source layers 7 through 11 are assigned a relative concentration of 1.

High-End Results (MT3D5-78):

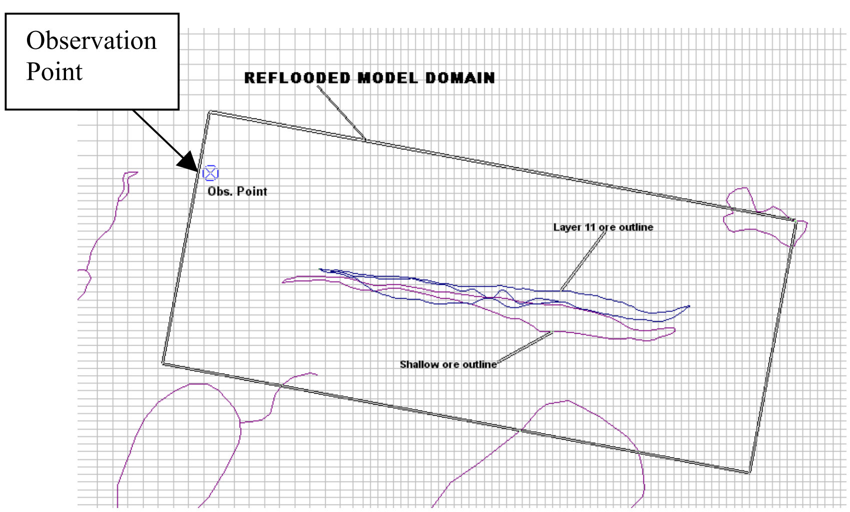
Layer	Percent Mass
1	0.000
2	0.041
3	0.390
4	2.097
5	5.427
6	2.687
7	9.642
8	9.397
9	20.876
10	19.742
11	29.700
12	0.000
13	0.000

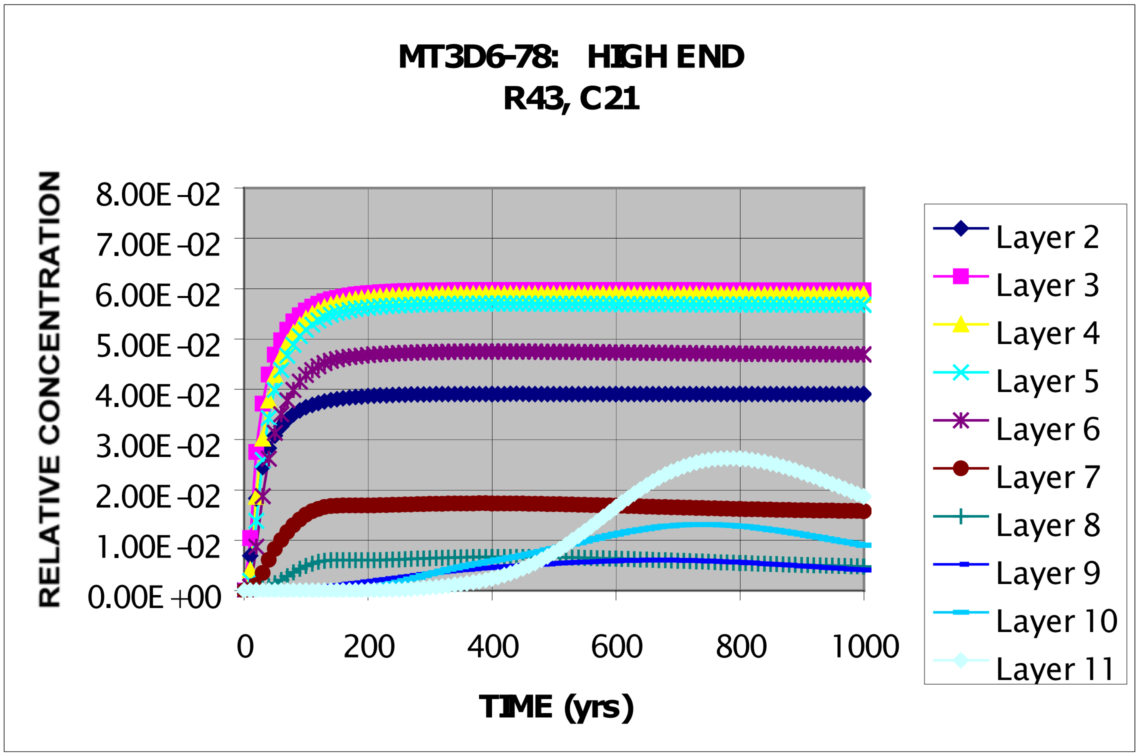
Low-End Results (MT3D5-8):

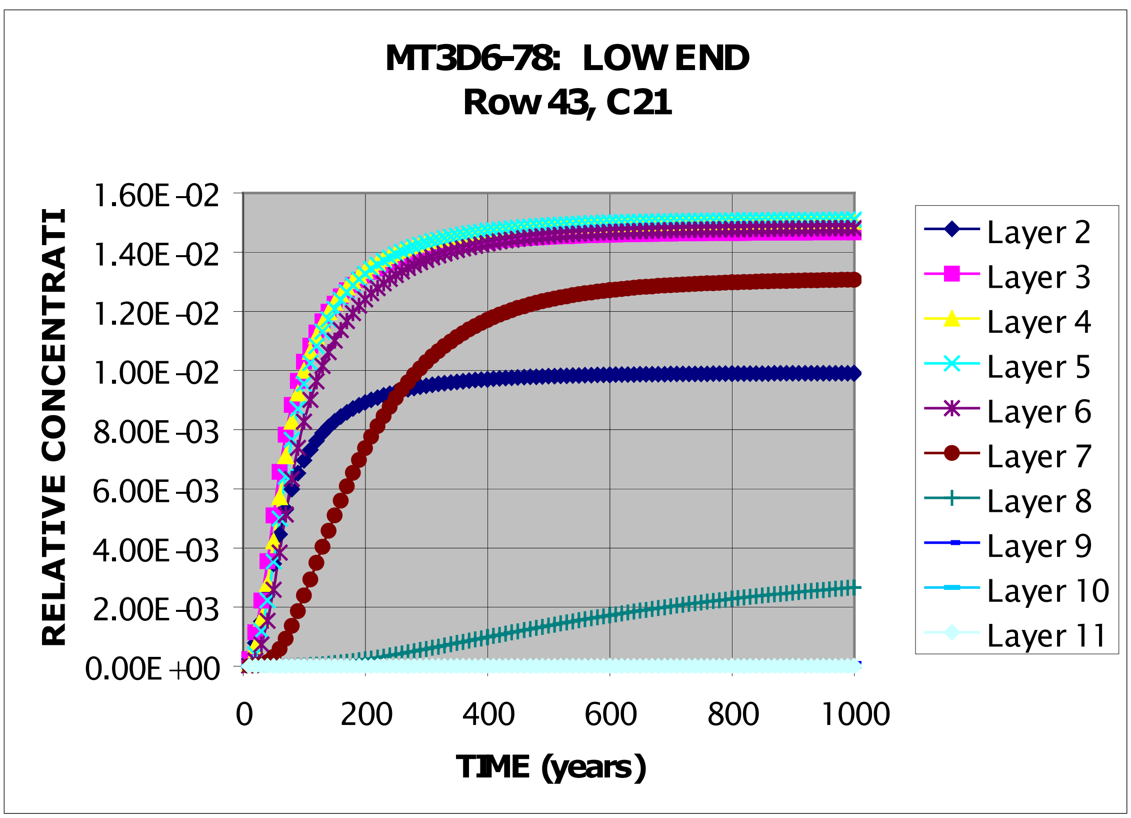
Layer	Percent Mass
1	0.000
2	0.014
3	0.173
4	1.665
5	3.428
6	2.432
7	10.020
8	9.854
9	21.860
10	20.446
11	30.110
12	0.000
13	0.000

These results illustrate the larger mass moved into the shallow layers (layers 2-5) in the *high-end* version. Note that the source layers have different percentages of mass in part because the thicknesses differ between the versions of the model.

In order to evaluate the transport results not only in terms of spatial distribution, but also in terms of changes through time, the regional transport simulations were extended from 200 years to 1000 years. We chose to compute breakthrough curves of relative concentration at a point at the downgradient (western) end of the transport domain, corresponding to row 43, column 21 of the regional model:




MT3D6-78: HIGH END
R43, C21
RELATIVE CONCENTRATION
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
200
400
600
800
1000
TIME (yrs)
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
Layer 8
Layer 9
Layer 10
Layer 11


MT3D6-78: LOW END
Row 43, C21
RELATIVE CONCENTRATI
1.60E-02
1.40E-02
1.20E-02
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
0
200
400
600
800
1000
TIME (years)
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
Layer 8
Layer 9
Layer 10
Layer 11

For the *high-end* run (given the assumed dispersivities and porosities), concentrations at the downgradient observation point reach a maximum constant concentration for most layers at around 120 years. For the *low-end* run, the asymptotic value is achieved much later because the ground-water velocities are lower in this version of the model.

Finally, the mass in the transport system at different times was calculated as another way to compare the *high-end* and *low-end* simulations. The bulk velocity through the system for the *high-end* case is roughly five times the velocity for the *low-end* case. Therefore, it is appropriate to compare the *high-end* mass results at **200 years** with the *low-end* results at **1000 years**. The sums show that:

- The total mass is very close (the *high end* is 1.01x the *low end*);
- The *high end* has more mass in layers 2-5, the *low end* more in layers 6-11;
- The *high end* mass in LAYER 2 is 2.76x the *low end*;
- The *high end* mass in LAYERS 3-5 is 1.36x the *low end*; and
- The *low end* mass in LAYERS 6-11 is 1.01x the *high end*.

Summary

It proved feasible to convert the regional model into a transport model. While its relatively coarse horizontal grid spacing (on the order of 100 ft in the area of the ore body) does not accommodate the fine details of the mine workings that are input to the inset model, it is possible to apply the regional transport model to the hypothetical case of an ore source across a block volume that approximates the ore body in the absence of the mine. To construct this transport model, the regional source was configured in such a way to approximate closely the source volume in the inset model. When the same source volume, same relative source concentration of 1.0, and the same transport parameters and solver parameters are used in both models, then the results should largely reflect the differences in the regional and inset flow fields simulated by MODFLOW and fed to MT3D. This memo presented results of the *high-end* and *low-end* regional simulations that allow comparison with the corresponding inset simulations.