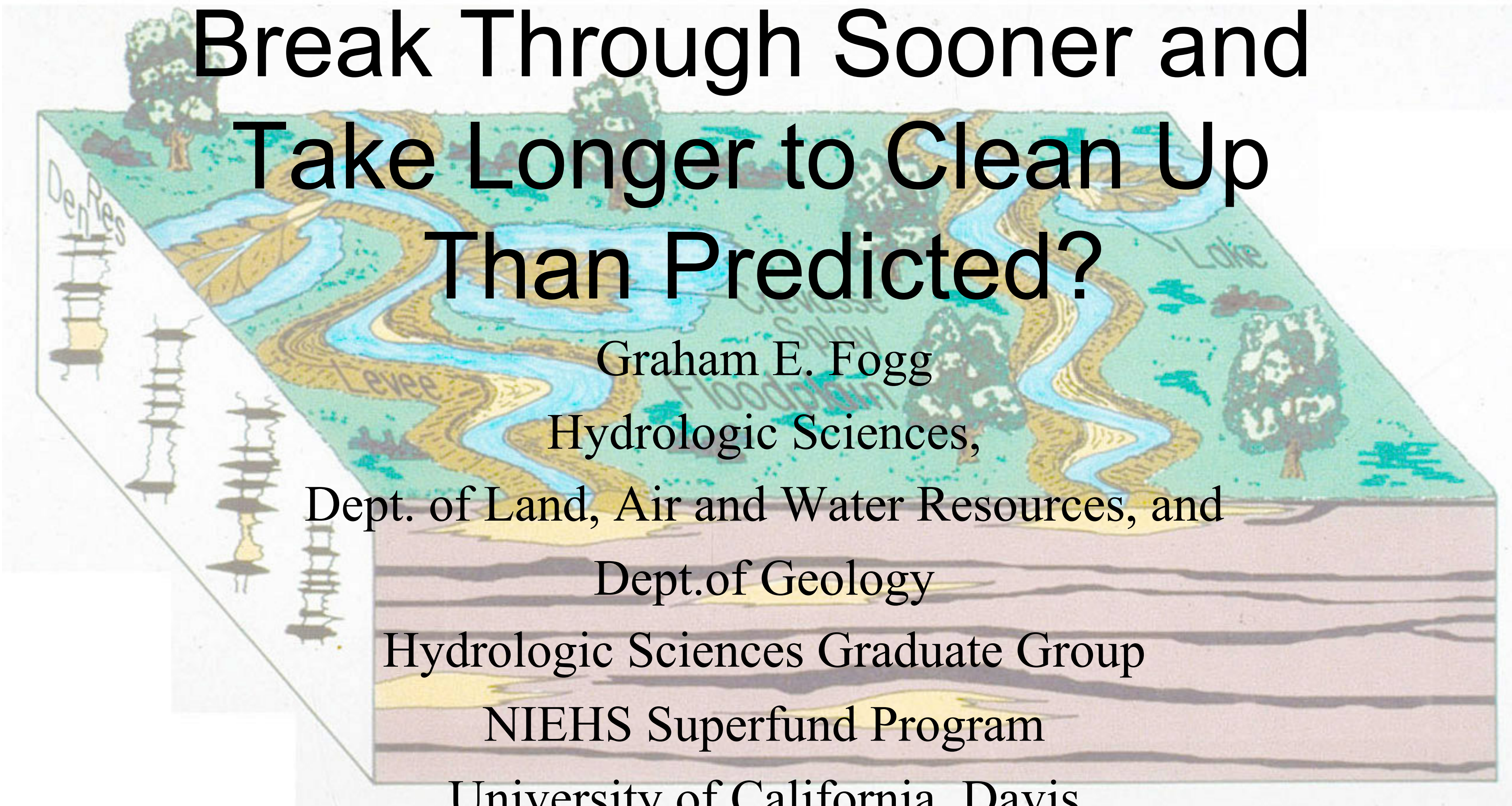
# Why Does the Plume Always Break Through Sooner and Take Longer to Clean Up Than Predicted?





Graham E. Fogg

Hydrologic Sciences,

Dept. of Land, Air and Water Resources, and

Dept.of Geology

Hydrologic Sciences Graduate Group

NIEHS Superfund Program

University of California, Davis


**EPA CLU-IN Webinar, Feb. 24, 2014**

# Collaborators/Contributors

Eric LaBolle*
Jeremy Quastel
Chris Green*
Yong Zhang
Bill Gustafson
G. Weissmann*

Steve Carle*
Janko Gravner
Si-Yong Lee*
Thomas Harter
Laura Roll*

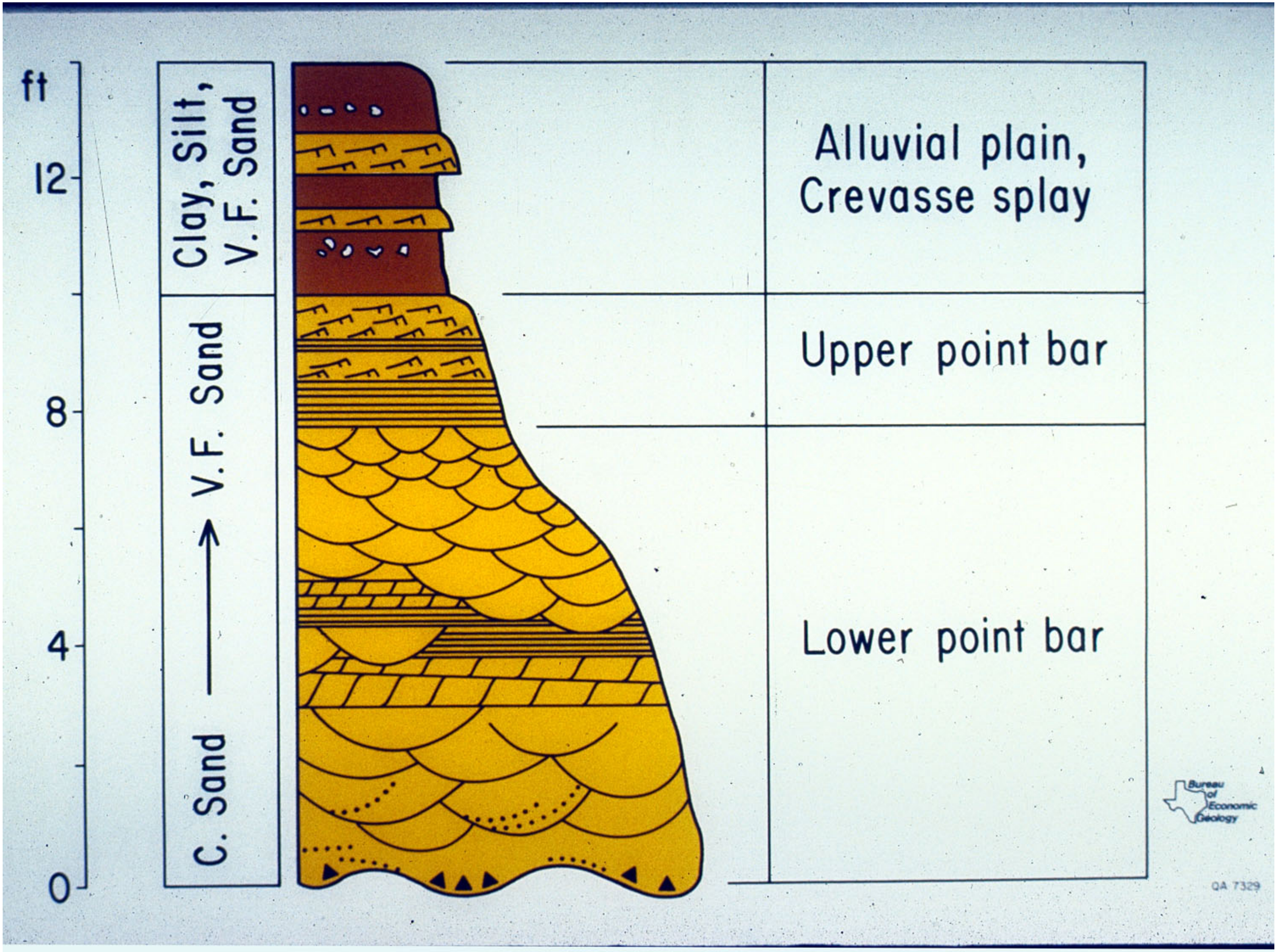
**Thesis/Dissertation work*

# Outline

- Geologic nature of the subsurface (clastics)
  - Aquifers and aquitards
  - K distribution
  - Connectivity
- Geologic facies, high-resolution heterogeneity approach
  - Why?
  - ~~Methods:~~
    - ~~TP-MC (T-PROGS)~~
    - ~~Methods motivated by connectivity~~
    - ~~Advanced random-walk particle method (RWHET)~~
- Hydrologic observations
  - Preferential flow
  - Mass sequestration; difficult remediation
  - Broad residence time distributions
  - Challenge of MNA

# Observations: Clastic Alluvial Sediments

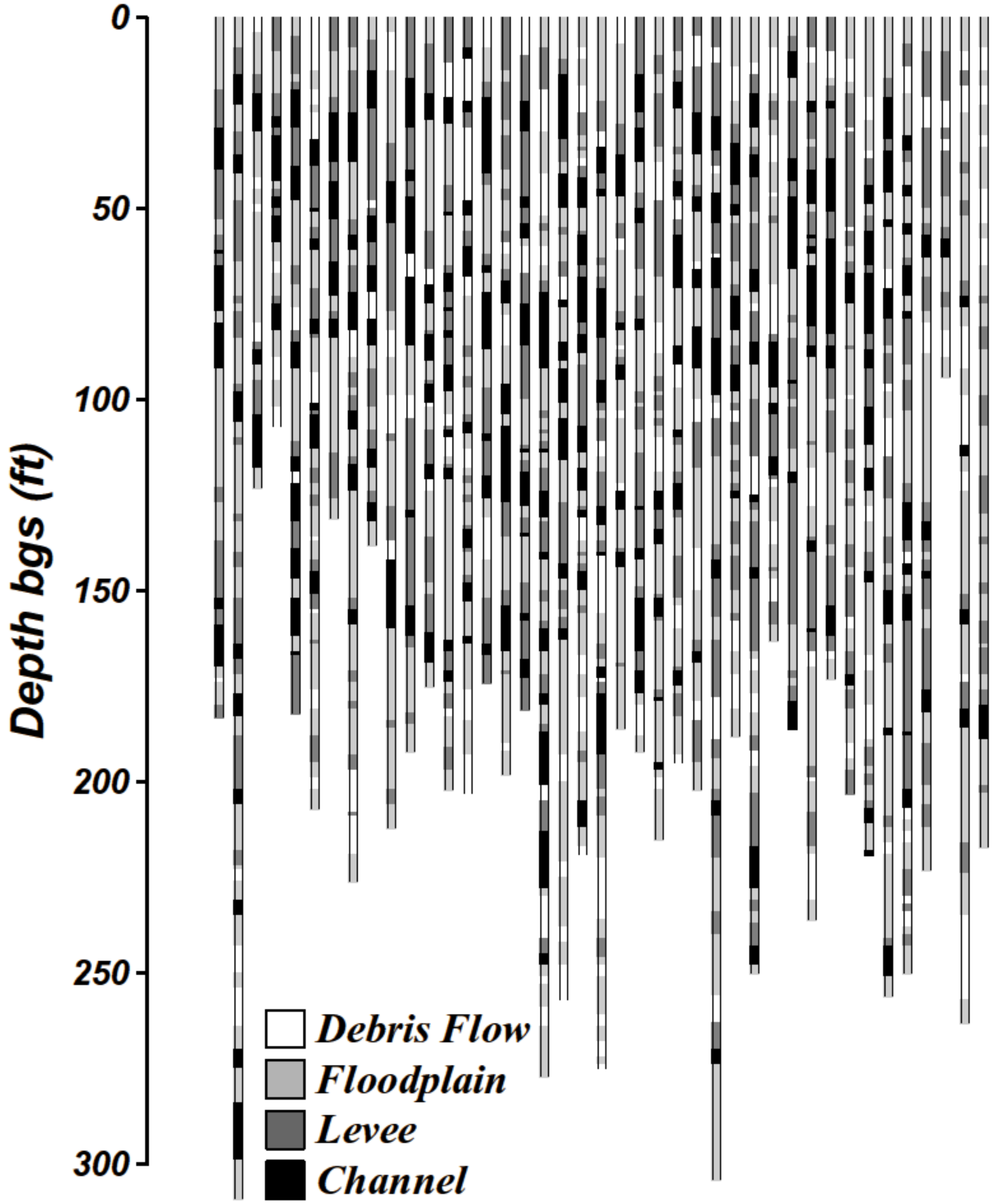
- Most can be subdivided into texture classes based on coarse, fine and mixed textures (textural facies).
- With the exception of eolian and glacial-fluvial outwash from continental glaciers…
- Most “aquifers” contain substantial fraction of non-aquifer sediments.
- ln-K $\sigma^2 < 2$ therefore is rare. (i.e., ‘extreme heterogeneity’ is the norm)

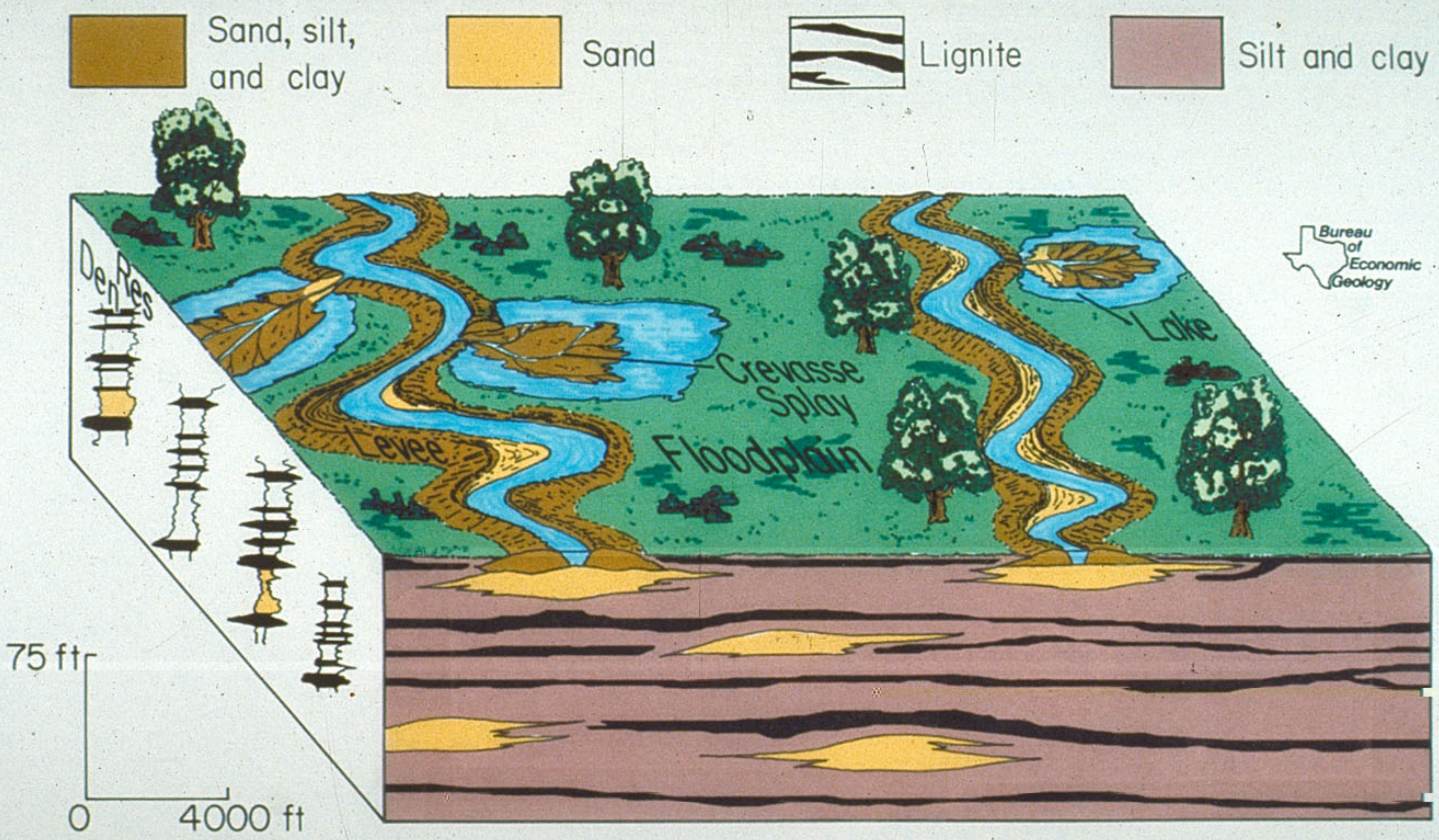


ft
12
8
4
0
Clay, Silt, V.F. Sand
C. Sand → V.F. Sand
Alluvial plain, Crevasse splay
Upper point bar
Lower point bar
Bureau of Economic Geology
QA 7329

E-logs
E. Texas Basin

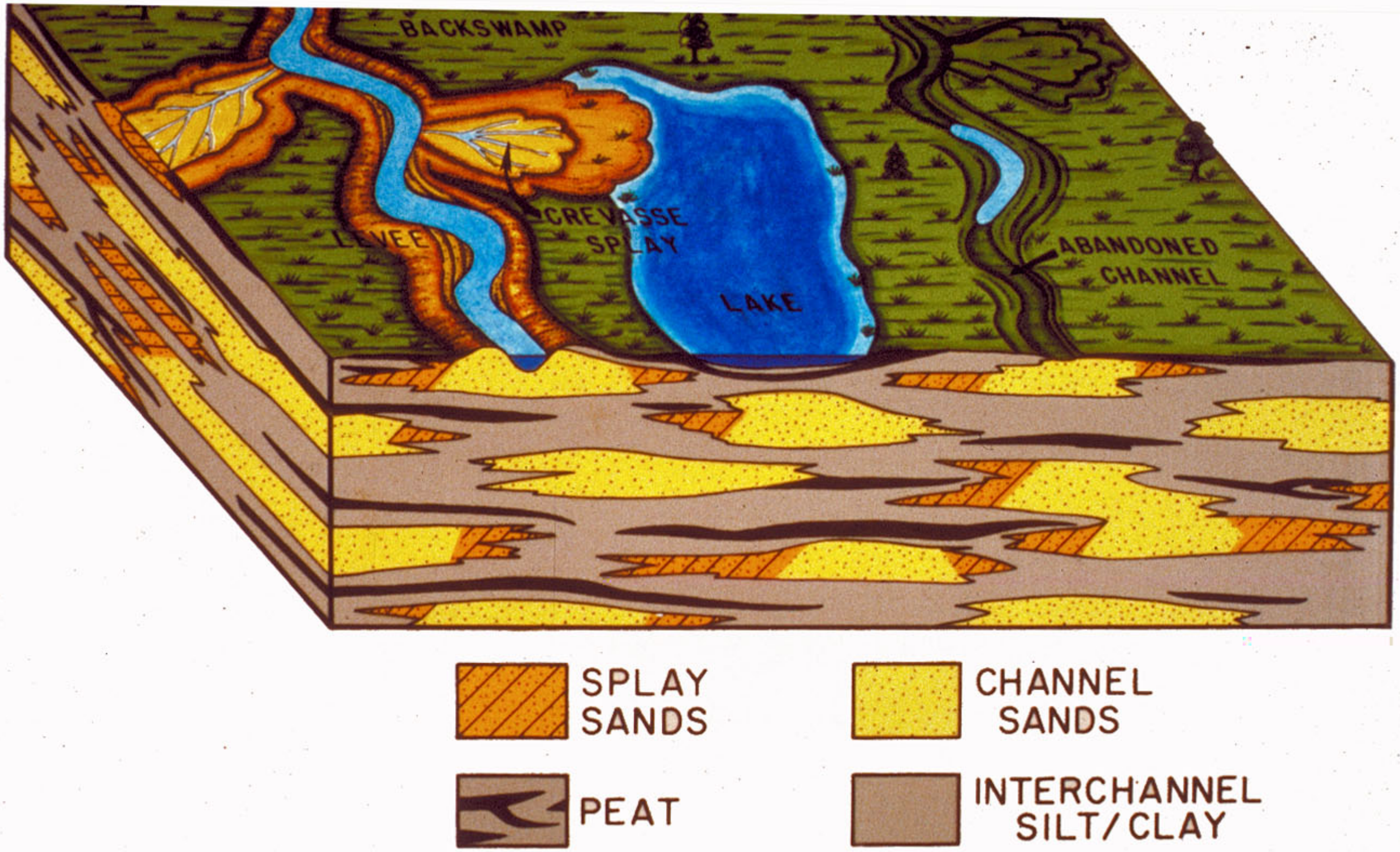
# Lithofacies Logs
# Lawrence Livermore National Laboratory





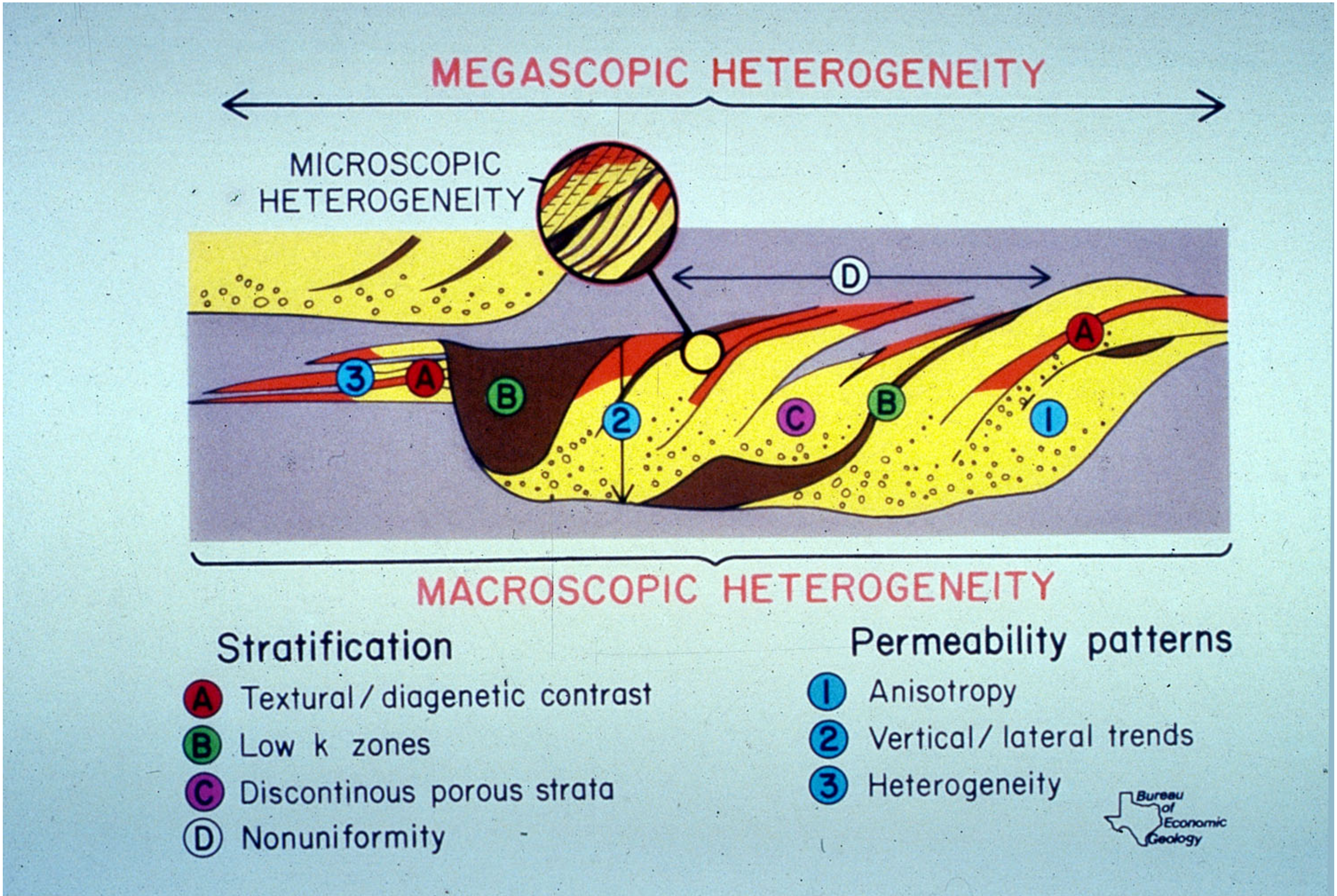

MIXED- AND SUSPENDED-LOAD CHANNEL SYSTEM
CALVERT BLUFF FORMATION

W.E. Galloway




MIXED-LOAD CHANNEL SYSTEM

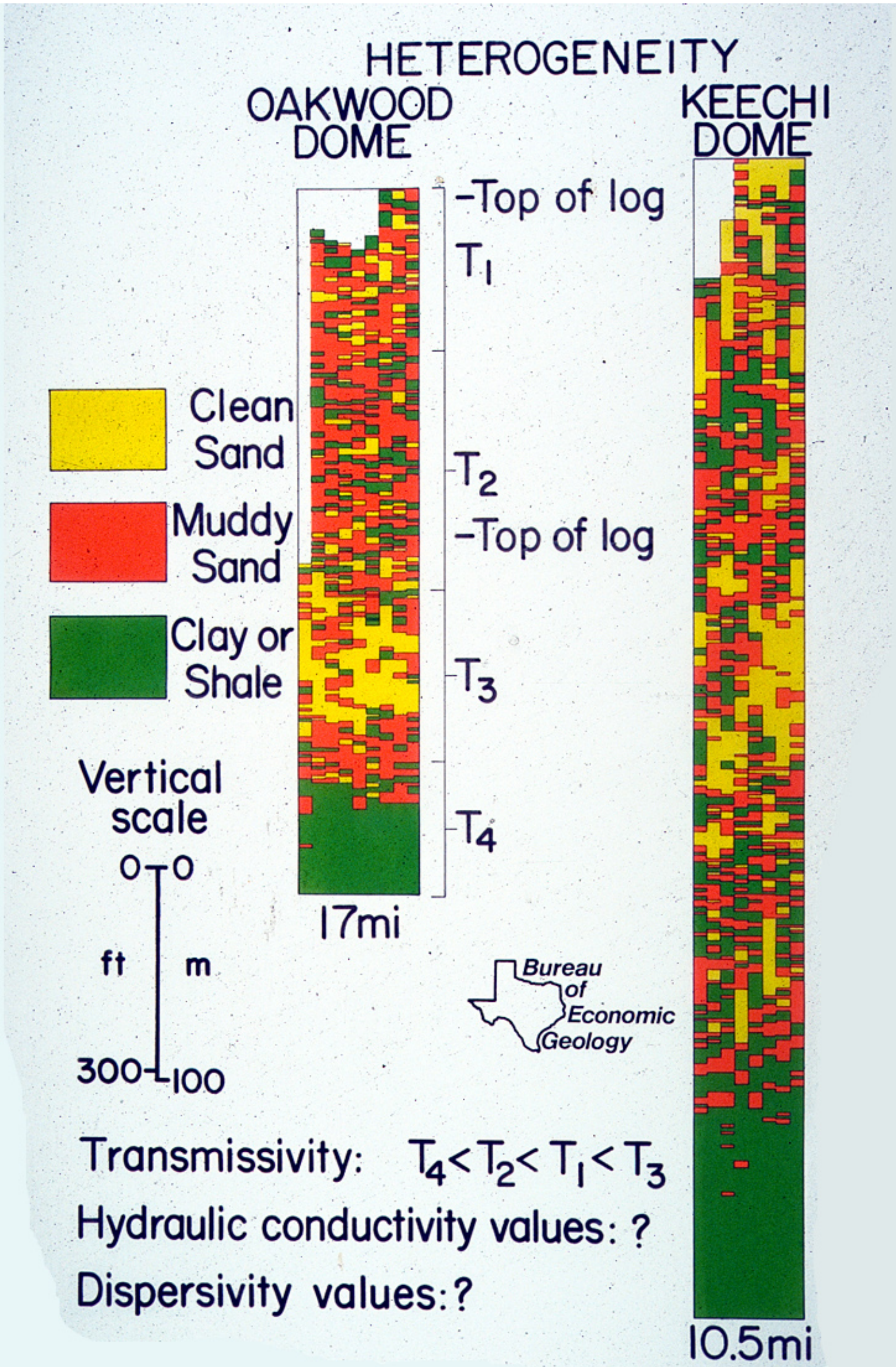
W.E. Galloway

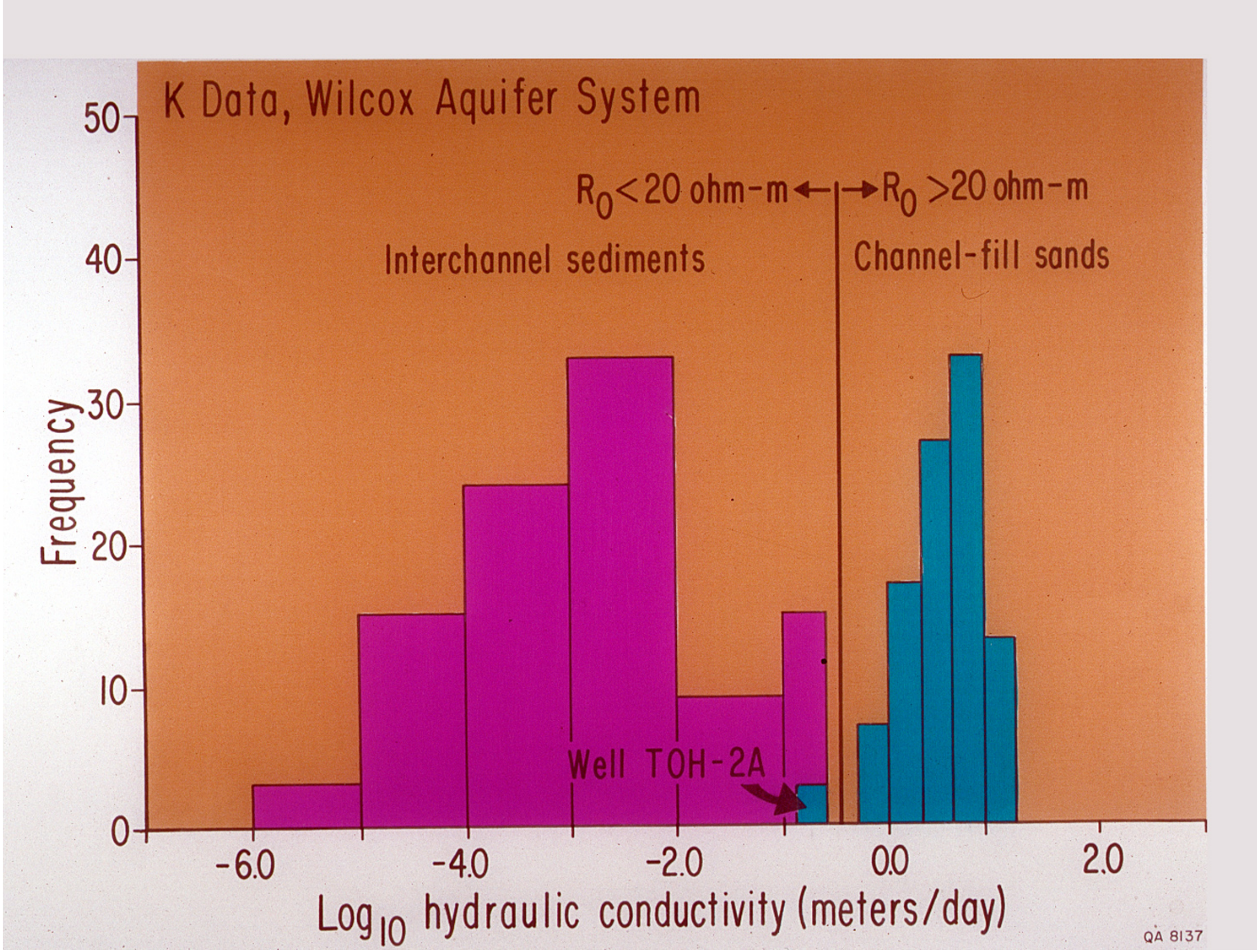

MEGASCOPIC HETEROGENEITY
MICROSCOPIC HETEROGENEITY
D
3
A
B
2
C
B
A
1
MACROSCOPIC HETEROGENEITY
Stratification
A Textural/diagenetic contrast
B Low k zones
C Discontinous porous strata
D Nonuniformity
Permeability patterns
1 Anisotropy
2 Vertical/lateral trends
3 Heterogeneity
Bureau of Economic Geology

# Large ln-K $\sigma^2$

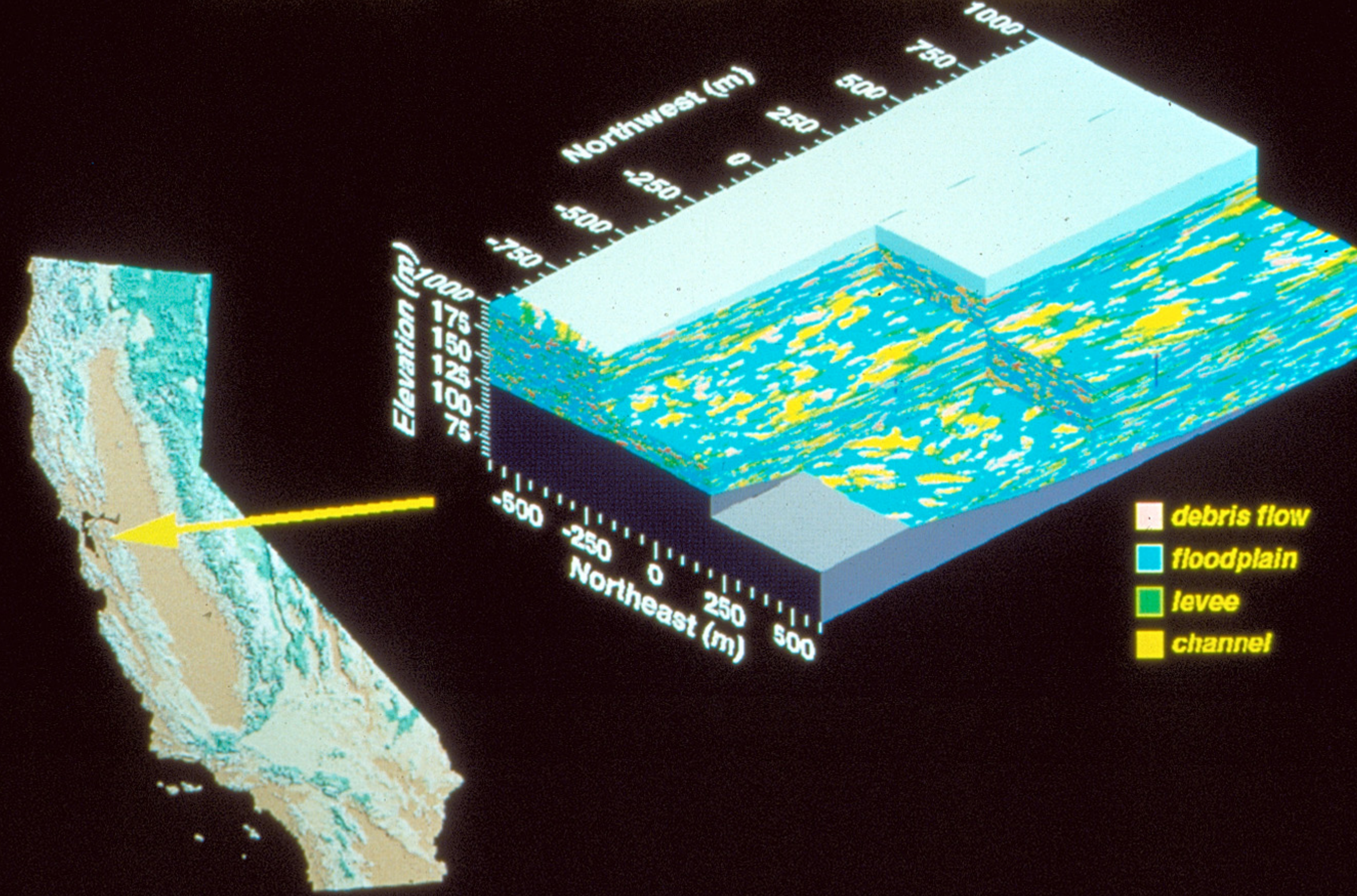
**Example 1: Wilcox Group, East Texas Basin (fluvial); Fogg (1986)**

**Example 2: Livermore Valley (LLNL)**


HETEROGENEITY
OAKWOOD DOME
KEECHI DOME
Clean Sand
Muddy Sand
Clay or Shale
-Top of log
T1
T2
-Top of log
T3
T4
Vertical scale
0 0
ft m
300 100
17mi
10.5mi
Bureau of Economic Geology
Transmissivity: T4 < T2 < T1 < T3
Hydraulic conductivity values: ?
Dispersivity values: ?


K Data, Wilcox Aquifer System
$R_0$ < 20 ohm-m
$R_0$ > 20 ohm-m
Interchannel sediments
Channel-fill sands
Well TOH-2A
Frequency
50
40
30
20
10
0
-6.0
-4.0
-2.0
0.0
2.0
$\log_{10}$ hydraulic conductivity (meters/day)
QA 8137

# LLNL STUDY AREA



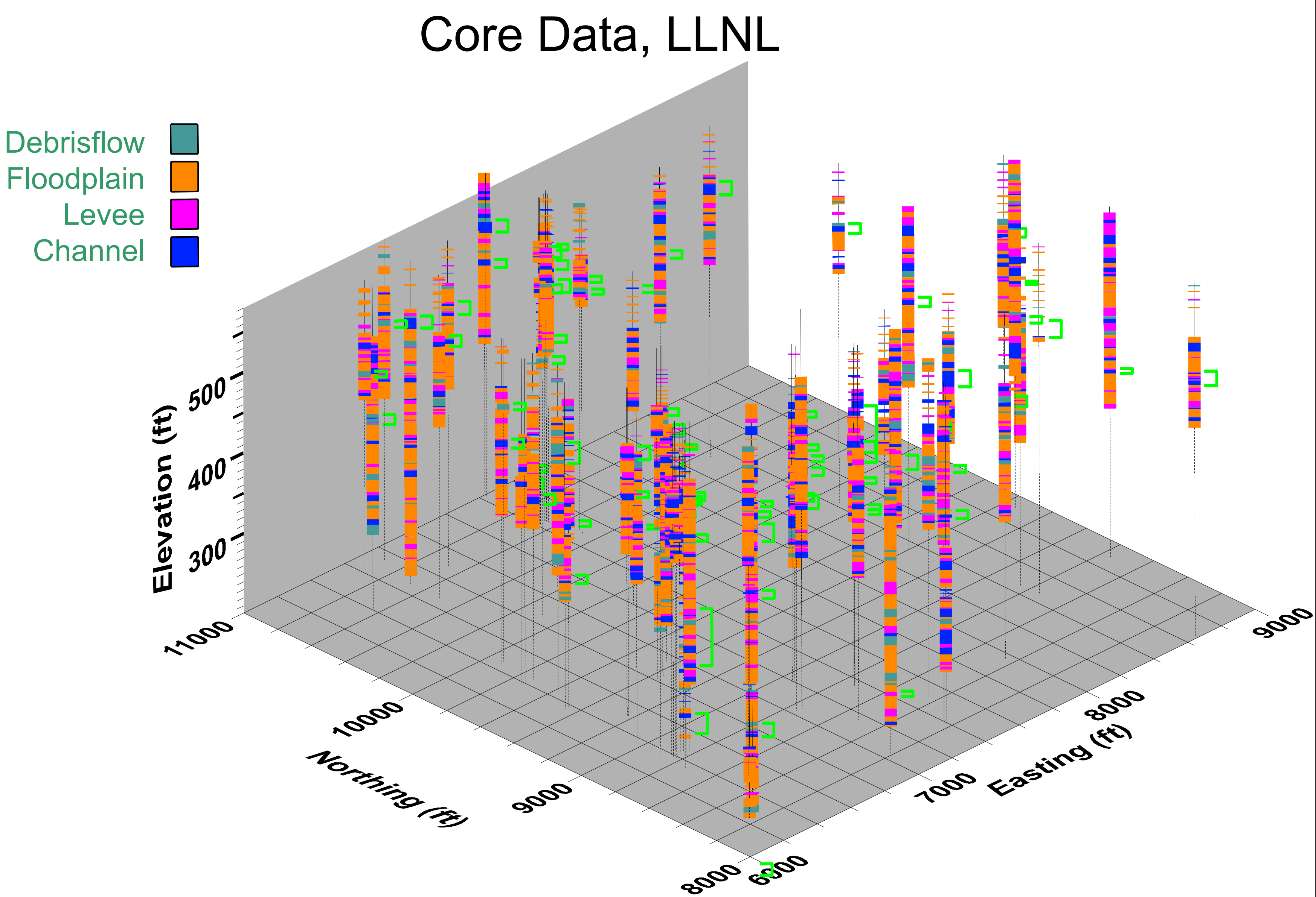
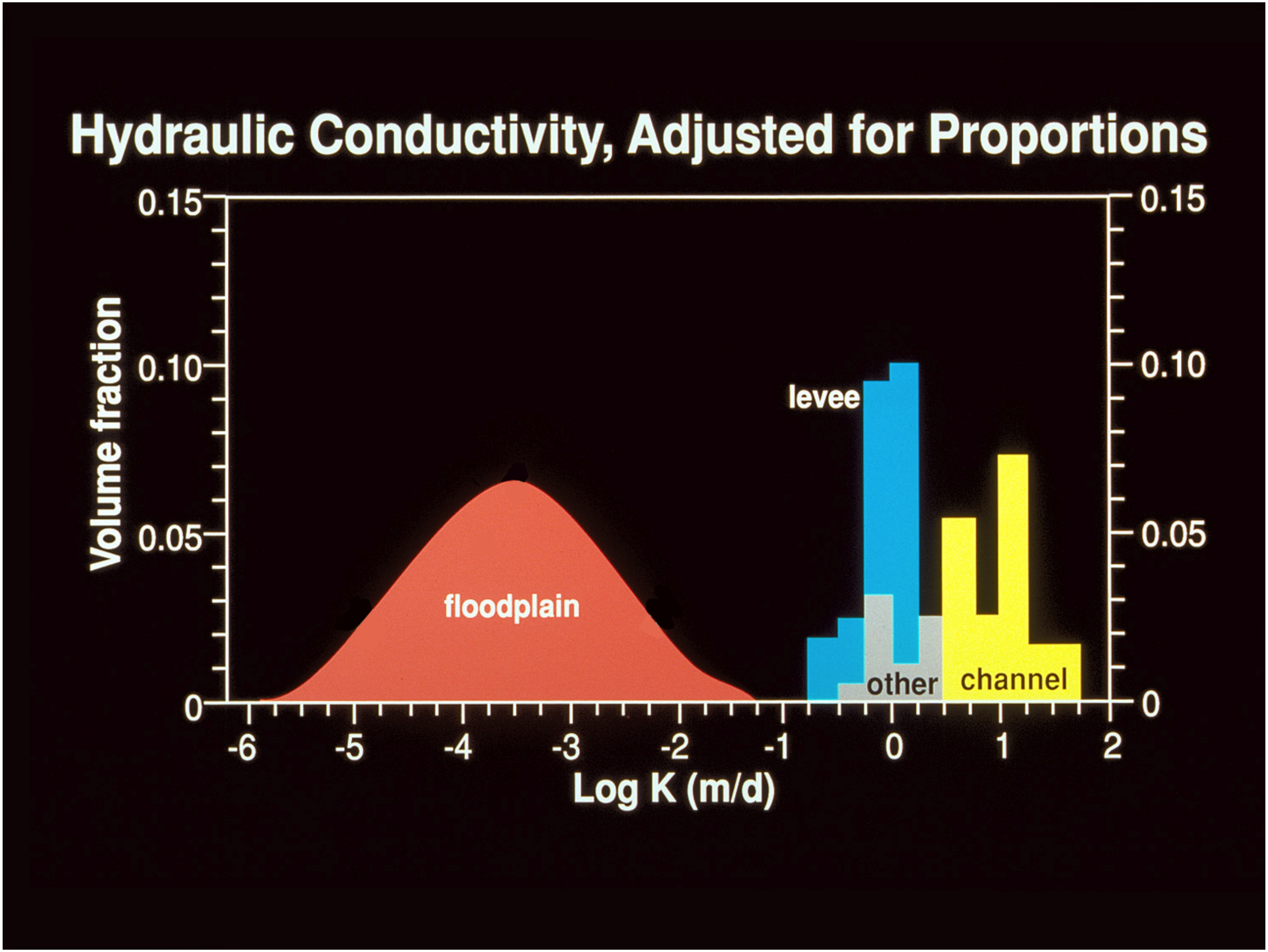



***Fig. 1*** *Core descriptions (from Carle, 1996)*



Hydraulic Conductivity, Adjusted for Proportions
Volume fraction
0.15
0.10
0.05
0
floodplain
levee
other
channel
-6
-5
-4
-3
-2
-1
0
1
2
Log K (m/d)

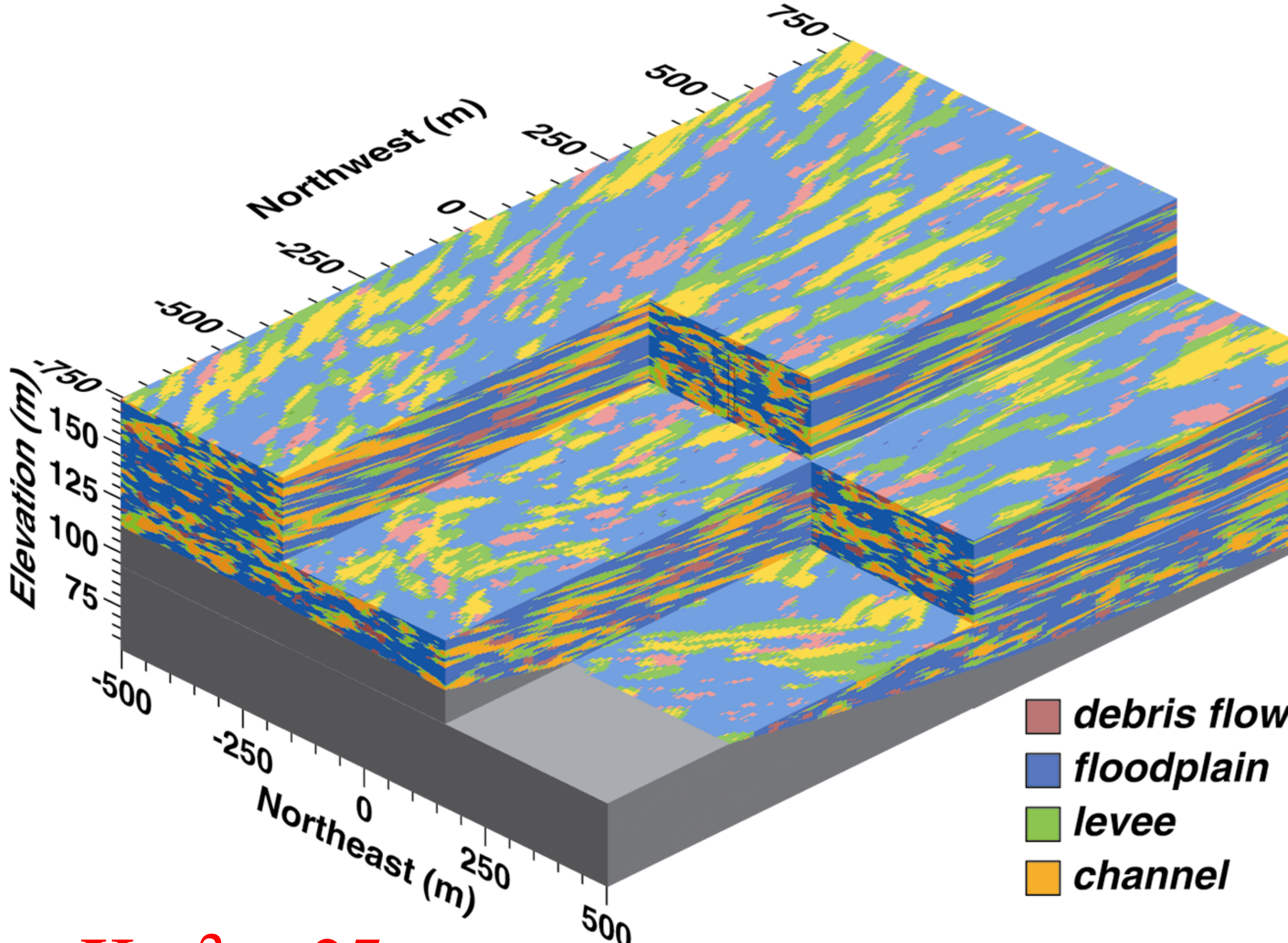
# HYDRAULIC PROPERTIES *for* Ground-Water Flow Experiments

| | ORIGINAL | | REVISED | |
|---|---|---|---|---|
| | K (m/s) | $S_s$ ($m^{-1}$) | K (m/s) | $S_s$ ($m^{-1}$) |
| Debris Flows | 5e-6 | 2e-5 | 5e-6 | 2e-5 |
| Floodplain | 2e-9 | 5e-4 | 5e-10 | 7e-4 |
| Levee | 3e-6 | 5e-5 | 2e-6 | 3e-5 |
| Channel | 6e-5 | 1e-5 | 6e-5 | 1e-5 |

** from pumping tests*

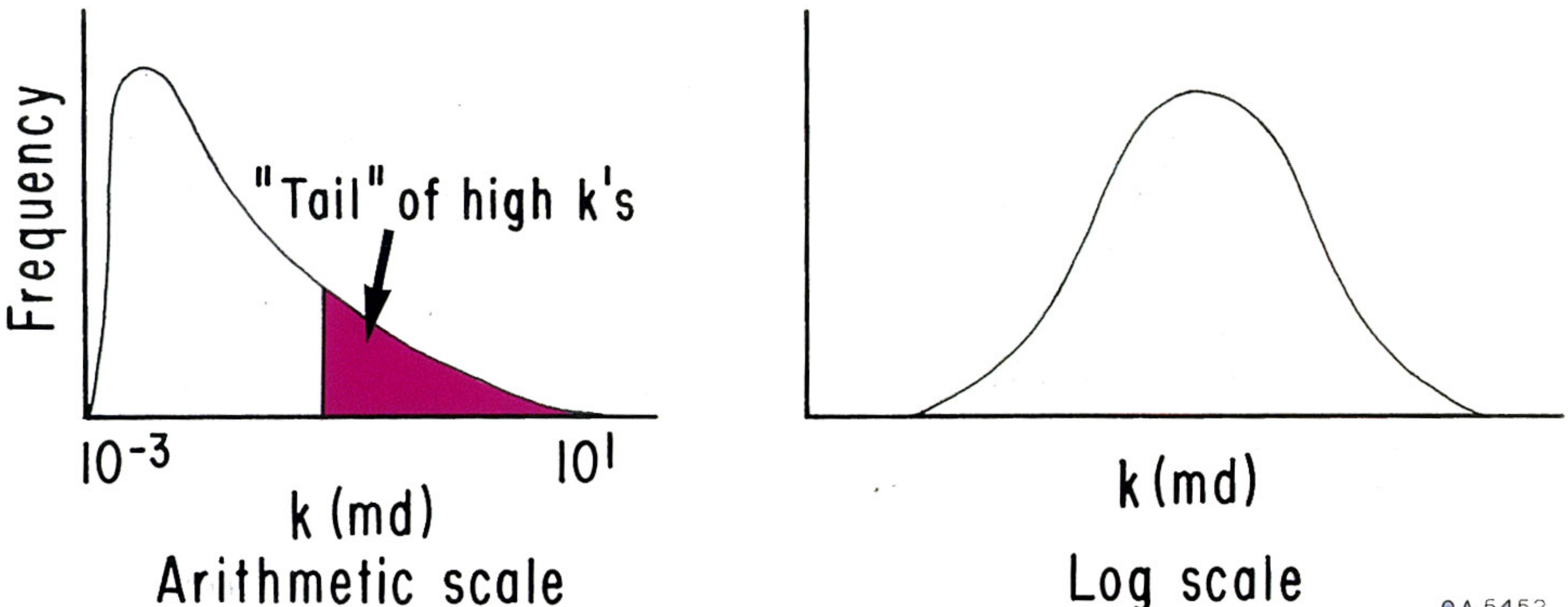
** from barometric efficiency*

# Typical Subsurface Complexty, LLNL Site (Carle & Fogg, 1996)



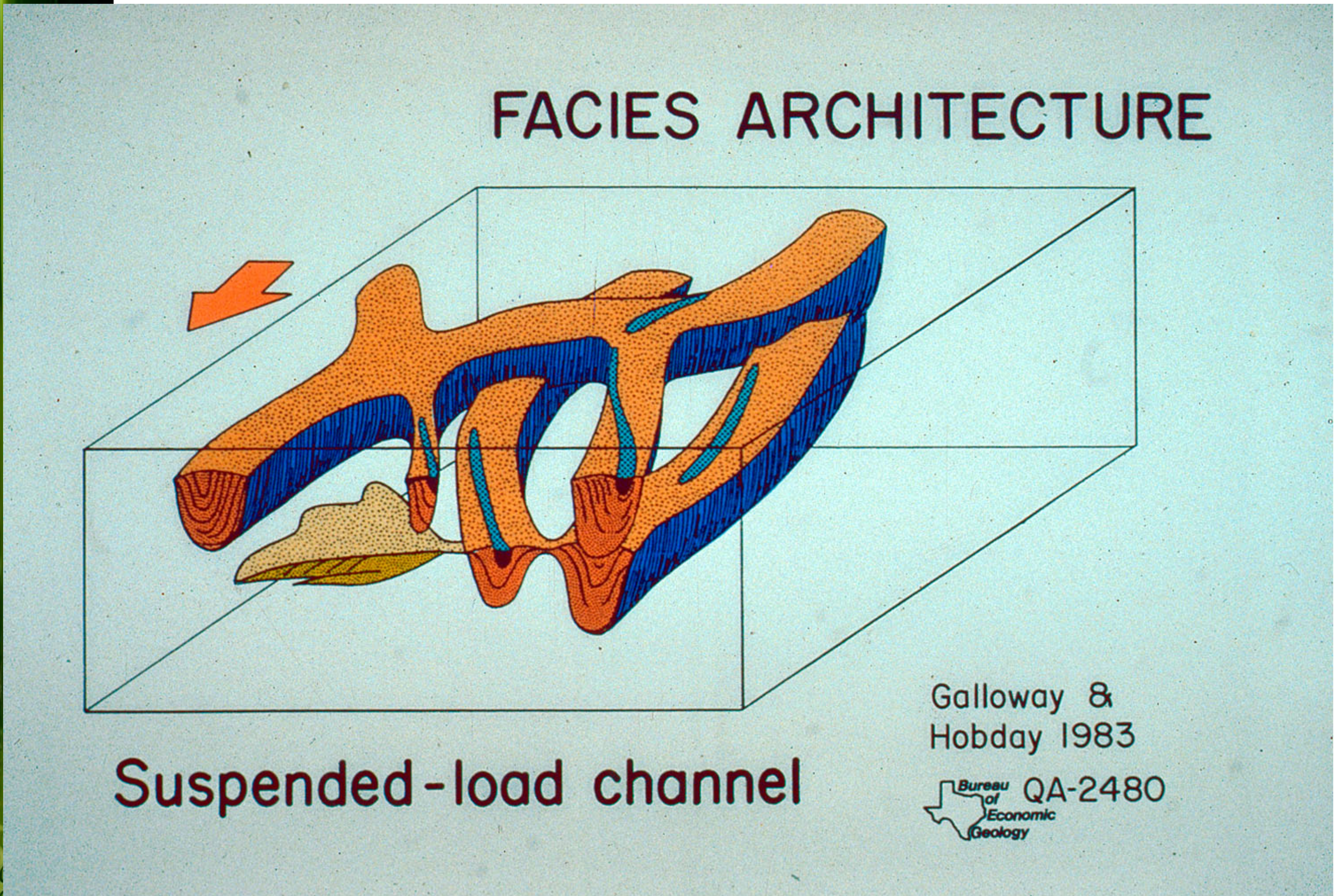

$\text{Ln K } \sigma^2 = 25$

# Log-Normal Permeability Distribution

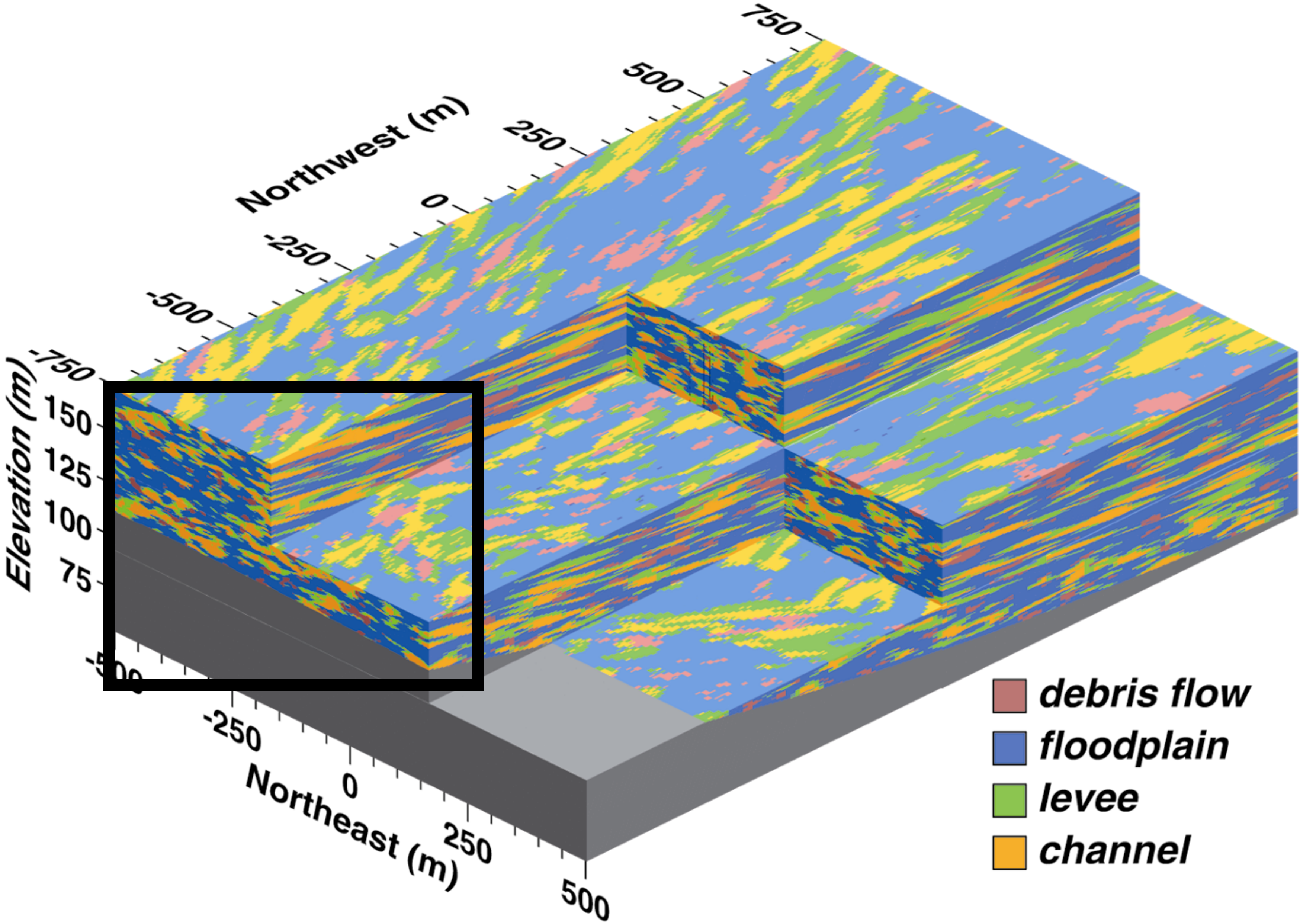


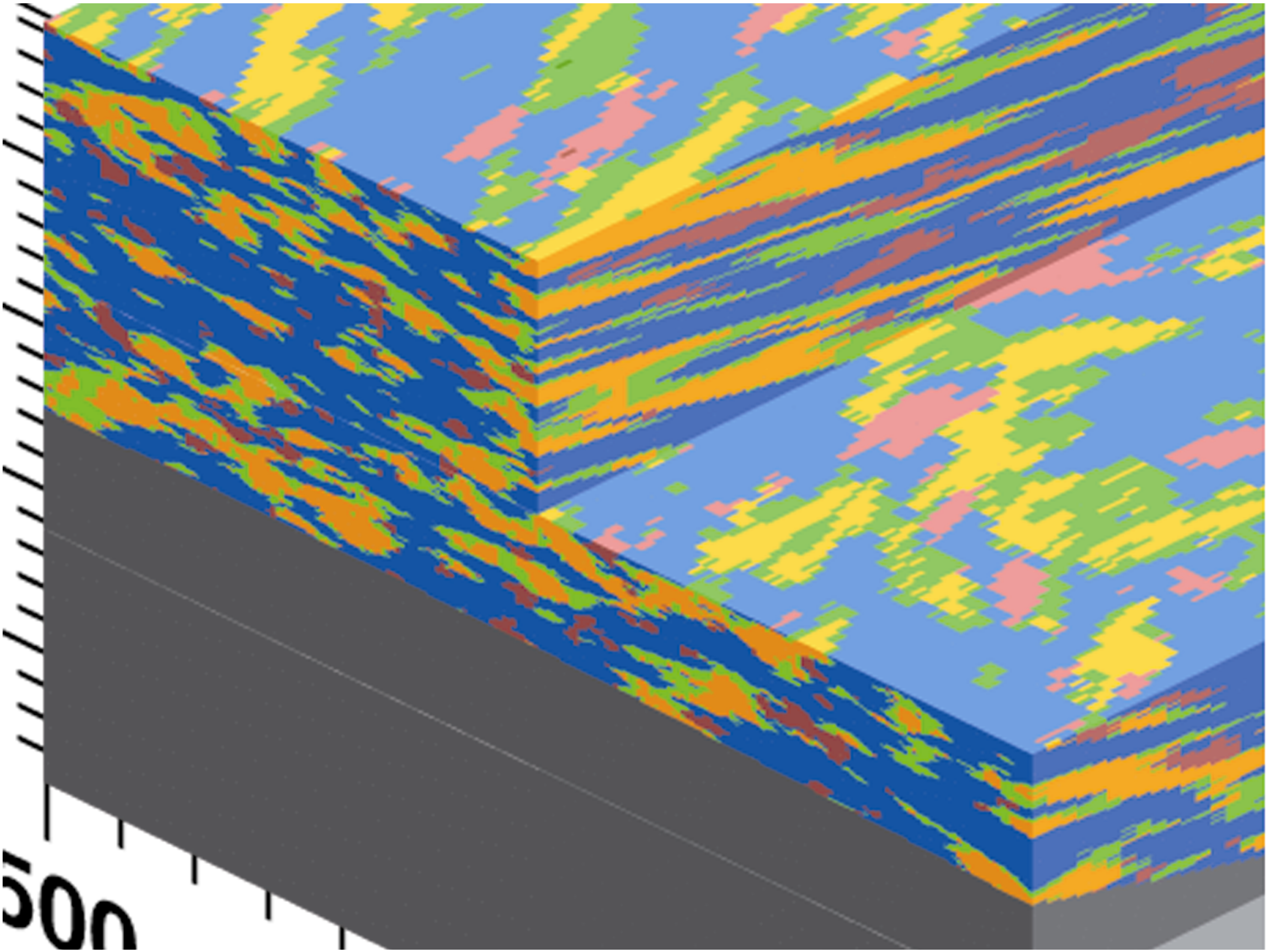

QA 5452

# Connectivity of High-K Facies Generally Good


FACIES ARCHITECTURE
Suspended-load channel
Galloway &
Hobday 1983
Bureau of Economic Geology
QA-2480

# Typical Subsurface Complexty, LLNL Site (Carle & Fogg, 1996)

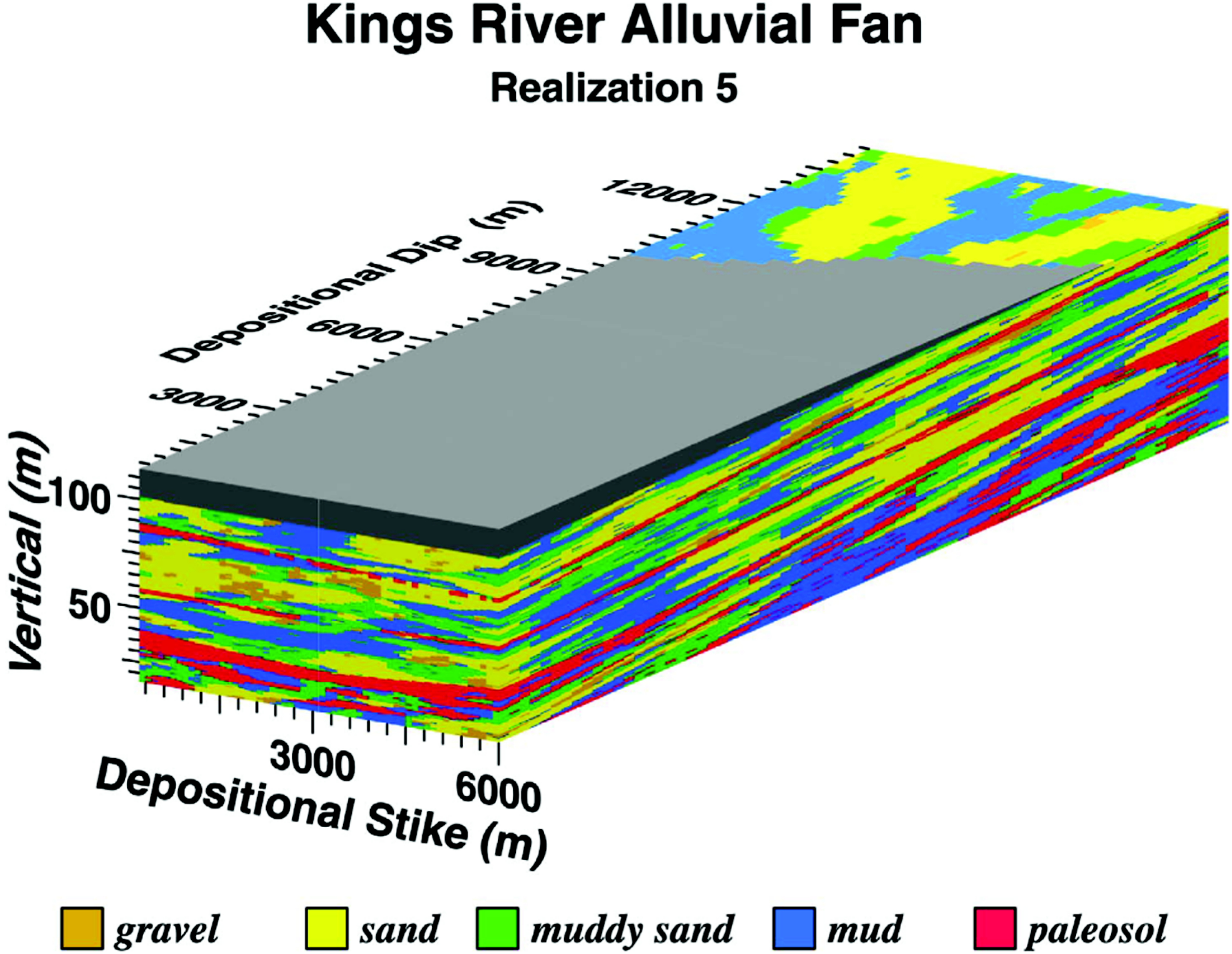



500

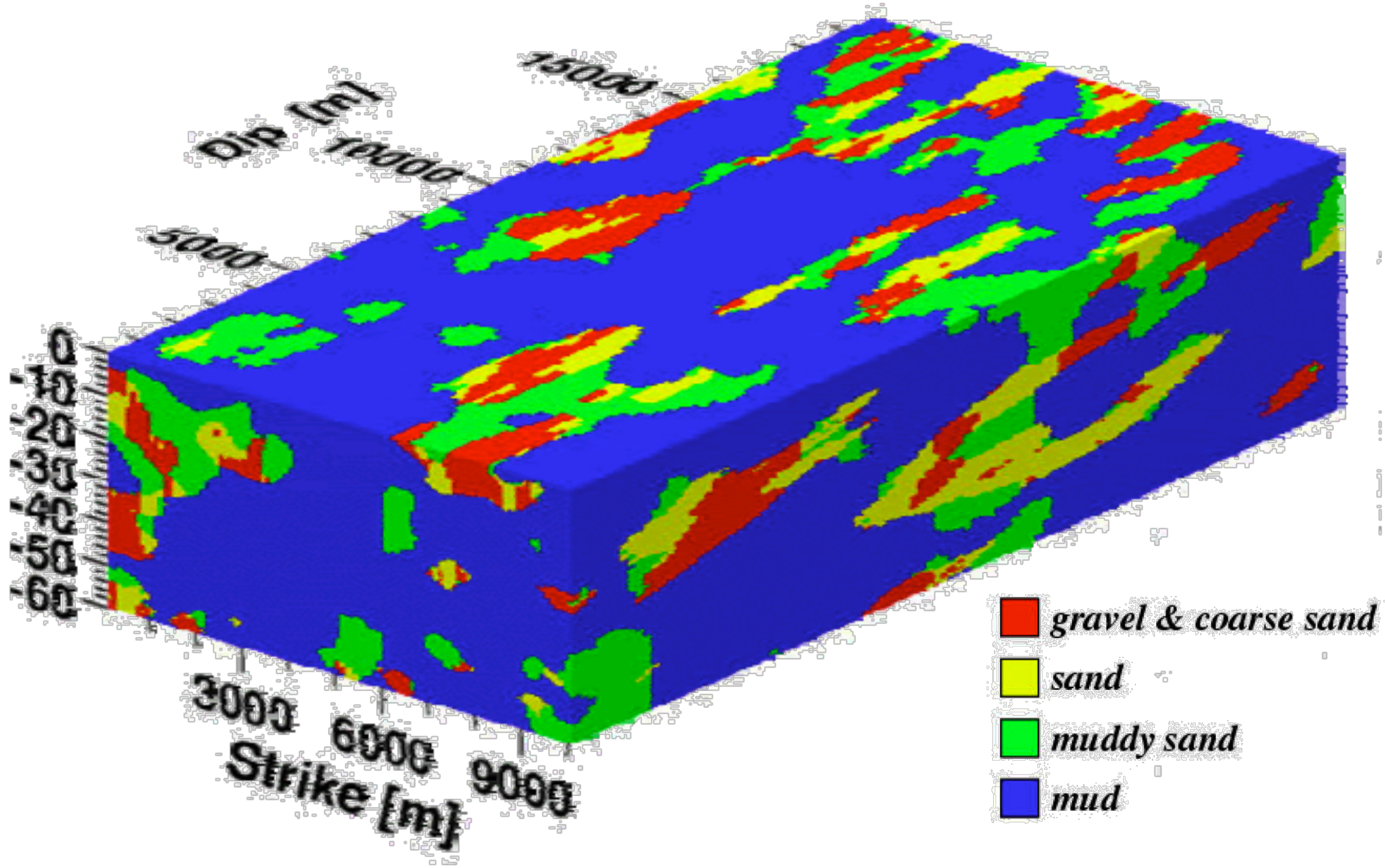
Geological Society of America
Special Paper 348
2000

# *Connected-network paradigm for the alluvial aquifer system*

**Graham E. Fogg**
*Hydrologic Sciences, University of California, Davis, California 95616, USA*
**Steven F. Carle**
*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
**Christopher Green**
*Hydrologic Sciences, University of California, Davis, California 95616, USA*


Kings River Alluvial Fan
Realization 5
Depositional Dip (m)
3000
6000
9000
12000
Vertical (m)
100
50
3000
6000
Depositional Stike (m)
gravel
sand
muddy sand
mud
paleosol

# R1-Subdomain



PHYSICAL REVIEW E **72**, 026120 (2005)

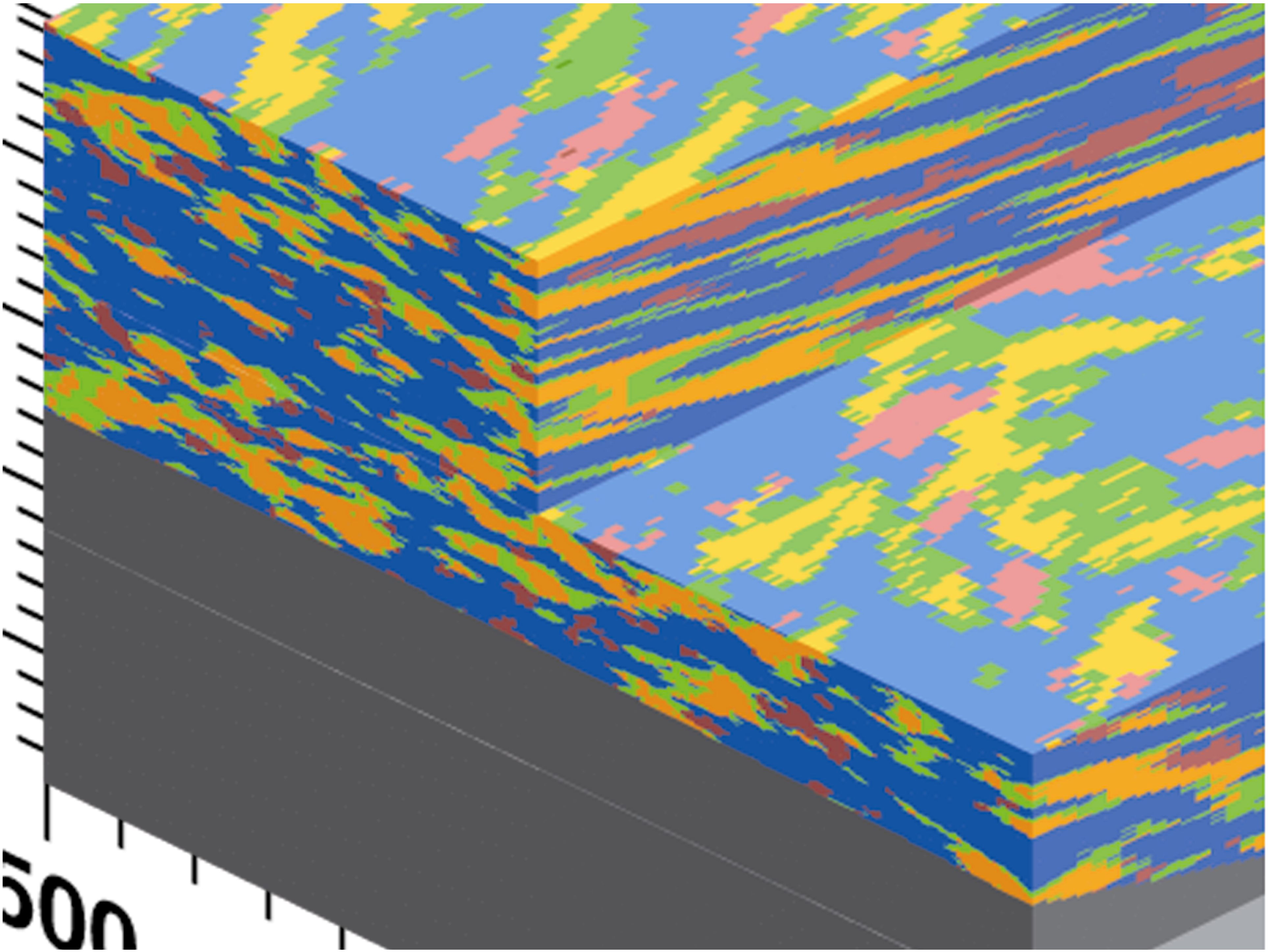
# Finite-size scaling analysis of percolation in three-dimensional correlated binary Markov chain random fields

Thomas Harter
*University of California, Davis, California 95616-8628, USA*
(Received 26 December 2004; published 18 August 2005)

- Lit.: percolation threshold $p_c$ = **0.3116** in uncorrelated, 3D fields.
- Percolation threshold $p_{av}$ decreases to **0.2-0.13** for correlated, 3D fields with

(mean length)/(system length) = 1/5 to 1/100

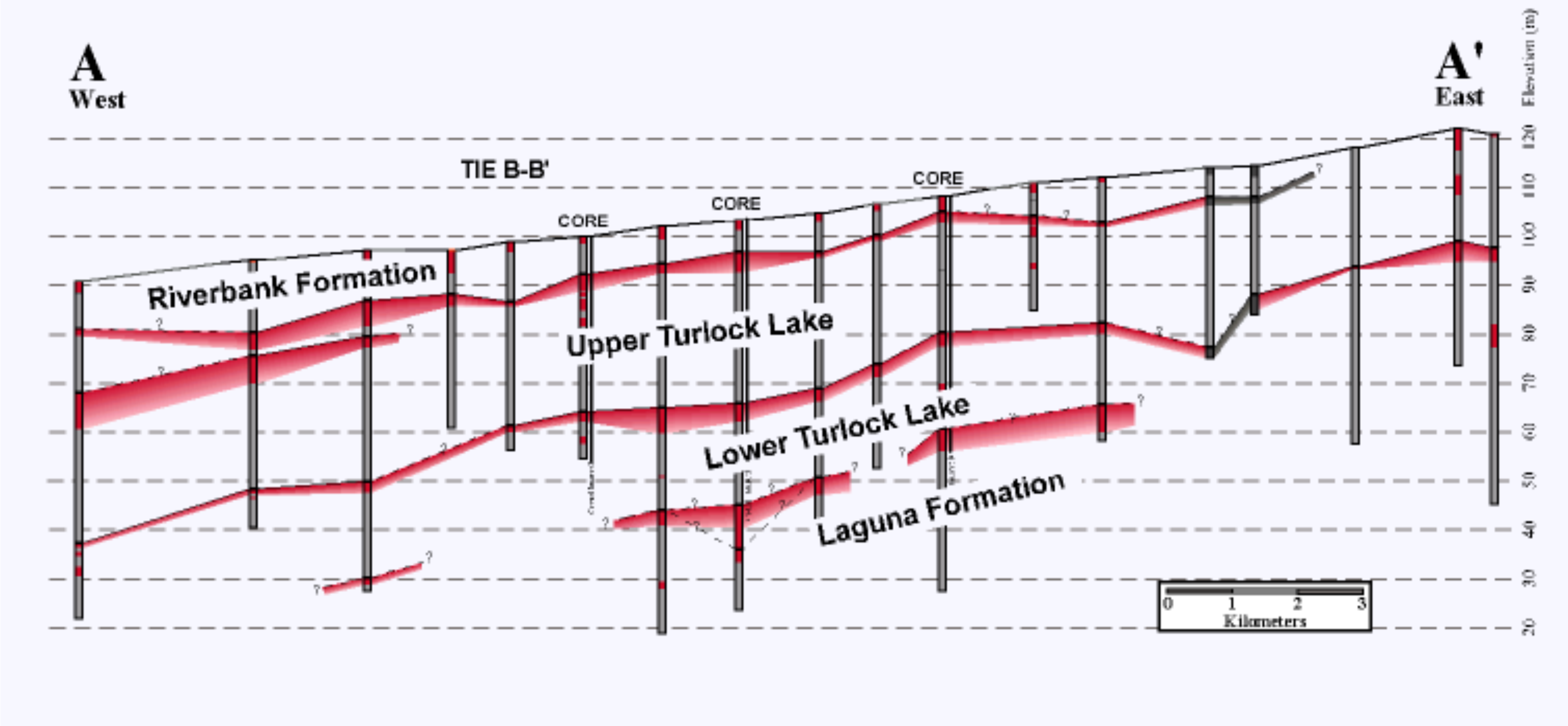
- Applies to TP-MC and Gaussian fields.


500

# Key Question Then:
# What Prevents Connectivity?

…..Mainly spatially persistent unconformities.

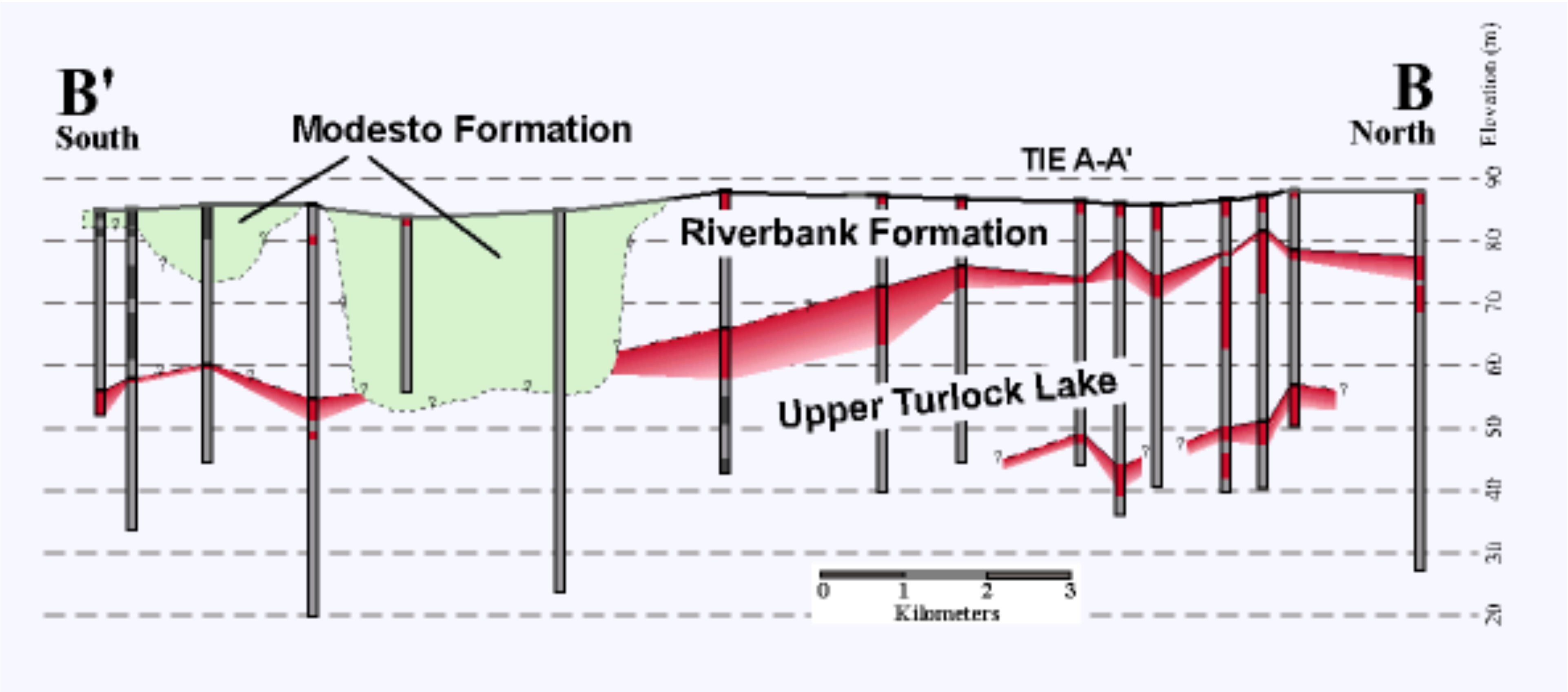
# Sequence Stratigraphic Organization; Paleosol Aquitards




Weissmann & Fogg, 1999

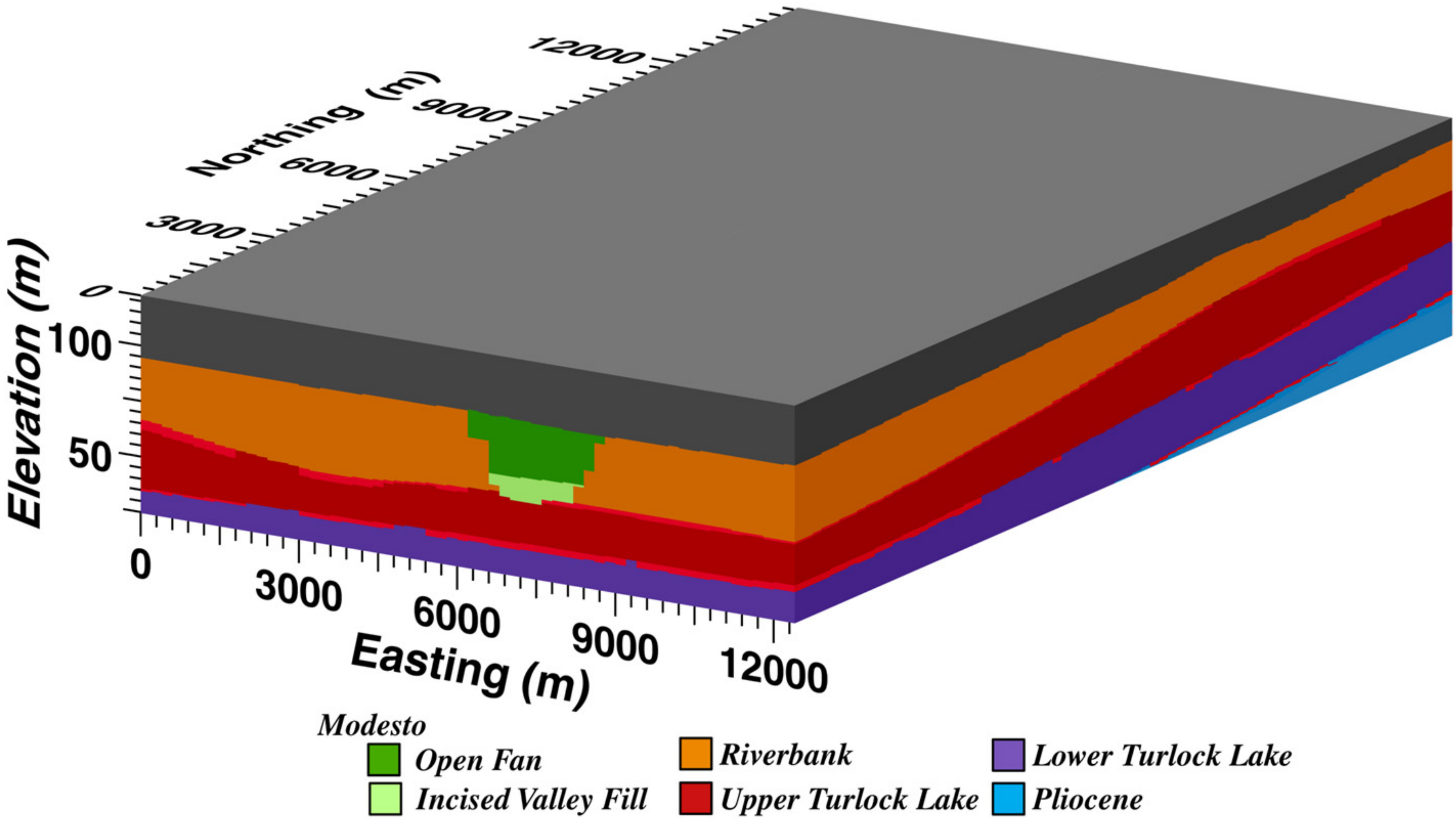
Graham E. Fogg, University of California, Davis

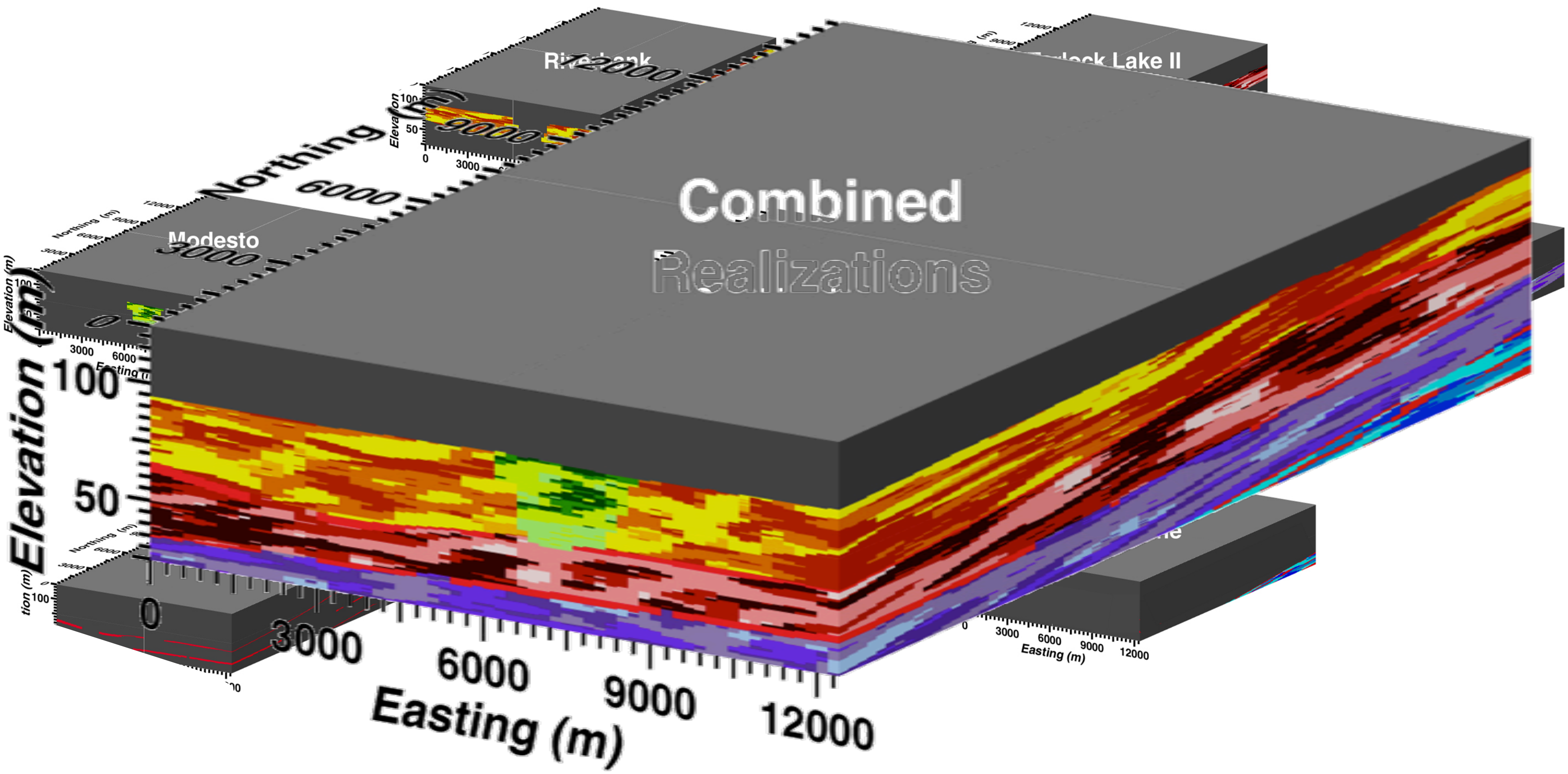
# Where Paleosols Channeled Out, Vertical Flow Enhanced




Graham E. Fogg, University of California, Davis

# Sequence Stratigraphic Units for Non-Stationary Conditional Simulation



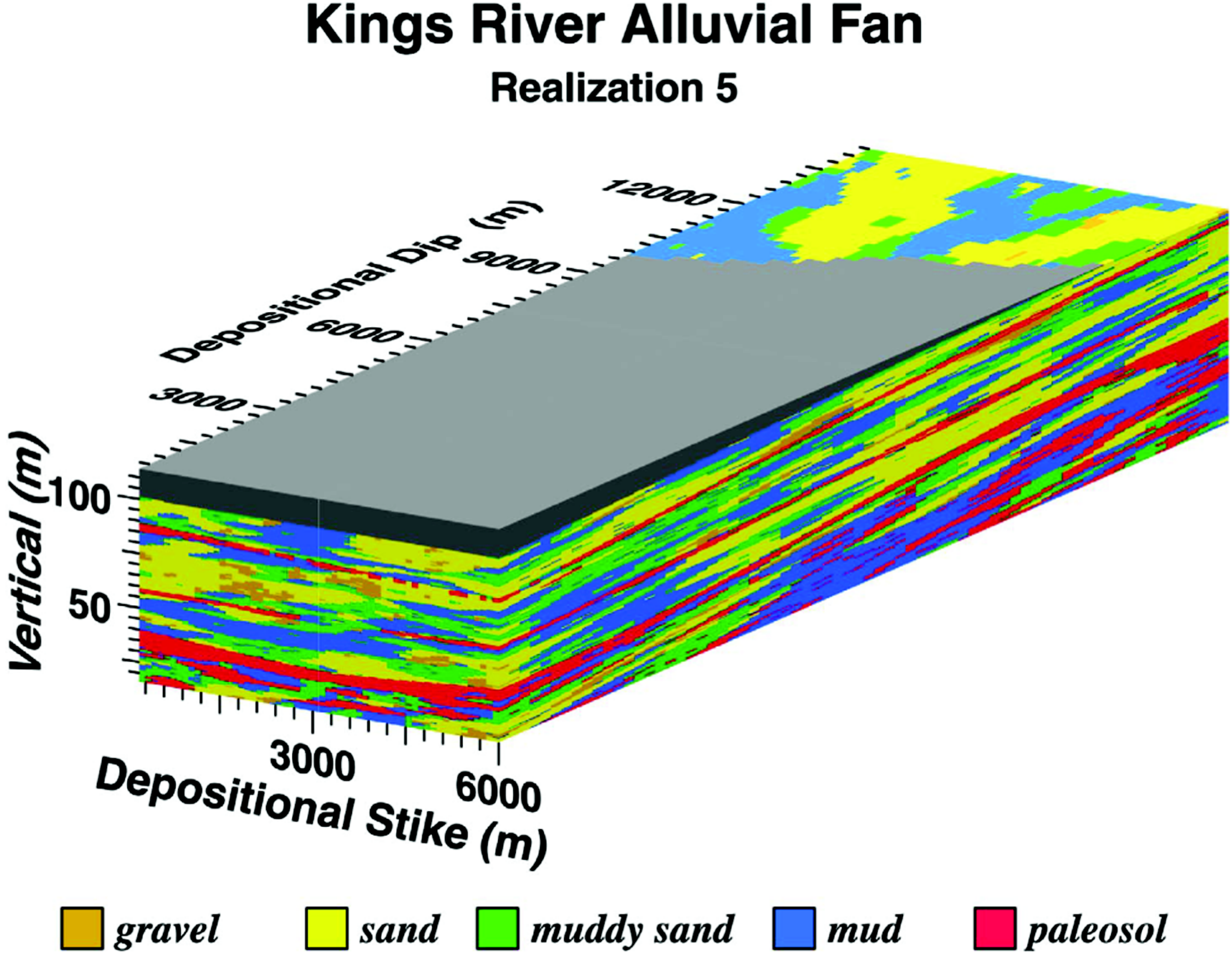


Combined
Realizations
Modesto
Turlock Lake II
Northing (m)
Elevation (m)
Easting (m)
0
3000
6000
9000
12000
50
100

Weissmann and Fogg (1999)
Weissmann, Carle and Fogg (1999)
Weissmann, Mount and Fogg (2002)

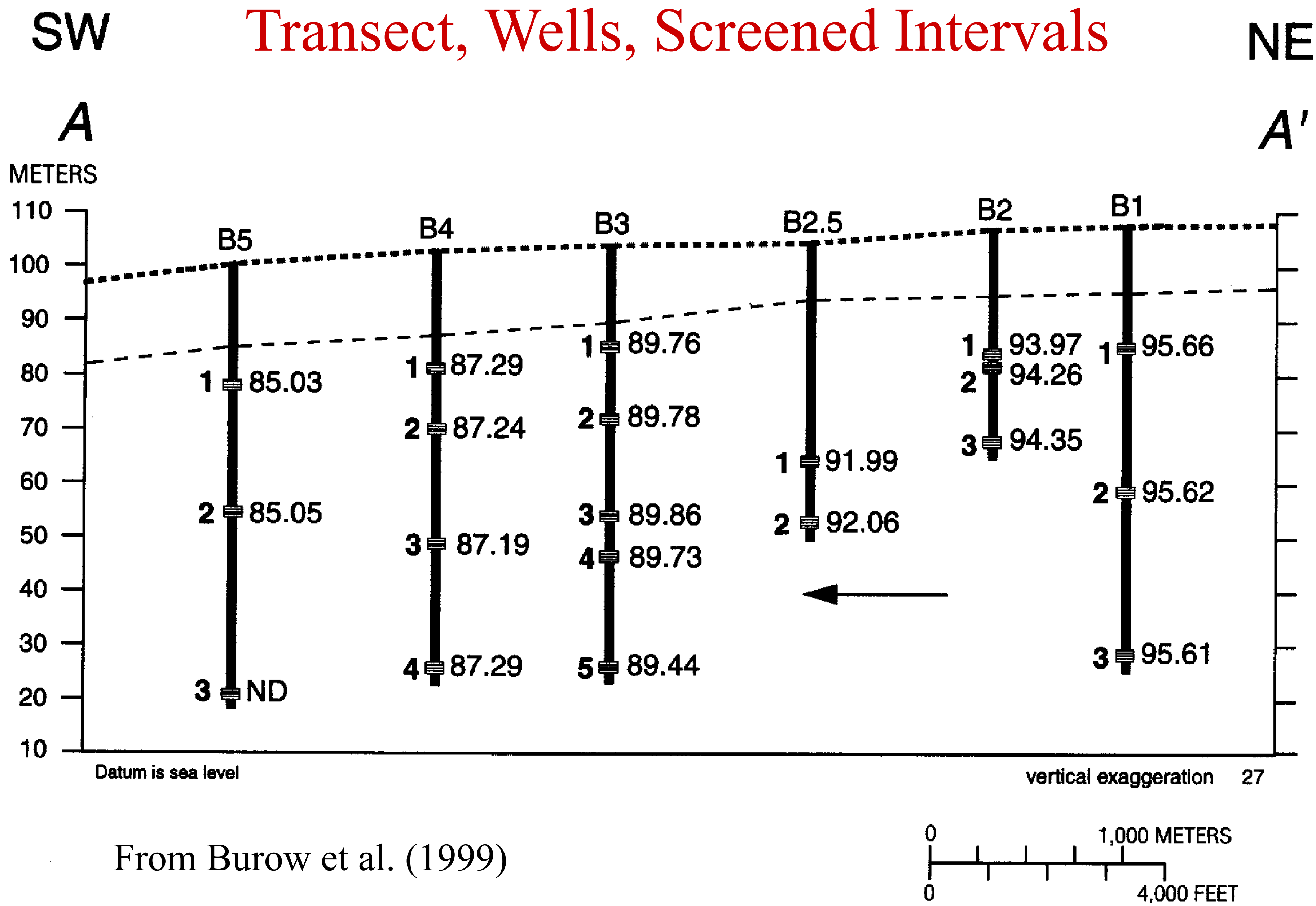
# Consequences: Examples

- Groundwater residence time distribution
- Plume modeling
- Pump and treat
- Monitored natural attenuation



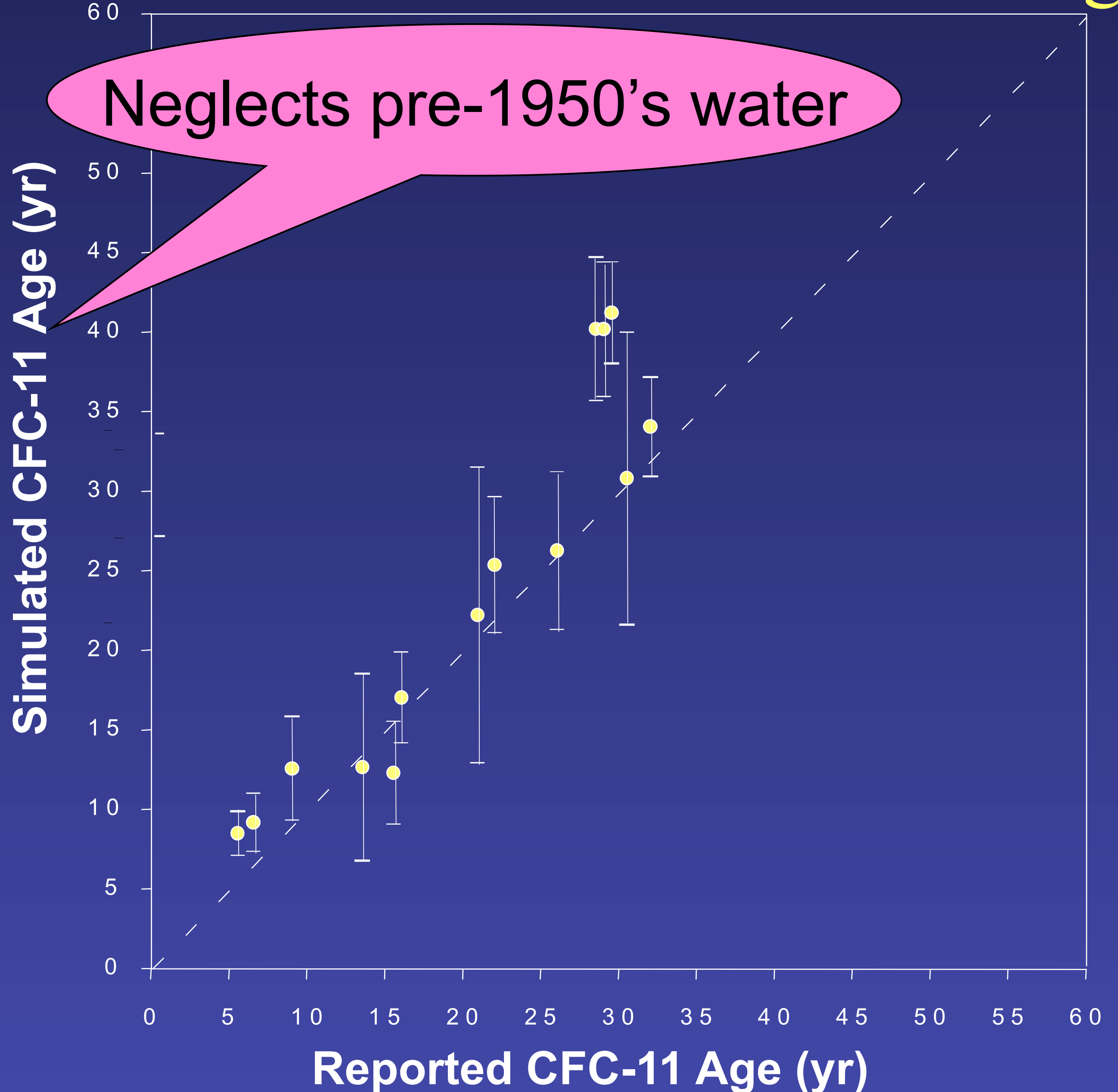
Kings River Alluvial Fan
Realization 5
Depositional Dip (m)
3000
6000
9000
12000
Vertical (m)
100
50
3000
6000
Depositional Stike (m)
gravel
sand
muddy sand
mud
paleosol

# Transect, Wells, Screened Intervals

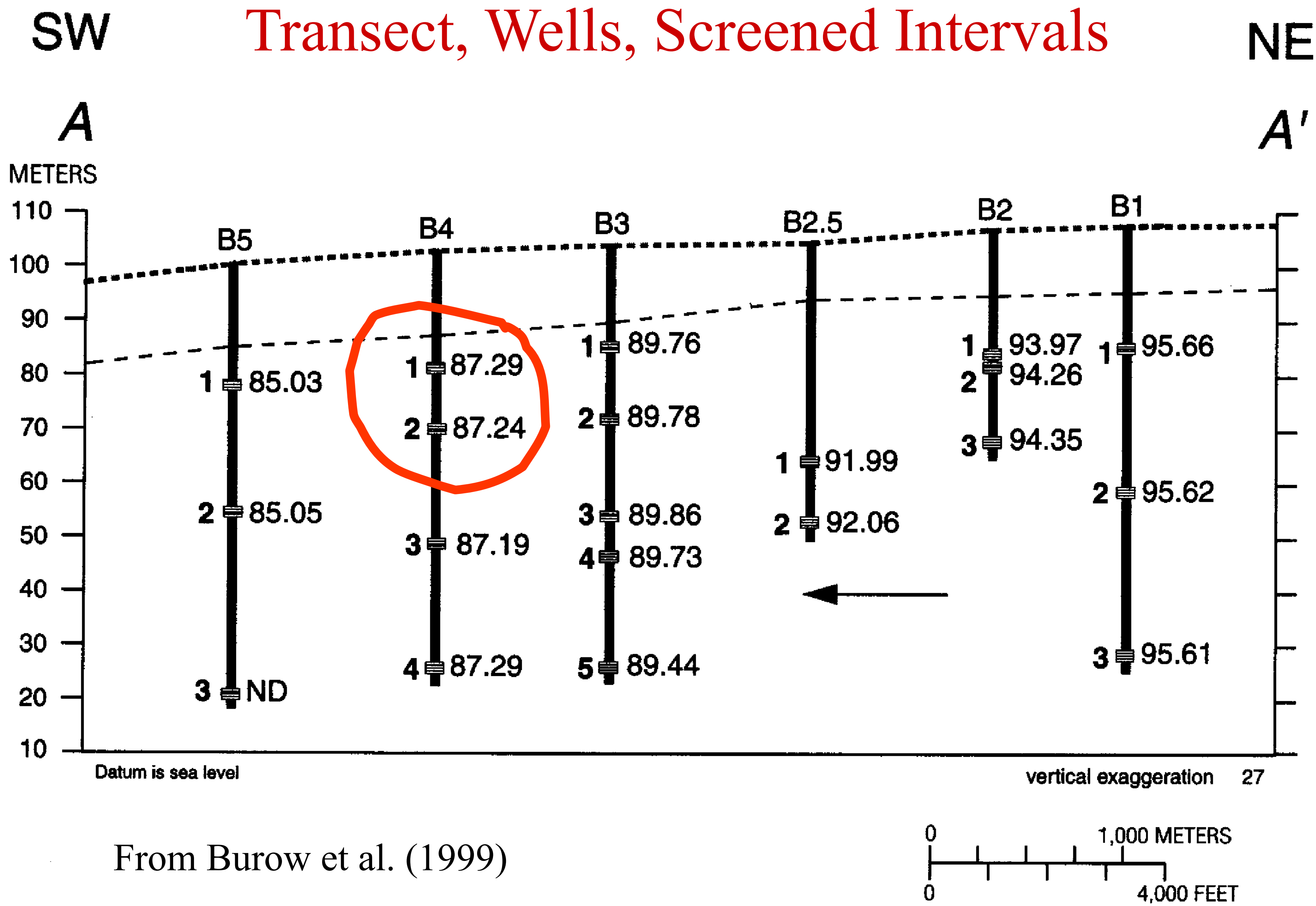



From Burow et al. (1999)

# Simulated and Measured CFC Age

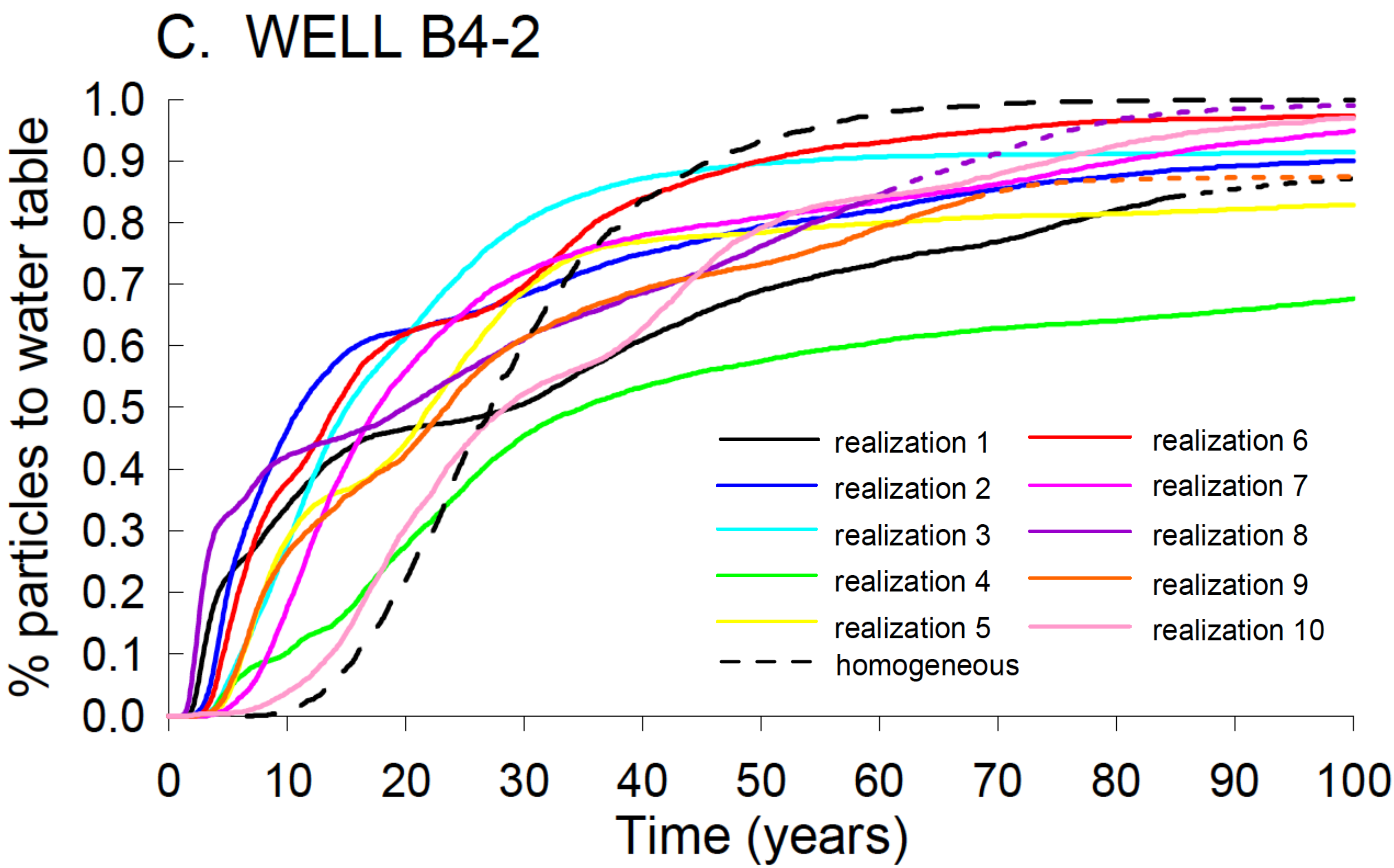


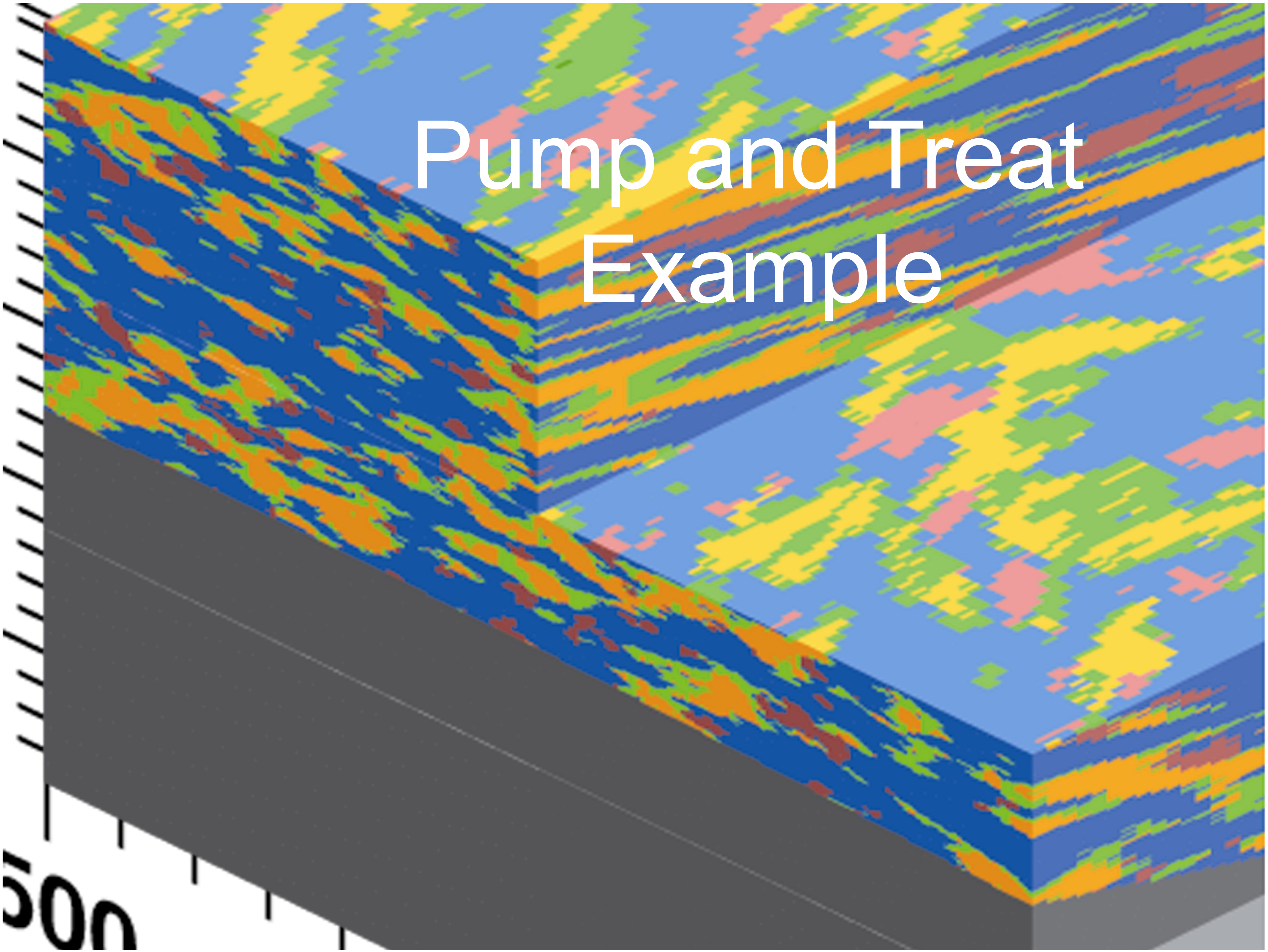
# Transect, Wells, Screened Intervals

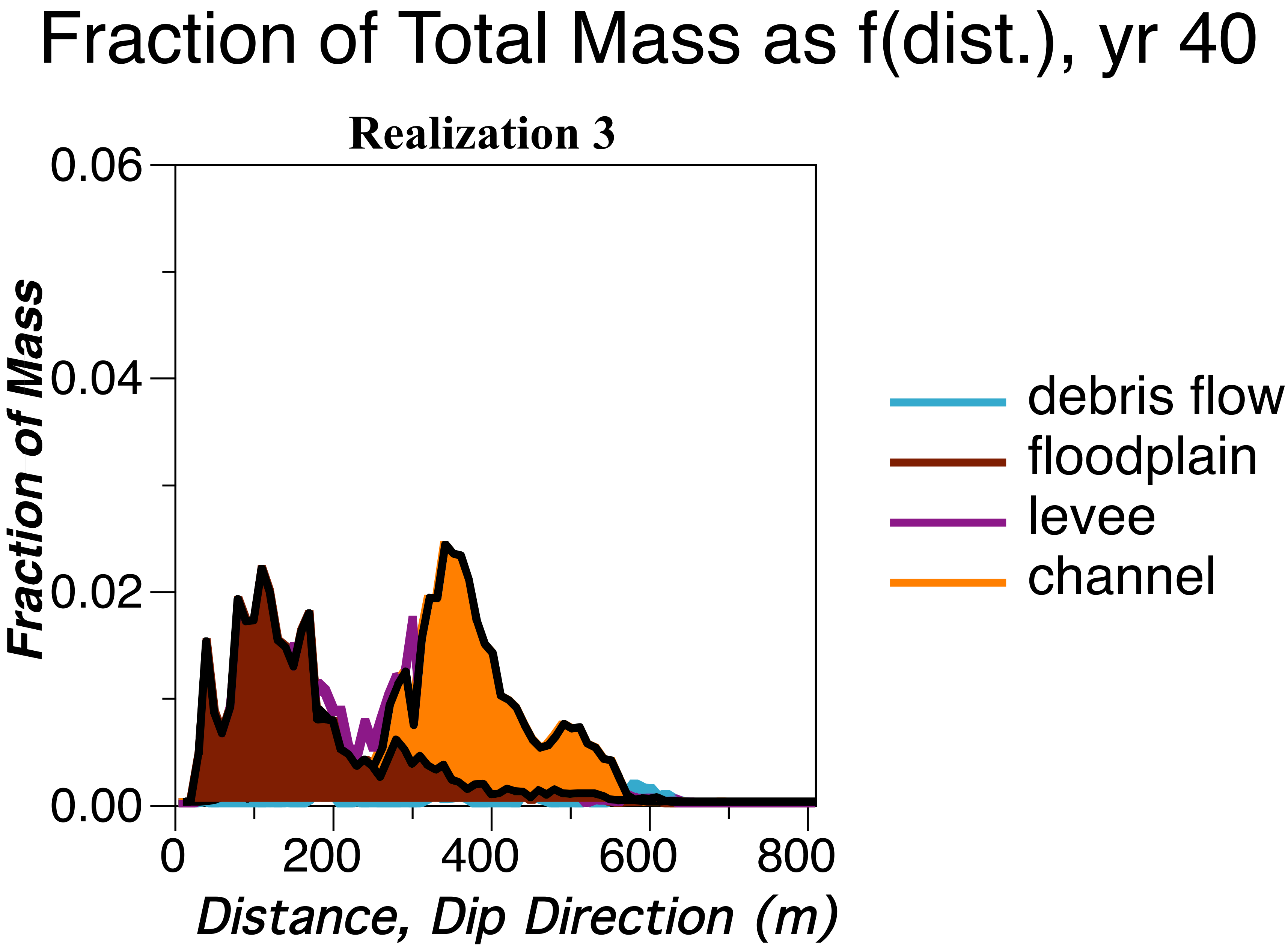



From Burow et al. (1999)

# Groundwater age distributions for well B4-2 (screen depth: 35.1 m)




Pump and Treat
Example

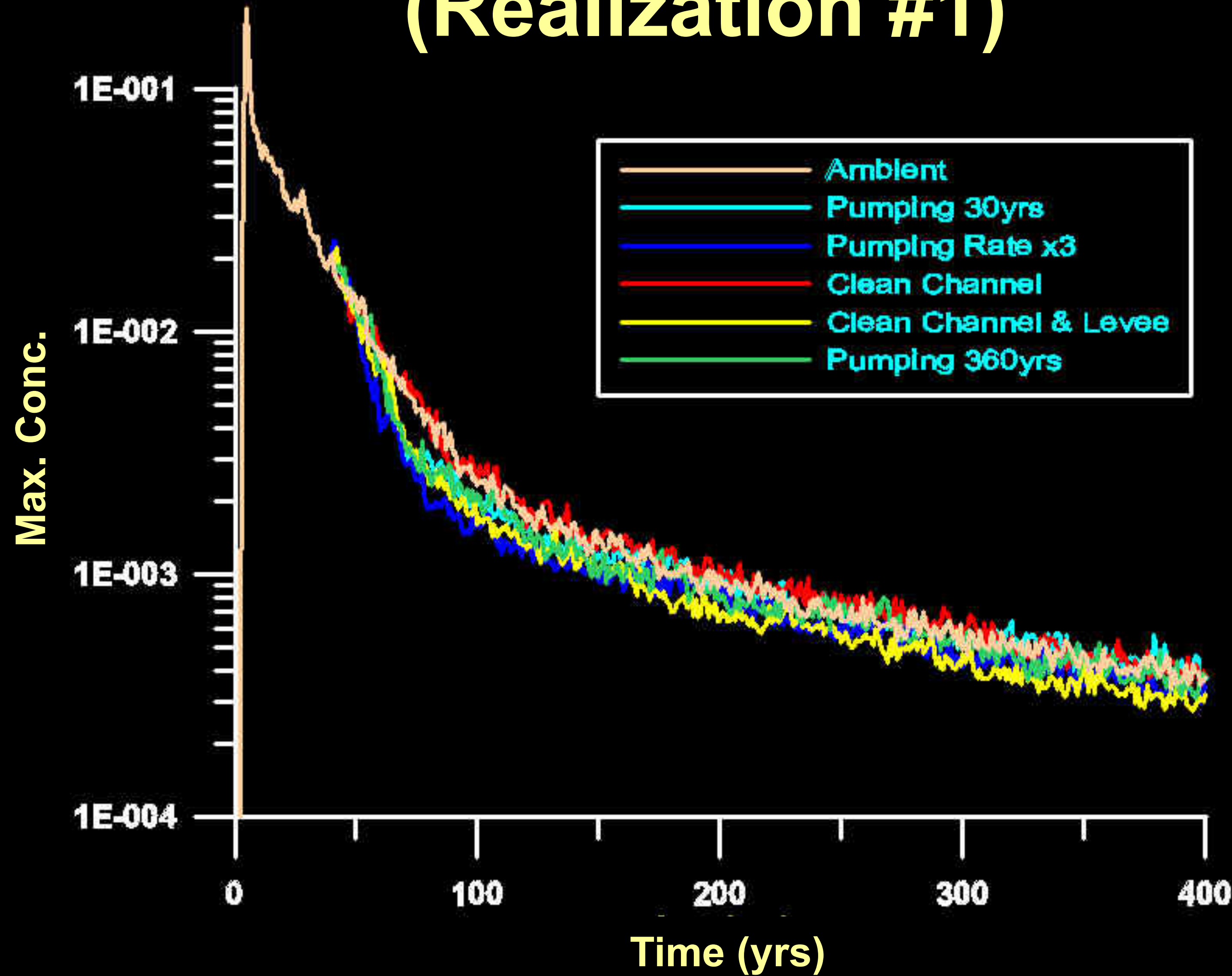


Fraction of Total Mass as f(dist.), yr 40
Realization 3
Fraction of Mass
0.06
0.04
0.02
0.00
0
200
400
600
800
Distance, Dip Direction (m)
debris flow
floodplain
levee
channel

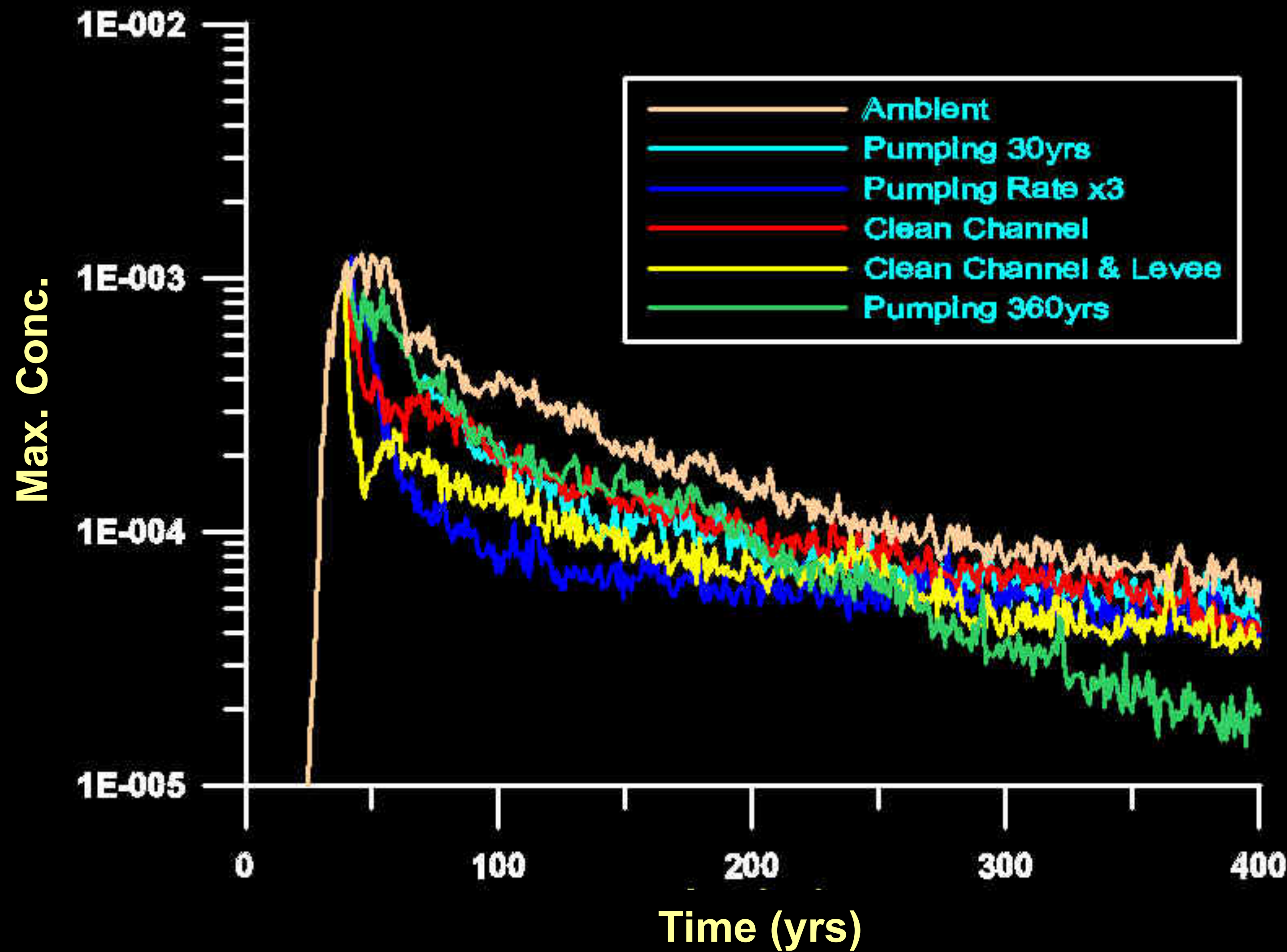
# Simulation Experiment: Pump-and-Treat (PAT)

- Simulate plume (TCE) development; 40 yr; 10 realizations.
- Simulate plume recovery via pumping well; yrs 41-70.
- $\alpha_T$ = 0.01 m (10 x 20 x 0.5 m grid blocks)
- $\alpha_L$ irrelevant.

# 50m Downgradient (Realization #1)



# 400m Downgradient (Realization #1)



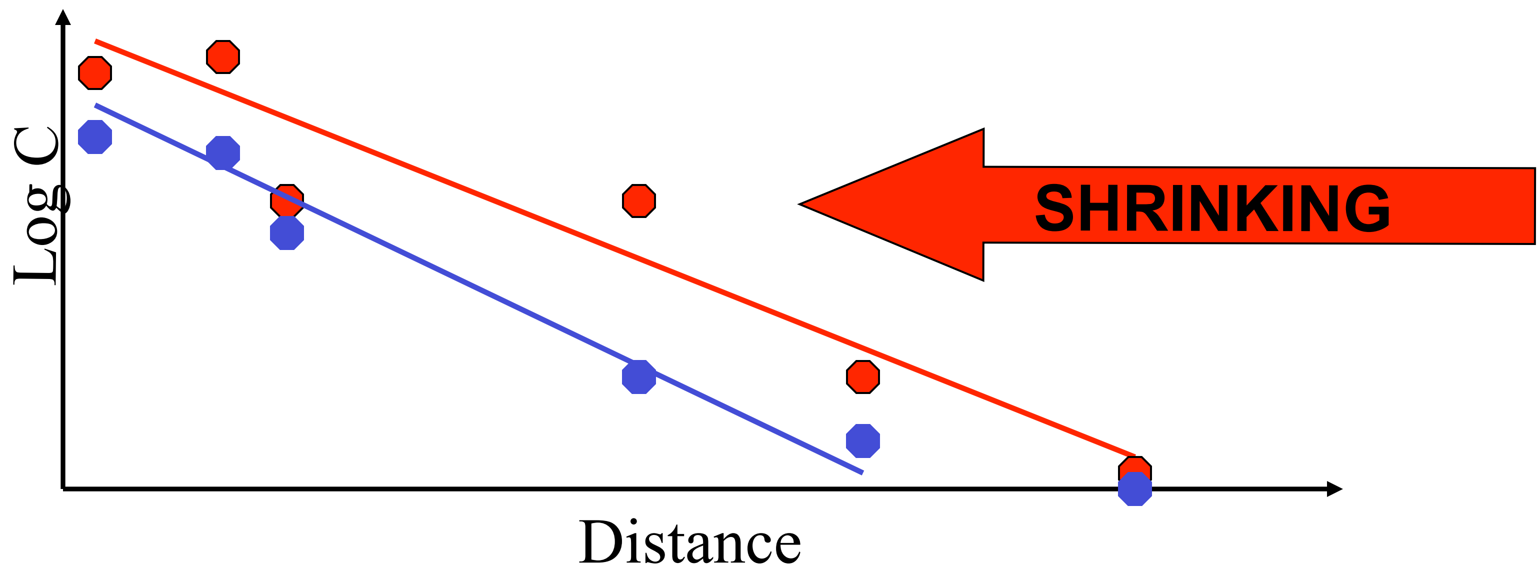
# Monitored Natural Attenuation (MNA)

- High-resolution transport experiments test the role of heterogeneity in MNA:
  - How can heterogeneity confound plume monitoring results?
  - Are conventional (proposed) monitoring schemes adequate?
  - How do we assess the uncertainty in apparent NA?

# Monitored Natural Attenuation: First-Order Rate Constants

US EPA November, 2002

- **Concentration vs. Distance**
  - Is plume “expanding, showing relatively little change, or **shrinking**?”

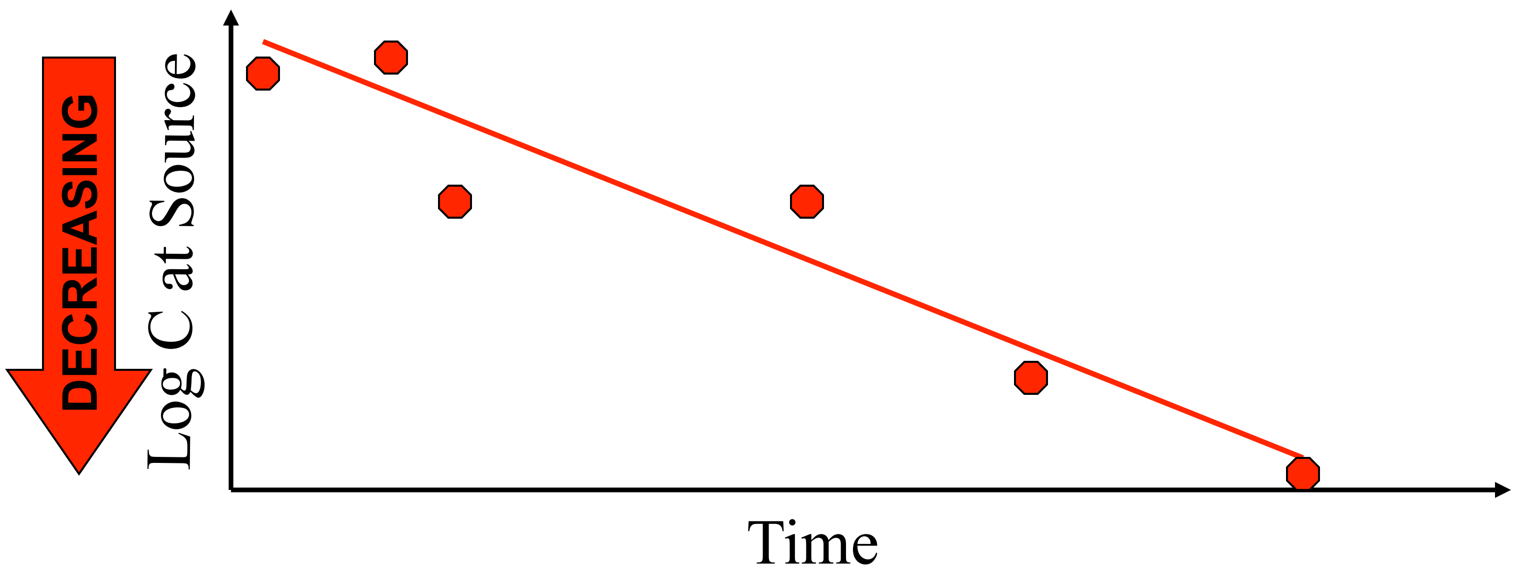



Graham E. Fogg, 2010

# Monitored Natural Attenuation: First-Order Rate Constants

US EPA November, 2002

- **Concentration vs. Time**
  - "Lifecycle of the plume is controlled by the rate" at the source location of a **shrinking** plume.

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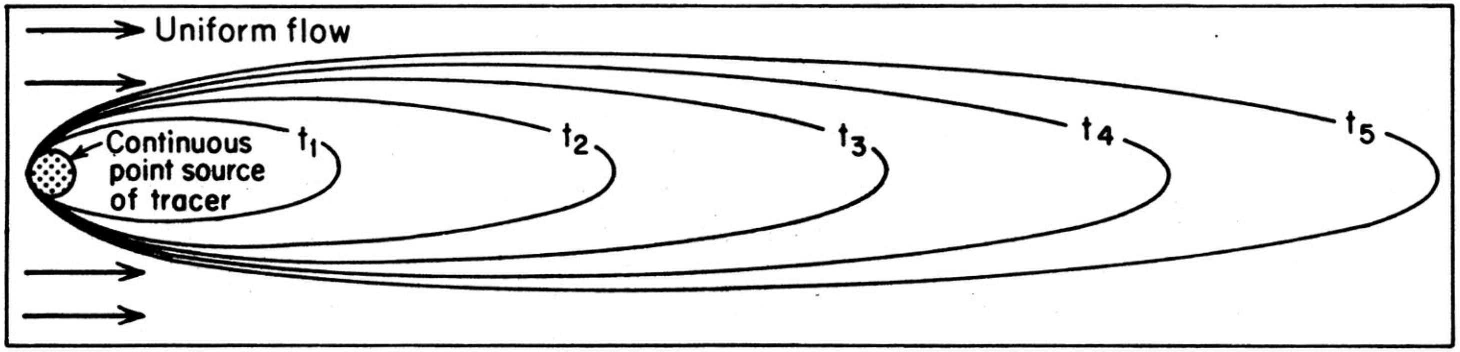
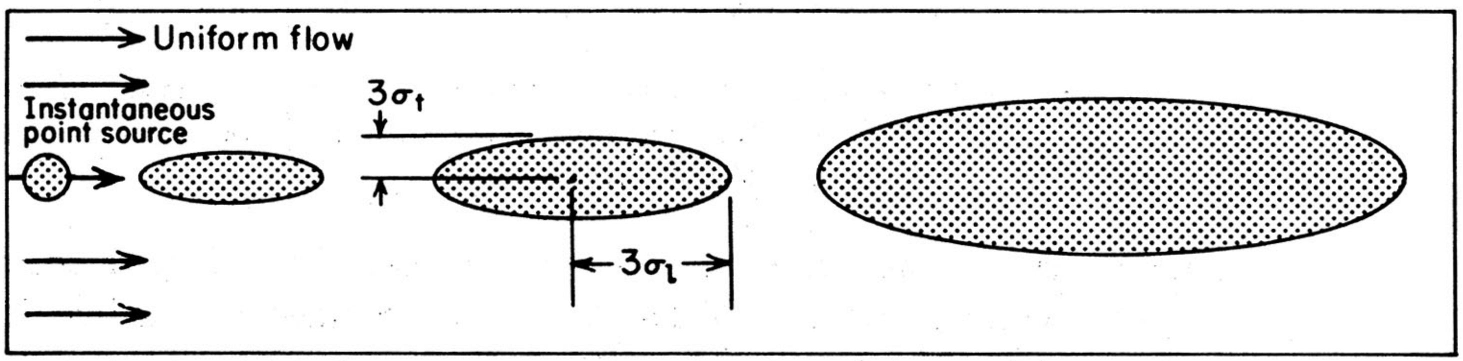
# Generic Plumes




(a)




(b)

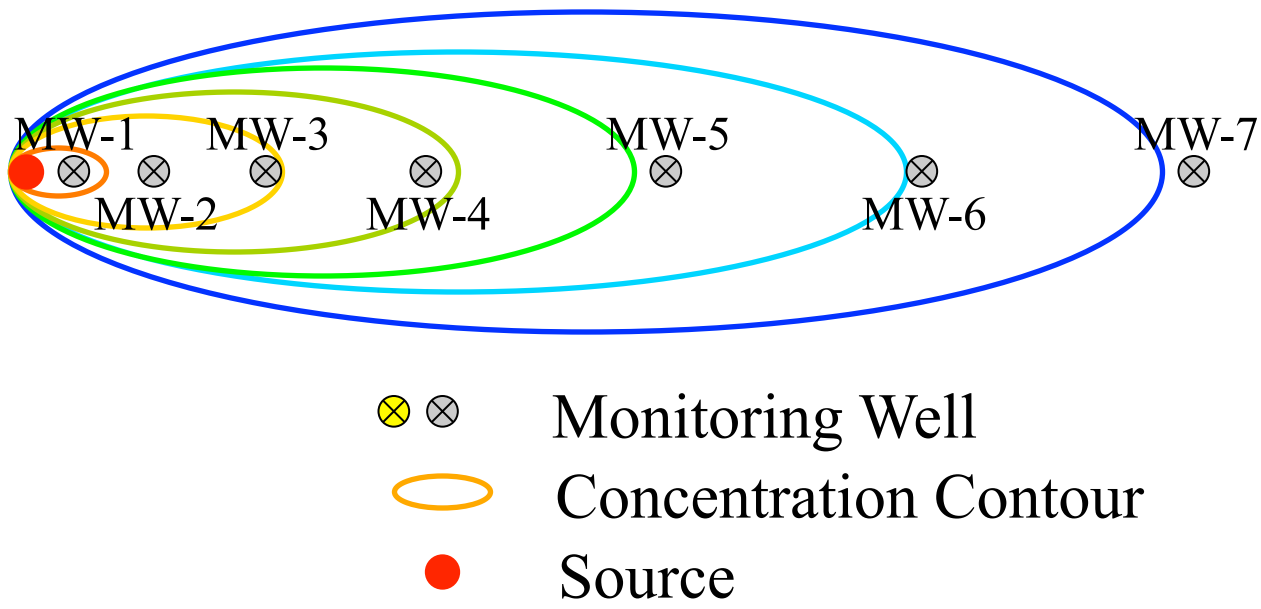
**Figure 9.5** Spreading of a tracer in a two-dimensional uniform flow field in an isotropic sand. (a) Continuous tracer feed with step-function initial condition; (b) instantaneous point source.

From Freeze and Cherry (1979)

Graham E. Fogg, 2010

# Groundwater Monitoring
# Well Network Along Primary Flow Path

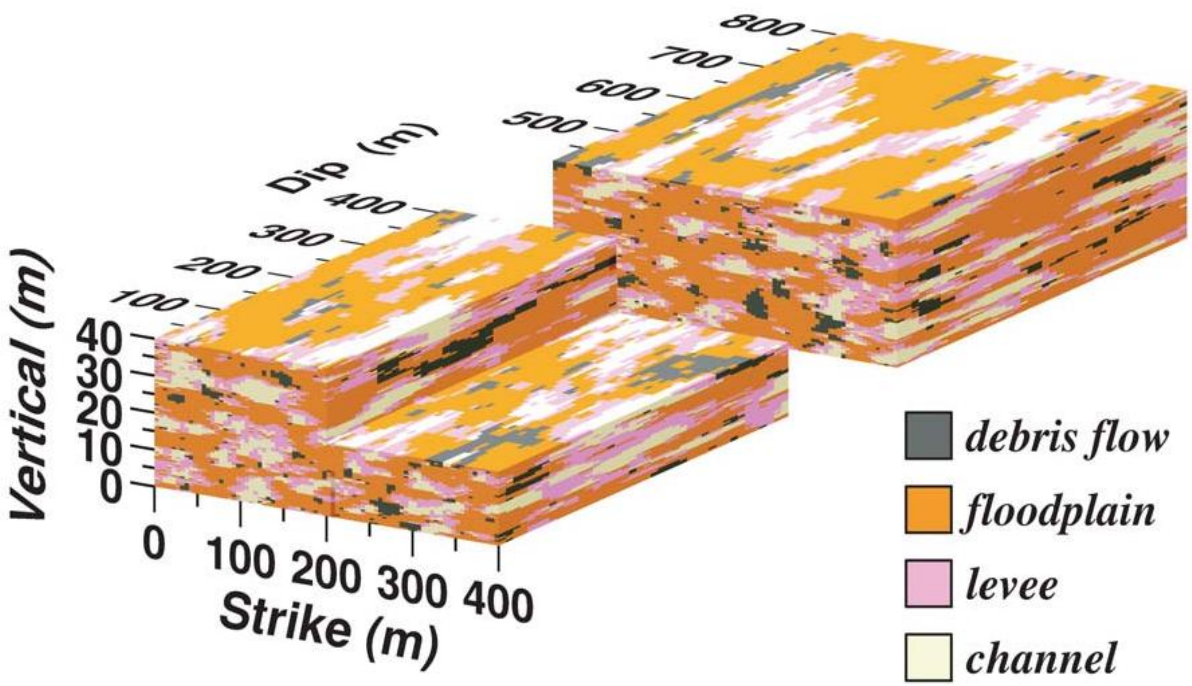
after *McAllister and Chiang* [1994]




† A practical approach to evaluating natural attenuation of contaminants in groundwater, *Ground Water Monitoring and Remediation*, 161- 173, Spring, 1994.

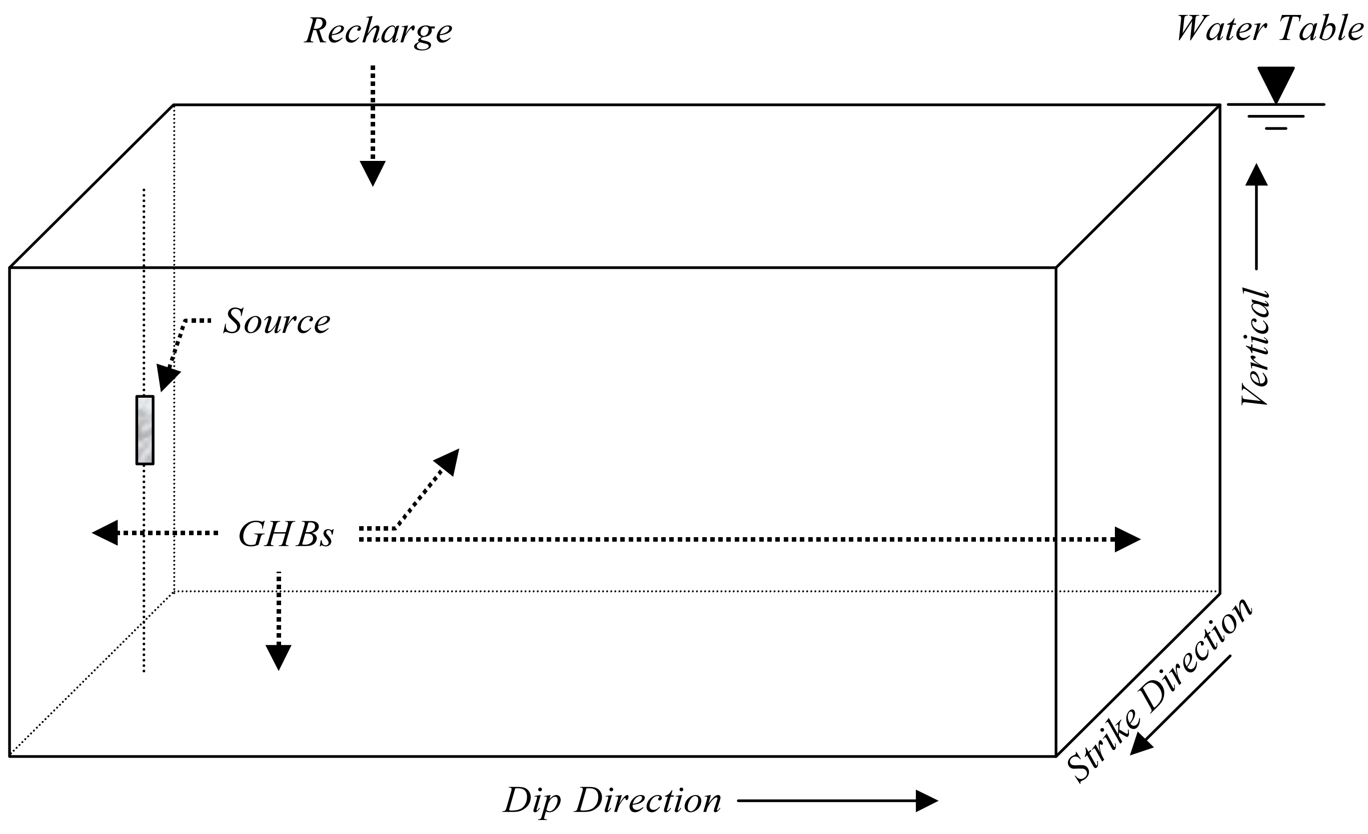
Graham E. Fogg, 2010

# LLNL System




Graham E. Fogg, 2010

# Flow System

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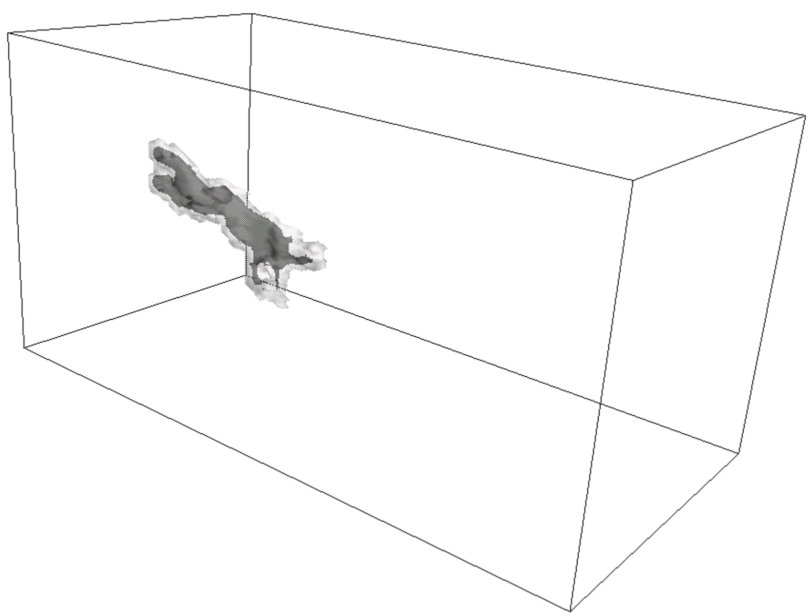
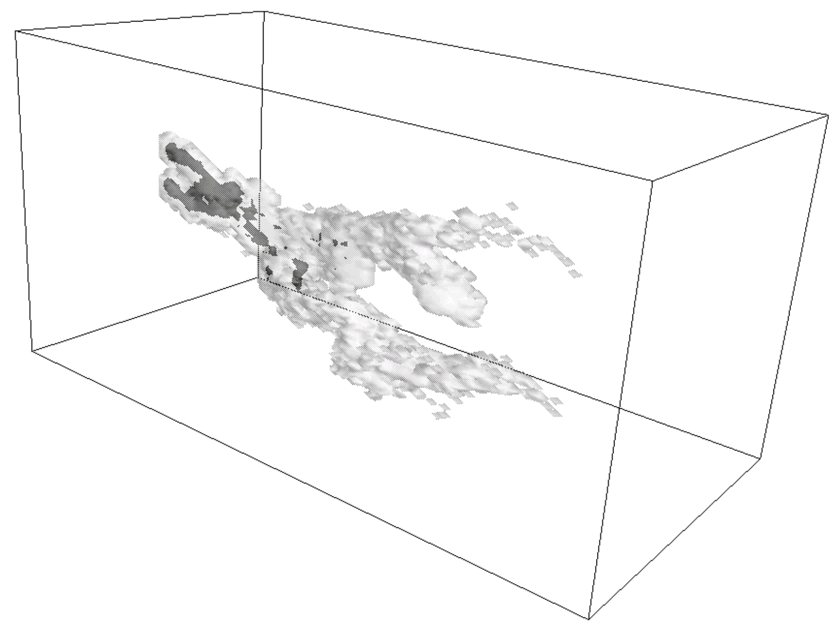
# Transport Results

20 Years



40 Years

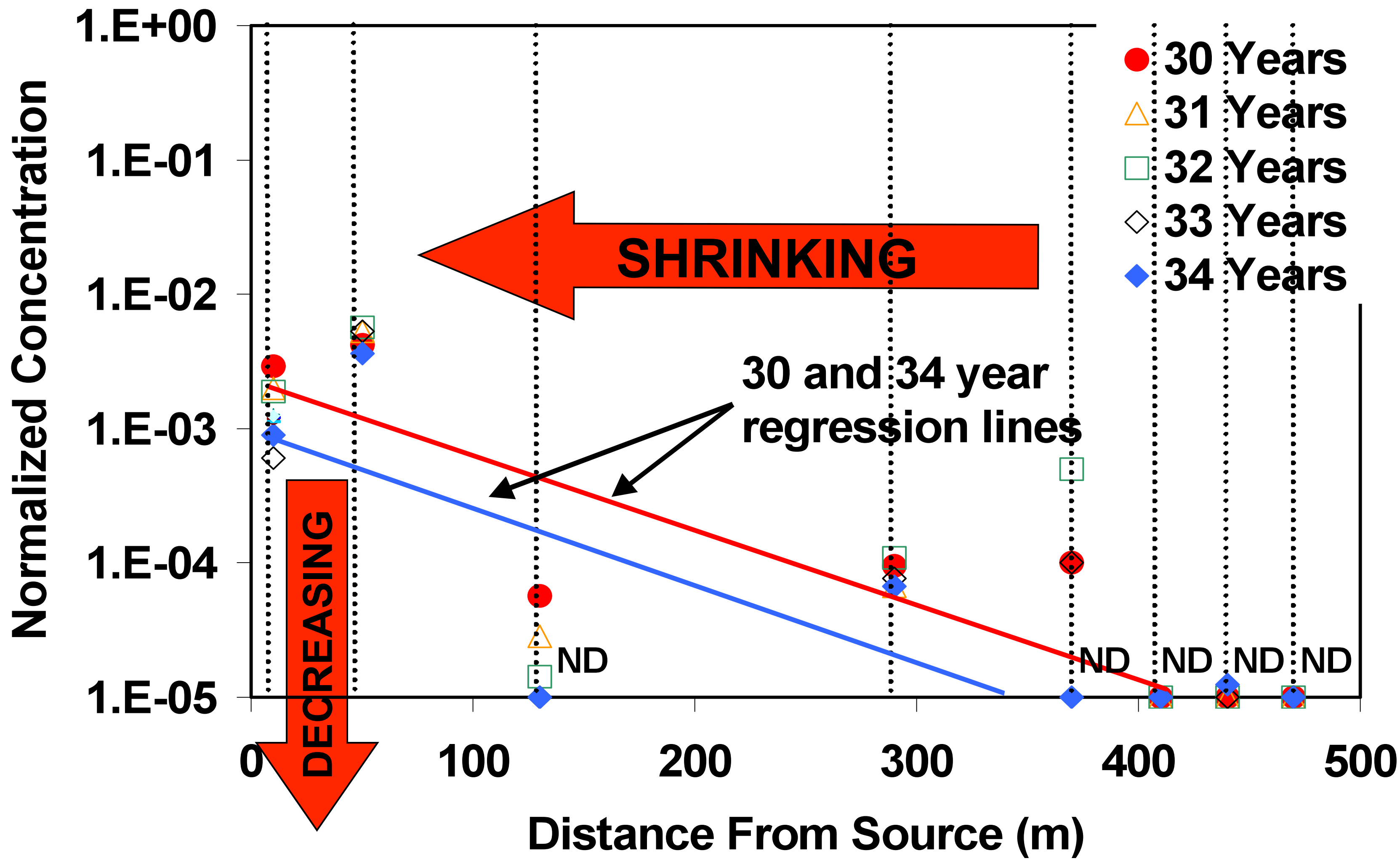


Graham E. Fogg, 2010

# Monitored Natural Attenuation

- Is the plume shrinking?
- Are source concentrations declining?

# Monitoring Results

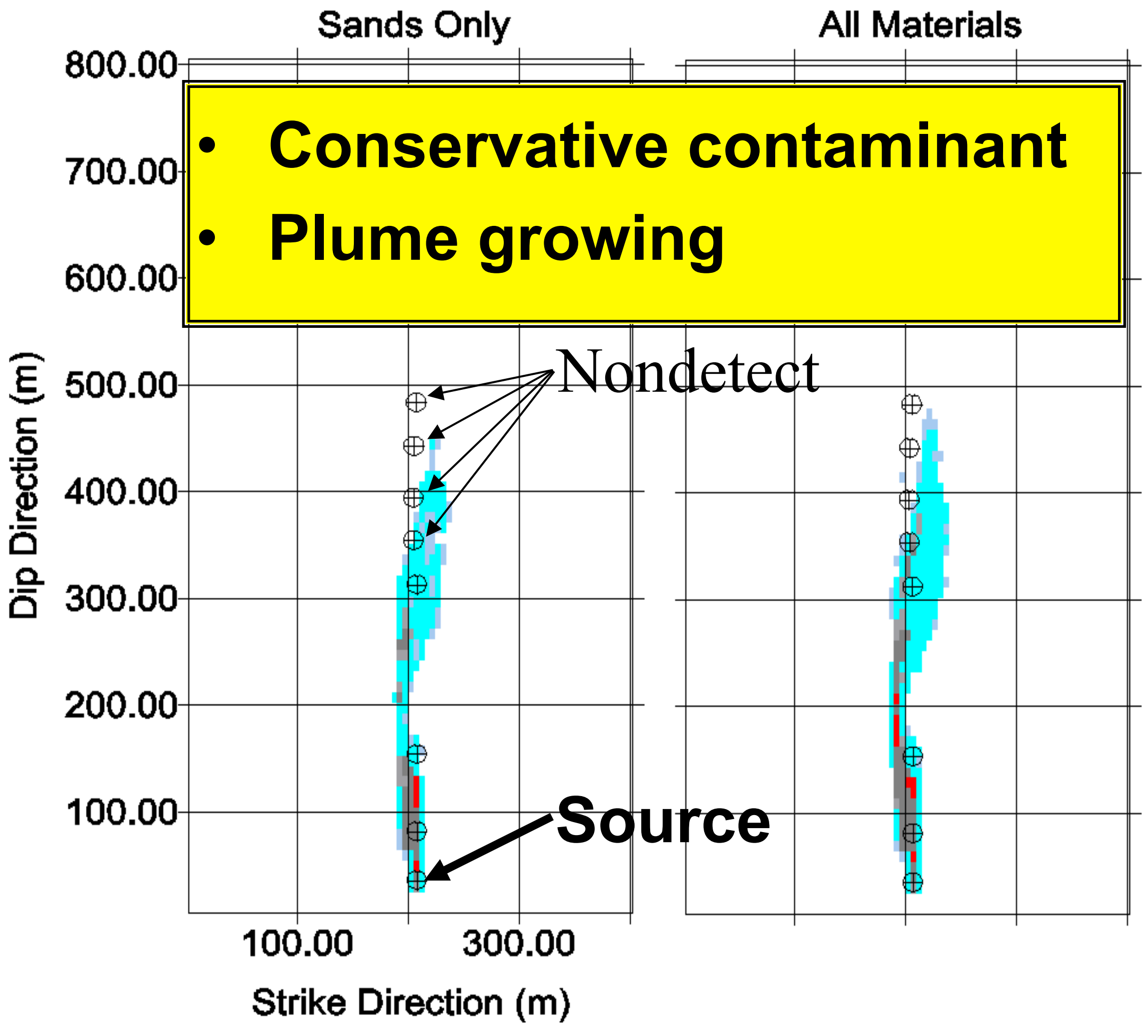



Graham E. Fogg, 2010

# “Observations”

- Plume is shrinking towards source.
- Source concentration is decreasing.
- Plume is naturally attenuating at an appreciable rate.

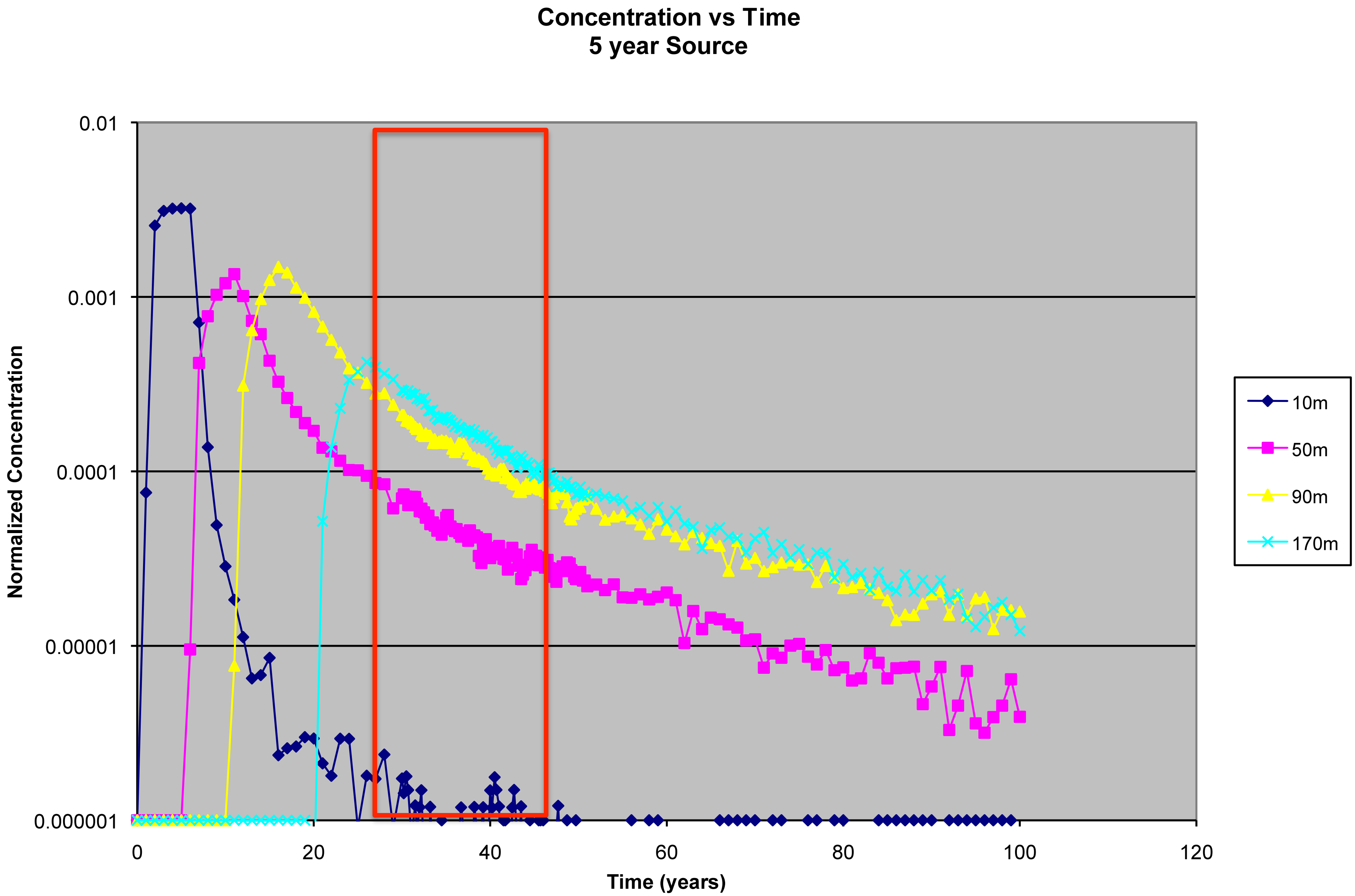
# Full Informed
# Year 30




- **Conservative contaminant**
- **Plume growing**

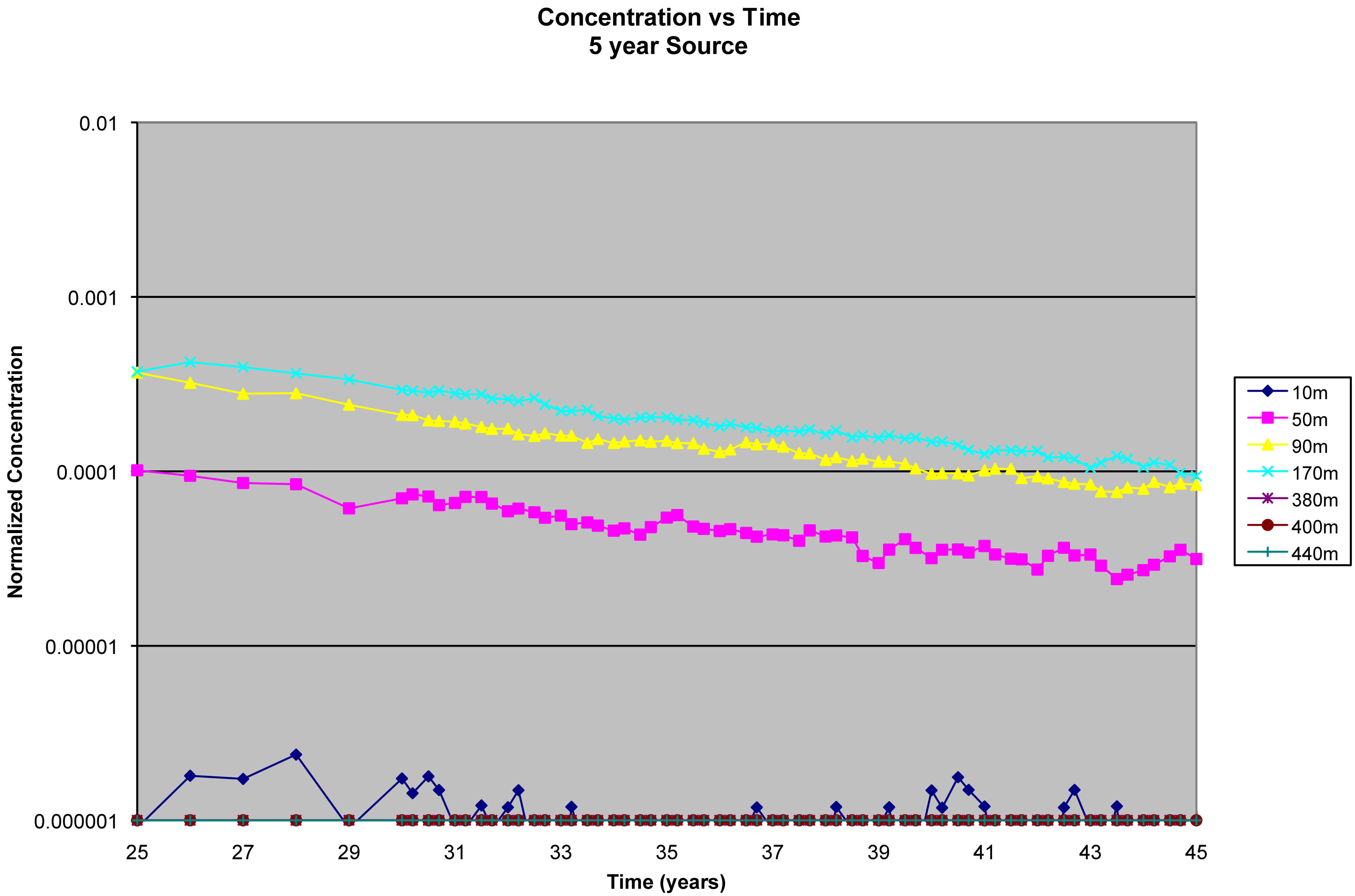
Graham E. Fogg, 2010

# Exhaustive Sampling: Total Mass in the Plane



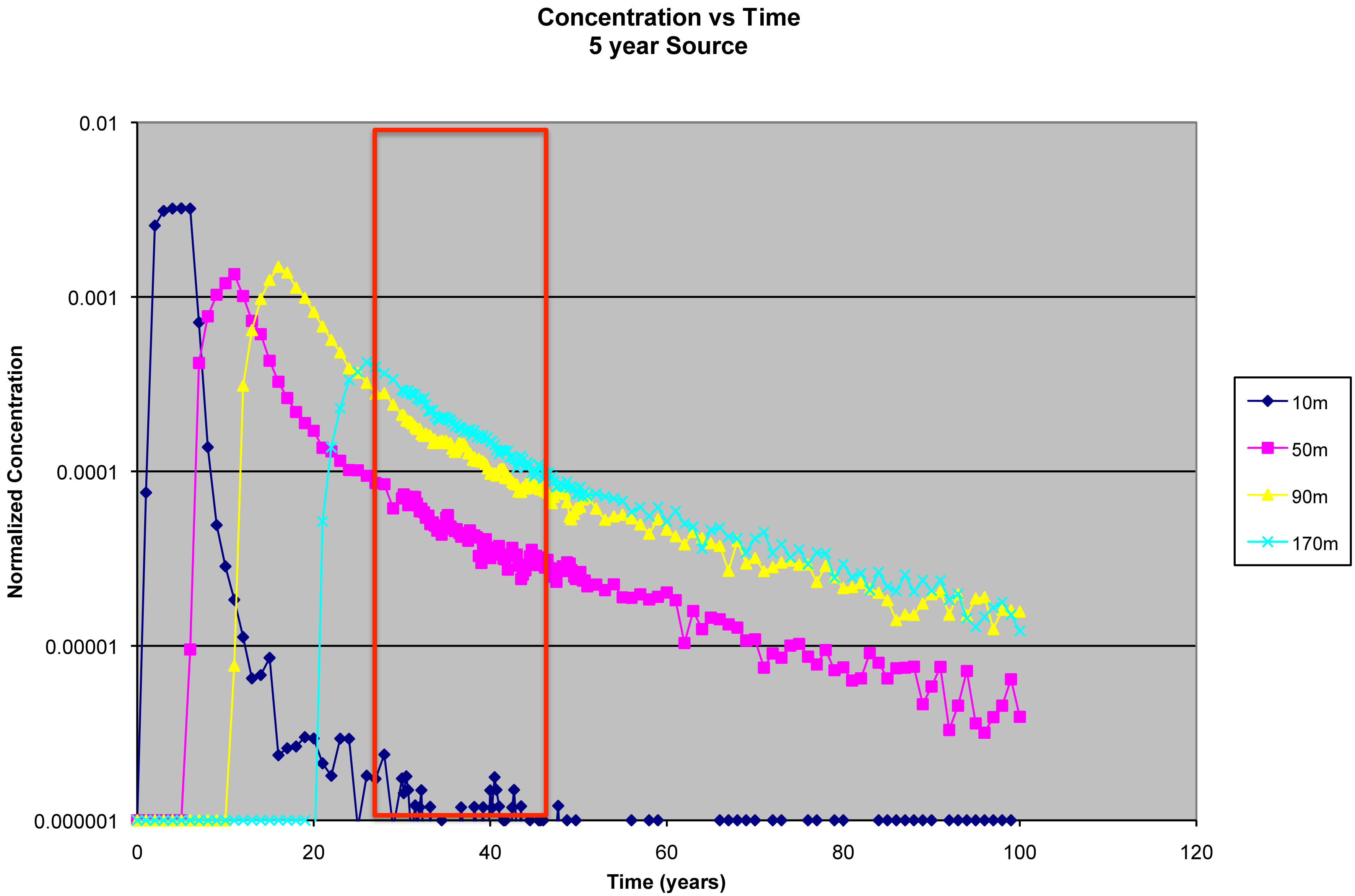

Graham E. Fogg, 2010

# Exhaustive Sampling: Total Mass in the Plane (25-45 yrs)



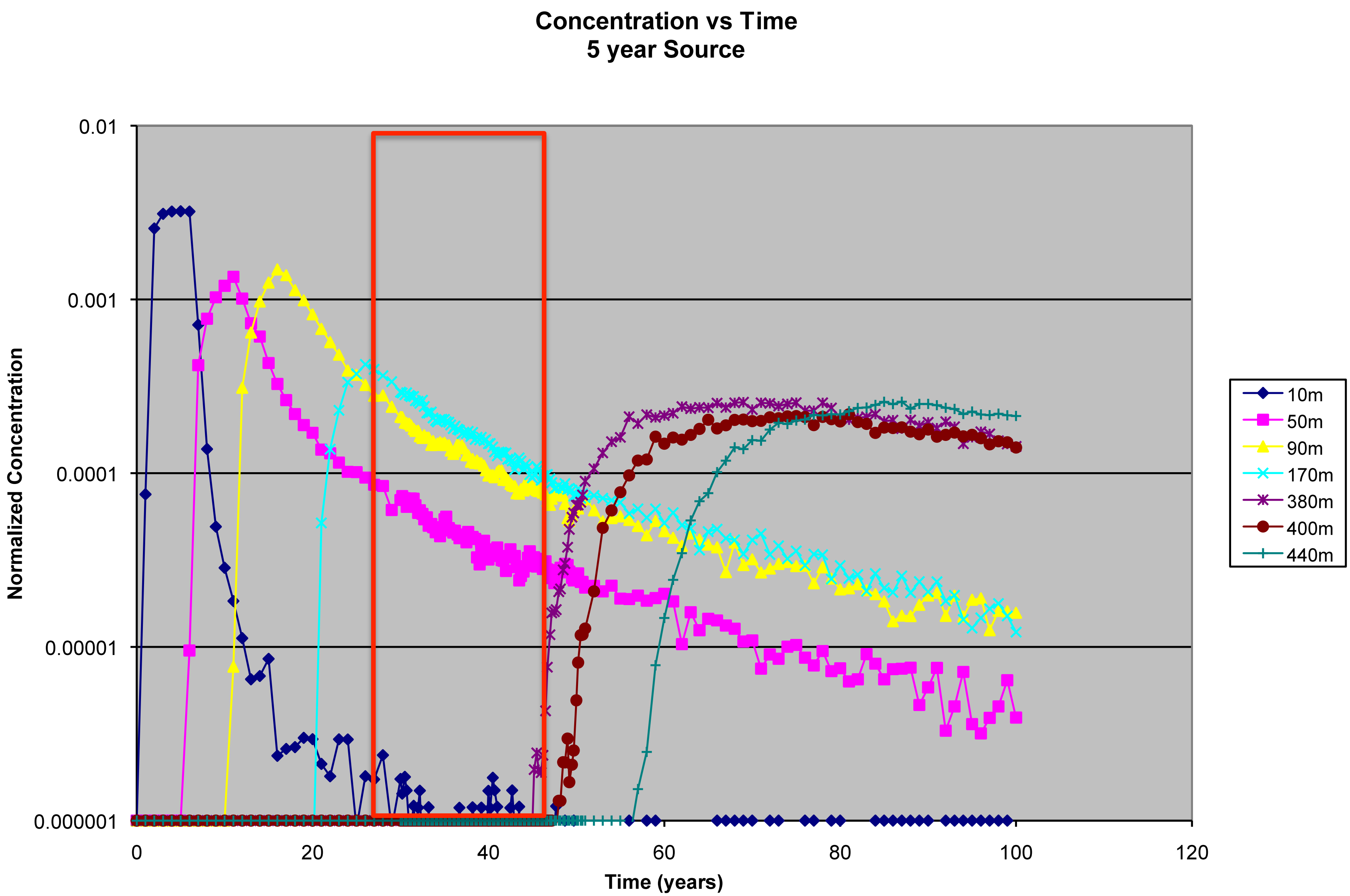

Graham E. Fogg, 2010

# Exhaustive Sampling: Total Mass in the Plane




Graham E. Fogg, 2010

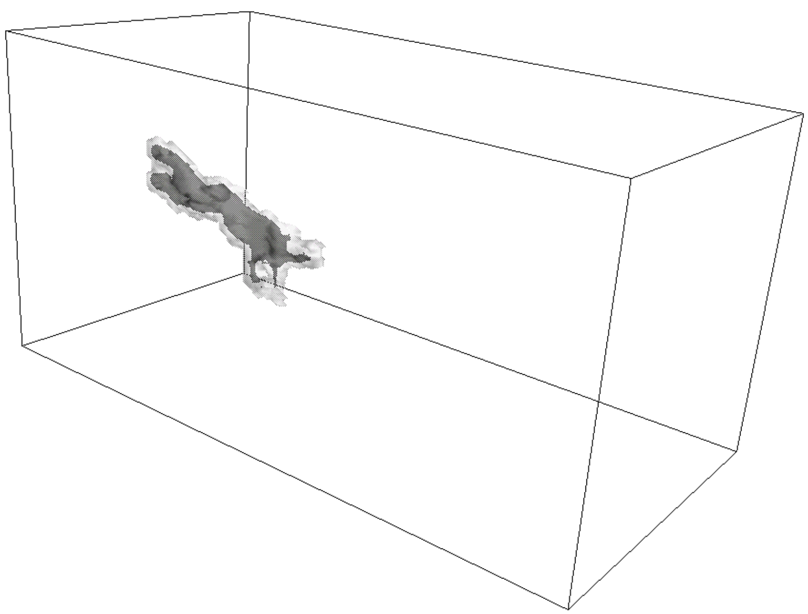
# Exhaustive Sampling: Total Mass in the Plane - The Rest of the Plume



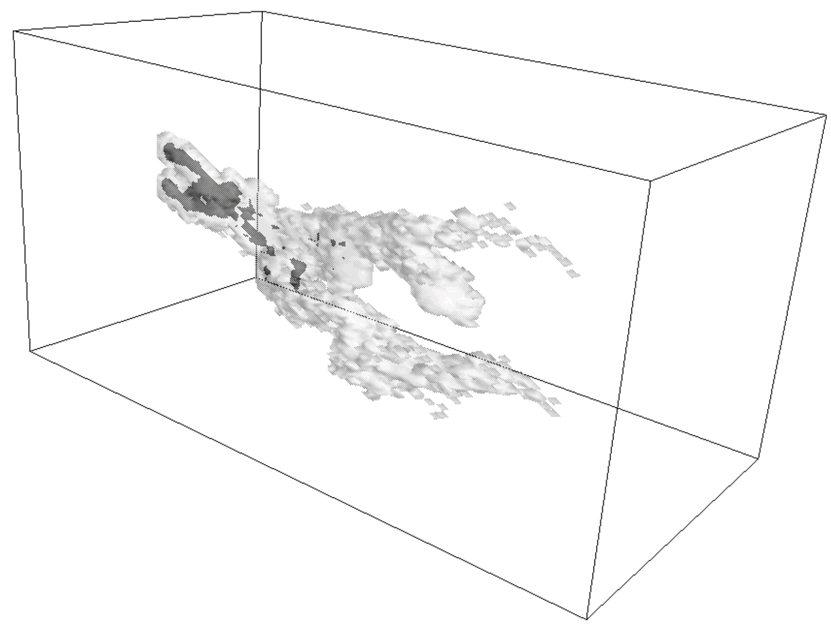

Graham E. Fogg, 2010

# Transport Results

20 Years



40 Years



Graham E. Fogg, 2010

# Conclusions: Monitoring for Natural Attenuation

- Heterogeneity can lead to unexpected plume behavior that can confound conventional monitoring schemes
- Apparent plume concentrations and/or plume lengths may deceptively appear stable or decreasing with time.
- Natural attenuation declared successful based on trends that can easily result from inadequate sample density or lack of an appropriate physical model.

Graham E. Fogg, 2010

# Summary

- Connected network paradigm, including substantial volumes of low-K media, is consistent with fairly wide range of geologic conditions, and hydrologic observations, including scale-dependent $\alpha$.
- Results in:
  - Early breakthrough
  - Difficult remediation
  - Widely varying groundwater ages within water samples
  - Monitoring challenges

# Disconnects:

- Remediation of groundwater contaminants is difficult and often impossible within project time scales (e.g., 5-10 yr).
- Typical models of groundwater contaminant transport often match plume extents but are abysmally optimistic at predicting cleanup times.
- Typical groundwater models are based on relatively homogeneous conceptualizations, including ln K variances < 1-2.
- Typical subsurface systems are sufficiently heterogeneous to have ln K variances >5-15.