INTRODUCTION

Proposed In-Situ Copper Mine Florence, AZ

Aquifer Protection Permit and Underground Injection Control Permit Application

Modeling Program

- Goal: To Simulate the Potential Effects of In-Situ Mining on the Regional Alluvial Aquifer

- Objectives: To Simulate the following
  - Regional Groundwater Flow Under Natural Conditions
  - Regional Groundwater Flow Under Extreme Conditions
  - Mine Facility Operations
  - Hydraulic Control of Mine Solutions Within the Facility Boundary
  - Mine Block Closure Rinsing
  - Mine Closure Operations
  - Post Closure Operations

Groundwater Flow Modeling

- Conceptual Model
- Code Selection
- Model Construction
- Model Calibration — site specific info inputs
- Model Sensitivity — understand what parameters need to be coupled with e.g. K

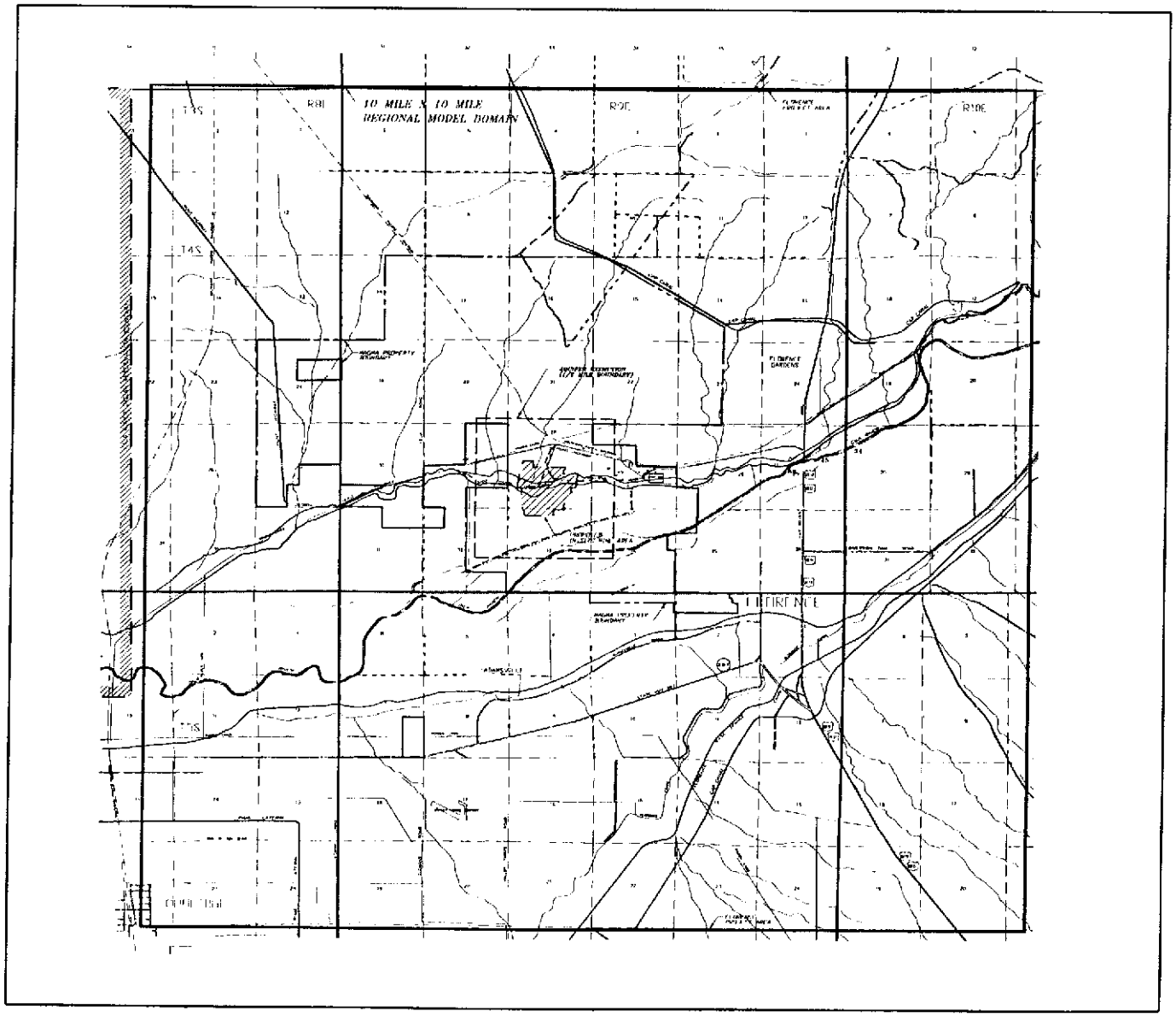
Conceptual Model

- Regional Geologic Environment
- Regional Groundwater Regime
- Local Geologic Setting
- Site Specific Groundwater Conditions

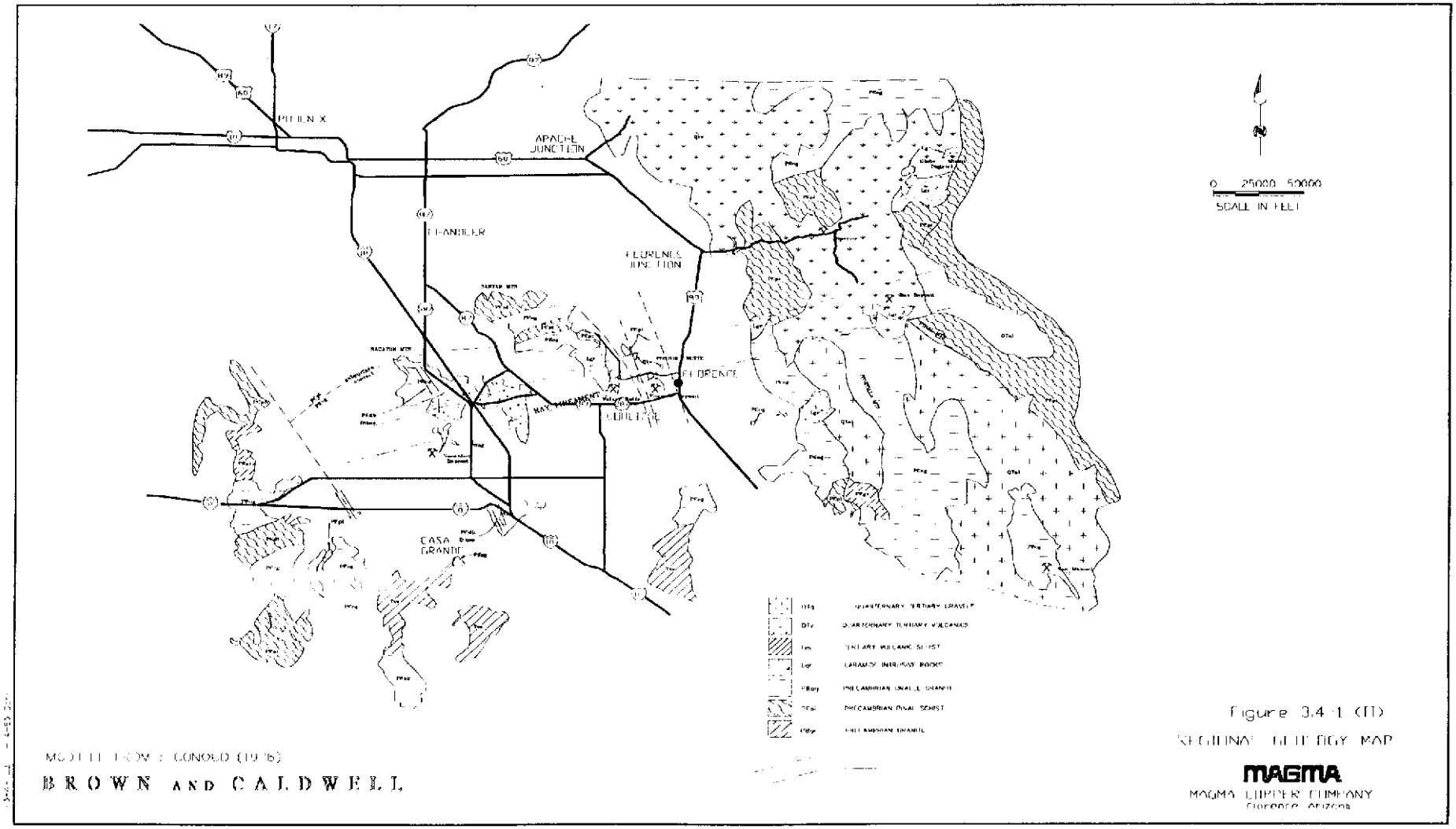
Regional Geologic Environment

- Physiography
- Surface Hydrology
- Structure
- Stratigraphy

Model Domain

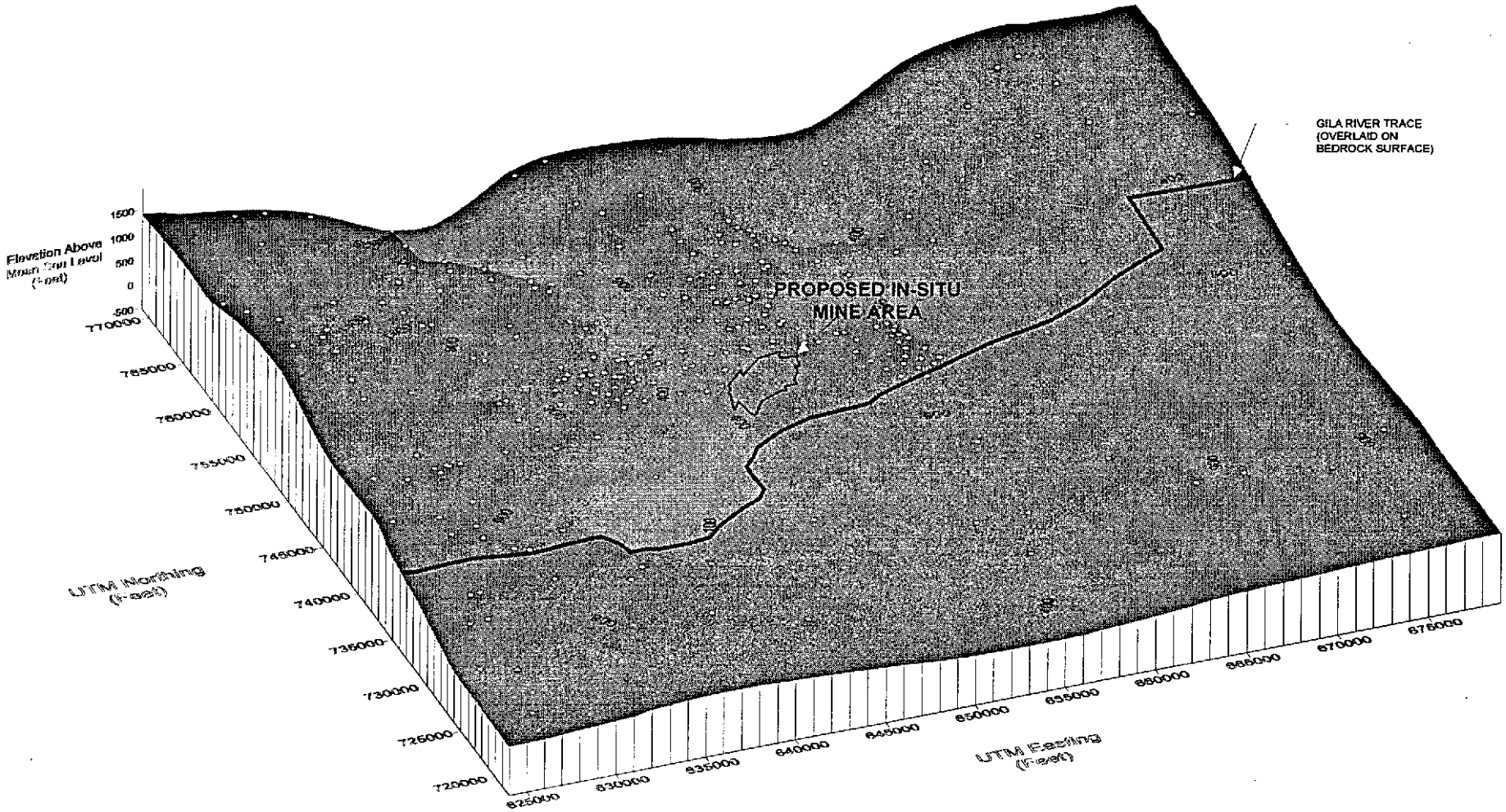


Regional Geologic Map



3 good layer

Top of Bedrock



Regional Groundwater Regime

- Sedimentary Aquifer
- Depth to Groundwater
- Flow Direction and Gradient
- Groundwater Use
- Recharge/Discharge Relationships

Local Geologic Setting

- Sedimentary Units
- Crystalline Rock
- Geometry
- Structure

Block Diagram of In-Situ Area

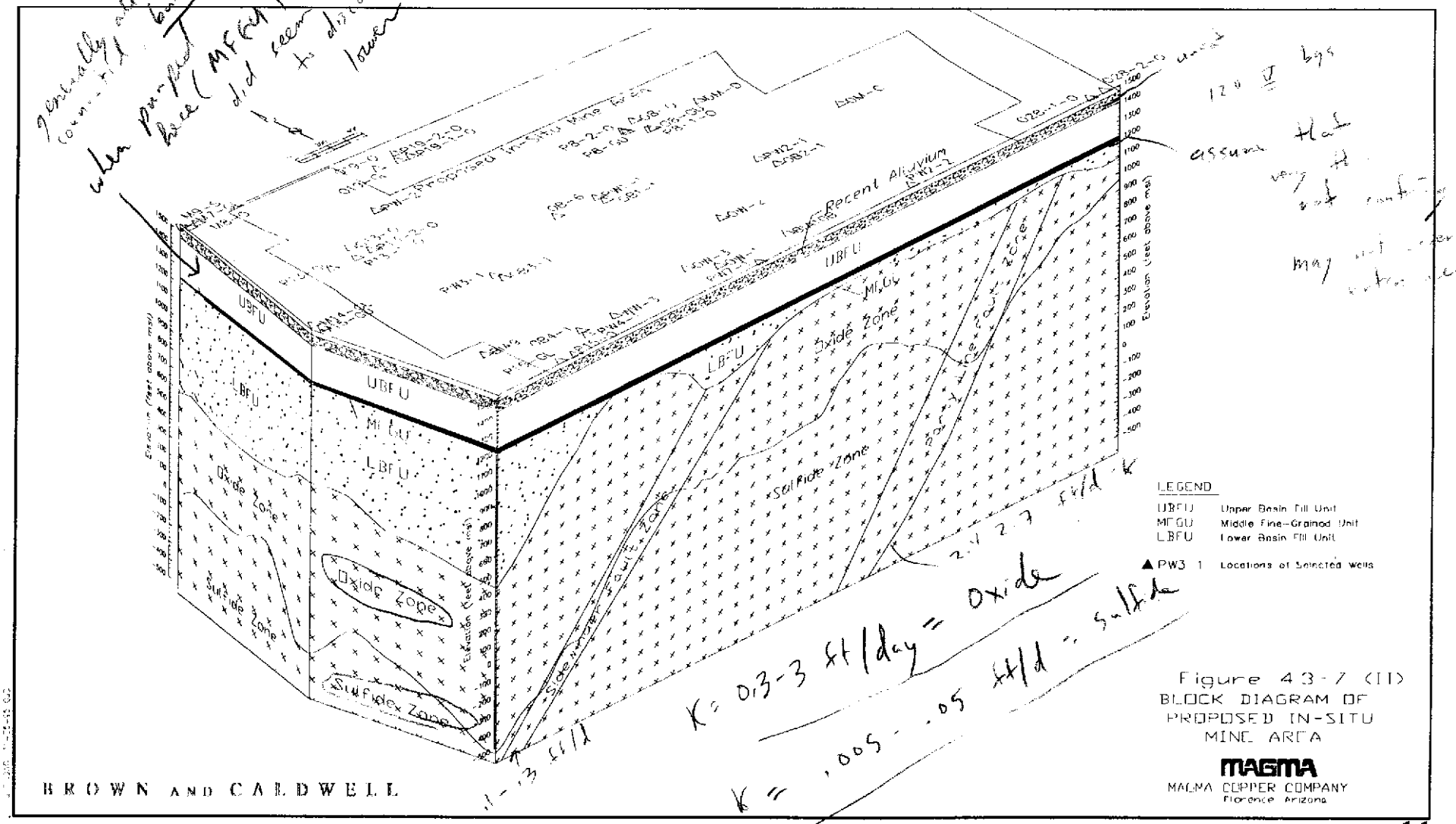
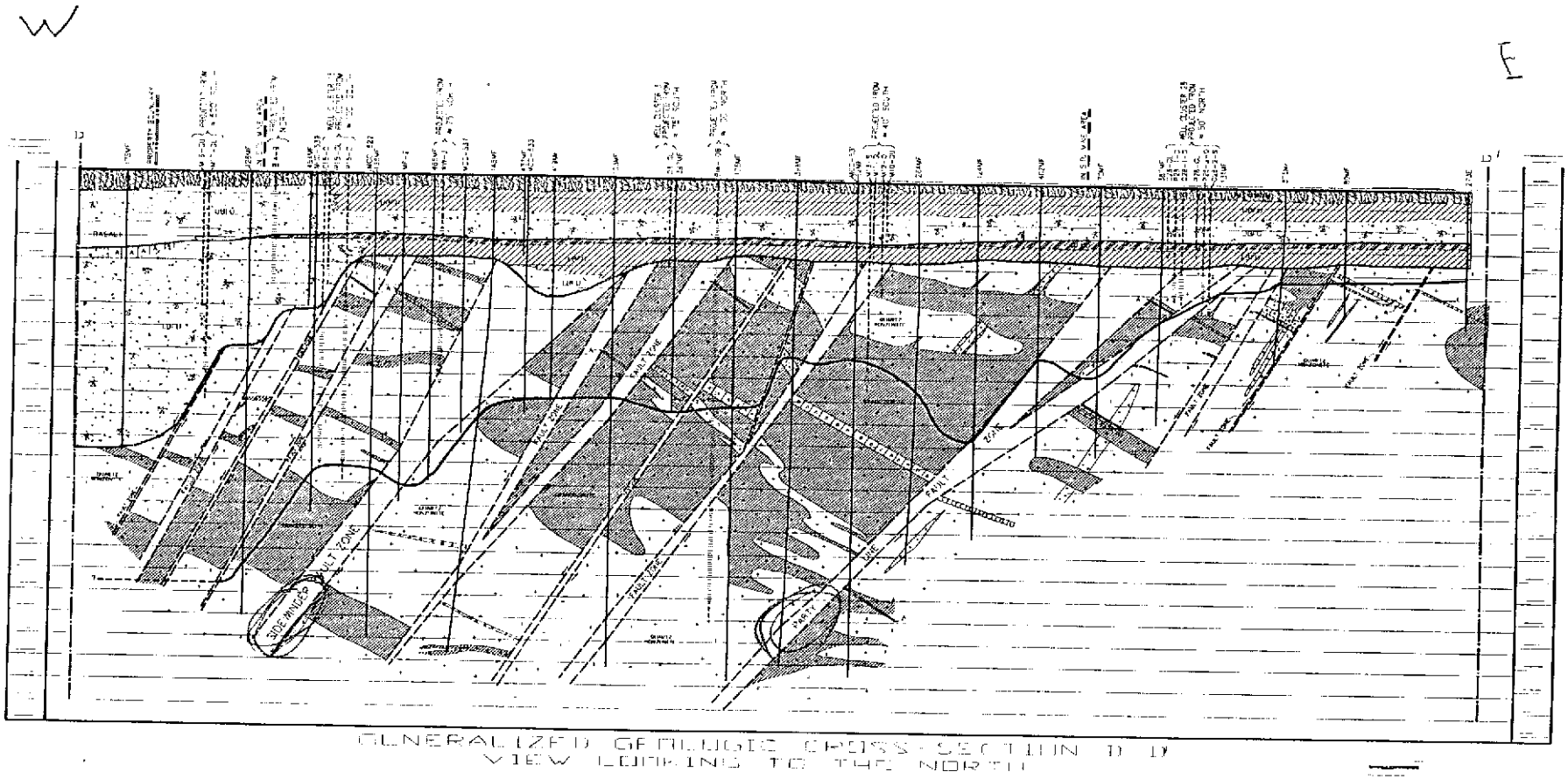


Figure 43-7 (II)
BLOCK DIAGRAM OF PROPOSED IN-SITU MINE AREA

K = 0.3-3 ft/day = oxide

K = .005 - .05 ft/d = sulfide

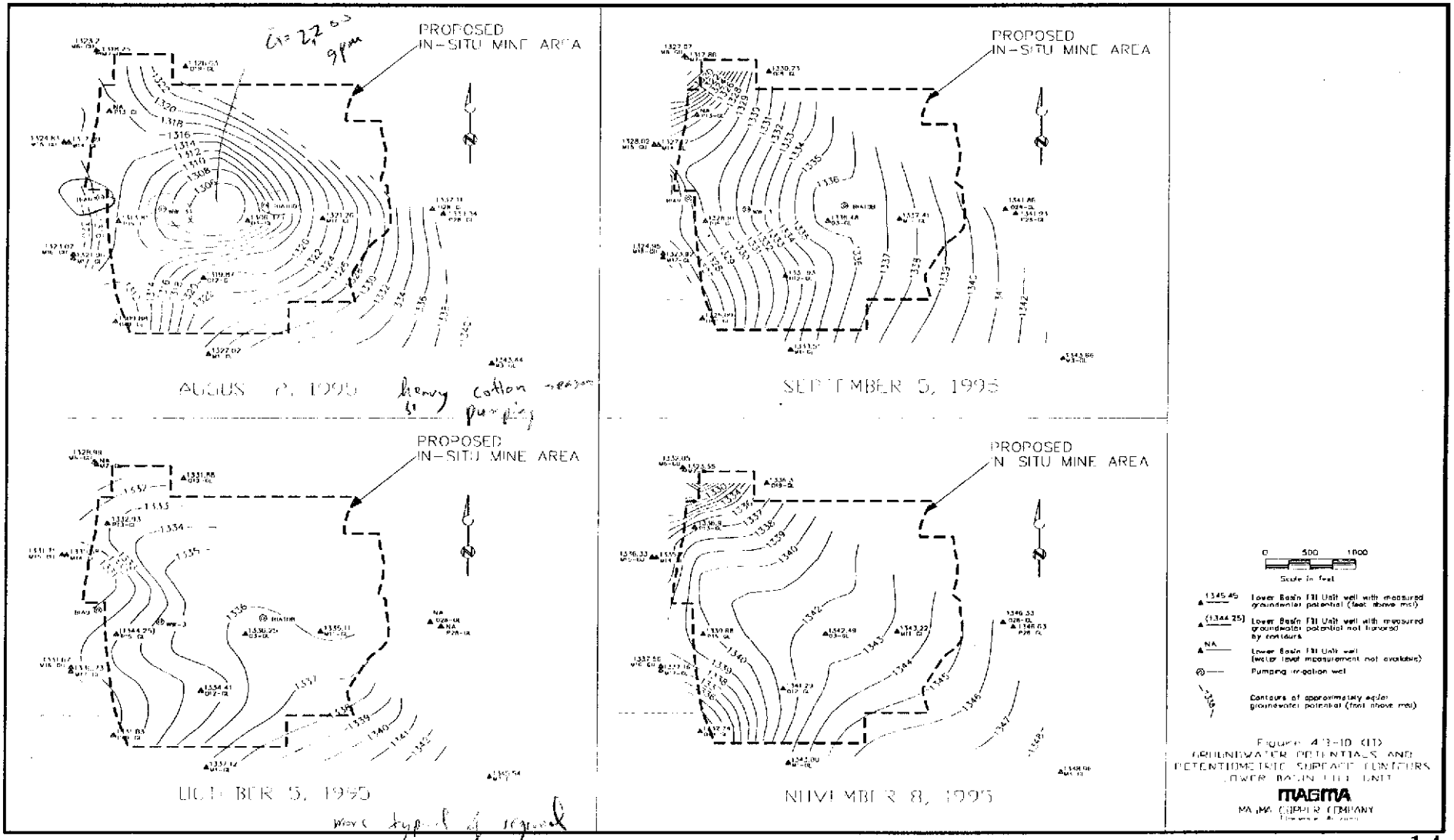
Generalized Geologic Cross-Section D-D'



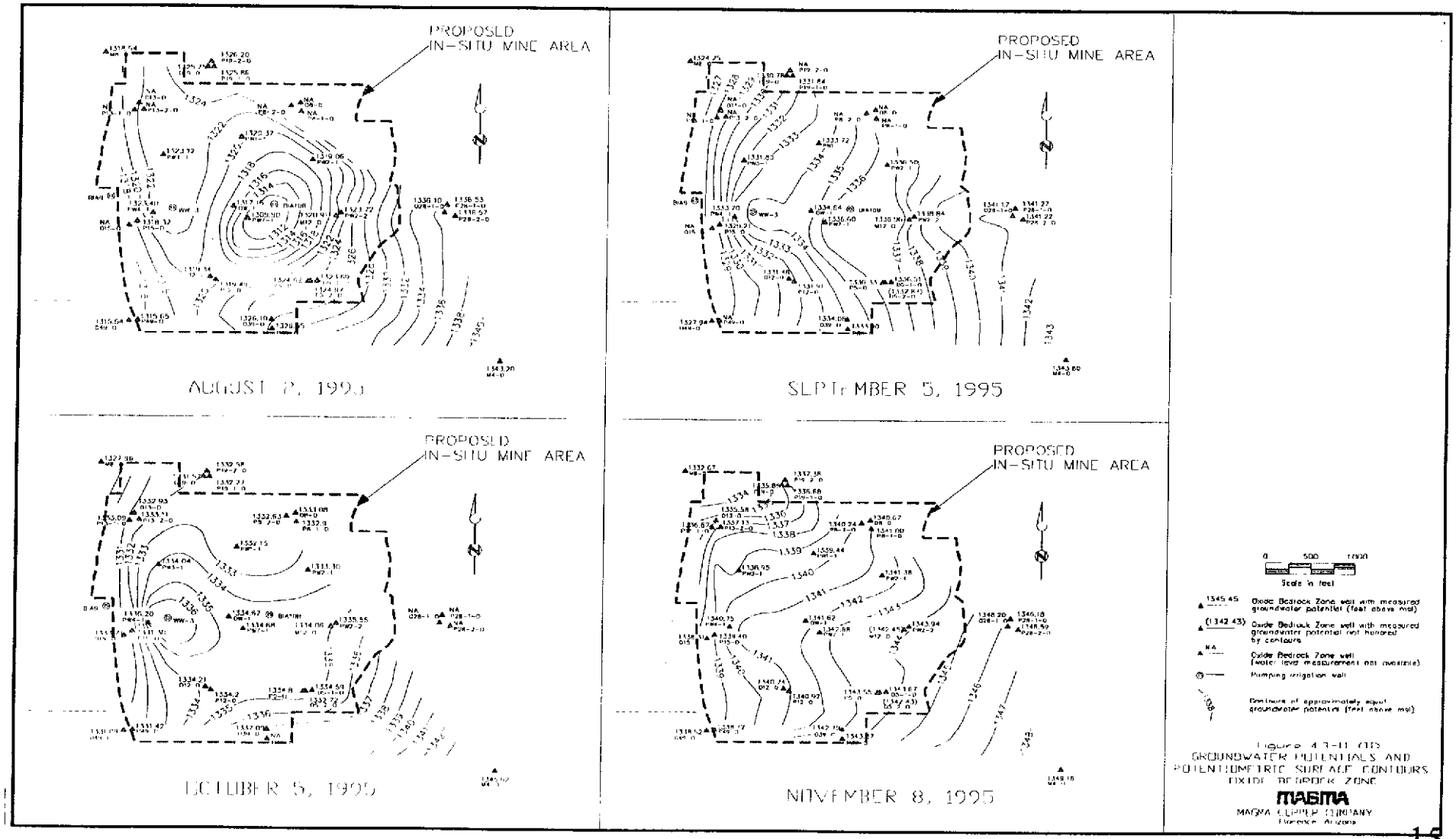
Site Specific Groundwater Conditions

- Depth to Water
- Flow Direction and Gradient
- Hydraulic Conductivities
- Vertical Hydraulic Gradients

Lower Basin Fill



Oxide/Sulfide Zone



1362 ft msl

842 ft msl

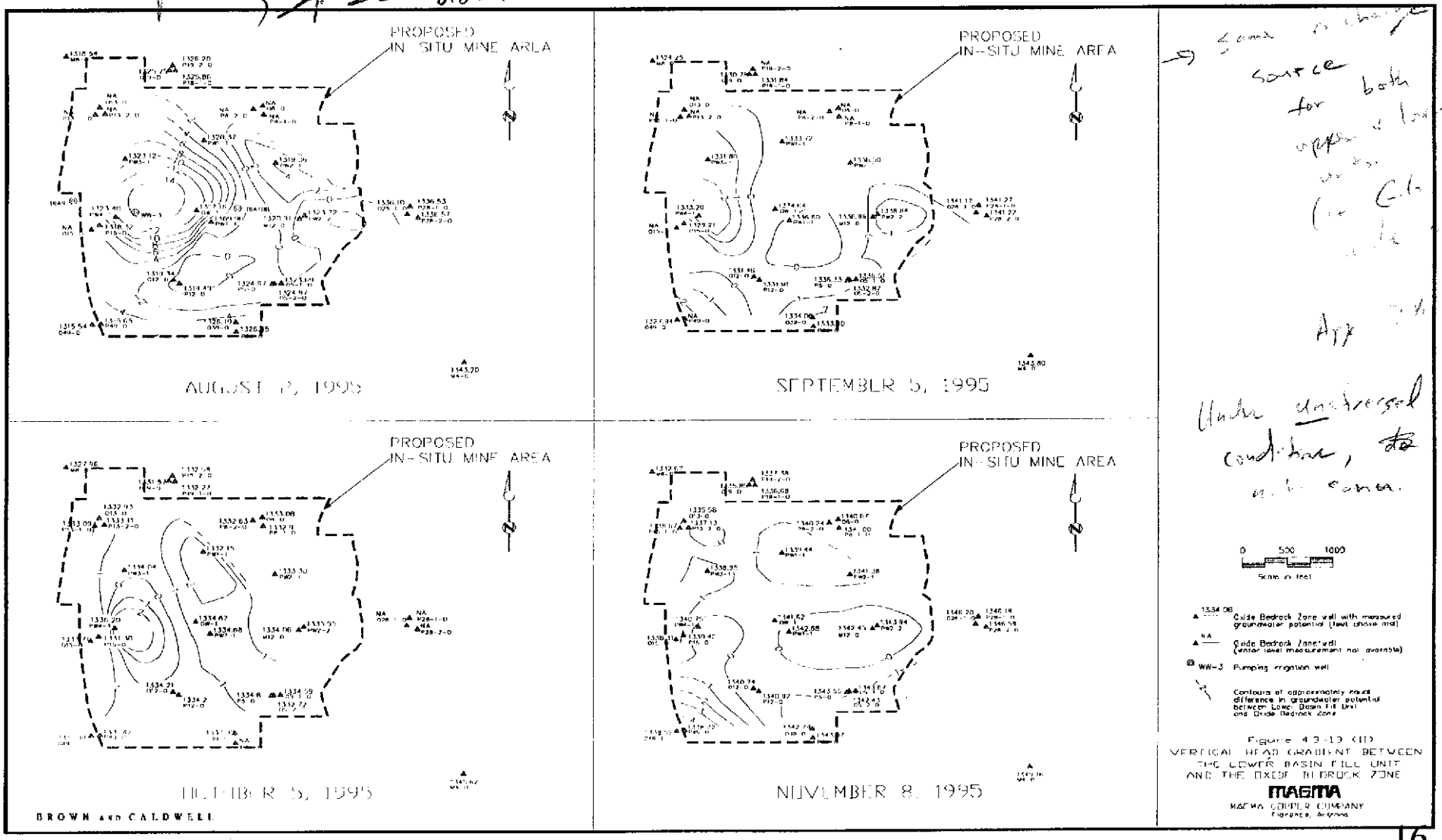
screened

400' - 200' screened

oxide bedrock and upper units are connected

Vertical Difference

if positive, ~~upwards~~ downward



→ some recharge source for both upper & lower units (i.e. Gila River water)

Air

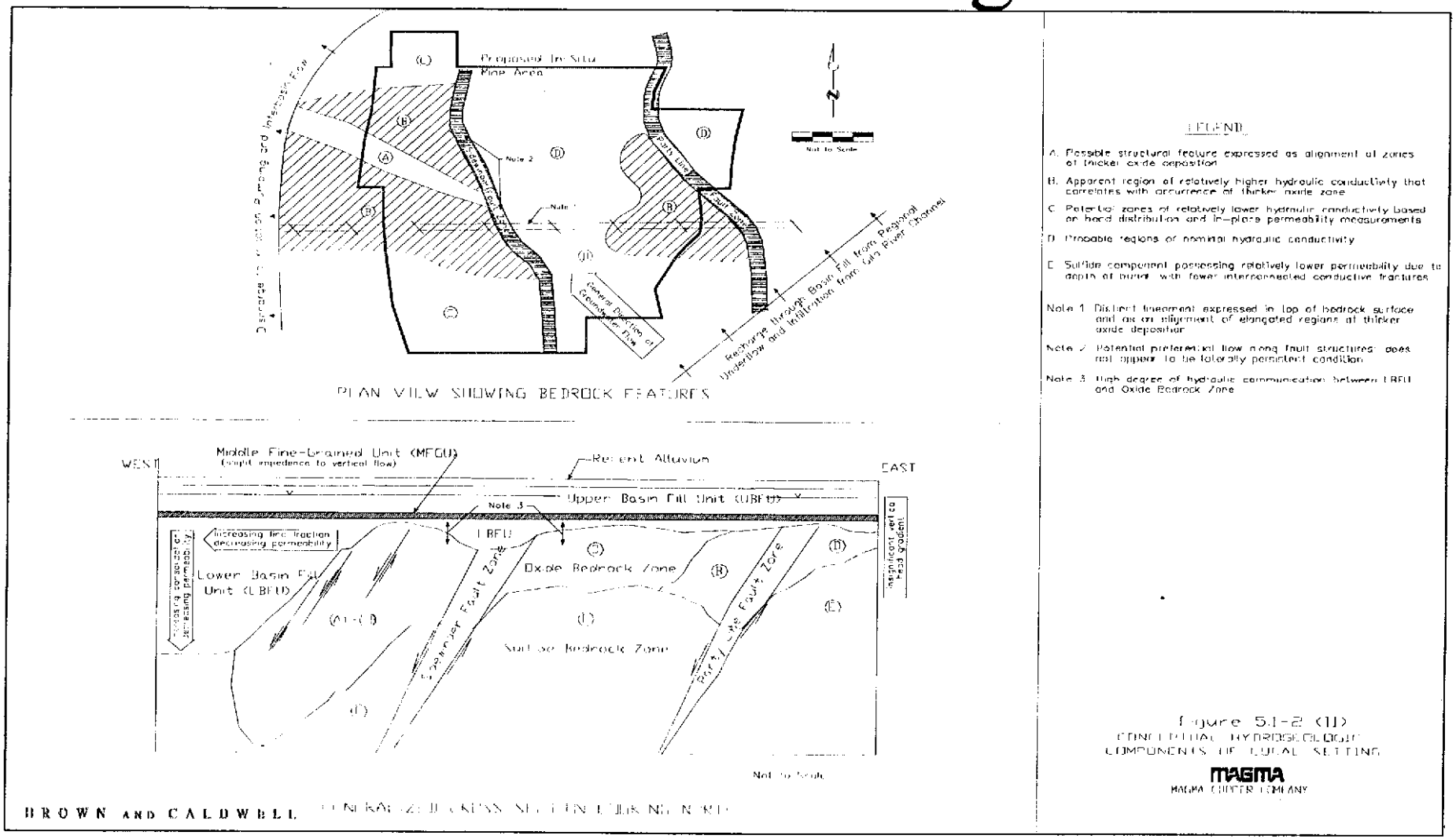
Under undressed conditions, the units are connected.

Site Specific Groundwater Conditions (continued)

- Degree of Interconnection Between Units
- Effects of Structure
- Ore Thickness and Permeability
- Morphology of Oxide/Sediment Contact and Permeability
- Persistence of Hydraulic Responses During Pumping

Figure 5-1.1 (II)

Conceptual Hydrologic Components of Local Setting



Code Selection

6-11 fractures/foot

- Equivalent Porous Media
- MODFLOW
- Path3D

aqua

SWIFT - ~~to~~ discrete fracture

too many fractures

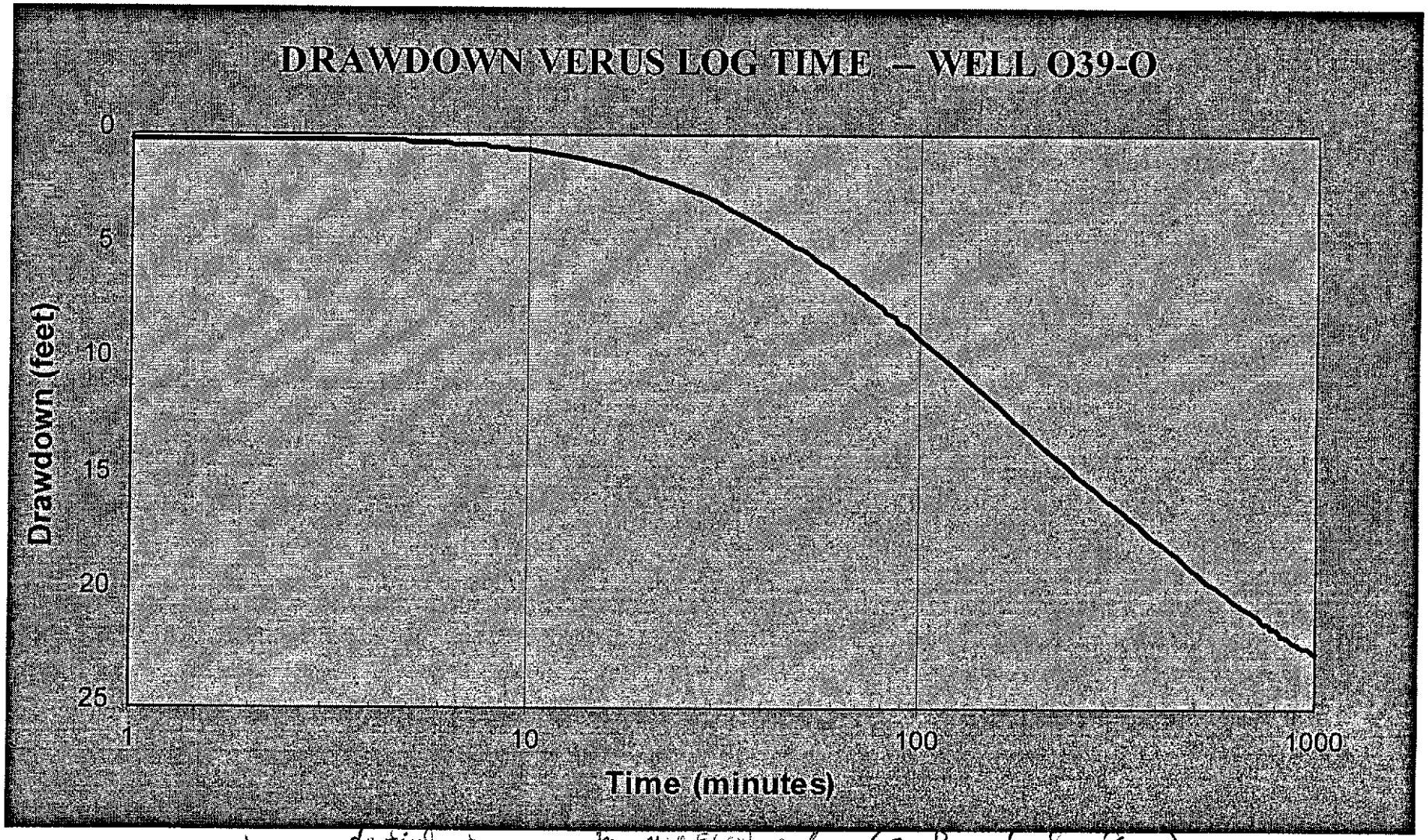
for SWIFT - much more similar to porous

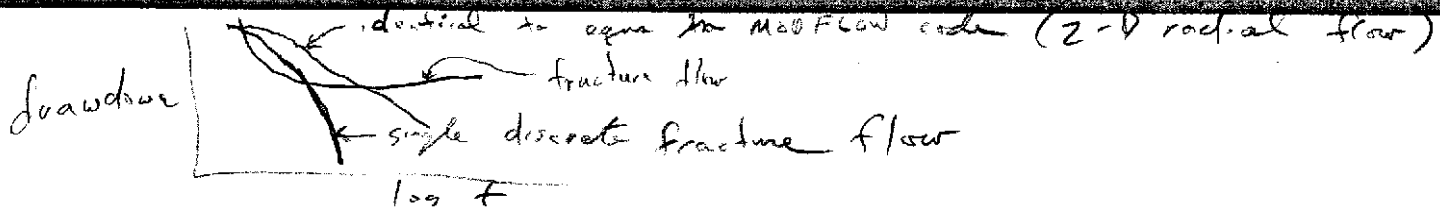
Equivalent Porous Medium

- Aquifer Testing
  - Packer Testing
  - Single Well Aquifer Tests
  - Regional Aquifer Tests
- 2D or 3D Flow
- Absence of Discrete Fracture Response
- Oxide Represented as Porous Medium

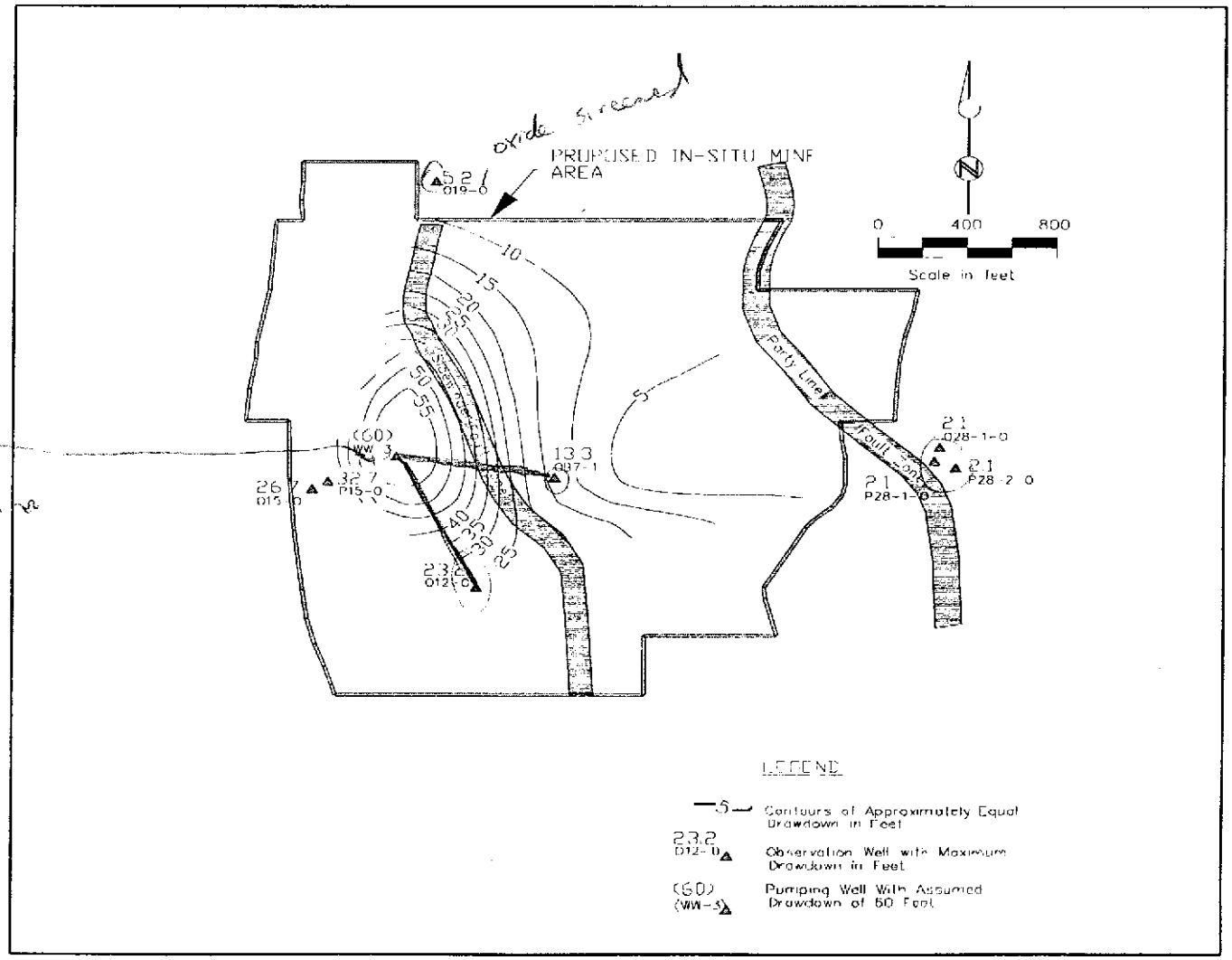
Drawdown versus Log Time

K = .3 ft/d





Maximum Drawdown in Well WW-3
Aquifer Test

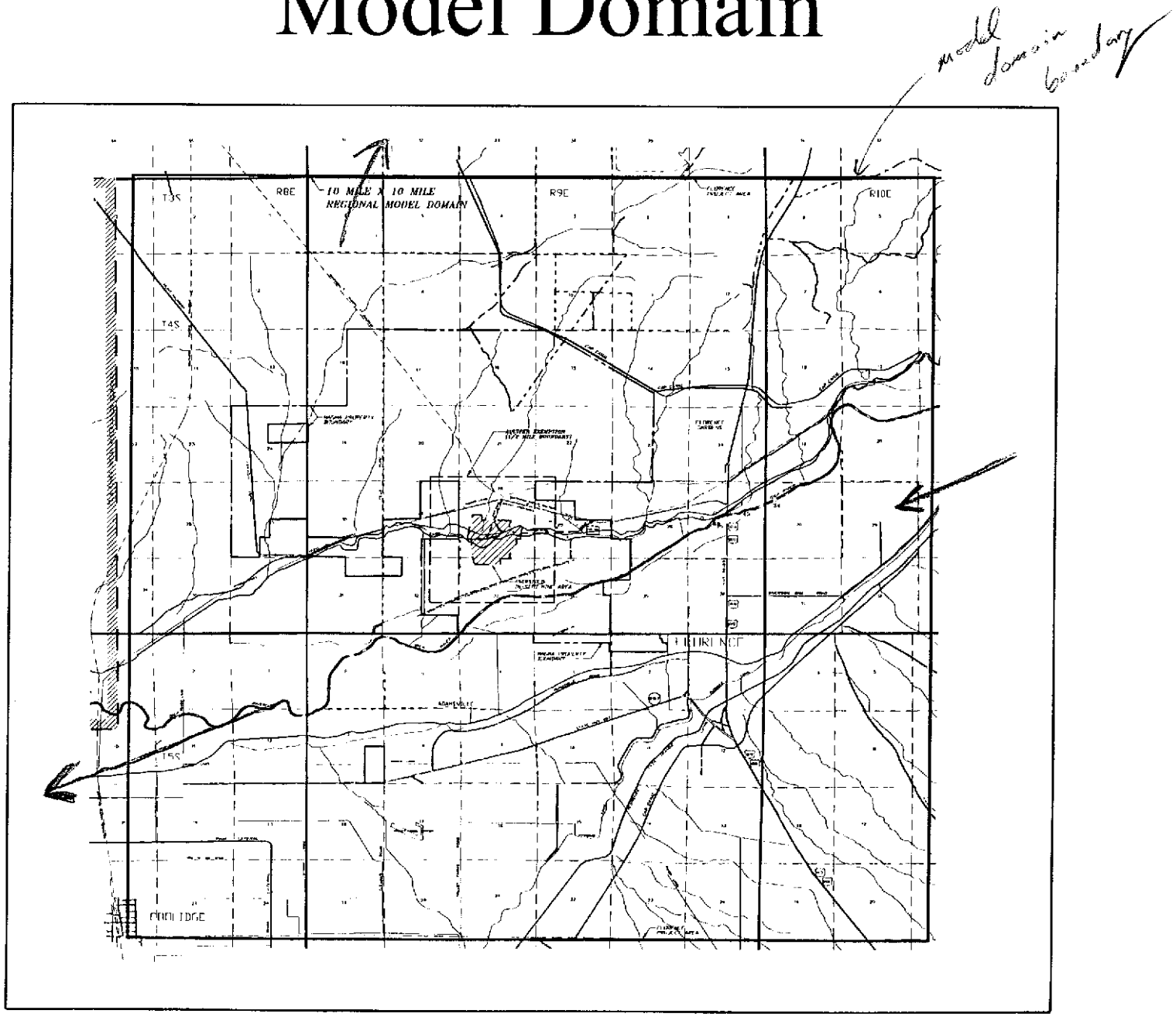


irrigation well pumping throughout all season

Model Construction

- Domain - what are you modeling
- Grid
- Layers
- Boundaries
- Initial Conditions
- Parameter Selection
  - Hydraulic Conductivity
  - Storage Coefficient
  - Porosity
  - Vertical Conductance

Model Domain



Model Construction

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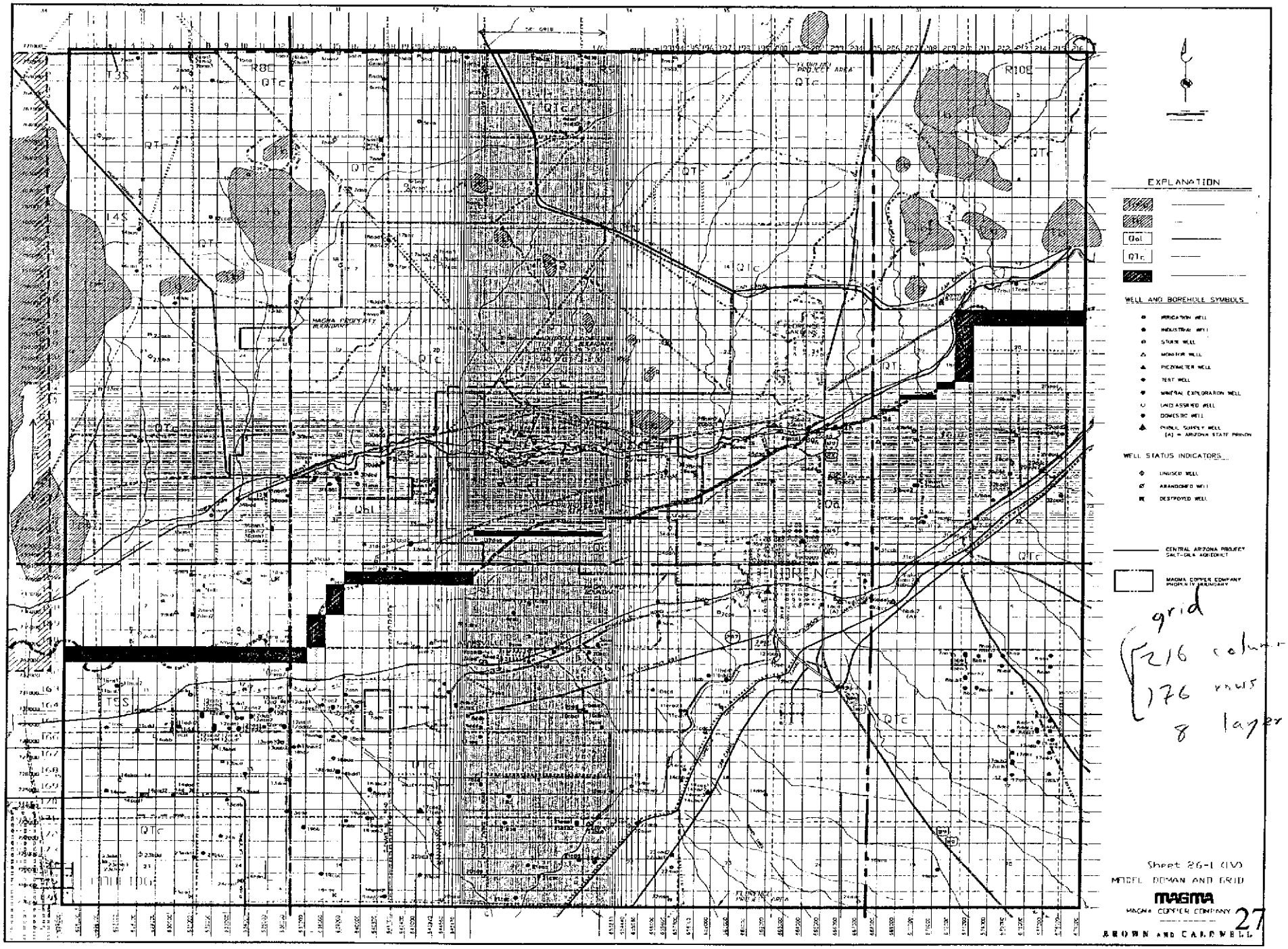

grid
216 columns
176 rows
8 layers

Sheet 26-1 (IV)
MODEL DOMAIN AND GRID

MAGMA
MAGMA COPPER COMPANY

BROWN AND CALDWELL

Model Construction

- Domain
- Grid
- Layers
- Boundaries
- Initial Conditions
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  - Hydraulic Conductivity
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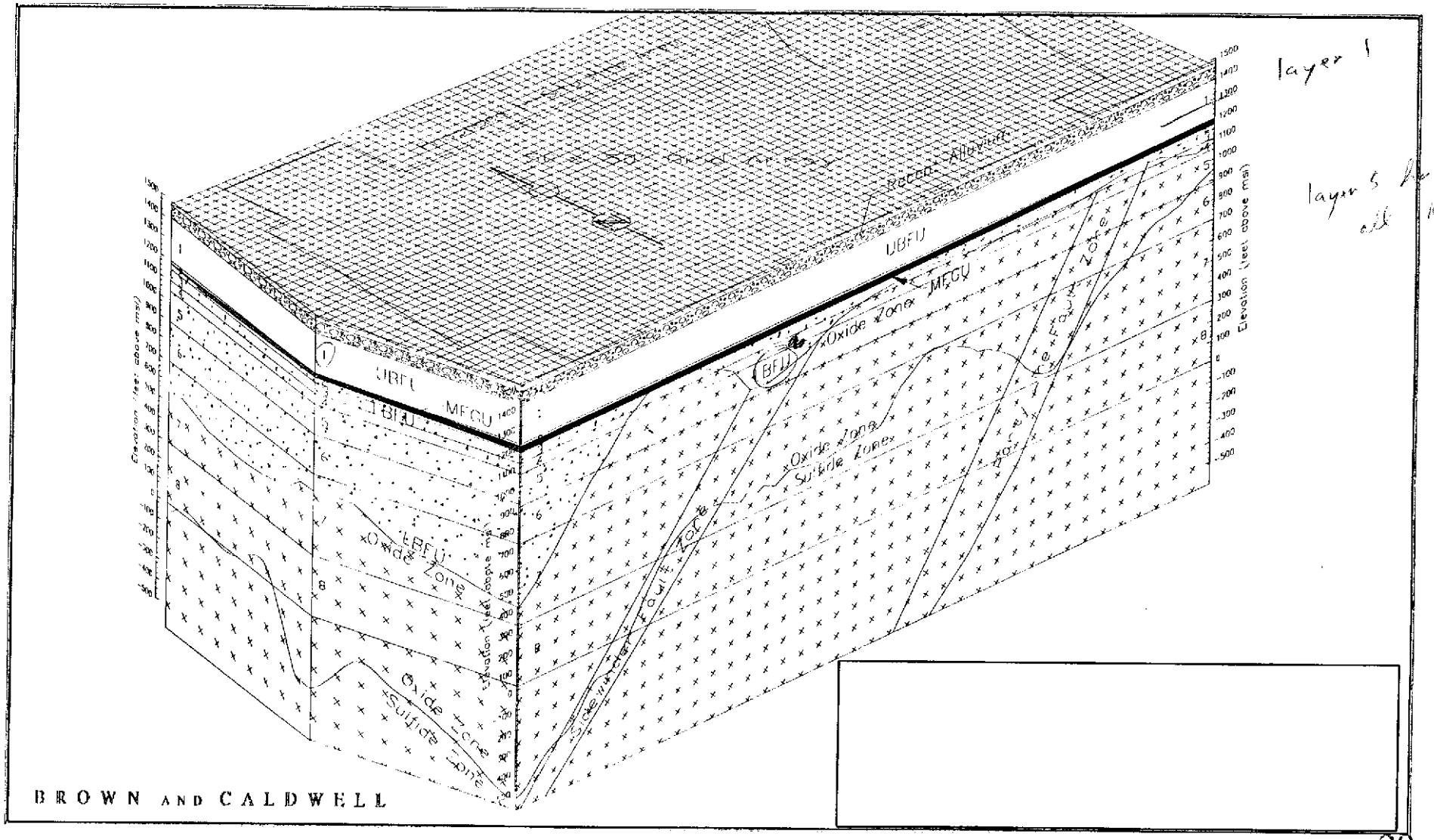
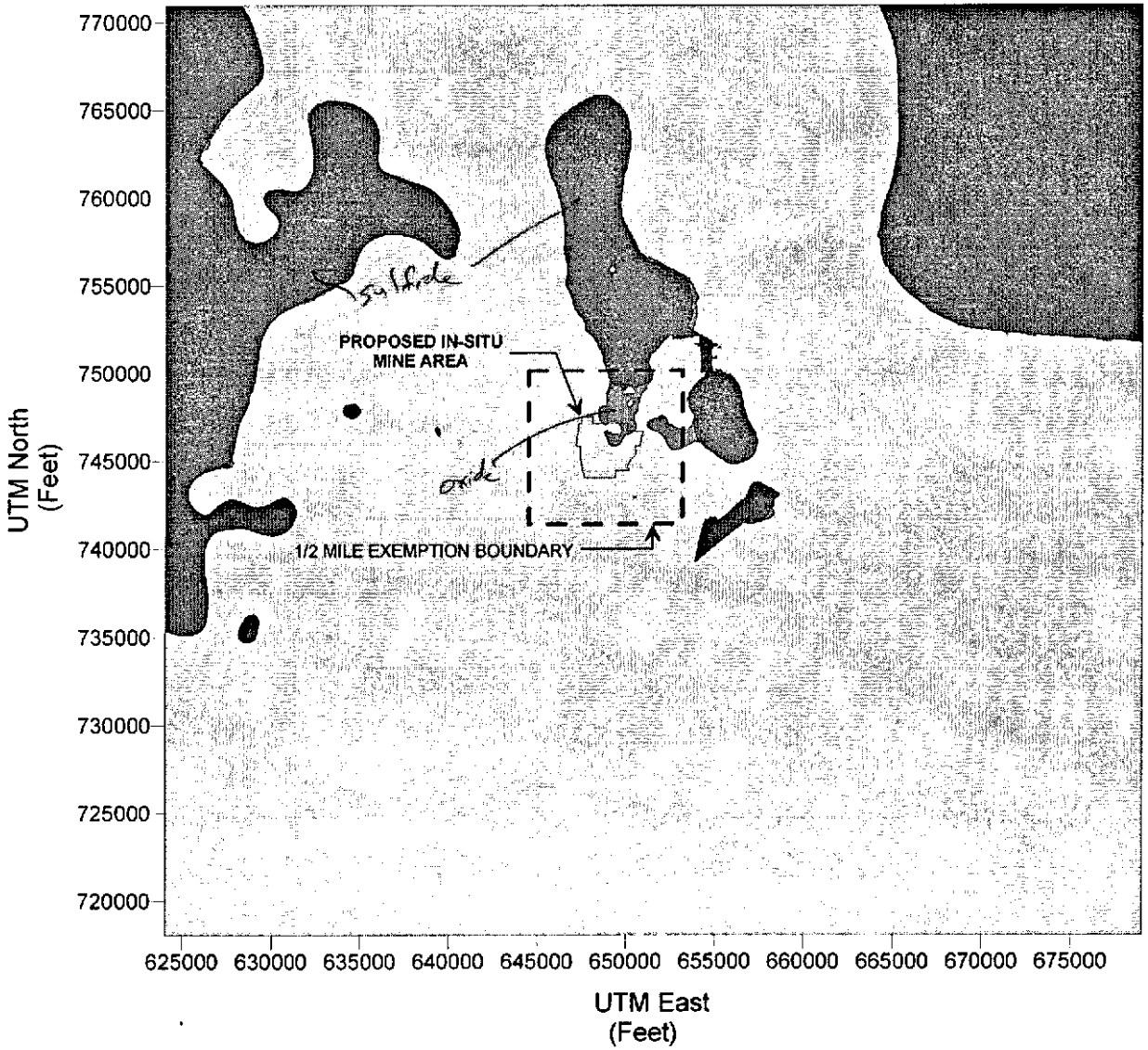
Isometric View of Model Layers

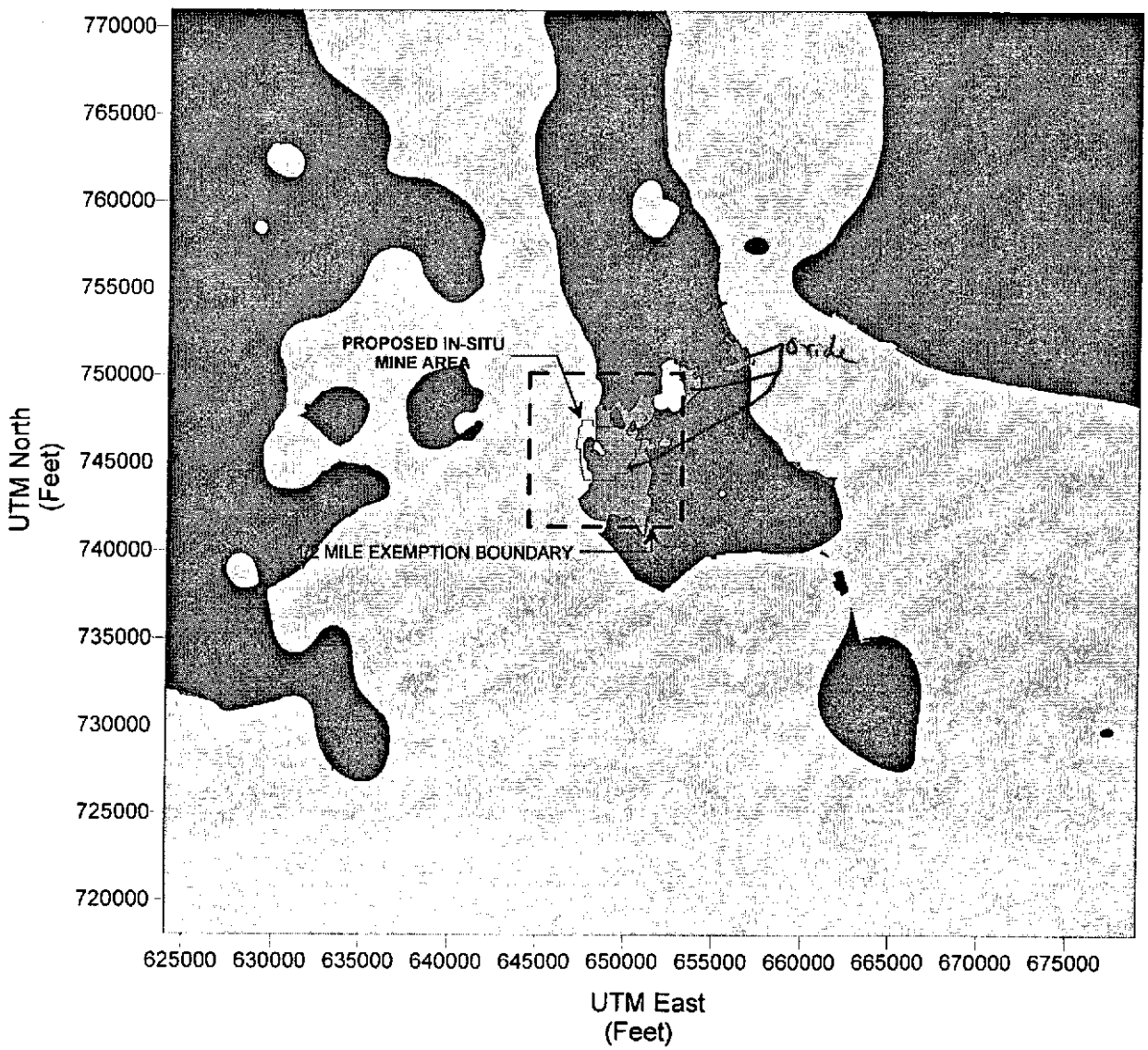


BROWN AND CALDWELL

Model Layer 2



Model Layer 5



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- Domain
- Grid
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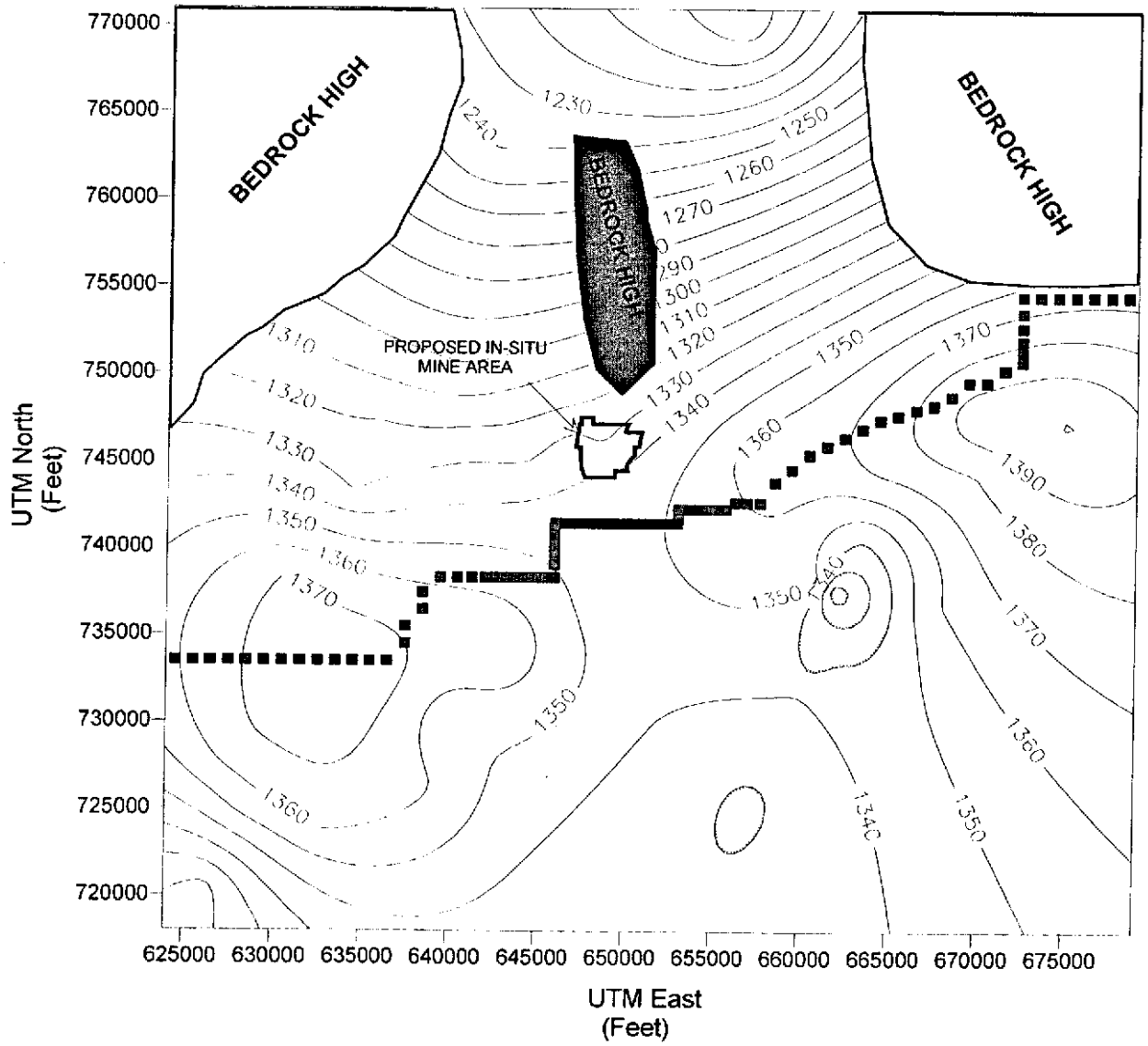
October 6, 1996 Measured Water Level Elevation Contours

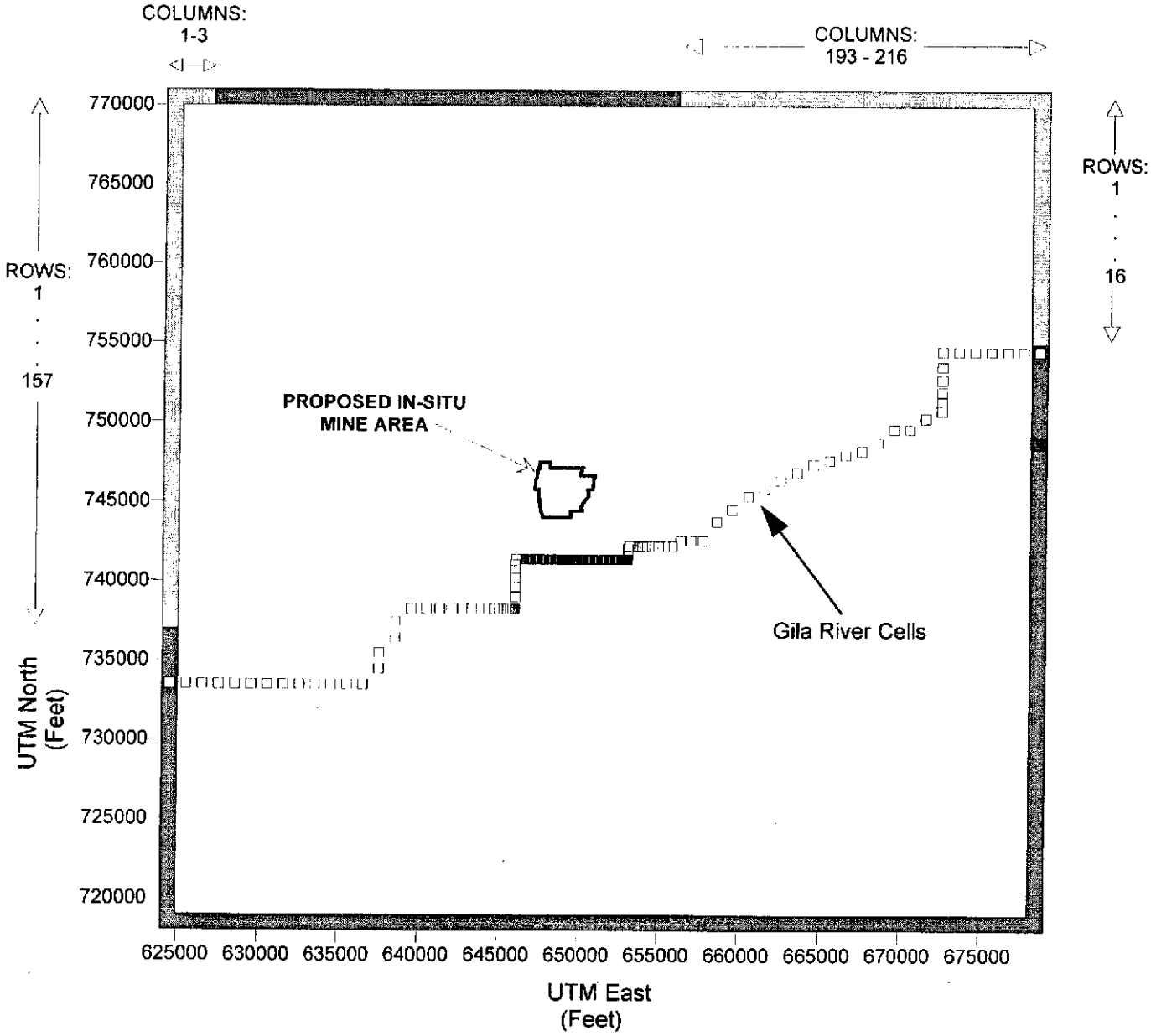


Boundary Conditions

- Type 1 - Specified Head
  - Constant Head e.g. a lake
- Type 2 - Specified Flow
  - Specified Flow or Flux constant rate q
- Type 3 - Head-Dependent Flow Boundary
  - Flux is Calculated Based on Given Boundary Head Value

General head

Boundary Conditions



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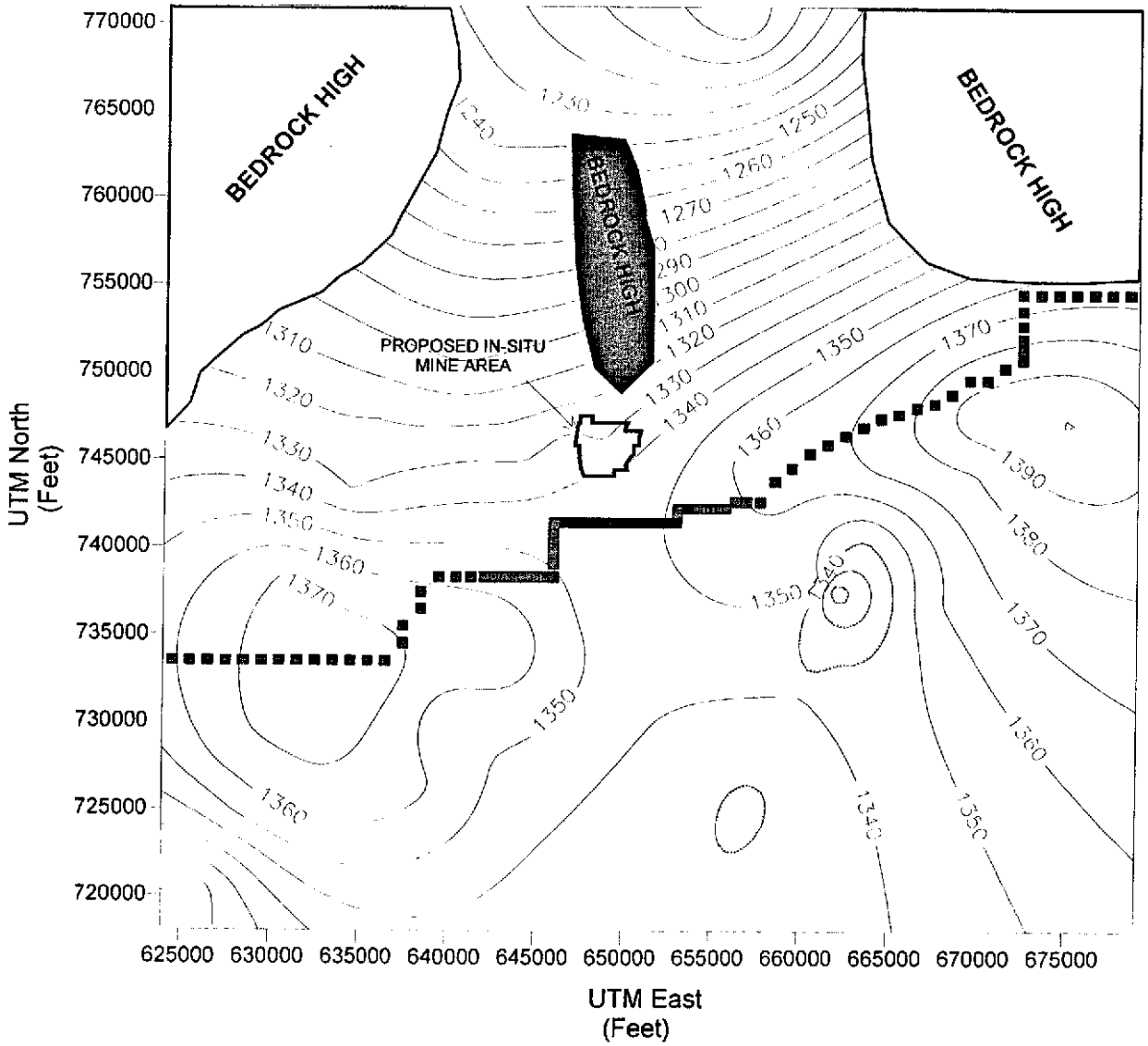
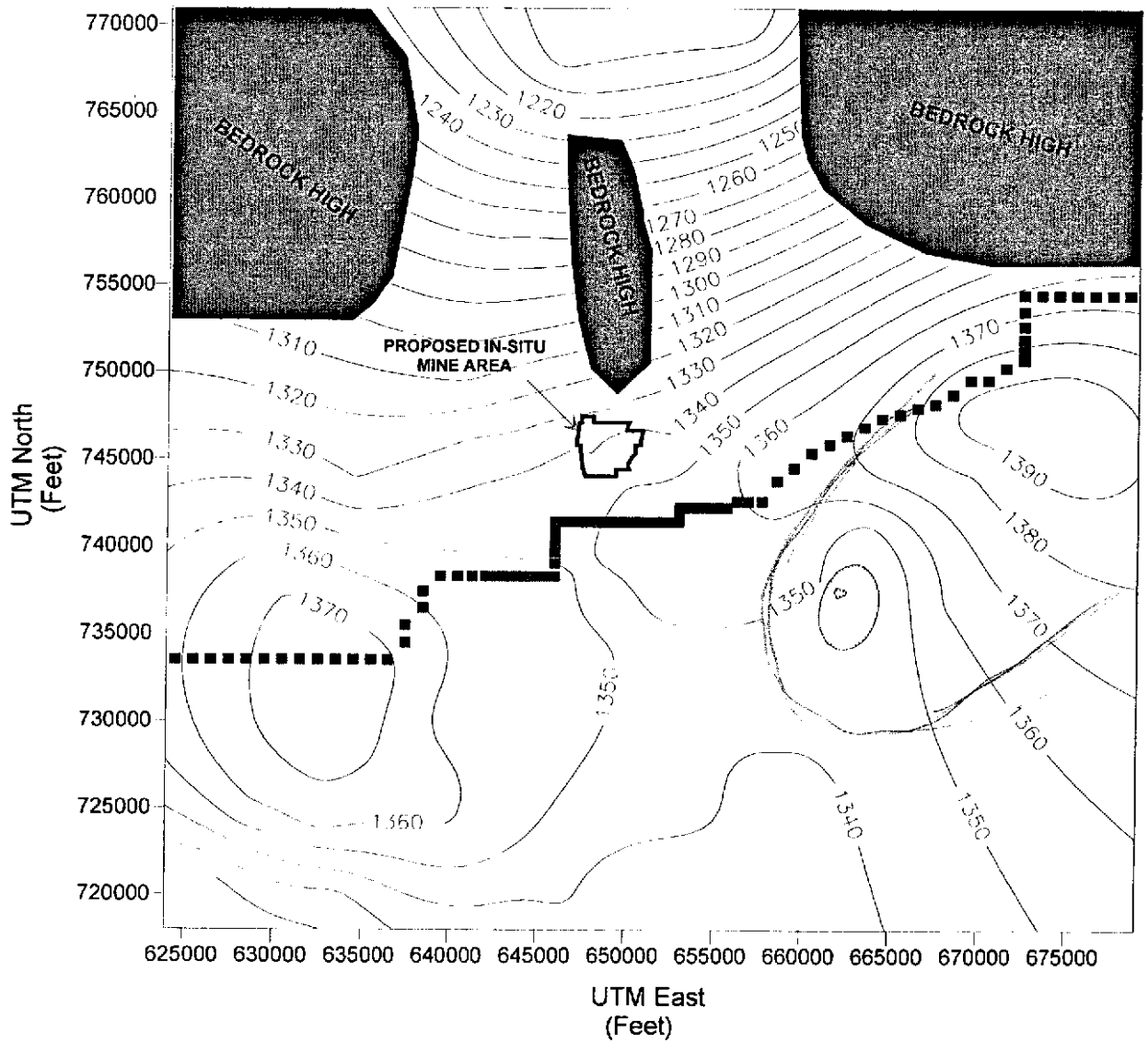


Measured November Water-Level Elevations

1995



Model Construction

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Hydraulic Conductivity Distribution

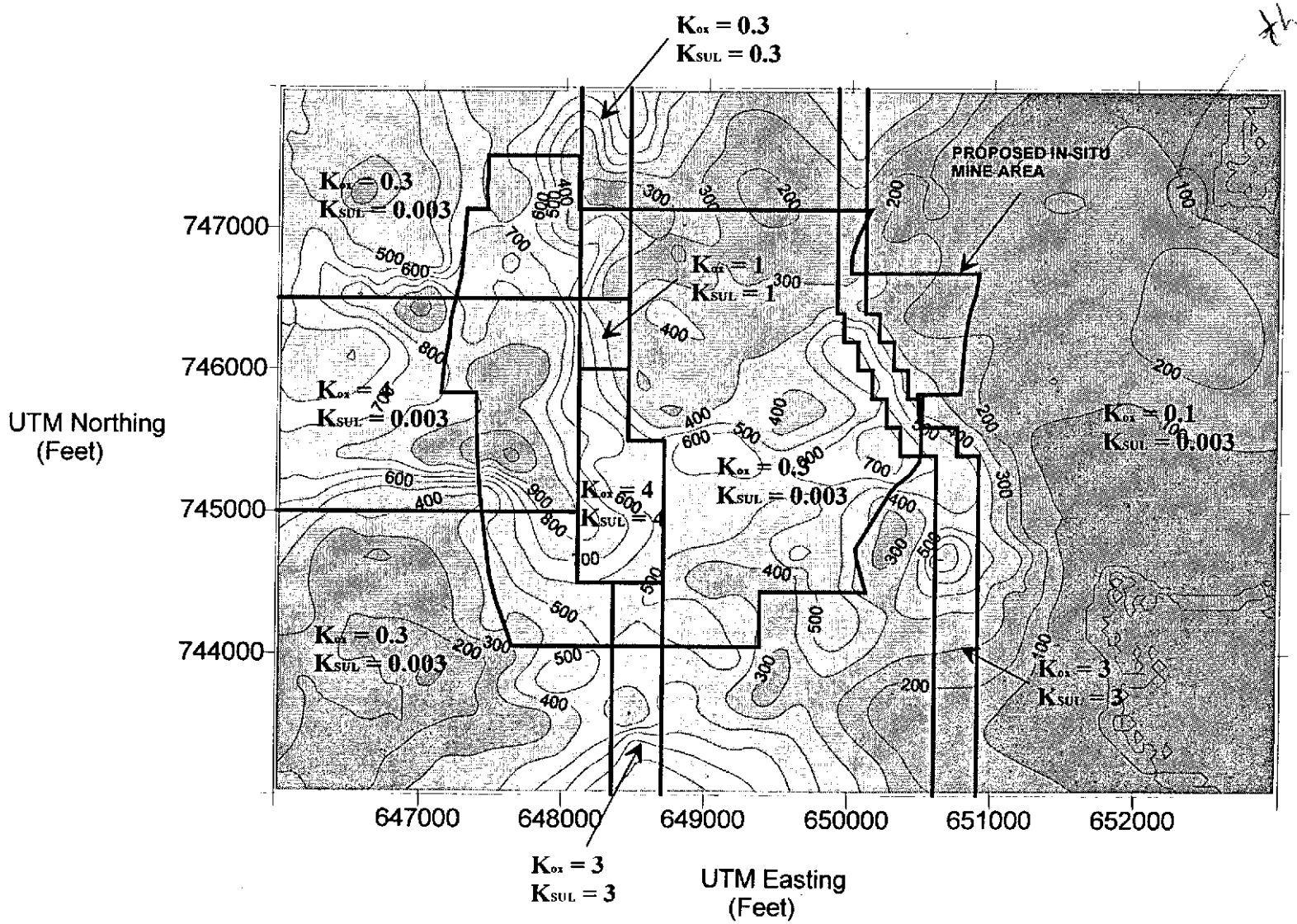
Summary of Hydraulic Conductivity Distribution

Model Layer	Top Elevation, ft., msl	Bottom Elevation, ft., msl	Calibrated Hydraulic Conductivity UBFU, ft/day	LBFU, ft/day	Oxide, ft/day	Sulfide, ft/day
1	ground surface	1200	40 and 60 (pump tests)	--	--	--
2	1200	1150	(calibrated better)	20	0.3 to 4	0.003 to 4
3	1150	1100	--	20	0.1 to 4	0.003 to 4
4	1100	1050	--	8	0.1 to 4	0.003 to 4
5	1050	900	--	3	0.1 to 4	0.003 to 4
6	900	700	--	2	0.1 to 4	0.003 to 4
7	700	300	--	1	0.1 to 4	0.003 to 4
8	300	0	--	0.5	0.1 to 4	0.003 to 4

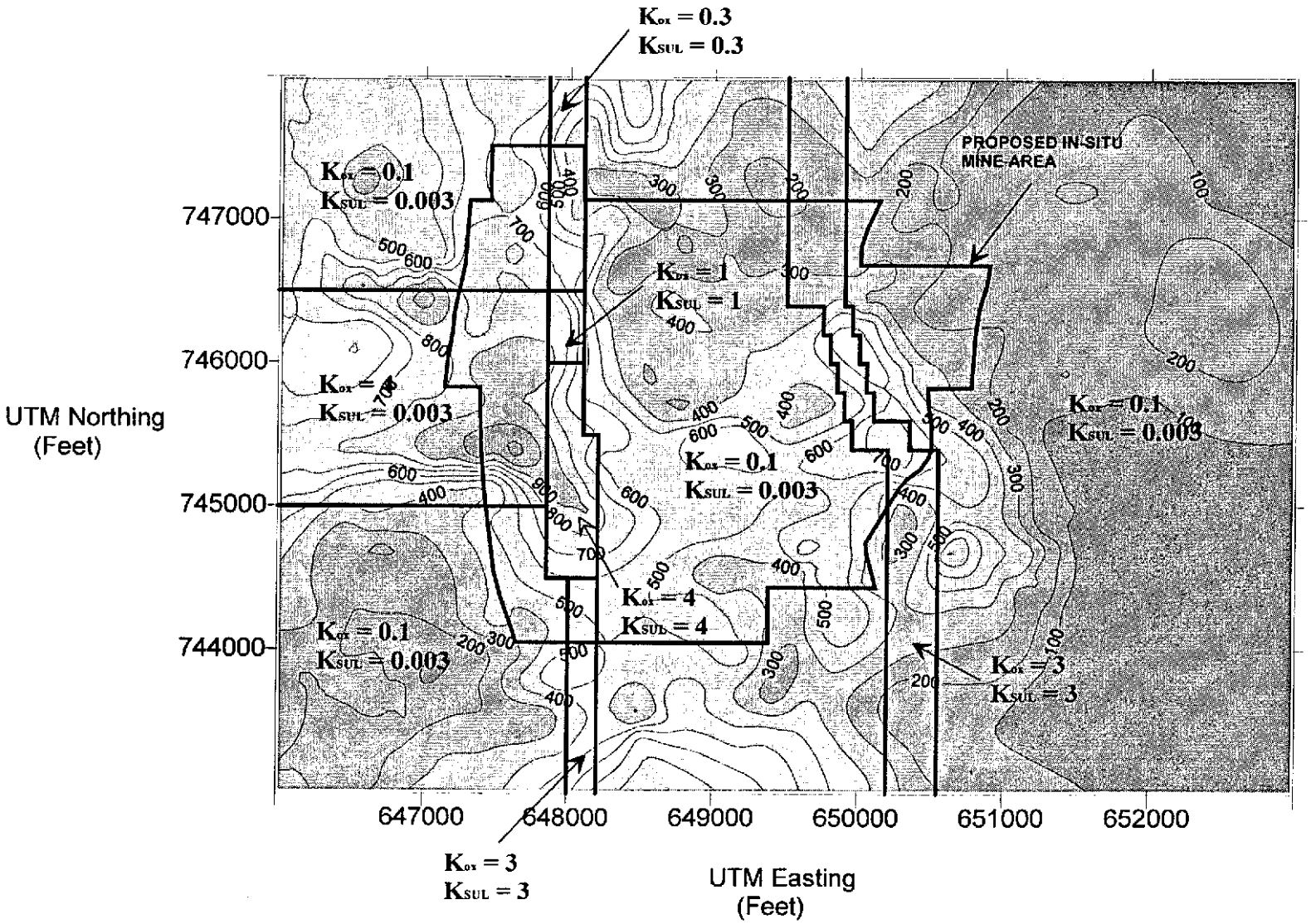
higher ranges are faults

- Hydraulic Conductivity Values Estimated From Approximately 40 Onsite Tests
- Conservative Values Used for Faults

Conductivity Distribution
Layer 5



Conductivity Distribution
Layer 7



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Model Construction

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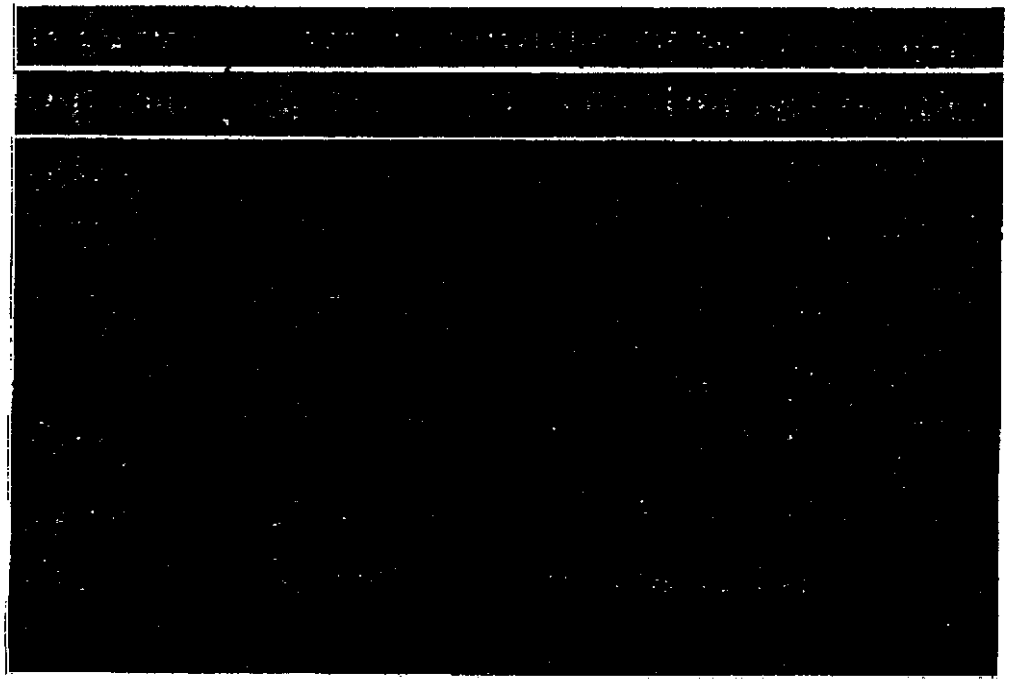
Specific Storage



- Previous Aquifer Tests S_s Ranged From 7×10^{-6} to 2.3×10^{-8}
- Confined Aquifers Set At 1×10^{-6}

Model Construction

- Domain
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- Layers
- Boundaries
- Initial Conditions
- Parameter Selection
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  - Porosity
  - Vertical Conductance

Values of Porosity for Various Geologic Materials

function of interconnection

effective porosity

Material	Porosity (%)
Sedimentary	
Gravel, coarse	24-36
Gravel, fine	25-38
Sand, coarse	31-46
Sand, fine	26-53
Silt	34-61
Clay	34-60
Sedimentary Rocks	
Sandstone	5-30
Siltstone	21-41
Limestone, dolomite	0-20
Karst limestone	5-50
Shale	0-10
Crystalline rocks	
Fractured crystalline rocks	0-10
Dense crystalline rocks	0-5
Basalt	3-35
Weathered granite	34-57
Weathered gabbro	42-45

Source: Davis (1969) or Johnson and Morris (1962)

- Upper Basin Fill Unit - 20%
- Lower Basin Fill Unit - 10%
- Oxide - 2%
- Sulfide - 0.2%

all published values

Model Construction

- Domain
- Grid
- Layers
- Boundaries
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  - Hydraulic Conductivity
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  - Vertical Conductance

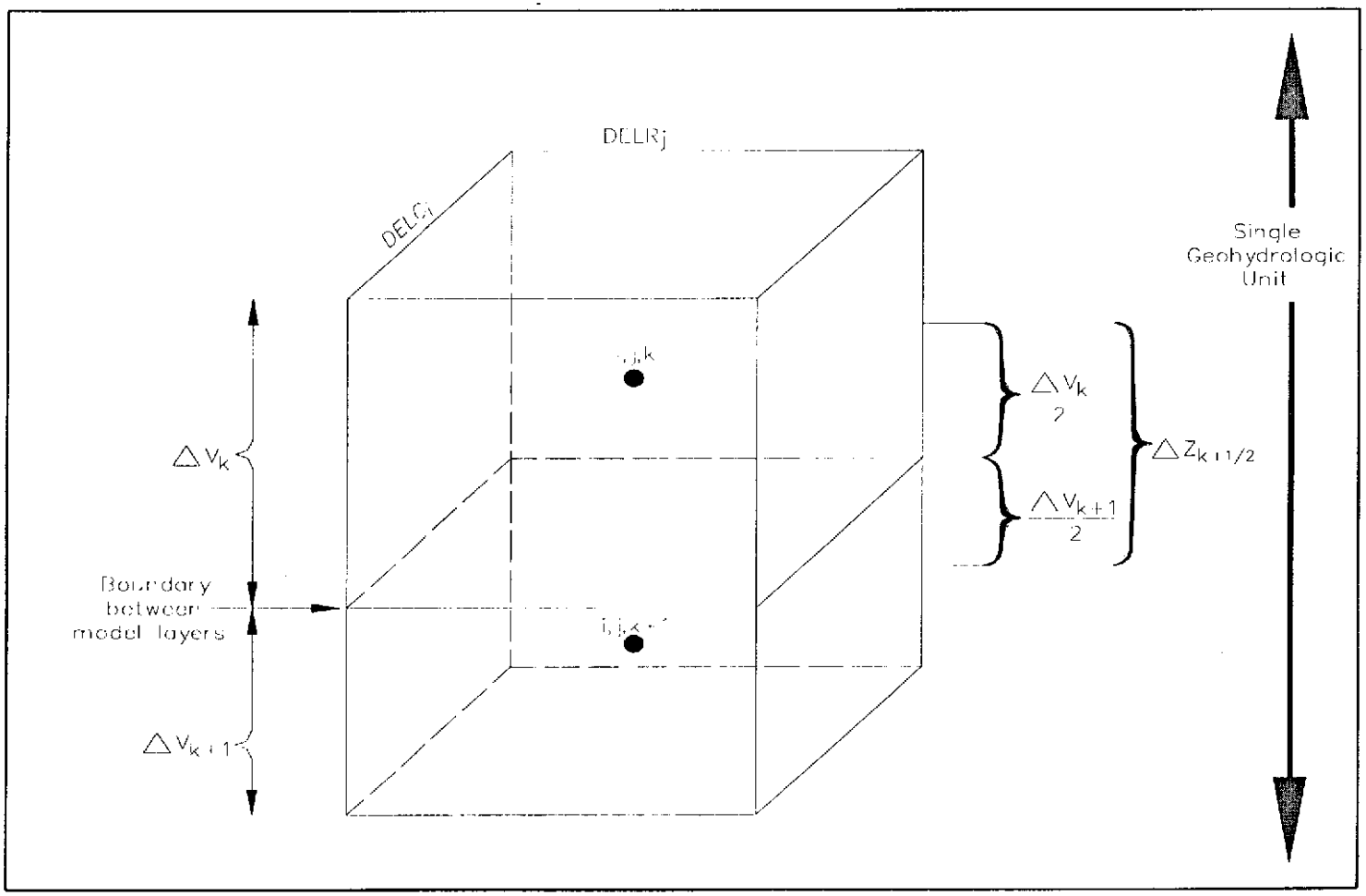
allows layers to connect to a kind of 3-D model

Vertical Conductance

don't use water pumping

10^{-6} - low permeability in field could be model hydraulic

Olsen says parameter not a big deal



Model Calibration

- Purpose of Calibration
- Regional Calibration
- Local Calibration

Model Calibration

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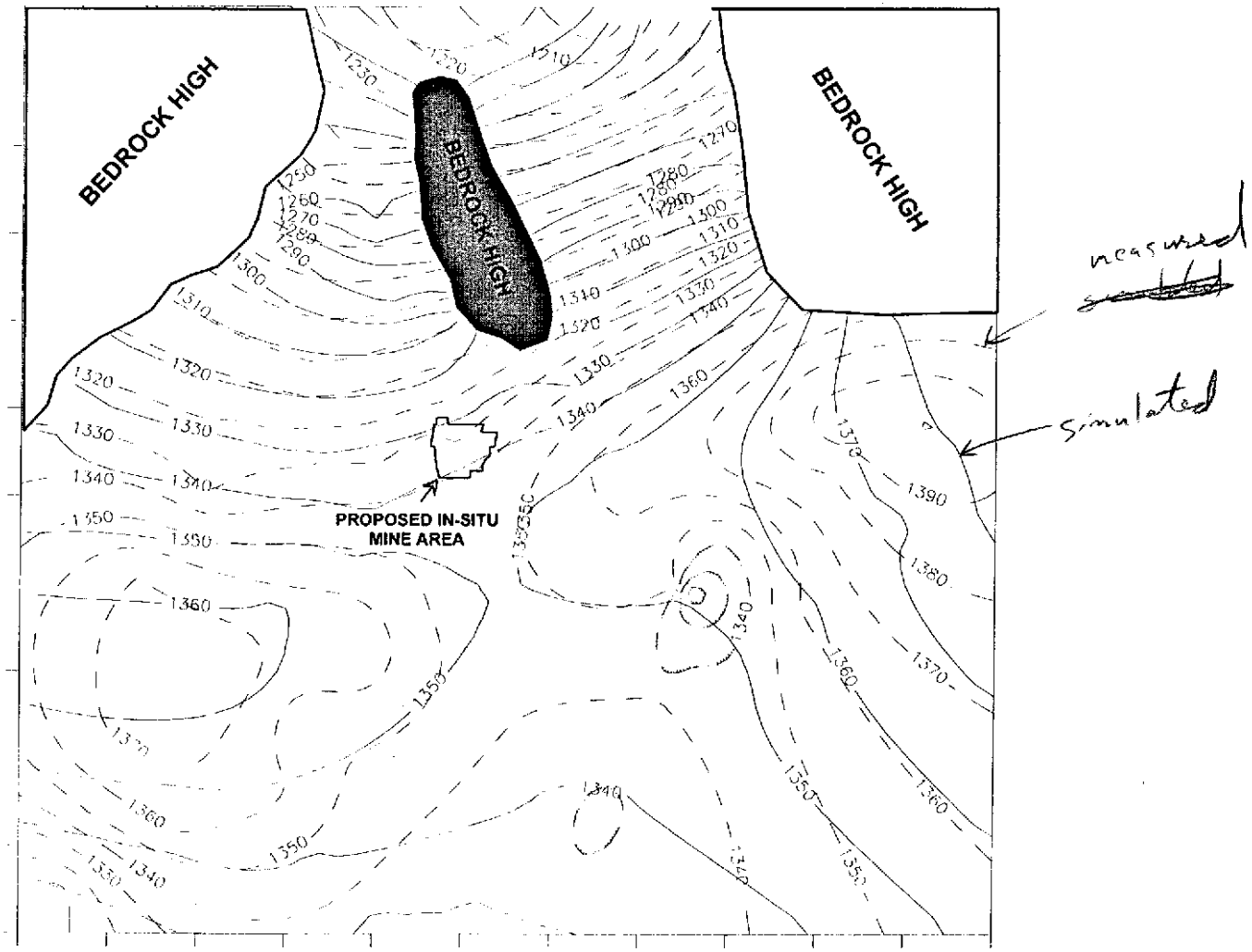
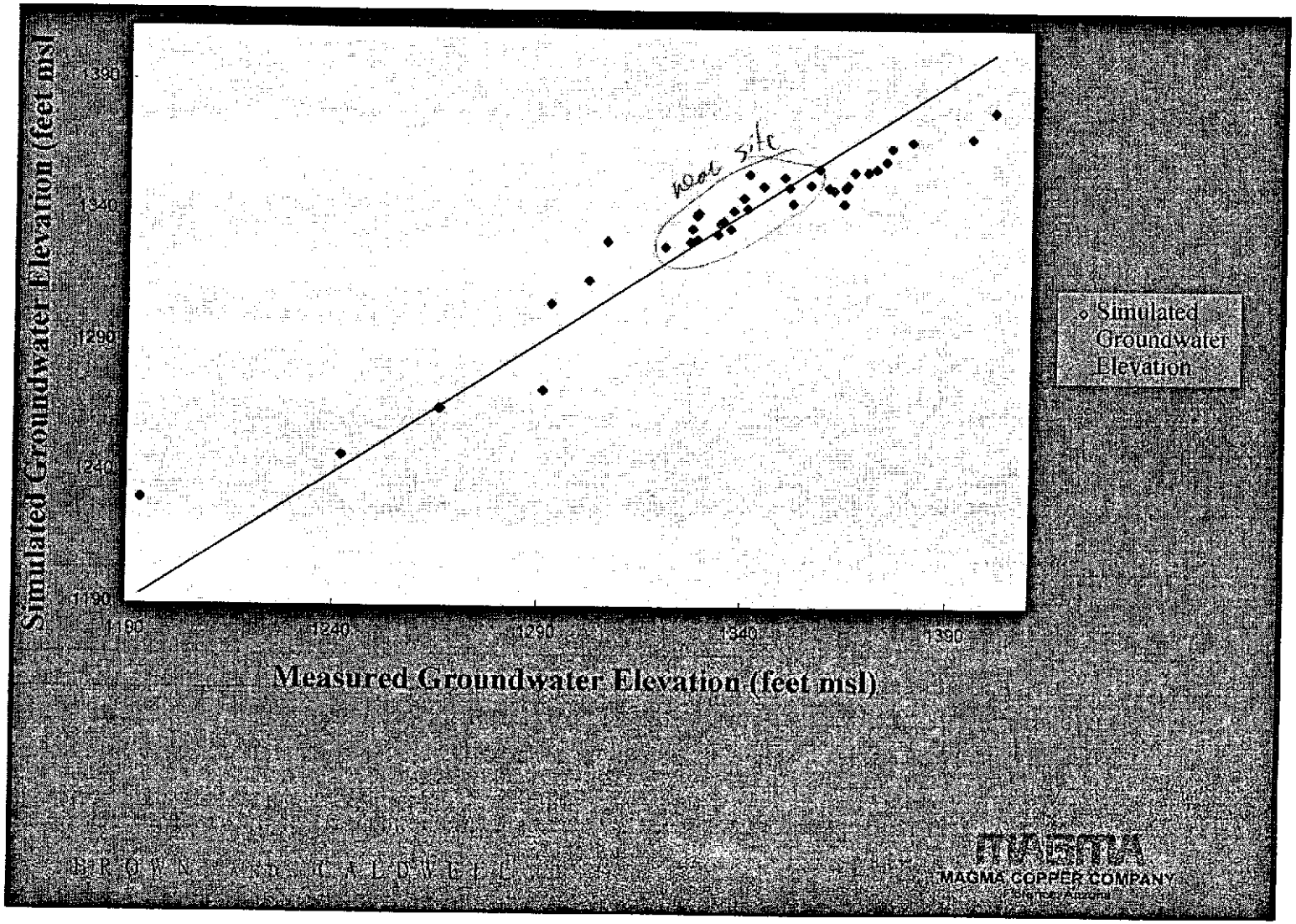
Simulated and Measured Water Level Contours



Scatter Plot of Simulated versus Measured WL Elevations



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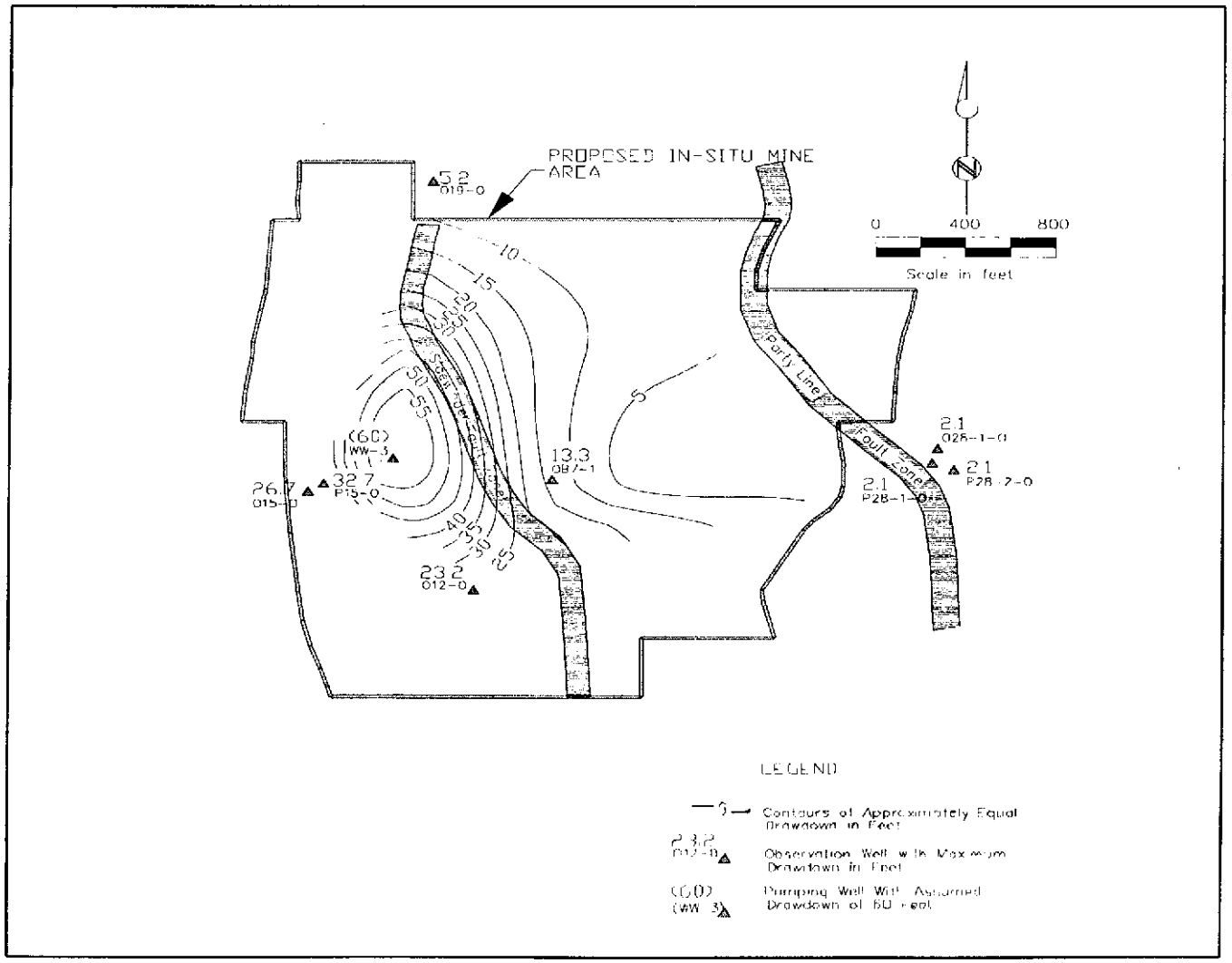
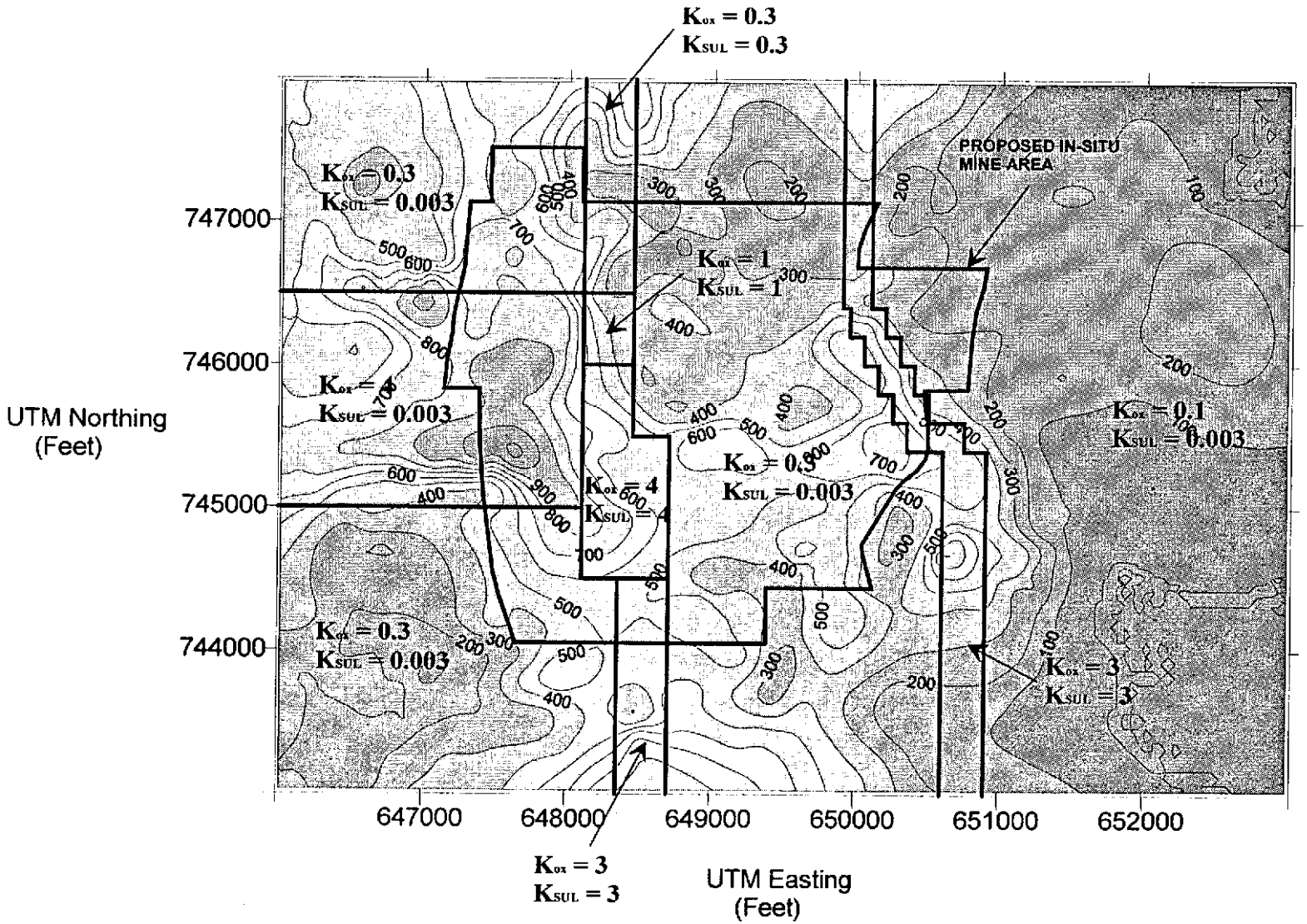
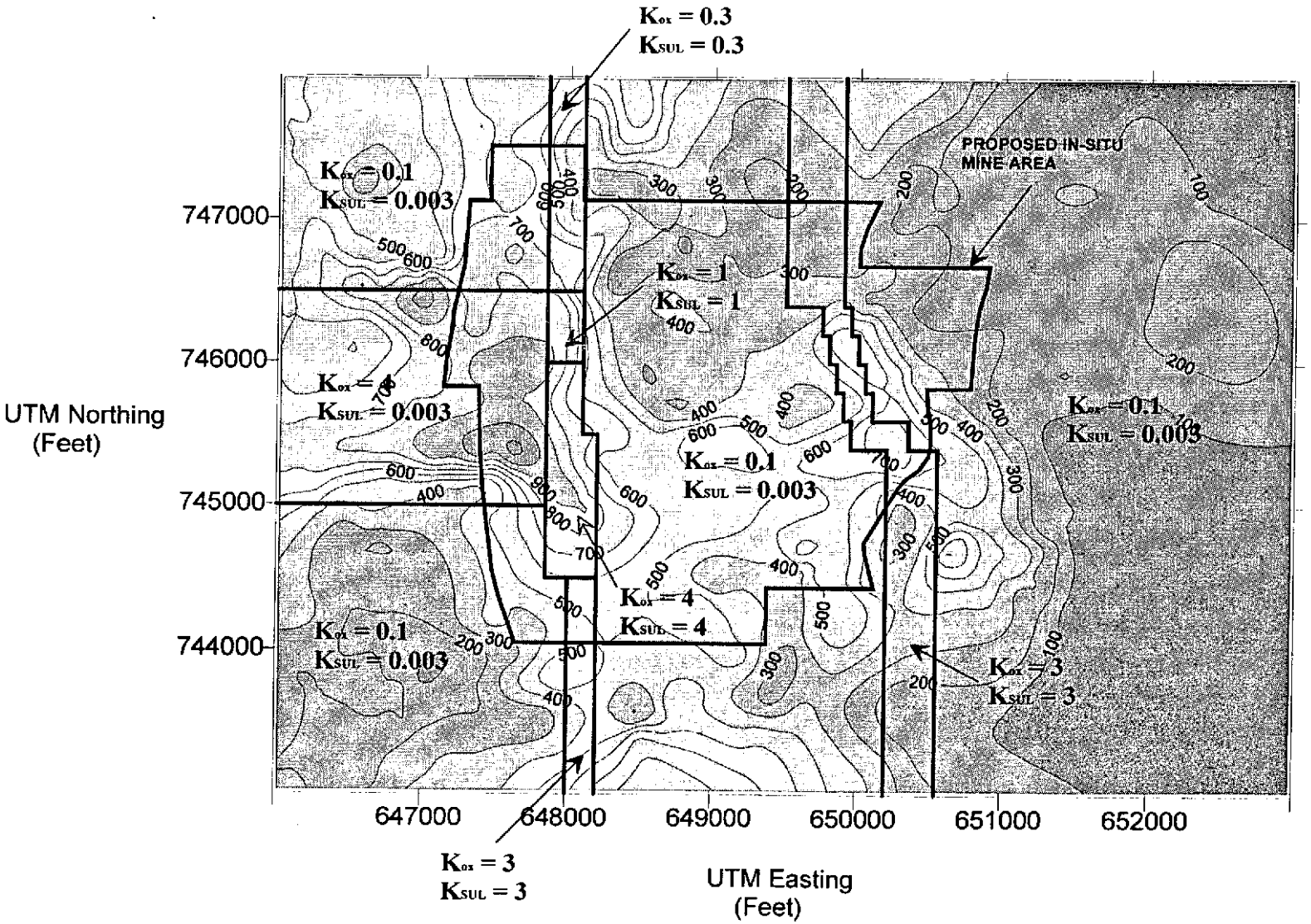
Maximum Drawdown in Well WW-3 Aquifer Test



Conductivity Distribution
Layer 5



Conductivity Distribution Layer 7



Model Sensitivity

- Objective: To Assess Which Parameters Have the Greatest Influence On Simulation Results

- Parameters:
  - Storage Parameters
  - Boundary Conditions
  - Hydraulic Conductivity
  - River Bed Conductance

- Conclusion: Insensitive to All Parameters Except Riverbed Conductance

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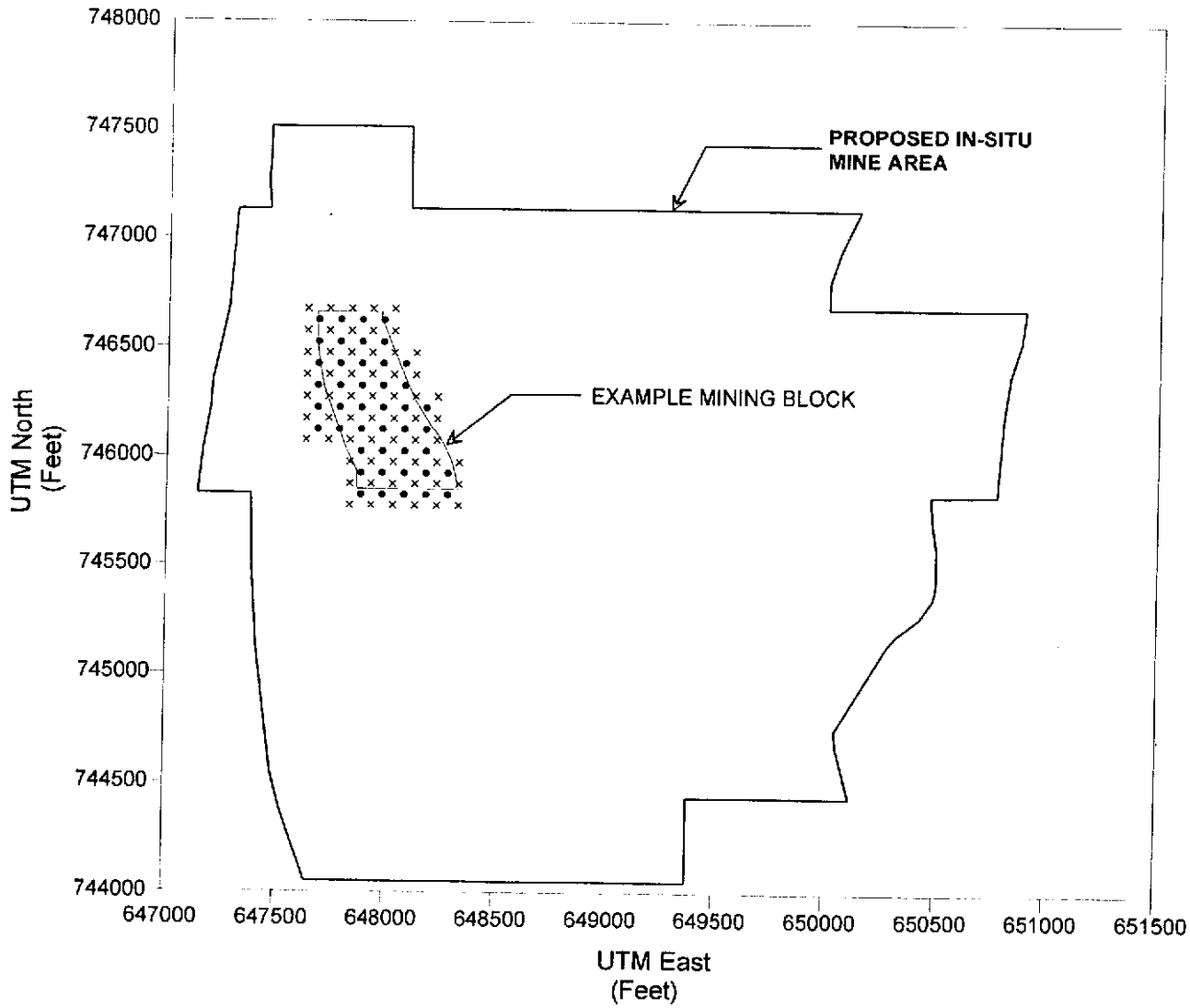
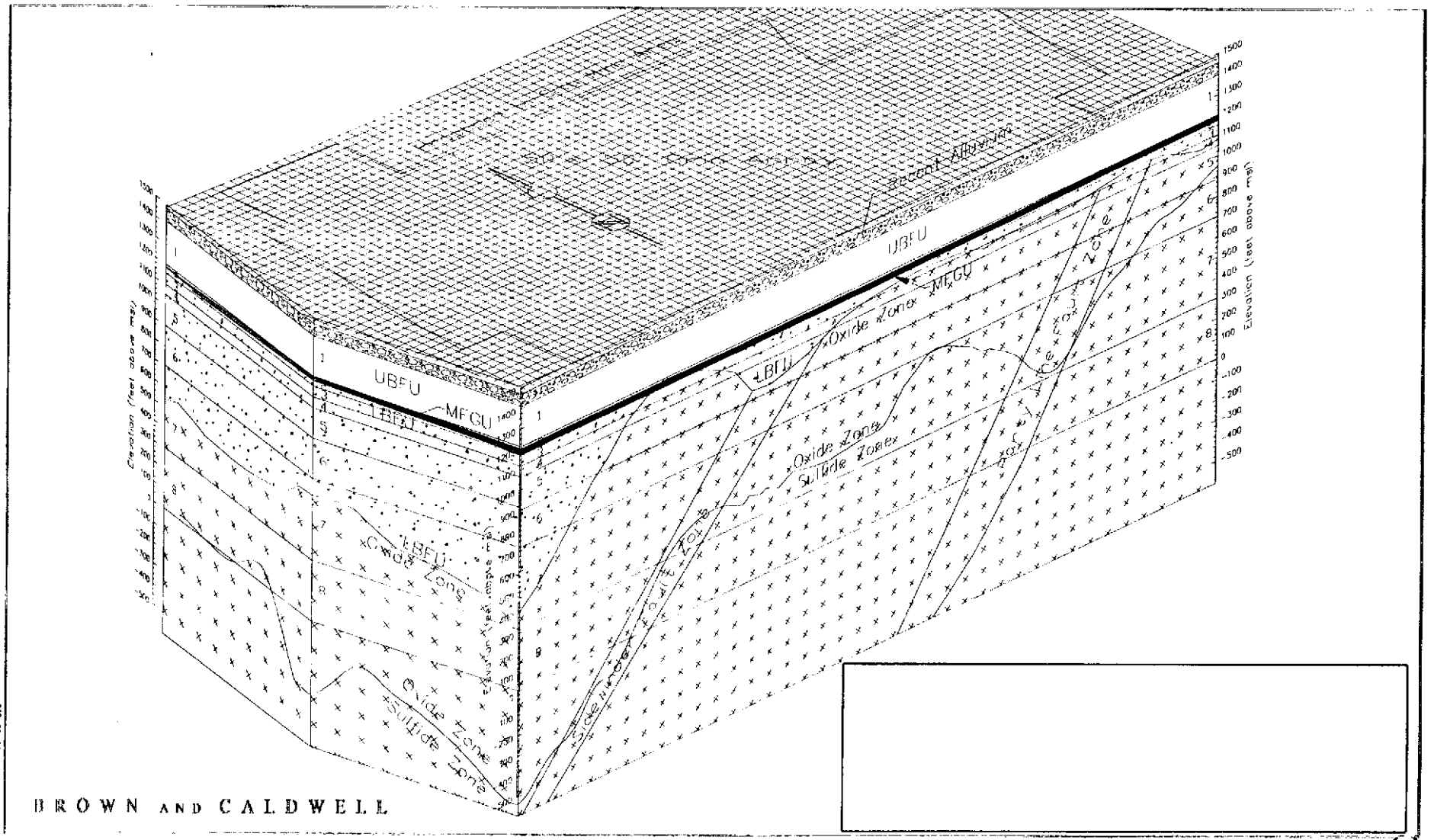
In-Situ Mine Operations

- Injection and Recovery
- Water balance

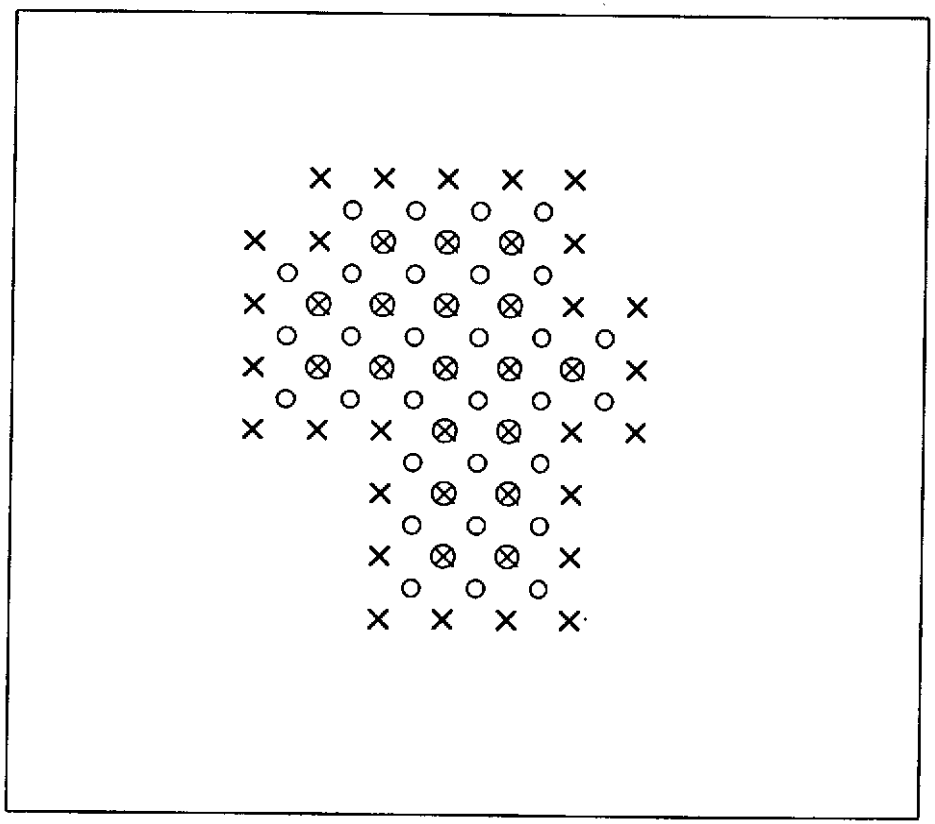
Example Mining Block



Isometric View of Model Layers



Example Injection and Recovery Well Pattern



○ INJECTION WELL

× PERIMETER RECOVERY WELL

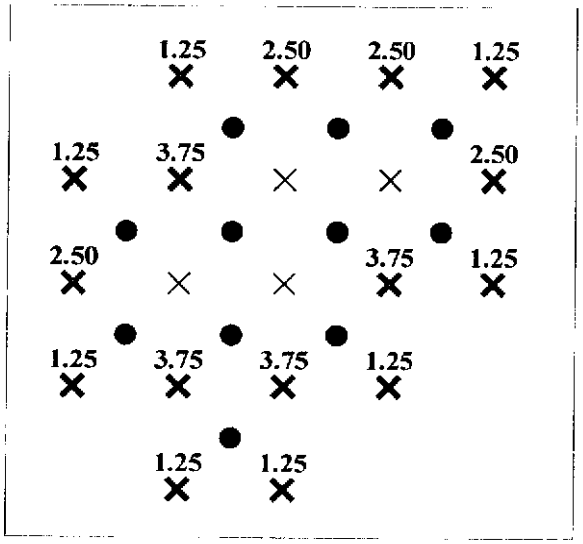
⊗ INTERIOR RECOVERY WELL

In-Situ Mine Operations

- Injection and Recovery
- Water balance

Well Pumping Strategy

Balanced Pumping

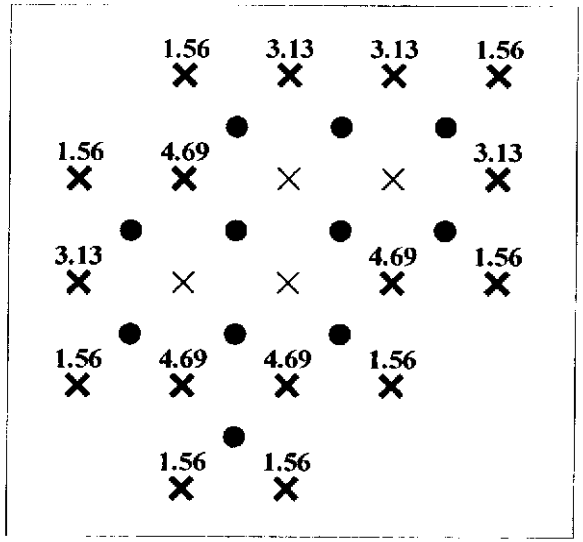


Total Injection = 55 gpm

Total Recovery = 55 gpm

Total Recovery = Total Injection

Net Out



Total Injection = 55 gpm

Total Recovery = 63.75 gpm

Total Recovery = Total Injection + 15.9%

● Interior Recovery Well (5 gpm)

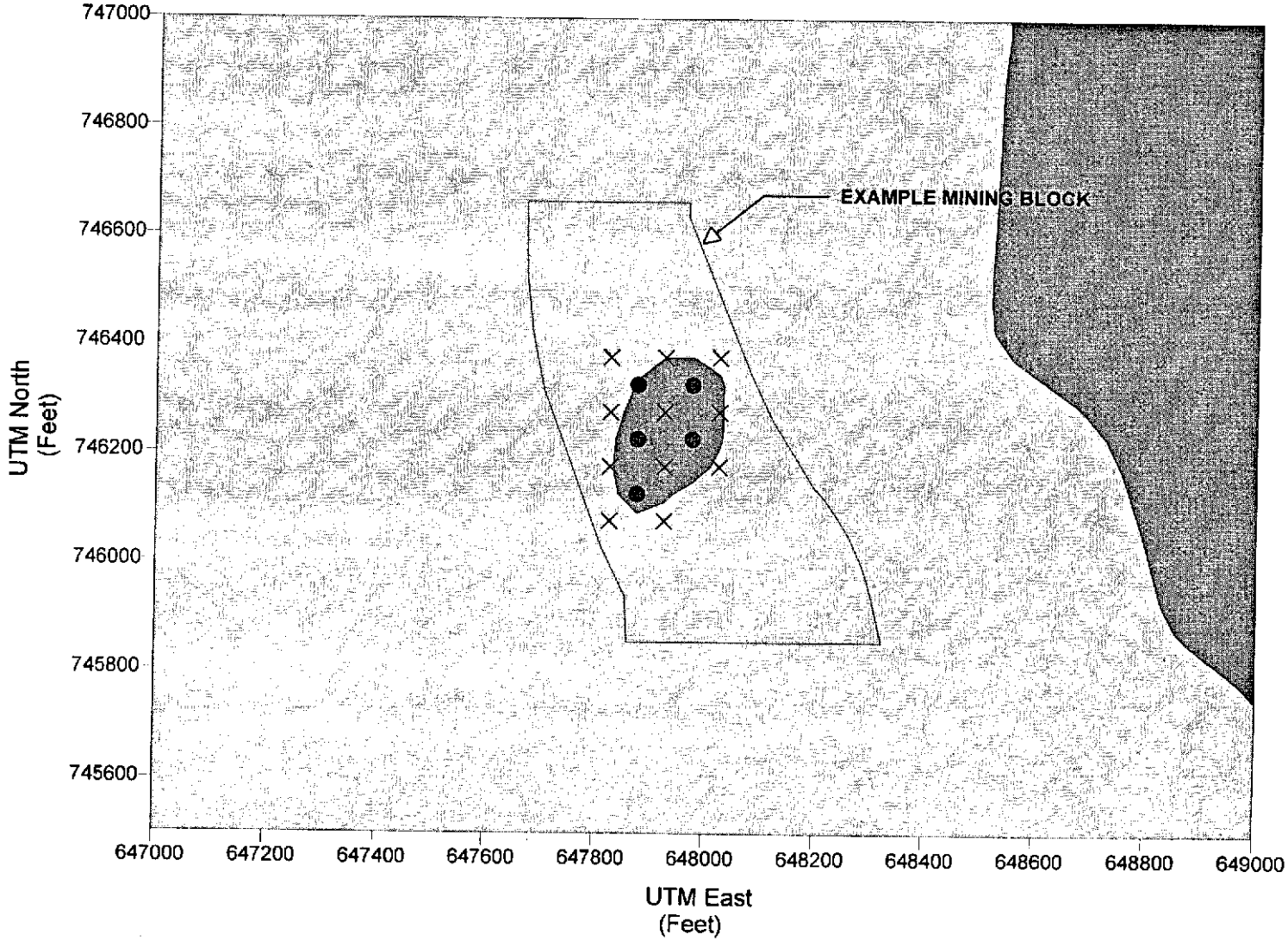
× Interior Injection Well (5 gpm)

✕ Perimeter Recovery Well (Variable Pumping Rate)

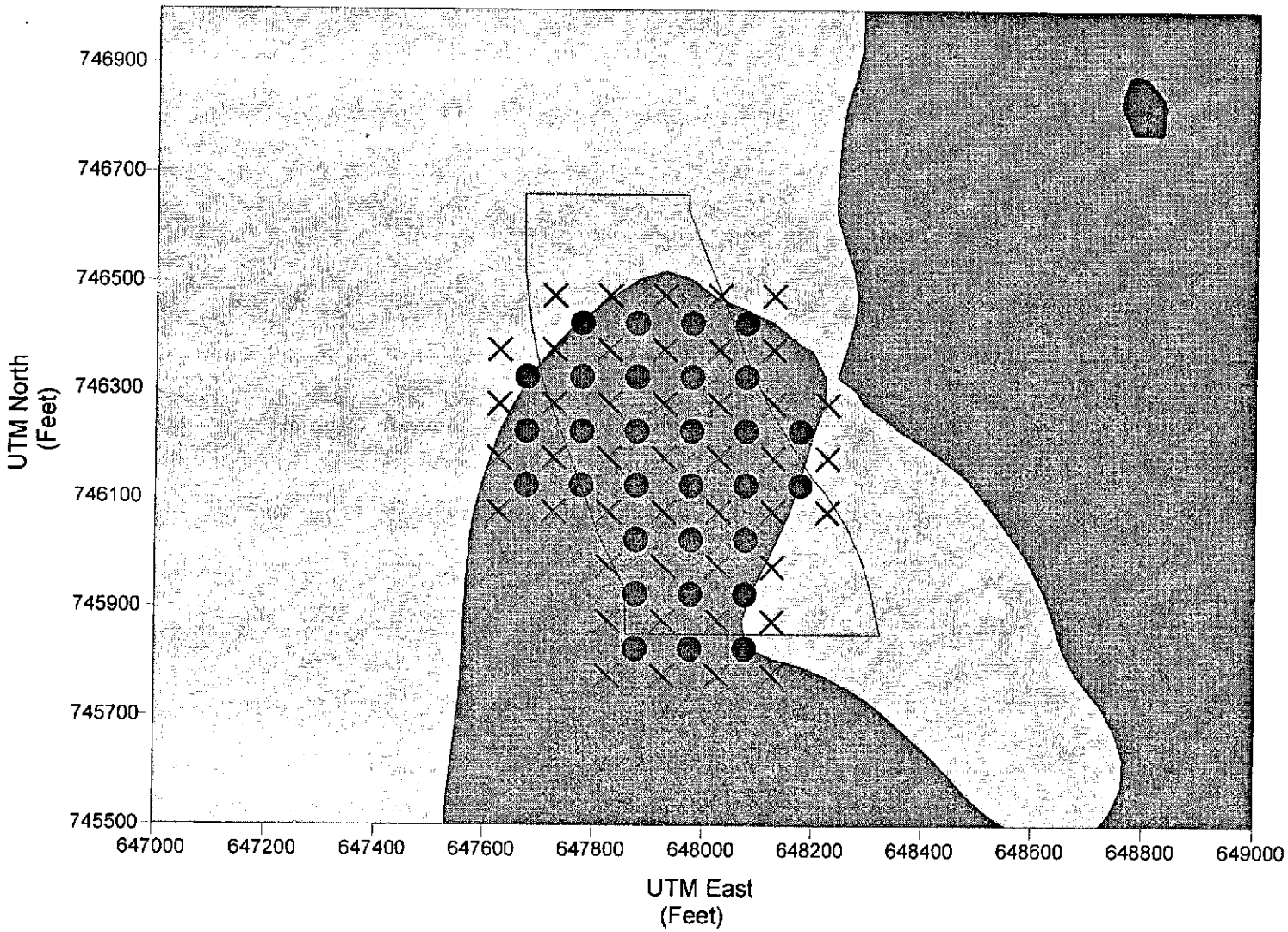
Simulation of Mine Block Operations

- Base Simulation
  - Example Mine Block
  - Demonstration of Hydraulic Control

Distribution of Injection and Recovery Wells in Layer 3



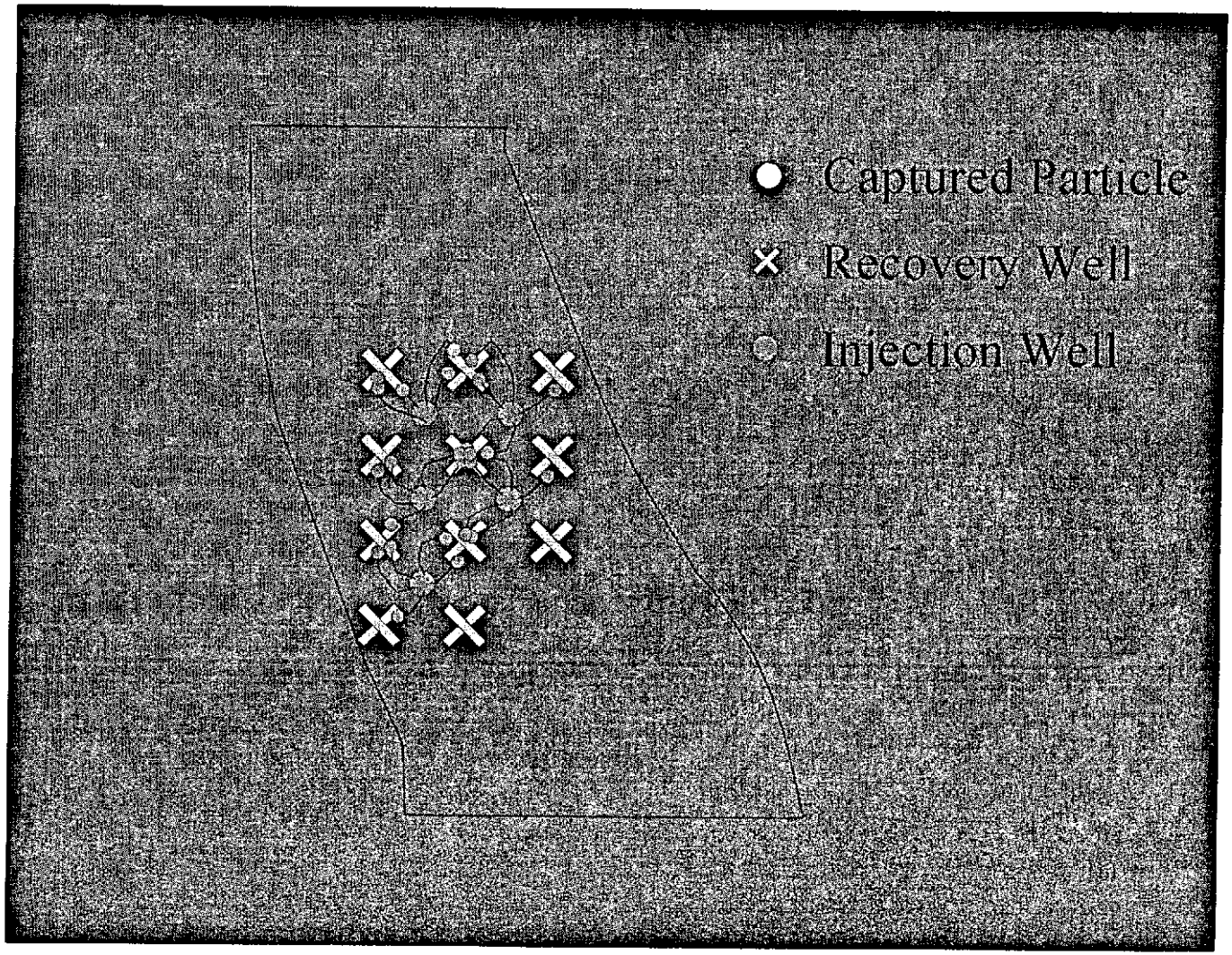
Distribution of Injection and Recovery Wells in Layer 5



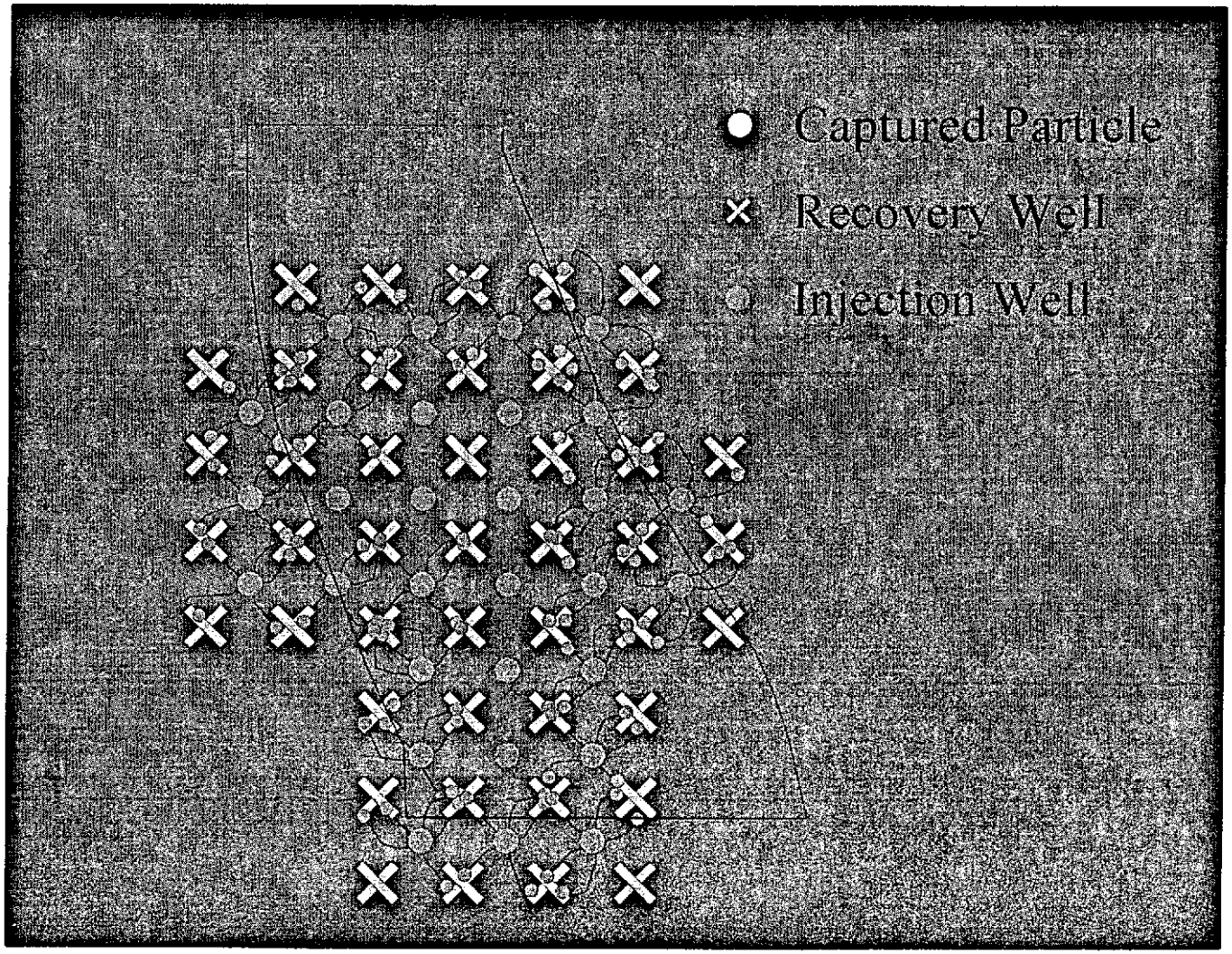
Hydraulic Control During In-Situ Mining

- Withdrawal Rate > Injection Rate
- Perimeter Recovery Wells
- Particle Tracking
  - Initial Location
  - Track Particles from Injection to Extraction

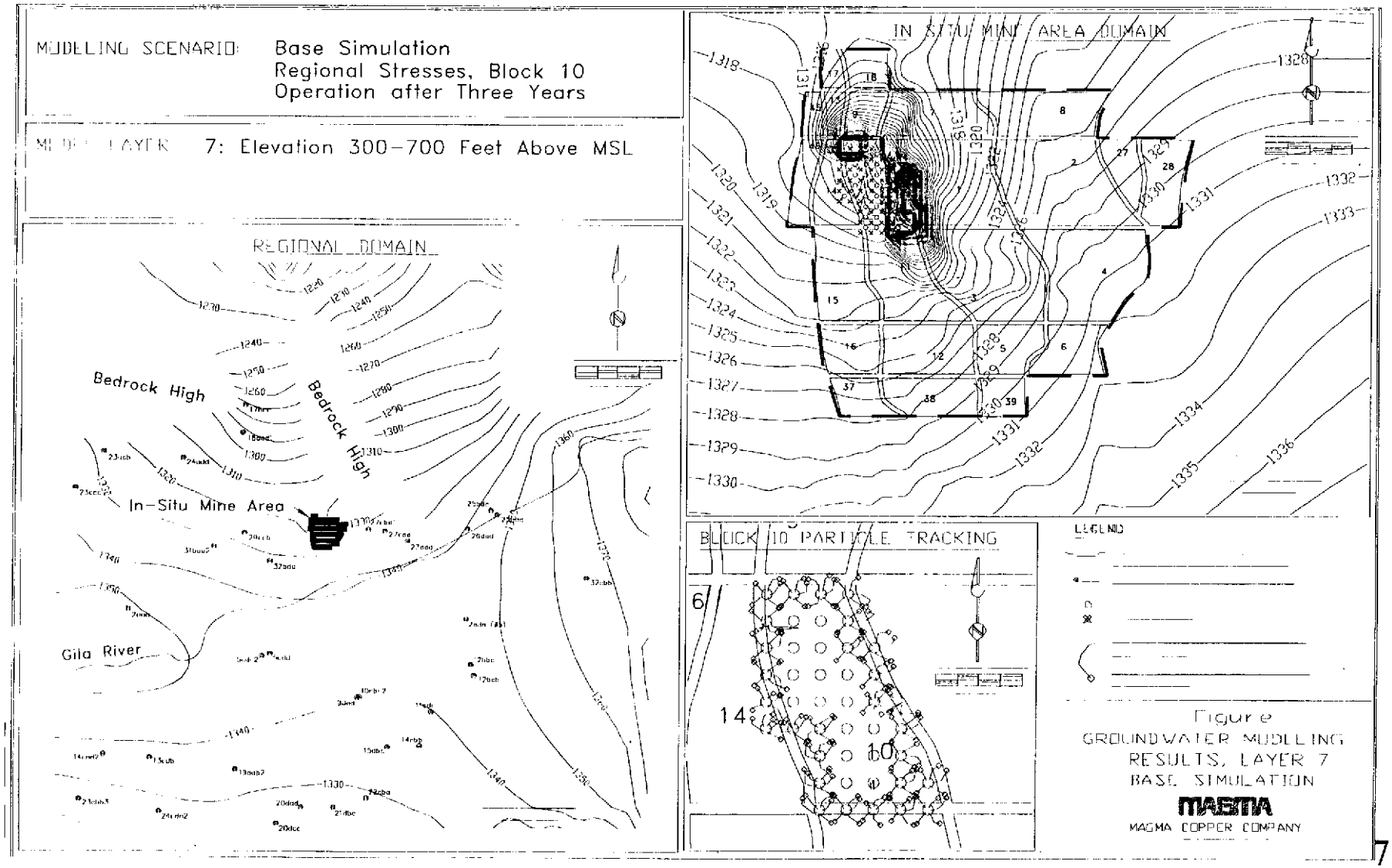
Particle Tracking
Layer 3



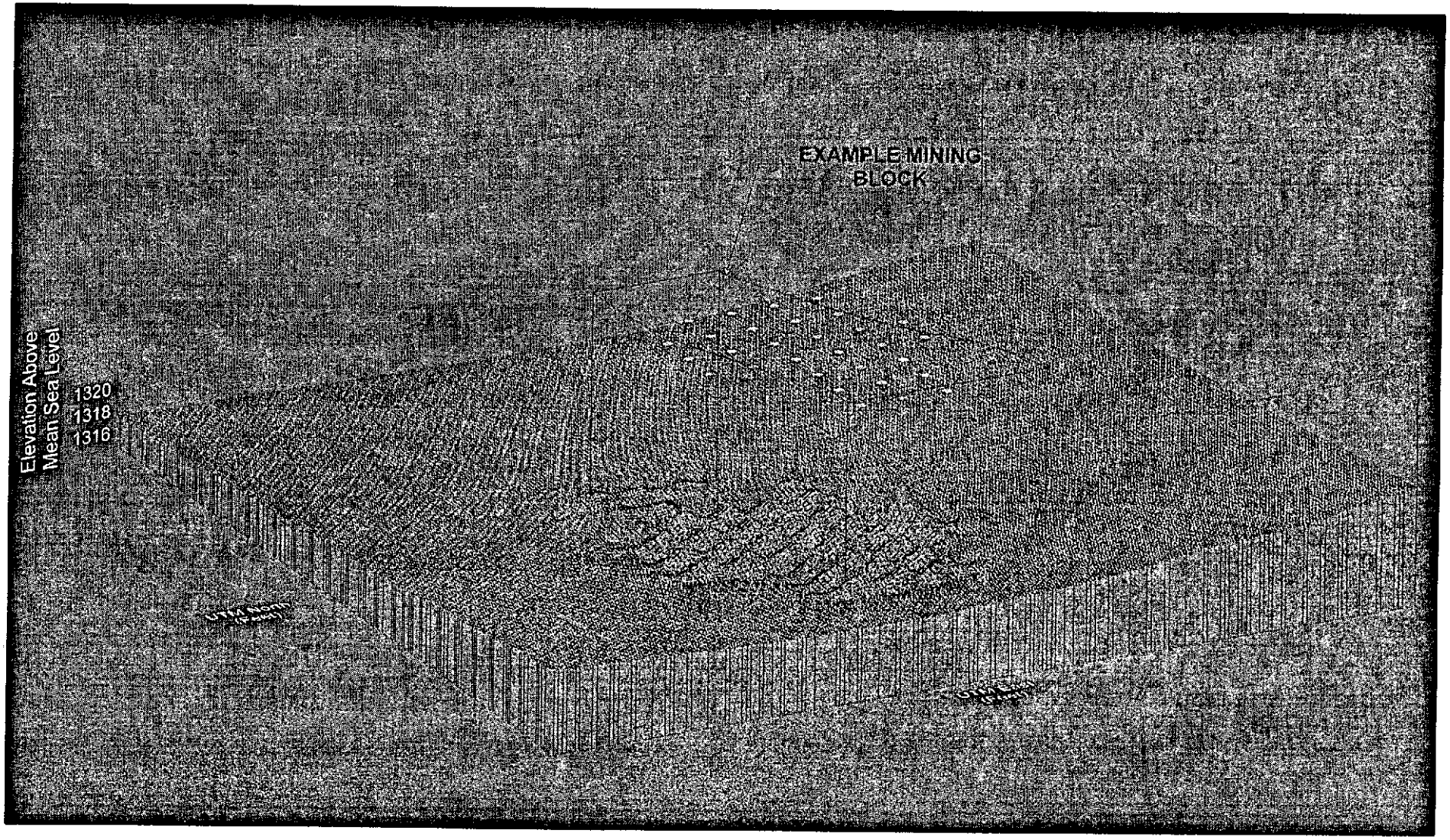
Particle Tracking
Layer 5



Base Simulation - Layer 7



Isometric View of Hydraulic Control



Extreme Simulations

- Increased Groundwater Withdrawal
  - 2x Irrigation Pumping
- Increased Groundwater Recharge
  - Gila River Flow for One Year
- Extreme Geologic Conditions

Extreme Geologic Conditions (continued)

- Layer 5 Conductivity 10x
- Layer 5 - North-South Anisotropy
- Layer 5 - East-West Anisotropy

Results and Conclusions

- Hydraulic Control Was Achieved in Normal Conditions
- Hydraulic Control Was Achieved in Extreme Conditions
- Outflow Rates > Inflow Rates + Regional Flow
- Final Outflow Rate Will Be Based On Mine Design
- Operation Monitoring Will Demonstrate Control

Simulation of Closure

- Block Washing
- Hydraulic Control During Closure
- Simulation of Closure
  - Particle Tracking

Simulation of Post-Closure

- No Hazardous Compounds
- Rinse Block to 750 ppm Sulfate
- Simulation of Post Closure
  - All Oxide at 750 ppm Sulfate
  - Normal Flow Condition
  - Simulation for 30 years

Chemical Transport Parameters

Table 4.5-1. Summary of Chemical Transport Parameters		
Initial Concentration		750 ppm
Simulation Time		30 years
Effective Porosity		
	UBFU	0.2
	LBFU	0.1
	Oxide	0.02
	Sulfide	0.002
Dispersivity		
	Longitudinal	10 feet
	Horizontal Transverse	1 foot
	Longitudinal Transverse	1 foot
Bulk Density		
	UBFU	1.6 g/cm^3
	LBFU	2.5 g/cm^3
	Oxide	2.6 g/cm^3
	Sulfide	2.6 g/cm^3
Distribution Coefficient (K_d)		1.5, 0.15 cm^3/g
Molecular Diffusion Coefficient		0 ft^2/day
Sorption Isotherm		Linear

Notes:

UBFU: Upper Basin Fill Unit
LBFU: Lower Basin Fill Unit
cm^3/g - cubic centimeters per gram
ft^3/day - cubic feet per day
g/cm^3 - grams per cubic centimeter
ppm - parts per million

Attenuation Coefficient

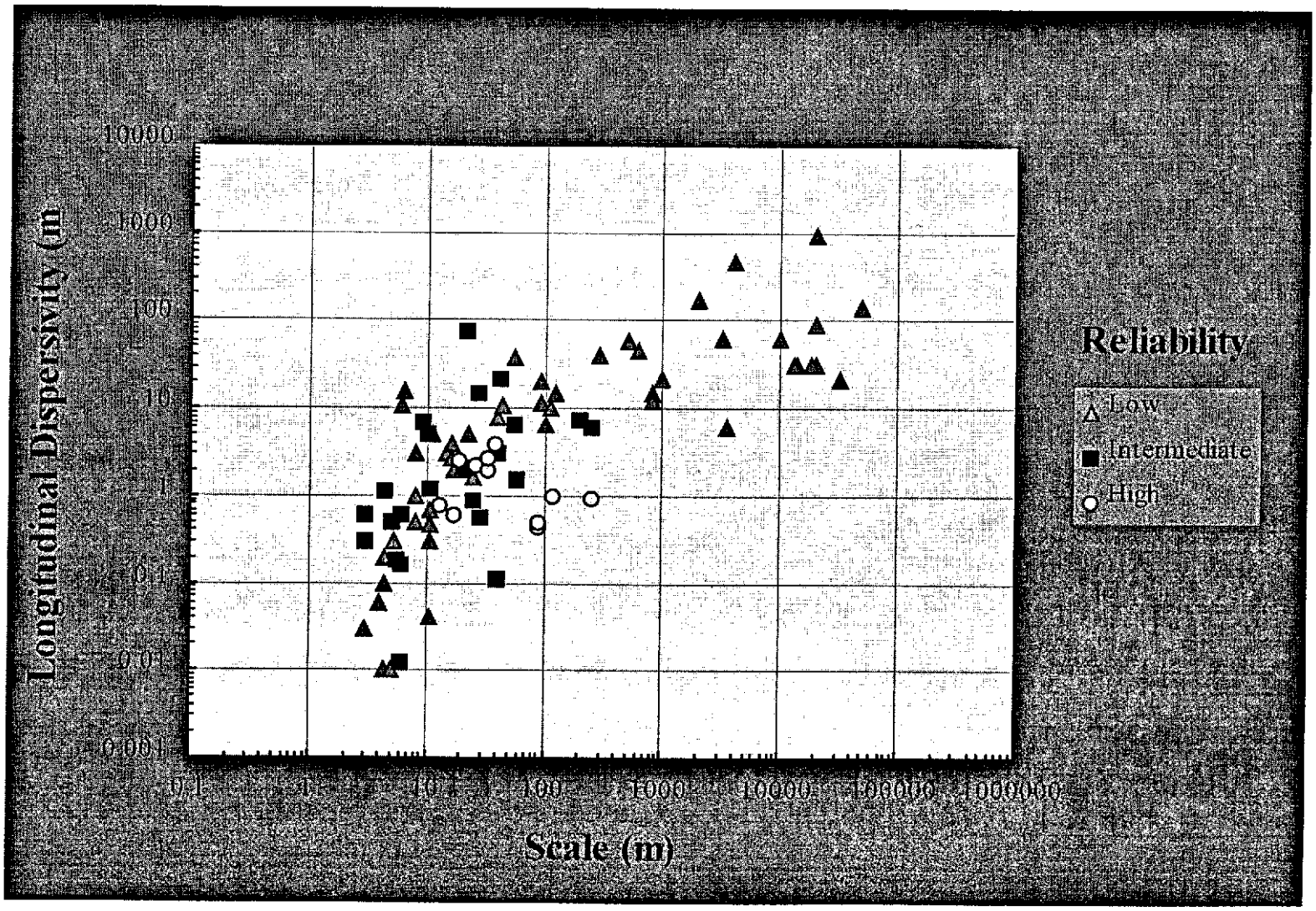
$$K_d = \frac{\text{Mass of solute on the solid phase per unit mass of solid phase}}{\text{Concentration of solute in solution}}$$

$$= (C_f - C_e) / C_e * V / M$$

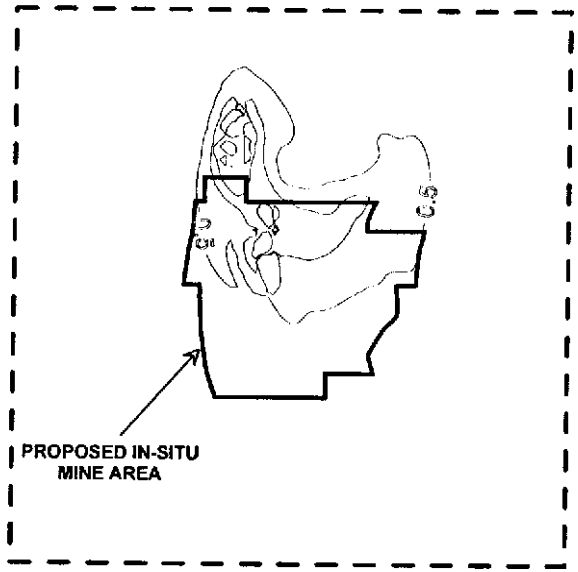
Where for each individual element,

C_f - concentration in the starting "STOCK" soulution (mg/l)
C_e - concentration in the solution at the end of a cycle or pass (mg/l)
V - volume of the starting solution in the first cycle of the sequential batch tests (ml), or
- volume of the solution at the start of the column test (ml)
M - total mass of rock contacted during the batch or column tests (grams).

Longitudinal Dispersivity versus Scale



Sulfate Concentration - Kd = 0.15



1/2 MILE EXEMPTION BOUNDARY

SIMULATION PARAMETERS

INITIAL CONCENTRATION = 750 PPM

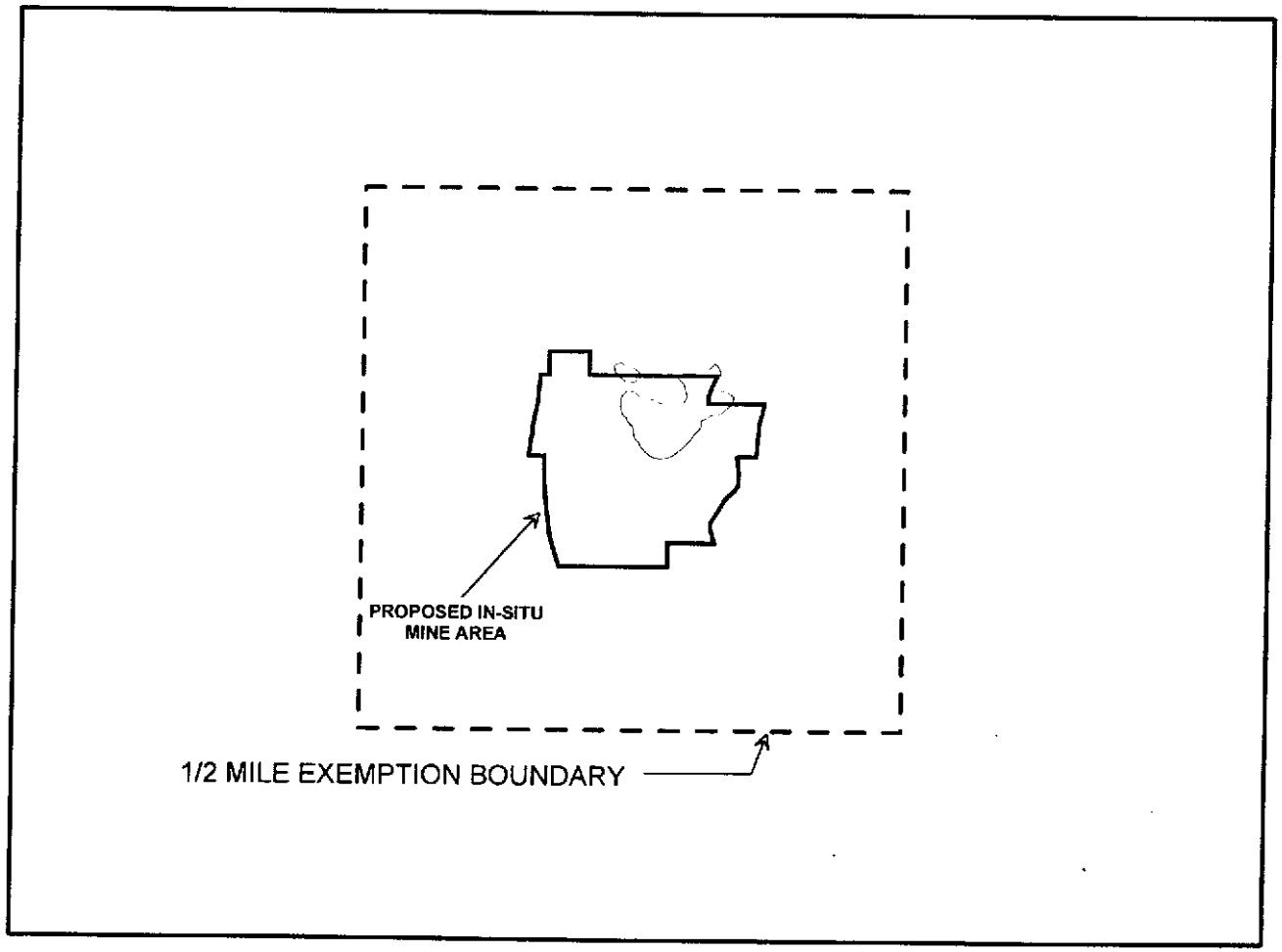
SIMULATION TIME = 30 YEARS

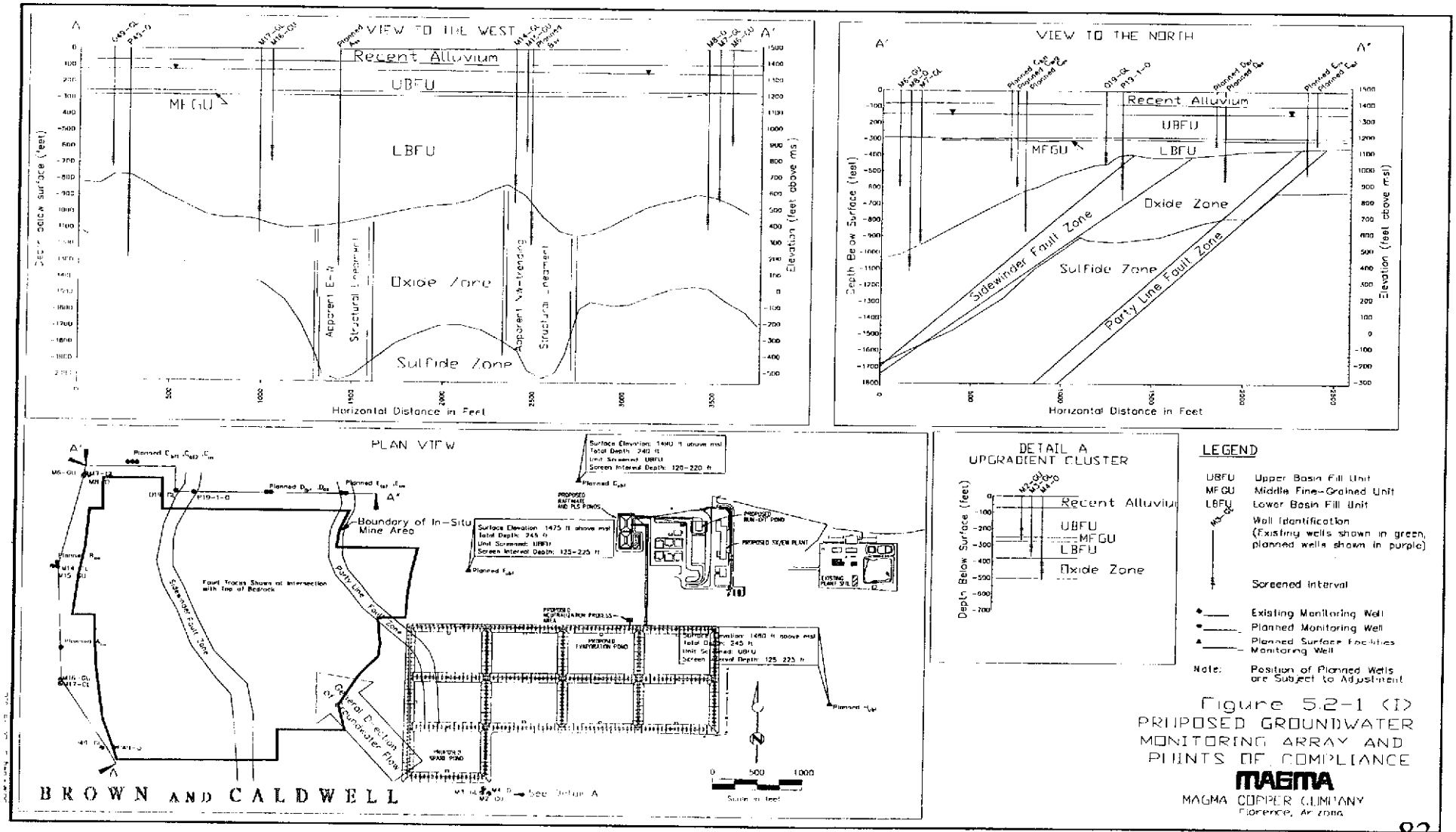
K_d = 0.15 cm^3/g

LONGITUDINAL DISPERSIVITY = 10 FEET

HORIZONTAL DISPERSIVITY = 1 FEET

Sulfate Concentration - Kd=1.5



SIMULATION PARAMETERS
INITIAL CONCENTRATION = 750 PPM
SIMULATION TIME = 30 YEARS
K_d = 1.5 cm^3/g
LONGITUDINAL DISPERSIVITY = 10 FEET
HORIZONTAL DISPERSIVITY = 1 FEET

Proposed POC Wells