Contaminant Plume Behaviour in Fractured Sedimentary Rocks

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- **Collaborators:** Drs. John Cherry, T. Gorecki, and R. Aravena, E.Sudicky, J. Molson, and others

- **Many research associates, technicians and students:**
  - Chapman, Meyer, Pehme, Quinn, Munn and others

- **Site owners, consultants and regulators**

This Talk Shows…

- An example of an intensive field study of chlorinated solvent contamination in fractured Cretaceous sandstone

- Strong plume retardation and attenuation due to matrix diffusion

SSFL in Public Eye

Judge's Ruling Goes Against Neighbors of Rocketdyne

■ **Litigation:** Decision says suit alleging contamination doesn't meet strict class-action requirements, but allows a chance to amend the action.

By MACK REED
TIMES STAFF WRITER

A federal judge in Los Angeles on Monday shot down attempts by Rocketdyne's neighbors to press a class-action lawsuit for property damage, but she left the door open for the plaintiffs to amend their complaint.

U.S. District Judge Audrey Collins ruled that the suit alleging that Rocketdyne's Santa Susana Field Lab and three San Fernando Valley facilities have contaminated nearby homes and businesses was too broadly focused and inadequately supported for the narrow legal constraints of class-action law.

But Collins also gave some weight to the plaintiffs' claims that off-site ground water contains traces of hundreds of thousands of

B6 FRIDAY, NOVEMBER 8, 1996 / F LA Times

VALLEY NEWS

Residents Criticize Pollution Study

■ **Ecology:** They accuse state environmental agency of approving Rocketdyne's plan before informing the public.

That offer prompted several in the audience of about 60 to scoff under their breaths during the meeting, which was often marred by bickering and accusations from the residents.

Rocketdyne's predecessor, North American Aviation, opened the lab in 1948 and over the years

The FBI is still looking into possible criminal charges against other Rocketdyne employees in connection with the blast.

As Thursday's meeting wore on, cleanup coalition members criticized Cal/EPA for backing out of a promise to give them copies of letters to and from Rocketdyne

Simi Star
November 12, 1996

ublic wary of EPA's reply

Los Angeles Times
VCCC† TUESDAY, MARCH 11, 1997

COUNTY

cketdyne Field Lab Neighbors Sue Boeing

ion: Residents file a class-action suit against the parent over contamination and health risks posed by research.

ED
ITER

LEY—Neighbors of Rocket-Susana Field Laboratory sued e firm's parent company in Monday, alleging that decar and chemical research at ntop complex poisoned their r and caused them to contract

San Fernando Valley filed a class-action suit against Boeing North American Inc., which in December bought the 2,668-acre research complex that its Rocketdyne division still runs.

The suit filed in Los Angeles demands that Boeing pay damages and set up a medical fund for future treatment of the cancer that the plaintiffs say they and their neighbors have and radioactive

It asks the court to order Rocketdyne to make public all past and present risks of contamination posed by the field lab's research into rocket engines and atomic reactors.

And it cites a laundry list of nuclear meltdowns, chemical explosions and toxic releases that Rocketdyne allegedly allowed to foul the air, water and land around the field lab ever since it opened in 1948 to design the first U.S. rocket engines.

Plaintiffs' attorney Tina Nieves said

brought on mainly by radiation exposure.

"They all live at opposite ends of the Santa Susana Pass," she said, referring to the road that hugs the hill where Rocketdyne sits, midway between Simi Valley and the San Fernando Valley.

"We thought that was p evidence that there was no going on up at Rocketdyne, reactor facility was betwe cancer clusters we found," N

One woman named in the

Rocketdyne to face onslaught of lawsuits

COMPLAINTS: *People living around facility allege chemical, radiation exposure.*

By Brett Johnson
Staff writer

An attorney who represented a cultural center in a pollution lawsuit against Rocketdyne said Tuesday she will file more than 30 individual cases against the company.

The cases involve people who live around Rocketdyne's Santa Susana Field Laboratory between Simi Valley and Canoga Park. They allege damages from radiation and chemical exposure from the longtime nuclear and scientific testing facility.

The people seek compensation for loss of property value and related medical costs. A total amount sought has not been

specified, attorney Helen Zukin said.

The complaints, Zukin said, will be filed Thursday in U.S. District Court in Los Angeles against Rocketdyne's parent company, Boeing North American Inc.

The cases, sparked by the recent release of a Rocketdyne worker health study, also could signal the start of another round of legal action stemming from alleged pollution coming from the Rocketdyne facility. Zukin said she will file other cases, including personal injury claims, against Rocketdyne within the next month.

"This is the first group of a series of cases we're filing," Zukin said.

Meanwhile, other attorneys have organized a public meeting at 7 p.m. Friday at the Radisson

Please see ROCKETDYNE on A6

Rocketdyne opens doors for cleanup

Public to tour Simi plant

By Christopher Noxon
Daily News Staff Writer

SIMI VALLEY — Rocketdyne is offering to lead members of the public around its 2,600-acre hilltop field lab used for nuclear and chemical experiments, and more than a dozen people have signed up so far for the tour.

Spokeswoman Lori Circle said Rockwell International Corp., which owns Rocketdyne, is opening the gates of the high-security facility in an attempt to reassure the public about the thoroughness of the $55 million cleanup operation now in its final stages.

"It's important the community feels confident in the work we're doing," Circle said. "This is another way of trying to partner with the community to let them know we do care about their concerns."

A training program is still in the works, but preliminary plans include more than 20 hours of instruction from health and safety authorities with tours beginning in January.

Rocketdyne has been cleaning radioactive and chemical pollution from the site since 1989, when a routine survey by the U.S. Department of Energy recorded contamination.

Environmental activists and some neighbors said the invitation was a public relations exercise which could easily backfire on Rocketdyne.

"It's clear that the cleanup is superficial and designed to declare dirty areas clean," said Dan Hirsch, an anti-nuclear activist and member of a citizen watchdog group charged with overseeing the cleanup. "With people along, it will be slightly tougher for them to get away with it."

Rocketdyne made the invitation after being criticized at a meeting of

See ROCKETDYNE / Page 2

B4 FRIDAY, OCTOBER 31, 1997 / F

State Begins Study of Field Lab's Toxic Path

■ **Health:** Investigators want to know if contamination reached areas such as Chatsworth and West Hills.

By KATE FOLMAR
TIMES STAFF WRITER

SIMI VALLEY—State health investigators are starting a study to determine if any chemical and radioactive contamination from the Rocketdyne's Santa Susana Field Laboratory could have seeped into surrounding neighborhoods.

While the outcome of the so-called "exposure assessment" is far from certain, it could be an important first step toward a long-awaited community health survey.

An environmental health investigator with the California Department of Health Services announced late Wednesday that her department would examine possible "pathways of contamination" from the field lab near the border of Los Angeles and Ventura counties to homes a few miles away.

Finding such pathways—through air, soil or water—could possibly lead to a full-blown community health survey if strong evidence of off-site contamination is found, said Marilyn C. Underwood, a toxicologist with the Environmental Health Investigations Branch of the state health department.

"This is an exposure assessment," Underwood said after the quarterly meeting of the Santa Susana Field Lab Workgroup. "It could lead to physician education, it could lead to a whole lot of things, one of which could be a [community] health study. But I wouldn't put any bets on it."

The 2,668-acre field lab outside Simi Valley was the site of nuclear research between the 1950s and 1980s and has long been used for rocket-engine research. For years, Rocketdyne critics have believed that chemicals and radiation from "the Hill" have caused illnesses, such as cancer, among field lab neighbors.

Rocketdyne officials, however,

of radiation effects on about 4,00[illegible] former and current Rocketdyne workers has only intensified neighbors' fears.

The $1.6-million UCLA study, released last month, linked some work at Rocketdyne to higher-than-expected cancer death rates. It will be followed next year by a study of workers exposed to chemicals believed to cause cancer.

While the UCLA study addressed health effects among workers, little research has been done in the surrounding communities of Simi Valley, Box and Bell canyons, the Santa Susana Knolls, Chatsworth and West Hills, much to the chagrin of neighbors who blame bladder cancers, leukemia and birth defects on their next-door neighbor.

Within six months, Underwood and her colleagues will examine all existing off-site measurements of air, water and soil contamination from the field lab and will determine whether further measurements are necessary, she said.

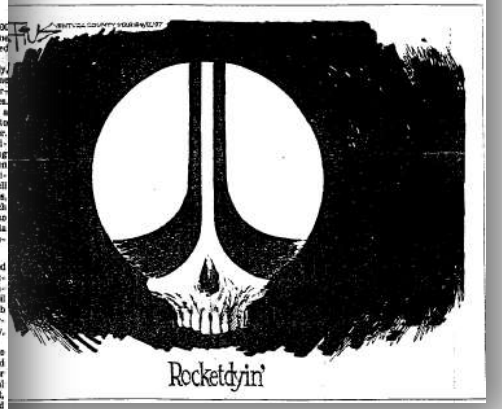
If more tests are needed, the environmental investigators would first ask another public agency or Rocketdyne to take the additional off-site measurements. If needed, however, the investigators could take soil and water samples themselves, she added.

"As with most sites, a lot of that data doesn't already exist," she said. "We have data from the [next-door] Brandeis-Bardin camp and the Santa Monica Mountains Conservancy, but we'll look for whatever other data might be needed from the south, east and west of [the field lab]. We always press for more data."

Rocketdyne recently settled a lawsuit in which the Brandeis-Bardin Institute, a Jewish studies center, claimed nuclear and rocket research polluted its land and water and lowered its property value.

The Star

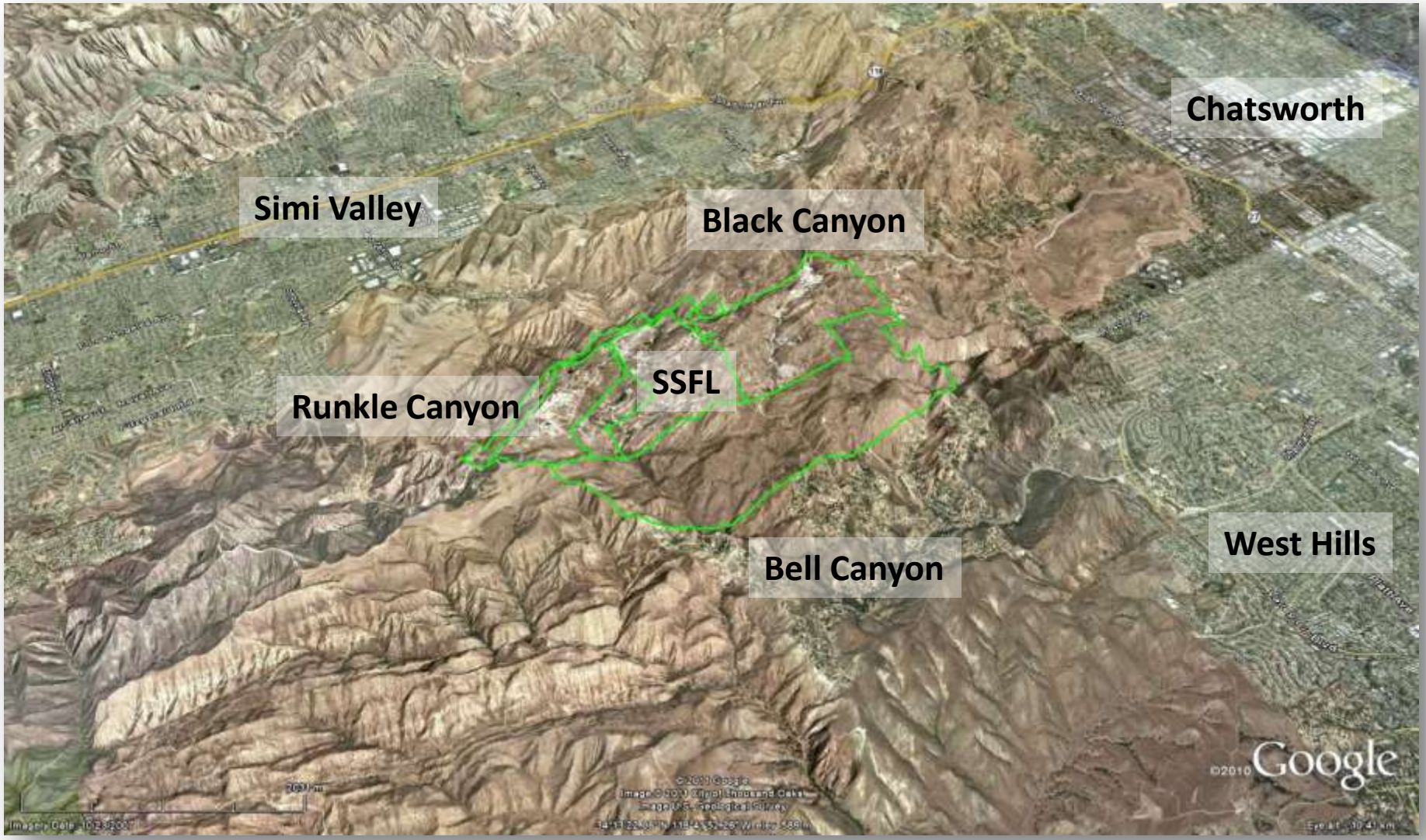
OPINION



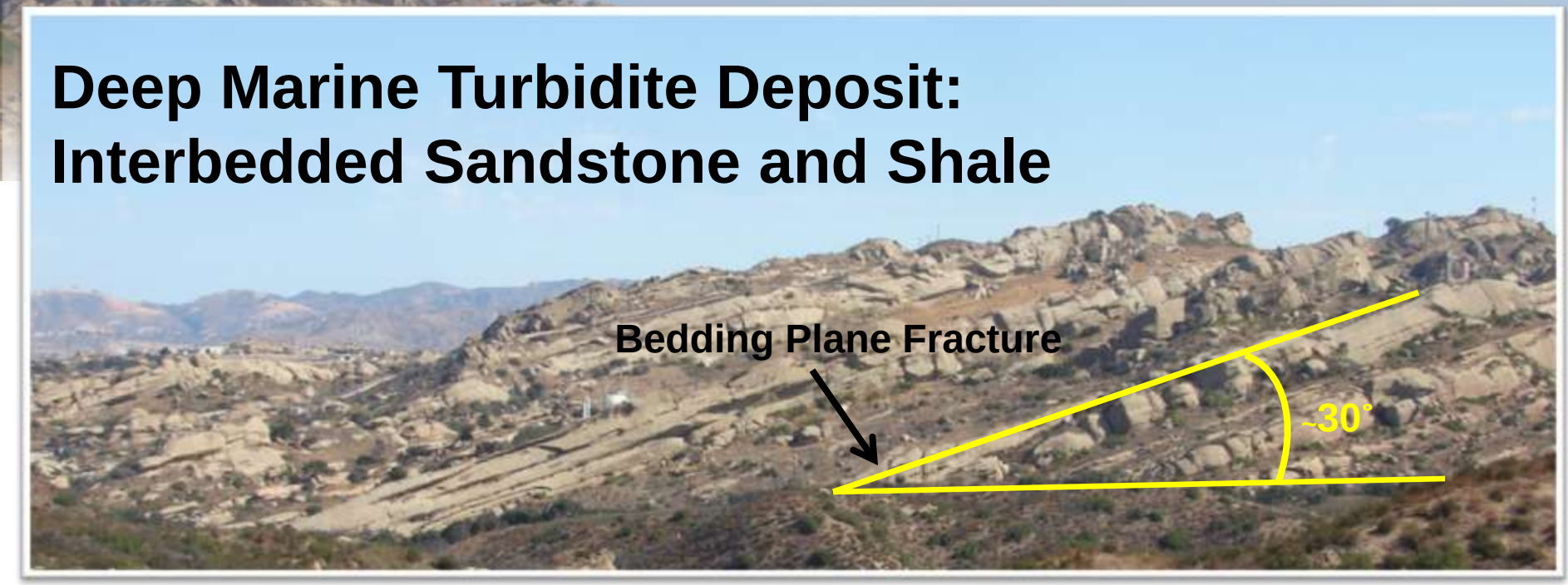
Site Location

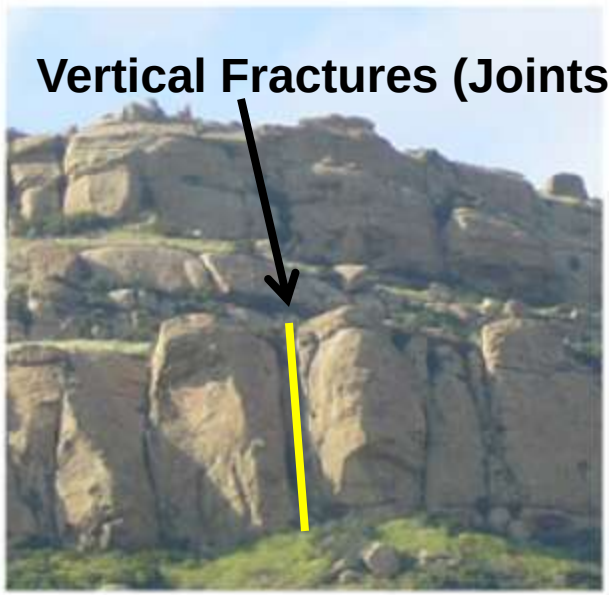
Located in Greater Los Angeles Area

Upland Site Between Communities



Deep Marine Turbidite Deposit: Interbedded Sandstone and Shale





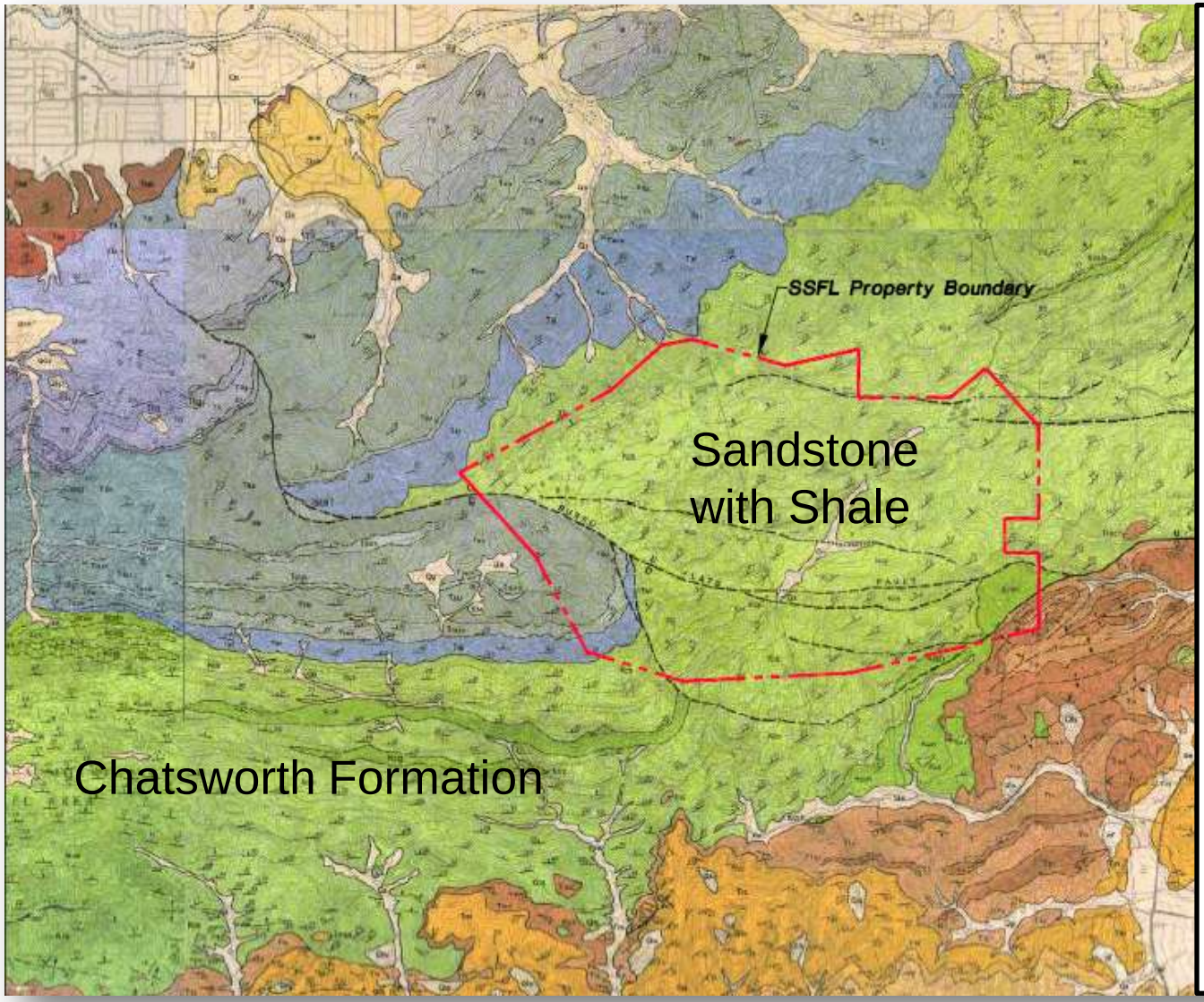
Nature of the Problem

At first glance the site is complex:

- Fractures
- Faults
- Dipping beds
- Numerous contaminant input areas
- DNAPL

Value of site conceptual model approach

Study Area All Within Chatsworth Fm



Simi Formation
Conglomerate

Santa Susana Formation
Sandstone

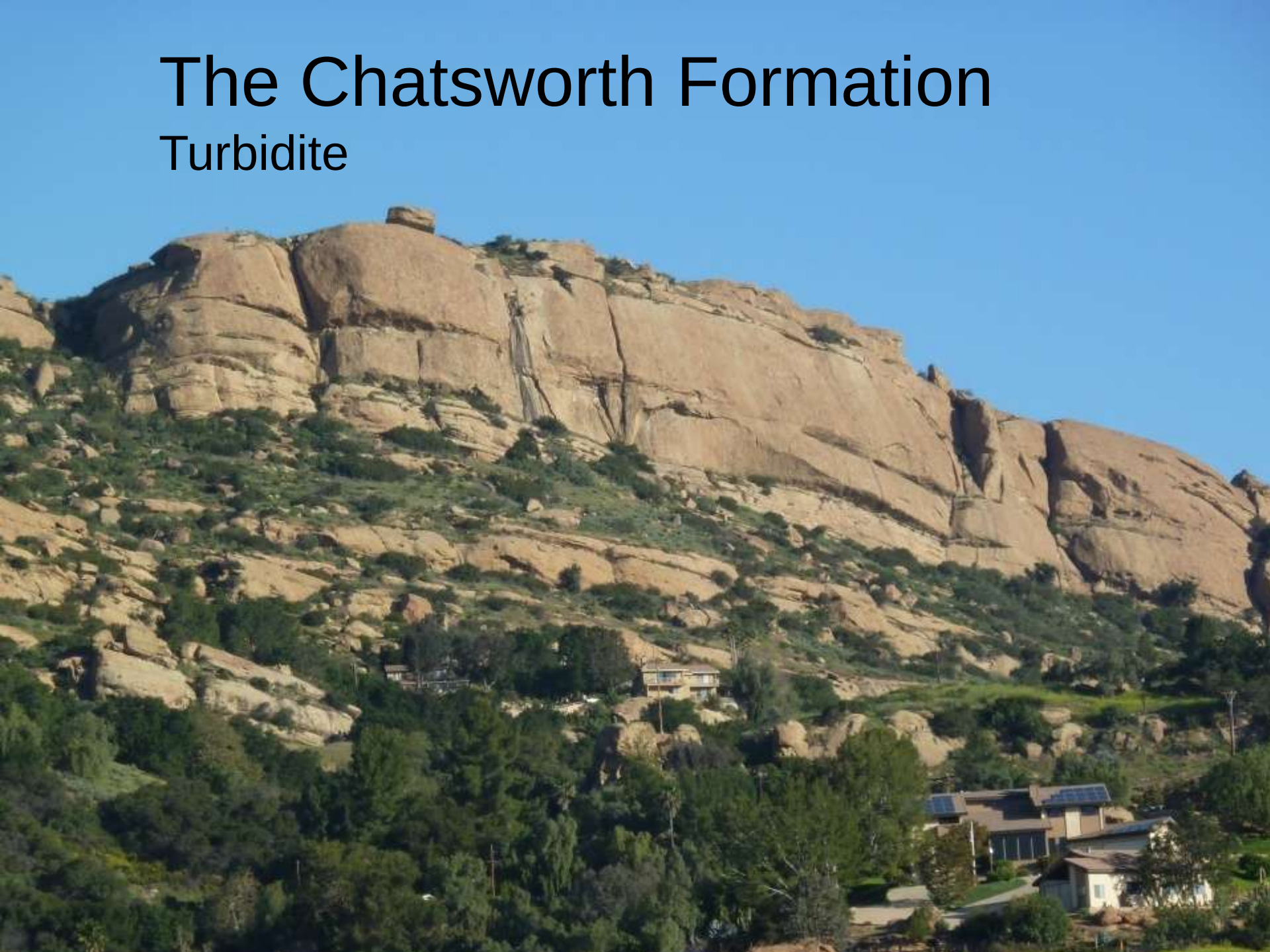
Chatsworth Formation
Sandstone

Monterey Formation
Sandstone

Sespe Formation
Sandstone and
Conglomerate

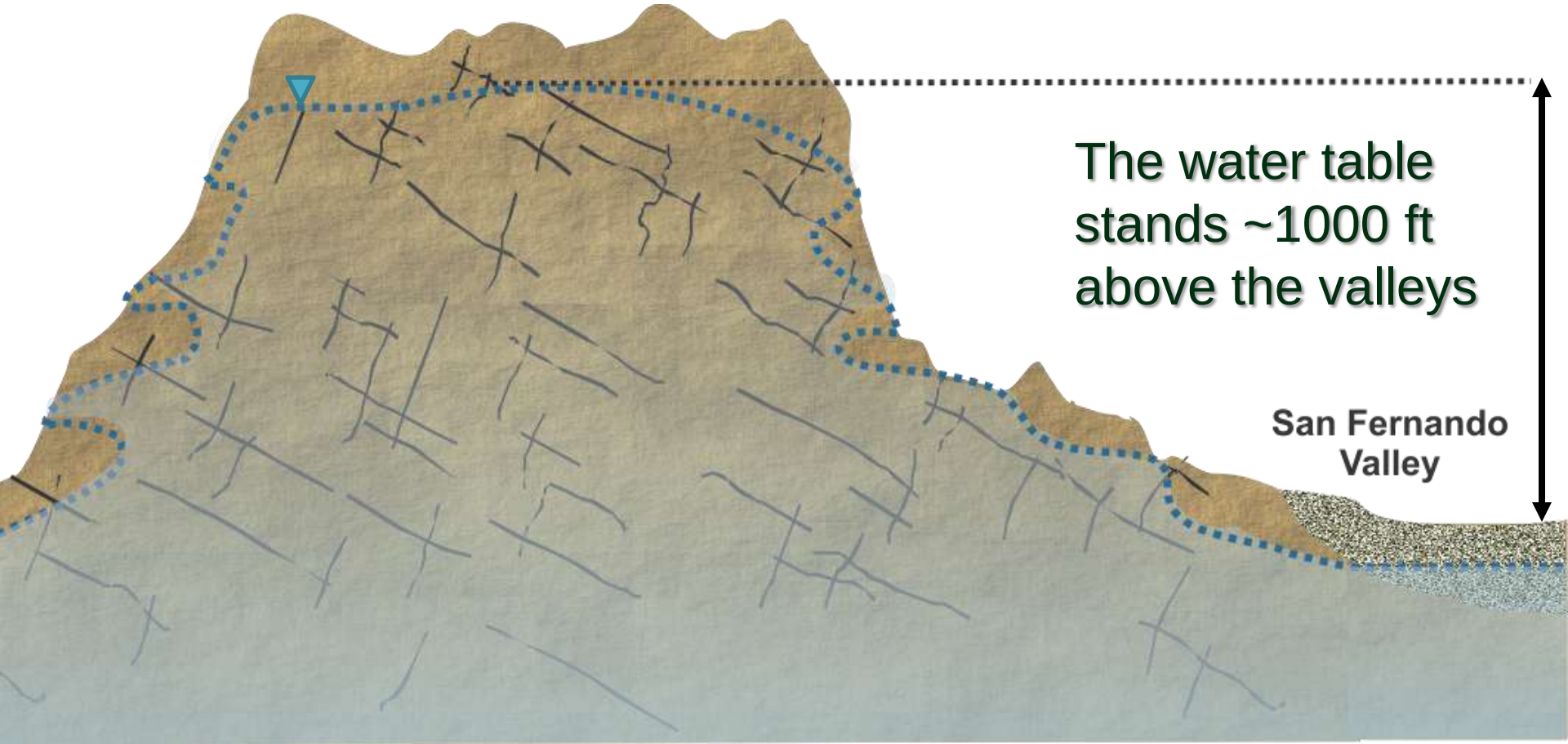
The Chatsworth Formation

Turbidite

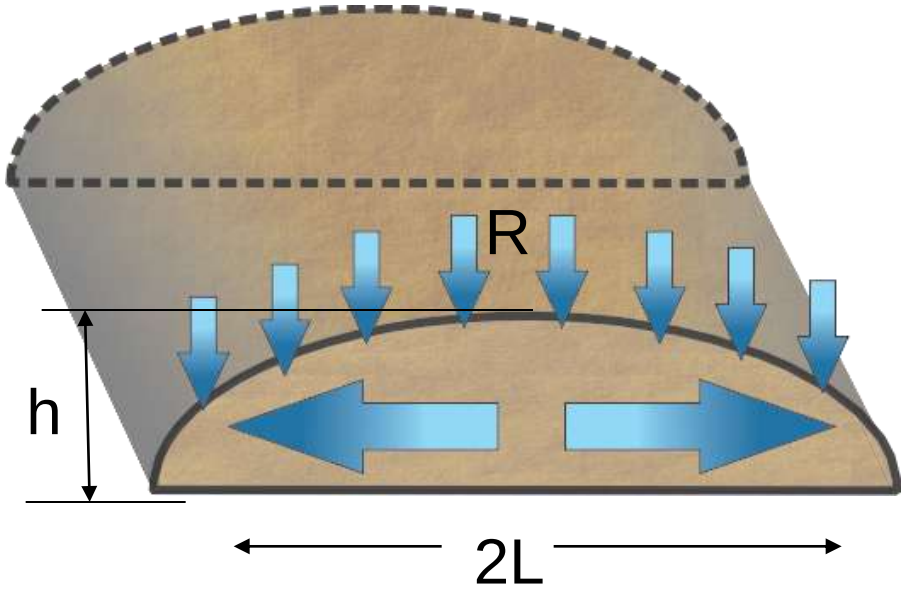


High water table and groundwater flow in fractures

Why does the SSFL groundwater level stay high above the surrounding valleys?



Mountain Approximated as a Ridge



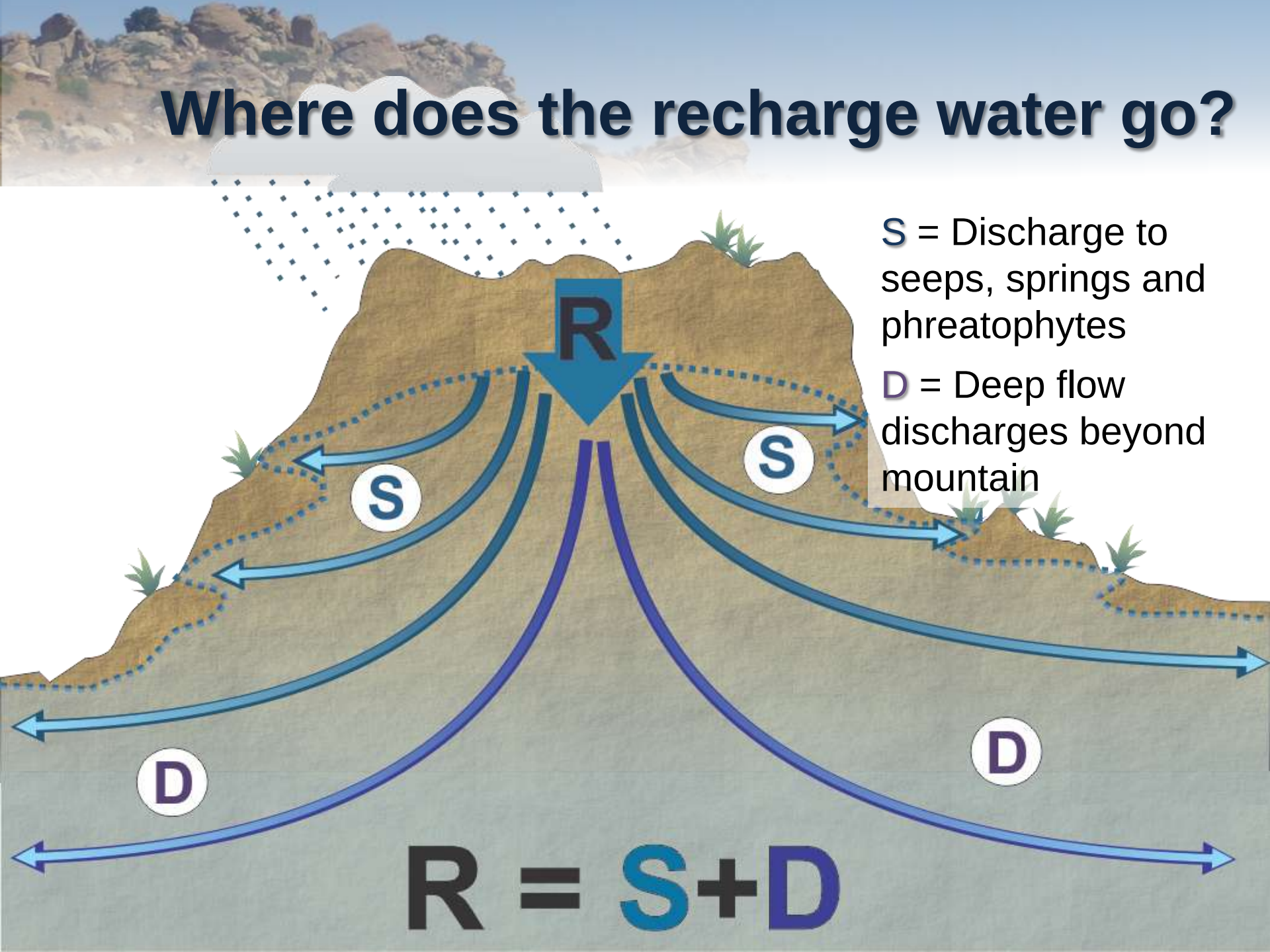
$K_b = R\ L^2 / \ h^2$

K_b = bulk hydraulic conductivity
R = recharge rate (~ 10% ppt)
L = width of mound
h = height of mound at center

Groundwater mound forms a long ridge of constant cross section.

$K \sim 10^{-5}$ cm/s

Where does the recharge water go?

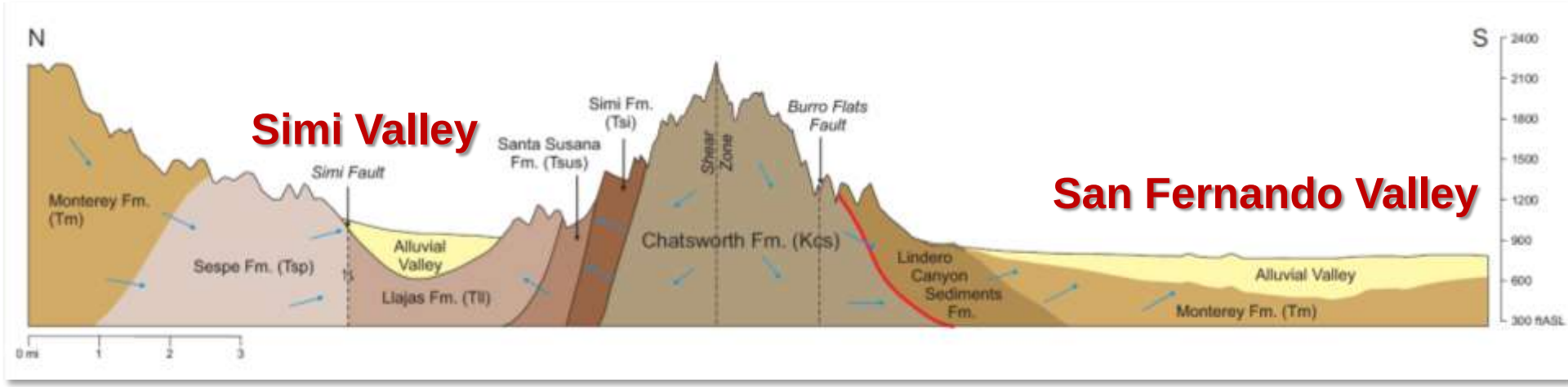


S = Discharge to seeps, springs and phreatophytes

D = Deep flow discharges beyond mountain

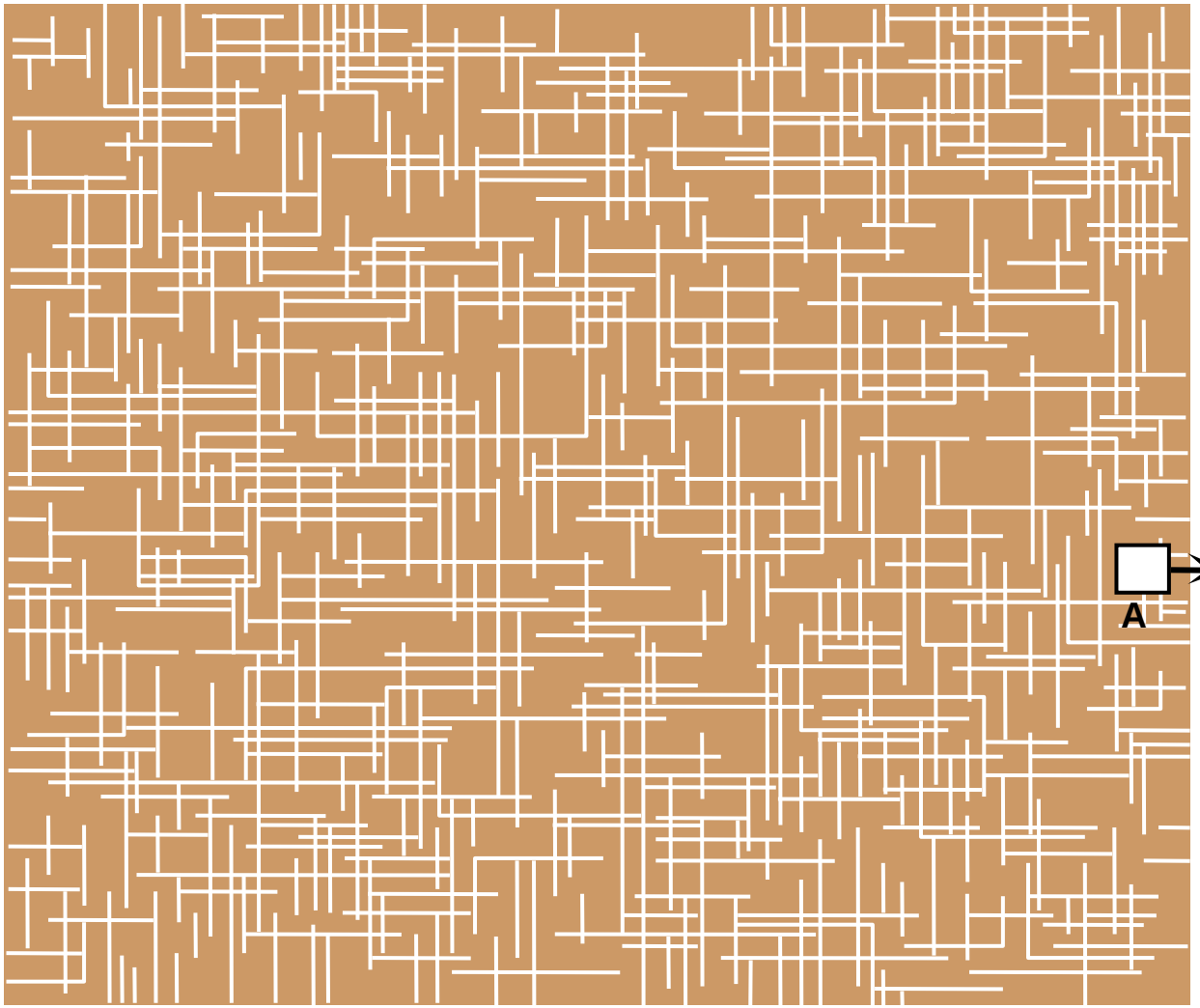
Regional Hydrogeologic Section

- Minimal municipal groundwater use in both San Fernando and Simi Valleys
- Local private wells



Vertical Exaggeration = 10

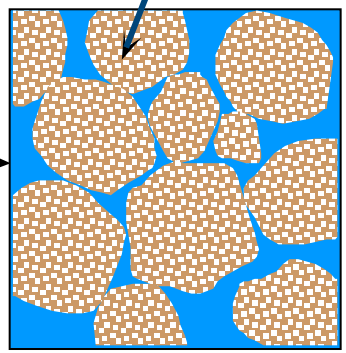
Dual Permeability System



Matrix Porosity: 2-20%

DETAIL A

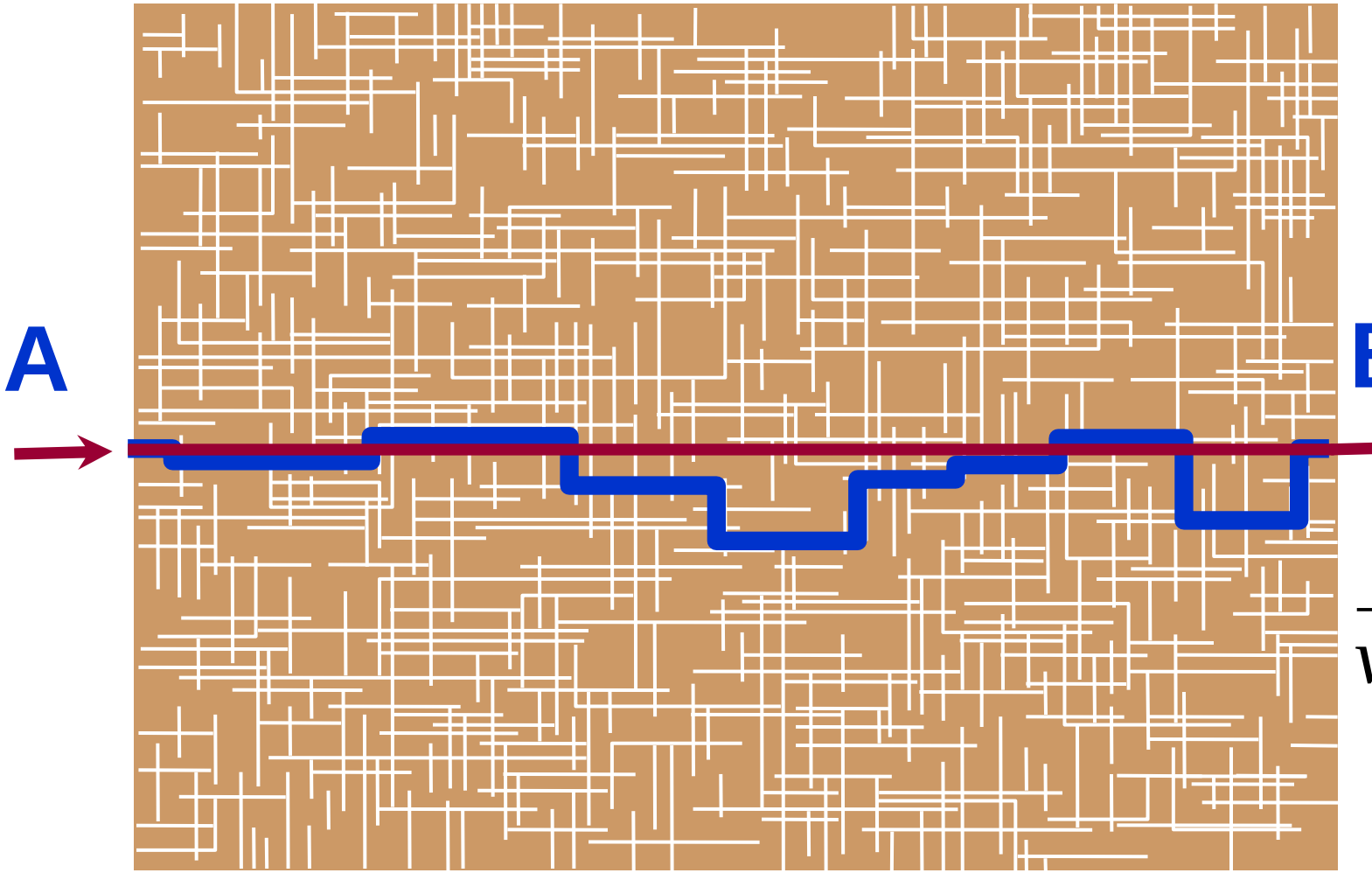
mineral particle



Microscopic view of rock matrix

Fracture Porosity: 0.01 to 0.001%

Fast Average Linear Groundwater Velocity in Fractured Rock



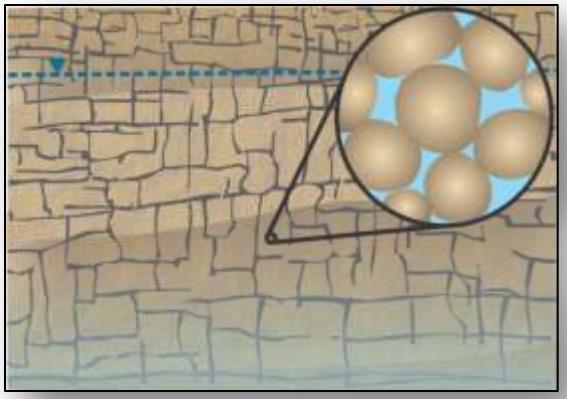
$$\bar{v}_f = \frac{K_b\, i}{\phi_f}$$

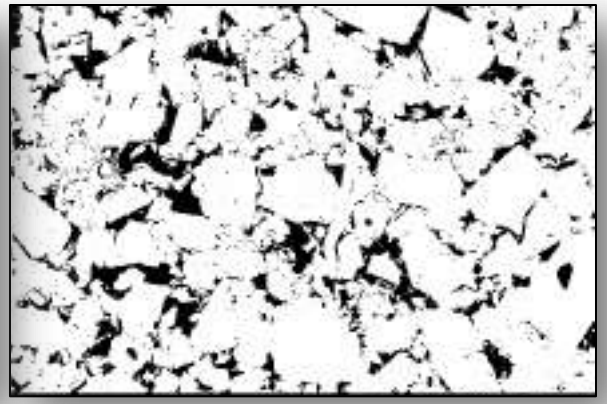
$\bar{v}_f$ *represents line path from A to B*

Virtually all groundwater is present in the low permeability matrix

Matrix porosity ~ 13 %

Matrix permeability ~ 10^{-6} to 10^{-11} cm/s

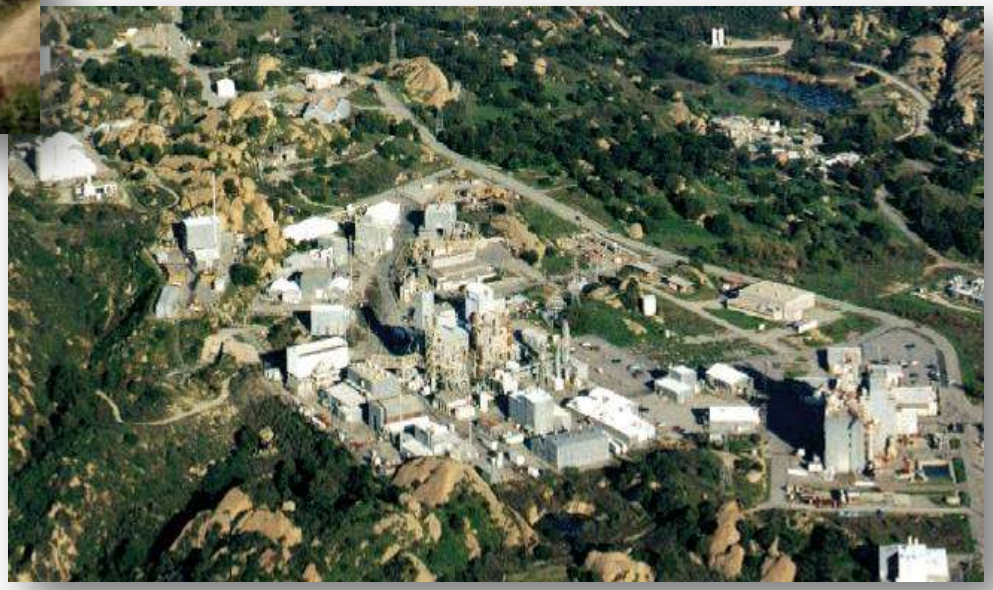




Two Primary Functions at SSFL

Rocket Engine Testing for NASA

- 1949-2006
- Six Test Stands – 17,000 Rocket Engine & Component Tests
- Last test March 3, 2006

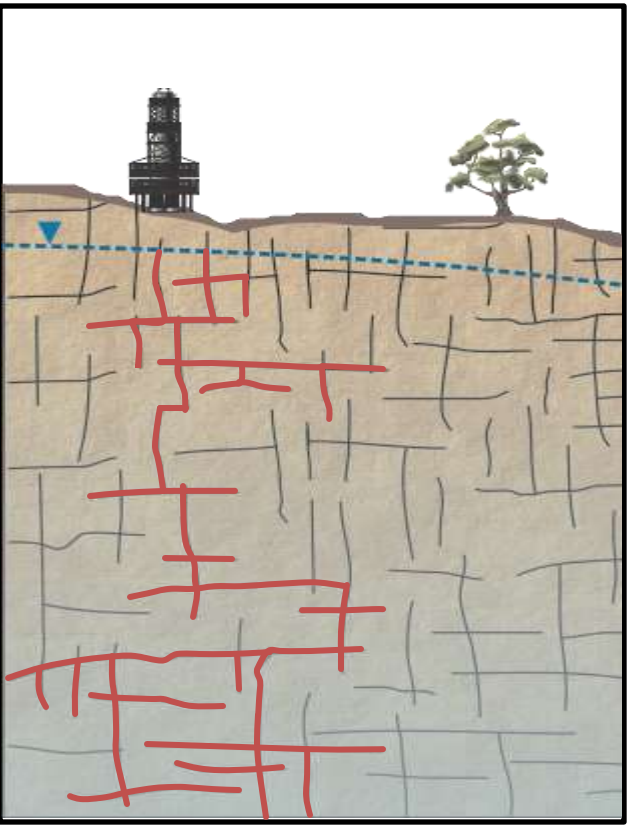


Nuclear Research & Liquid Metal Research for DOE

- Nuclear Power Research: 1956-1983
- Ten reactors
- Sodium component test facilities
- DOE Program ends 1988

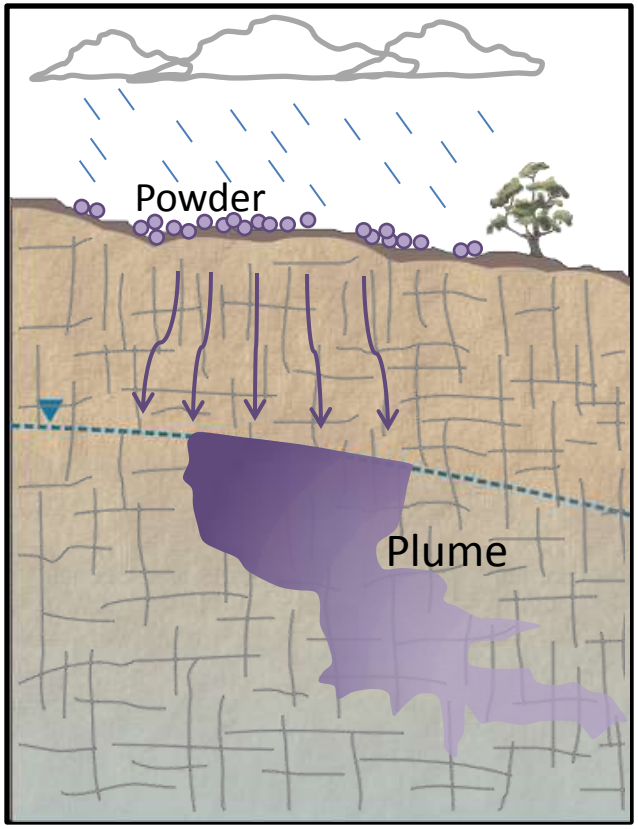
How Did Contaminants Get Into SSFL Groundwater?

DNAPL Infiltration



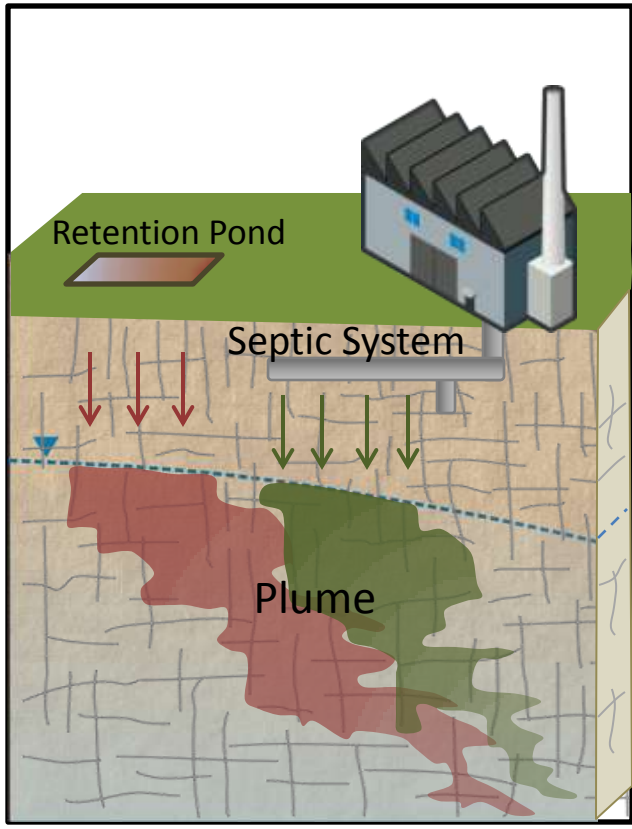
Trichloroethene
Perchloroethene
Trichloroethane

Leaching of Solids



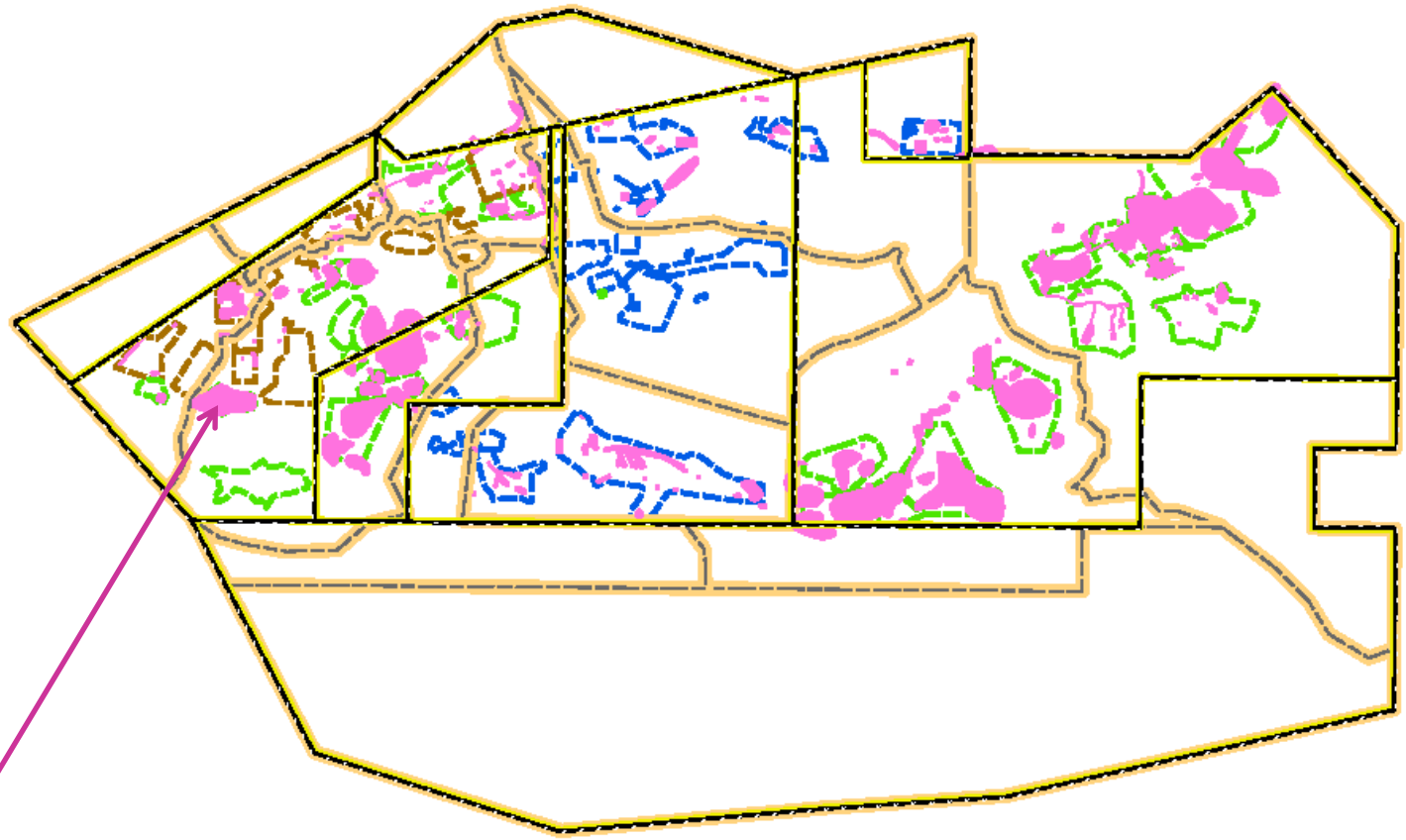
Perchlorate (ClO_4)
Metals

Water Infiltration



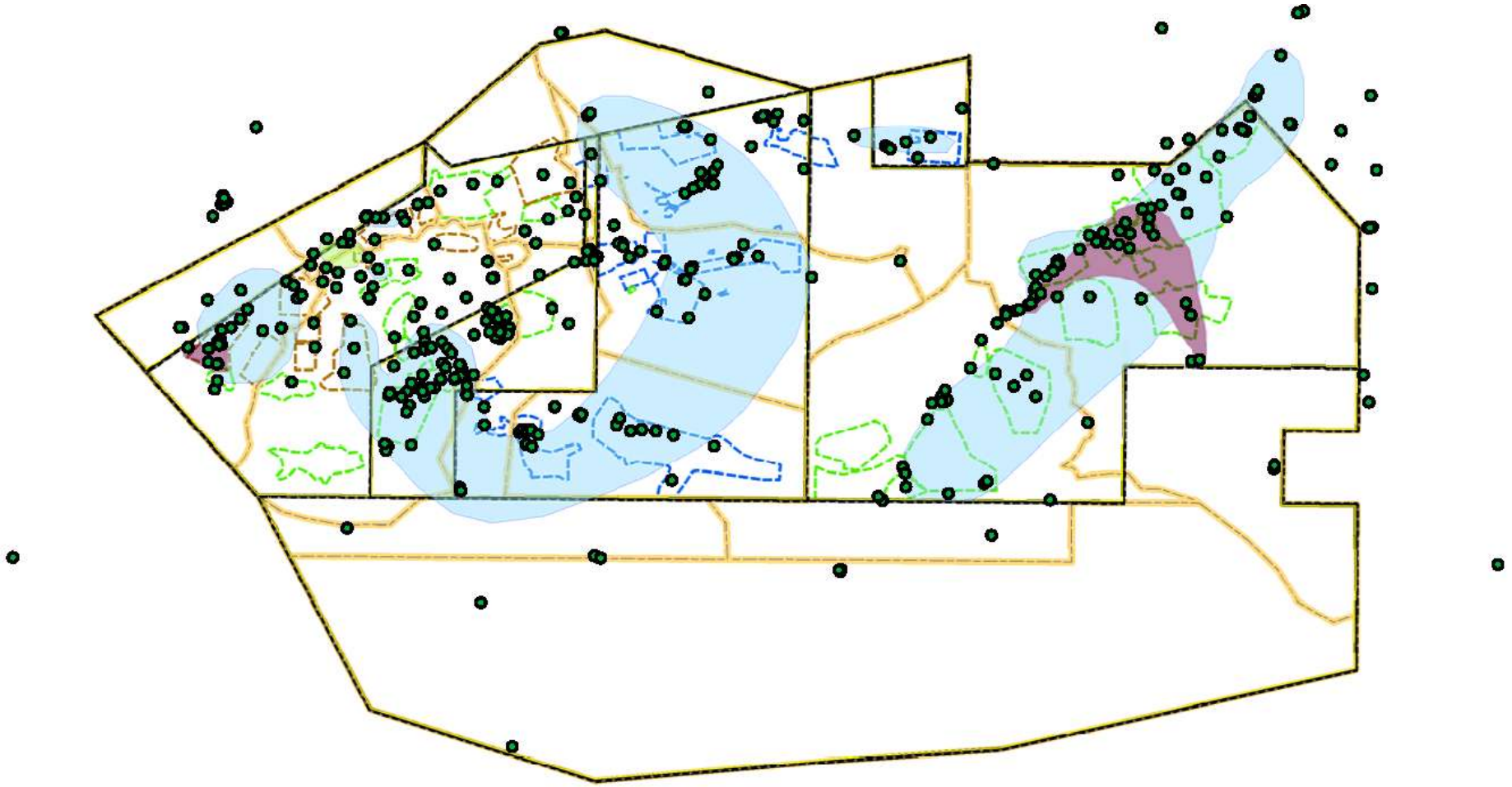
Nitrate
Chloride
Tritium
Dissolved Solvents

Surficial Media Contaminated Areas



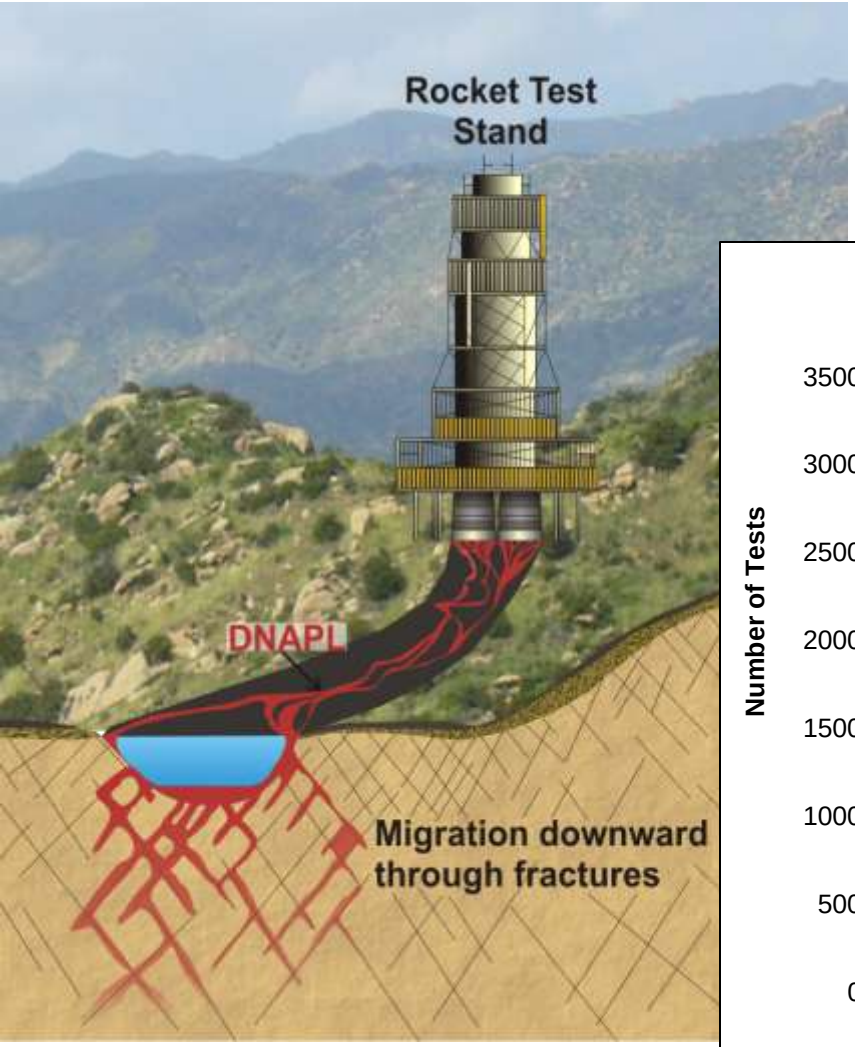
Areas recommended for corrective measures study based on suburban residential land use

Bedrock Groundwater Monitoring Network

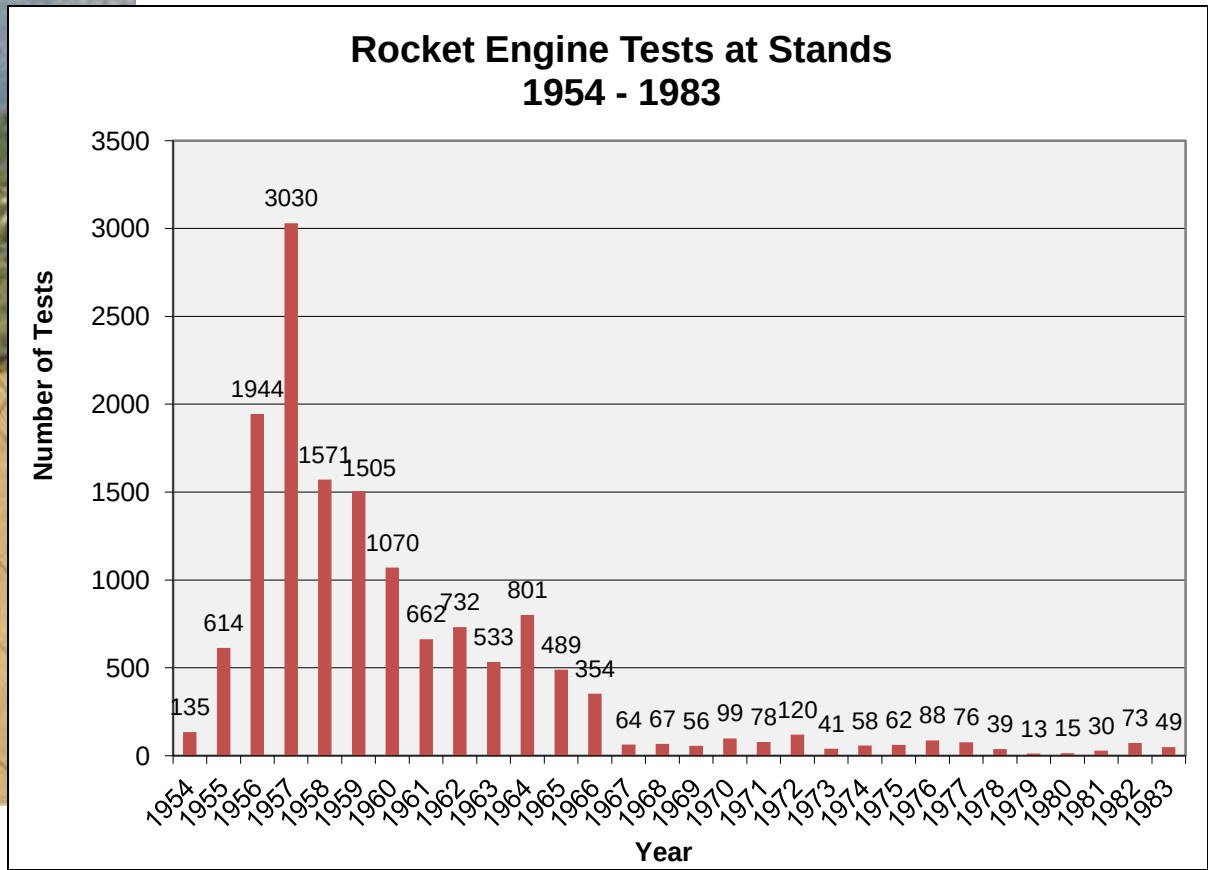


428 wells used to define extent of groundwater contamination

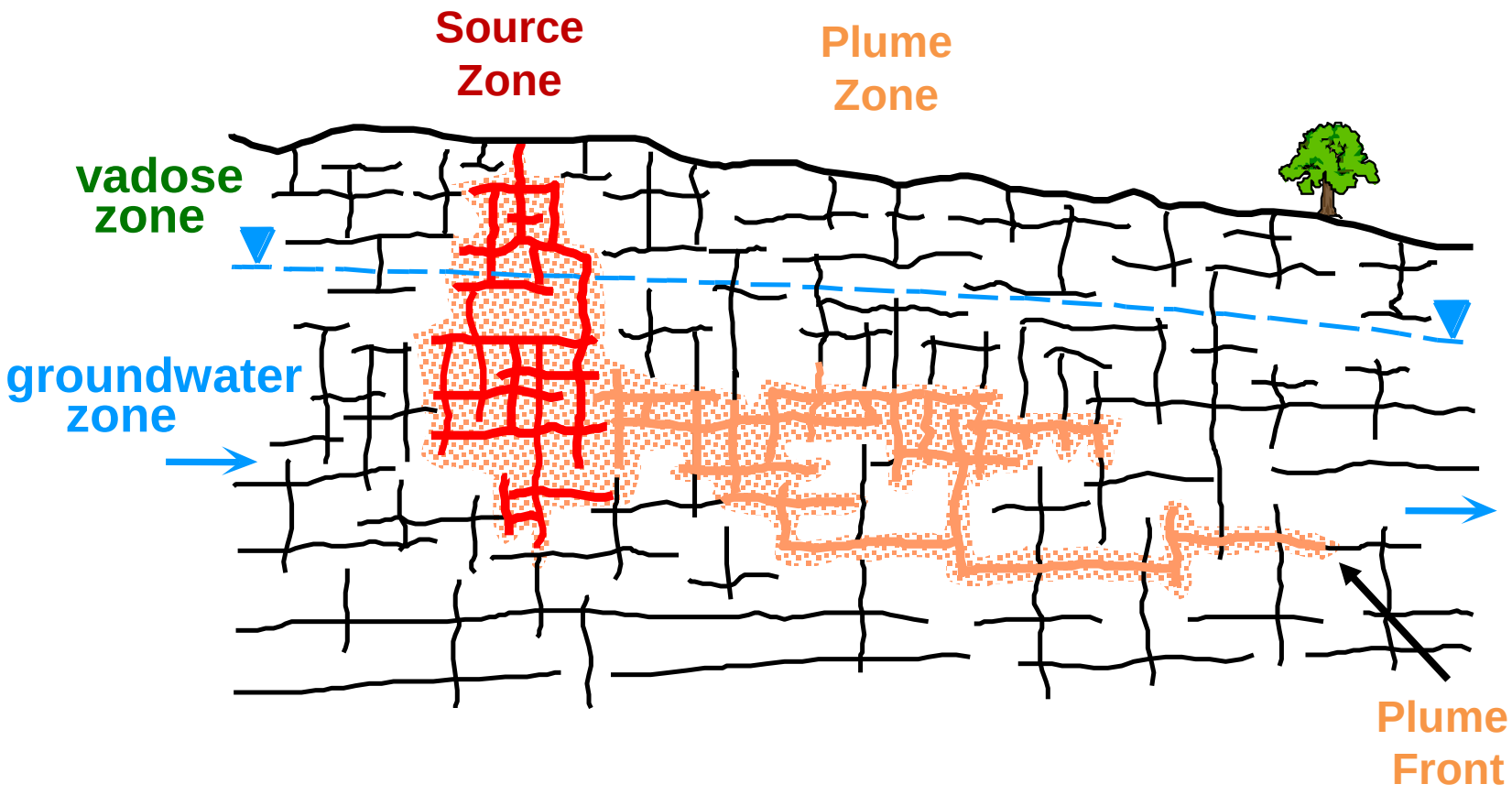
Much TCE DNAPL Went into the Ground – What Happened to it?



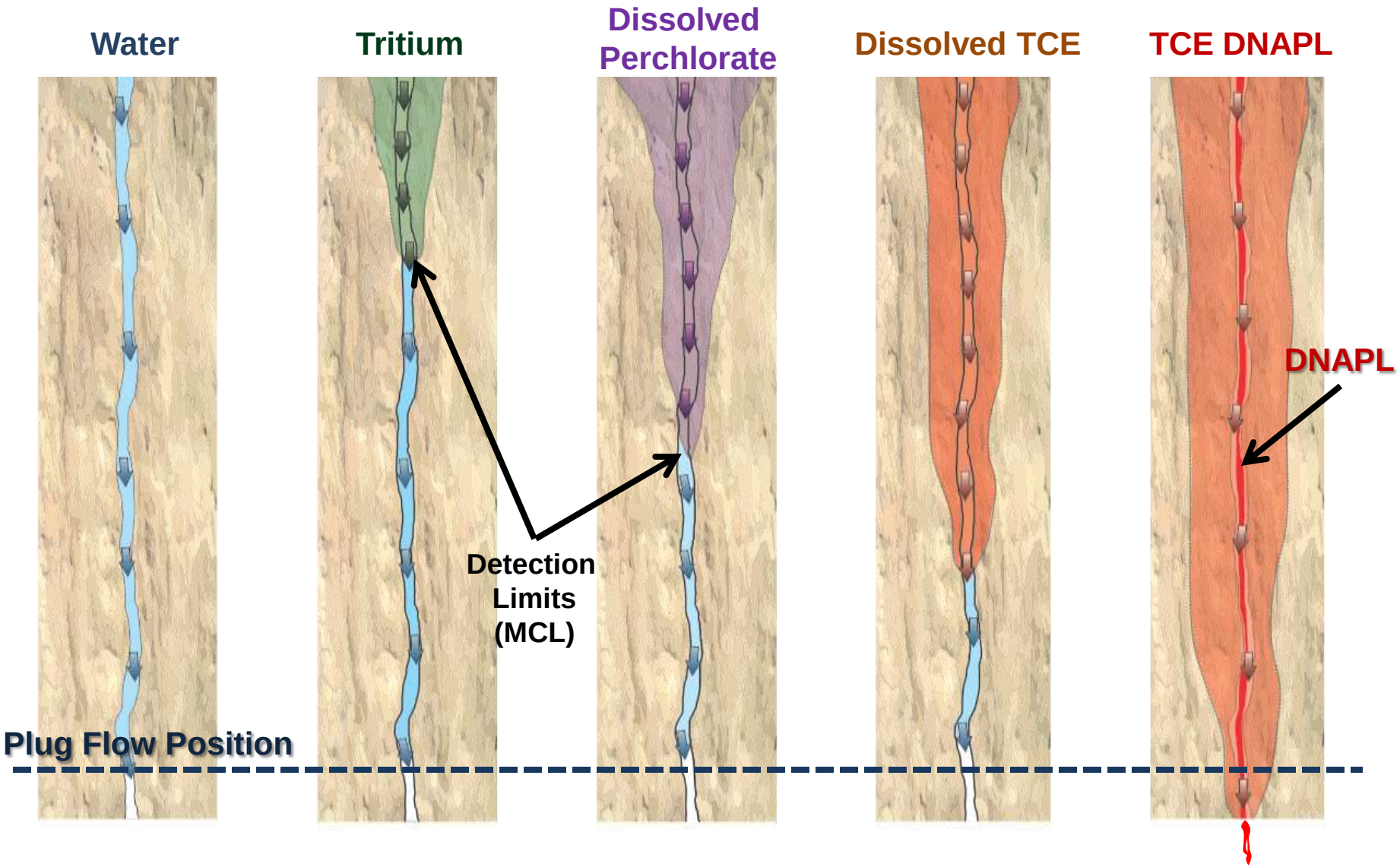
CH2M Hill Estimate (1993) ~ 500,000 gallons entered subsurface



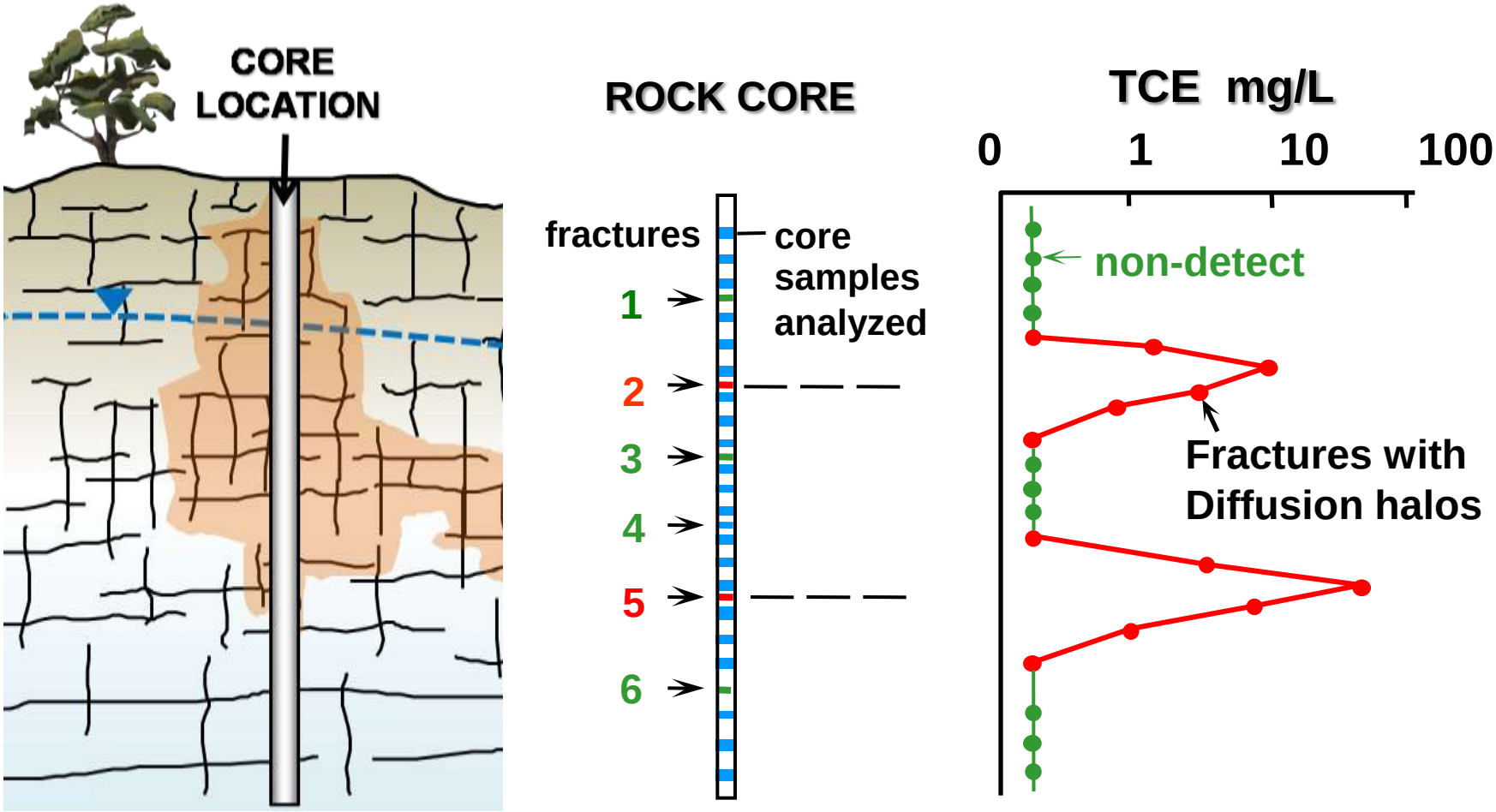
Nature of Contamination in Fractured Sedimentary Rock



TCE is Most Mobile Contaminant Due to DNAPL

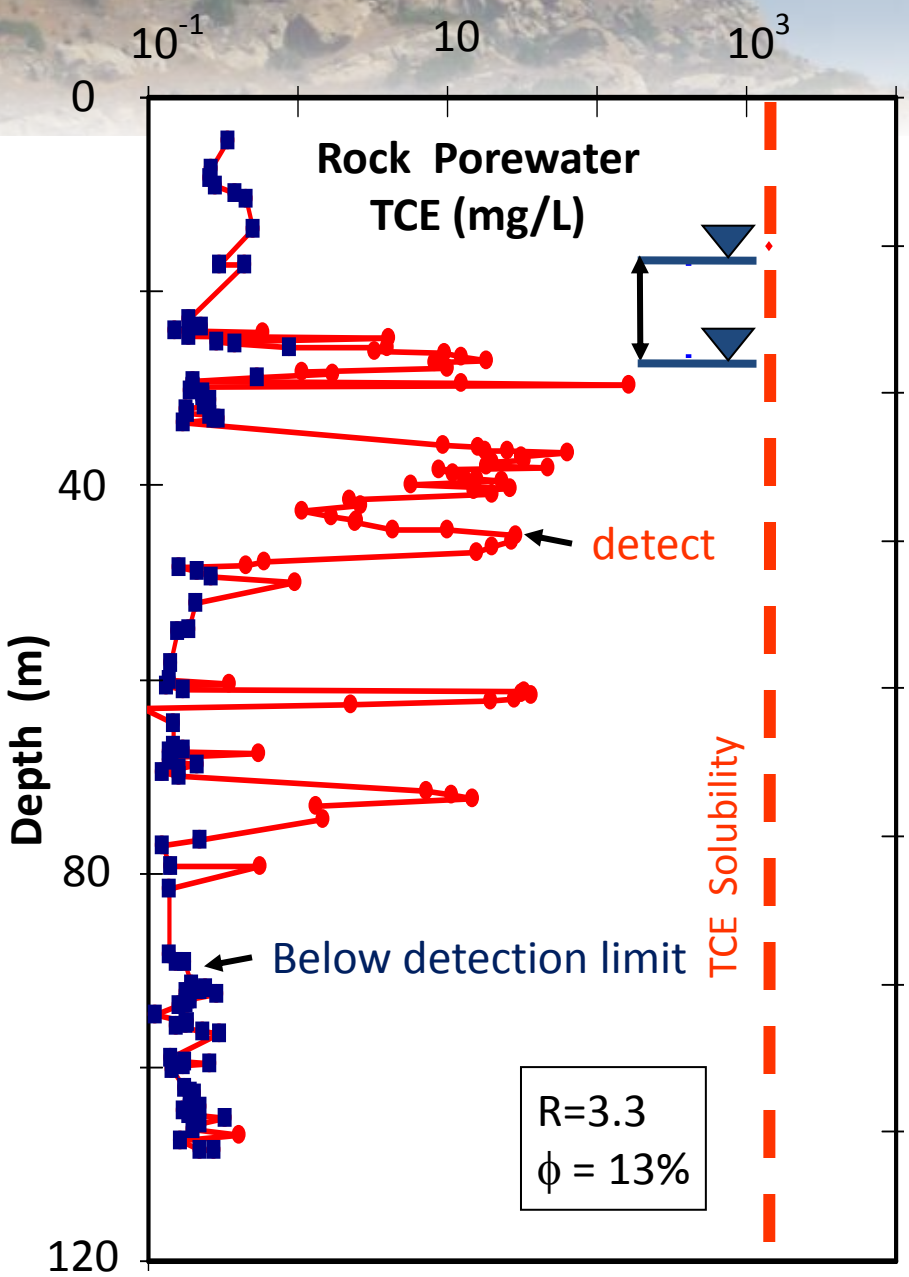


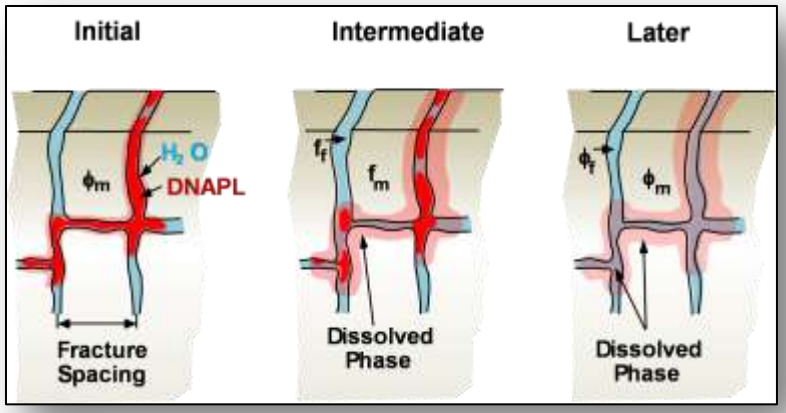
Rock Core Sampling to Find Contaminants



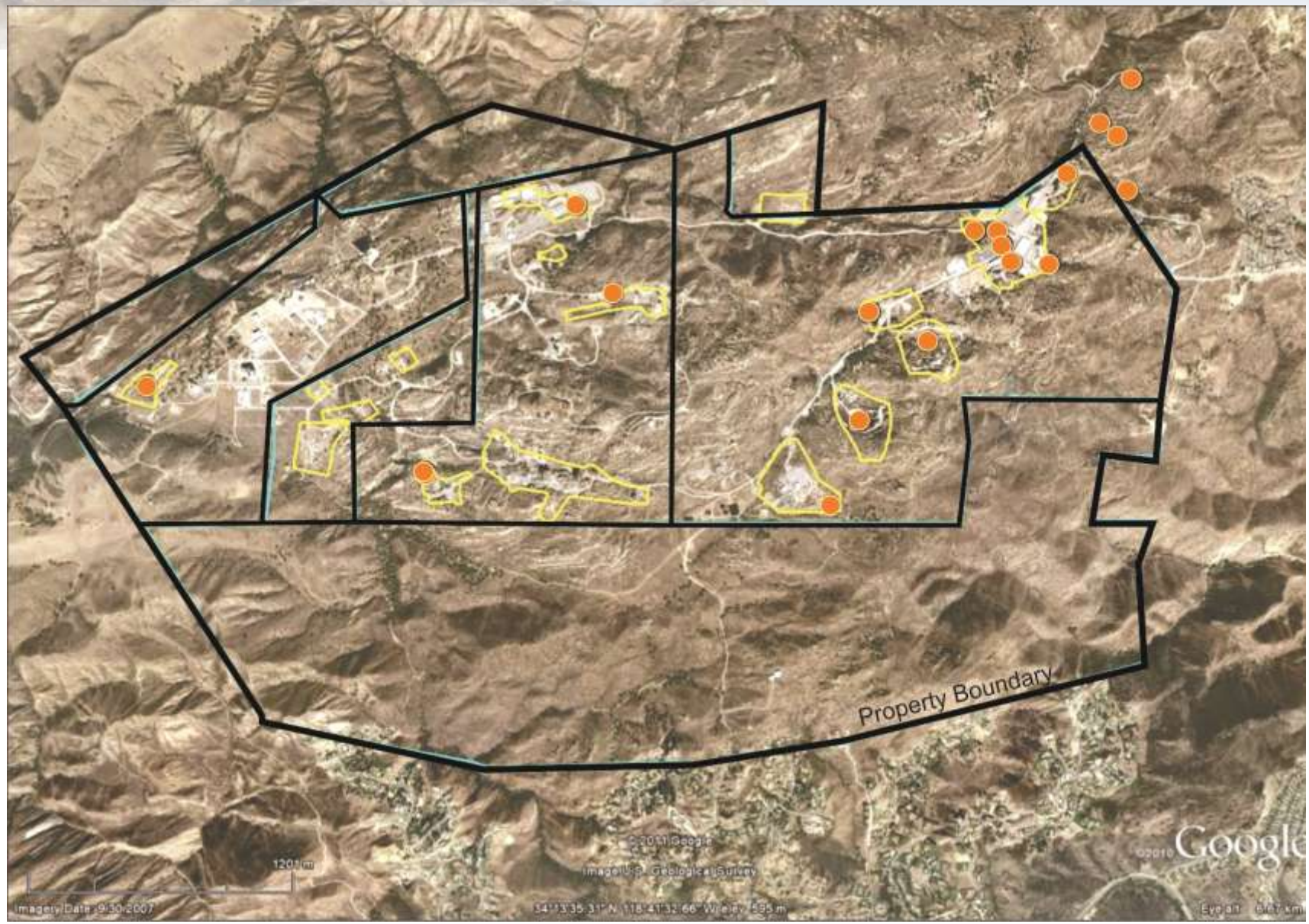
Rock Core Drilling at C-2, Canyon Test Stand

Rock Porewater TCE Profile RD-35B



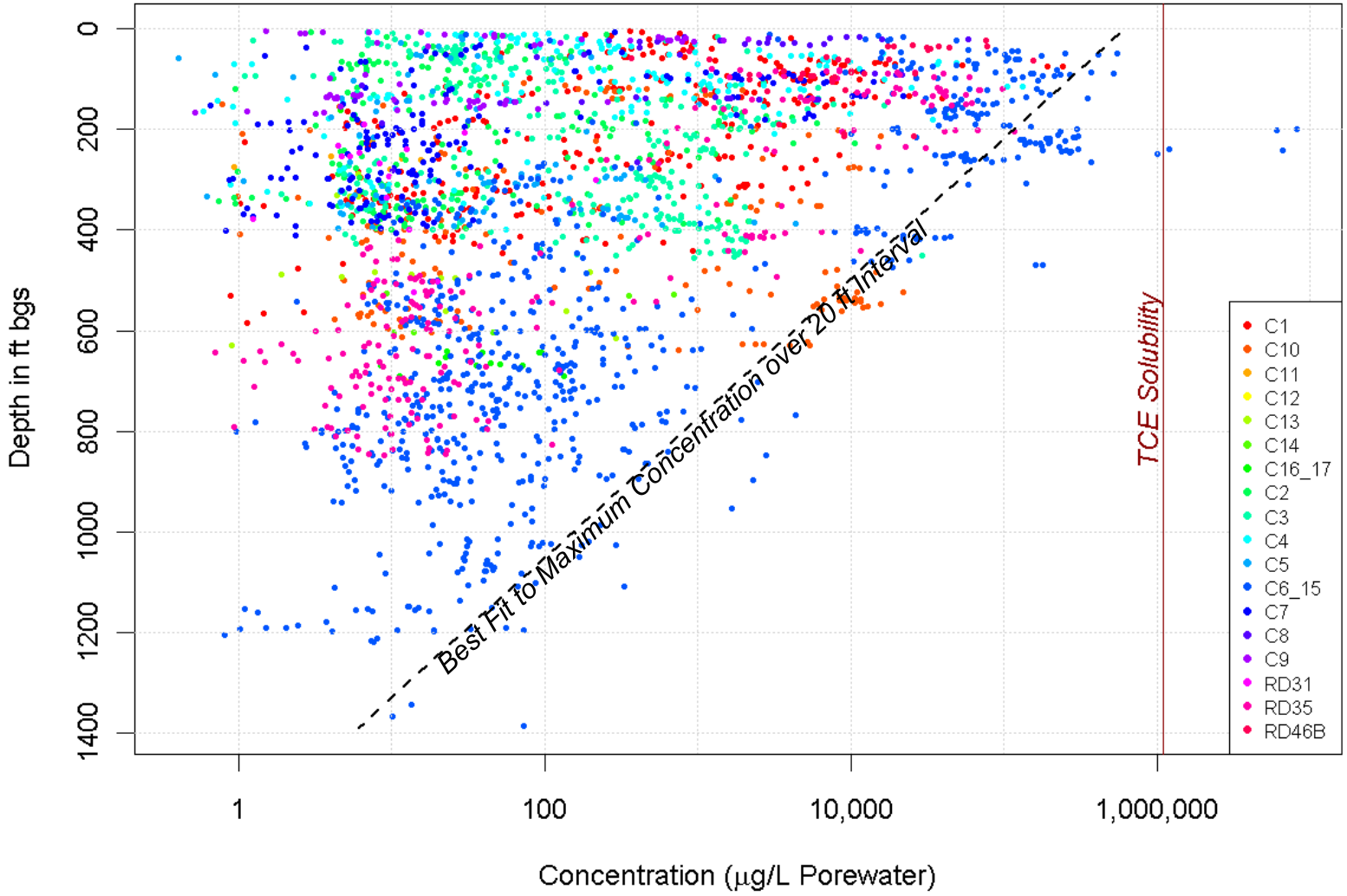


Total of 20 Coreholes at 18 Locations



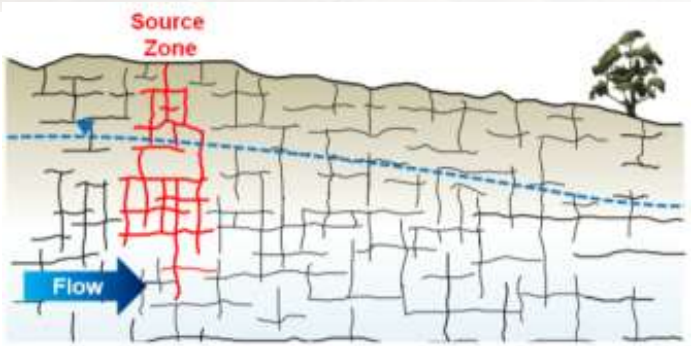
TCE Concentrations Decline with Depth

> 7,000 Rock Core Samples in 20 Core Holes



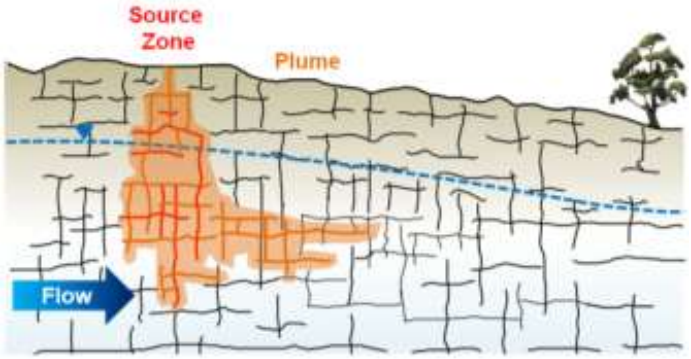
Source Zone / Plume Evolution Conceptual Model

Early Time



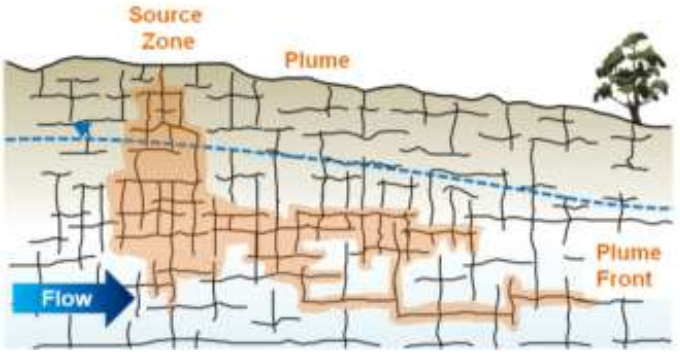
DNAPL reaches stationary phase in fractures

Intermediate Time



Much DNAPL disappeared, diffusion into matrix in source and plume zones

Late Time

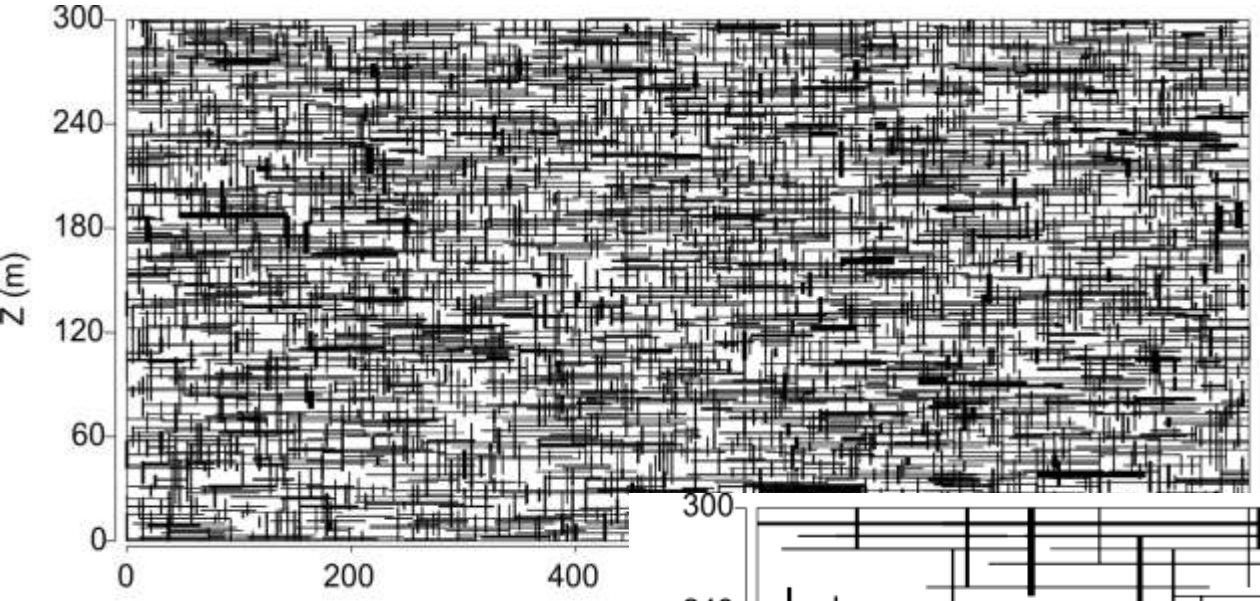


No DNAPL remains and most mass occurs in the matrix, diffusion and other processes cause strong plume attenuation

Key Issues:

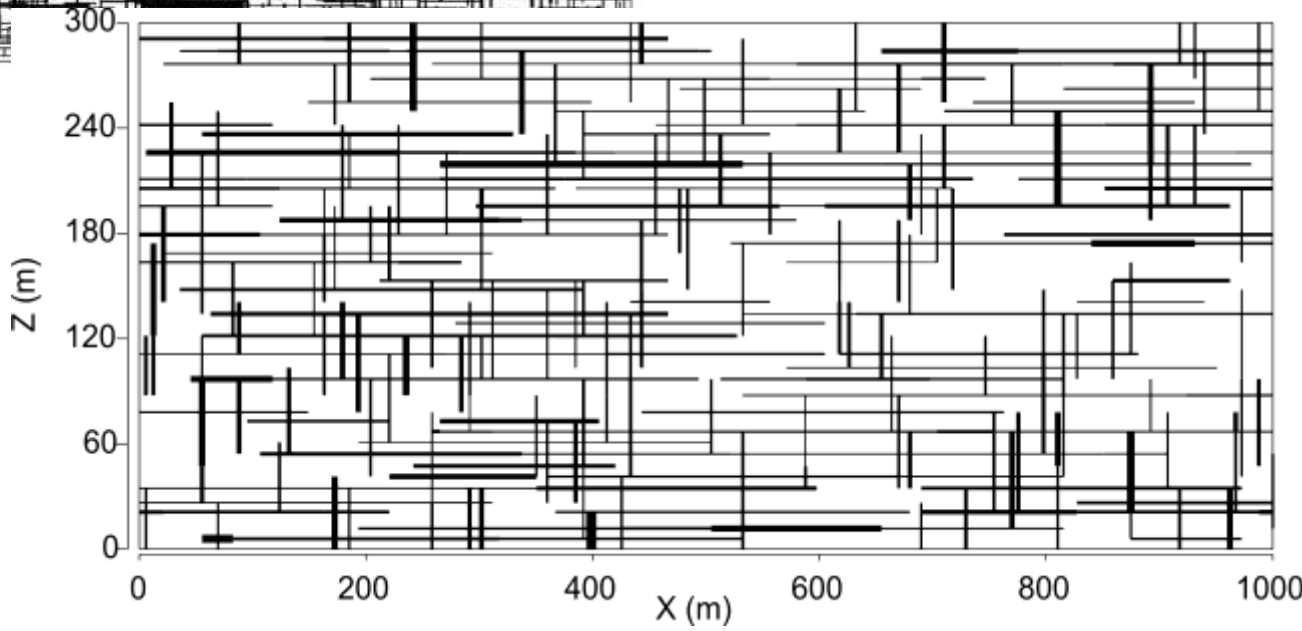
How many active fractures?

What is their Interconnectivity?

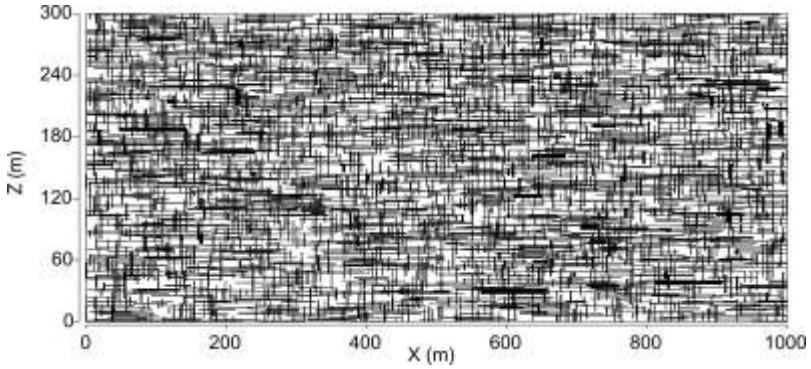


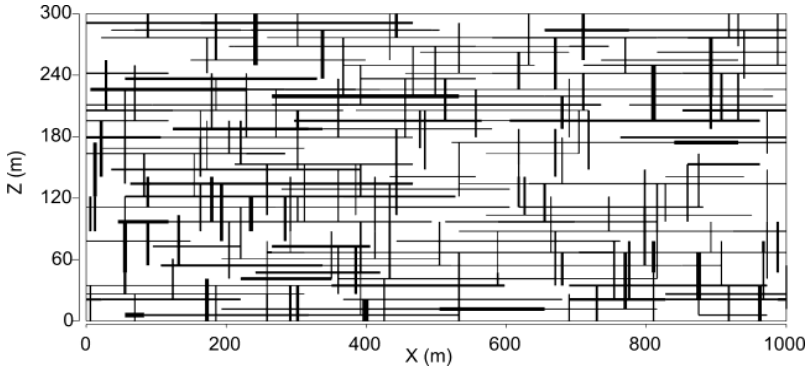
Dense Network

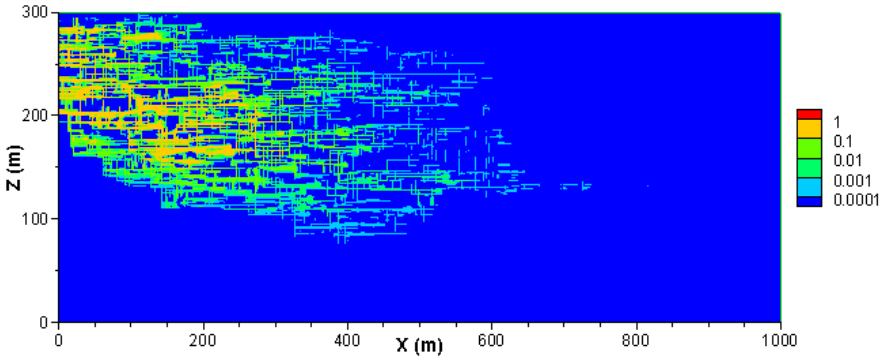
Sparse Network

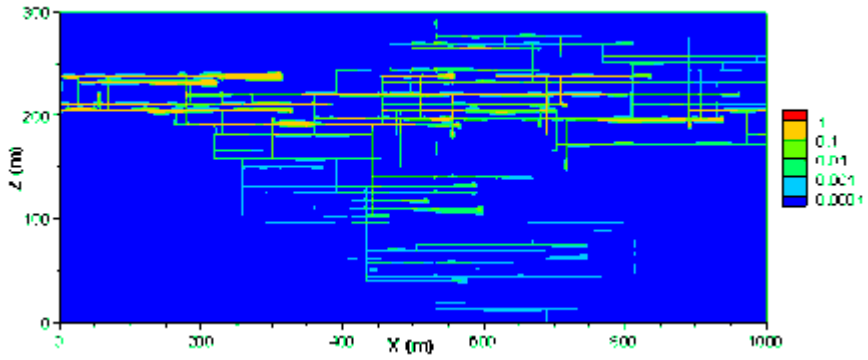


Interplay Between Matrix and Fractures Controls Plume Behavior



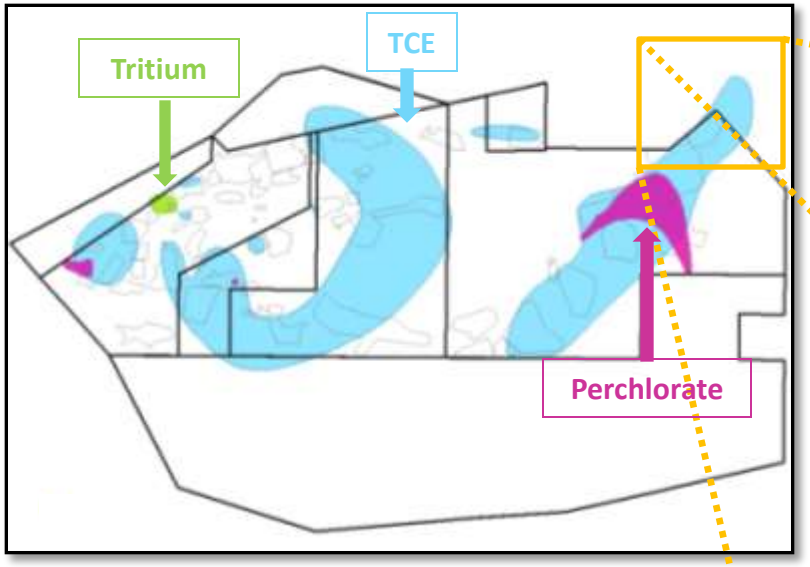


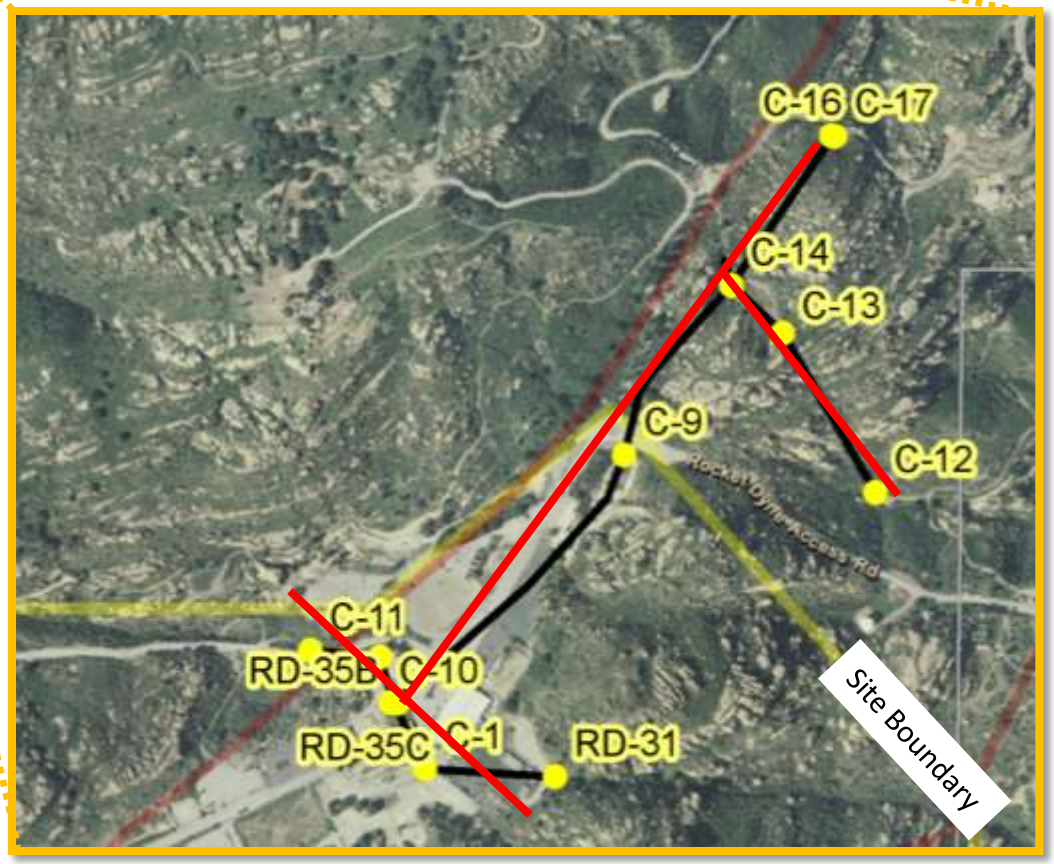




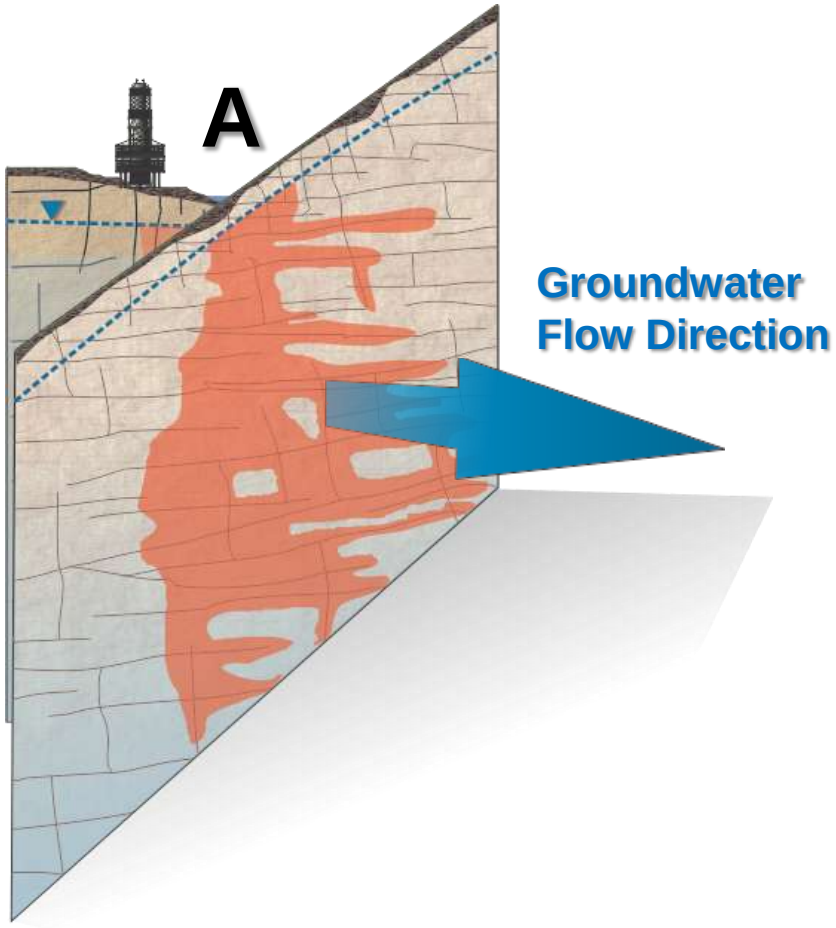
Same bulk K but dissimilar plumes

Focused Look at Northeast Plume

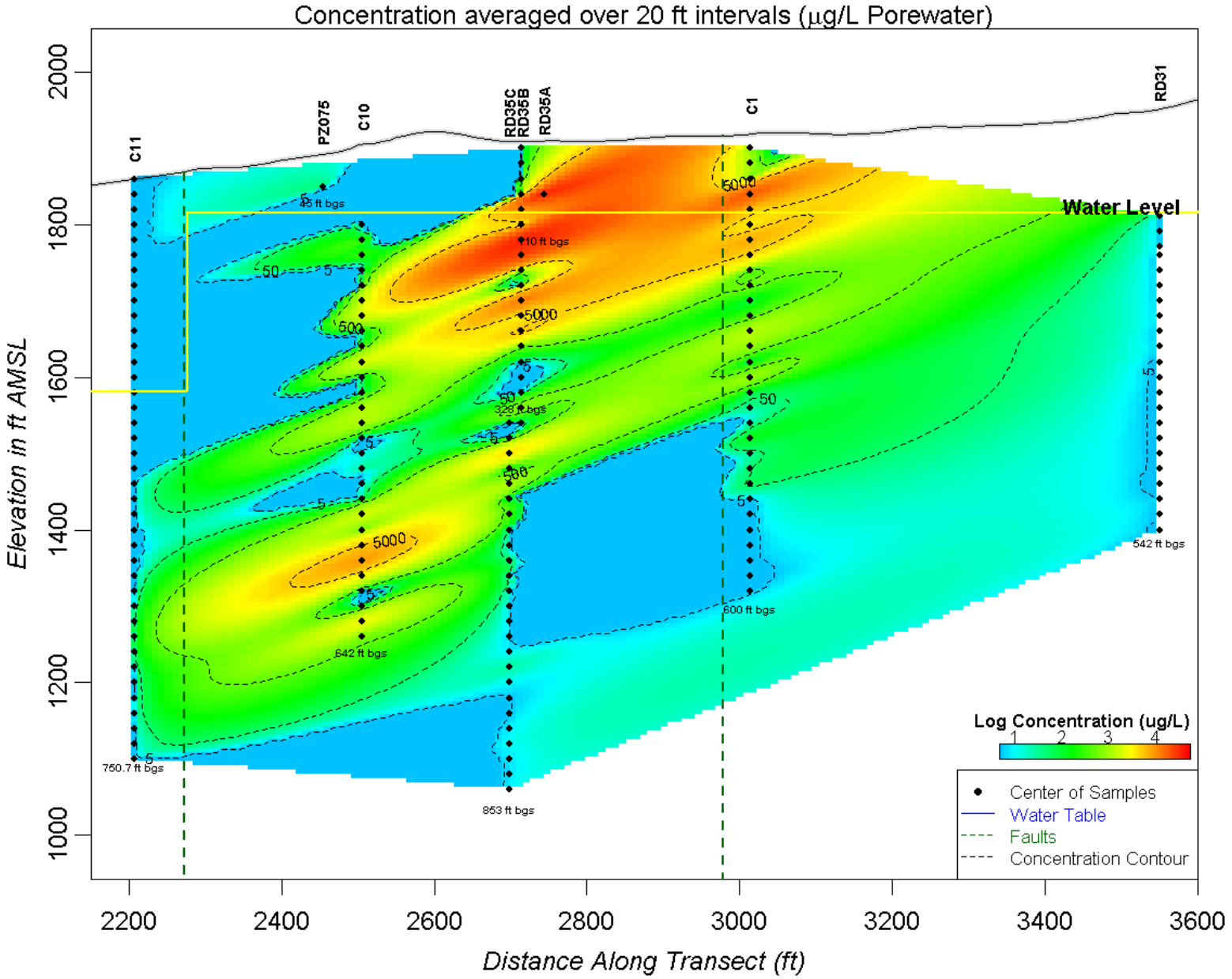




Source Zone Transect

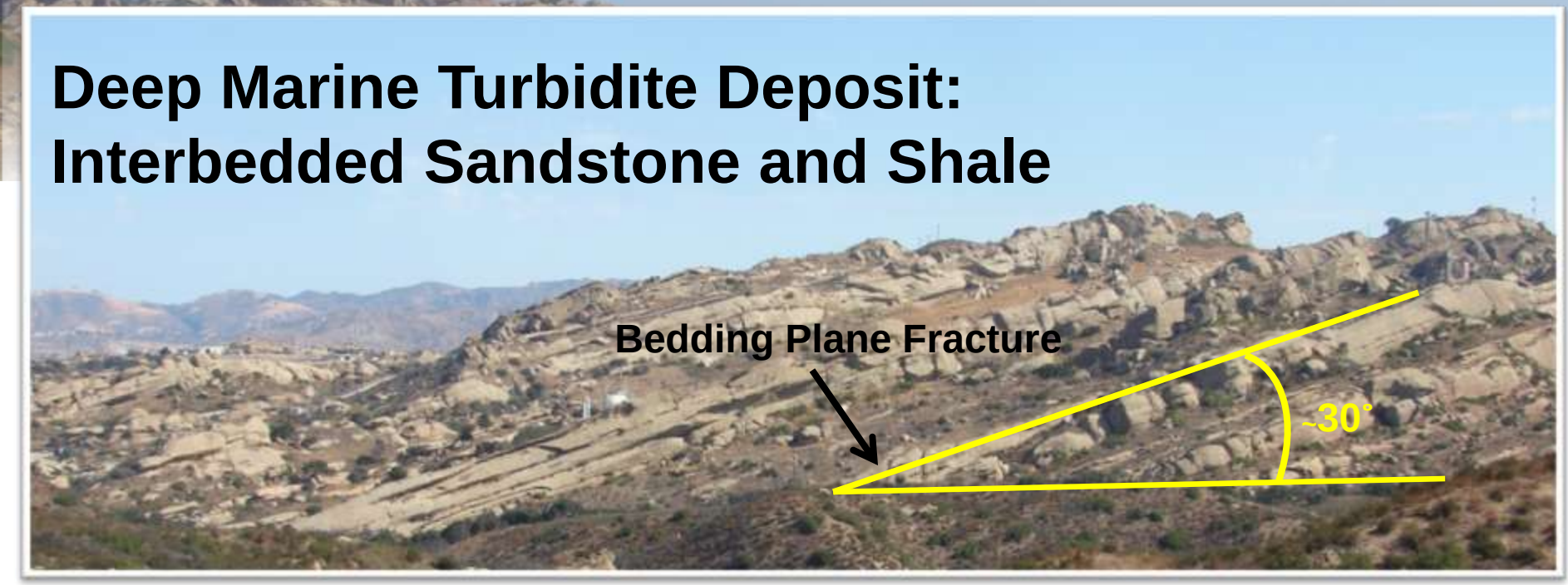


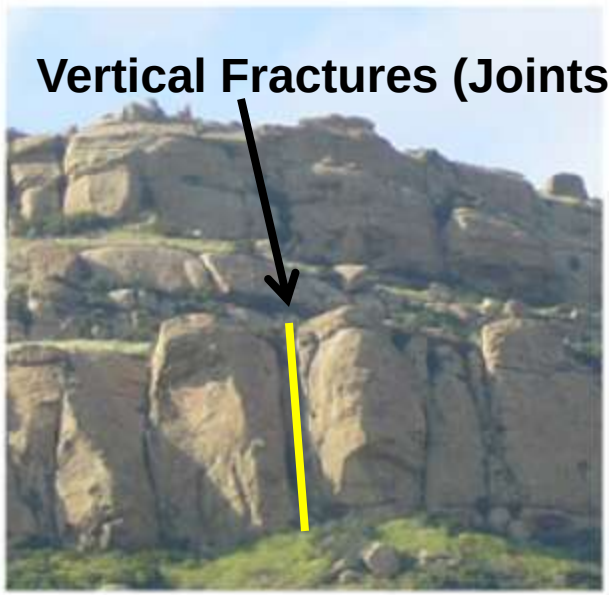
Total Equivalent Porewater Concentration along Source Zone Transect



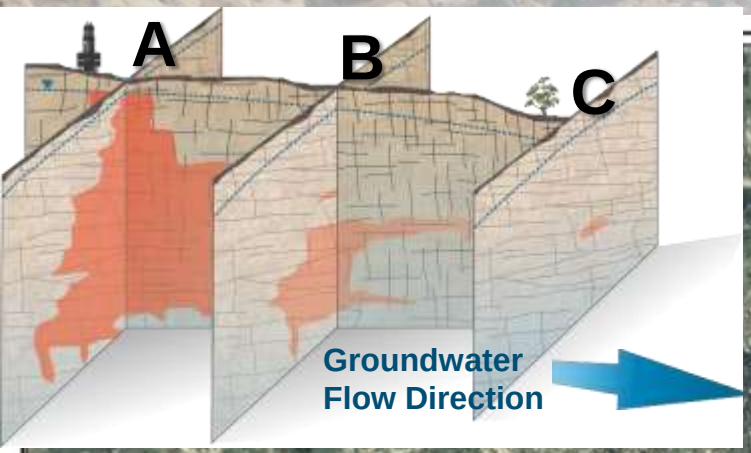
*Ordinary kriging with anisotropy ratio = 5, anisotropy angle = 20 degrees

Deep Marine Turbidite Deposit: Interbedded Sandstone and Shale





Northeast Plume Longsect



Plume Longsect

Source Transect

Plume Transect

Site Boundary

C-16 C-17 C B' C-14 C-13 C-9 C-12 B A' C-1 C-10 C RD-35B RD-35C C-1 RD-31 A

Ventura County
Los Angeles County

0 0.05 0.1 0.2 0.3 0.4 Miles

Legend

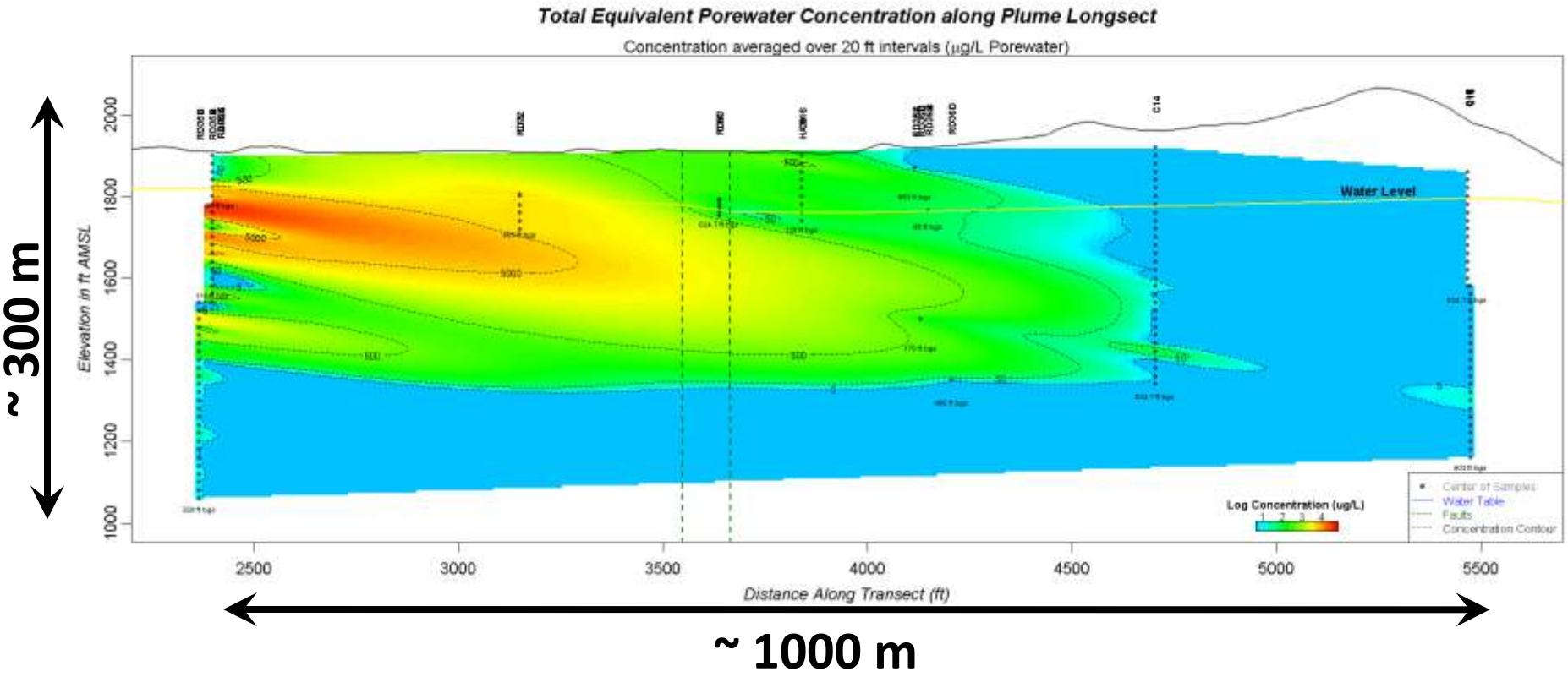
Faults
Monitoring Wells
Deep Cored
Shallow Cored
Cross-Sections
Site Polyline

SSFL Rock Core VOC
NE Plume Coreholes

TCE Distribution along NE Plume Longsect

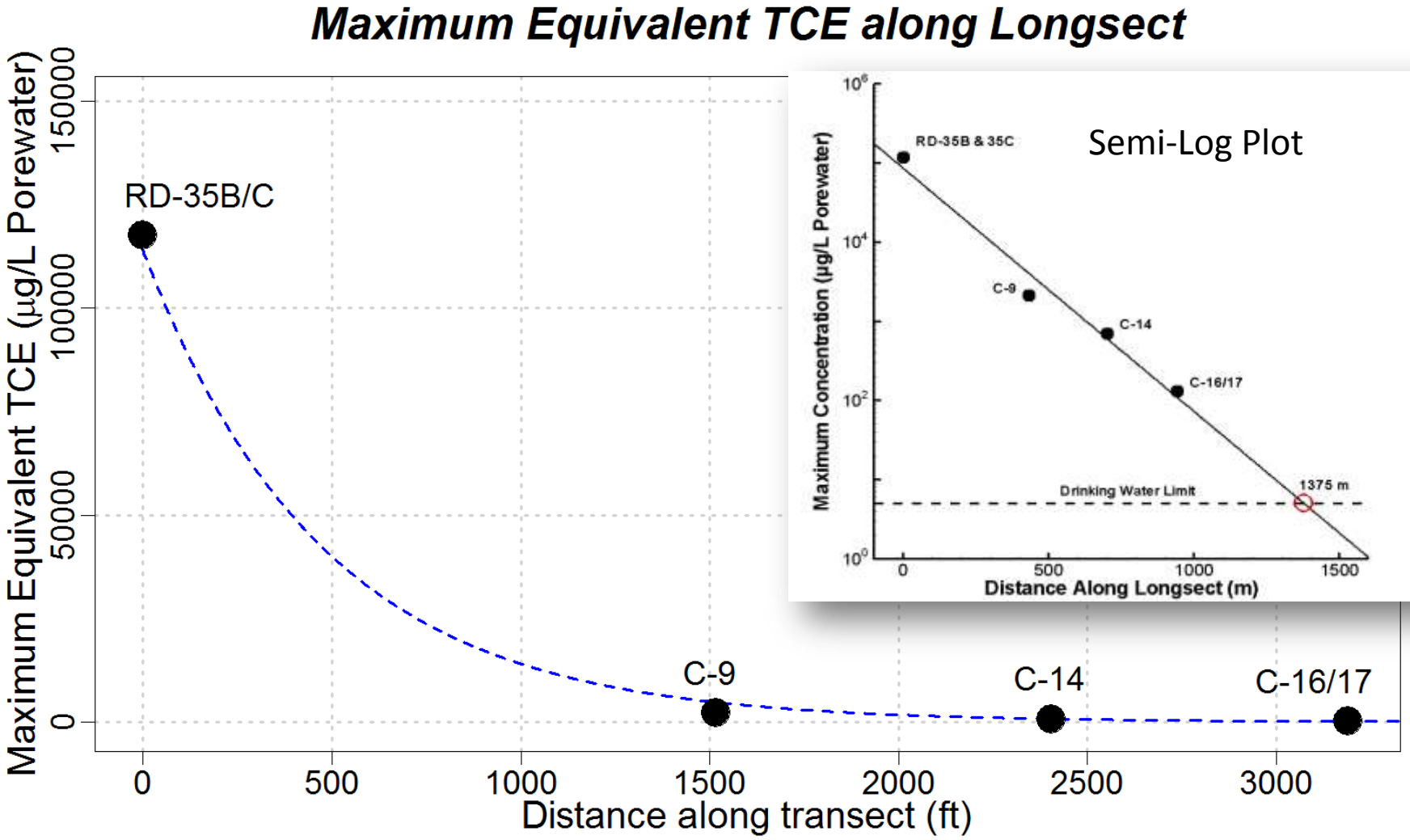
(estimated porewater concentrations from rock core VOC subsampling averaged over 6 m intervals)

TCE Migration @ 60 yr since initial releases



Groundwater Flow ➡

Concentrations Decline Rapidly with Distance from Source



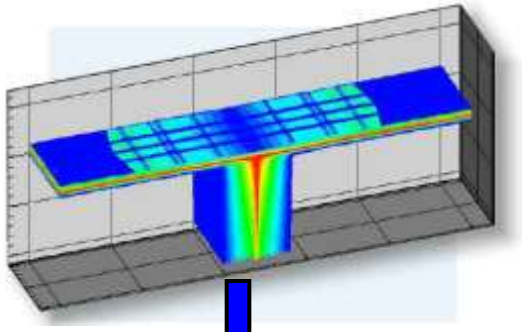
Plume concentrations decline rapidly with distance in the direction of groundwater flow

Commercially Available DFN Models

Windows 98/NT/2000/XP

FRAC3DVS

FRAC3DVS is a 3D finite element model for steady-state/transient, variably-saturated flow and advective-dispersive solute transport in porous or discretely-fractured porous media



HydroGeoSphere

HydroGeoSphere
A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport

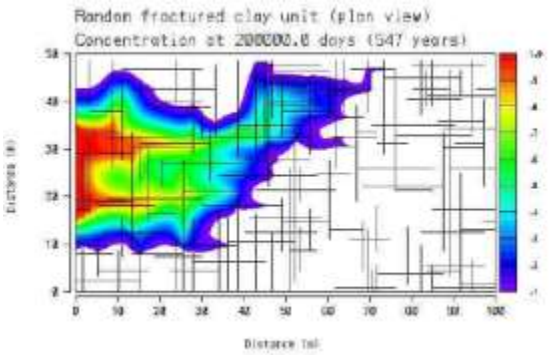
R. Therrien, Université Laval
R.G. McLaren, University of Waterloo
E.A. Sudicky, University of Waterloo
S.M. Panday, Hydrogeologic Inc./University of Waterloo

©R. Therrien, E.A. Sudicky, R.G. McLaren
Groundwater Simulations Group

Windows 98/NT/2000/XP

FRACTRAN

FRACTRAN is a 2D finite element model for simulating steady-state groundwater flow and time-variant contaminant transport in discretely-fractured, fully-saturated porous media



University of Waterloo

Waterloo Hydrogeologic, Inc.
Groundwater is our business

FracMan

www.fracman.com

Software

FracMan® is the premier software for analysis and modeling of heterogeneous and fractured rock masses.

- Software Information
- Downloads
- FracMan Theory
- Workshop Information
- Benchmark
- Guided Tour
- FracMan Virtual Reality Worlds

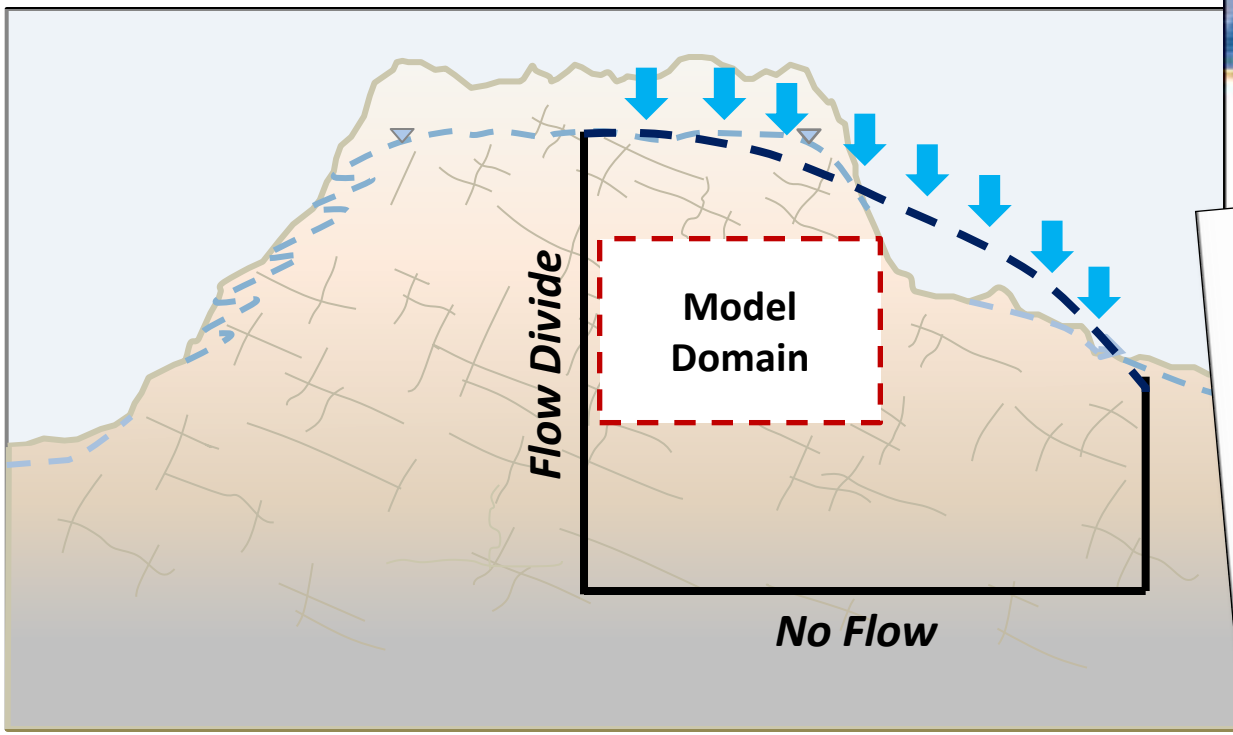
Golder Associates

FEFLOW®

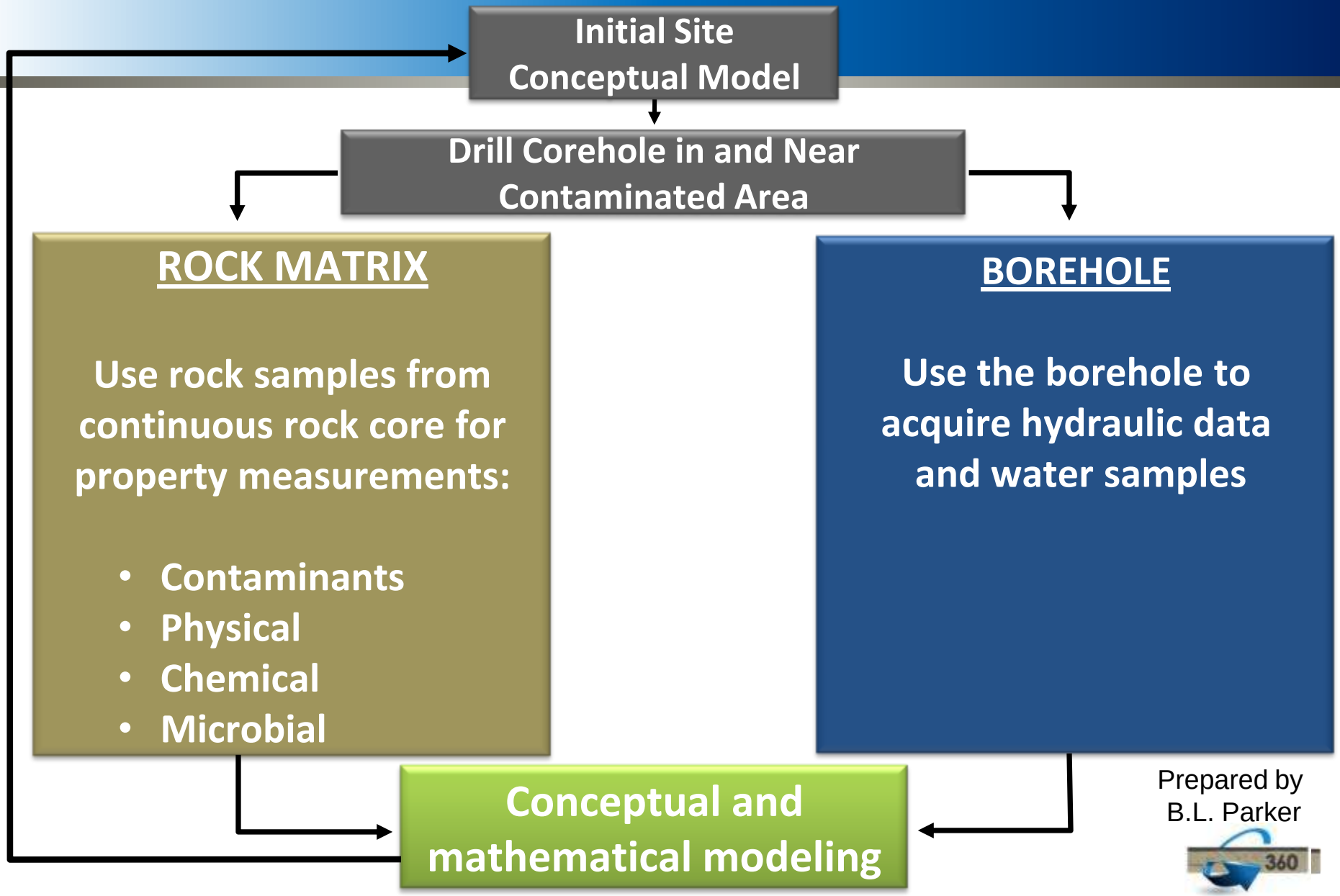
Advanced 3D Finite Element Groundwater Flow, Heat & Contaminant Transport Modeling!

WASY

Simulate Plume Using DFN Numerical Model

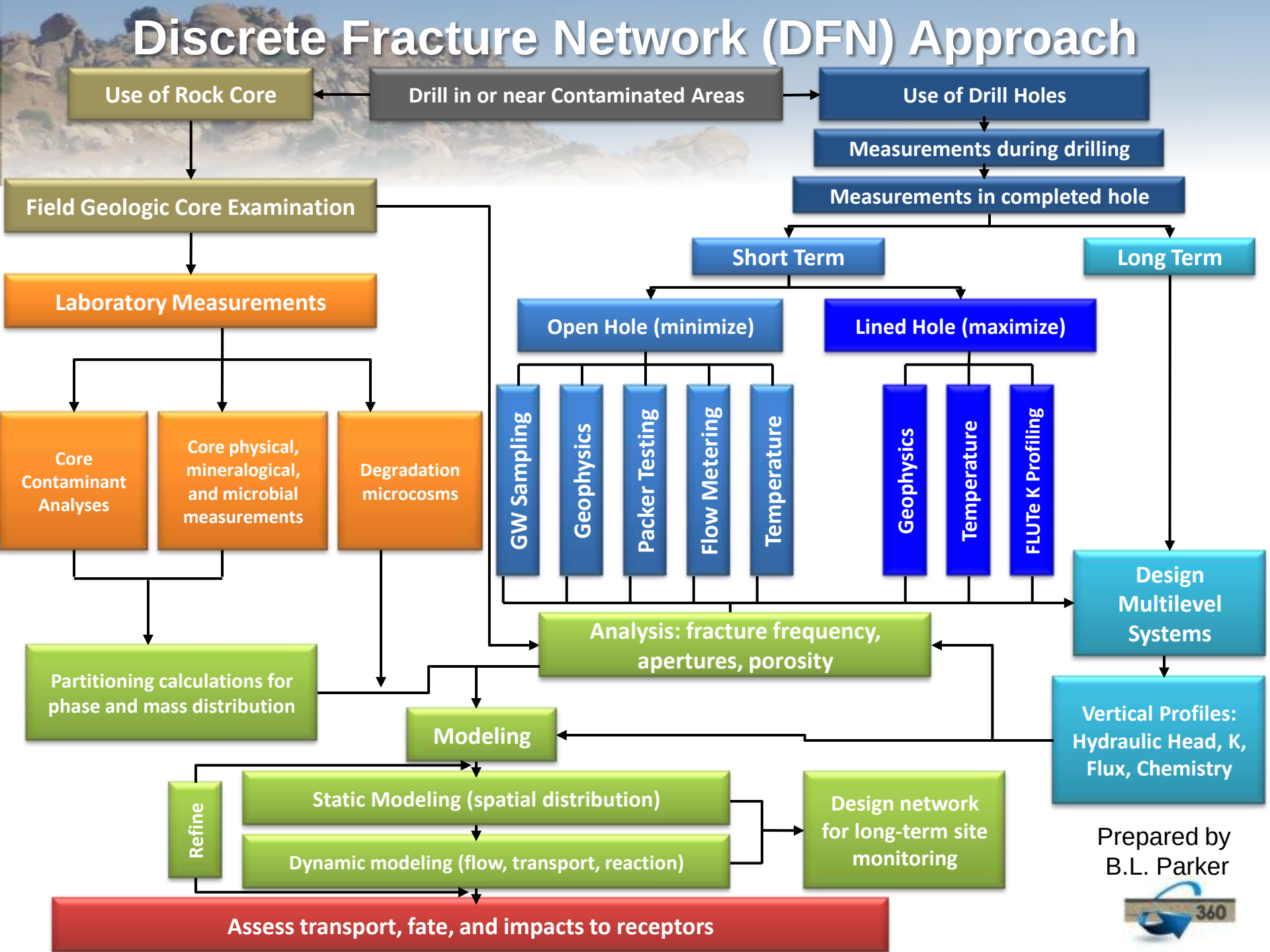


Discrete Fracture Network (DFN) Approach Characterization of Contaminated Bedrock



Prepared by
B.L. Parker

Discrete Fracture Network (DFN) Approach



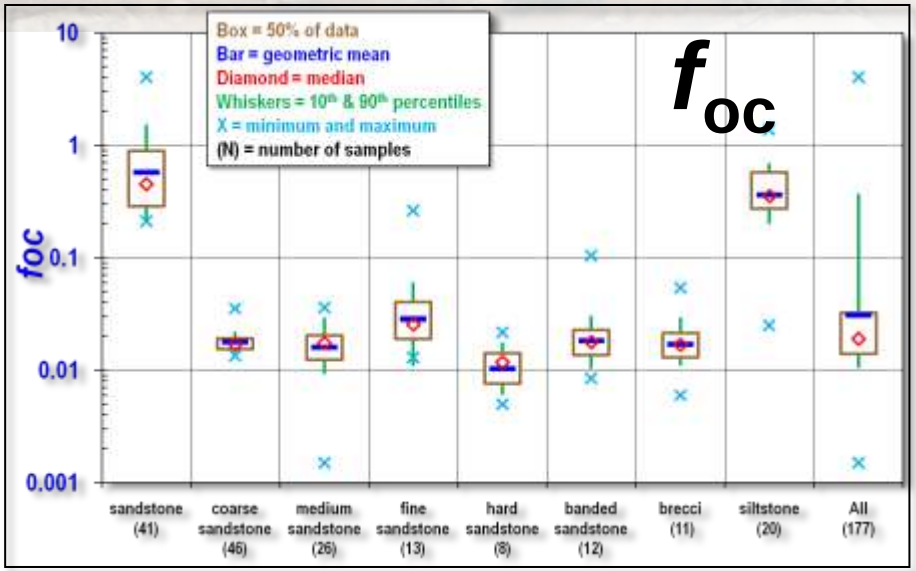
Prepared by
B.L. Parker

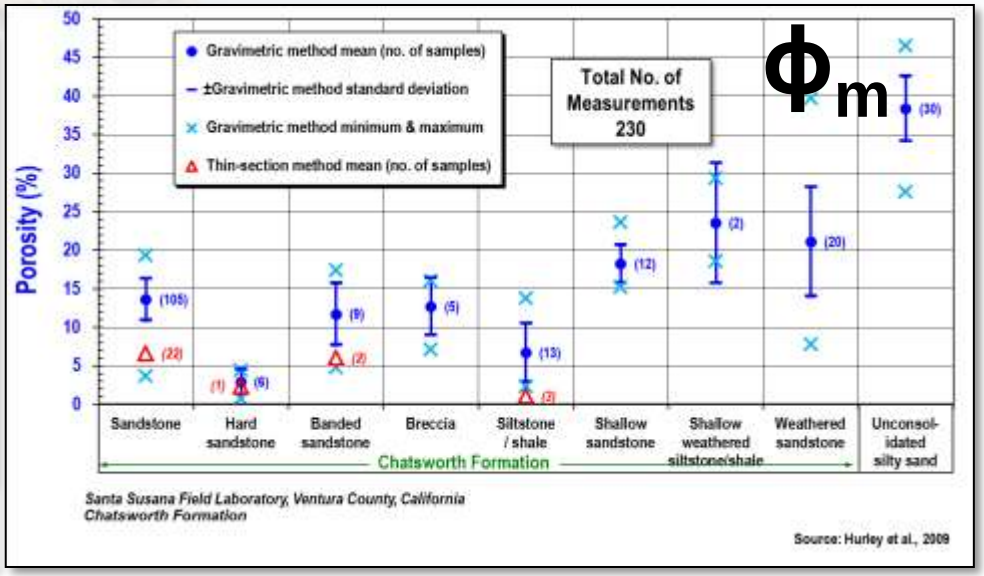
Overview of DFN Methods

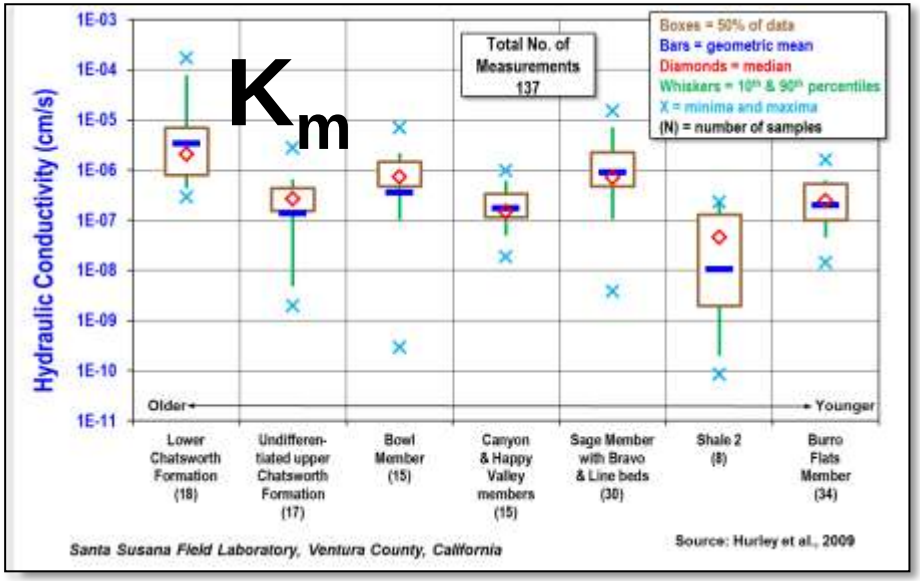
- Rock Core Chemical Analyses
- Improved Borehole Geophysics
- Impermeable Flexible Liner (FLUTe™)
- High Resolution Temperature Logging
- Improved Hydraulic Tests Using Straddle Packers
- High Resolution Multilevel Monitoring Systems

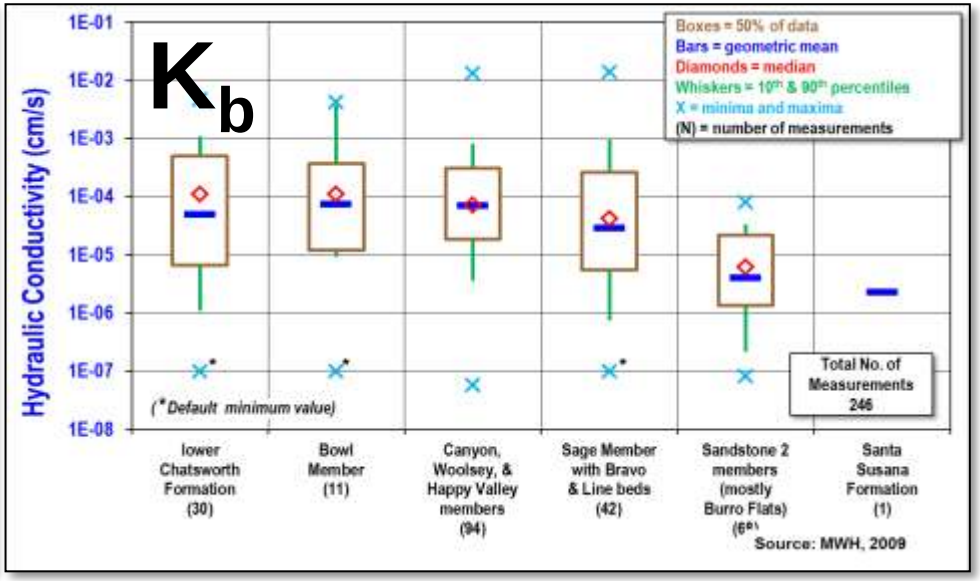
Multiple Methods Applied in Boreholes

Site-Derived Parameters

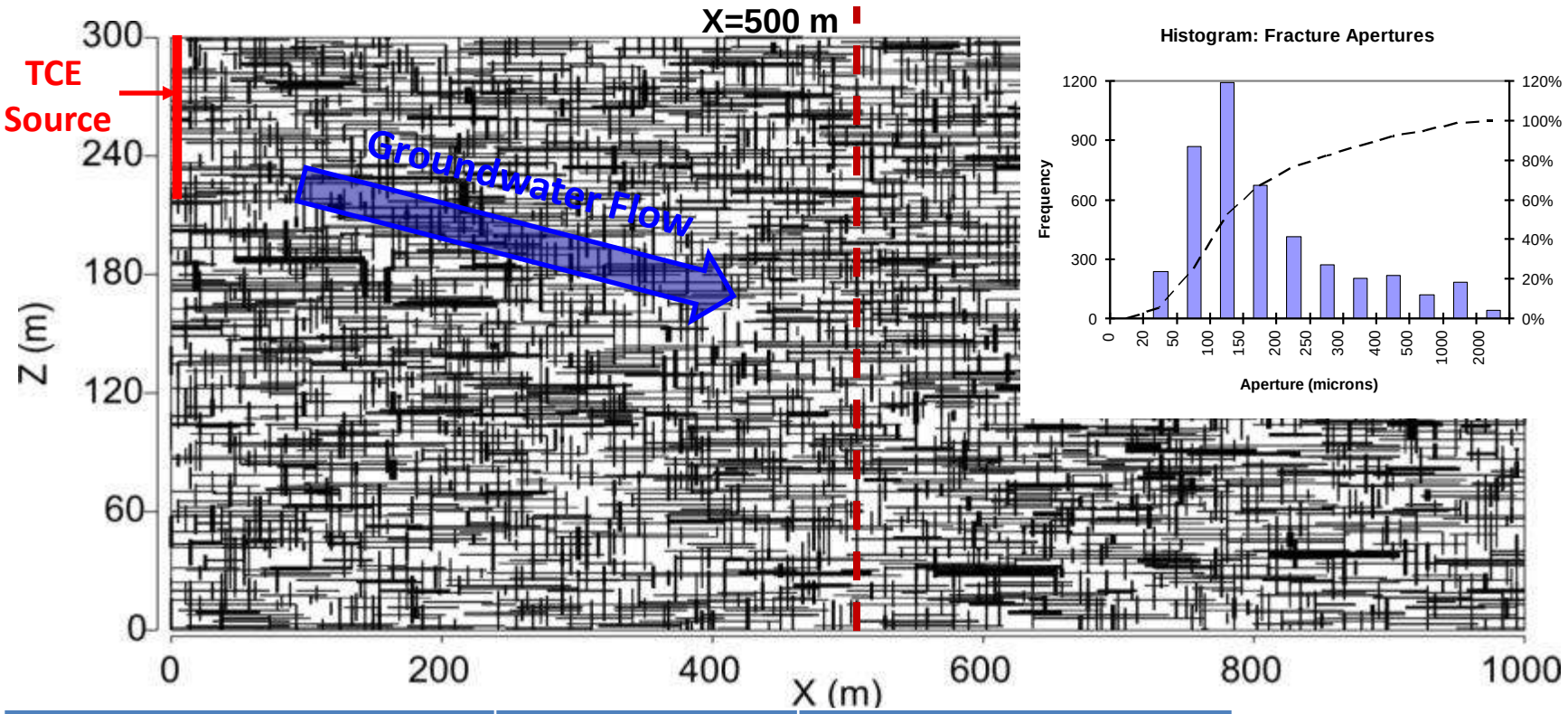








FRACTRAN Domain: Vertical Cross-Section Tailored to Conditions along Plume Longsect

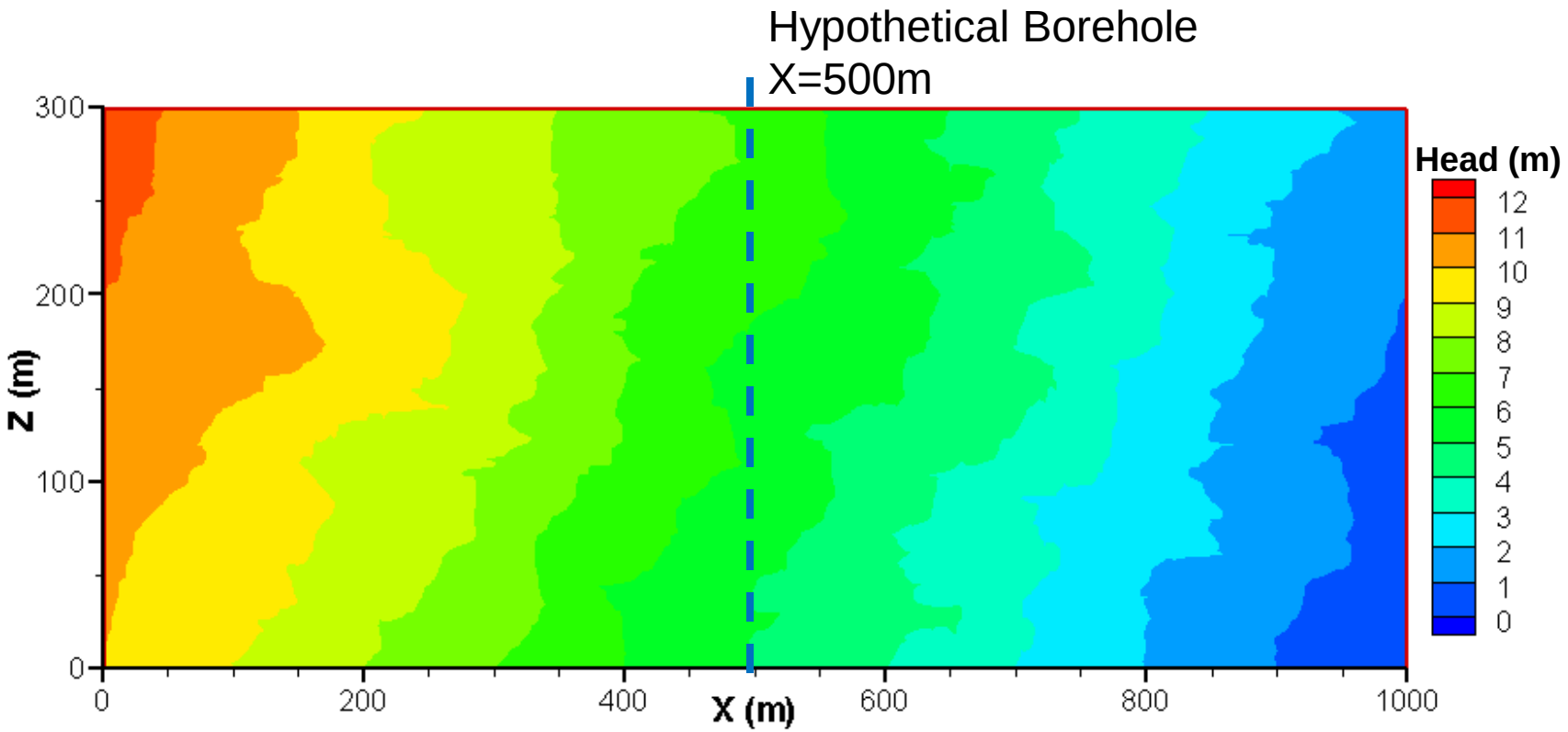


Fracture Statistics	Horizontal	Vertical
Mean aperture (microns)	100	100
Length range (m)	20 - 100	5 - 20
Fracture density (fracs/m^2)	0.007	0.010
Average fracture spacing (m)	**~3**	**~10**

$\phi_f = 5 \times 10^{-5}$

Darcy Flux Constraint

Simulated Hydraulic Head Distribution



Average Hydraulic Gradients:

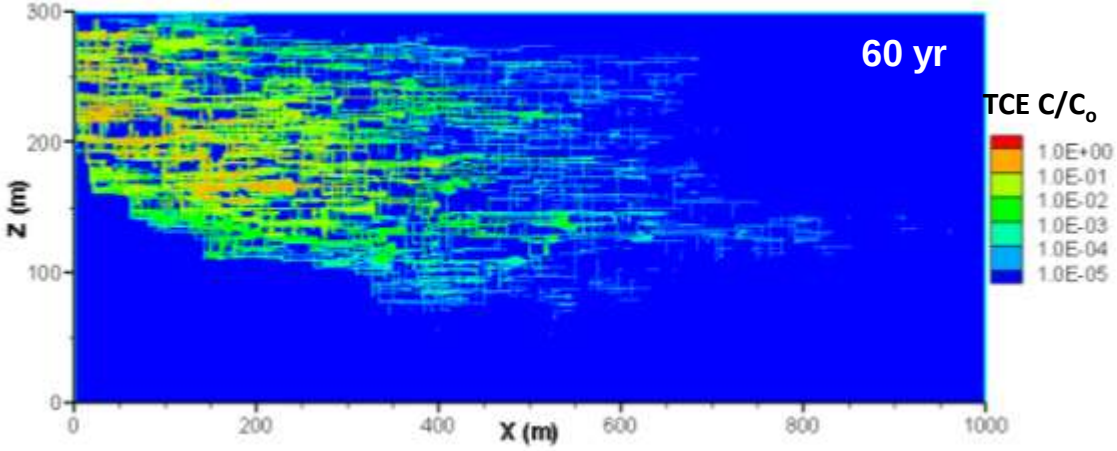
1% → **1.5%** ↓

Average GW Velocity in Fracture Network:

$$\bar{v}_f = \frac{K_b\, i}{\phi_f} \sim 2500\ m/yr$$

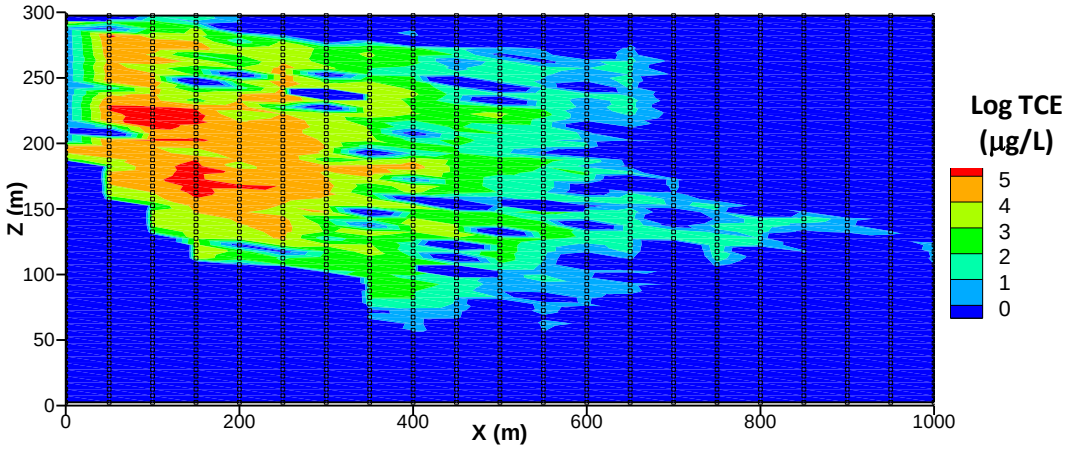
FRACTRAN Contaminant Plume Averaged over 5 m Intervals

Original (point data) – 60 years

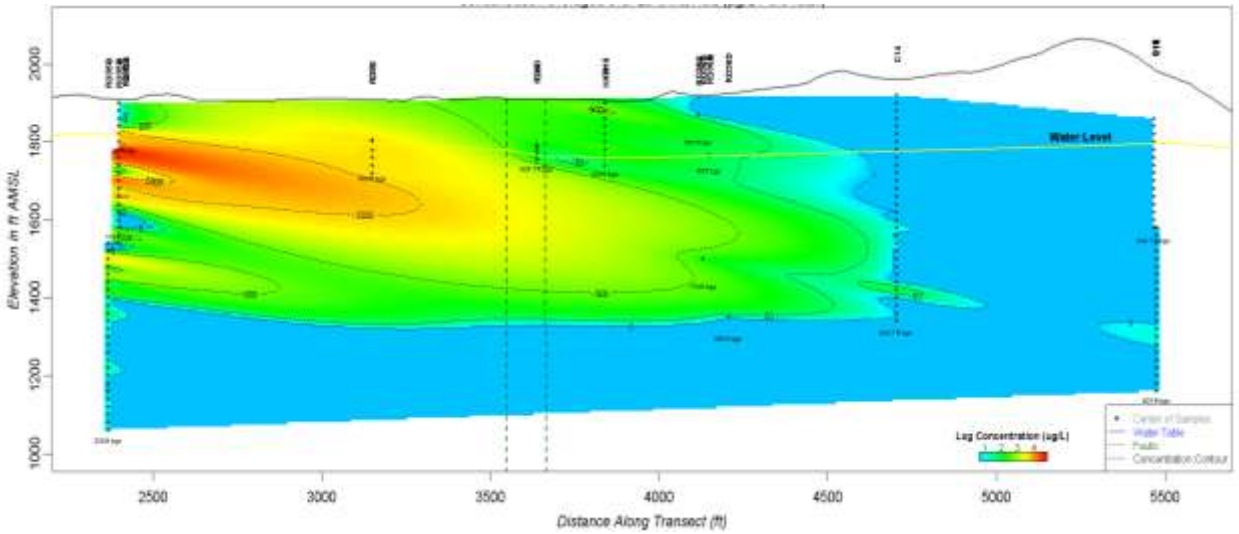


Point concentrations extracted at 50 m intervals along flowpath, averaged vertically over 5 m intervals and resulting dataset kriged.

Averaged over 5m intervals

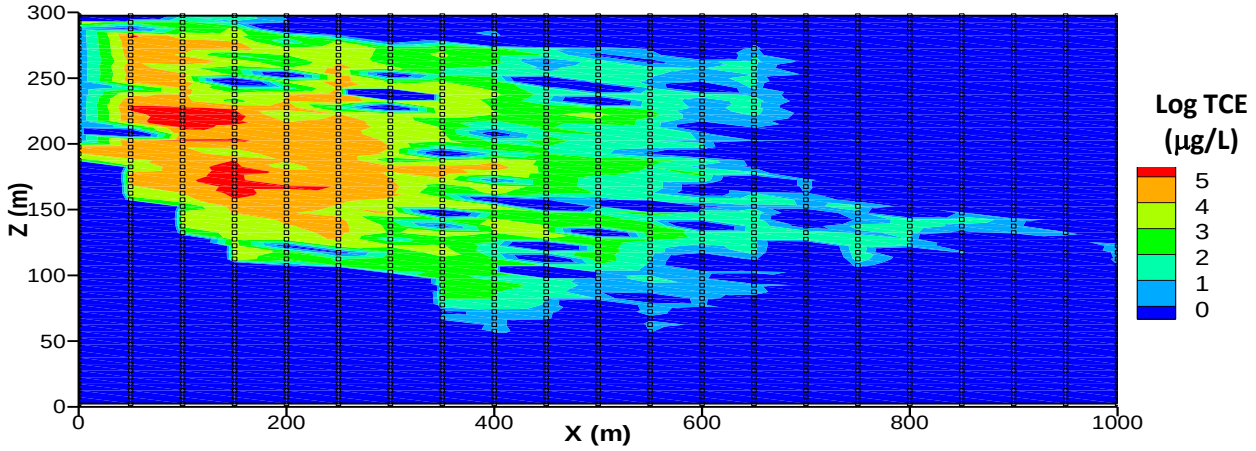


Comparison of FRACTRAN versus Field Results along Plume Longsect



Field Plume Longsect (averaged)

FRACTRAN @ 60 yr (averaged)

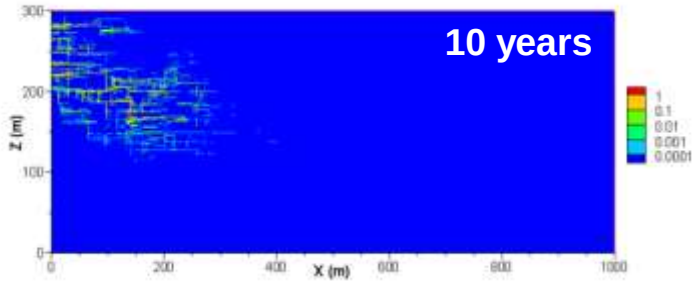


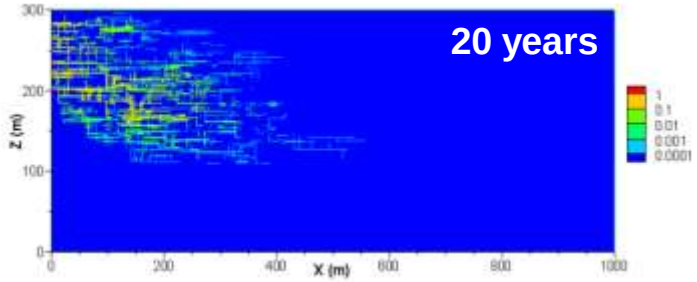
Field and model show similar bulk plume style and extent

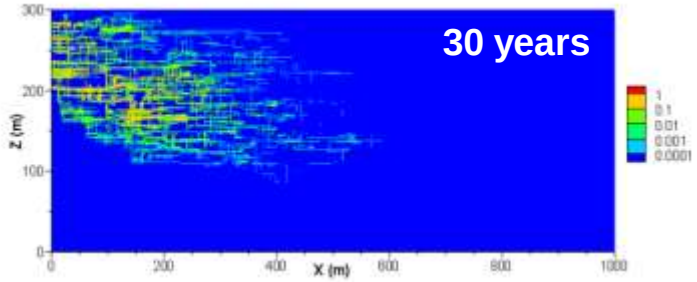
Simulated Northeast Plume

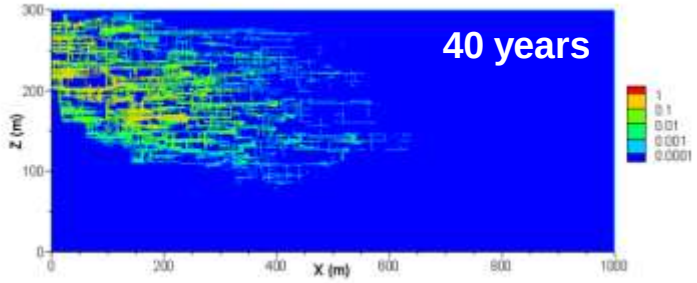
No degradation included

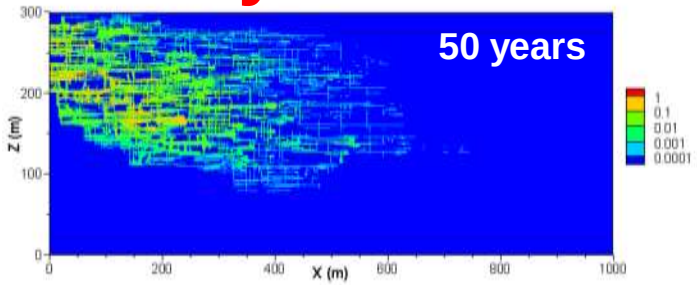
Plumes are nearly stable after 50 years

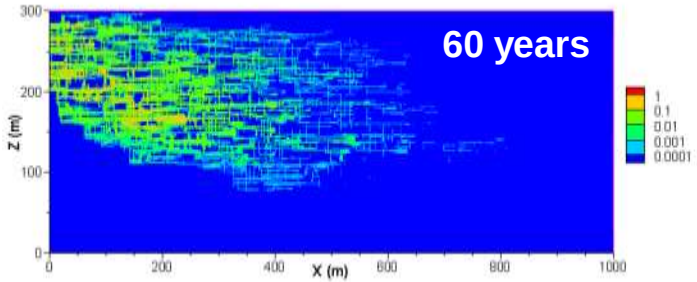


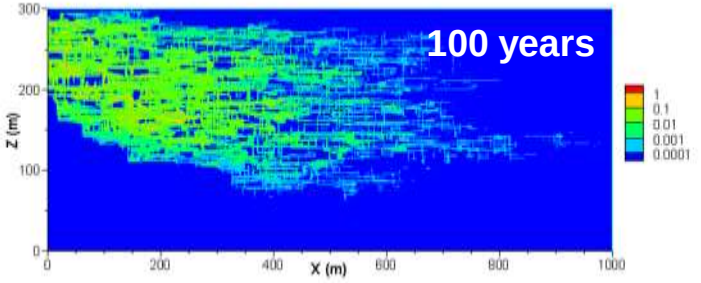




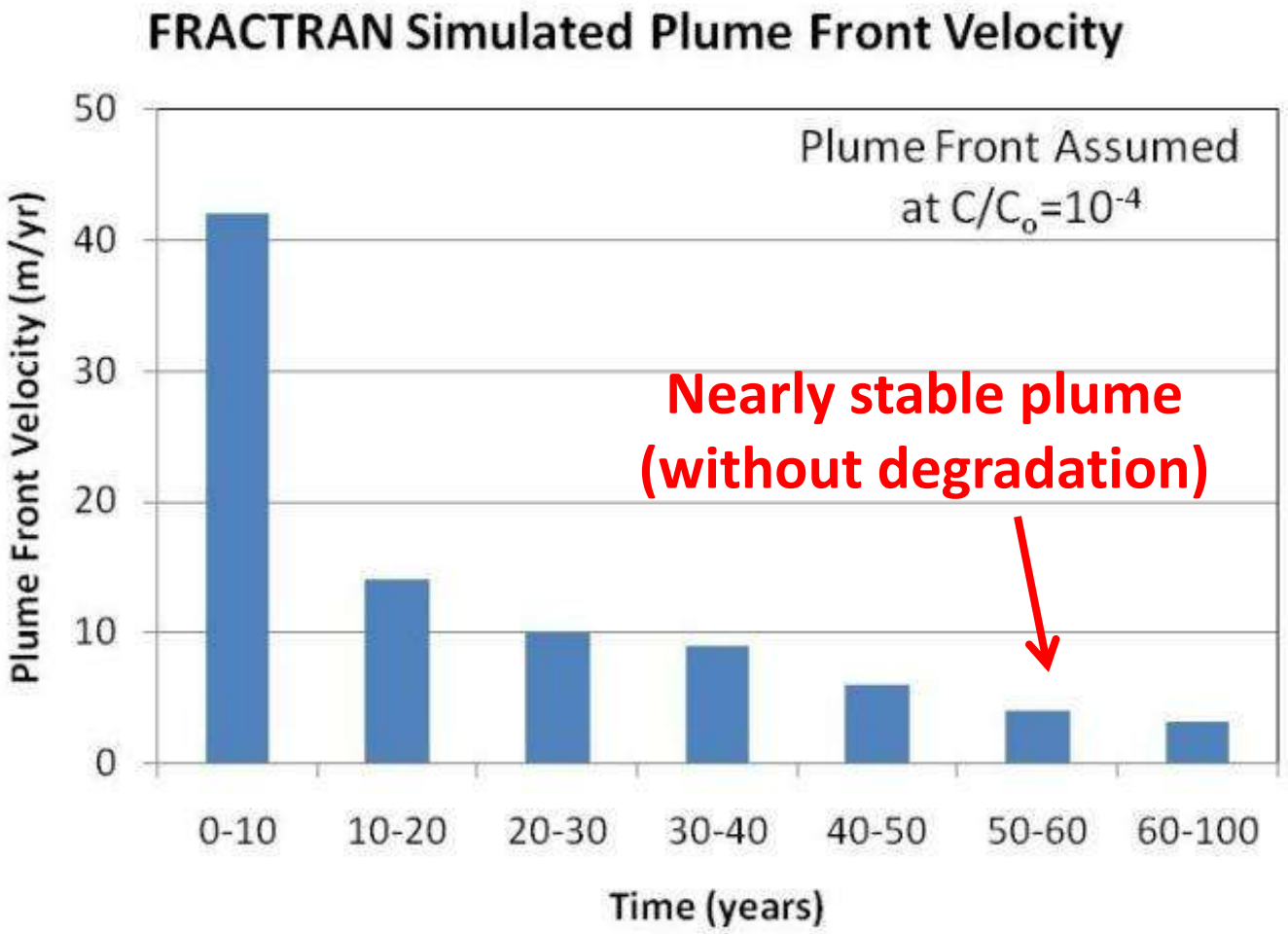




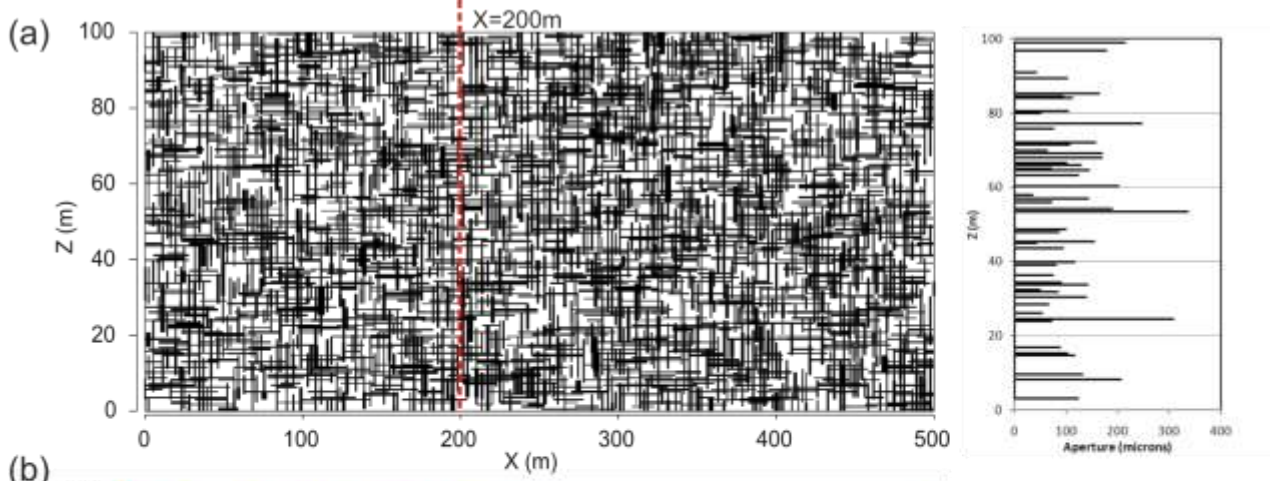




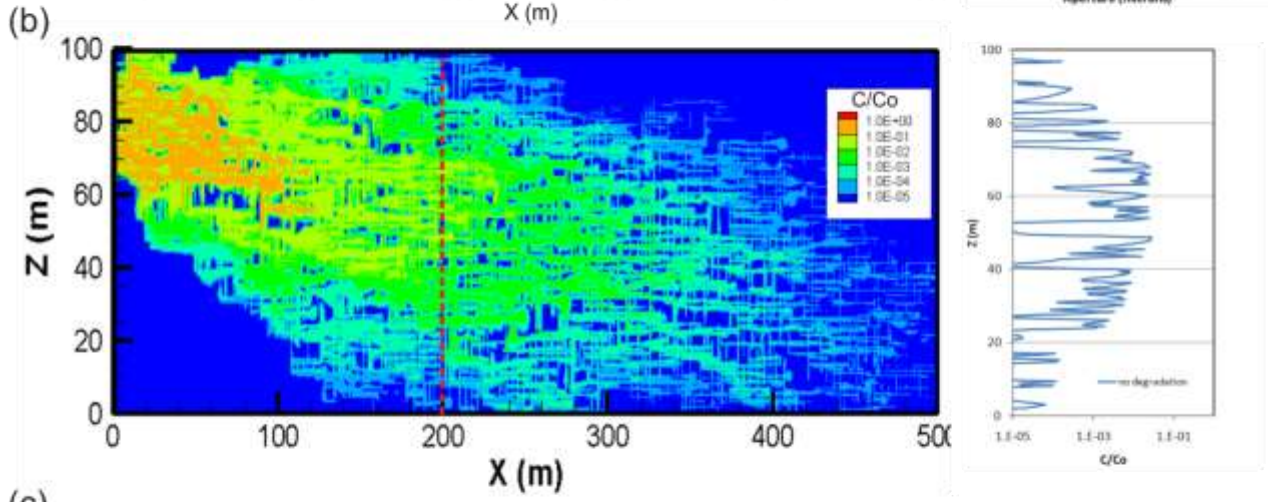
FRACTRAN results suggest plume front nearly stationary (physical processes only)



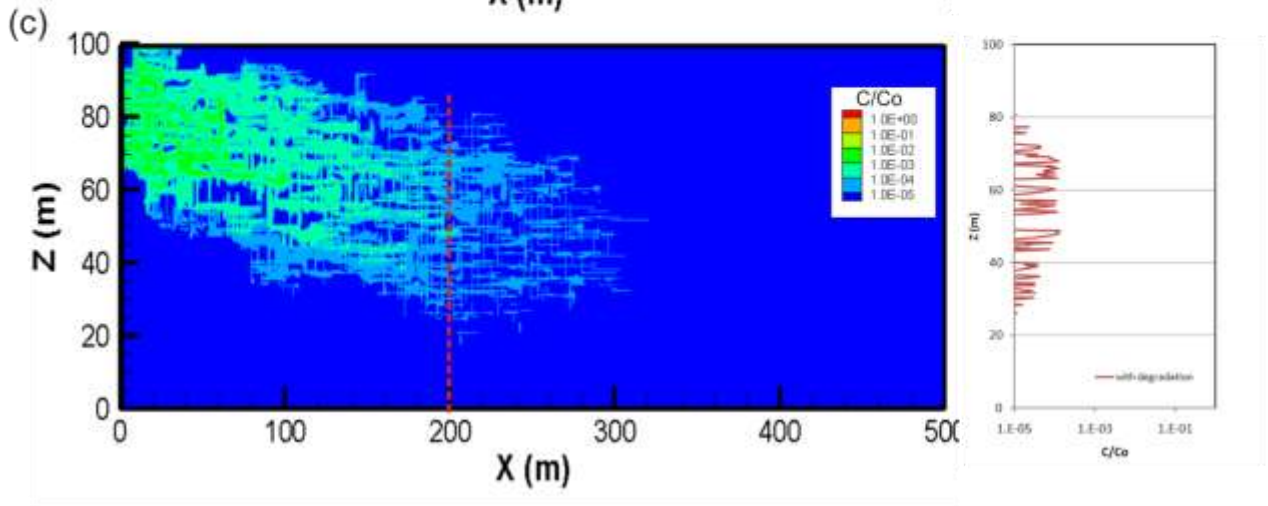
TCE Degradation



Well-Interconnected Fractures

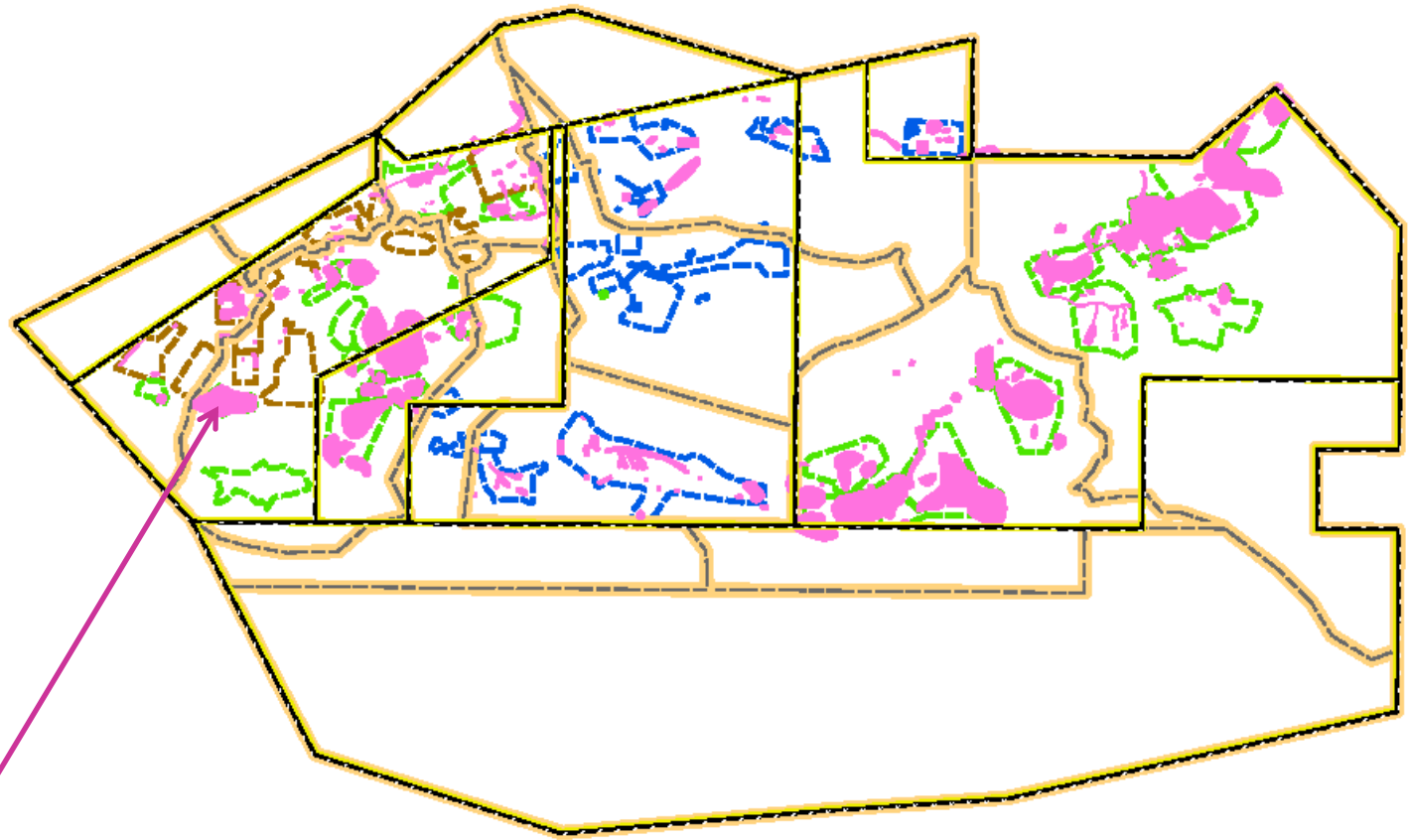


20 year DNAPL Source
No Degradation
50 years



20 year DNAPL Source
Degradation (5 yr half life)
50 years

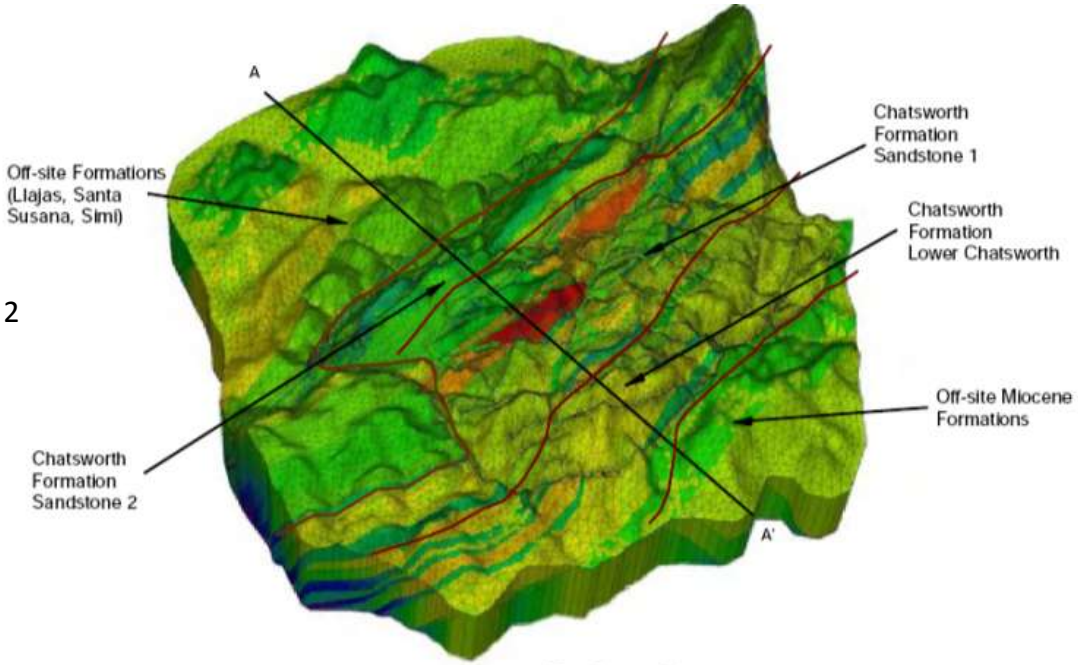
Numerous Chemical-Use Areas



Areas recommended for corrective measures study based on suburban residential land use

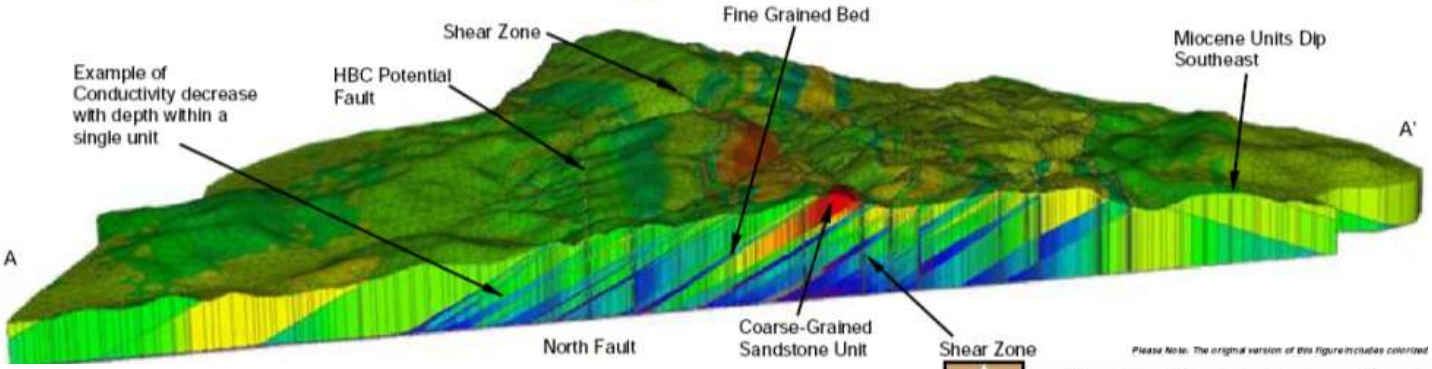
Mountain Scale 3-D FEFLOW EPM Model

- 8 km x 8 km domain
- 250,000 elements per layer
- 46 layers
- 11.5M elements total
- average element area ~ 256 m^2
- average layer thickness ~10 m



Site Macro-Complexity

- major hydrogeologic units
- faults, dipping beds
- hydraulic head
- water balance

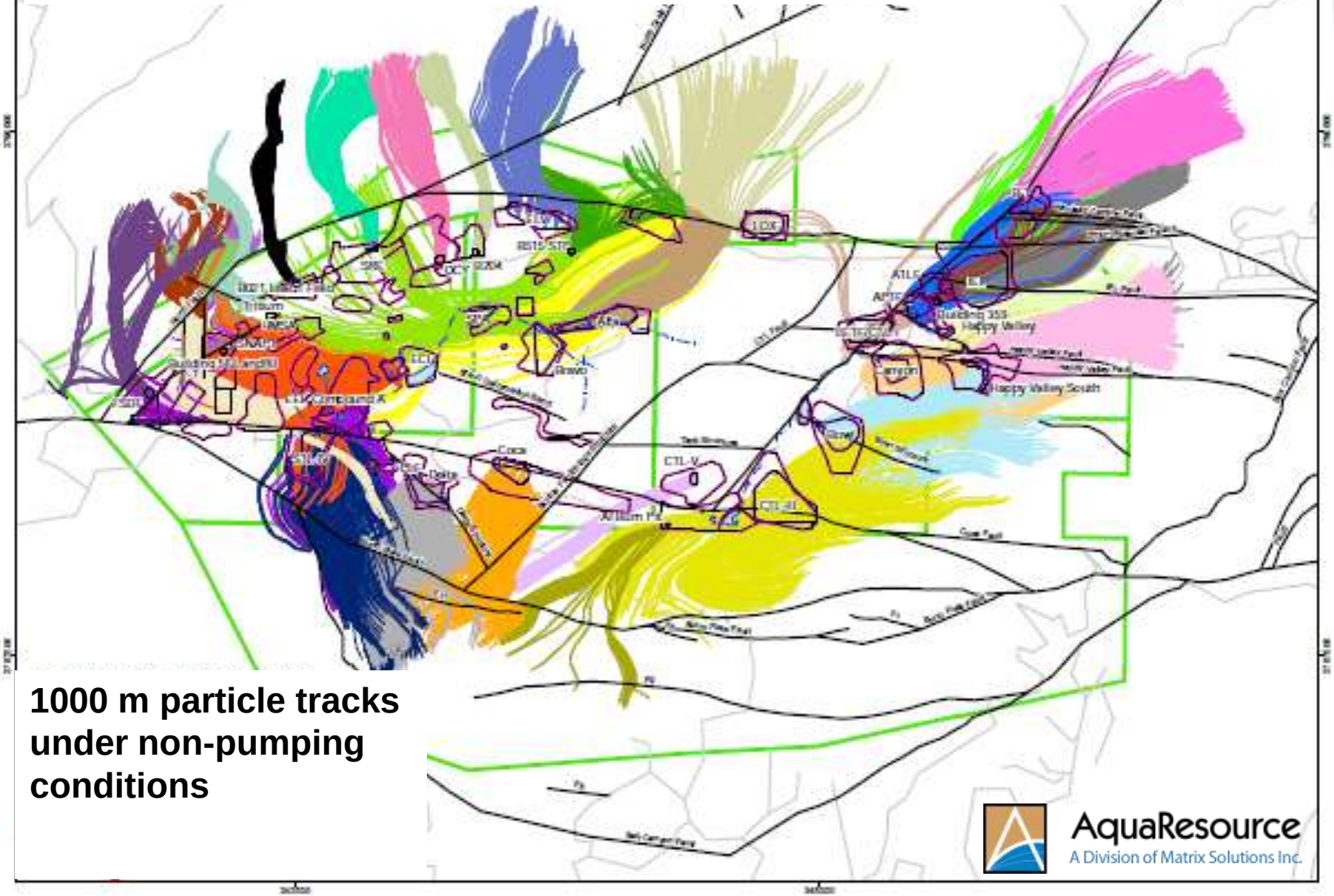


Please Note: The original version of this figure includes colored

AquaResource Inc.
Integrity • Technology • Solutions

Forward Particle Tracks in Bedrock

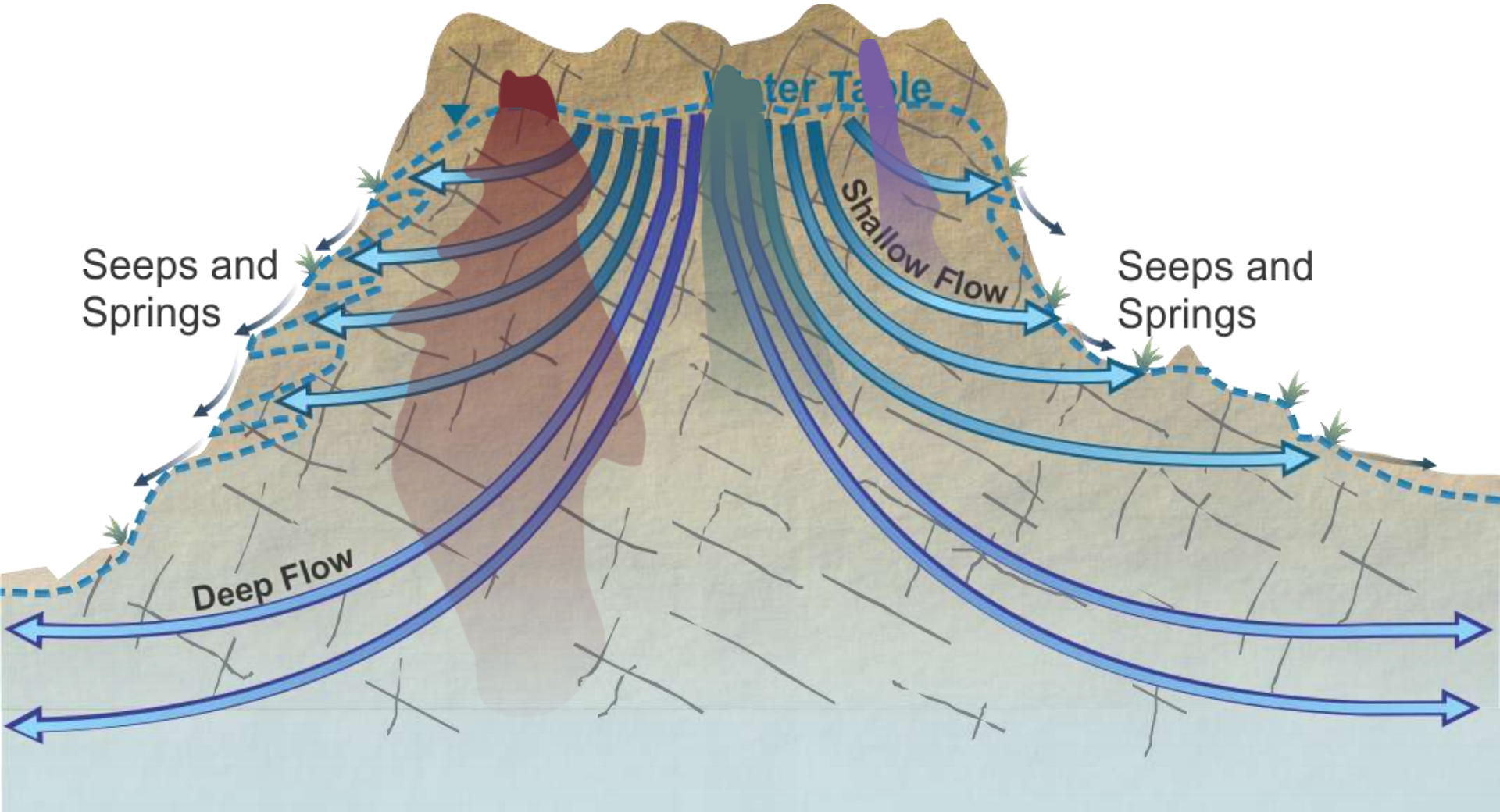
FEFLOW 3D Groundwater Flow Model



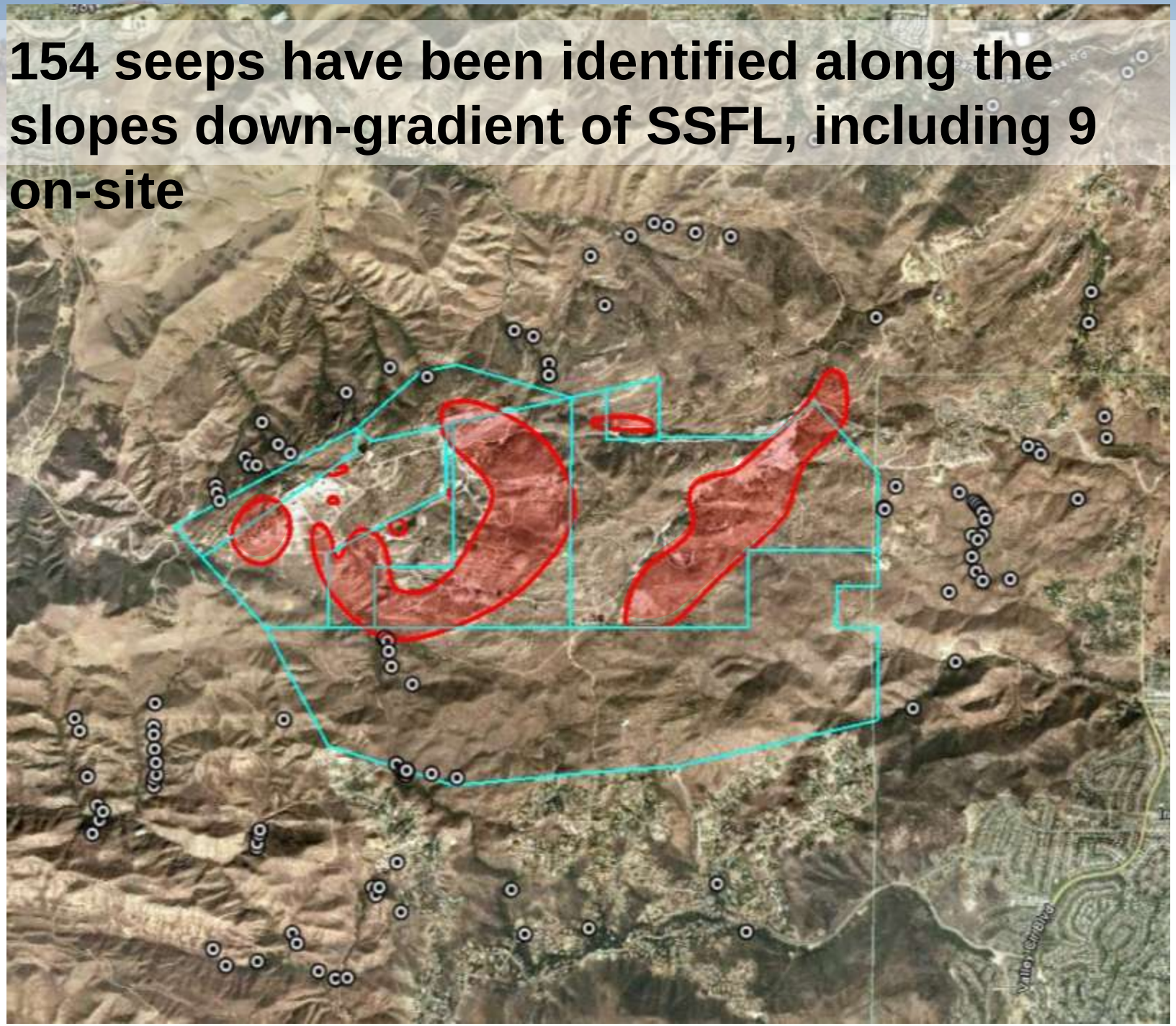
1000 m particle tracks under non-pumping conditions

AquaResource
A Division of Matrix Solutions Inc.

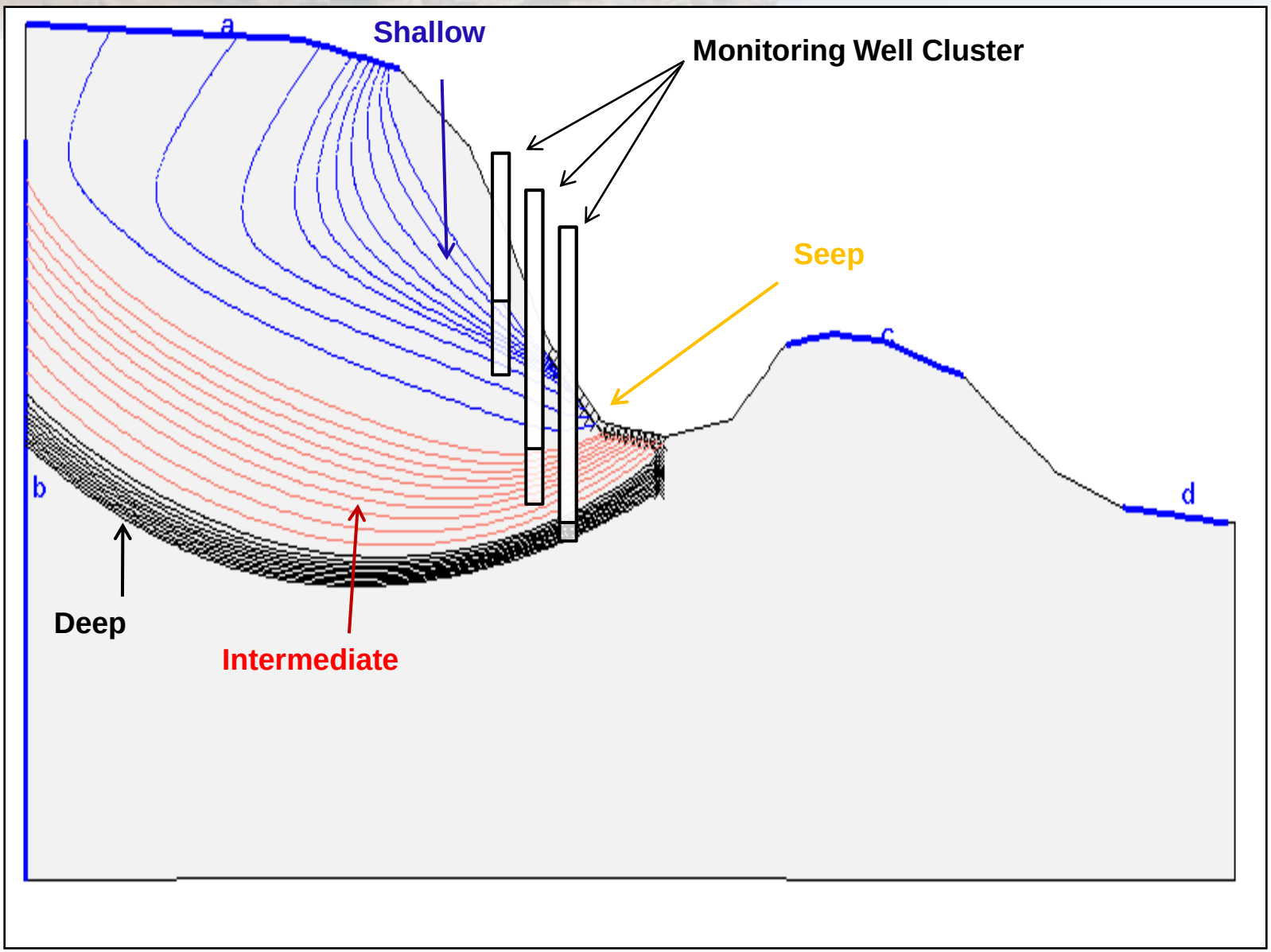
Have plumes migrated to off-site receptors?



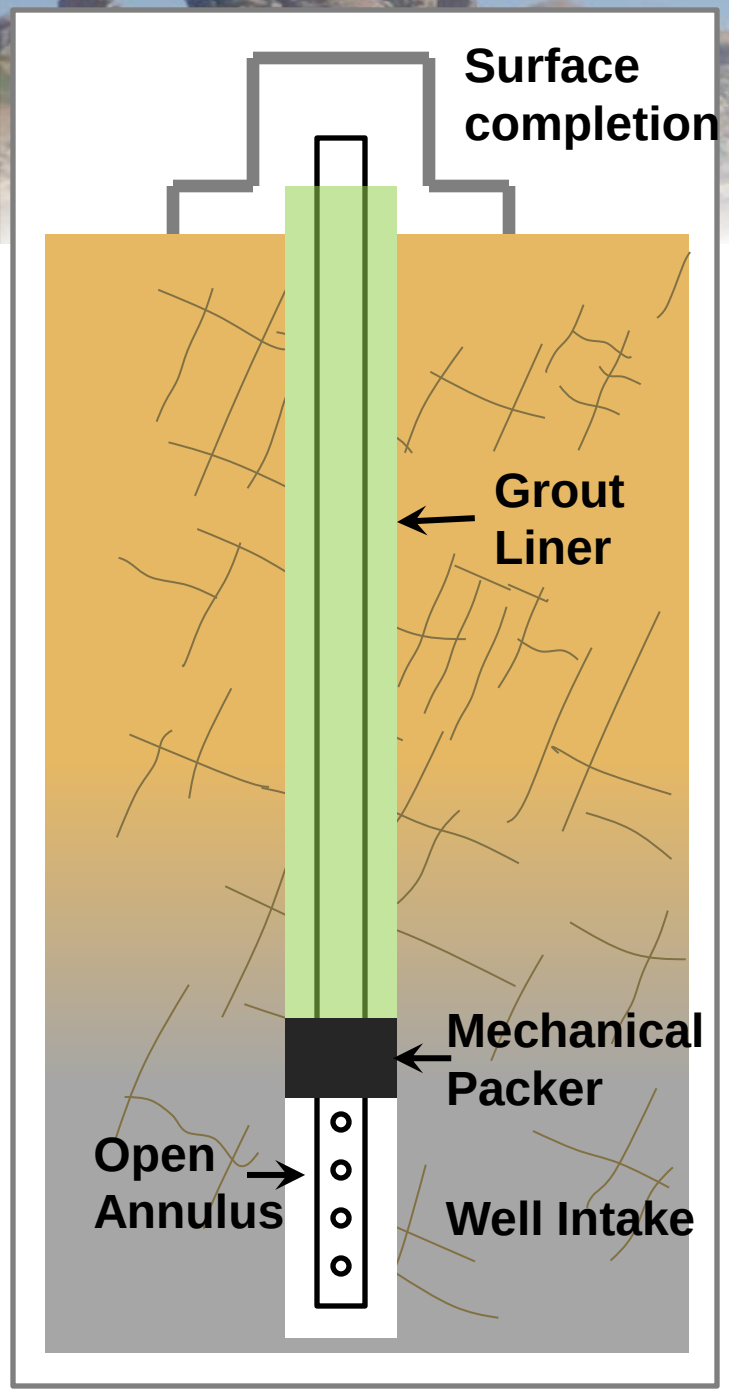
154 seeps have been identified along the slopes down-gradient of SSFL, including 9 on-site



Approach: Use Portable Drills to Instrument Seeps With Monitoring Wells



Monitoring Well Design



- One well at the bottom of each corehole
- Hole fully sealed above well intake
- No grout escapes into fractures
- No sand pack around well screen

Monitoring Well Goals

- To develop a better understanding of the origins of seeps water.

- To determine whether seeps with no SSFL contaminants have groundwater discharging to them carrying contaminants.

Approach

- Advance coreholes to depths ranging from 5 to 54 ft using portable drilling equipment.
  - Shaw Portable Core Drill
  - Winkie Drill
- Installation of small diameter wells for:
  - water level measurements
  - sampling

Winkie Drill

www.minex-intl.com (sole manufacturer)

Depths: 50 to 75 ft
Corehole Diameter: 1.87”
Run Length: 5 ft

Fred Wink (1914-2007)
Inventor of the Winkie Drill

Shaw Portable Core Drill

www.backpackdrill.com

Depths: 20 to 40 ft
Corehole Diameters: 1.65 or 2.00-inches
Run Length: 1.5 to 2 ft

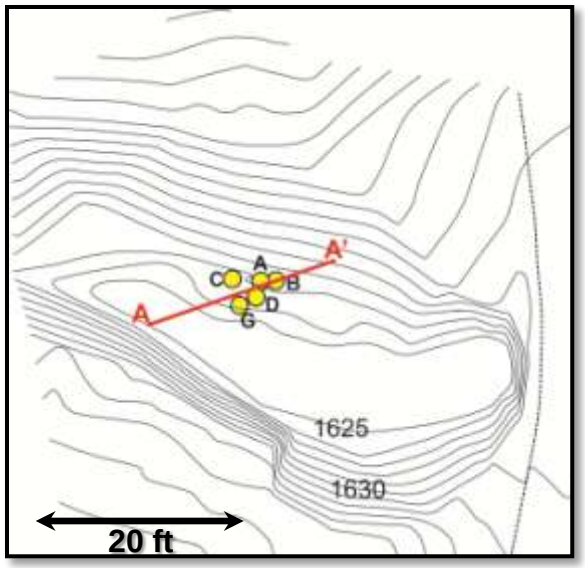
Neil Shaw
Inventor of the Shaw Drill

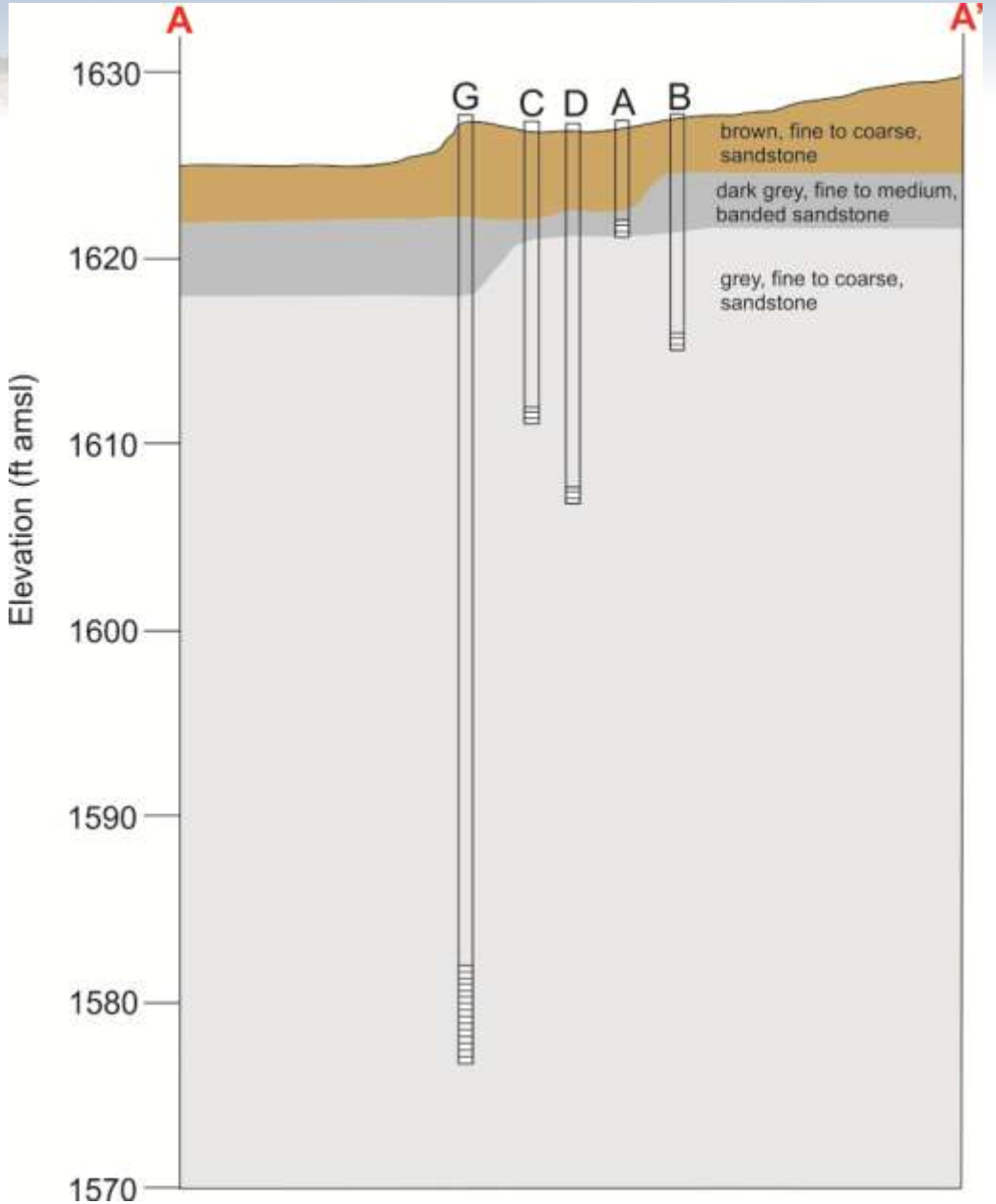
Maximum Depths Drilled at SSFL

- **Shaw Core Drill**
  - Maximum depth drilled: **37 ft**
- **Winkie Drill**
  - Maximum depth drilled: **54 ft**

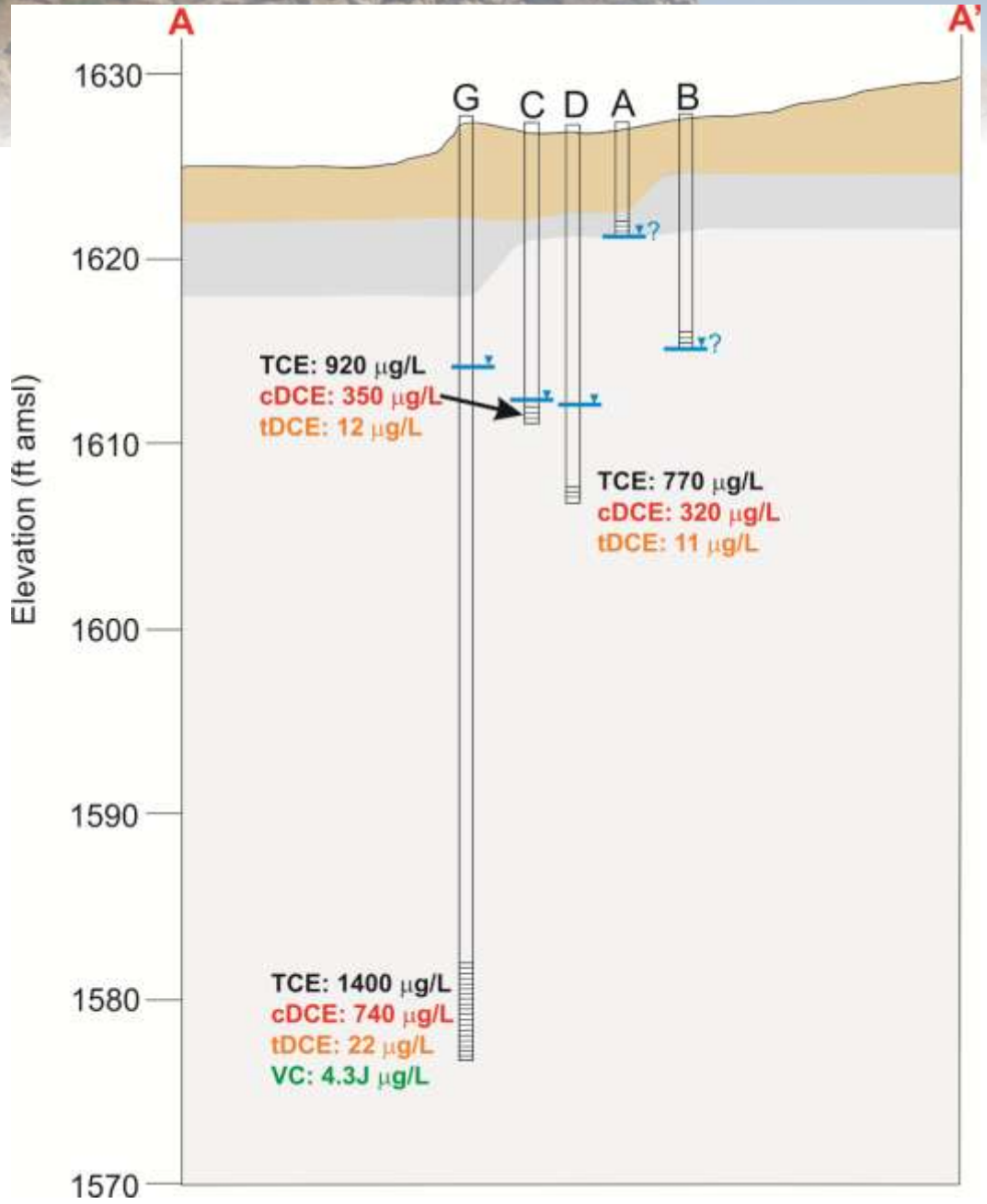
Completed Cluster in Drainage

Seep Well Cluster: SP-890





Results of Groundwater Sampling for VOCs
SP-890 Cluster

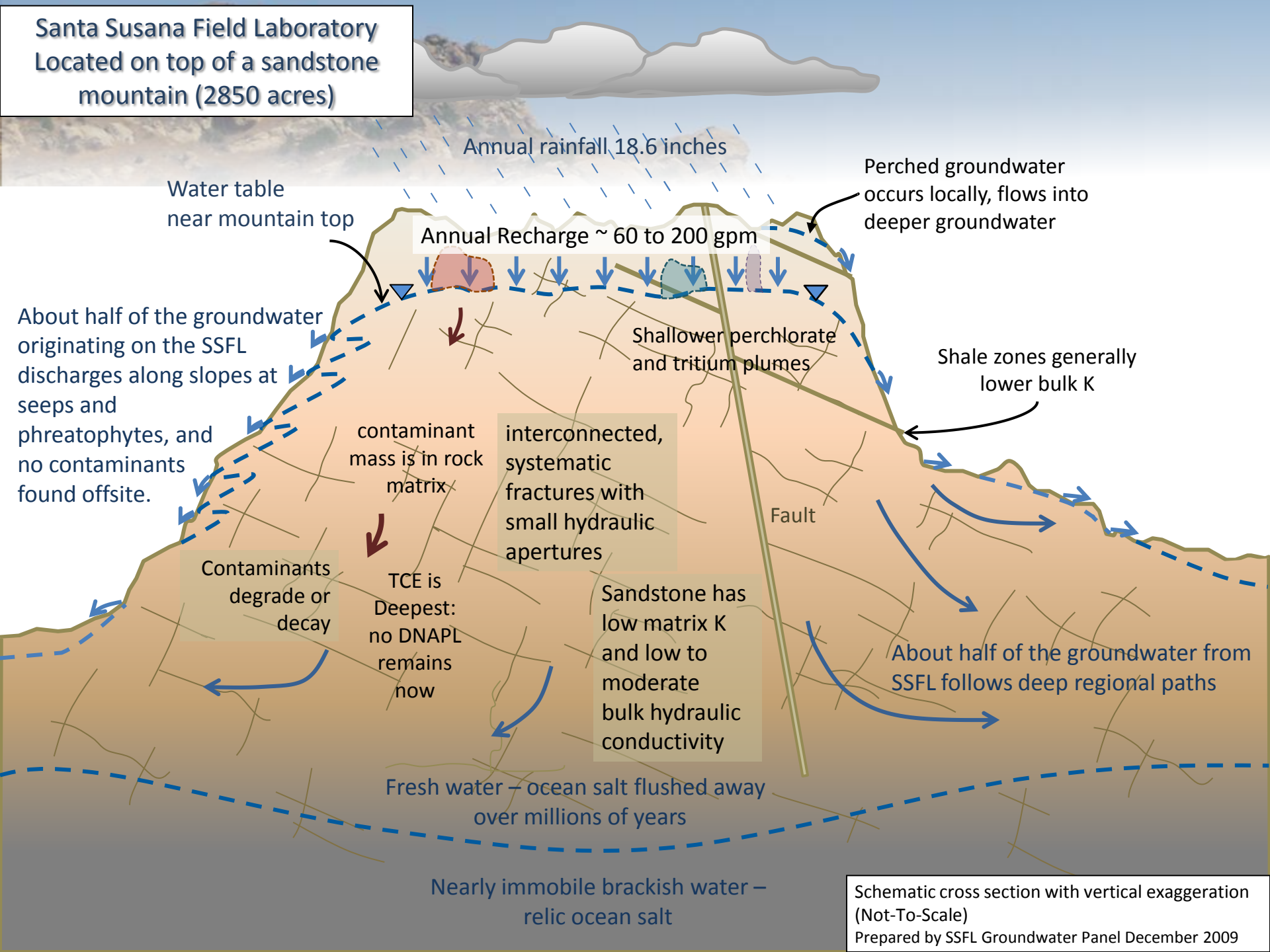


Groundwater Sampling Dates

SP-890C → July 5, 2011
SP-890D → July 5, 2011
SP-890G → September 12, 2011

FDP-890, Seep Sampling Results

TCE: 200 µg/L
cDCE: 440 µg/L
tDCE: 18 µg/L
VC: 1.0 µg/L


Santa Susana Field Laboratory
Located on top of a sandstone mountain (2850 acres)
Annual rainfall 18.6 inches
Water table near mountain top
Perched groundwater occurs locally, flows into deeper groundwater
Annual Recharge ~ 60 to 200 gpm
About half of the groundwater originating on the SSFL discharges along slopes at seeps and phreatophytes, and no contaminants found offsite.
Shallower perchlorate and tritium plumes
Shale zones generally lower bulk K
contaminant mass is in rock matrix
interconnected, systematic fractures with small hydraulic apertures
Fault
Contaminants degrade or decay
TCE is Deepest: no DNAPL remains now
Sandstone has low matrix K and low to moderate bulk hydraulic conductivity
About half of the groundwater from SSFL follows deep regional paths
Fresh water – ocean salt flushed away over millions of years
Nearly immobile brackish water – relic ocean salt
Schematic cross section with vertical exaggeration (Not-To-Scale)
Prepared by SSFL Groundwater Panel December 2009

Summary of Key Findings

- **Diffusion of contaminants readily occurs in sandstone and shale and is a very important process at SSFL.**
- **Nearly all the contaminant mass is in the low permeability rock matrix.**
- **Most of the contamination is found close to where it went into the ground.**
- **Groundwater plumes are now stable and plume fronts are nearly stationary.**
- **Contamination has not been found at offsite seeps.**

SSFL Groundwater Team

Property Owners
The Boeing Company, NASA, and the US Department of Energy
Boeing Project Managers (David Dassler, Michael Bower)

Groundwater Advisory Panel
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Clemson University (David Freedman)

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THANK YOU
Questions?