AIPG WEBINAR
GROUNDWATER ISSUES ENCOUNTERED IN MINING PROJECTS

PRESENTED BY

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- HYDROGEOLOGY DURING THE OPERATIONS PHASE
- HYDROGEOLOGY DURING THE CLOSURE PHASE
- CONCLUSIONS

INTRODUCTION

- **Presenter background -**
  - BS/MS from Colorado State University, Ft. Collins, CO
  - 46 years of experience in geology, hydrogeology, consulting
    - Anaconda Minerals exploration geologist – Denver
    - 22 years with Dames & Moore in Denver, CO and Phoenix, AZ – Arizona Geoscience manager
    - 24 years: co-founder Clear Creek Associates, Arizona; now part of Geo-Logic Associates
  - Expertise in groundwater modeling, hydrogeologic investigations at mining properties, design and testing of bedrock monitoring and production wells (and other stuff)
  - Canadian National Instruments Qualified Person – four mining properties, AZ and CA
  - Testifying expert in legal cases involving water rights and contaminant hydrogeology
  - Member – AIPG Executive committee (2015-2019 Treasurer and President)
  - Member: Arizona Hydrological Society, SME, ASCE, GRA of CA, NGWA, IAH
  - Registered geologist: Arizona, California, Oregon, Washington, Alaska
  - Certified Hydrogeologist: California
  - Certified Professional Geologist - AIPG

BARTLETT CAVEAT

- Presenters experience is focused on hard rock mining in the southwest U.S. with only limited experience in foreign countries or in other parts of the U.S.
- Much of my work is considered confidential by my clients, therefore, my presentation is necessarily generic in nature
- I will not discuss hydrogeology associated with sand and gravel, coal, or uranium mining operations

MINING AND GROUNDWATER
KEY MILESTONES IN A MINE'S LIFE

- Water is a key part of mining – there is either too much of it, or too little of it; rarely does a mine achieve the "goldilocks" scenario relative to water!
- Regardless of the quantity and "richness" of an ore body – it is worthless if there is an insufficient water supply
- To discuss water and hydrogeology of mines it is best to think of the life cycle of a mine
- The life cycle of a mine can vary significantly from <5 years to >100 years
- There are three main chapters in the life of any mine:
  - Planning
  - Operations
  - Closure

PLANNING

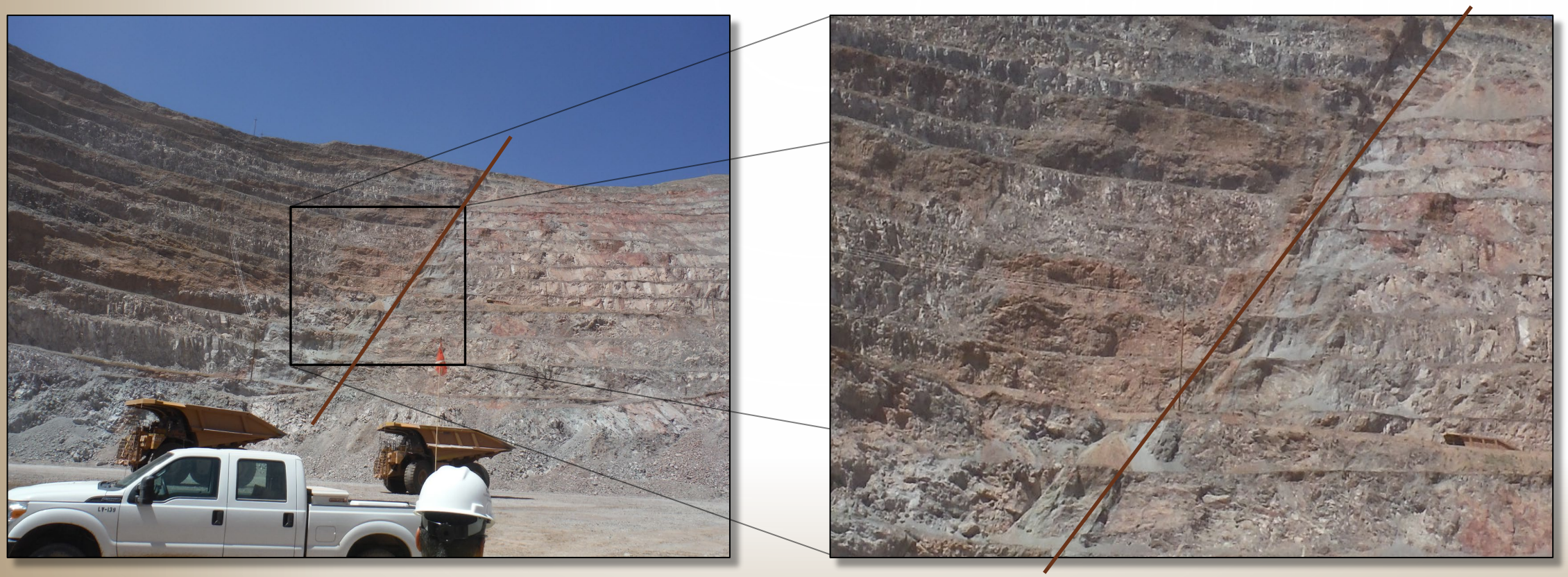
PLANNING

- Hydrogeologic settings common to mining operations
- Opportunities to augment data from mineral exploration and development drilling
- Assembling data: ArcGIS, LeapFrog, databases
- Surface geophysics / downhole geophysics
- Exploration and Test Wells in fractured rock aquifers
- On-going Monitoring: water levels, meteorology, water quality
- Integrating data collection: cross pollination of disciplines
- Groundwater models – types, utility, limitations
- Permitting requires hydrogeologic input: UIC, AZ Aquifer Protection Permits, Exploration MPO, etc

HYDROGEOLOGIC SETTINGS

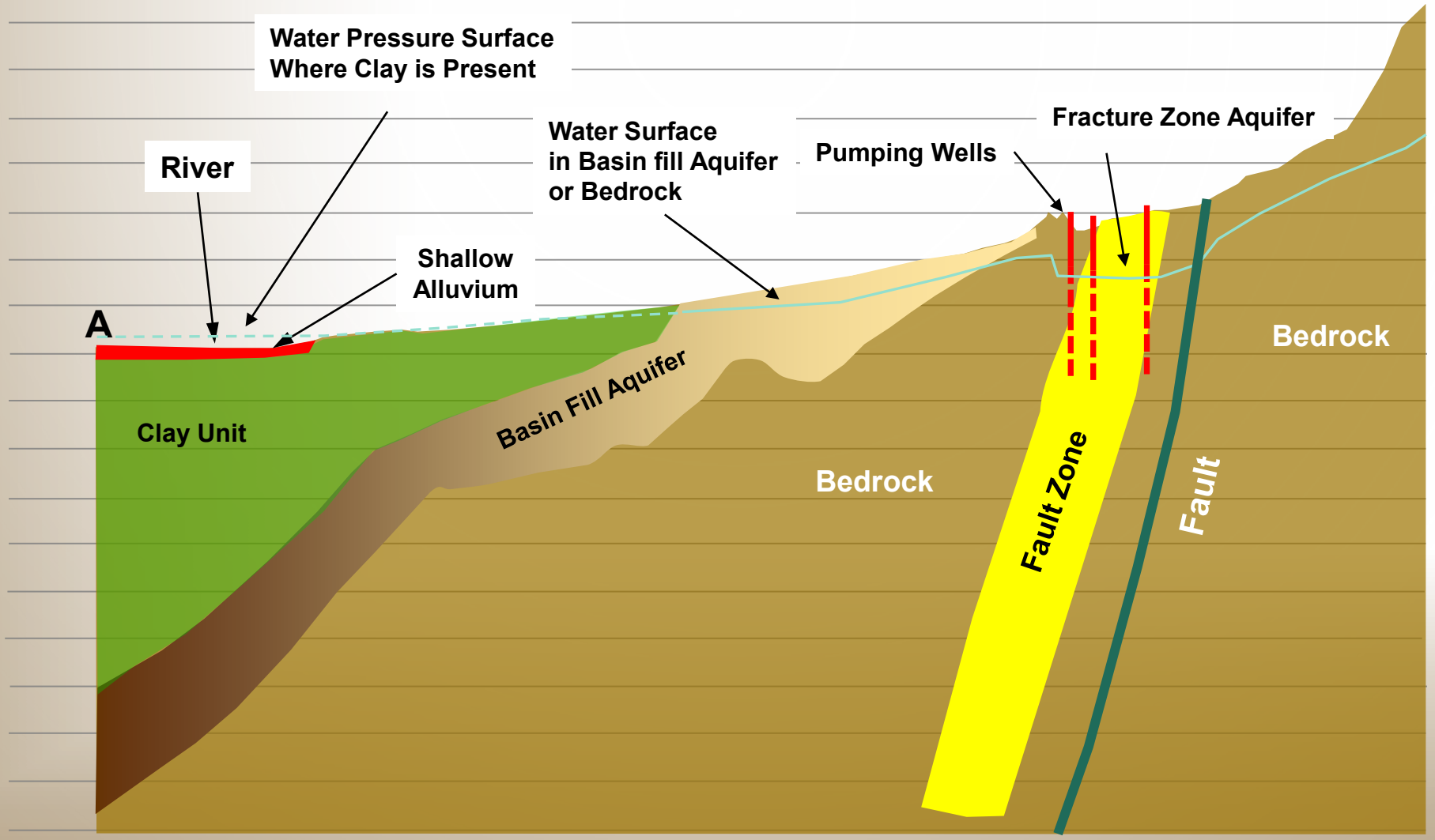
- Many mines are located in hard rock settings
  - Fractured igneous, sedimentary, metamorphic terrains
  - Groundwater flow strongly influenced by fractures, fracture zones, joints, etc
  - Anisotropic responses common
- Often adjacent to basin fill settings that have significant permeabilities and groundwater storage
- Hard rock and basin fill aquifers can be strongly linked
- Field investigations can be quite complex
  - Necessitates extensive drilling and well installation programs
  - Not always financially feasible for smaller mining operations

FRACTURED ROCK AQUIFER



Major fault zone in Tertiary volcanic sequence
(Barrier or conduit to groundwater flow??)

SCHEMATIC CROSS SECTION

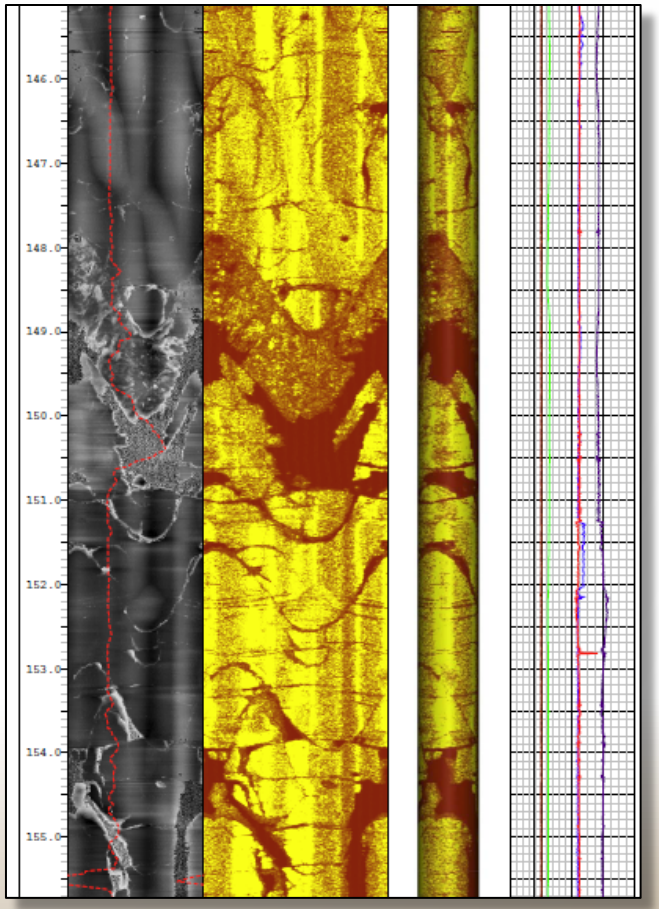


DATA COLLECTION DURING EXPLORATION

- Exploration and development drilling programs designed to define mineral reserves can be an opportunity to obtain useful hydrogeologic data
- Drillers and site geologists can collect information helpful to the hydrogeologist including:
  - Locations of significant faults and fractures encountered in holes
  - Lost circulation zones
  - RQD (rock quality designation) or fracture intensity
  - Downhole geophysics (esp. e-logs, sonic, ATV)
  - Characteristics of basin fill overlying bedrock (often overlooked by exploration)
- Surface geophysics: IP, gravity, AMT

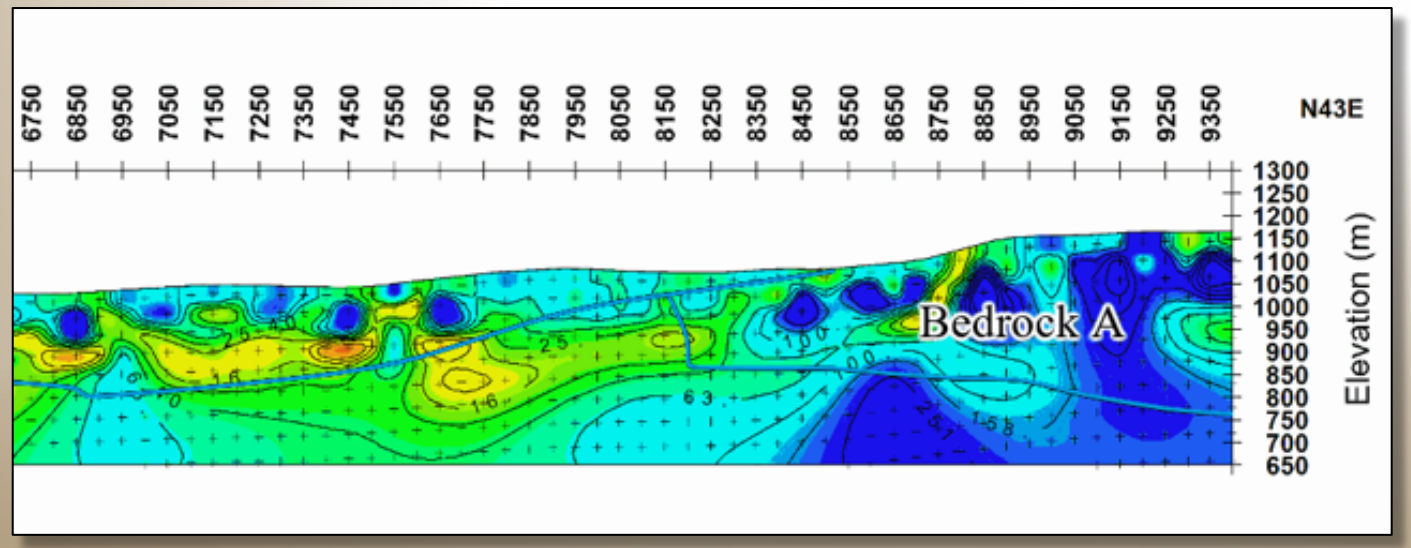
EXPLORATION DATA

Rock Core
RQD
Fracture Intensity



Acoustic Televiewer Log (downhole)

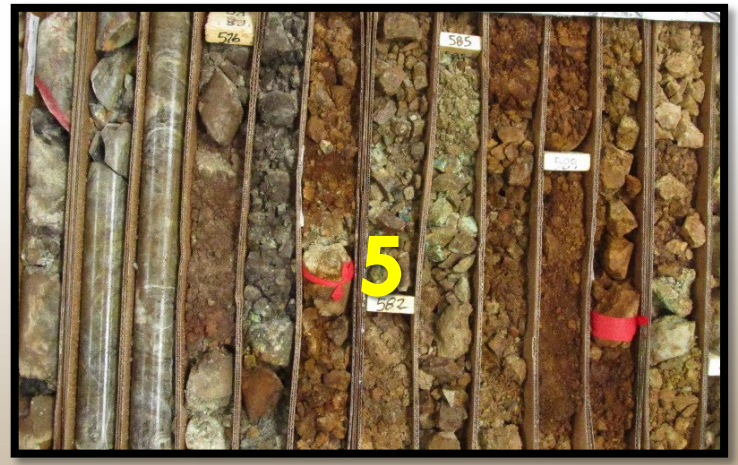
Surface Geophysics: CSAMT Data



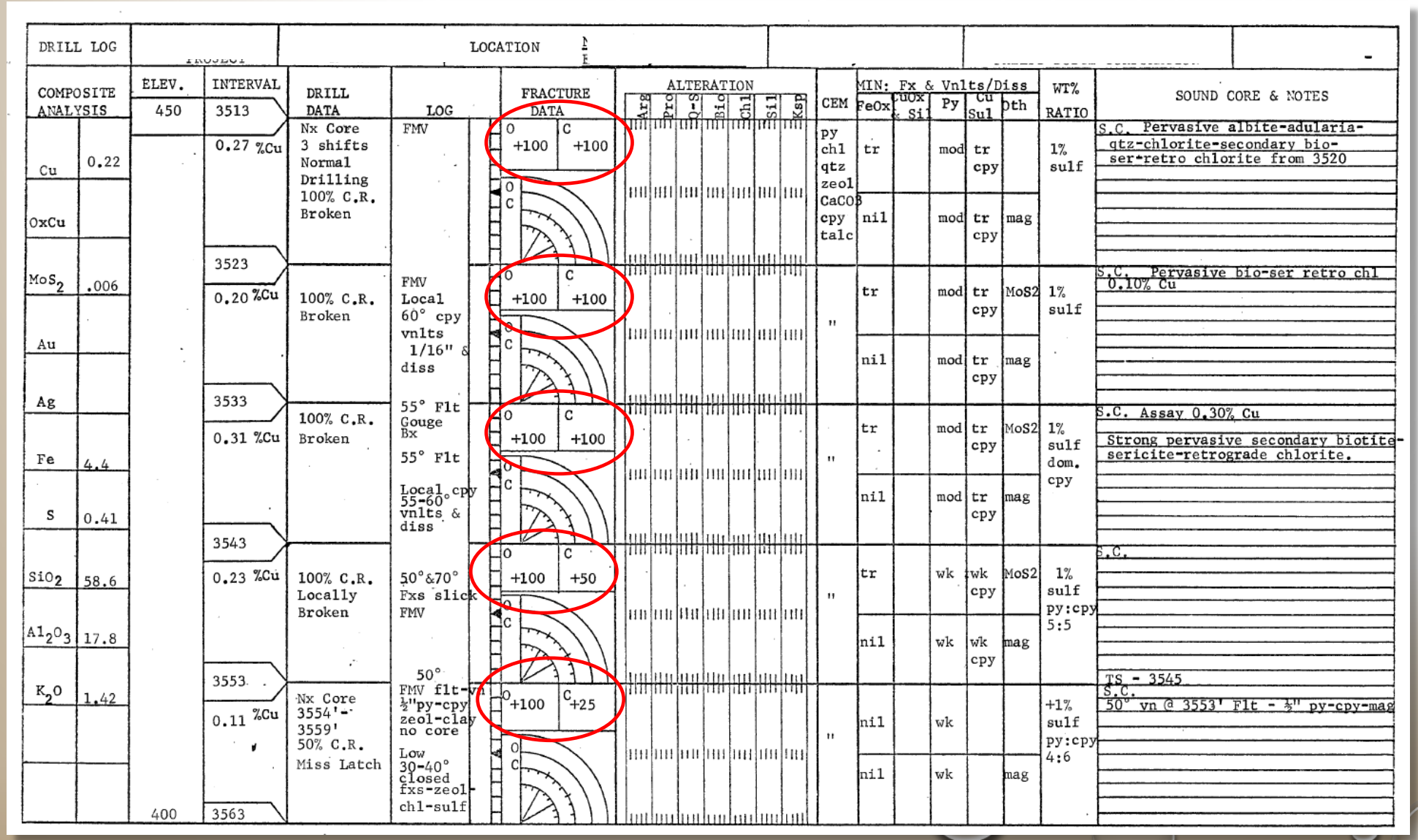
CORE LOGGING

- RQD: Rock Quality Designation: is a rough measure of the degree of jointing or fracturing in a rock mass. Measure the total length of core >10 cm and divide by the total length of the core run. High-quality rock has an RQD of more than 75%, low quality of less than 50%.
- Fracture Intensity: An alternative to RQD that allows a more refined analysis of fracturing useful for hydrogeologic analyses. Depends on qualitative judgement of fracturing. Can isolate zones less than a foot long.

FRACTURE INTENSITY



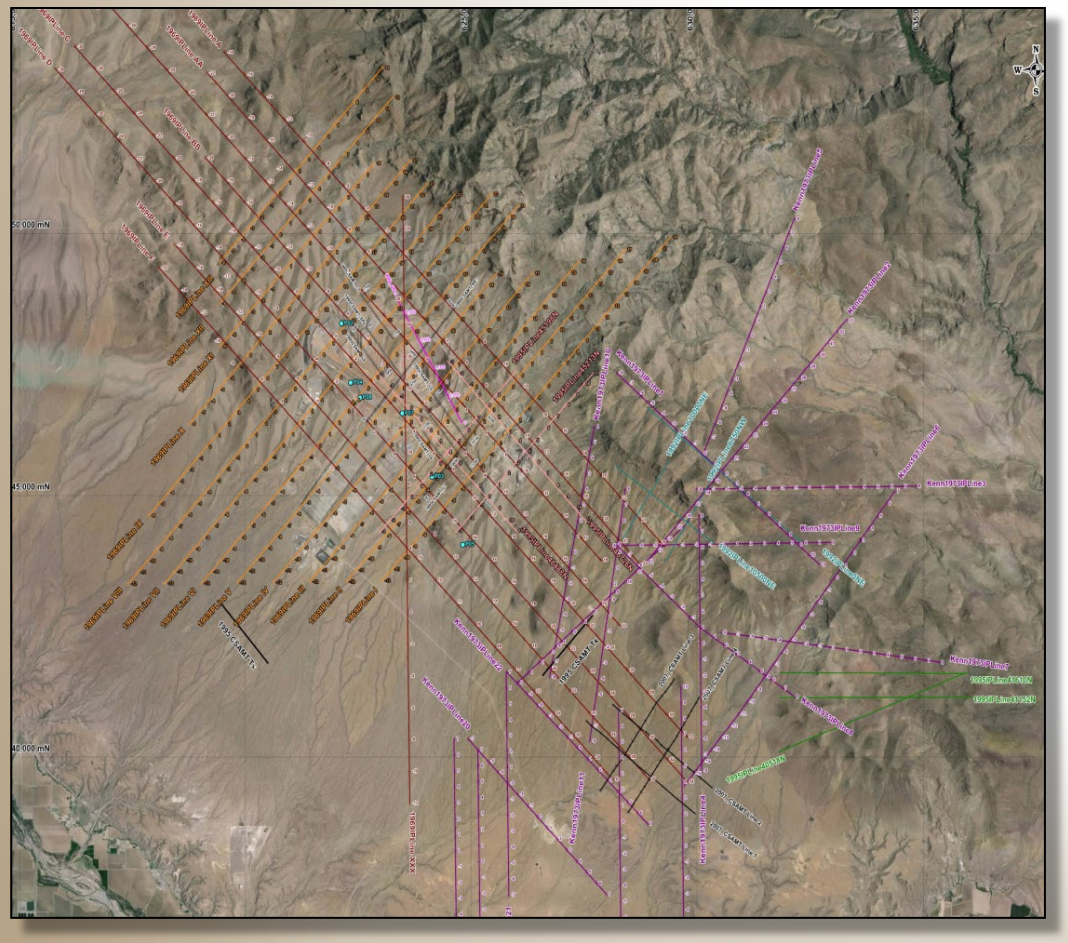
Exploration Hole Log
Observing the degree of open vs closed fractures

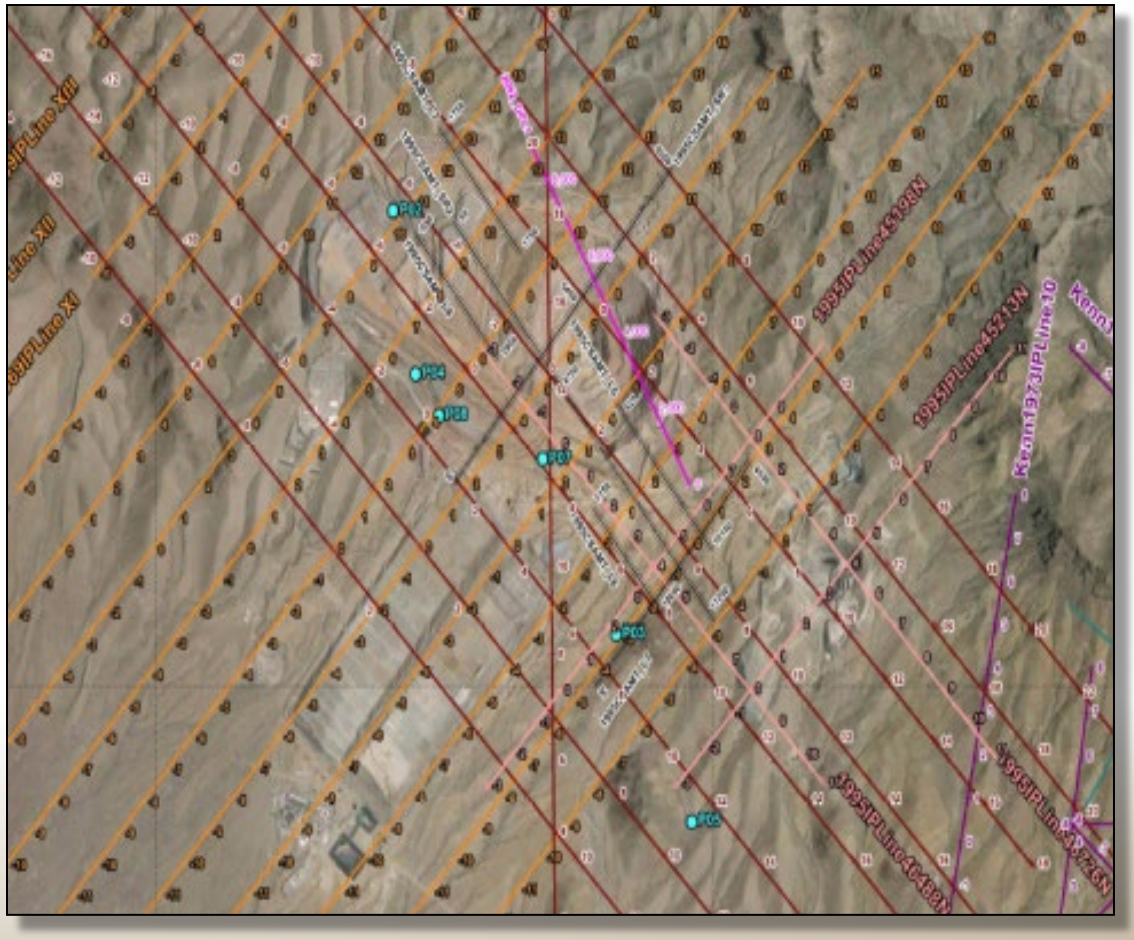


DRILL LOG — LOCATION

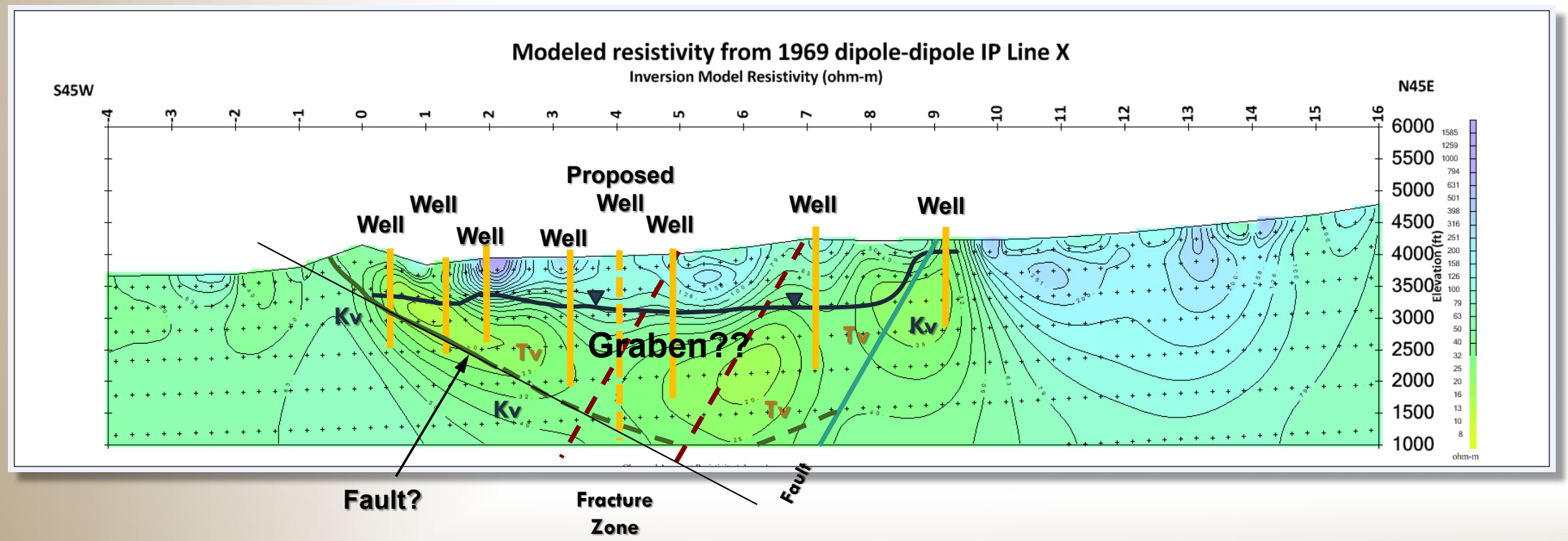
COMPOSITE ANALYSIS		ELEV.	INTERVAL	DRILL DATA	LOG	FRACTURE DATA	ALTERATION (Arg Pro Q-S Bio Chl Sil Ksp)	CEM	MIN: Fx & Vnlts/Diss FeOx	CuOx & Sil	Py	Cu Sul	Oth	WT% RATIO	SOUND CORE & NOTES
Cu	0.22	450	3513	Nx Core 3 shifts Normal Drilling 100% C.R. Broken	FMV	O +100 C +100		py chl qtz zeol CaCO3 cpy talc	tr		mod	tr cpy		1% sulf	S.C. Pervasive albite-adularia-qtz-chlorite-secondary bio-ser-retro chlorite from 3520
OxCu			0.27 %Cu			O C			nil		mod	tr cpy	mag		
MoS_2	.006		3523	100% C.R. Broken	FMV Local 60° cpy vnlts 1/16" & diss	O +100 C +100		"	tr		mod	tr cpy	MoS2	1% sulf	S.C. Pervasive bio-ser retro chl 0.10% Cu
Au			0.20 %Cu			O C			nil		mod	tr cpy	mag		
Ag			3533	100% C.R. Broken	55° Flt Gouge Bx 55° Flt Local cpy 55-60° vnlts & diss	O +100 C +100		"	tr		mod	tr cpy	MoS2	1% sulf dom. cpy	S.C. Assay 0.30% Cu Strong pervasive secondary biotite-sericite-retrograde chlorite.
Fe	4.4		0.31 %Cu			O C			nil		mod	tr cpy	mag		
S	0.41		3543	100% C.R. Locally Broken	50°&70° Fxs slick FMV	O +100 C +50		"	tr		wk	wk cpy	MoS2	1% sulf py:cpy 5:5	S.C.
SiO_2	58.6		0.23 %Cu			O C			nil		wk	wk cpy	mag		
Al_2O_3	17.8		3553	Nx Core 3554'-3559' 50% C.R. Miss Latch	50° FMV flt-vn ½"py-cpy zeol-clay no core Low 30-40° closed fxs-zeol-chl-sulf	O +100 C +25		"	nil		wk			+1% sulf py:cpy 4:6	TS - 3545 S.C. 50° vn @ 3553' Flt - ½" py-cpy-mag
K_2O	1.42		0.11 %Cu			O C			nil		wk		mag		
		400	3563												

DISTRICT-WIDE IP SURVEY (FROM 1960’S- 1970’S)

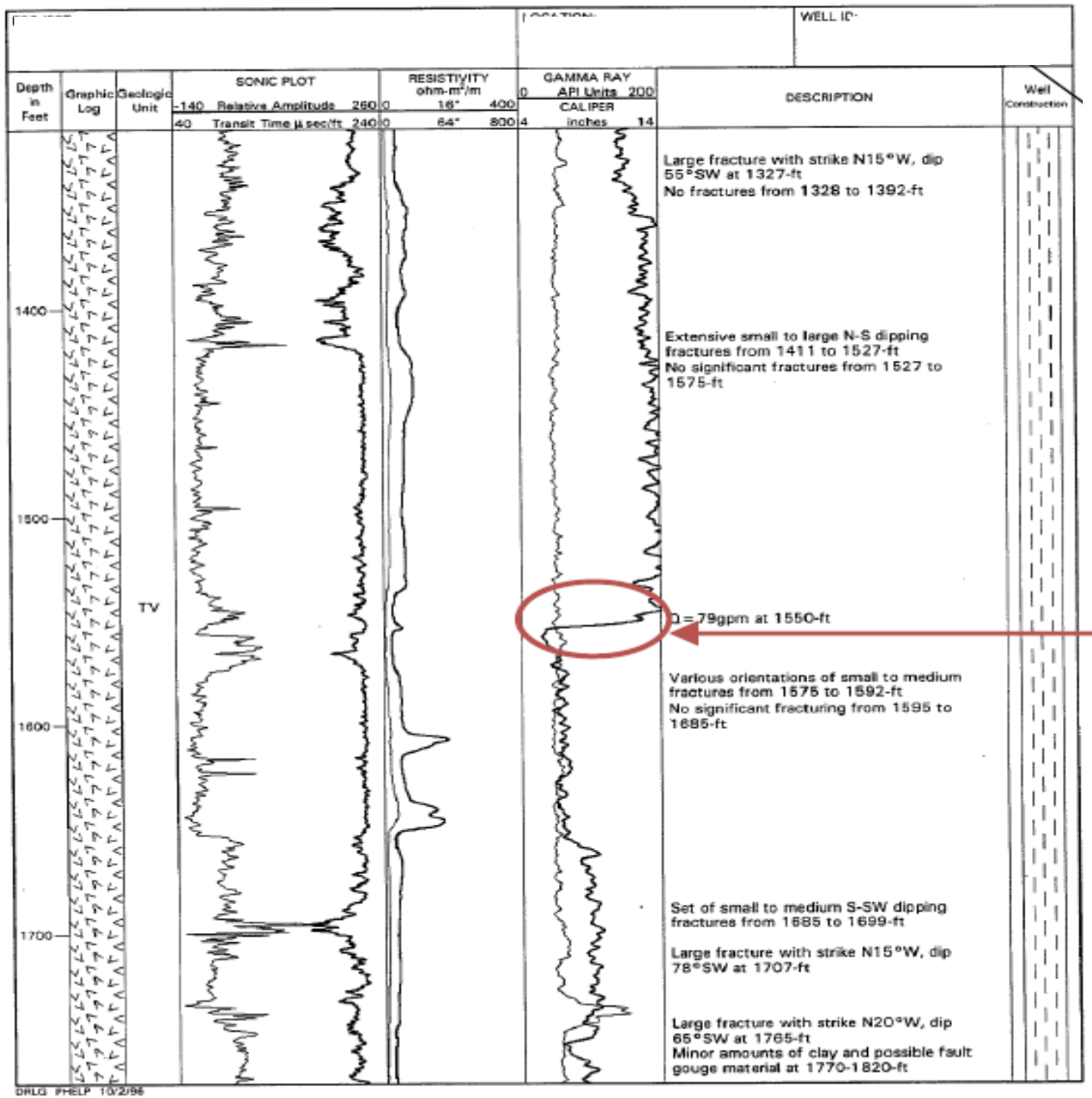




Induced Polarization (IP) Geophysical lines


Modeled resistivity from 1969 dipole-dipole IP Line X
Inversion Model Resistivity (ohm-m)
S45W
N45E
Well
Well
Well
Well
Proposed
Well
Well
Well
Well
Kv
Kv
Kv
Tv
Tv
Tv
Graben??
Fault?
Fracture
Zone
Fault
Elevation (ft)
ohm-m

WELL LOG



Gamma Ray Anomaly

Surface Geologic Mapping

Highly broken rhyolite flows at ground surface

Aphanitic Rhyolite – A Dream Volcanic Aquifer

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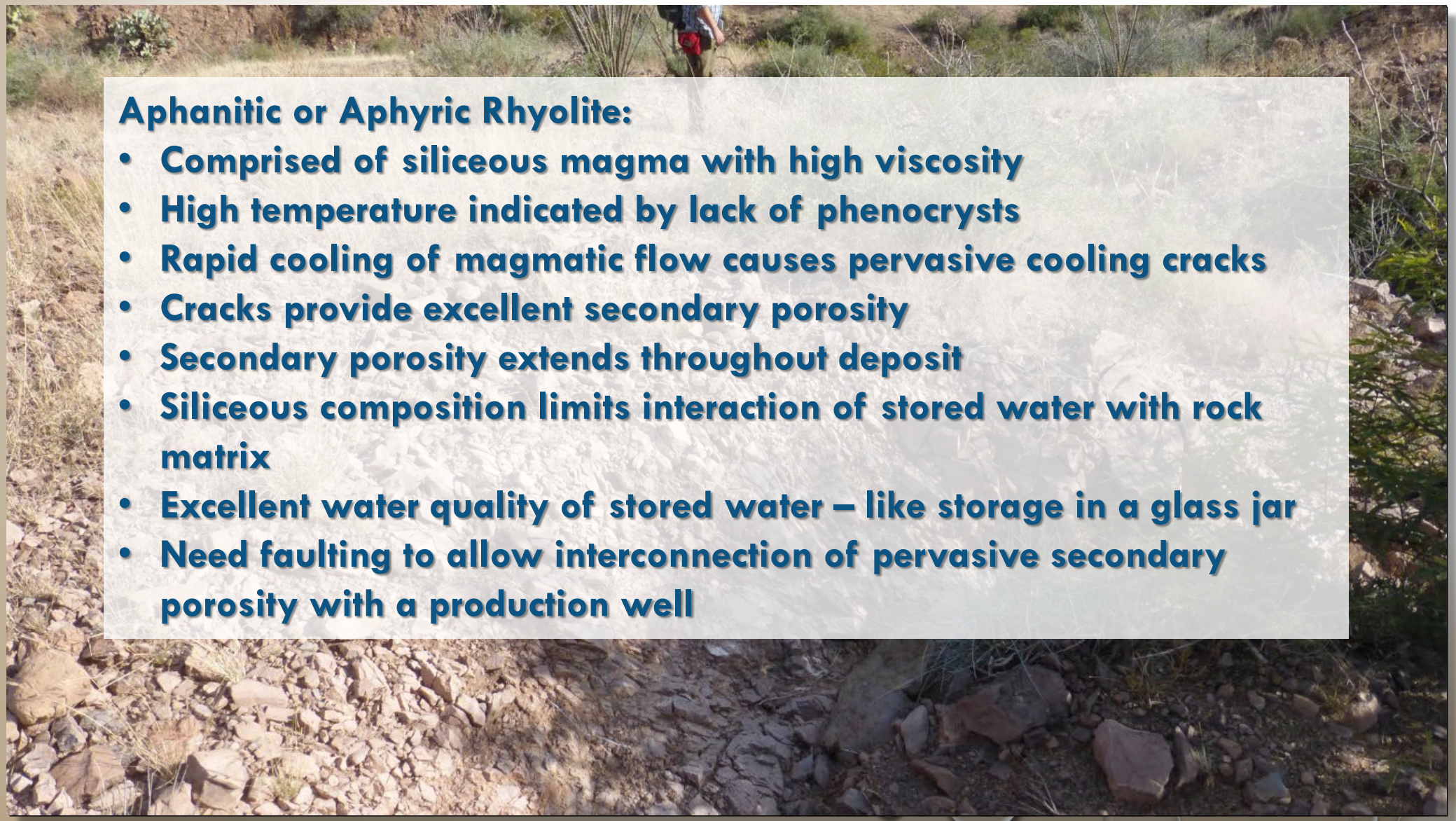
Aphanitic Rhyolite – A Dream Volcanic Aquifer



Aphanitic or Aphyric Rhyolite:

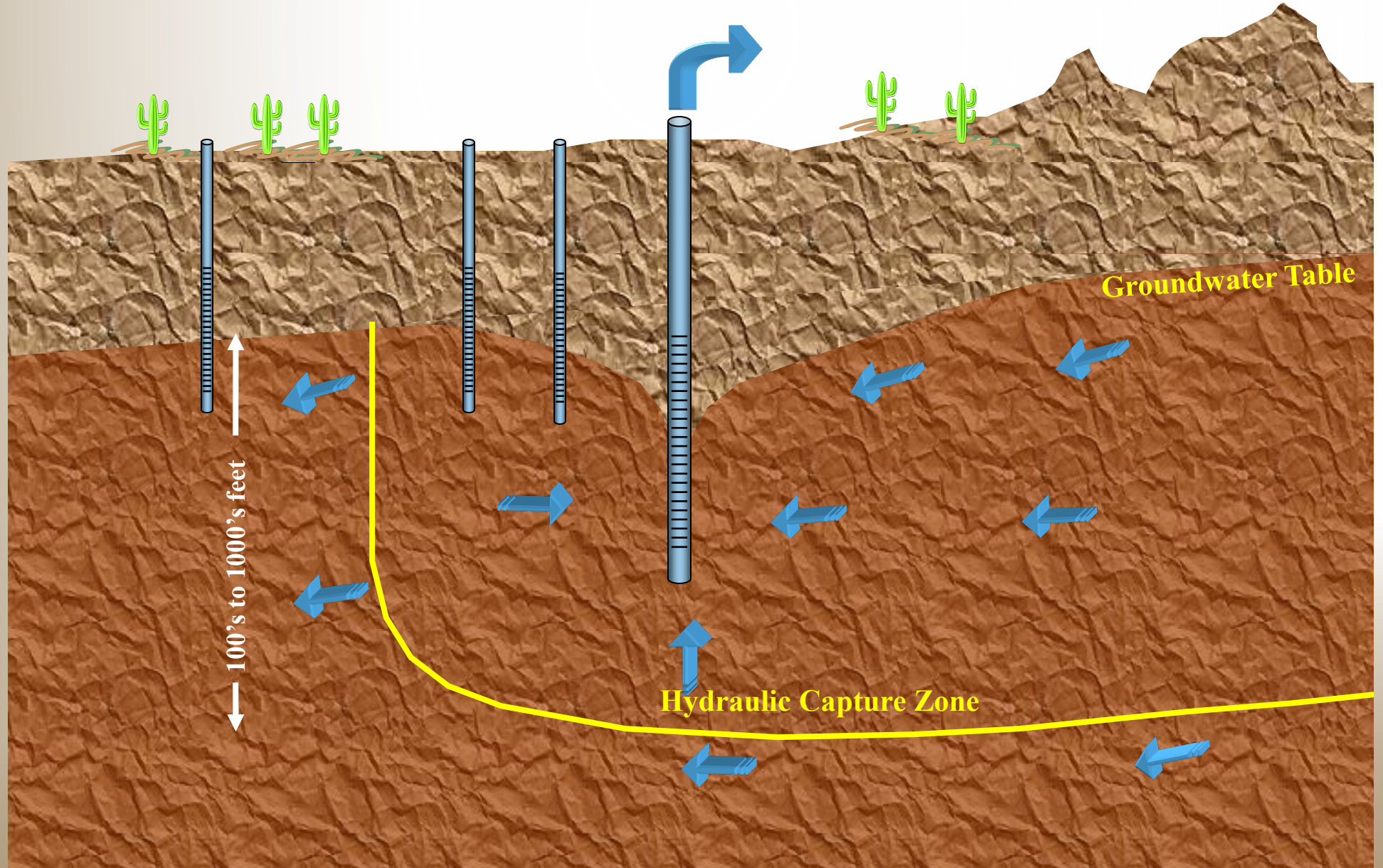
- Comprised of siliceous magma with high viscosity
- High temperature indicated by lack of phenocrysts
- Rapid cooling of magmatic flow causes pervasive cooling cracks
- Cracks provide excellent secondary porosity
- Secondary porosity extends throughout deposit
- Siliceous composition limits interaction of stored water with rock matrix
- Excellent water quality of stored water – like storage in a glass jar
- Need faulting to allow interconnection of pervasive secondary porosity with a production well

PASSIVE CONTAINMENT CAPTURE

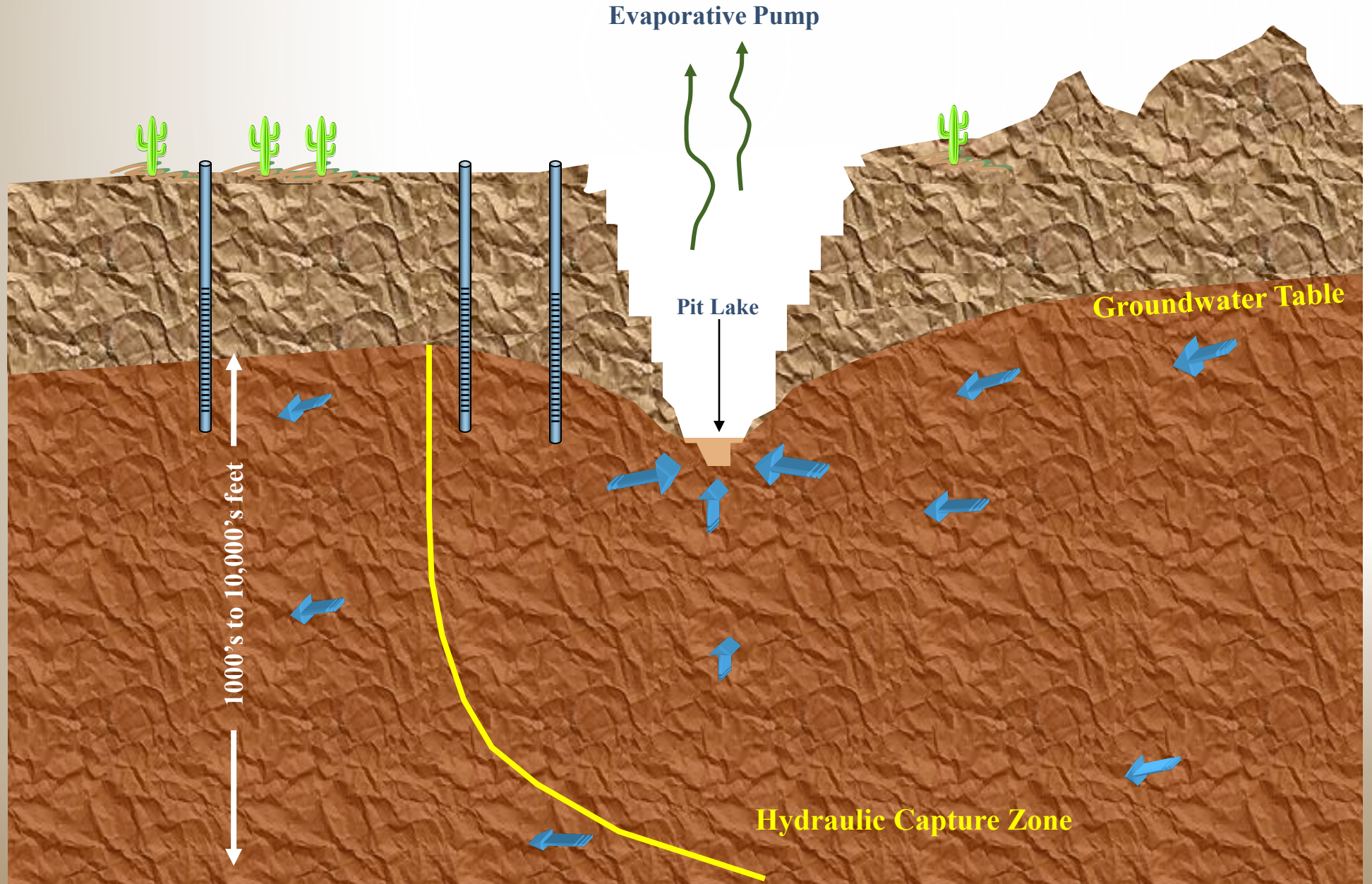
- After closure of open pits, if the bottom of the pit is below the water table, groundwater flows into the pit creating a pit lake
- In areas with high evaporation (SW U.S.), the pit lake can act like an evaporative “pump” – keeping the lake level below the regional water table surface
- The depression in the water table creates a capture zone around it that persists in perpetuity. This capture area is called a “Passive Containment Capture Zone” or PCCZ
- A PCCZ can benefit a mine by allowing less engineered liner systems for leach pads, ponds, or other facilities that may discharge to groundwater
- Over time, the pit lake will evapoconcentrate parameters that may be toxic to wildlife

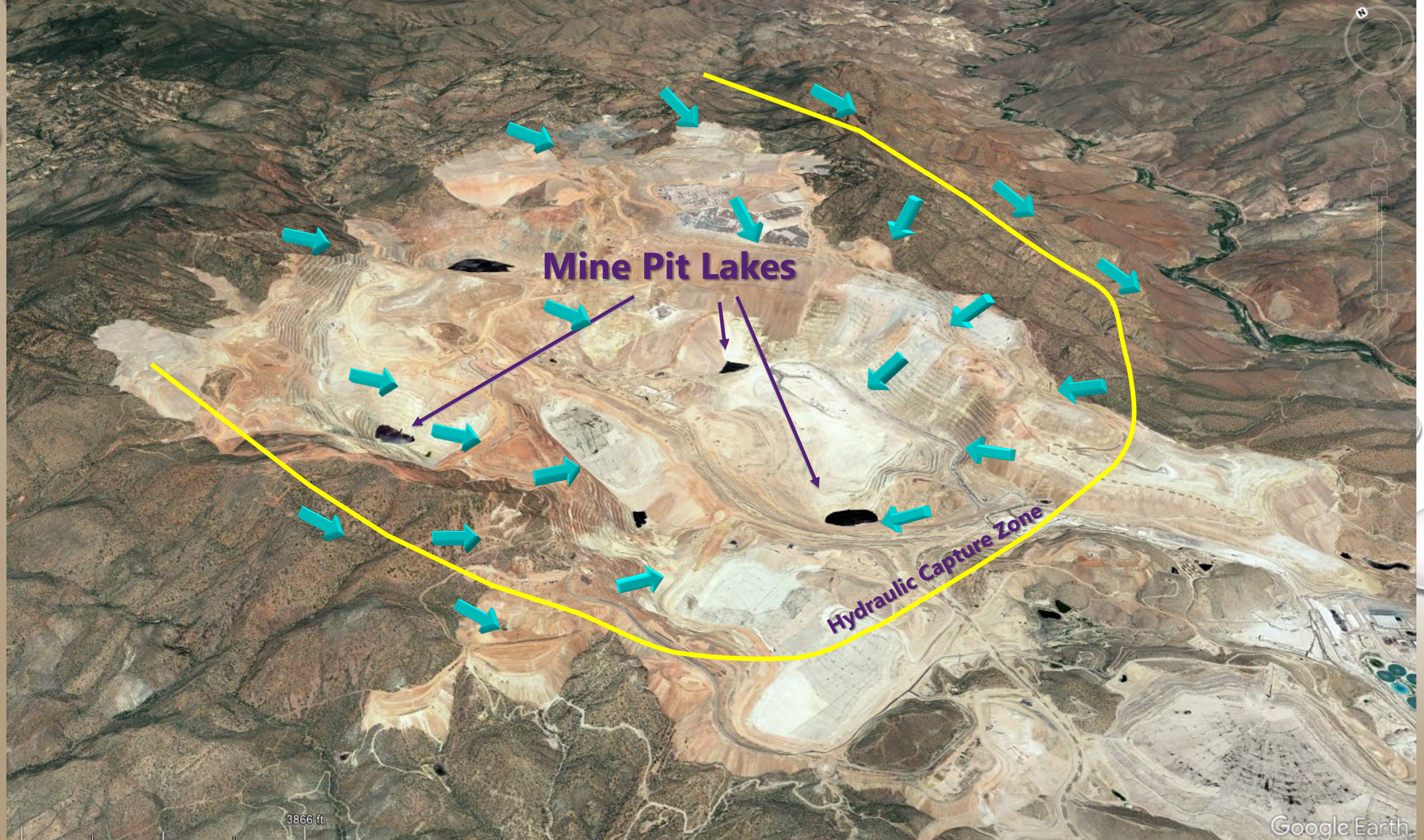
PIT LAKES

HYDRAULIC CAPTURE BY A WELL

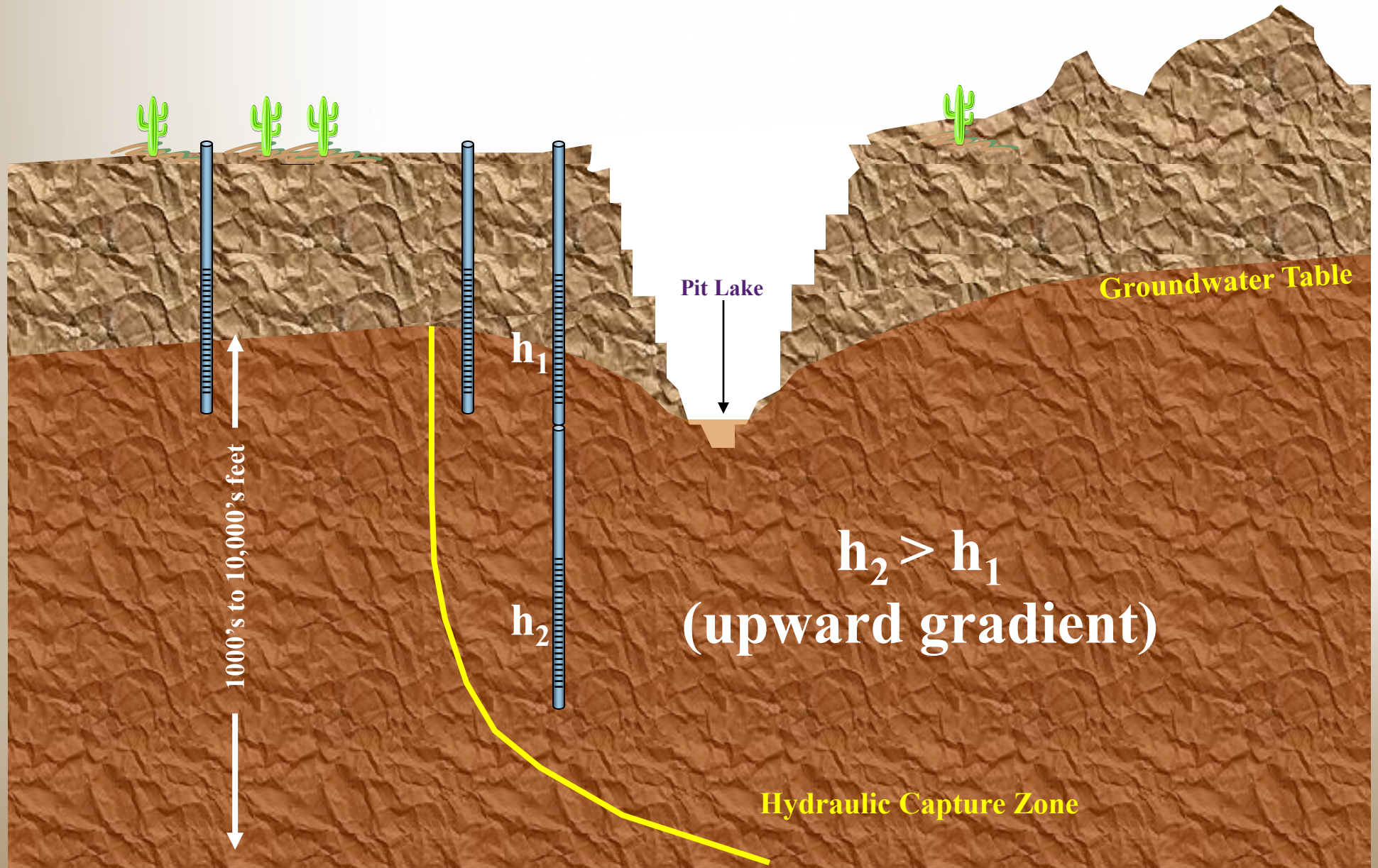


HYDRAULIC CAPTURE FROM AN OPEN PIT

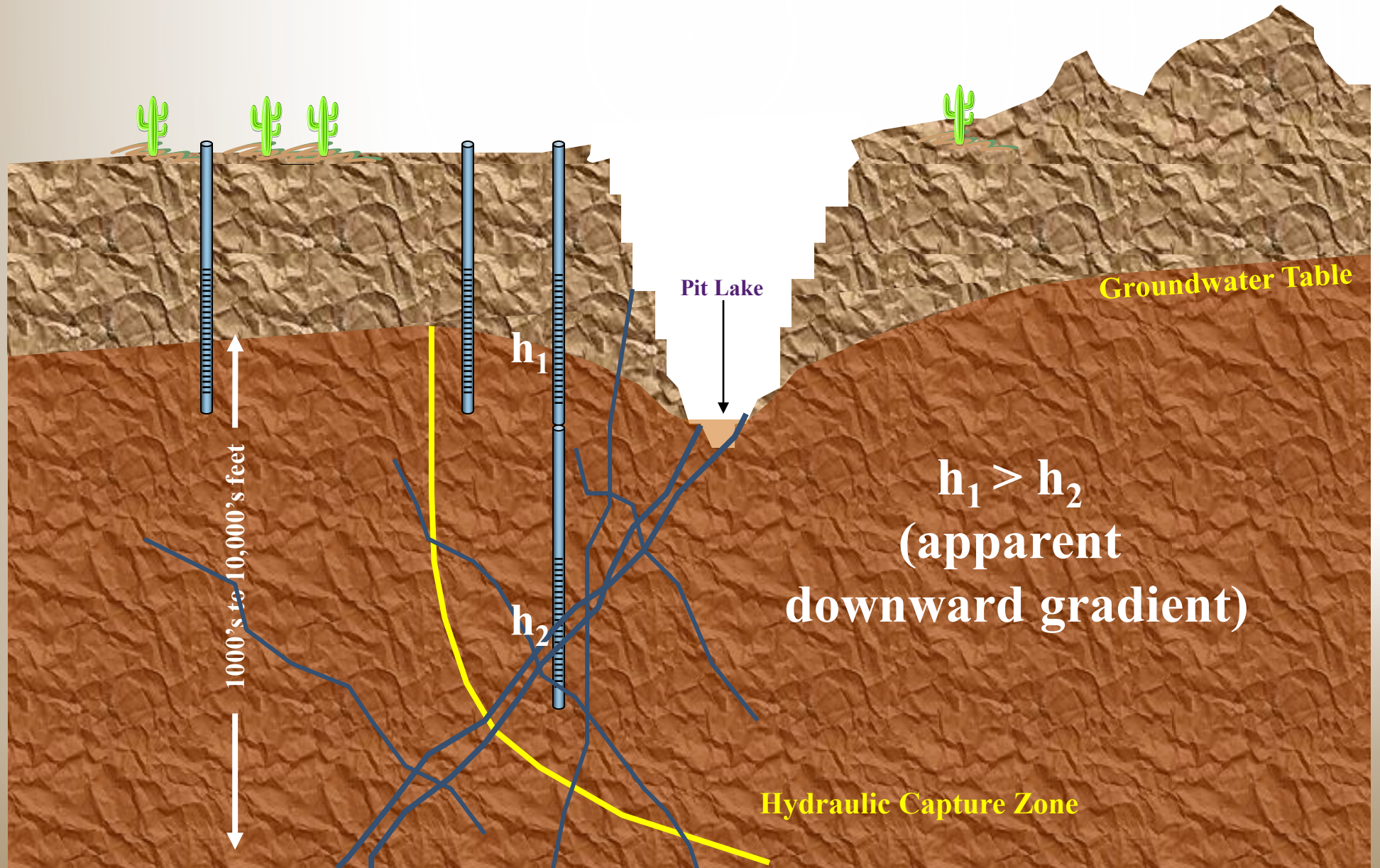



Mine Pit Lakes
Hydraulic Capture Zone
3866 ft
Google Earth

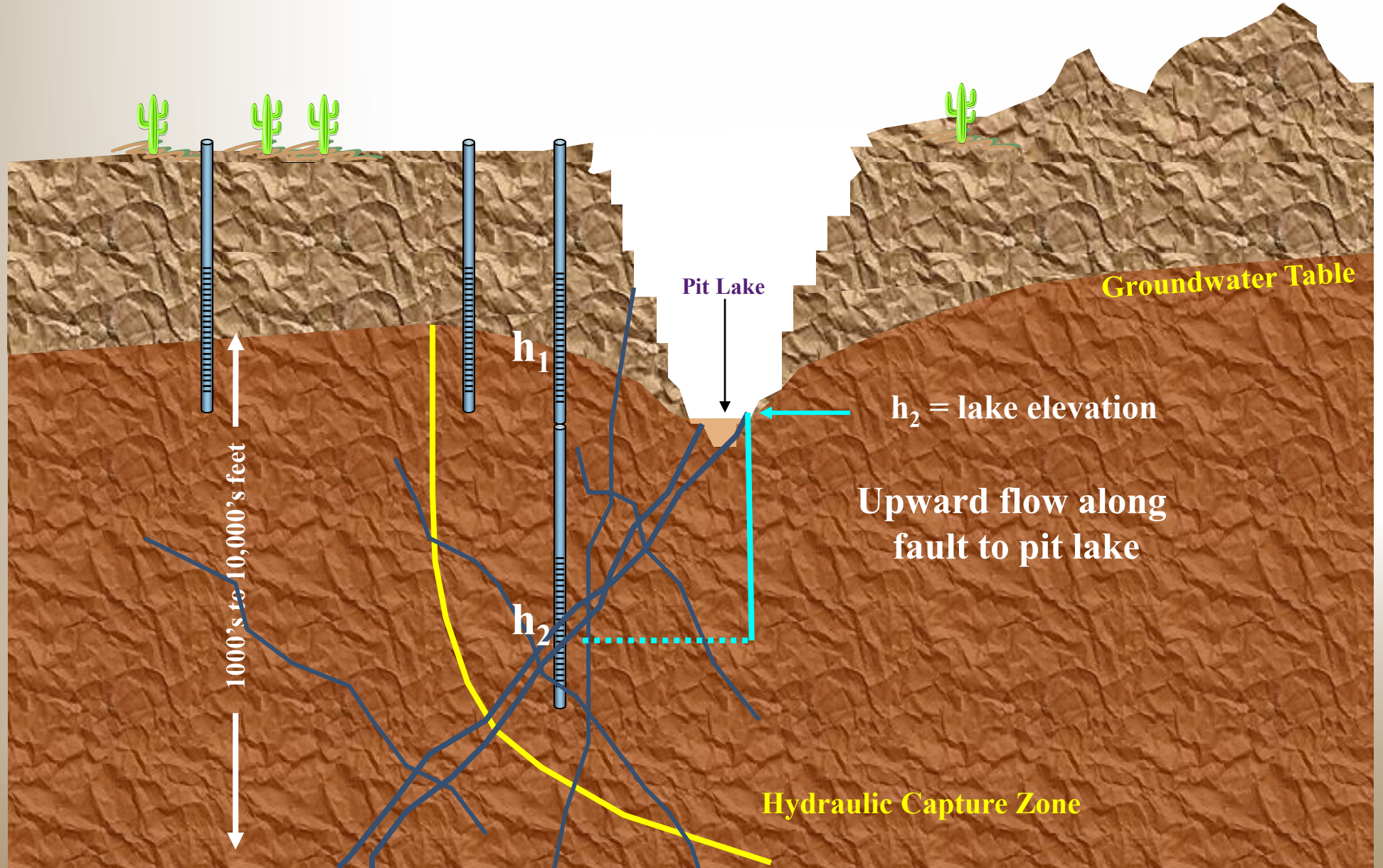
VERTICAL GRADIENTS NEAR OPEN PITS



HYDRAULIC CAPTURE BY A WELL



VERTICAL GRADIENTS NEAR OPEN PITS



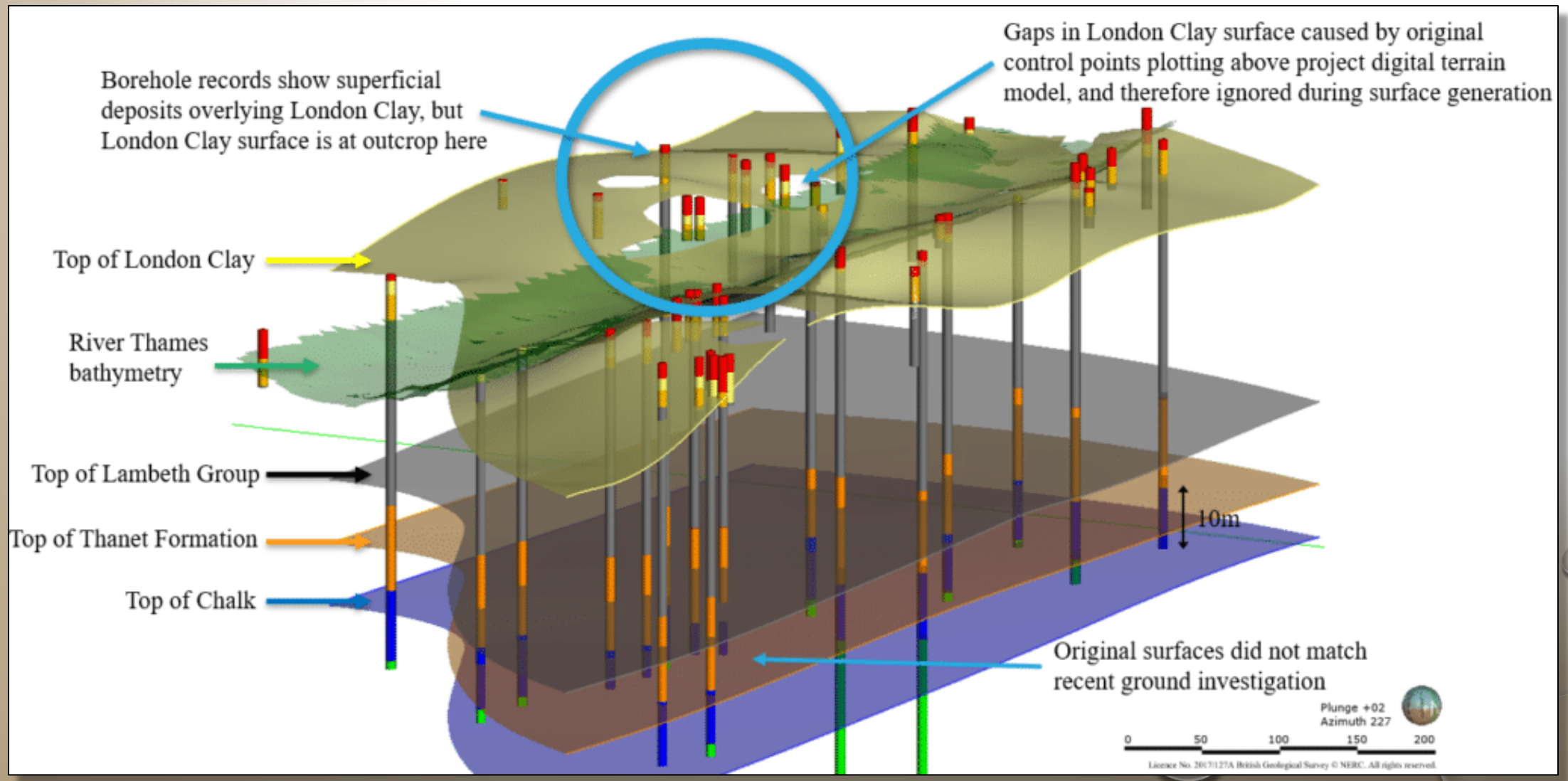
DEMONSTRATING A PCCZ

- Demonstrating a PCCZ requires both monitoring and groundwater modeling
- A monitoring network needs to be comprised of enough wells that the full extent of the PCCZ can be readily determined from empirical data
- Groundwater modeling is needed to prove that the PCCZ will be maintained into the future thereby making it “passive”

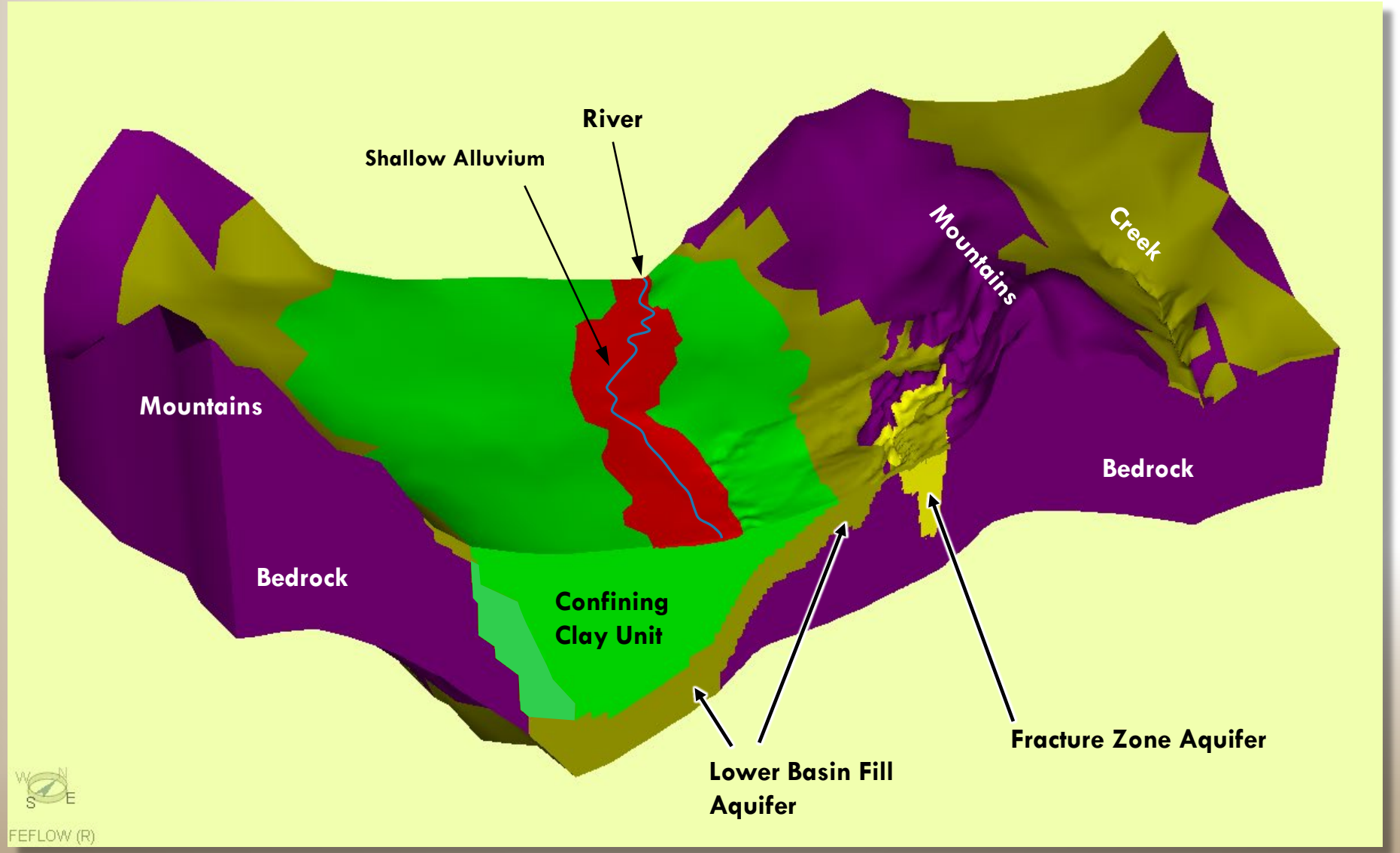
GROUNDWATER MODEL: STEPS TO DEVELOP

- Compile and assemble all relevant information
- Construct Conceptual Hydrogeologic Model
- Select appropriate domain boundaries and model code platform
- Construct and test model
- Run steady state model to establish starting head conditions
- Check calibration of steady state model
- Run transient state model to match changes in groundwater elevations over time
- Check calibration of transient state model
- Run selected scenarios
- Conduct sensitivity runs to determine the most sensitive input parameters
- Validate the model
- Prepare summary report

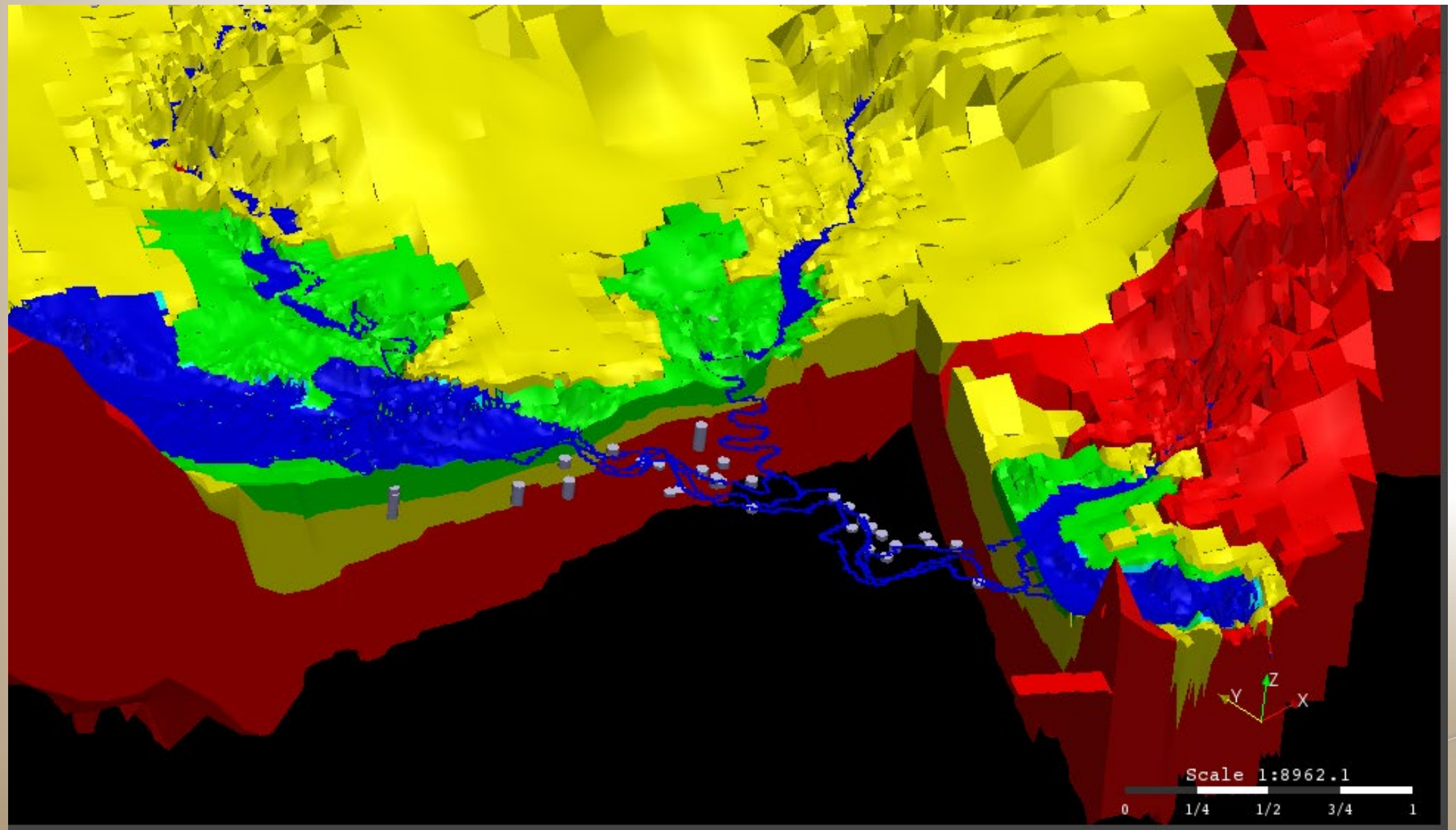
LEAPFROG MODEL



CONCEPTUAL HYDROGEOLOGIC MODEL



HYDROGEOLOGIC COMPUTER MODEL



OPERATIONS

MINE OPERATIONS

- Mine operational tasks pertinent to hydrogeologists include:
  - The siting, construction, and performance of water supply wells
  - Monitoring impacts of mine operations on local and regional groundwater levels
  - Monitoring local and regional springs, rivers, lakes
  - Groundwater quality monitoring to satisfy regulatory rules/permits
  - Dewatering open pits or underground operations
  - Identify geothermal reservoirs to enhance leaching operations
  - Obtain additional subsurface data from condemnation holes

MINE OPERATIONS

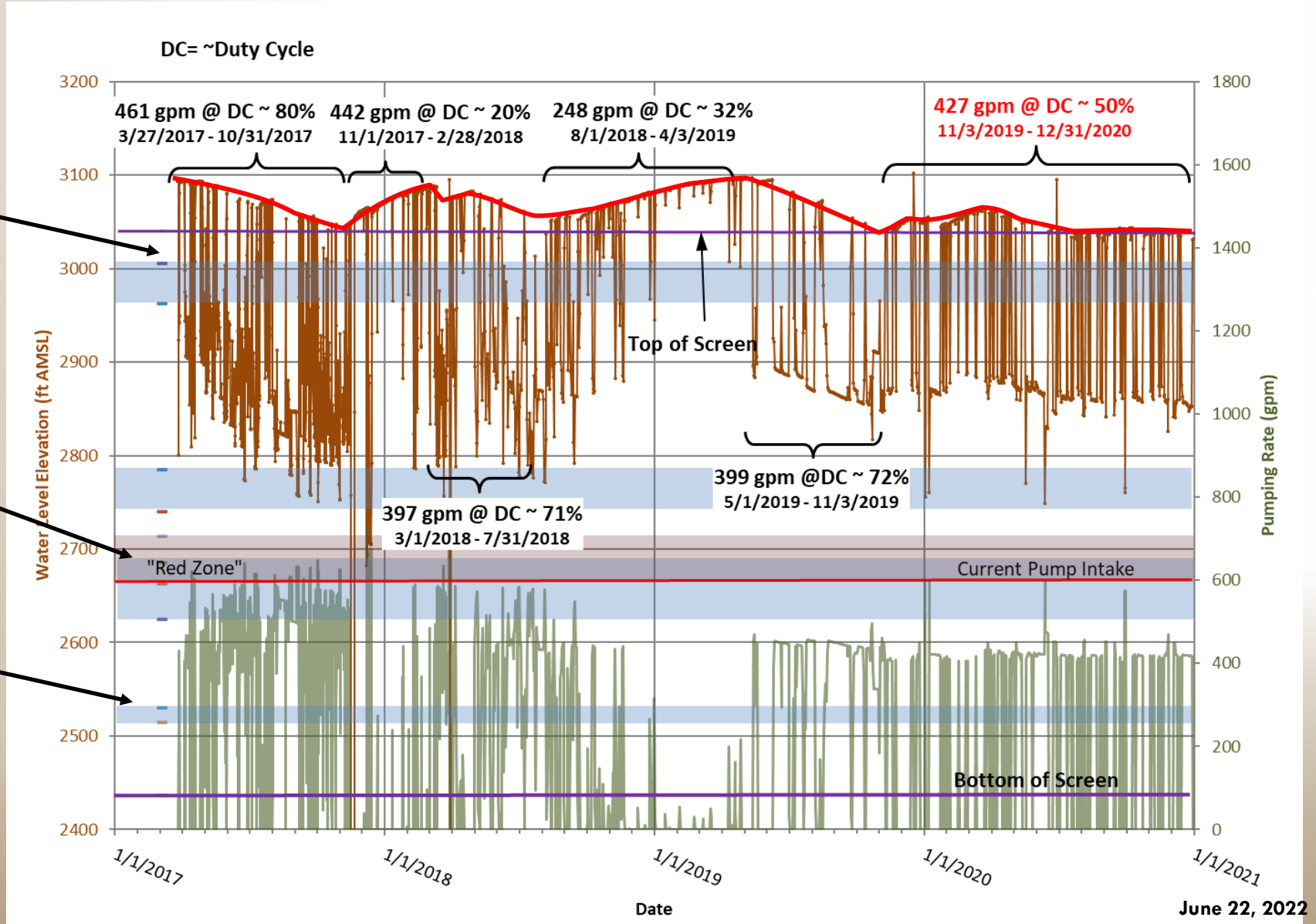
- Production well performance is a critical component of a mine
- Bedrock wells are typically inefficient (greater drawdown in well casing than in surrounding aquifer)
- Mine operators can have a difficult time managing pumping rates and duty cycles
- Example of how to manage bedrock pumping wells follows:

PRODUCTION WELL TRANSDUCER AND PUMPING DATA

Water level data from transducer

Pump setting

Pumping rate

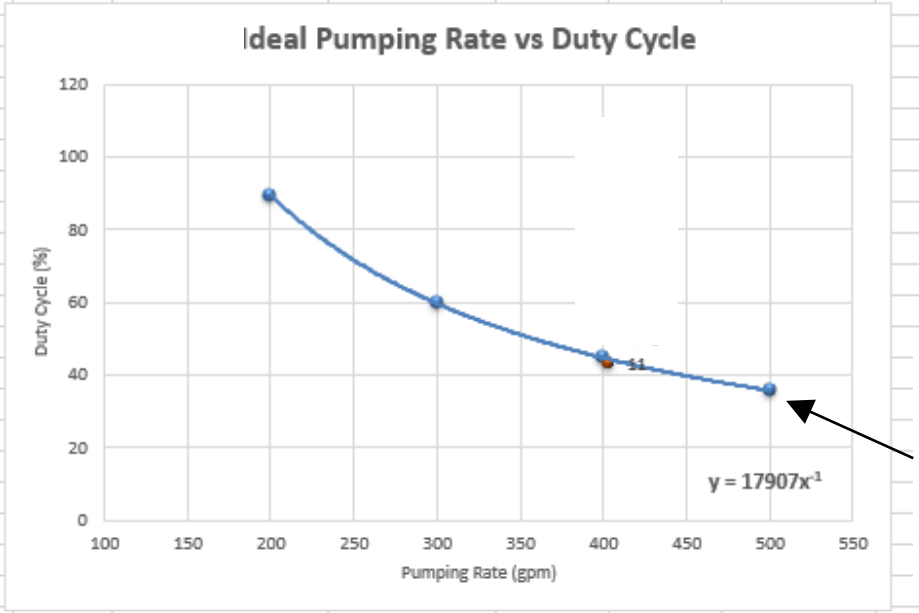


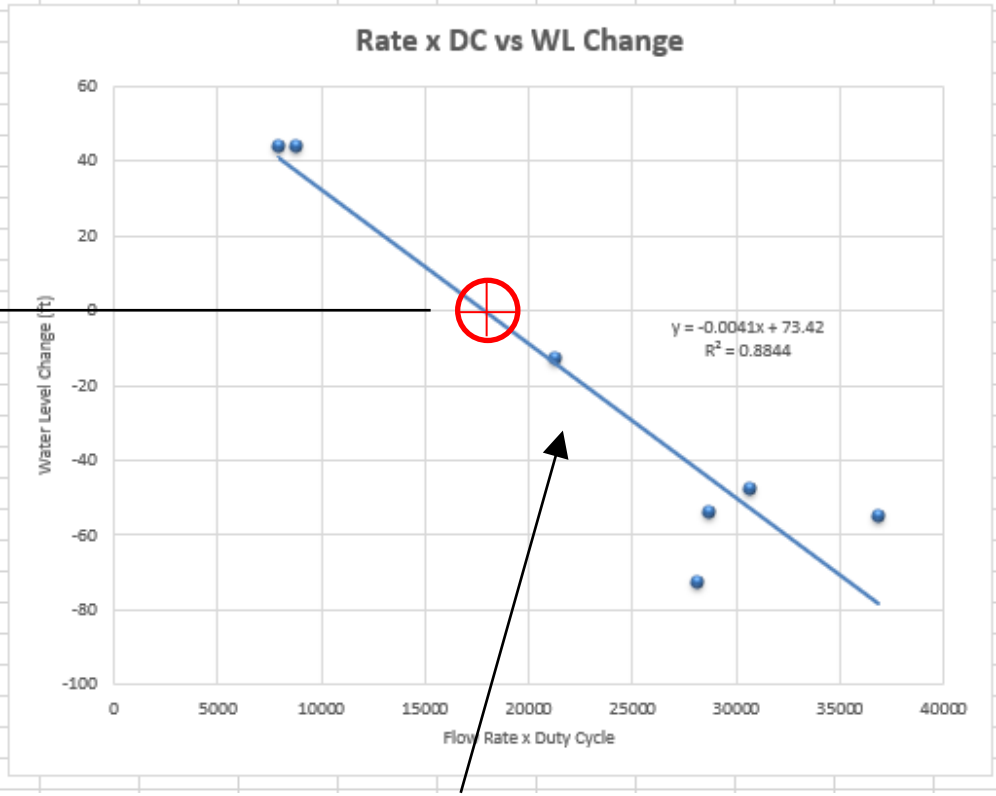
CALCULATION OF IDEAL FLOW RATES VS DUTY CYCLES

Well ID	Date Range	Ave. Rate (gpm)	Duty Cycle	gpm x DC	WL Change (ft)
	3/27/17 - 10/31/17	461	80	36880	-55
	11/1/17 - 2/28/18	442	20	8840	44
	3/1/18 - 7/31/18	397	71	28187	-73
	8/1/18 - 4/3/19	248	32	7936	44
	5/1/19 - 11/3/19	399	72	28728	-54
	11/3/19 - 12/31/20	427	50	21350	-13
	12/31/20 - 12/27/21	409	75	30675	-48

Q	DC	17,907.3
200	89.5	
300	59.7	
400	44.8	
500	35.8	

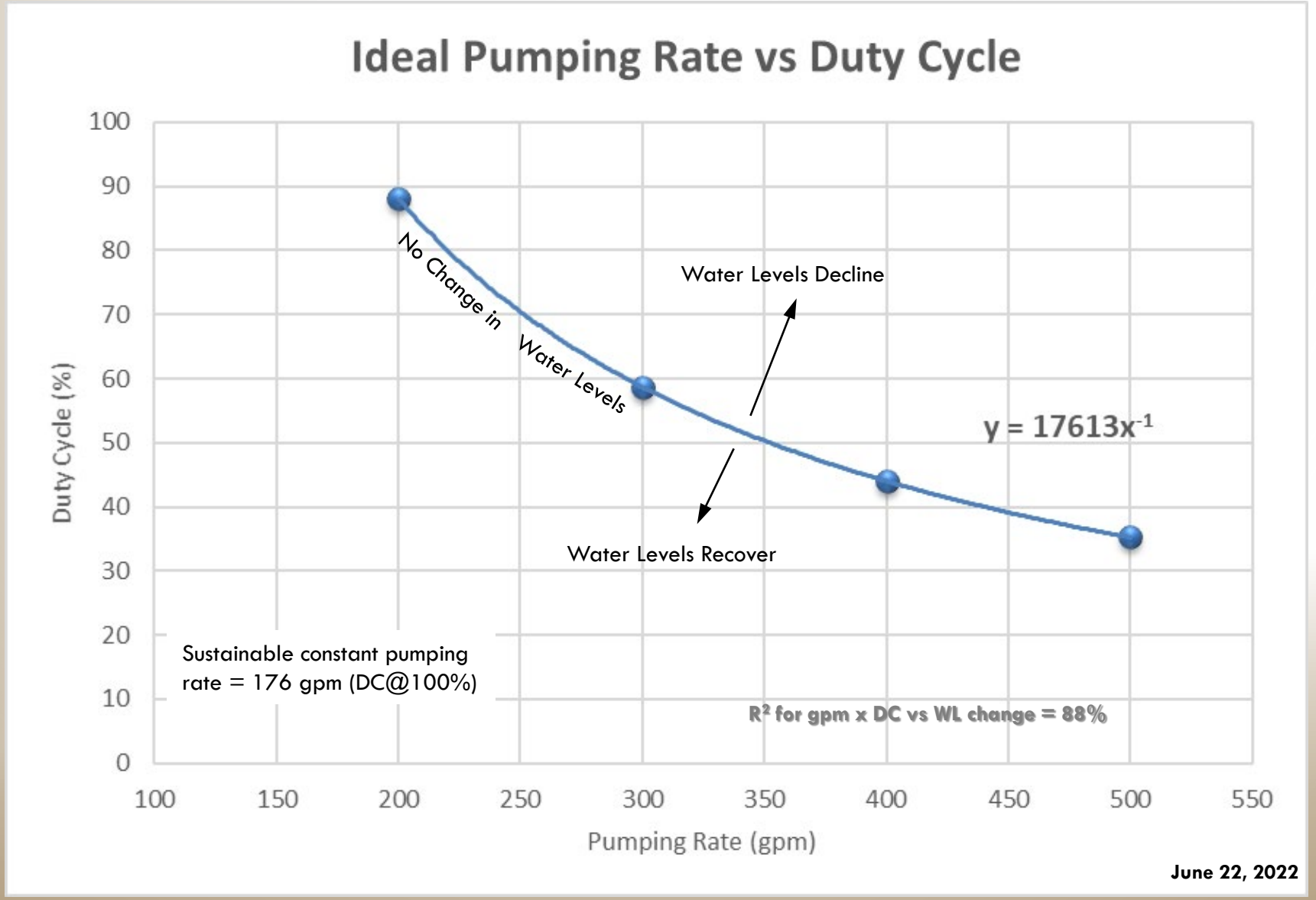
179.07





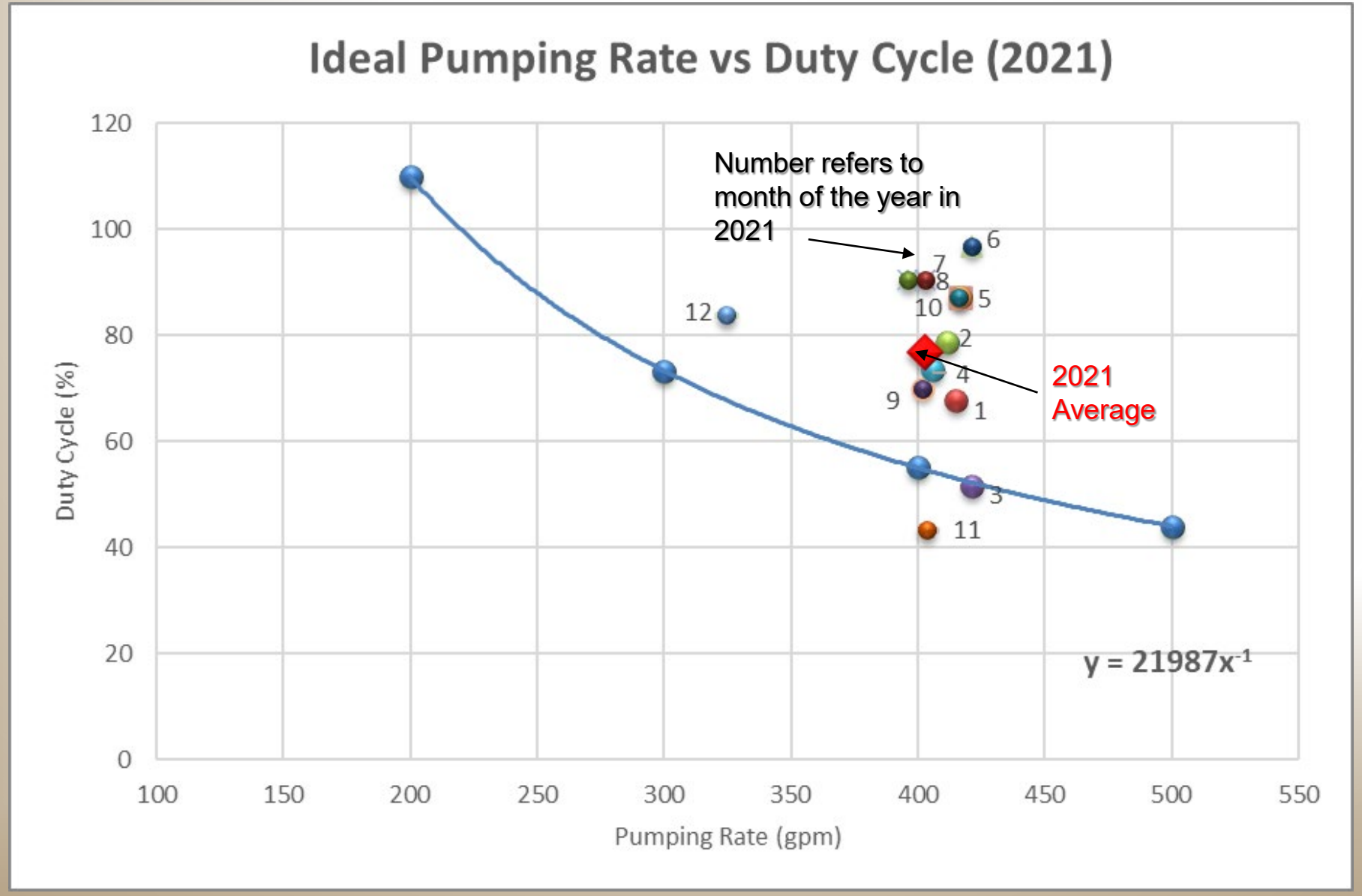
- **Correlate the flow rate x duty cycle versus the change in water level**
- **Use calculated weighted value for "0" change in water level to associate range of flow rates with duty cycle that yields no change in water level**

FLOW RATE VS DUTY CYCLE GRAPH

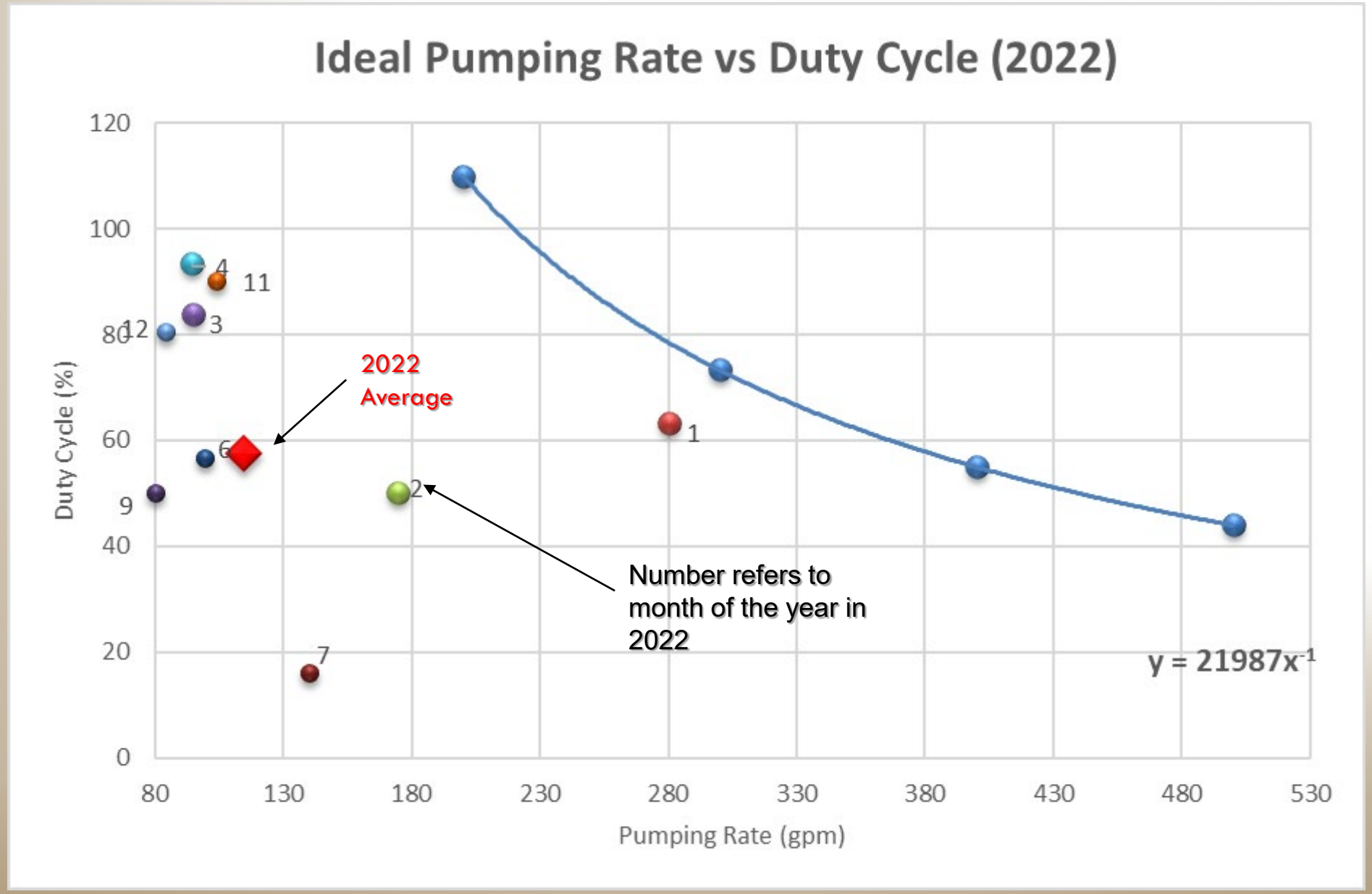


June 22, 2022

FLOW RATE VS DUTY CYCLE GRAPH



FLOW RATE VS DUTY CYCLE GRAPH



GEOTHERMAL GROUNDWATER

- Leaching of copper ore is partially a microbiological process which can be enhanced with increasing temperature (up to a point)
- Arizona mines are enhancing leaching by adding a “thermal blanket” to the top of their leach piles
- They are also looking into use of geothermal groundwater to increase the temperature of the leach pile and thereby increase the efficiency of leaching
- Geothermal groundwater is common in many basins in the Basin and Range province
- It’s a good idea to record and document the temperature of groundwater during compilation of planning and operational data in case water temperature becomes important to the operation

CLOSURE

NATURAL ENRICHMENT OF ORE

- Naturally Occurring Process – e.g. Supergene Enrichment
- Fe transported upward and precipitated in the gossan
- Other metals transported downward below the water table and precipitated in the enriched zone (e.g. CuS)

Mining Activity Increases Atmospheric Exposure of Sulfide Containing Mine Waste (or Ore)

ACID ROCK DRAINAGE (ARD)

- Process in which Sulfide minerals (PRIMARILY PYRITE) oxidize in a weathering environment forming sulfuric acid

- With sulfuric acid (low pH) – the mobility of many metals is increased

PYRITE OXIDATION

Pyrite Oxygen Water Acid

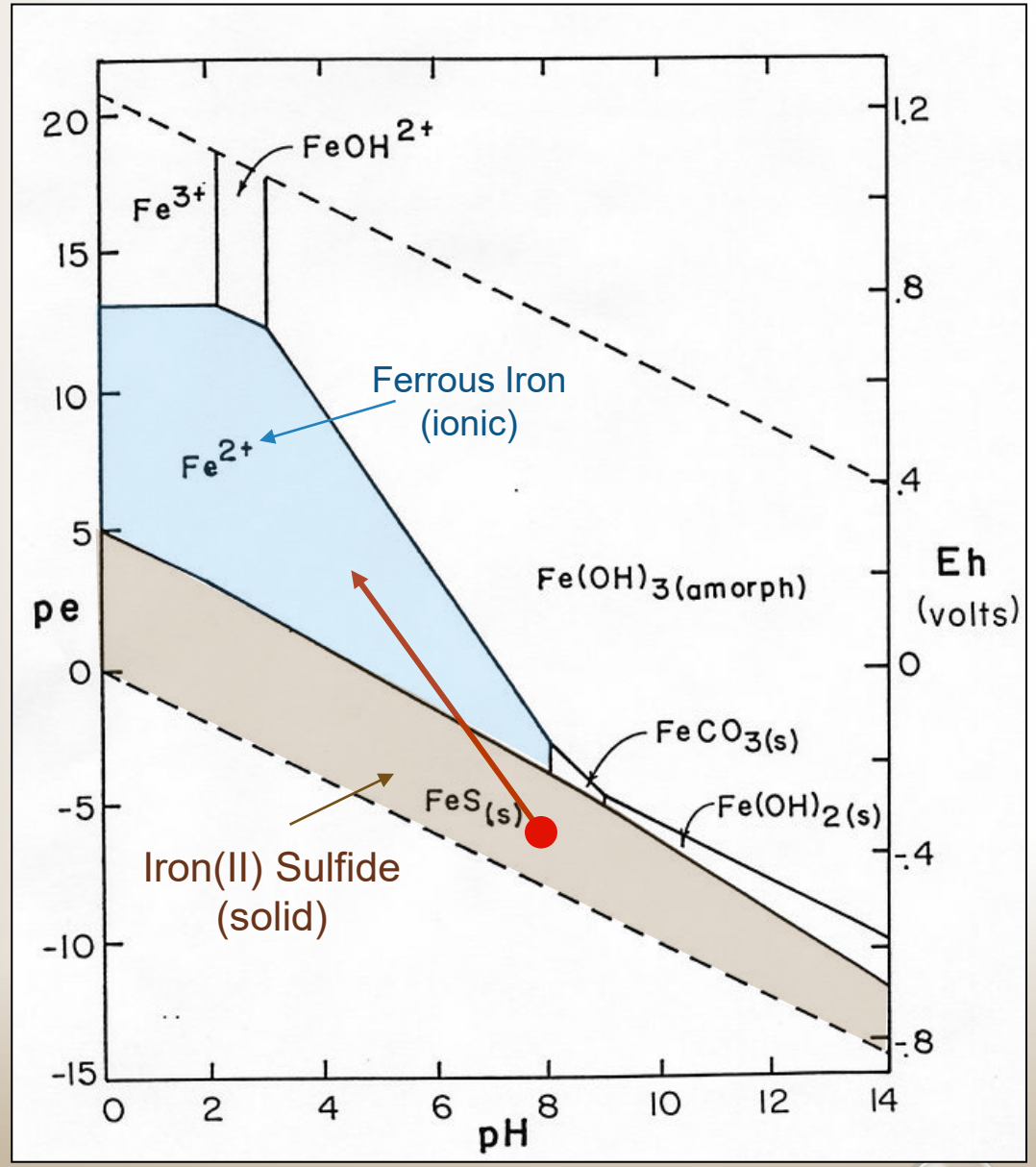
$$FeS_2(S) + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3(S) + 4H^+ + 2SO_4^{2-}$$

PYR *FERRIHYDRITE*

Factors that affect oxidation rate of pyrite:

- Surface area exposed
- pH & oxygen concentration (in water and gas phase)
- Ferric iron concentration
- Temperature and chemical activation energy
- Bacteriological activity

PHASE DIAGRAM



METAL MOBILITY

ELEMENT MOBILITY			
Element	**Acid <5.5**	**Neutral**	**Alkaline >7.5**
Aluminum	High-V. Low	V. Low	V. Low
Arsenic	Medium	Medium	Medium
Barium	Low	Low	Low
Beryllium	Medium	Low	Low
Cadmium	Medium	Medium	Medium
Chromium	V. Low	V. Low	V. Low
Copper	High	Med.-Low	V. Low
Fluorine	High	High	High
Iron Fe (III)	High-V. Low	V. Low	V. Low
Iron Fe (II)	High	Med.-Low	V. Low
Lead	Low	Low	Low
Manganese	High	High	High-V.Low
Mercury	Medium	Low	Low
Nickel	High	Medium	Low
Selenium	High	High	V. High
Silver	High	Med.-Low	V. Low
Tin	Insoluble	Insolube	Insoluble
Uranium	Low-Med	High	V. High
Zinc	High	High-Med.	Low-V.Low
from Hoffman, 1986			

OTHER ACID PRODUCING SULFIDE MINERALS

Sulfide minerals exposed to surface conditions are unstable and will, with time, dissolve and oxidize

PYRRHOTITE

CHALCOCITE

GALENA

SPHALERITE

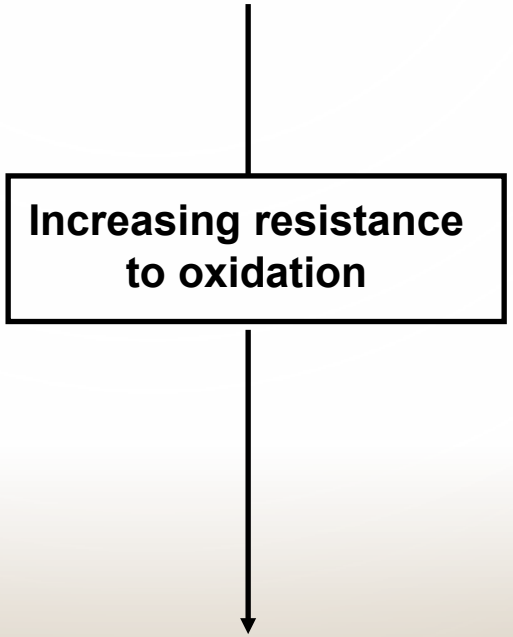
PYRITE

ENARGITE

MARCASITE

CHALCOPYRITE

MOLYBDENITE



ARD Drainage from Underground Working

GOLD KING MINE
AN ACID MINE DRAINAGE NIGHTMARE!

RELEVANT HISTORY:

- Gold King Mine discovered in 1887; for most of its history, workings were dry due to regional drain known as the American Tunnel from Sunnyside mine
- Sunnyside mine closed in 1991; American Tunnel sealed in 1996
- Discharge from Gold King Adit 7 in 2002; nearby Mogul Mine sealed in 2003 – flow increased to >300 gpm from adit 7; discharge to Cement Creek then to Animas R.
- In 2009, CO DRMS closed all four Gold King adits by filling entrances with old mine backfill; drains installed to prevent build up of pressure; complicated by partial collapse
- In 2014, DRMS asked EPA to re-open and stabilize No. 7 adit; seepage observed 6 feet above floor of tunnel; figured that meant there was 6 feet of water in tunnel

DRMS: Division of Reclamation, Mining and Safety

GOLD KING MINE
AN ACID MINE DRAINAGE NIGHTMARE!

RELEVANT HISTORY:

- Work began by EPA and contractor in June 2015; noted that landslide had covered drains
- Planned to excavate down to level of observed seepage (top of water pool) then insert a pipe to drain pool
- At 10:51am on Aug. 5, 2015, backhoe operator saw spurt of water from fracture adjacent to plug indicating high pressure water behind plug.
- Uncontrolled release of mine water ensued resulting in discharge of about 3 million gallons of mine water to Cement Creek.

GOLD KING MINE DISASTER – AUG. 5, 2015

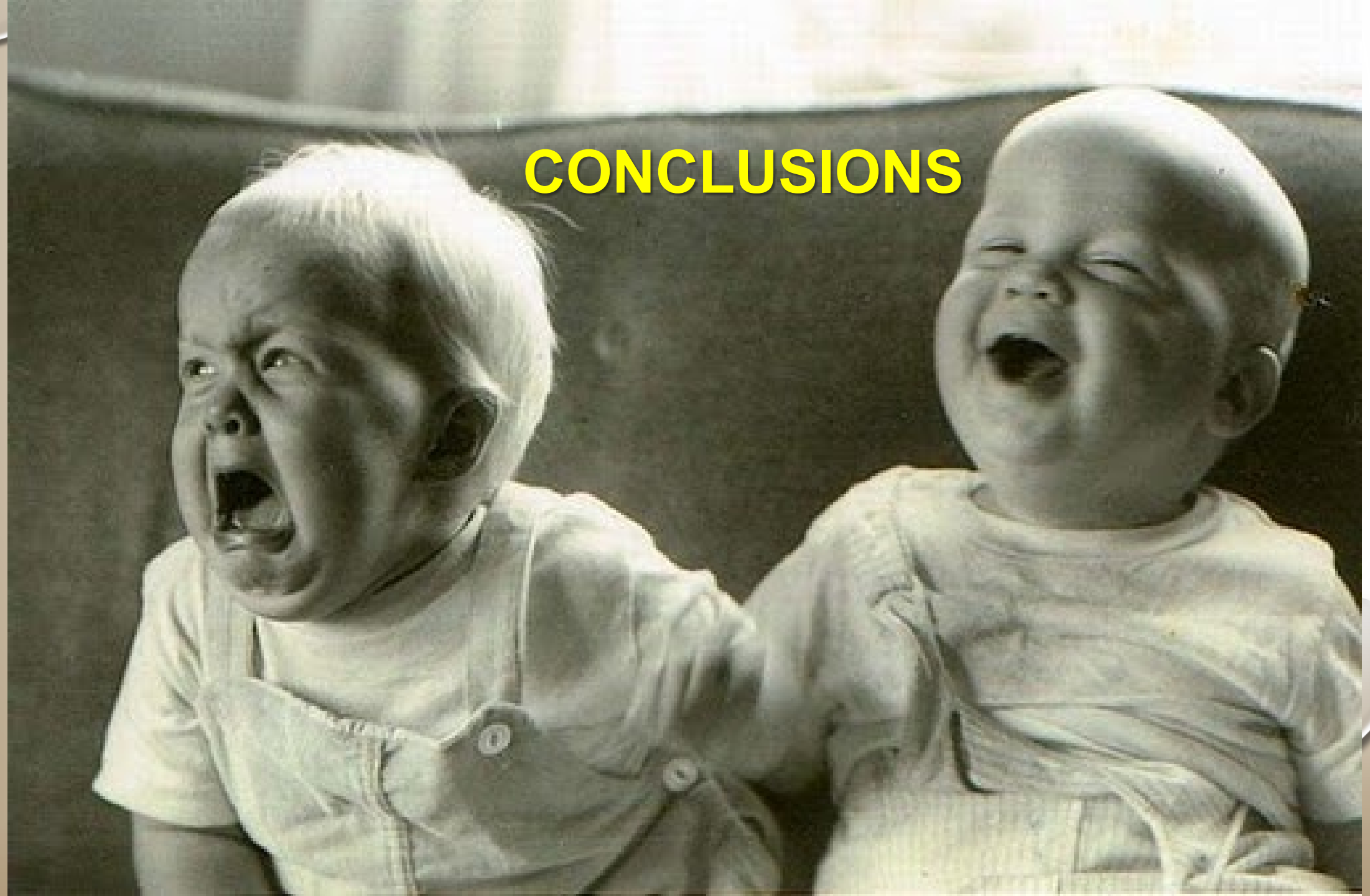
SOMETHING YOU NEVER WANT TO SEE!

- AUGUST 5, 2015
- EPA RELEASES GOLD KING MINE BLOWOUT FOOTAGE: 'GET OUTTA HERE?!... WHAT DO WE DO NOW?' - YOUTUBE

GOLD KING MINE IMPACT - DURANGO

FOLLOW UP REMEDIATION

CONCLUSIONS



CONCLUSIONS

- Groundwater can be both a curse and a blessing to mining projects
- When planning a mine, take advantage of all surface and subsurface studies to provide insights into the hydrogeology of the site and area
- A good hydrogeologic conceptual model is essential and should be based on sufficient field data to justify the components of the model
- A groundwater supply for a mining operation should be identified early in the planning process; developing a sufficient water supply is a time-consuming process
- Mine plans constantly change – this requires frequent re-assessment of groundwater conditions, model re-calibration, revision of water supply needs/sources

QUESTIONS?

THANK YOU FOR YOUR ATTENTION!

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SEE YOU IN DURANGO, 2024!

CLEAR CREEK ASSOCIATES
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