The Role of Aquitards in Groundwater Flow Systems

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June 21, 2012

Acknowledgements

Beth Parker, main collaborator since 1991

Bob Gillham and **Garth Vander Kamp**, during the 1970s and 1980s

Bob Ingleton, field technician since 1980

Barbara Lund, initiated first aquitard project, 1967

Atomic Energy Canada

Numerous other colleagues and grad students

Major funding sources:

- Natural Sciences and Engineering Research Council of Canada
- Many industrial site owners/sponsors

Origin of Terms - Latin

Aquifer: aqua = water, fer = to bear

Aquitard: tard from tardus = to slow

Aquiclude: clude from claudere = to shut

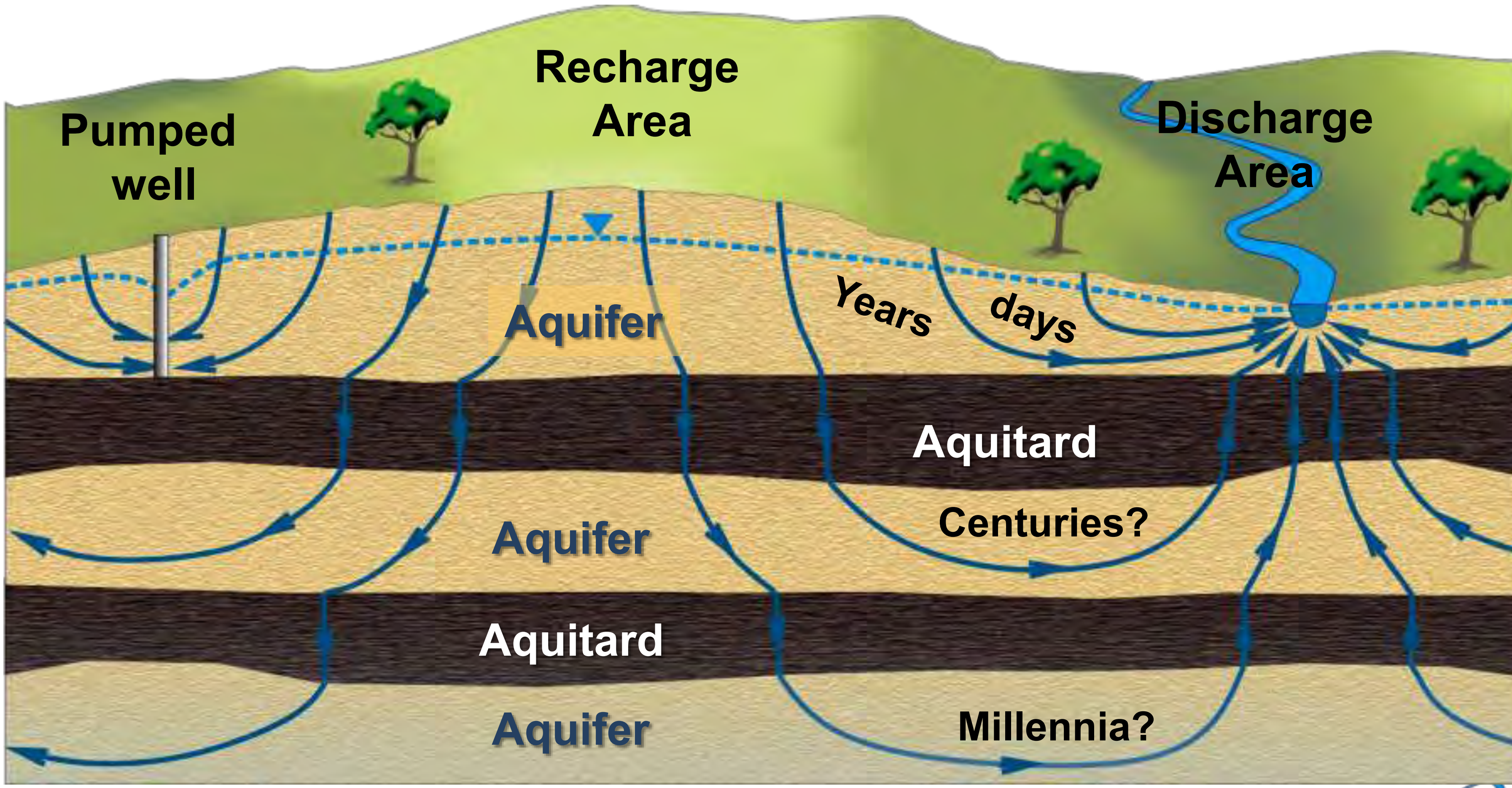
Aquifuge: fuge = expel or drive away

Source: Todd, 1988

AQUITARD:

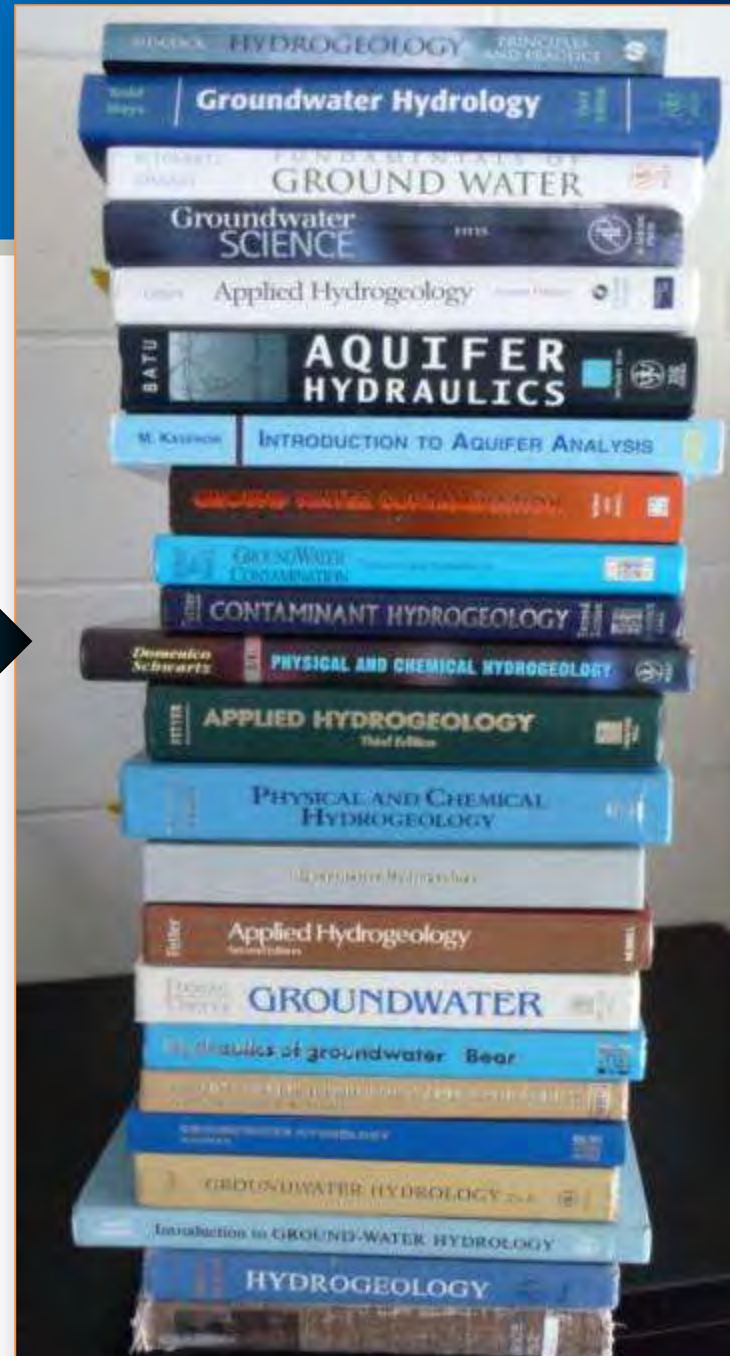
Used since late 1960's and now a common term in hydrogeology, except in the U.S. where 'confining bed' is preferred.

Groundwater flow lines and groundwater age in an aquifer-aquitard system



Groundwater Text Books Focus on Aquifers

Contain almost nothing about aquitards



Geotechnical Text Books

Emphasis on aquitards

with focus on:

- consolidation
- Strength
- permeability

$K_v = 10^{-8} - 10^{-10}$ cm/s

Typical range of non indurated clayey aquitards

Geotechnical Tests to Determine K

- Consolidometer, oedometer and triaxial cell tests on cores

$K_v = 10^{-8} - 10^{-10}$ cm/s

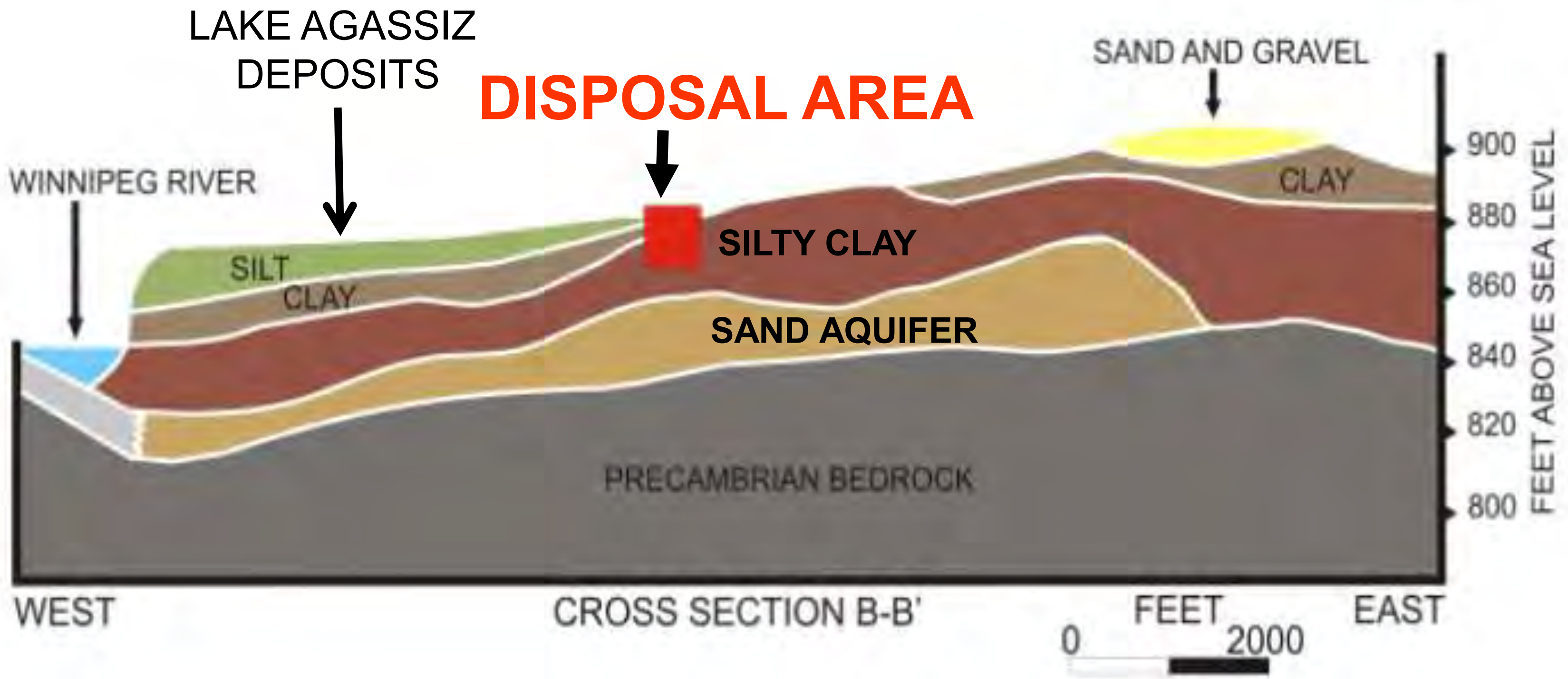
Typical range of non indurated clayey aquitards

My Aquitard Adventure Begins 1967

Whiteshell Nuclear Research Establishment Radioactive Waste Disposal Area

Waste Disposal in Clayey Aquitard

Wastes deposited 1963-1999



Calculated Groundwater Velocity in Typical Unfractured, Non-Indurated Clayey Aquitard and is extremely small

$$\bar{v} = \frac{Darcy\ Flux}{Bulk\ Effective\ Porosity}$$

Using K = 10^{-8} to 10^{-9} cm/sec and
typical values for gradient and porosity

$$\bar{v} = \frac{K}{\phi}\frac{\Delta h}{\Delta L} = \textit{Millimeters per year}$$

$$= \textit{Meters per Millennia}$$

Rad-Waste in Weathered Fractured Zone

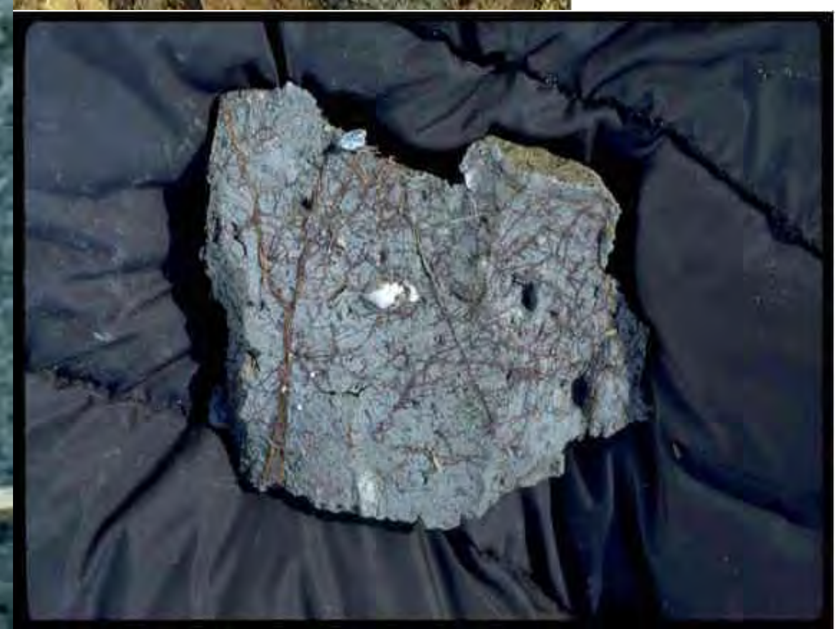
High water table in spring 1968

Unanticipated

Low water table in the summer

Test Pit Beside Disposal Area

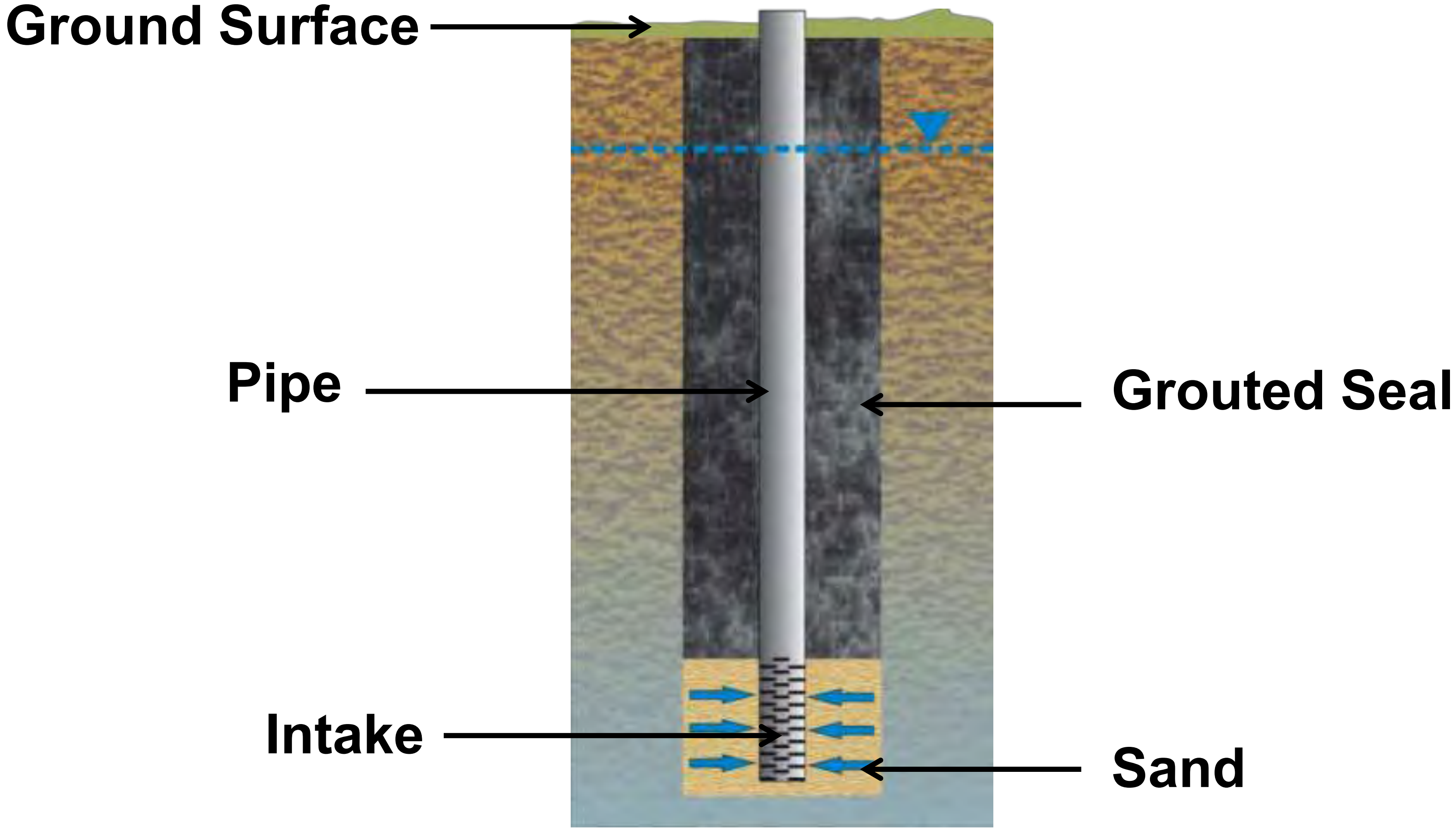
Root Imprints on Fracture Surface



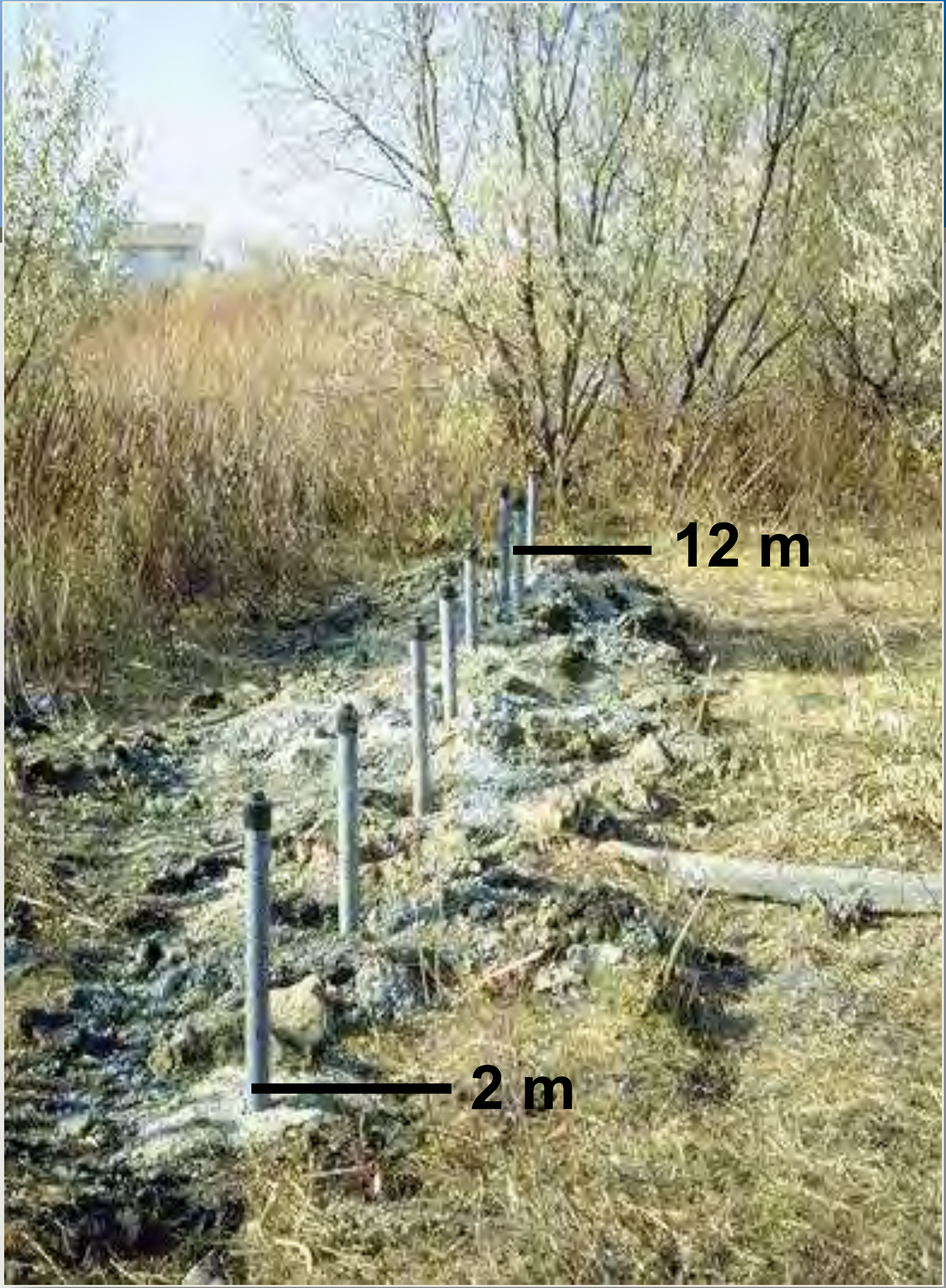
Natural Fractures

Contraction Fractures on a Modern Mud Plain

Simple Piezometer



Piezometer Cluster In Aquitard

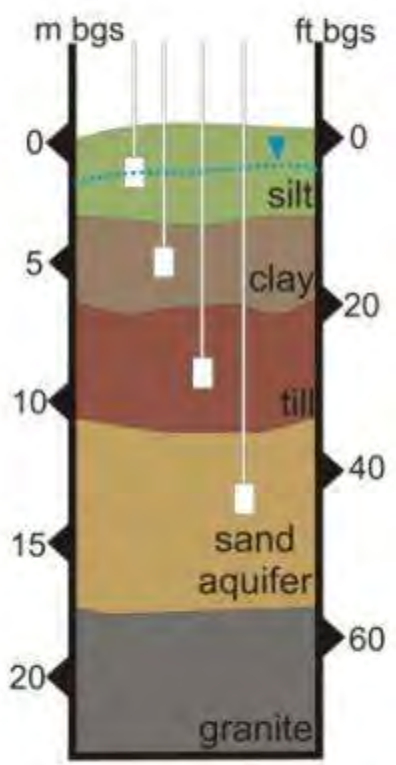


Aquitard studies require profiles of:

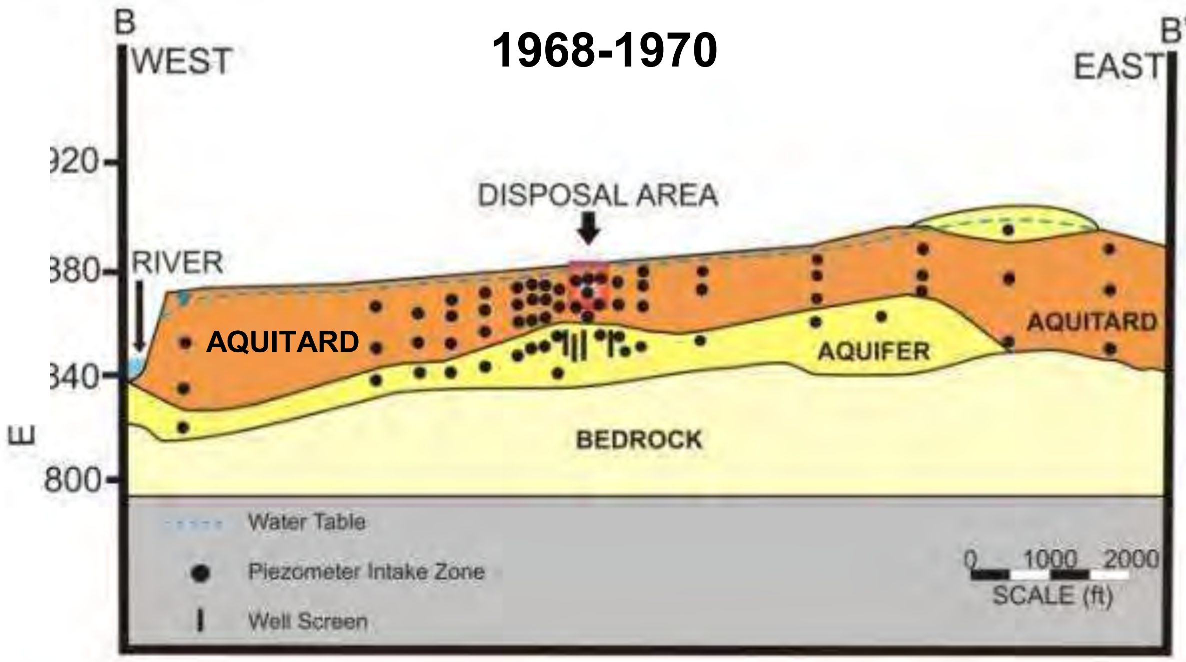
- Hydraulic head
- Water isotopes
- Water chemistry

Piezometers to Understand Flow System

Schematic of Piezometer Cluster

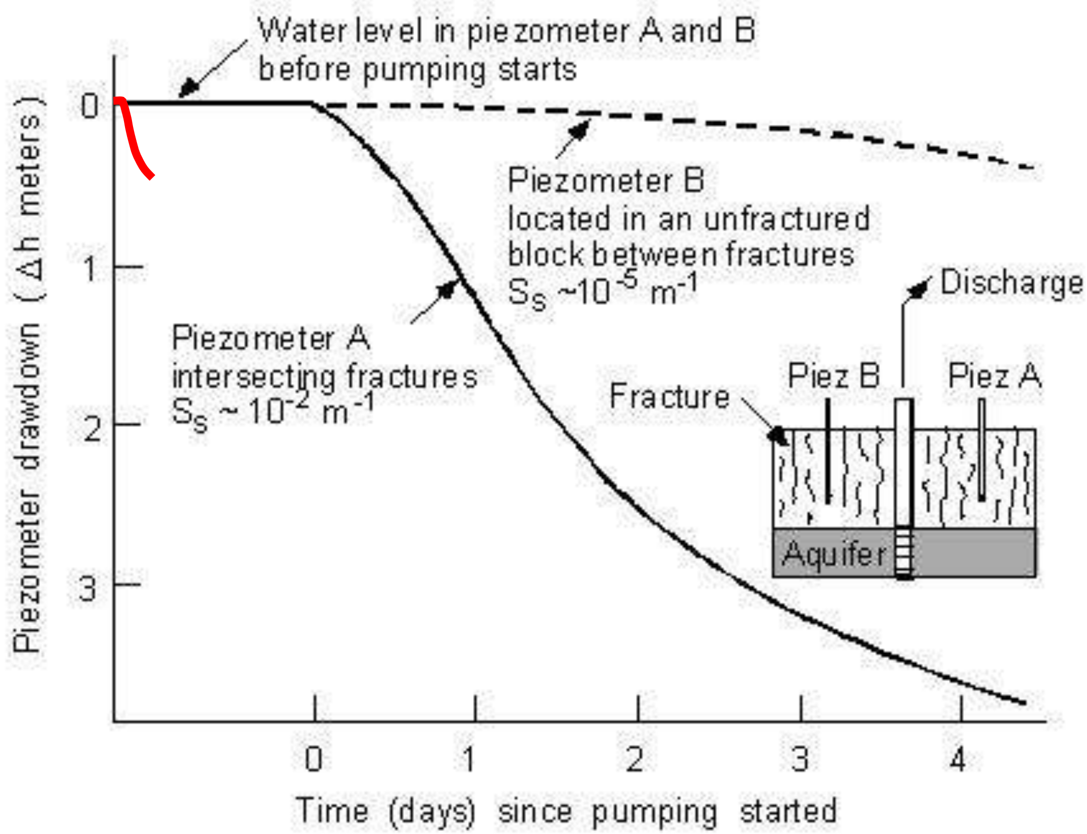


Network of Conventional Piezometers



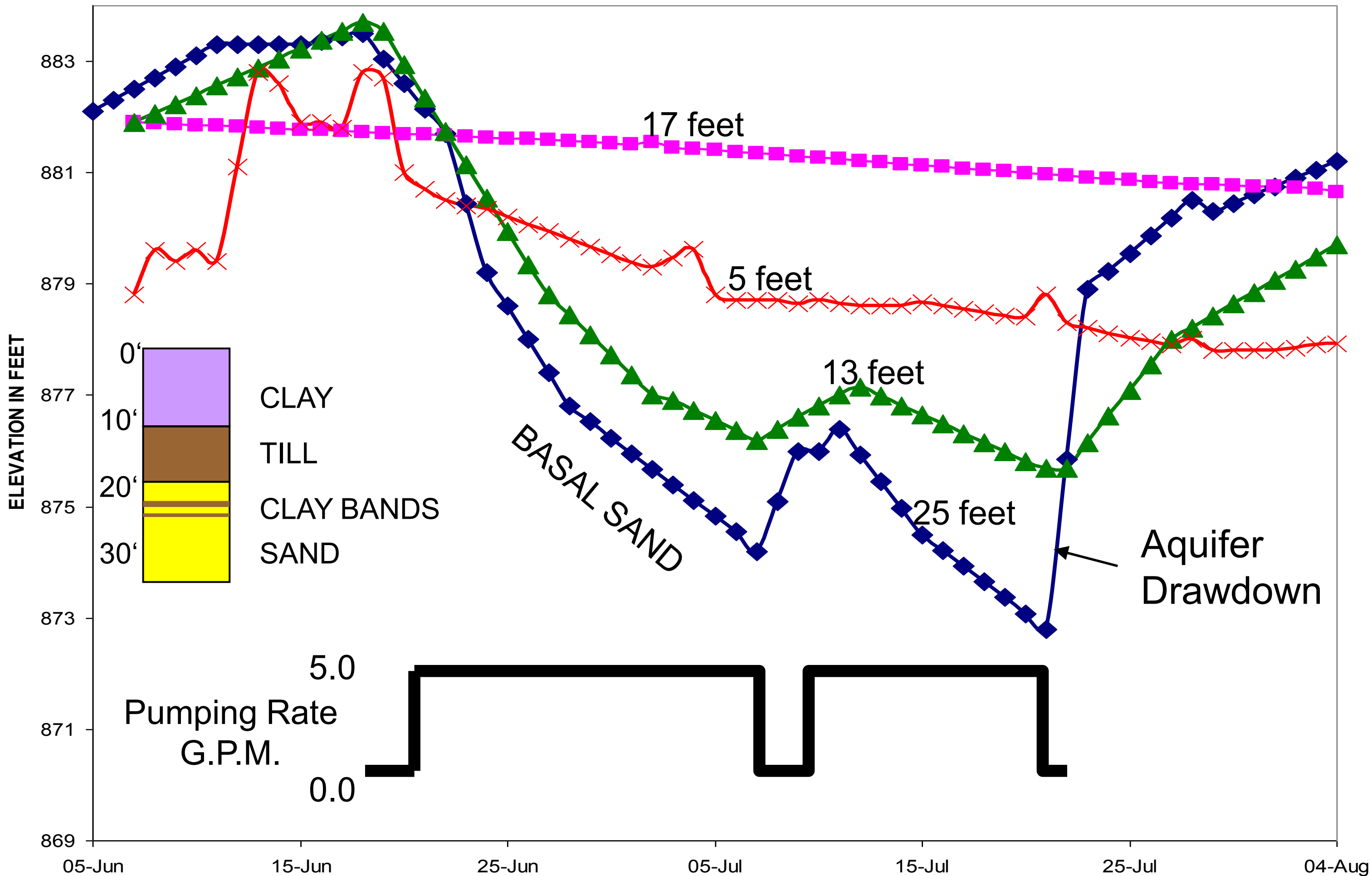
Pumping Test Schematic

Pump Aquifer and Monitor Aquitard

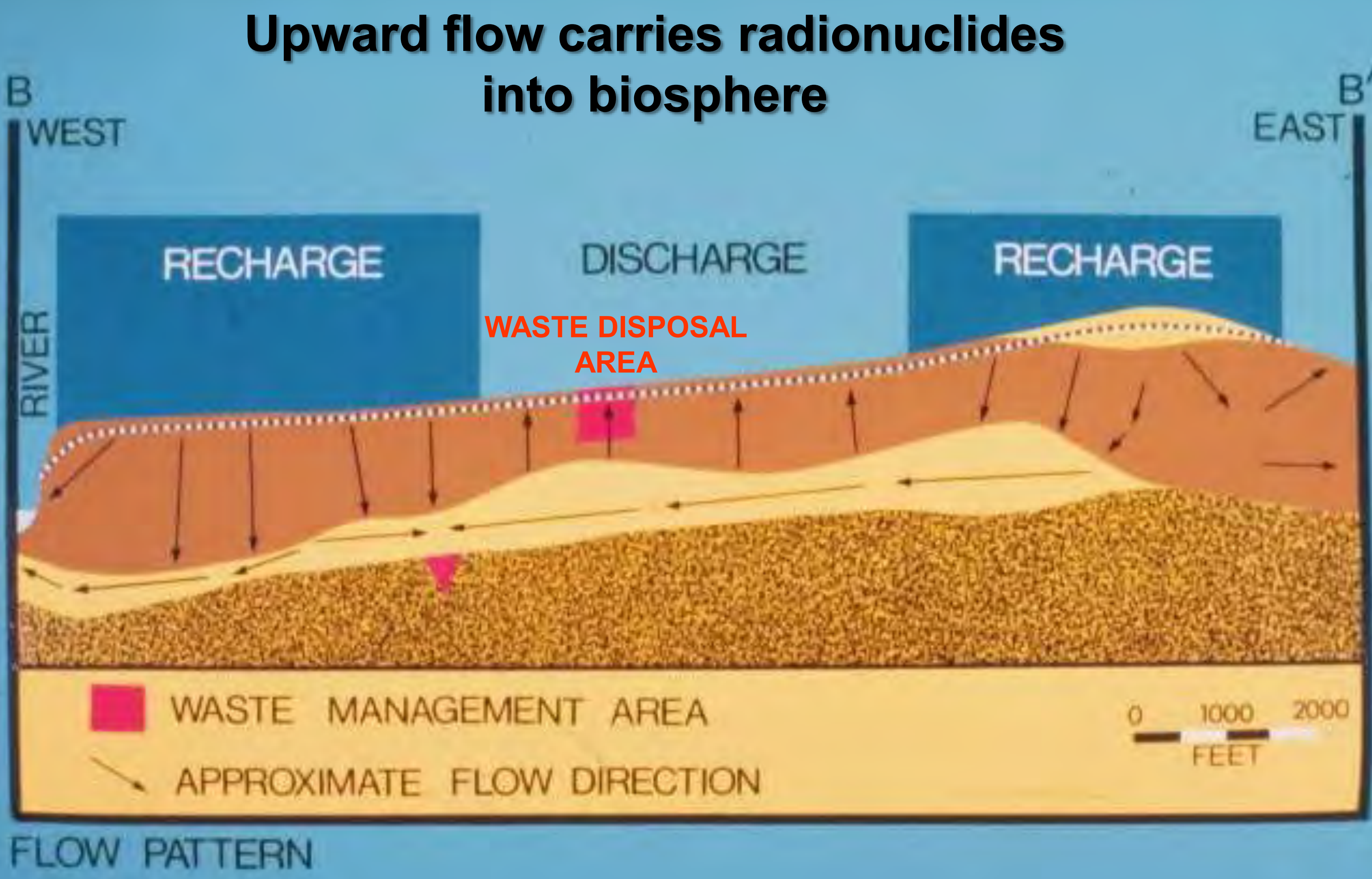


(Grisak et al., 1976)

Pumping Test: *Rapid response in some aquitard piezometers proves fully penetrating fractures*



Active Groundwater Flow System



WNRE Radioactive Waste Case

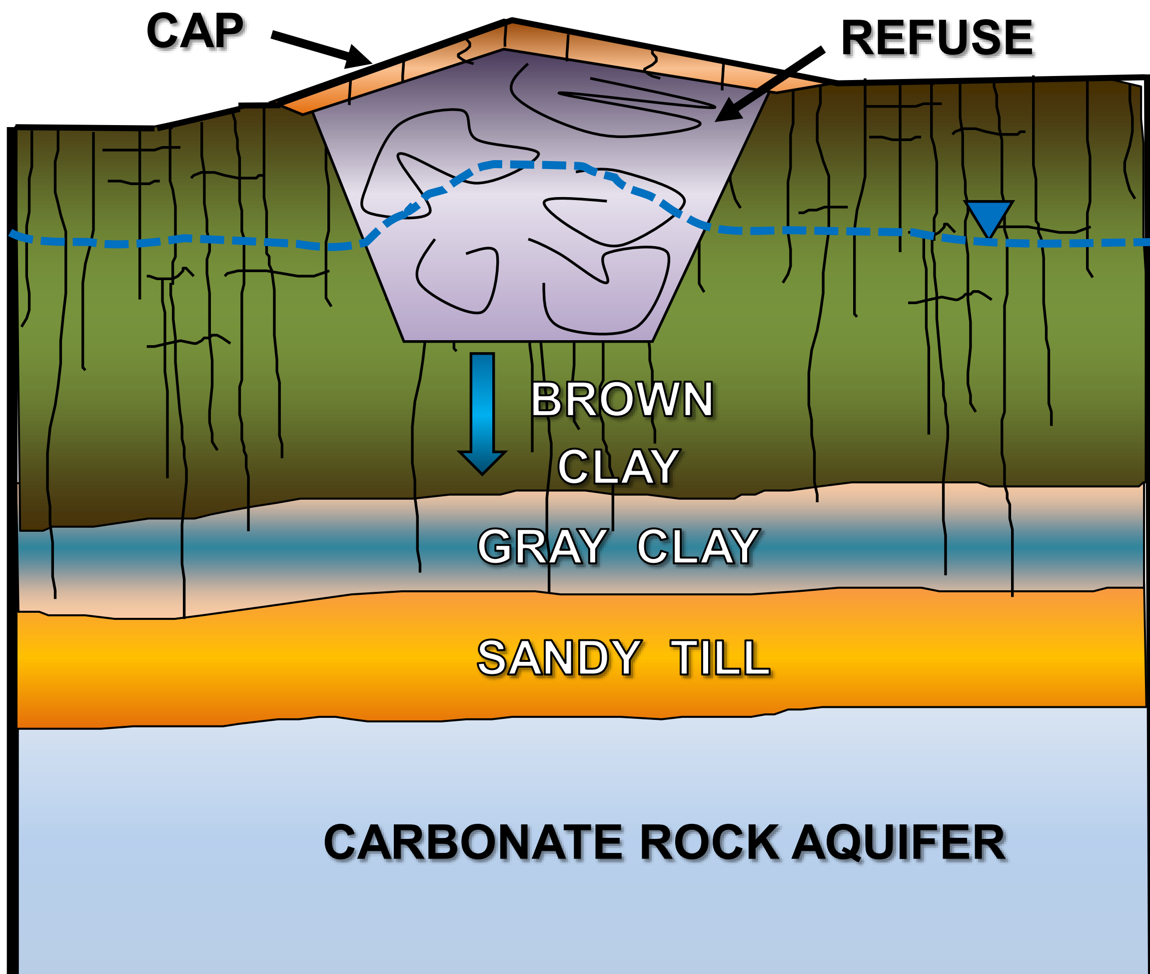
The waste disposal facility was established in the early1960s without realistic hydrogeological concepts

Good site hydrogeology

but bad engineering design because human control of leachate must continue for ~1000 years

Typical Winnipeg Landfill on Fractured Lake Agassiz Clay Aquitard

Is the gray clay an effective barrier even though it has vertical fractures?



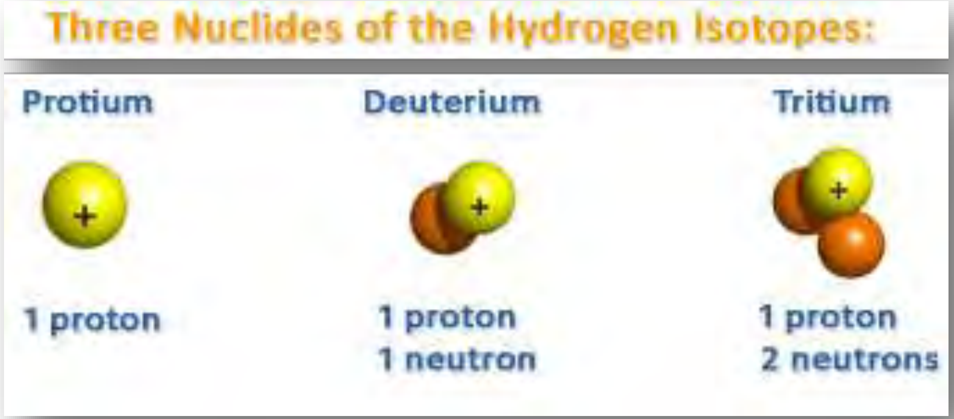
Tritium (^{3}H)

Radioactive isotope of hydrogen with a decay half-life of 12 years.

^{1}H is normal Hydrogen

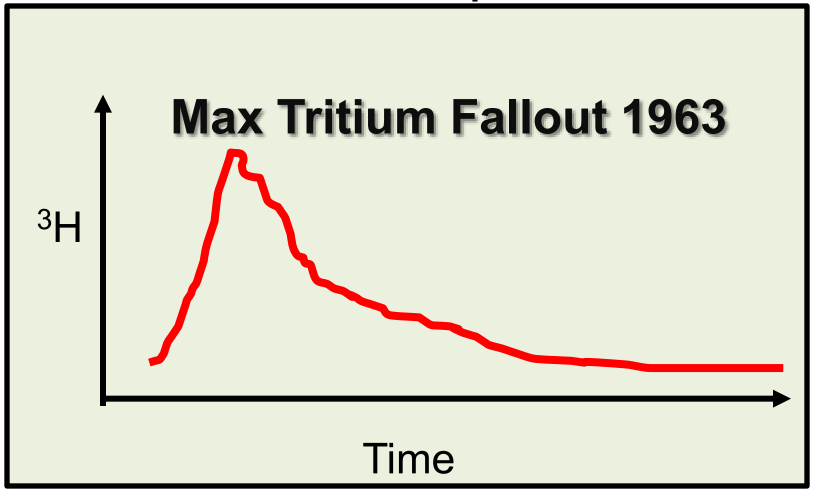
^{2}H is heavy hydrogen

^{3}H is radioactive hydrogen

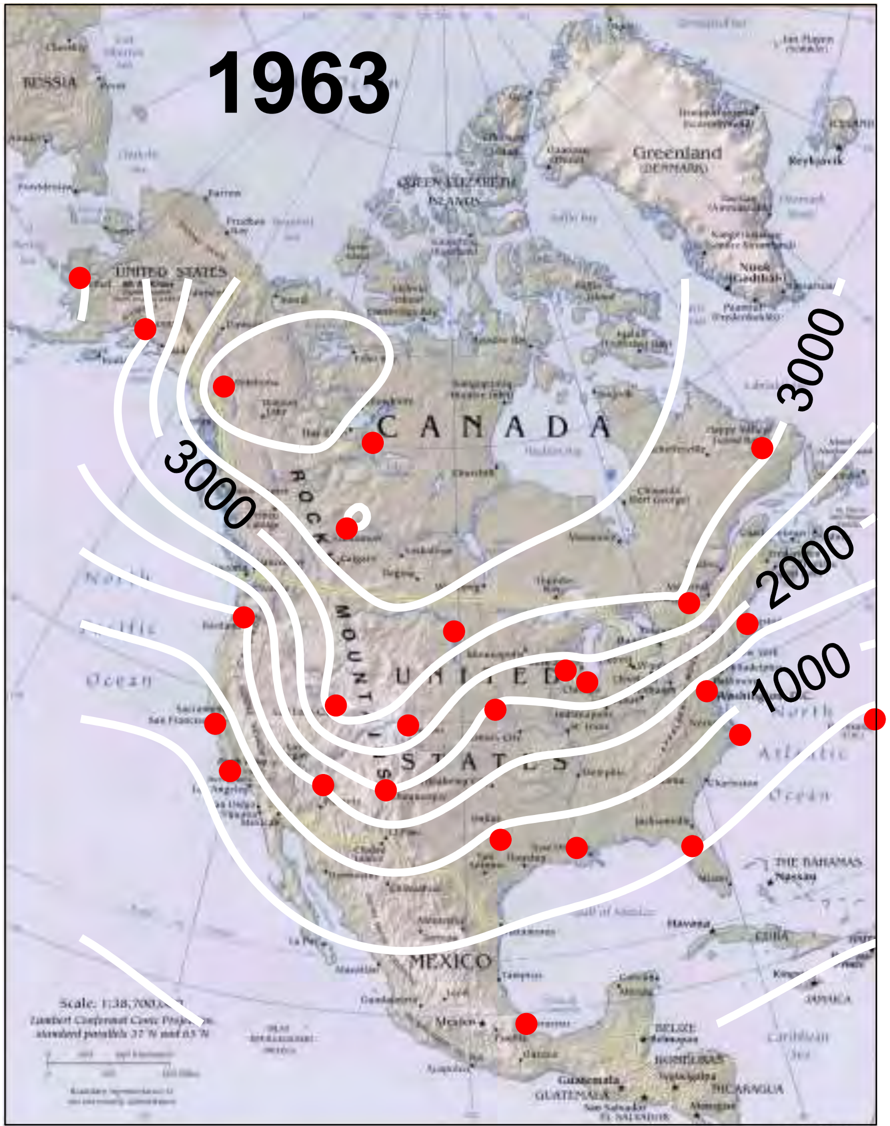


Tritium is a recent groundwater tracer

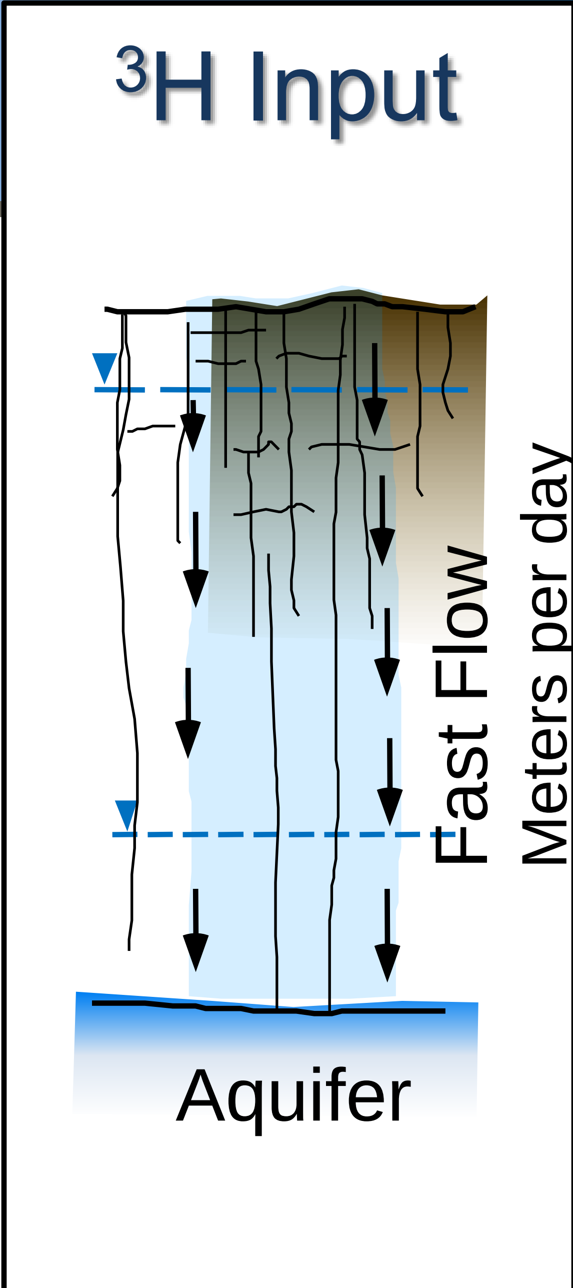
Tritium in Rain from Atmospheric Nuclear Tests



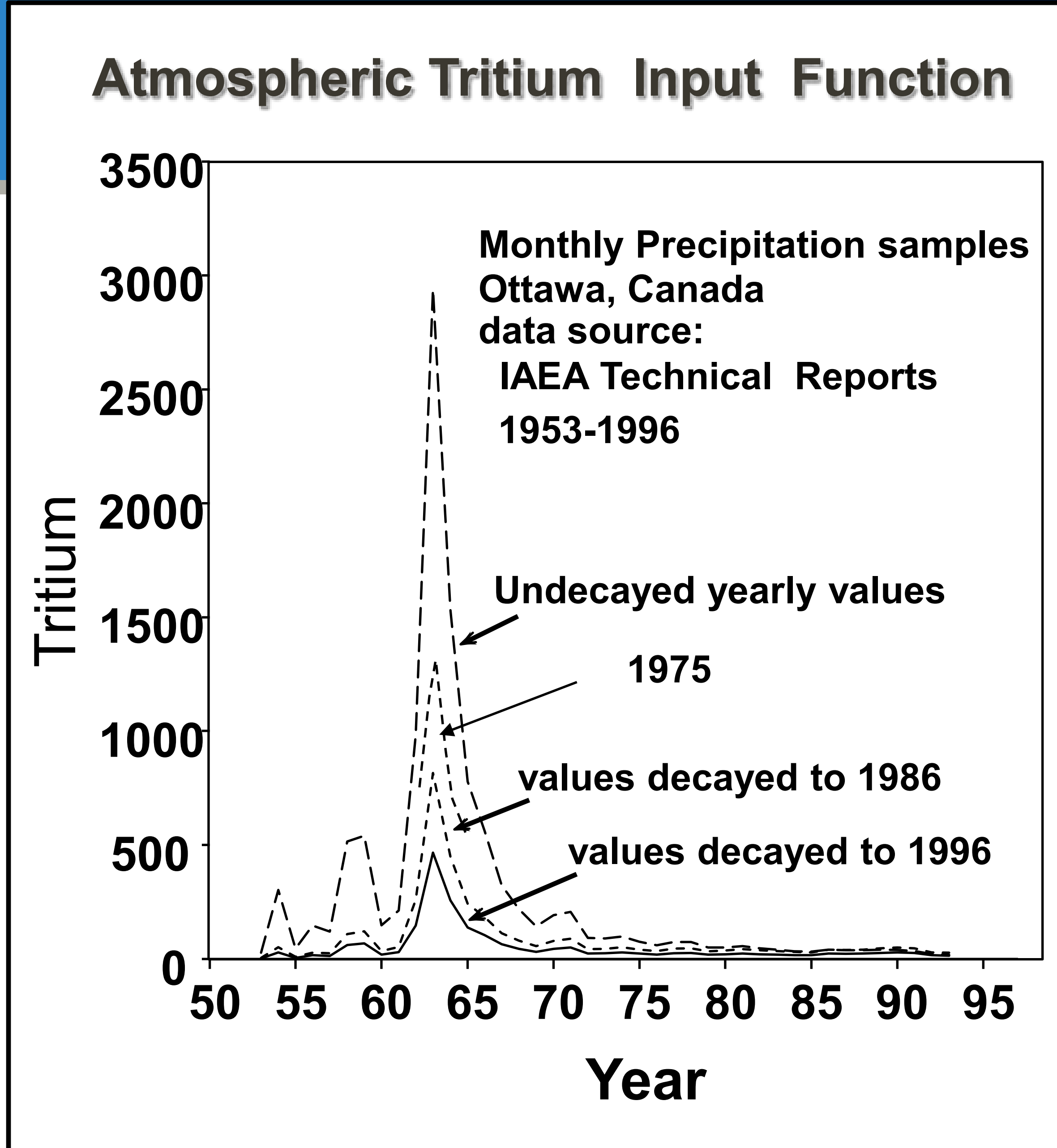
Since 1952, Tritium in rain is from atmospheric bomb tests



Base map: courtesy of the General Libraries, The University of



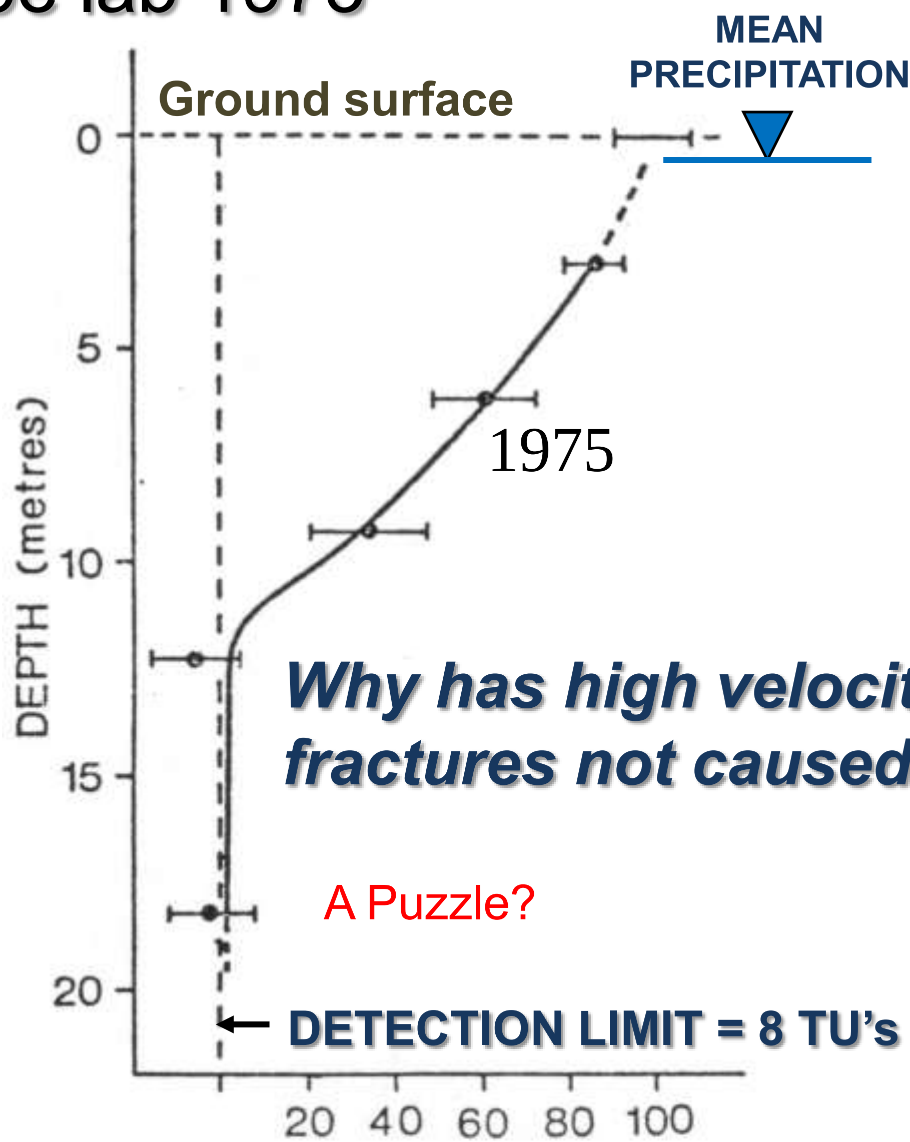
^{3}H Input
Fast Flow
Meters per day
Aquifer



Atmospheric Tritium Input Function
Monthly Precipitation samples
Ottawa, Canada
data source:
IAEA Technical Reports
1953-1996
Undecayed yearly values
1975
values decayed to 1986
values decayed to 1996
Tritium
Year
3500
3000
2500
2000
1500
1000
500
0
50
55
60
65
70
75
80
85
90
95

Peter Fritz creates UW isotope lab 1973

^{3}H not found deep



Why has high velocity in fractures not caused deep ^{3}H?

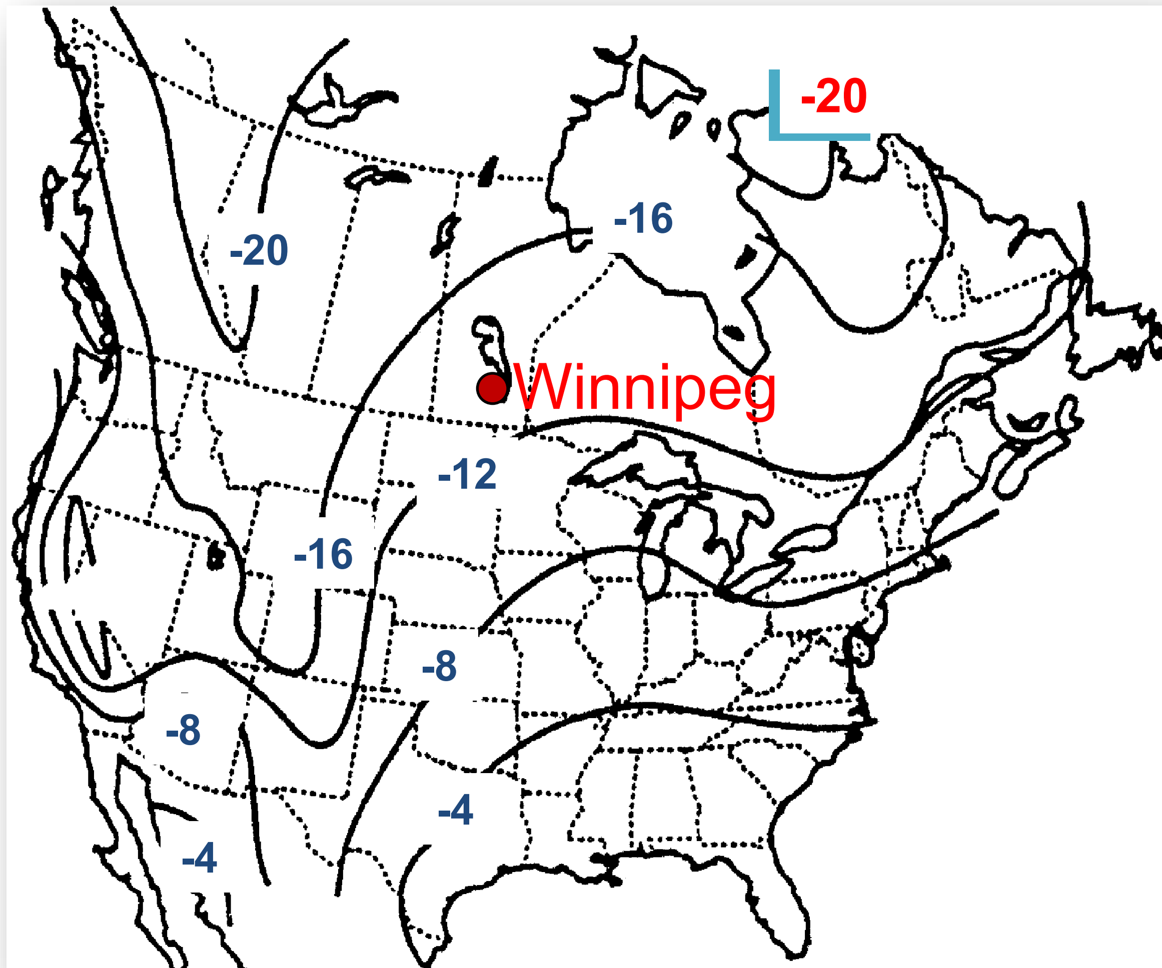
Downward Migration of Bomb ^{3}H began In early 1950's

Weighted Mean $\delta^{18}O$‰ in Precipitation Winnipeg ≈ -14 ‰

Today's values represent conditions during the past 10,000 years

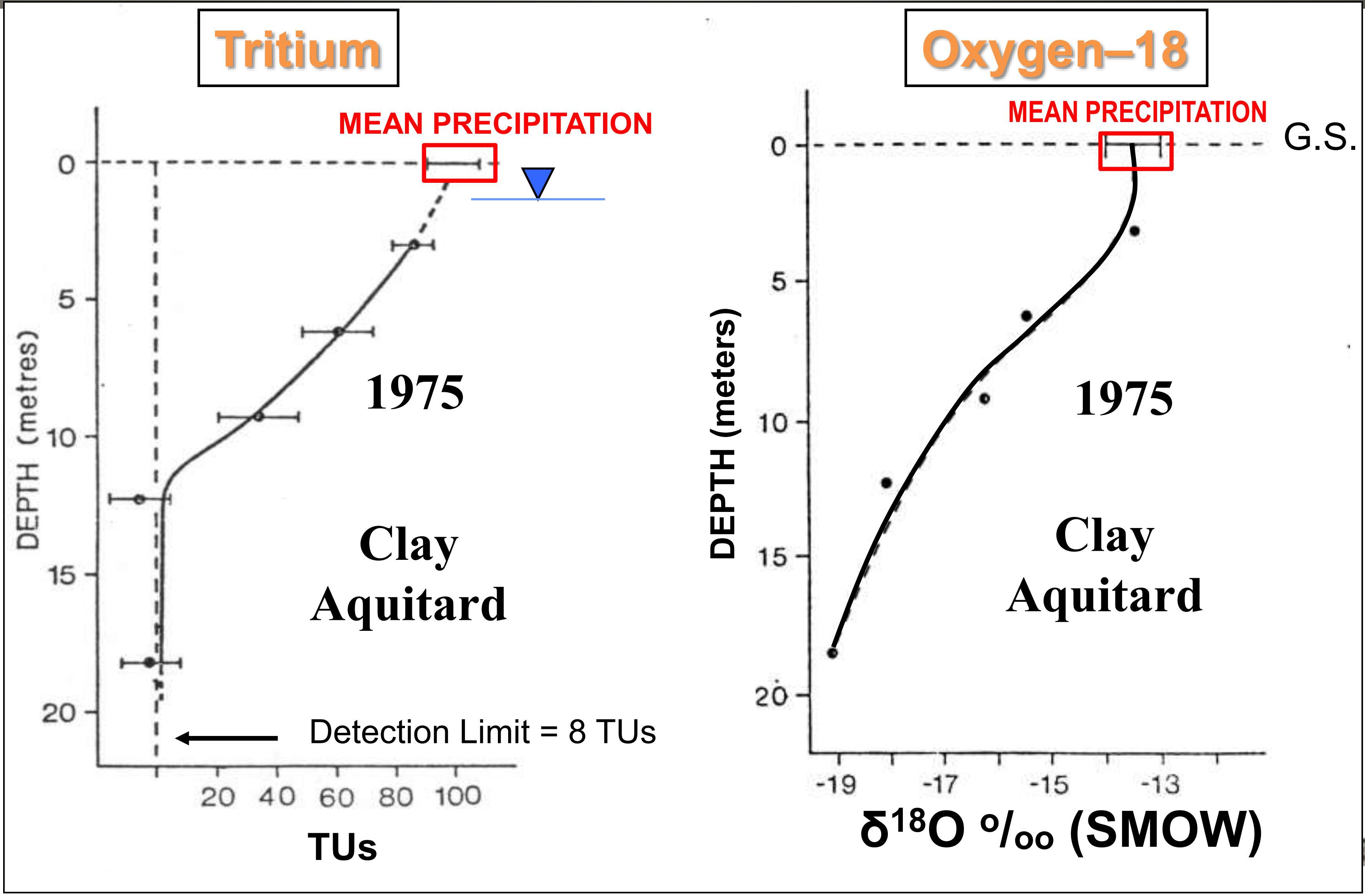
Since glaciers disappeared

~Holocene time



(Clark and Fritz, 1999)

How can these isotope profiles exist in an aquitard with fully penetrating fractures?



Puzzle Solved by diffusion

Introduces Fick's Law of diffusion to Hydrogeology

Journal of Hydrology, 25 (1975) 159–165
© North-Holland Publishing Company, Amsterdam – Printed in The Netherlands

Stephen Foster (UK) 1975

THE CHALK GROUNDWATER TRITIUM ANOMALY – A POSSIBLE EXPLANATION

S.S.D. FOSTER
Hydrogeological Department, Institute of Geological Sciences, London (Great Britain)

(Received August 30, 1974; accepted September 3, 1974)

...dwater tritium anomaly – a possible explanation.

...in the interpreta-

...the Chalk aquifer, with impo...

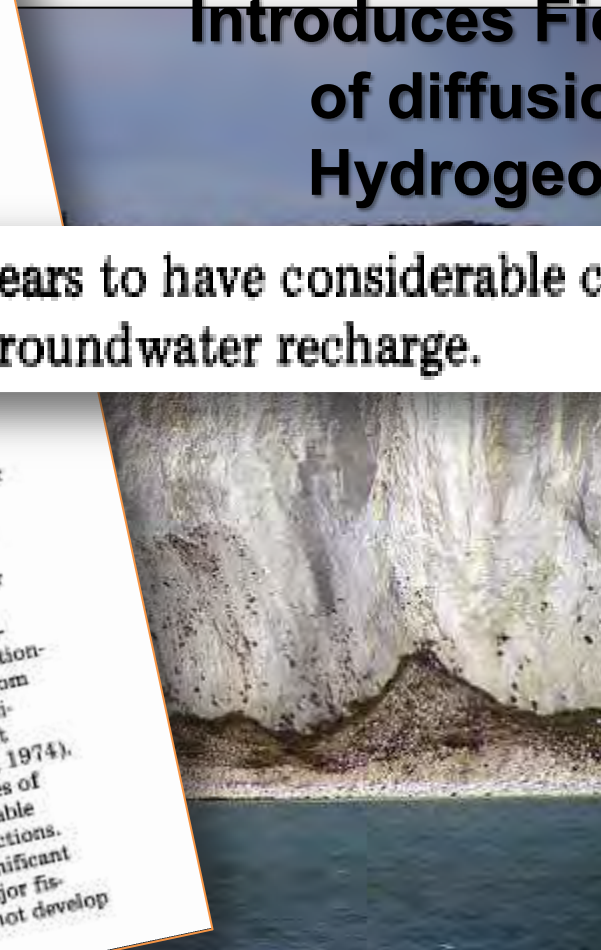
In summary, the diffusion process appears to have considerable capacity for reducing HTO concentrations in Chalk groundwater recharge.

BACKGROUND

The low level of thermonuclear tritium in groundwater from the saturated zone of the Chalk aquifer throughout much of its intake area has been recognised as a major anomaly in British hydrogeology in recent years. The tritium profile of pore-water from the *unsaturated zone* at a Berkshire site in October 1968 led Smith et al. (1970) to suggest that about 85% of the total flow of vadose groundwater was by intergranular seepage at a mean rate of less than 0.9 m/year, contradicting the widely-held concept that fissure-flow dominated downward movement. A similar profile was determined in September 1970 for a site in Dorset (Smith, 1973).

This work had serious implications for resources management and pollution protection in this important aquifer, from which about 15% of all national water-supplies are derived. In the case of nitrate pollution resulting from arable farming for example, a critical question was the potentially high nitrate concentration of vadose pore-waters, by implication, in slow transit through a thick unsaturated zone to the water-table (Foster and Crease, 1974).

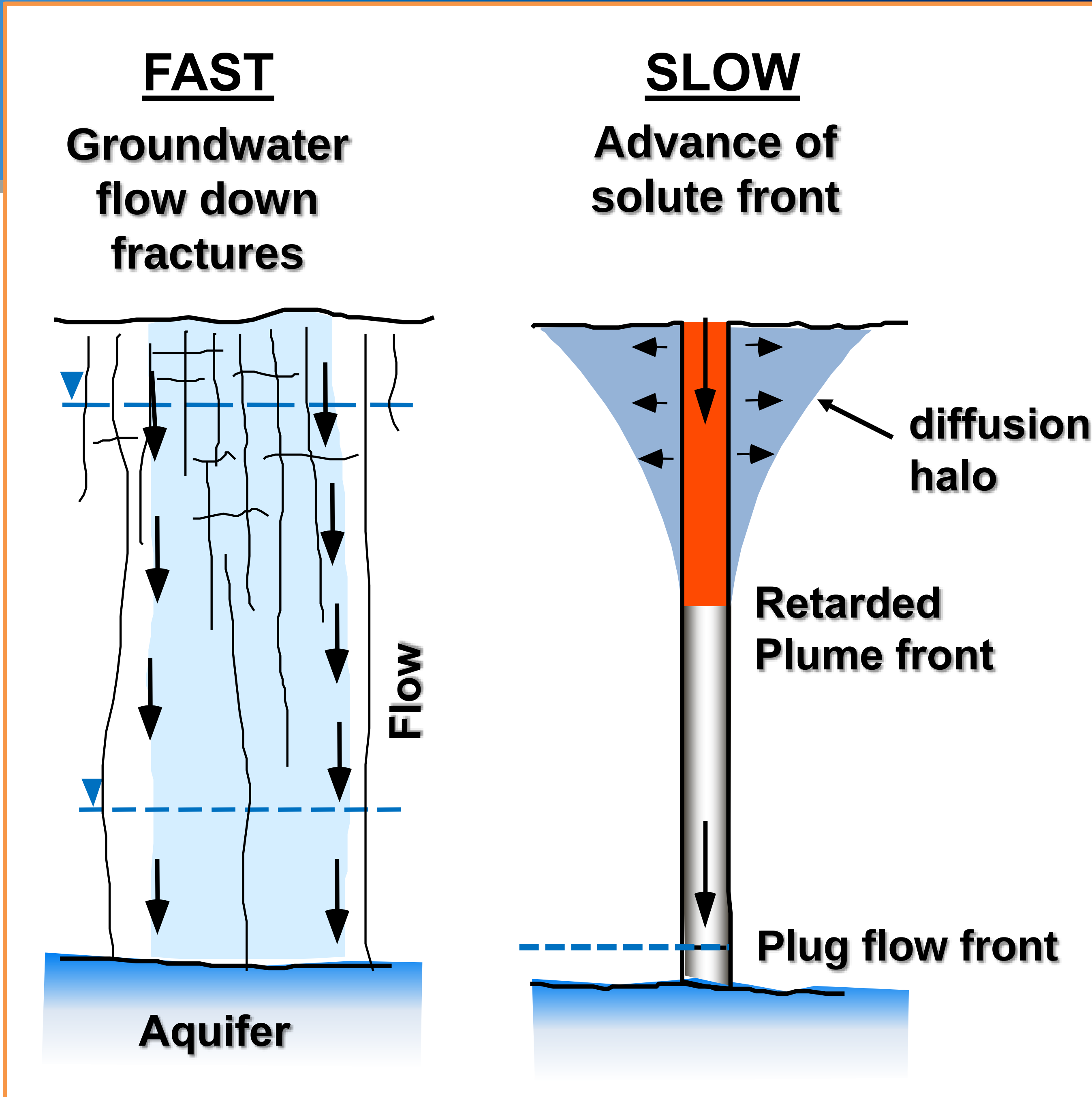
The unquestionable advantages of tritium (HTO) as a tracer in studies of groundwater movement (e.g. Libby, 1961; Smith, 1973) give considerable strength to the interpretation, but there are significant hydraulic objections. While the physical properties of Chalk are not such as to preclude significant intergranular seepage in the unsaturated zone, in the absence of a major fissure-flow component, it is difficult to see why surface run-off does not develop



Foster Conceptual Model

Solute Retardation due to Matrix Diffusion

Diffusion drives molecules into the clay



Remenda et al, 1994

Isotope profiles where aquitard is so thick that no deep fractures found

Reprint Series
23 December 1994, Volume 266, pp. 1975–1978

SCIENCE

Isotopic Composition of Old Ground Water from Lake Agassiz: Implications for Late Pleistocene Climate

V. H. Remenda,* J. A. Cherry, and T. W. D. Edwards

^{18}O diffusion profiles in thickest Lake Agassiz clay indicate extremely cold paleo climate: 18O = -24‰

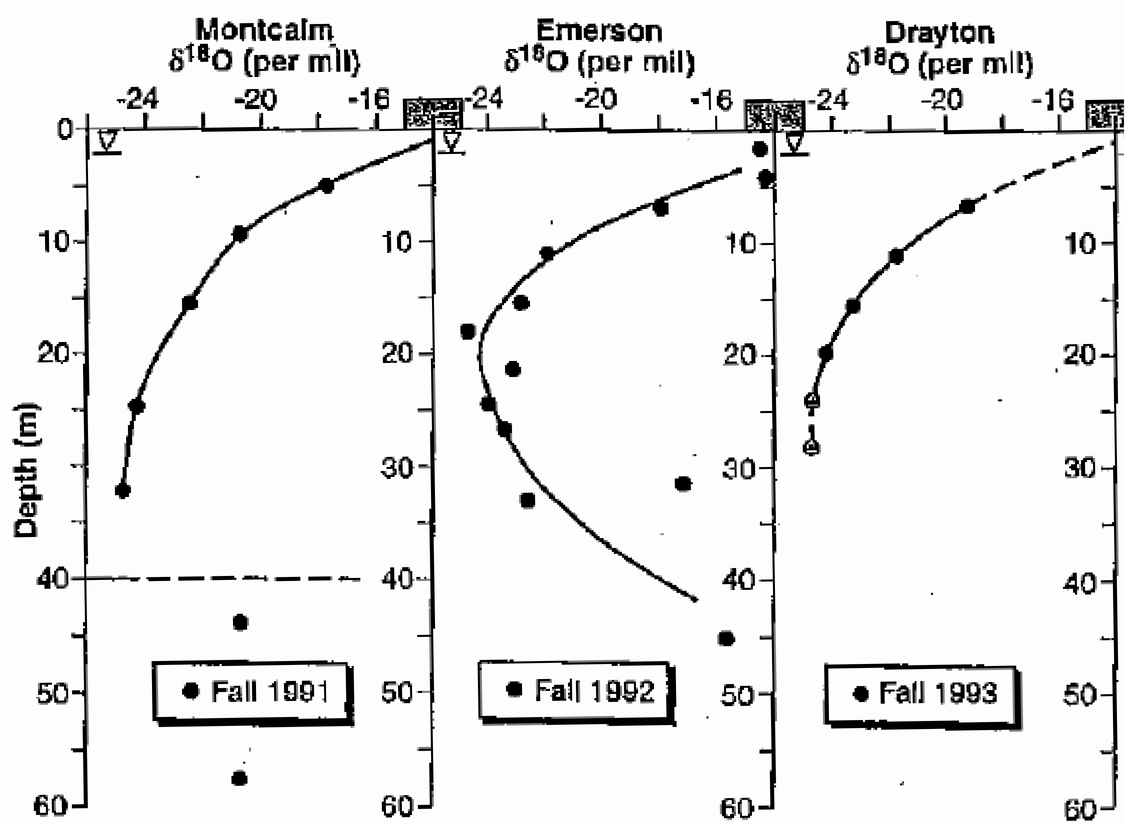


Fig. 2. The $\delta^{18}O$ values (relative to VSMOW) of ground water sampled from monitoring wells at Montcalm, Drayton, and Manvel and from cores at Emerson.

Fractures

No Fractures

pleistocene water

Proposal for Waste Entombment Below Water Table

A CONCEPT FOR LONG-TERM ISOLATION OF SOLID RADIOACTIVE WASTE IN FINE-GRAINED DEPOSITS

J. A. Cherry
R. W. Gillham
University of Waterloo
Waterloo, Ontario

G. E. Grisak
Alberta Environment
Lethbridge, Alberta
(Inland Waters Directorate
Fisheries and Environment Canada
Ottawa, Ontario)

D. L. Lush
Beak Consultants Limited
Mississauga, Ontario

1979

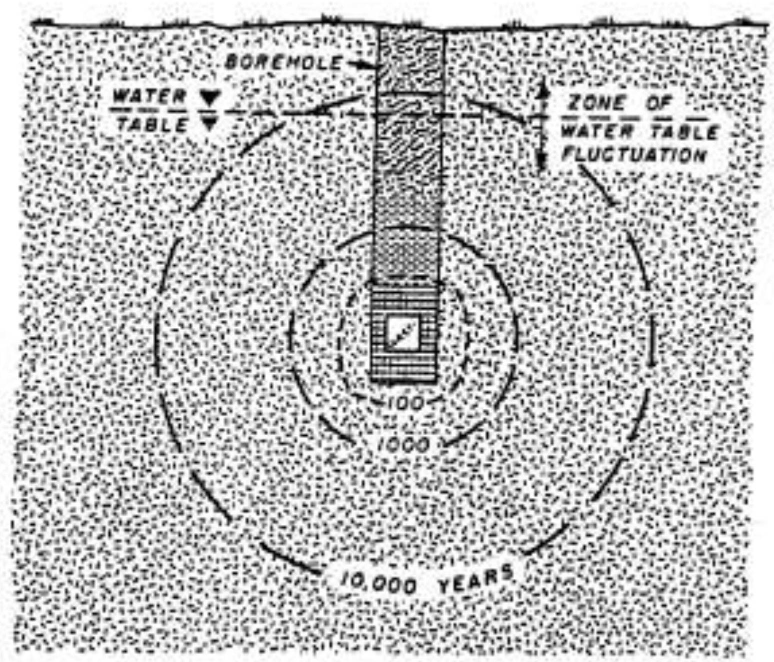


Figure 3 Diffusion halo emanating from buried waste after wetting occurs. The waste is 20m below ground surface. Diffusion front contours represent C/Co = 0.1 for $D^* = 1 \times 10^{-6}$ cm^2/s.

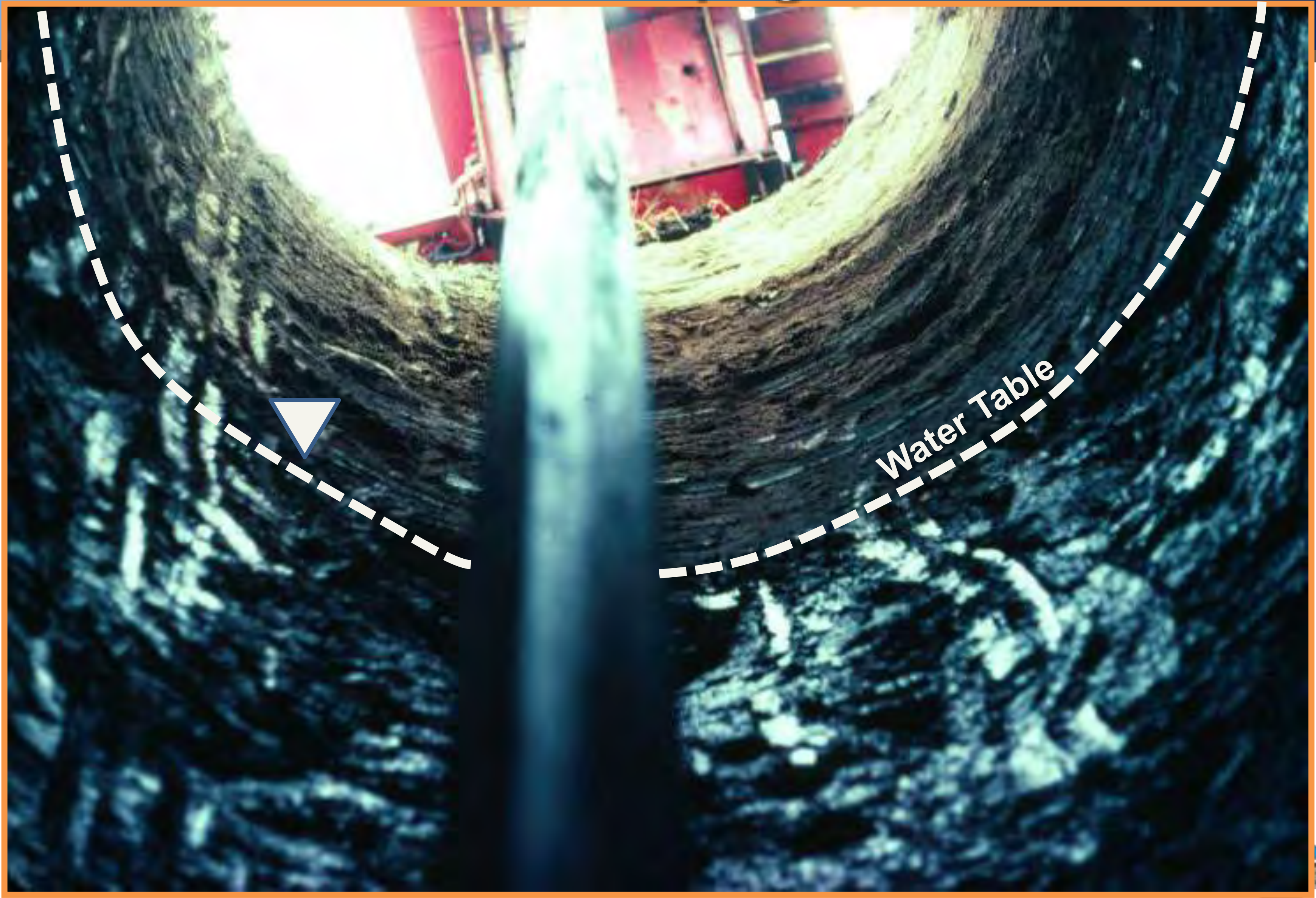
Earliest Proposal for Diffusion Controlled Radioactive Waste Disposal

Management Of Low-Level Radioactive Waste, Vol. 2, Editors, M. W. Carter, A. A. Moghissi, and B. Kahn, Pergamon Press, 1979.

Warman site near Saskatoon 1978: Proposed for uranium refinery waste disposal site in thick glacial till

Photographer uses the auger as an elevator

Shining borehole wall due to water seepage from fractures




Fractured water
inflow zone (<10m)
sealed off using
caisson allows
deeper inspection

Saturated clay but
no flow

PREDICTABILITY OF SOLUTE TRANSPORT IN
DIFFUSION-CONTROLLED HYDROGEOLOGIC REGIMES

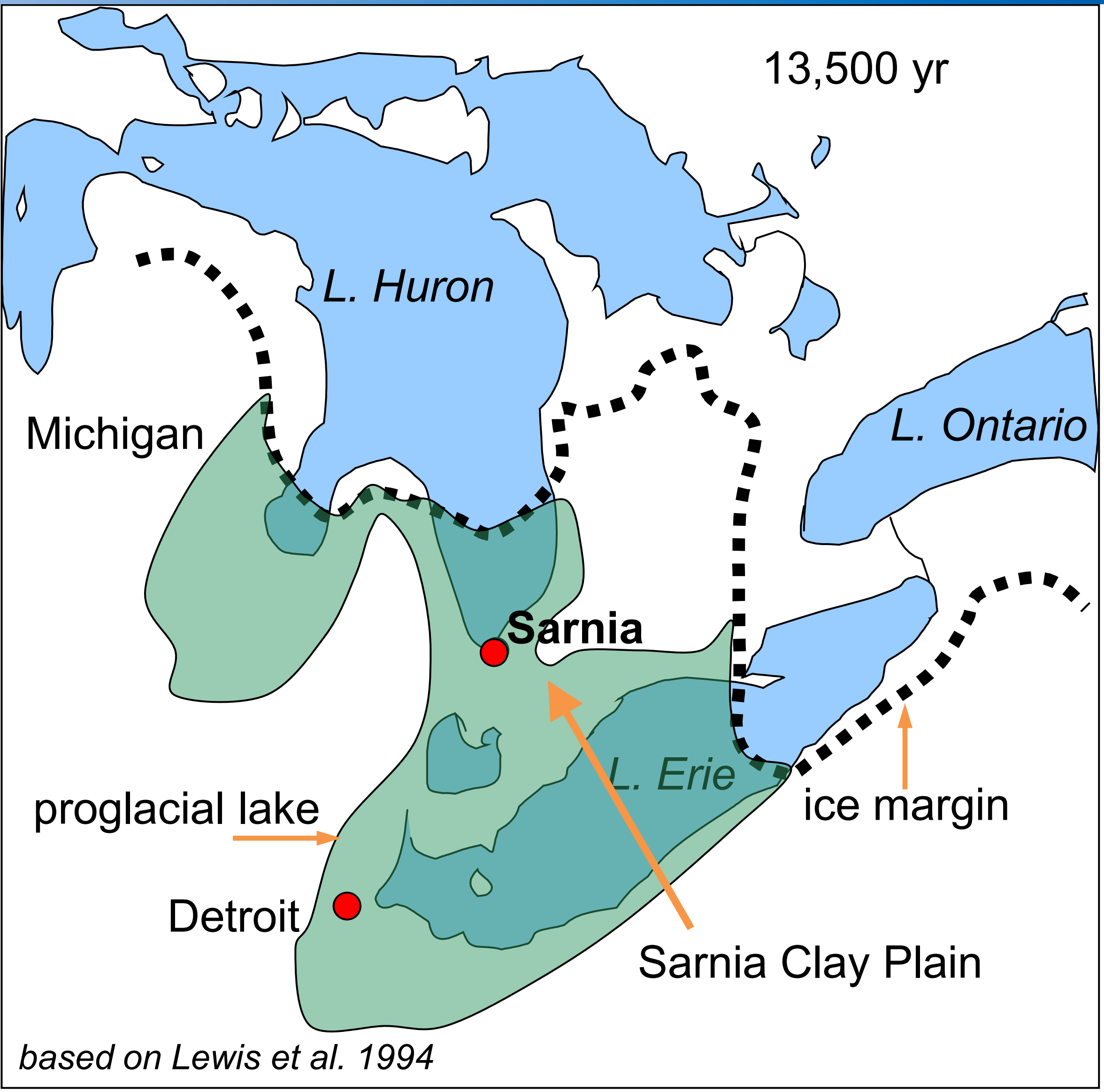
Robert W. Gillham and John A. Cherry
Depratment of Earth Sciences
University of Waterloo
Waterloo, Ontario

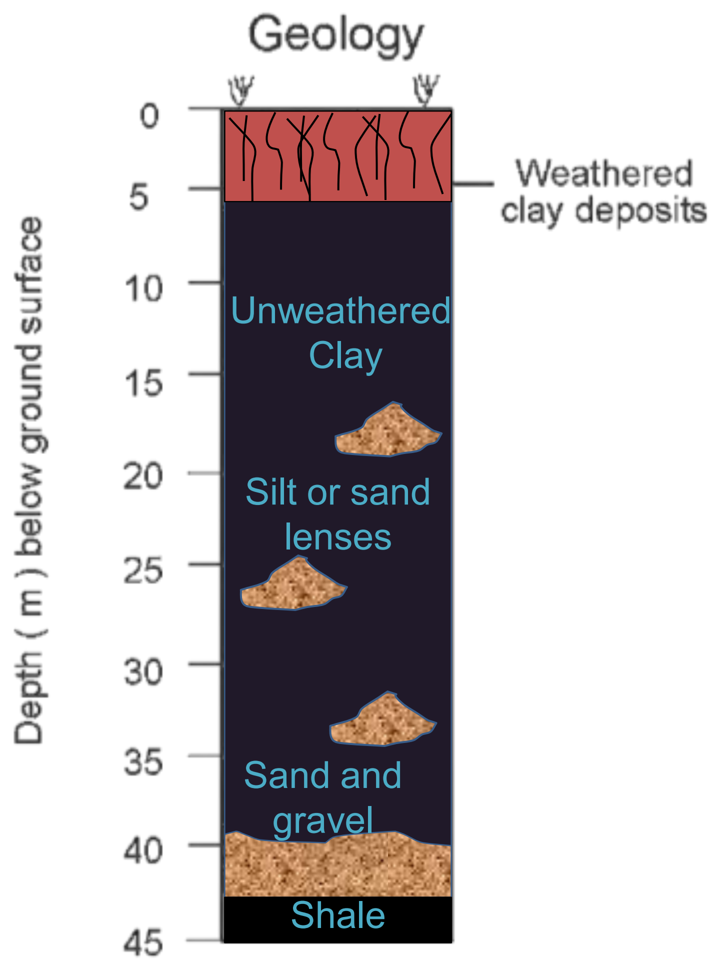
1983

Proceeding of the Symposium on low level waste Disposal:
Facility Design, Construction and Operating Practices.
September 28-29, 1983 Washington D.C. Nuclear Regulatory Commission

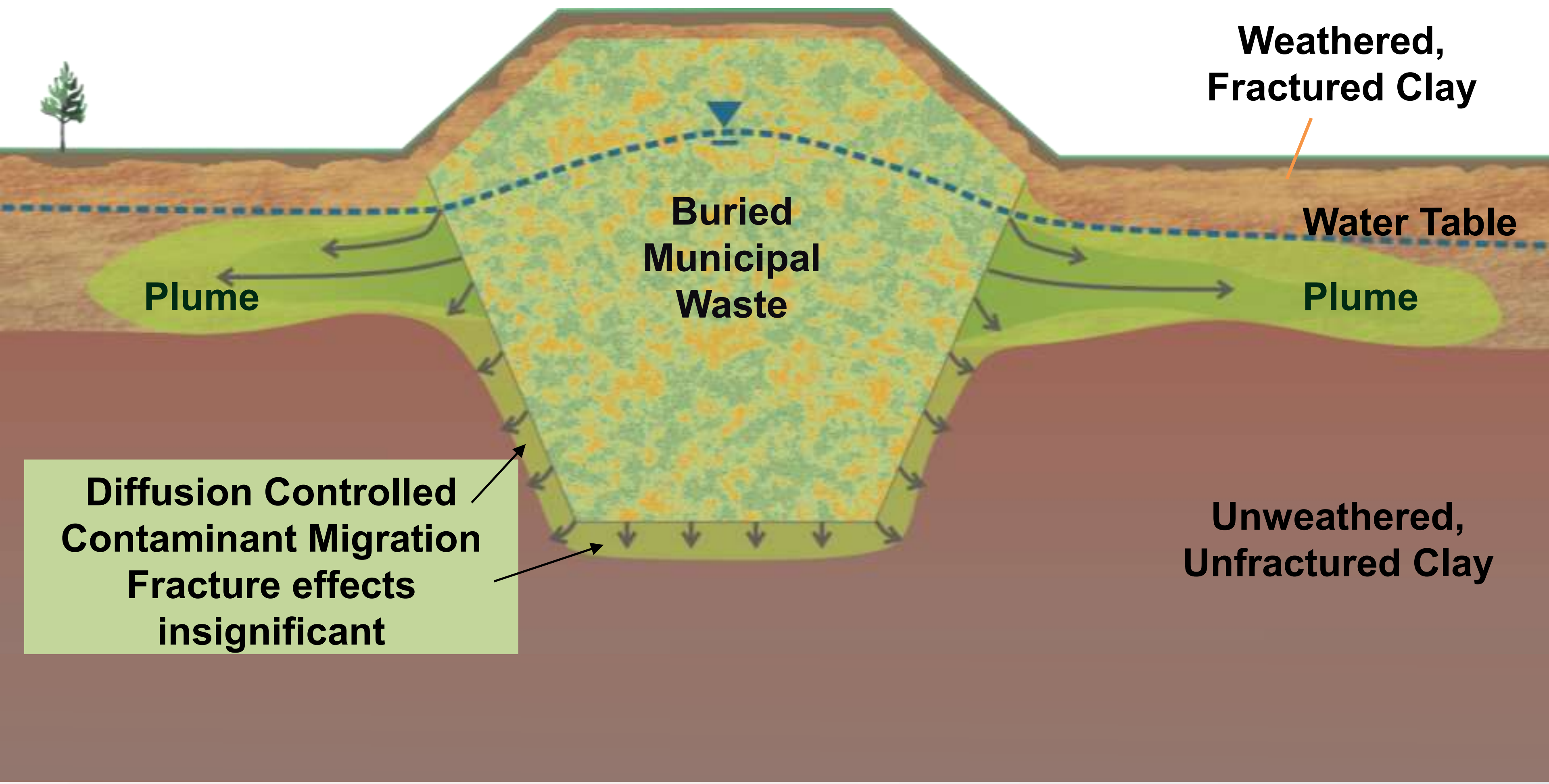
"This paper presents arguments to show that in addition to having favorable velocity characteristics, transport in saturated, diffusion-controlled hydrogeologic regimes is considerably more predictable than in the most common alternatives."

Clayey Aquitard Formed in Proglacial Lakes



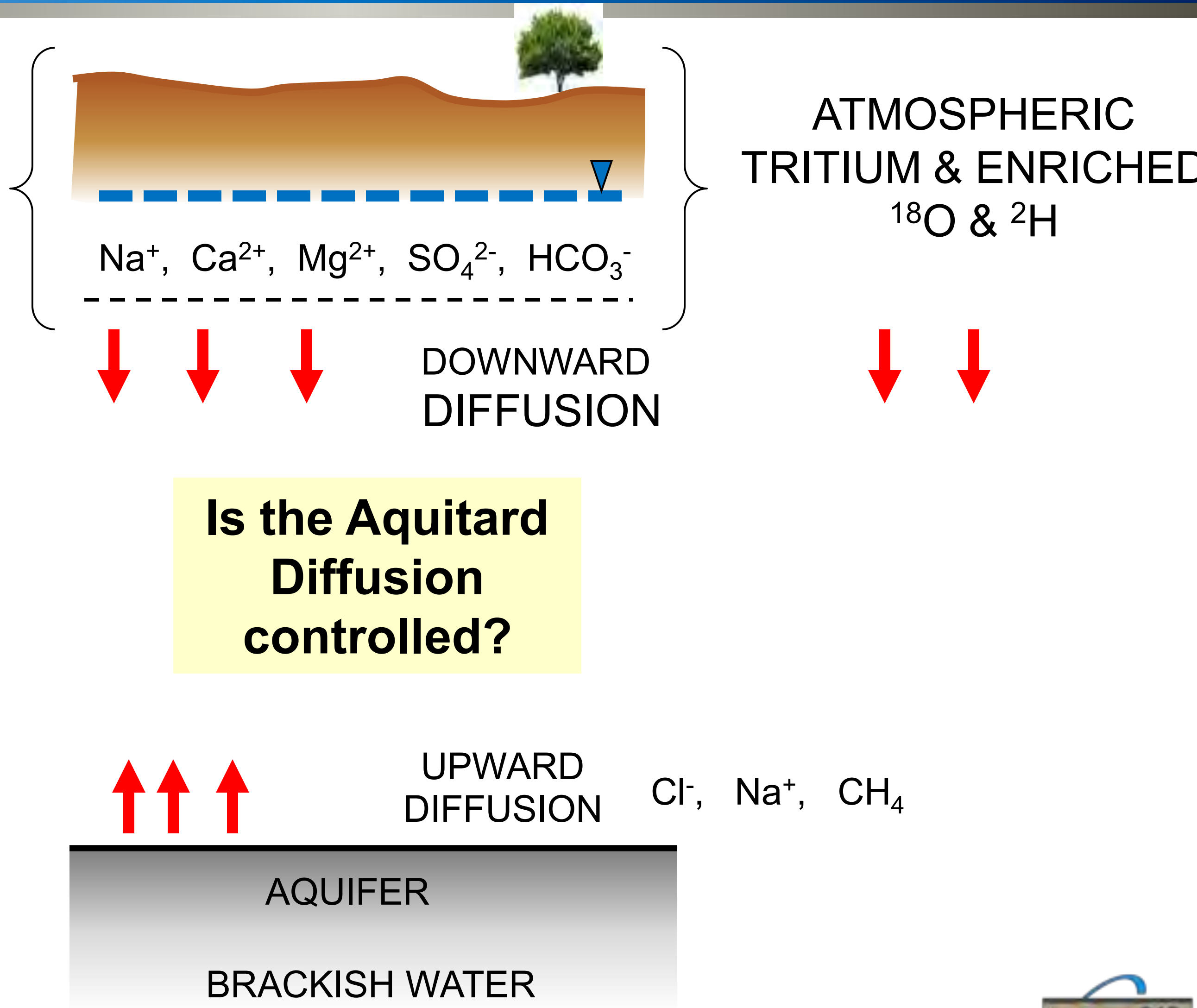


Typical Municipal and Industrial Waste Disposal in Pits Before 1980s



Schematic View of Hydrochemical Conditions: Sarnia Clay Plain

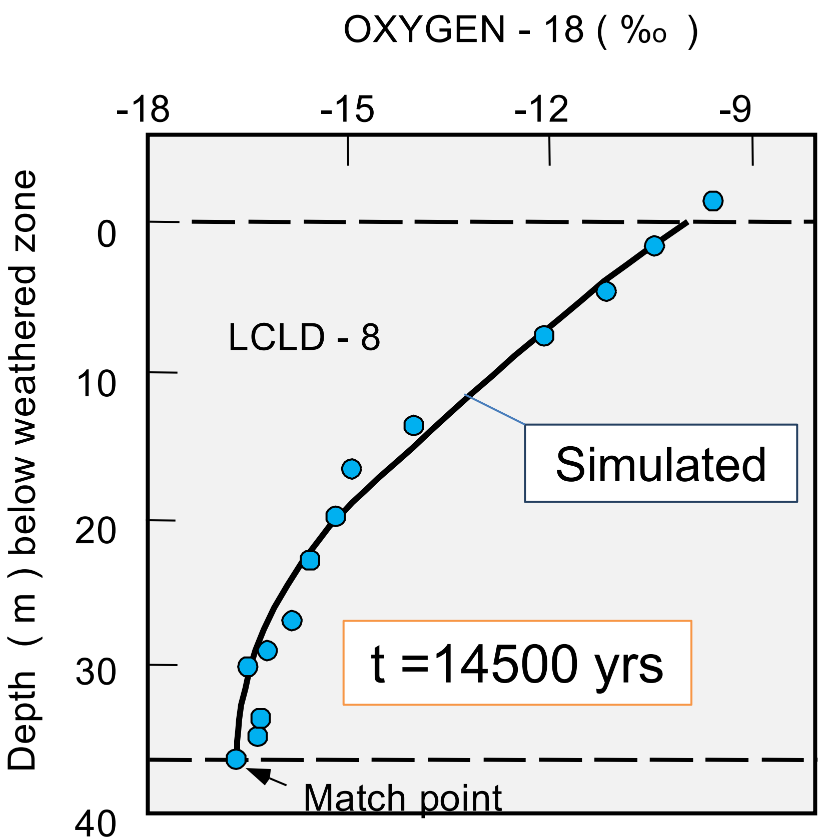
- SULFUR OXIDATION
- CATION EXCHANGE
- CALCITE DISSOLUTION

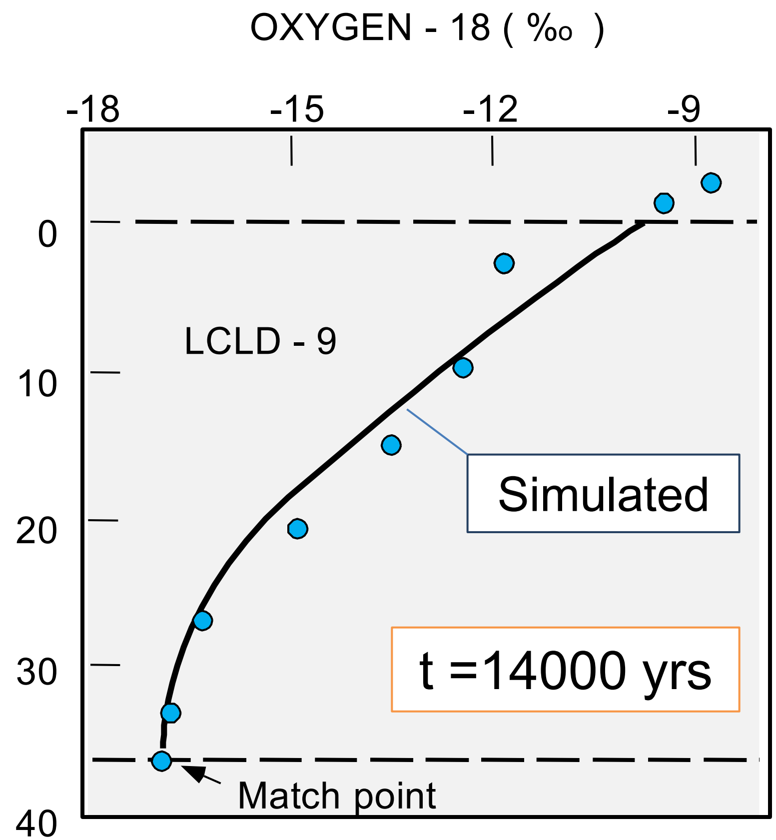


Examine chemical and isotope profiles

^{18}O Profiles fit diffusion models1-D Simulations of downward diffusion: Time is the fitting parameter

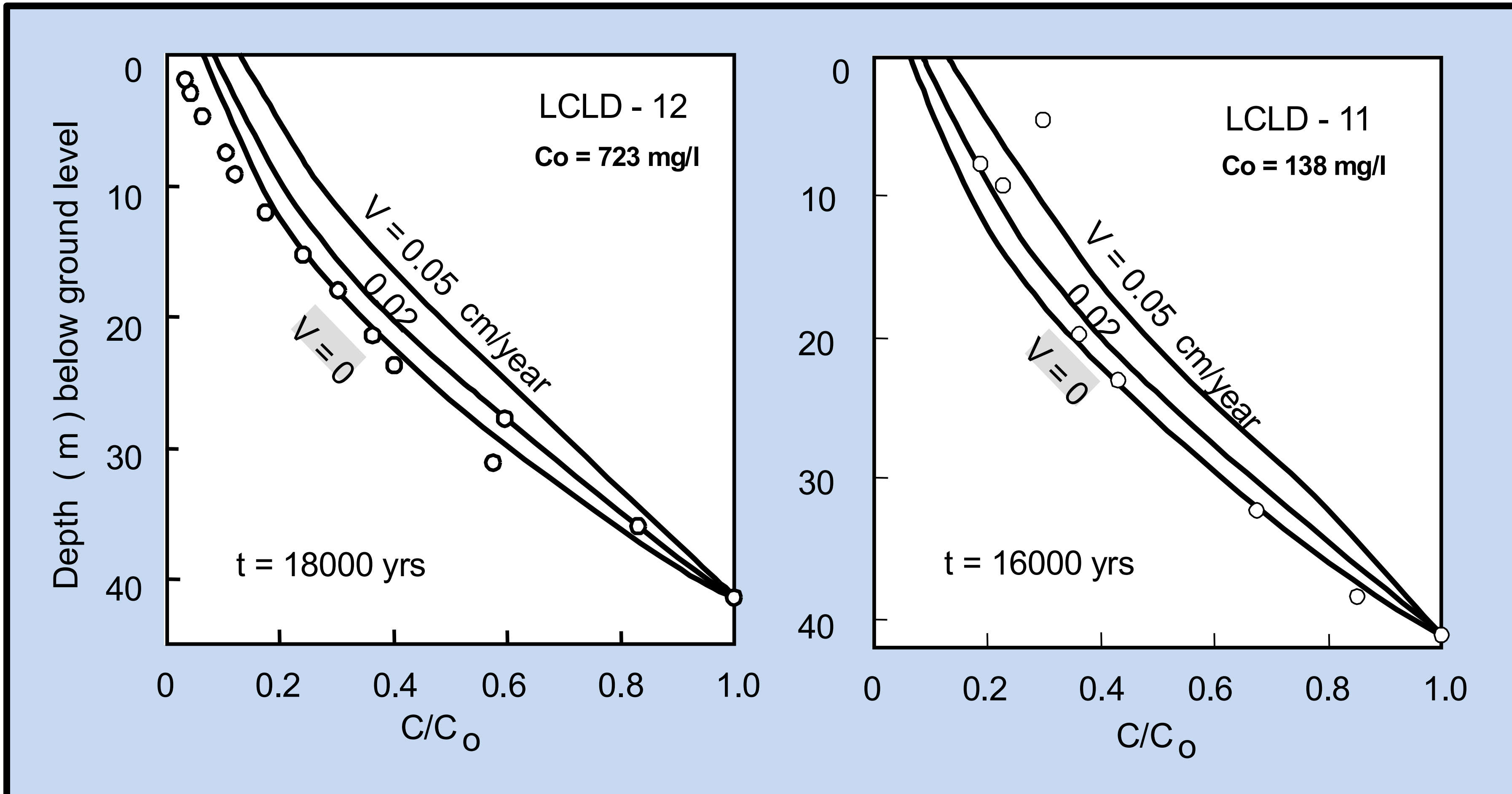
Diffusion dominated downward migration





Husain PhD Thesis, 1997

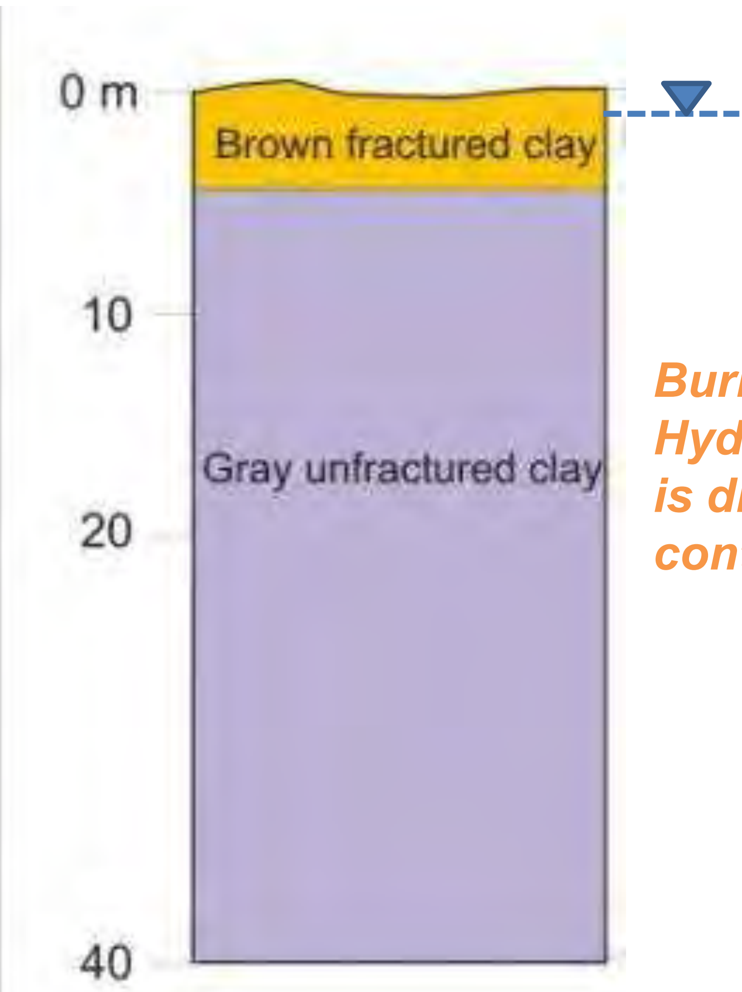
Upward Cl^- Diffusion Upward from Bedrock Begins



Negligible influence of advection

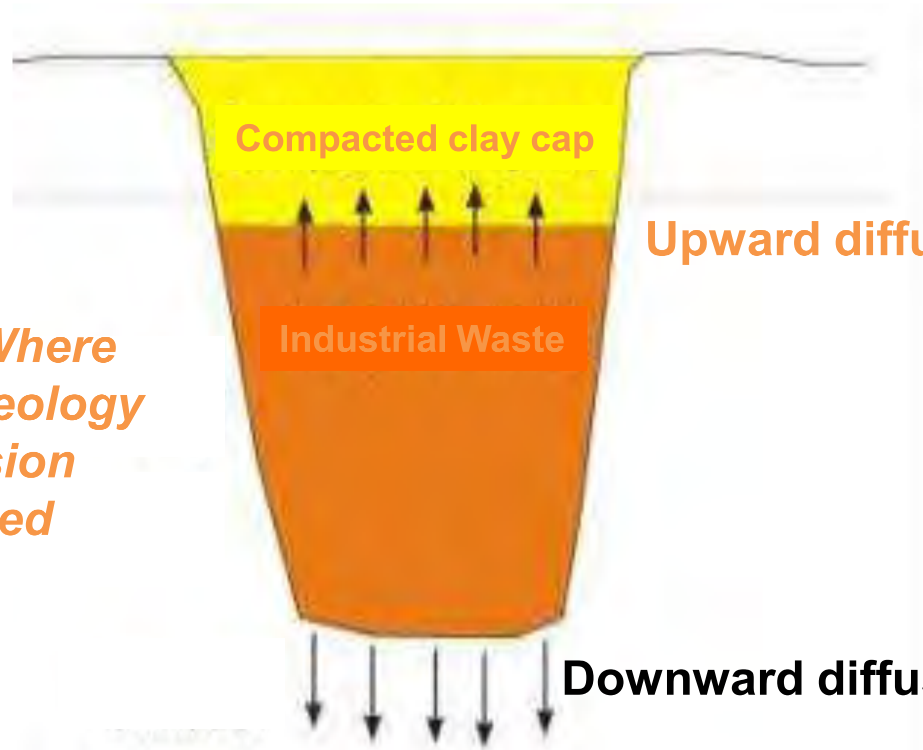
One of Canada’s two main hazardous waste disposal sites ‘uses’ this aquitard

New Landfill Design (1985):
Waste Entombment Below the Water Table and Below the Weathered Zone



Burial Where Hydrogeology is diffusion controlled

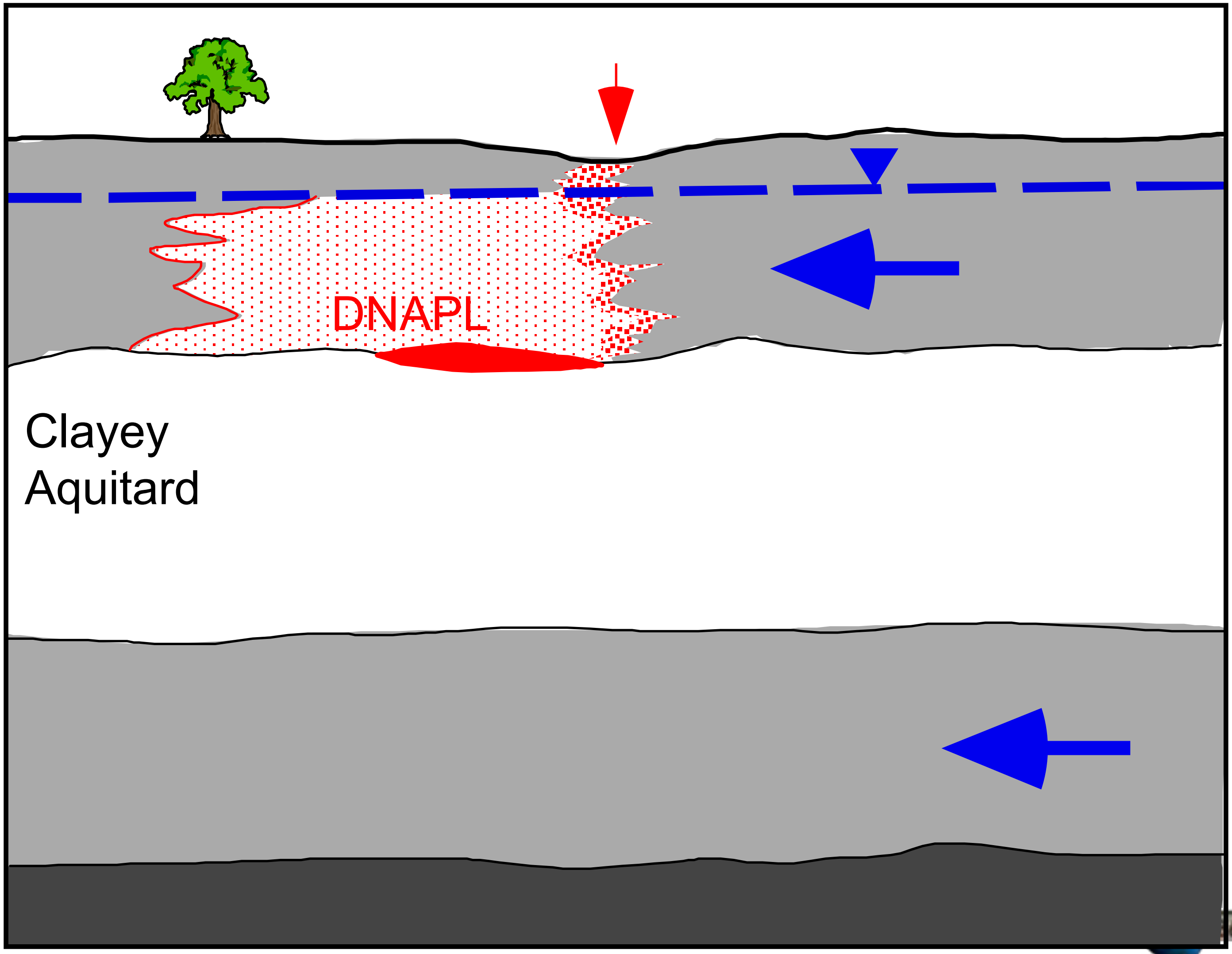
Passive Engineering



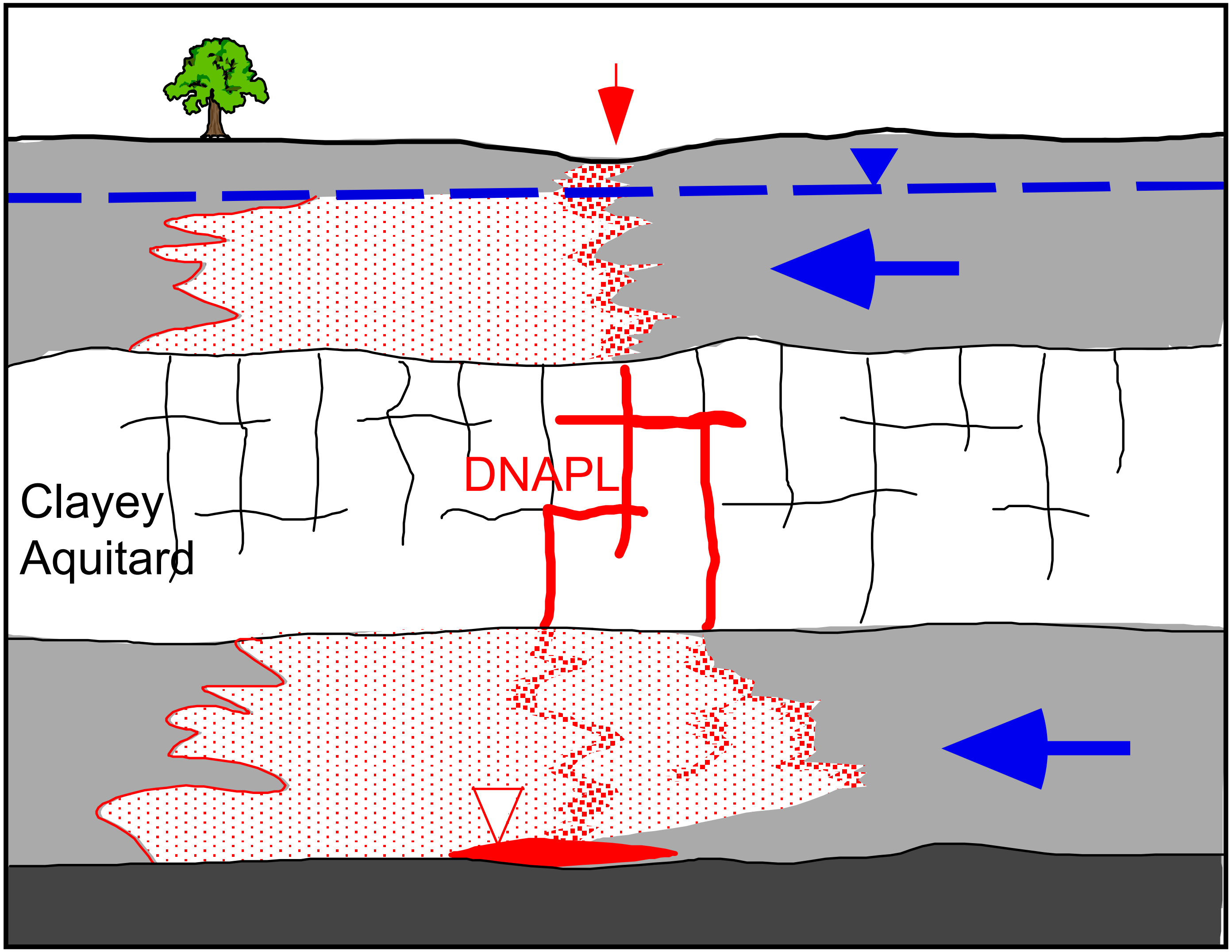
Contaminant residence time greater than 1000 years

Buried Aquitard: No Fracture Scenario can Protect Lower Aquifer

No DNAPL entry to aquitard



Buried Aquitard: Fractures Allow DNAPL to Pass Through Aquitard



Does DNAPL Move Through Small Fractures?

Large Laboratory Column Experiment

Using the Danish technique developed by Peter Jorgensen 1991 - 1993

Suzanne K. O'Hara
MSc. Thesis, University of Waterloo, June, 1997.

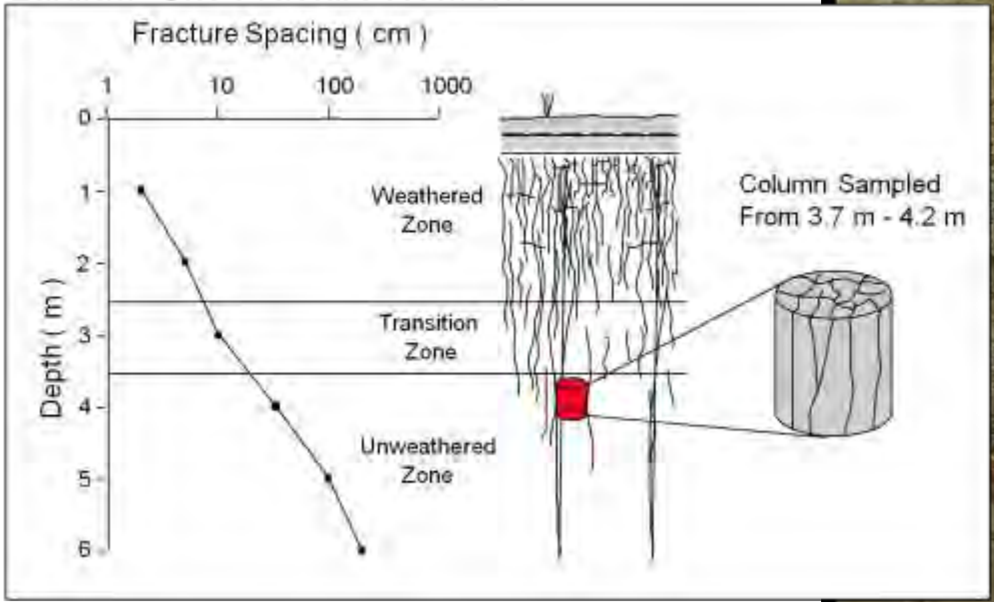
O'Hara, Parker, Cherry and Jørgensen (2000)
Water Resources Research
Vol. 36, No. I, pp 135-147

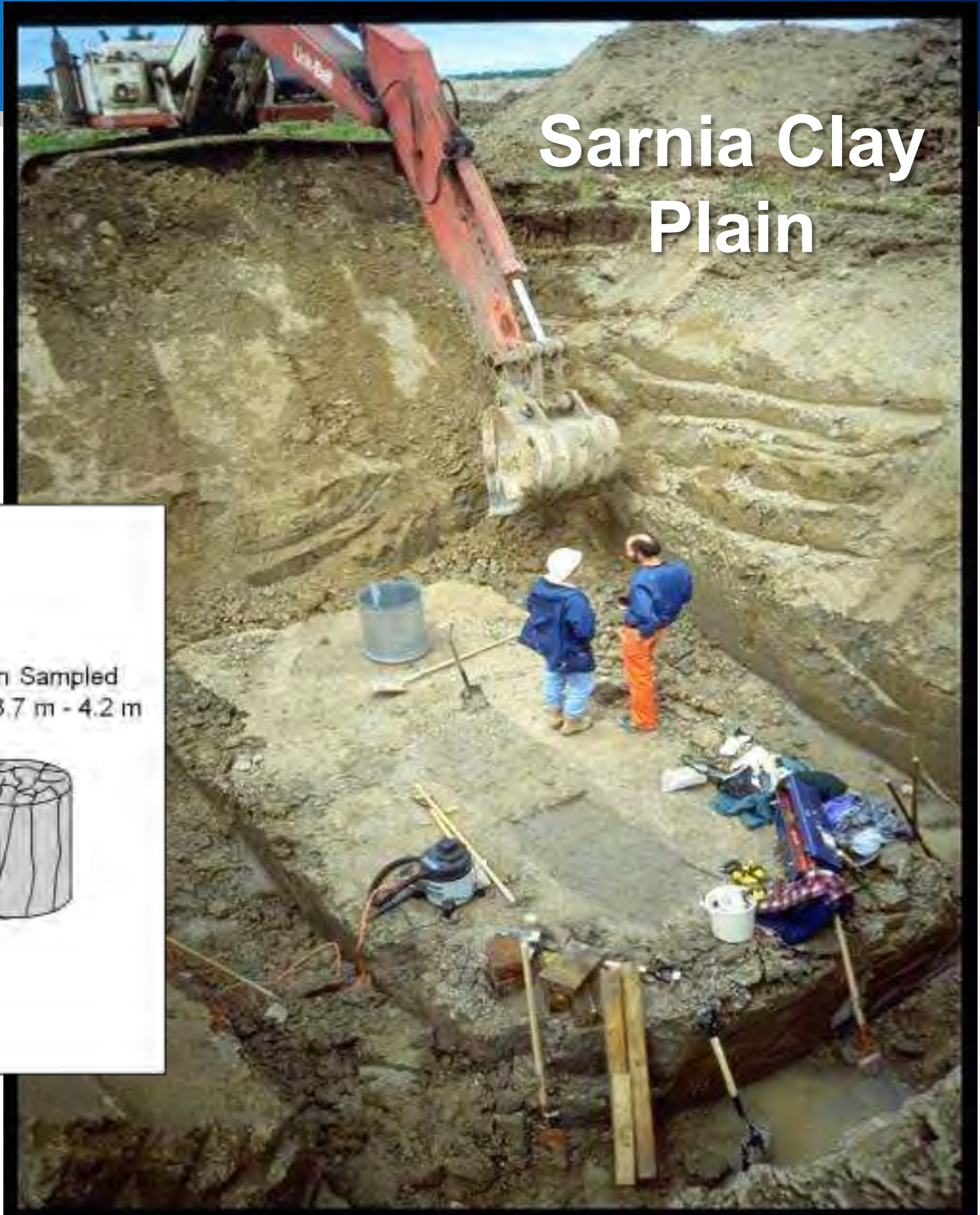
The Danish technique recreates *in situ* stress

DNAPL Entry Flow Experiment

Excavation to 3.5m to obtain column

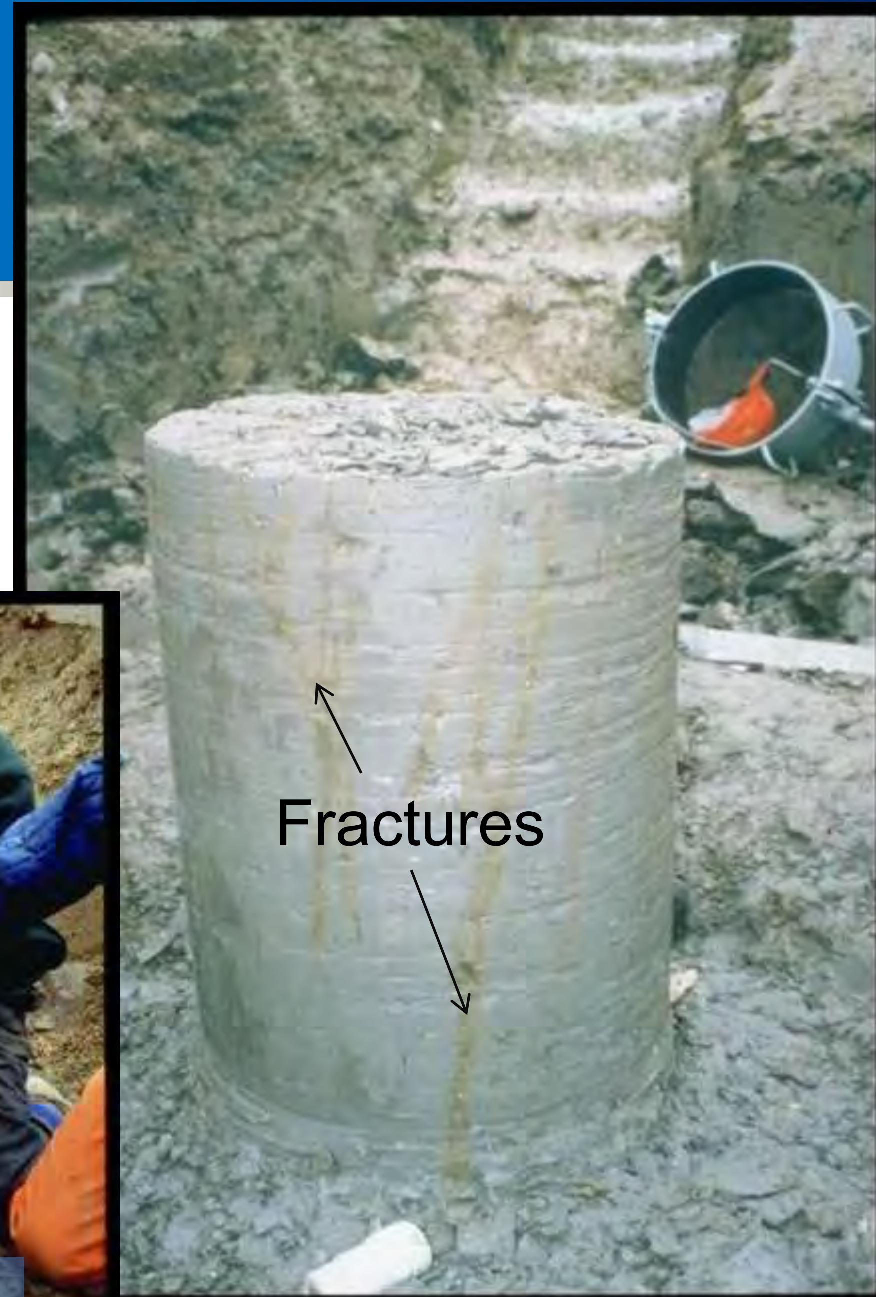
Laidlaw Site Fracture Network





Obtain large sample with minimal disturbance

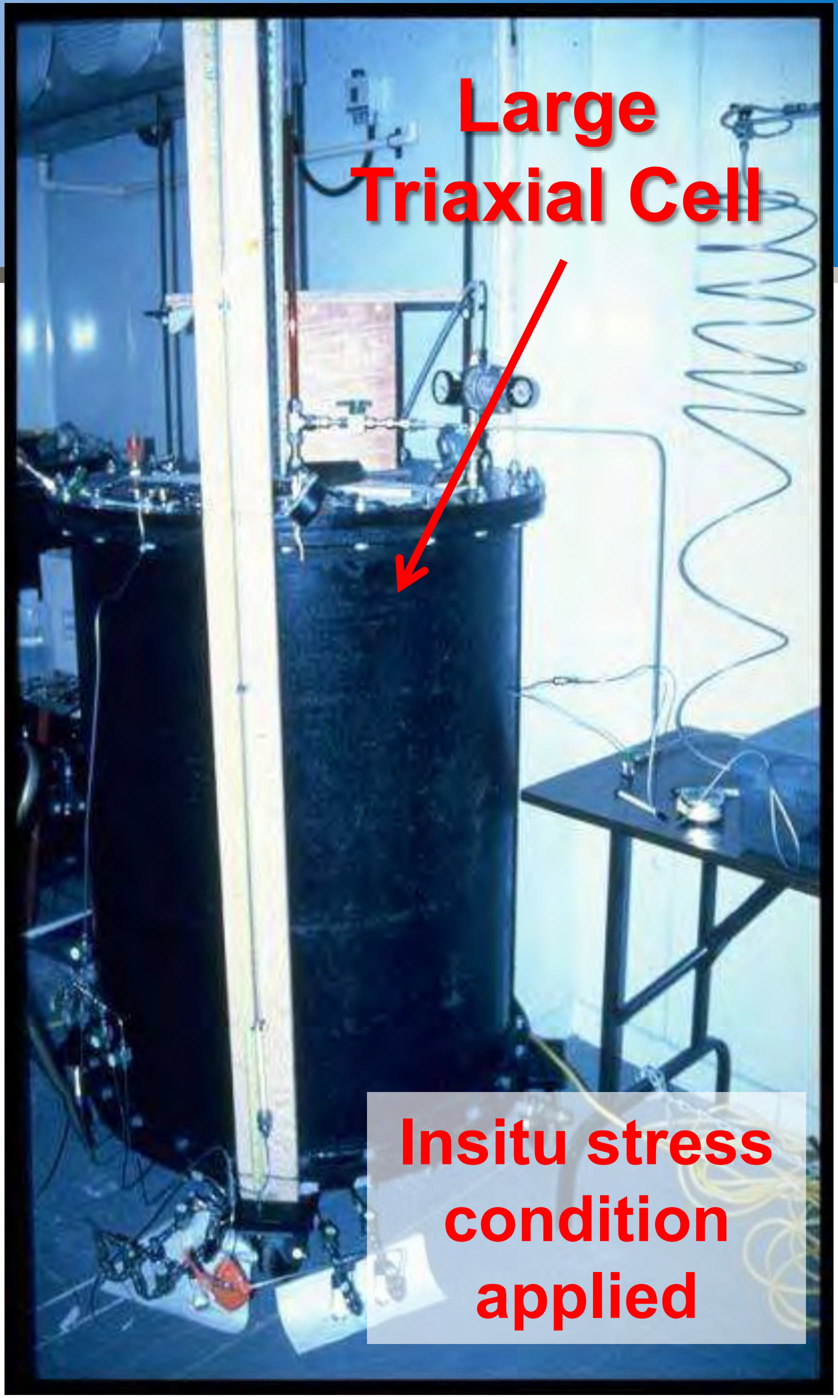
Hand-carved clay column




1. Hand cut clay column


2. Flexible Polymer Membrane


3. Steel container to lab



First test: Water Flow

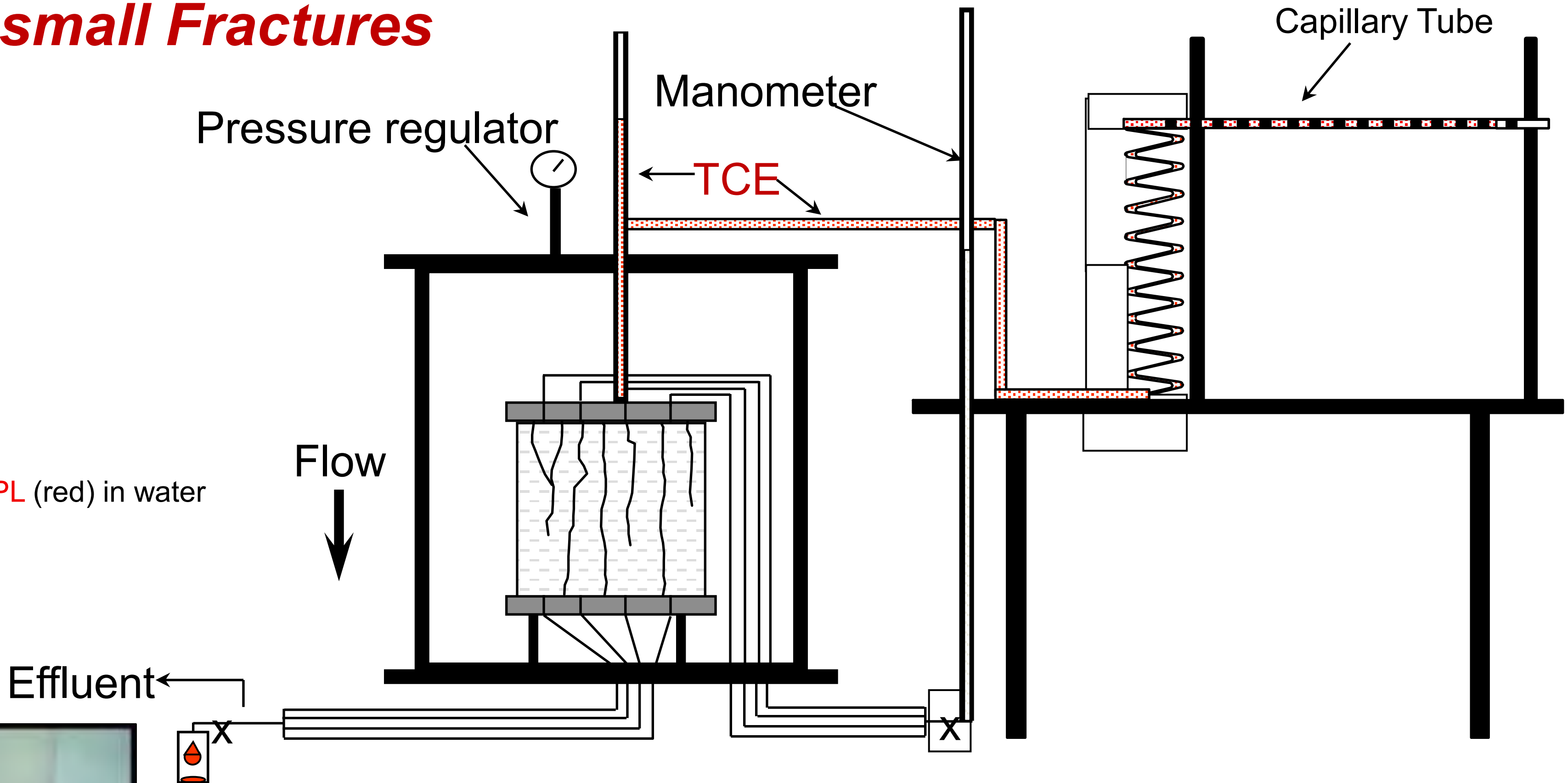
- Estimated fracture spacing = 23 cm
- Measured hydraulic gradients
- Measured Q = 1 ml/hr
- Calculated K_b
  - $K_b = 5.9 \times 10^{-8}$ cm/s - 1.1×10^{-7} cm/s
- Calculated fracture aperture

  = 4.6 μm - 5.8 μm

  based on the cubic law

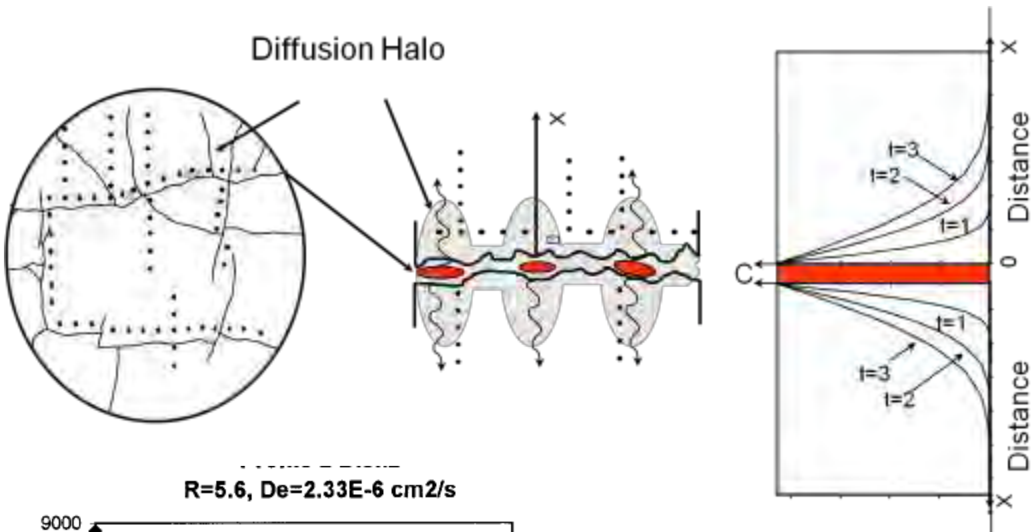
Second Test: TCE DNAPL Flow

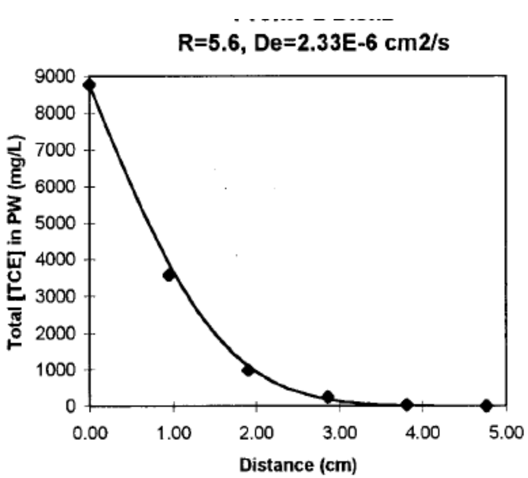
DNAPL flowed quickly through very small Fractures



TCE DNAPL (red) in water

Identify DNAPL Pathways Using Diffusion Halos





Measured Diffusion Profile

Fracture aperture estimates:
Extremely small fractures

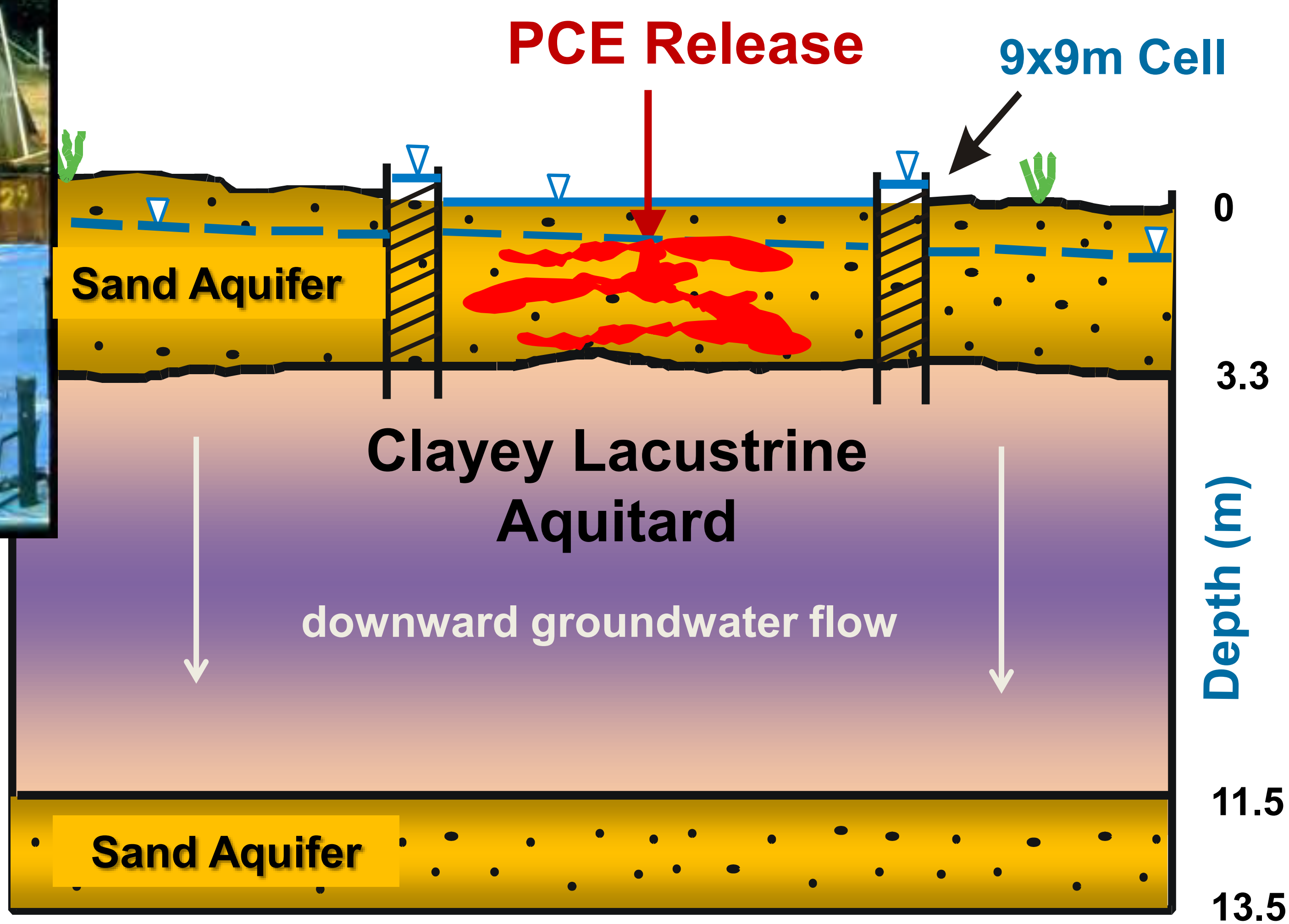
- Fracture apertures very small: $K_b \cong K_m$
- Average hydraulic apertures (parallel plate)
  - Visible fractures 4.6 – 5.8 μm
  - DNAPL identified channels 7.5 – 12.5 μm
- DNAPL entry pressure
  - Corresponds to an aperture of 16.4 – 30 μm

100 μm is the average diameter of a human hair

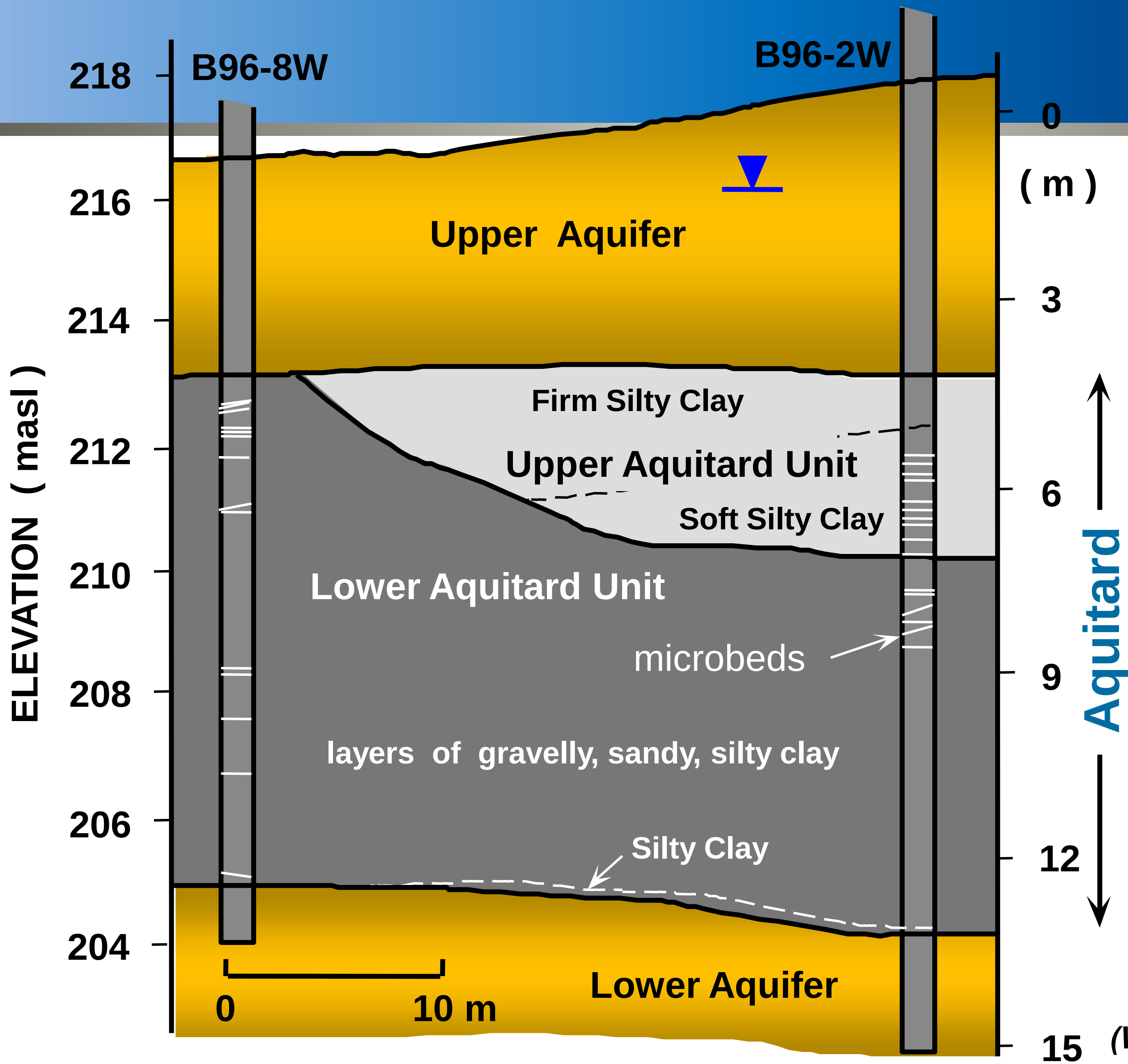

Hydraulic test shows aquitard K < 10 $^{-8}$ cm/s
Aquitard and sheet piling prevent detectable water leakage

Cell Prepared For Release of PCE DNAPL at Borden Site, 1991

Cherry confident that aquitard will allow no DNAPL penetration



Glaciolacustrine Aquitard



Deposited ~11,000 years ago

Grey unweathered clay

(W. Morrison MSc, 1998)

Red PCE DNAPL found on augers outside the cell

How could DNAPL escape the cell?

(photos by B.L. Parker)

Horizontal Microbeds

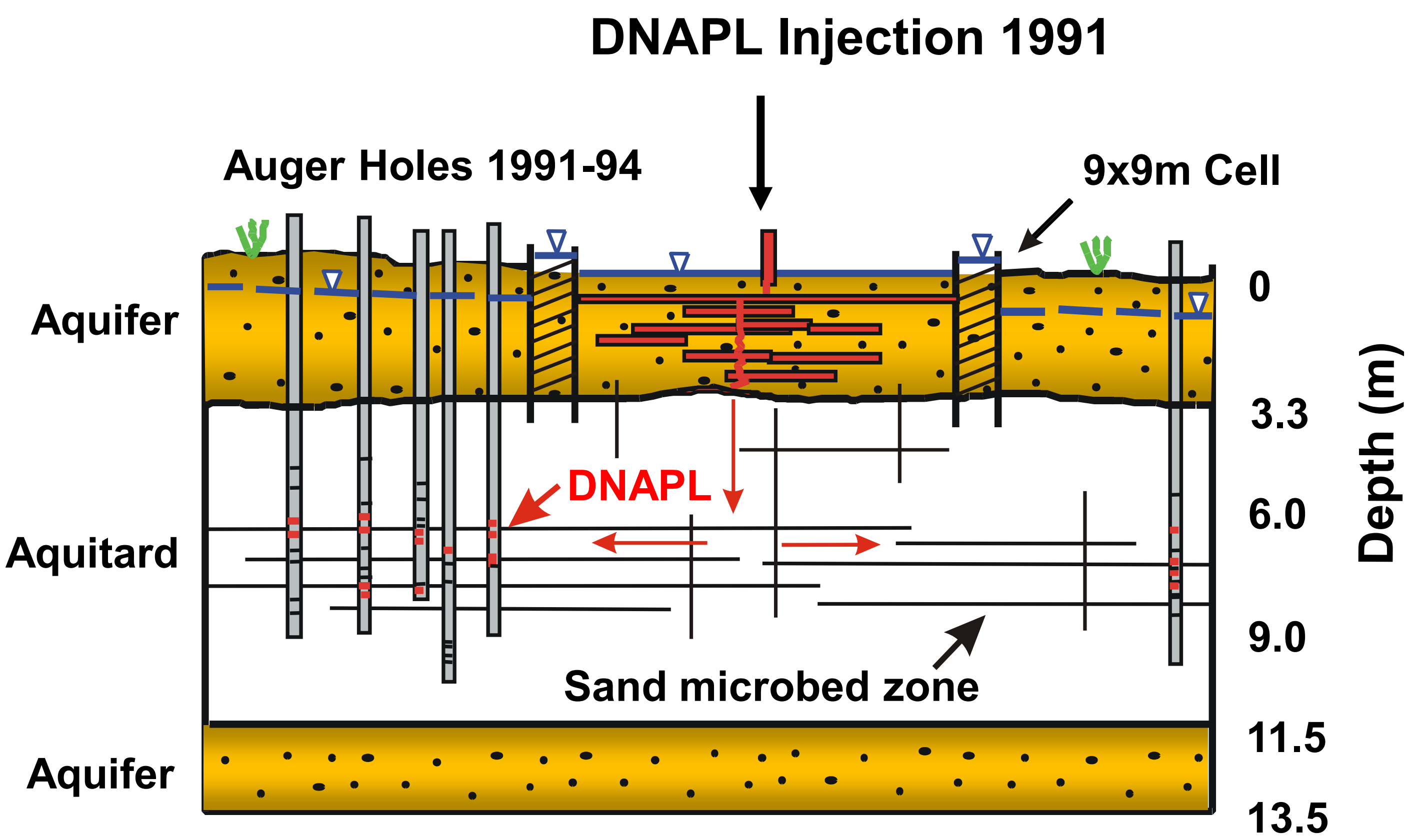
PCE in Thin Sand Bed

Dyed Red DNAPL in Sand Layer

(photo by S. Foley)

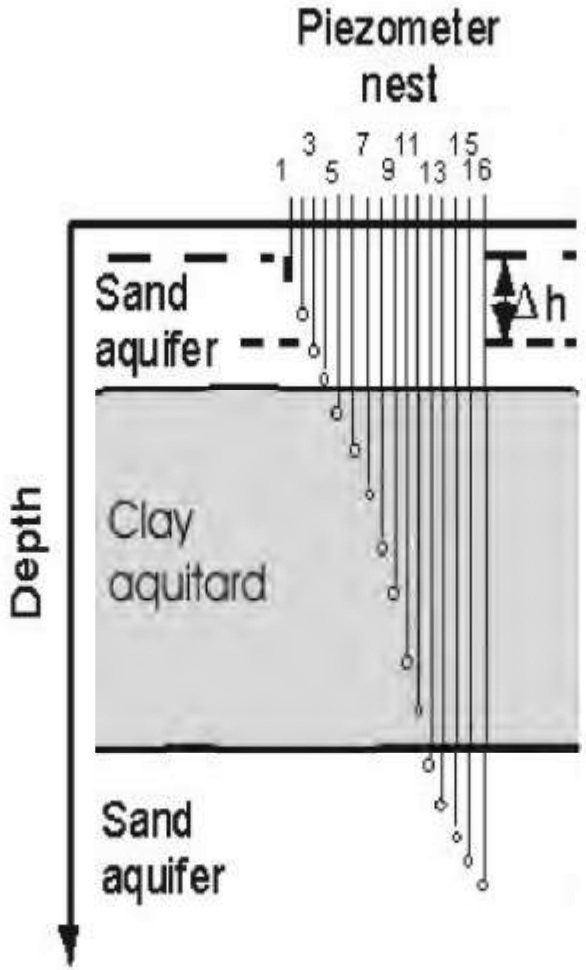
DNAPL Escaped by Downward Flow in Small Fractures and Horizontal Flow in Microbeds

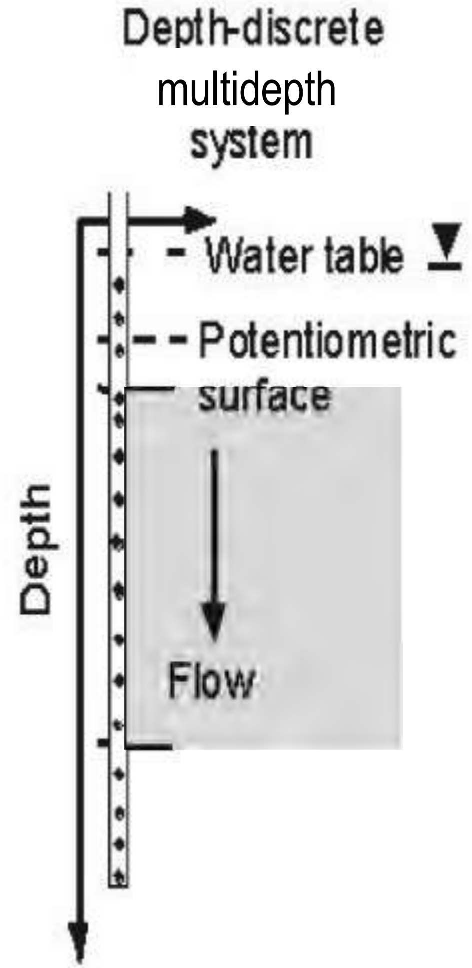
Red DNAPL pulled up on augers from aquitard outside the cell



(W. Morrison MSc Thesis, 1998)

Essential data for aquitard study: Hydraulic Head Profiles





The Four Commercially Available Multidepth Systems for Head Profiles

Westbay

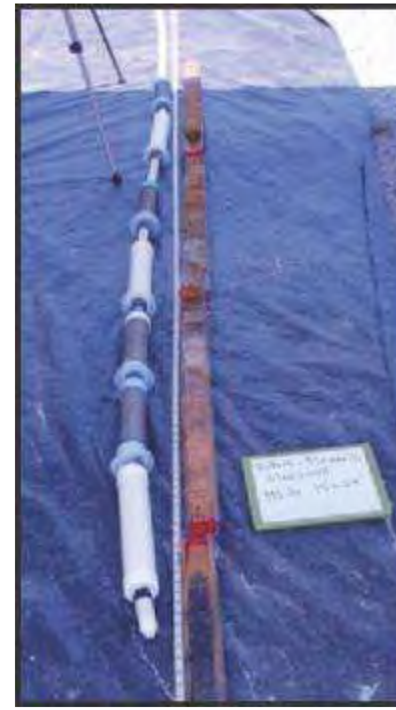
Schlumberger
WATER SERVICES

Vancouver

Waterloo

Solinst

Waterloo



Water FLUTe

FLUTe
Flexible Liner Underground Technologies, Ltd. Co.

Los Alamos and
Santa Fe

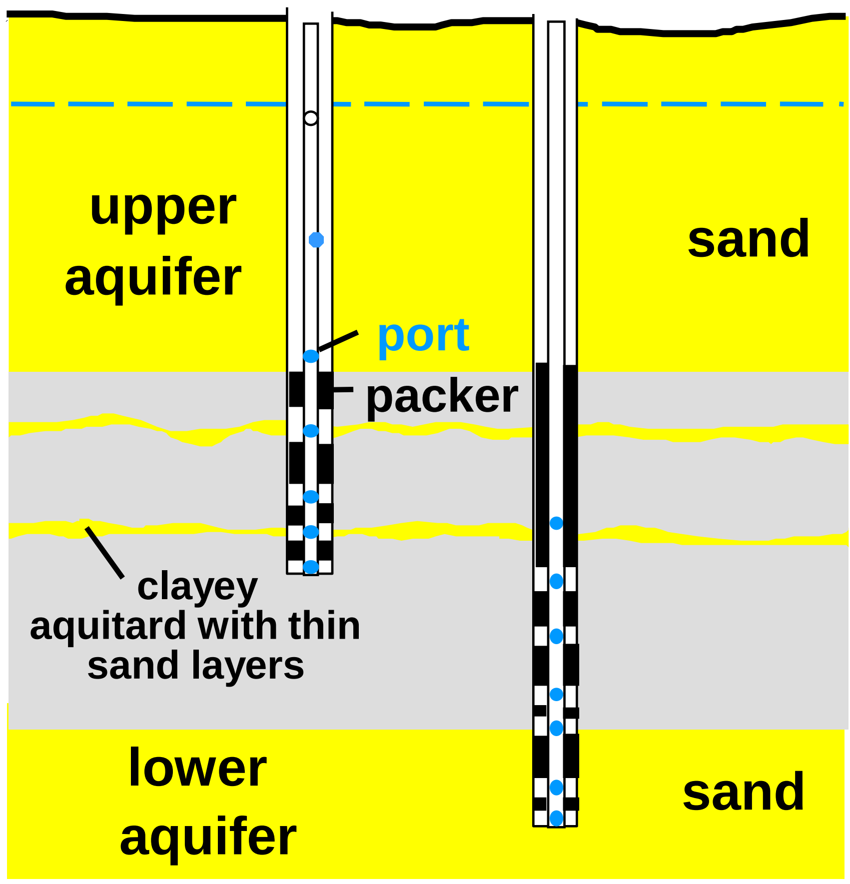
CMT

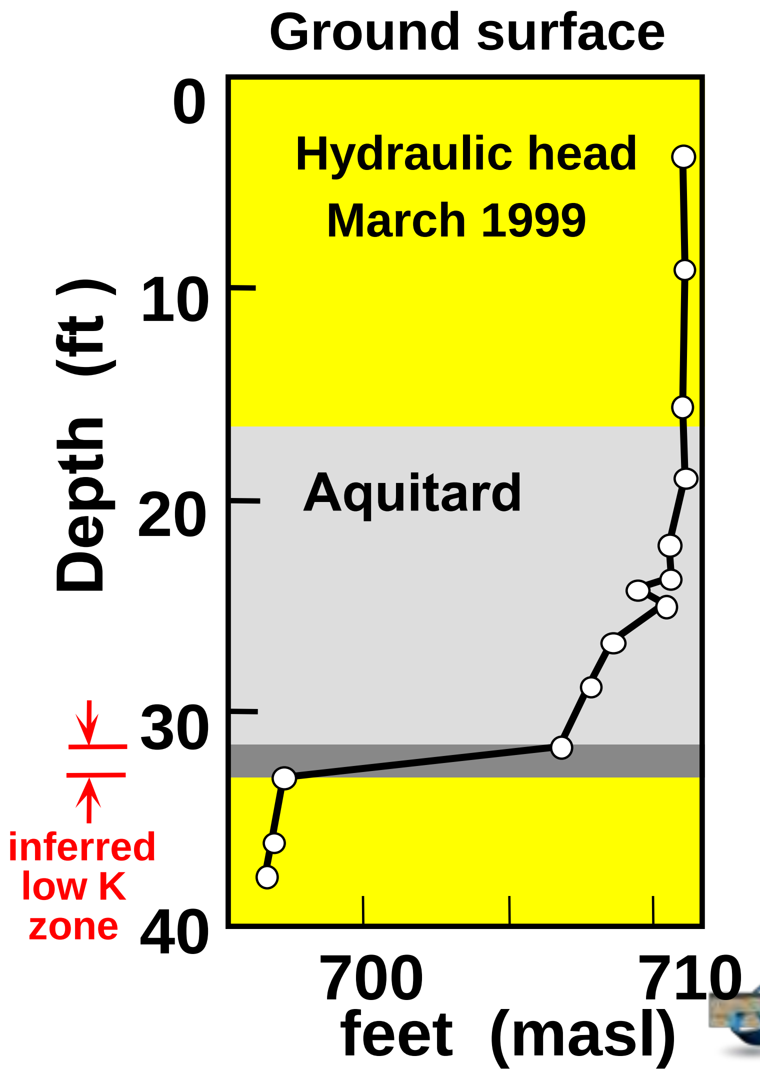
Solinst

Palo Alto

Borden Aquitard: Head Profile Shows Nearly all Resistance Occurs Across 2 ft Zone at Bottom of Aquitard

CMT multi-levels

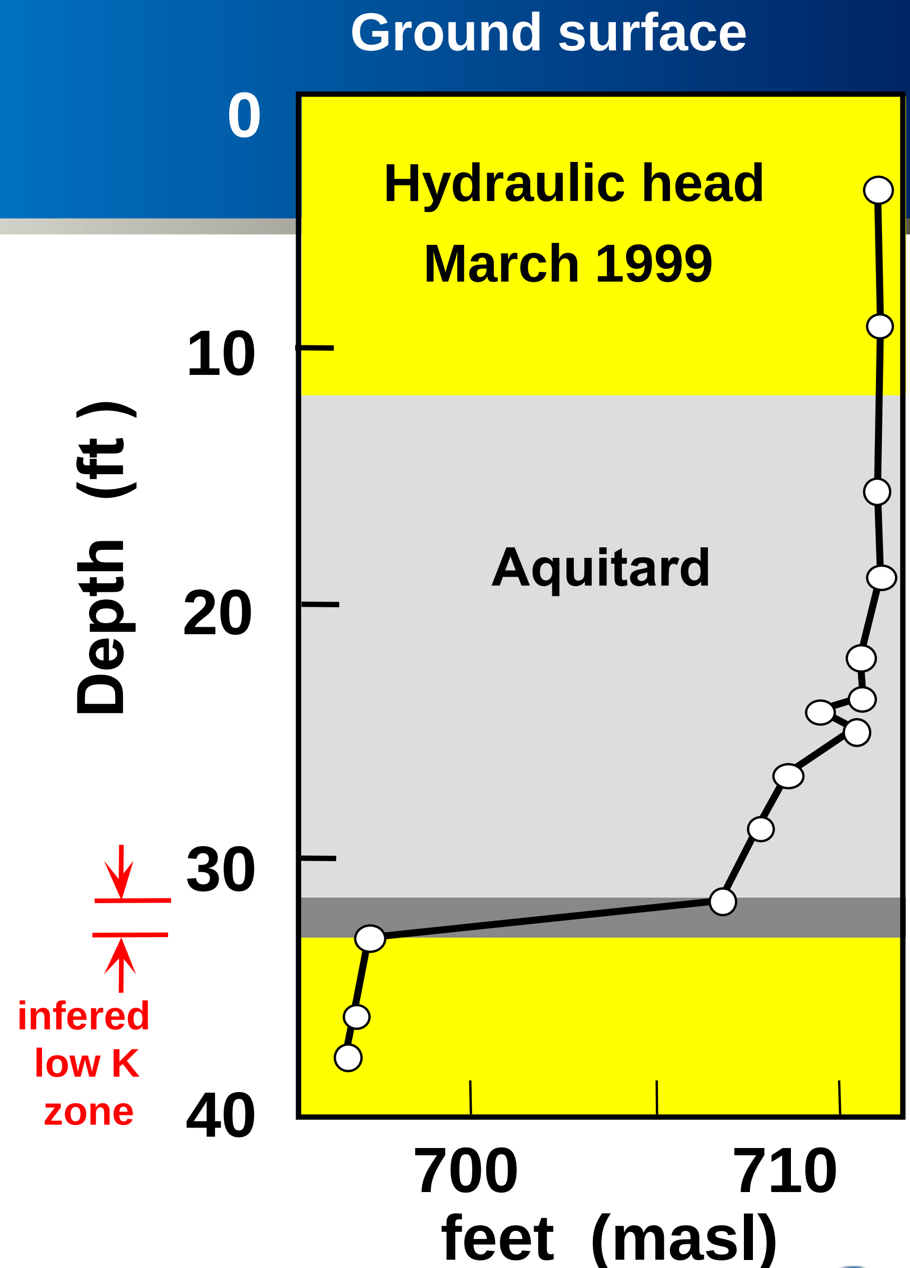




(Meldrum BSc. 1999)

Borden Aquitard:

This detailed vertical hydraulic head profile indicates a much higher K_v in the upper part of the aquitard

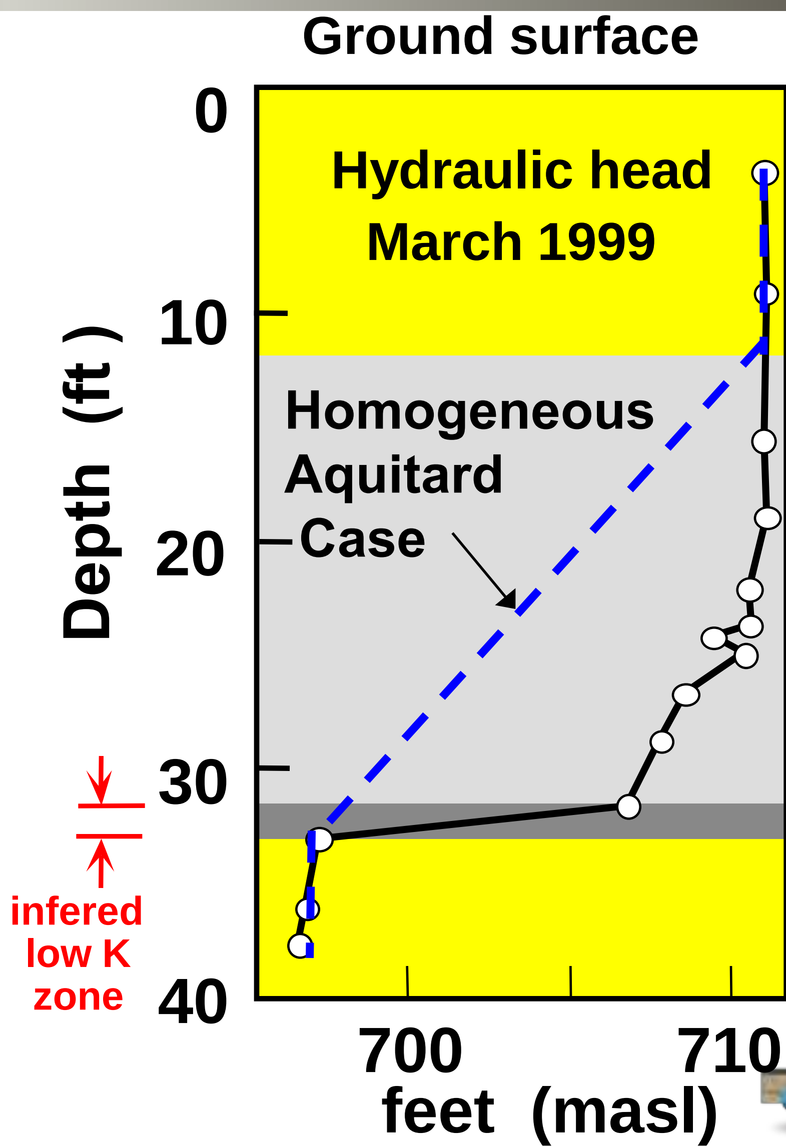


Why?

Vertical Fractures can be Inferred from Shape of Head Profile

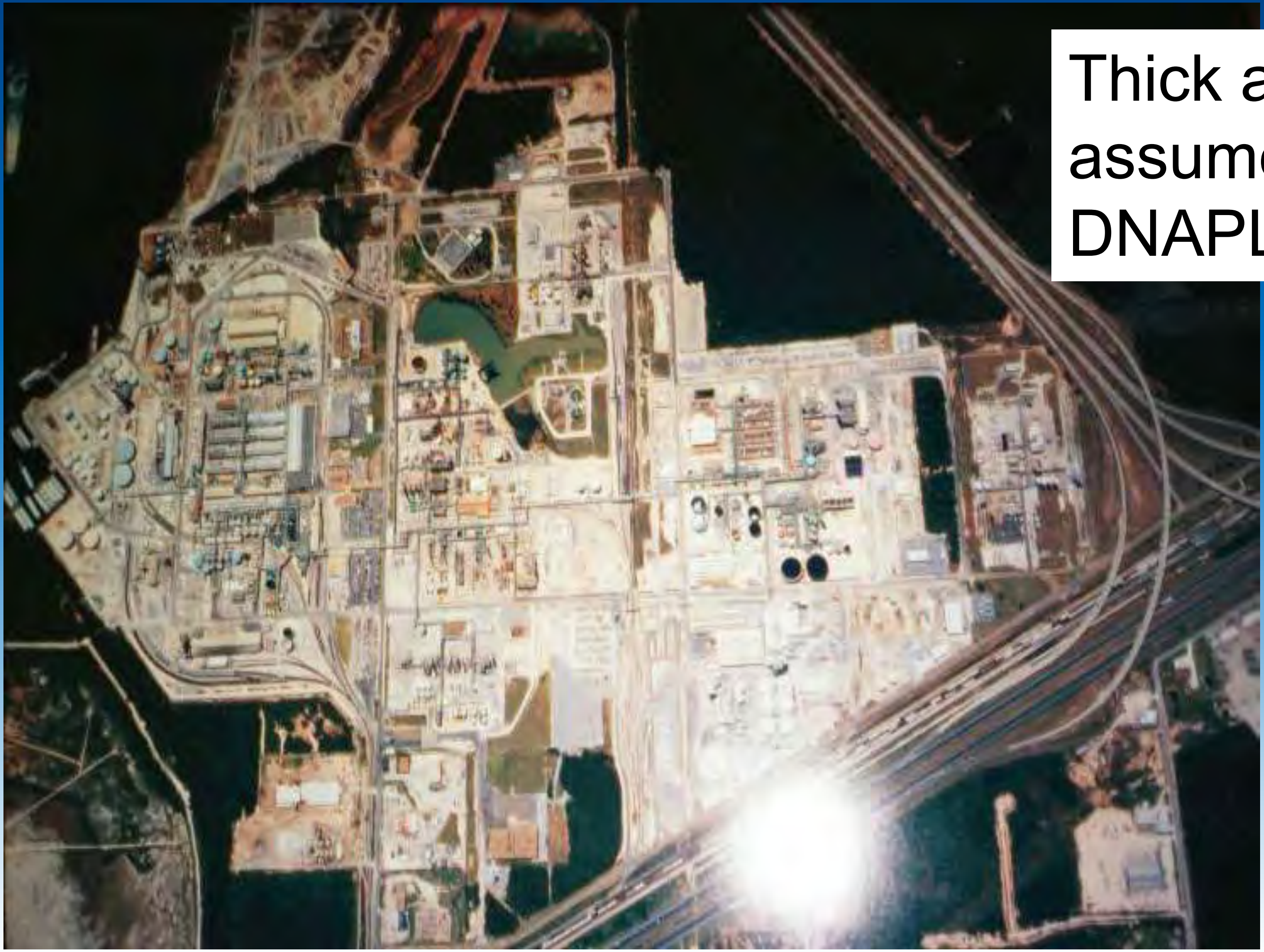
Indicates a much higher K_v in the upper part of the aquitard

Because of lesser hydraulic gradient with depth

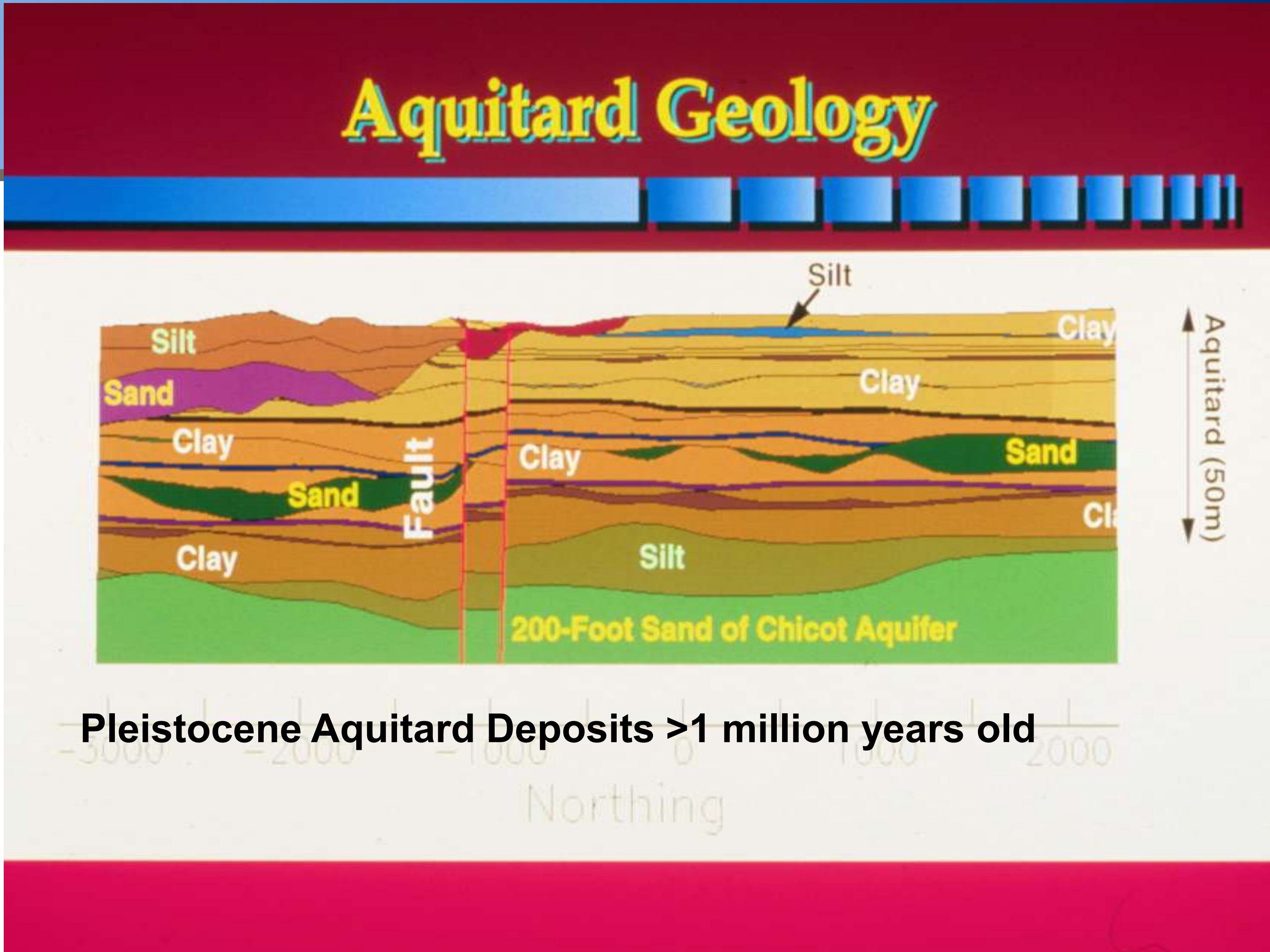


Petrochemical plants typically have abundant DNAPL in the subsurface

Example Petrochemical Plant in Lake Charles, Louisiana

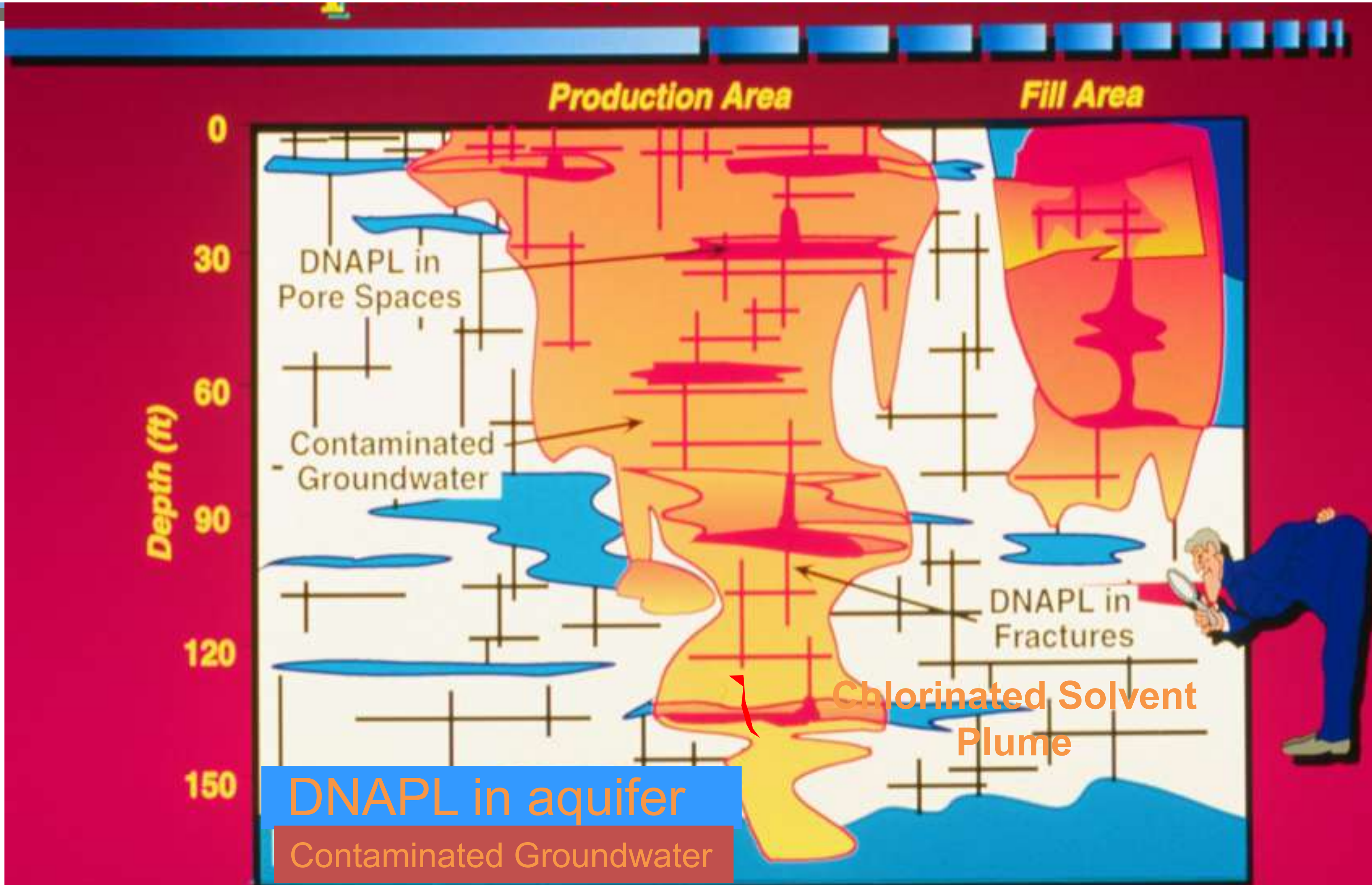


Thick aquitard assumed to be DNAPL barrier



Pleistocene Aquitard Deposits >1 million years old

DNAPL passed through aquitard into regional sole source aquitard



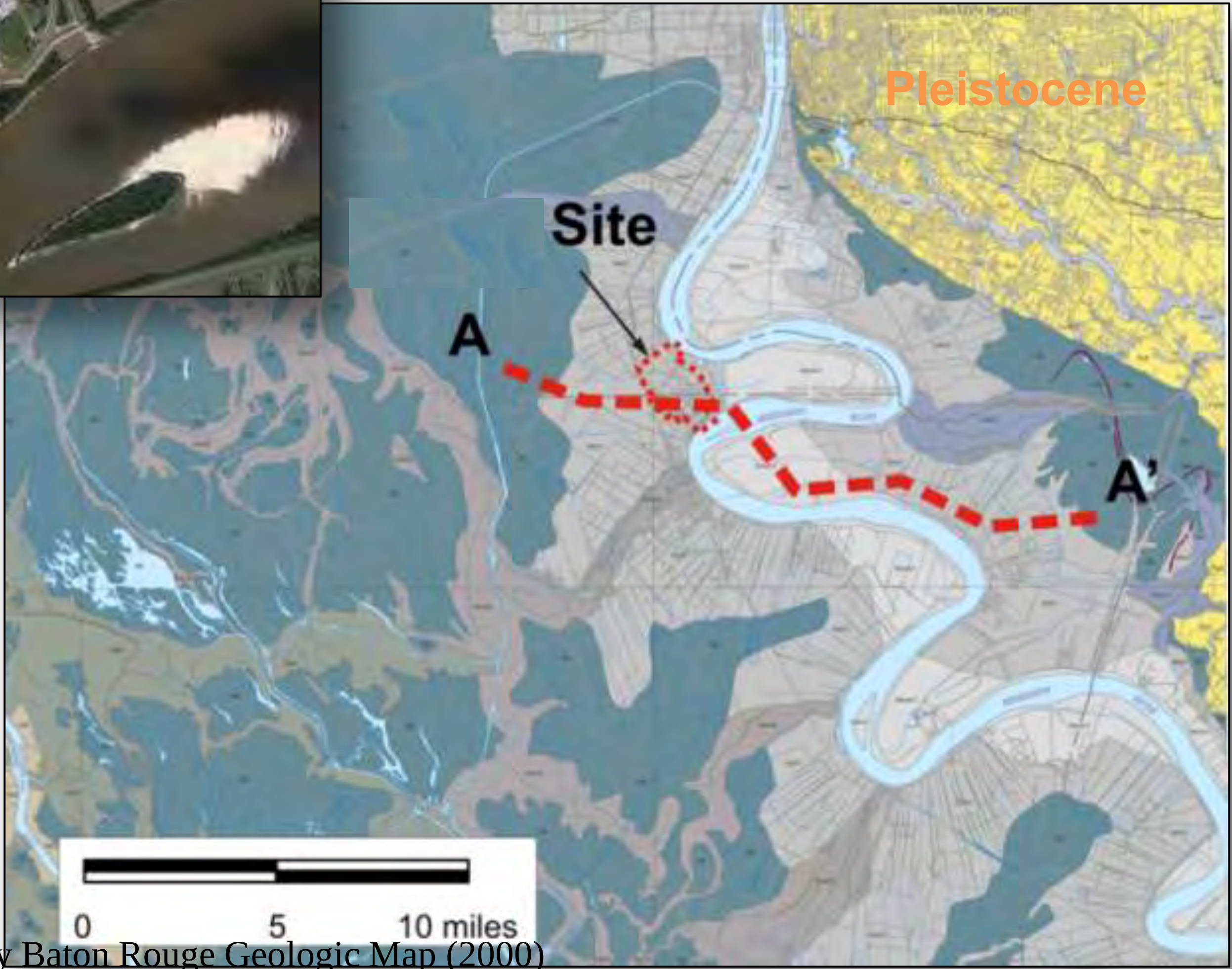
Integrity of Louisiana Aquitards

Previous studies of clayey Louisiana aquitards at contaminated sites show poor integrity due to secondary permeability caused by fractures, root and worm holes

However, only Pleistocene aquitards have been investigated

Case study; Holocene Aquitard (2004-2011): Groundwater contamination beneath regional aquifer near Baton Rouge

Large Chemical Production Facility

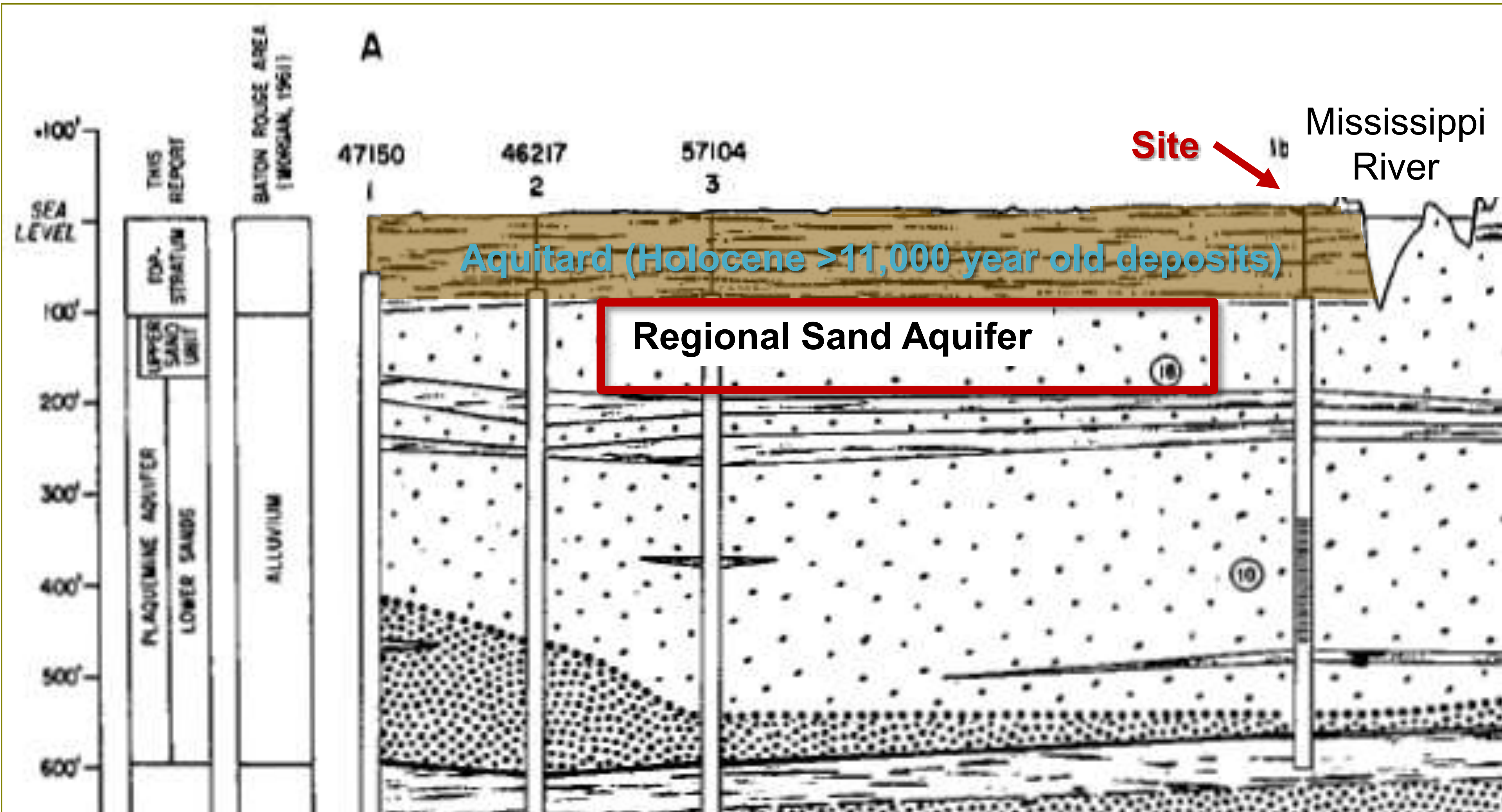


Regional Surficial Geological Map, Site Location and Whiteman (1972) Cross-Section

Adapted from Louisiana Geological Survey Baton Rouge Geologic Map (2000)

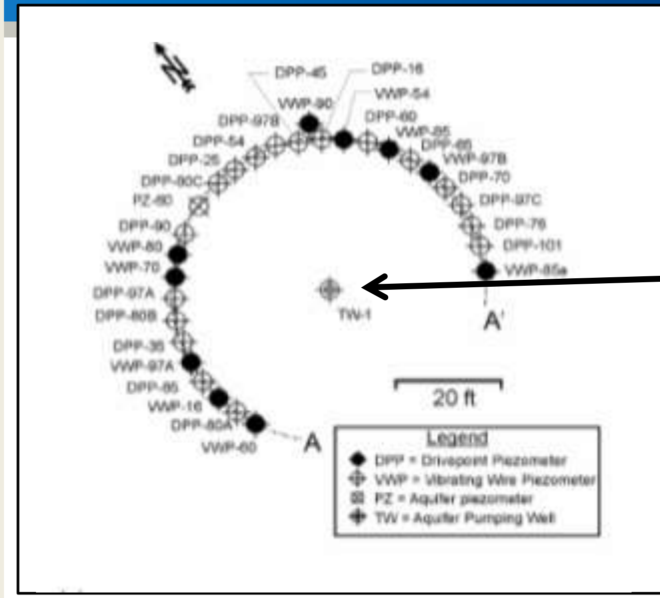
Aquifer Contamination: Only cis-DCE and Vinyl Chloride Present
All concentrations below 50 µg/L

Clayey aquitard ~ 100ft thick



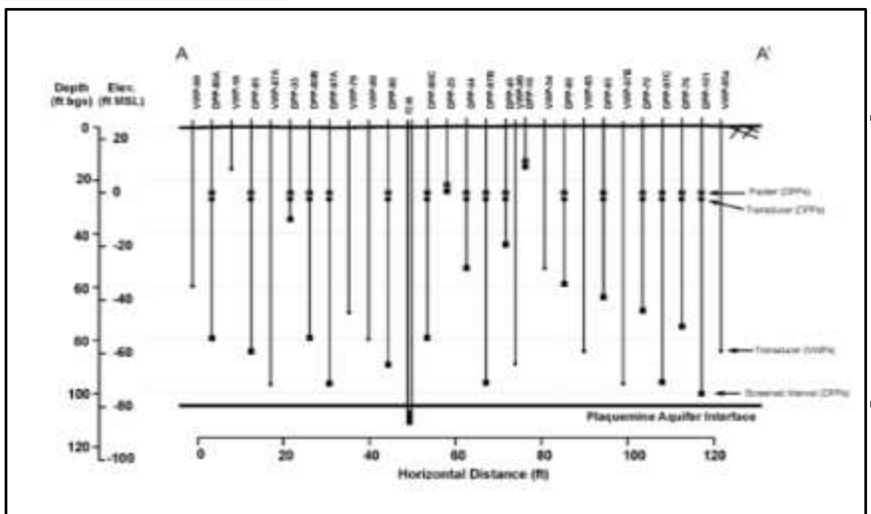
Water Resources Bulletin No. 16, Department of Conservation Louisiana Geological Survey and Louisiana Dept. of Public Works, 1972.

Detailed Piezometer Cluster in Uncontaminated Area to obtain profiles



Large Capacity Well for Pumping Tests

Piezometer Array



AQUITARD

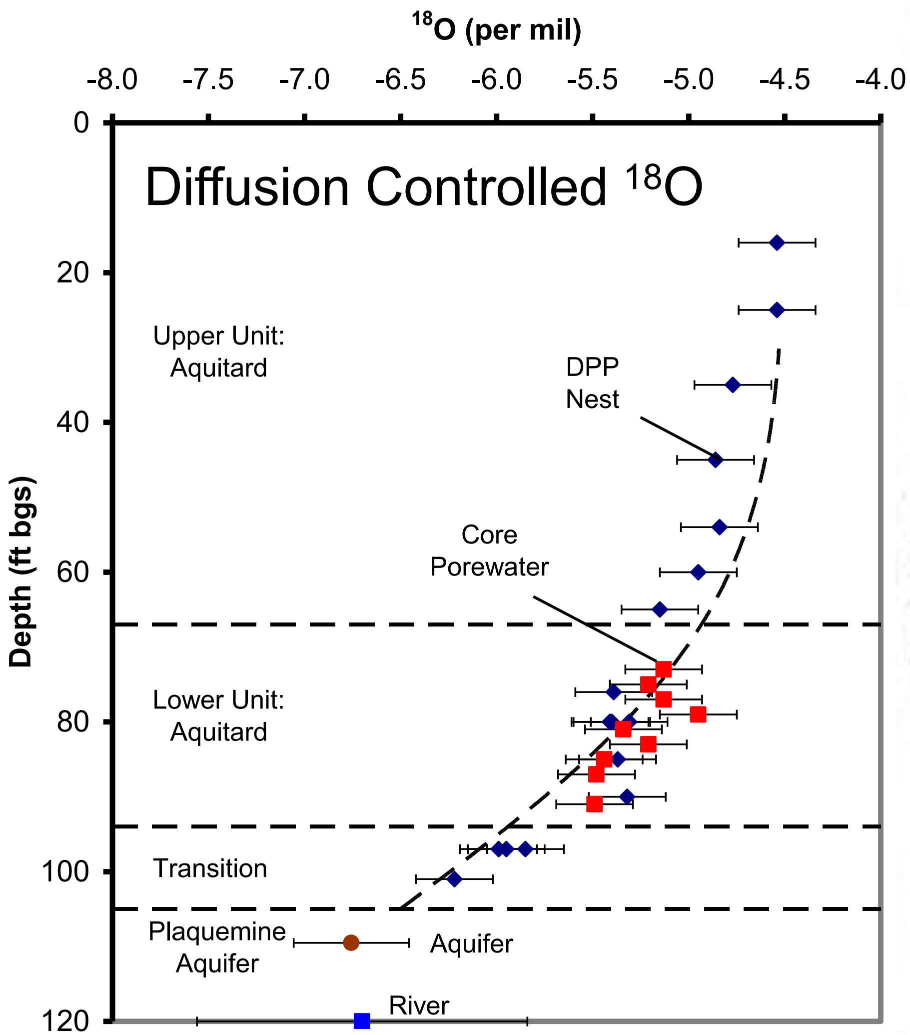
Parker et al. unpublished data

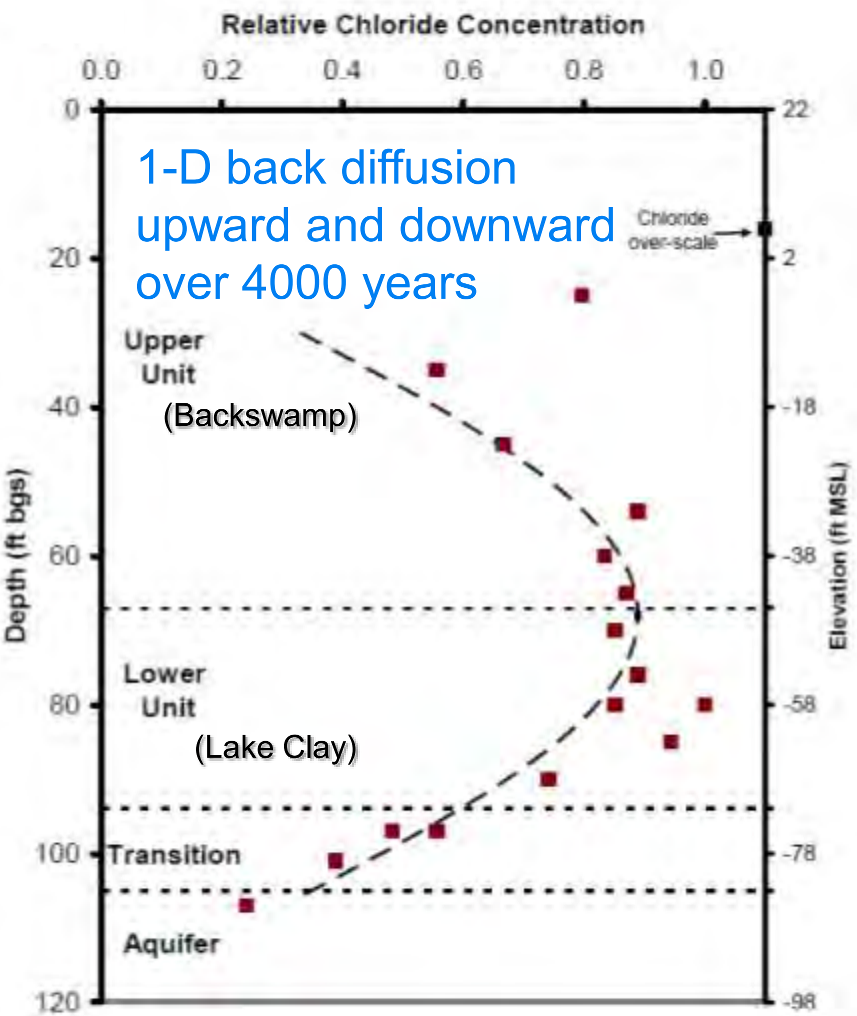
Types of Piezometers Used in the Aquitard

UV Drive-Point Piezometer

Drive-Point Piezometer with Vibrating Wire Transducer (VWP)

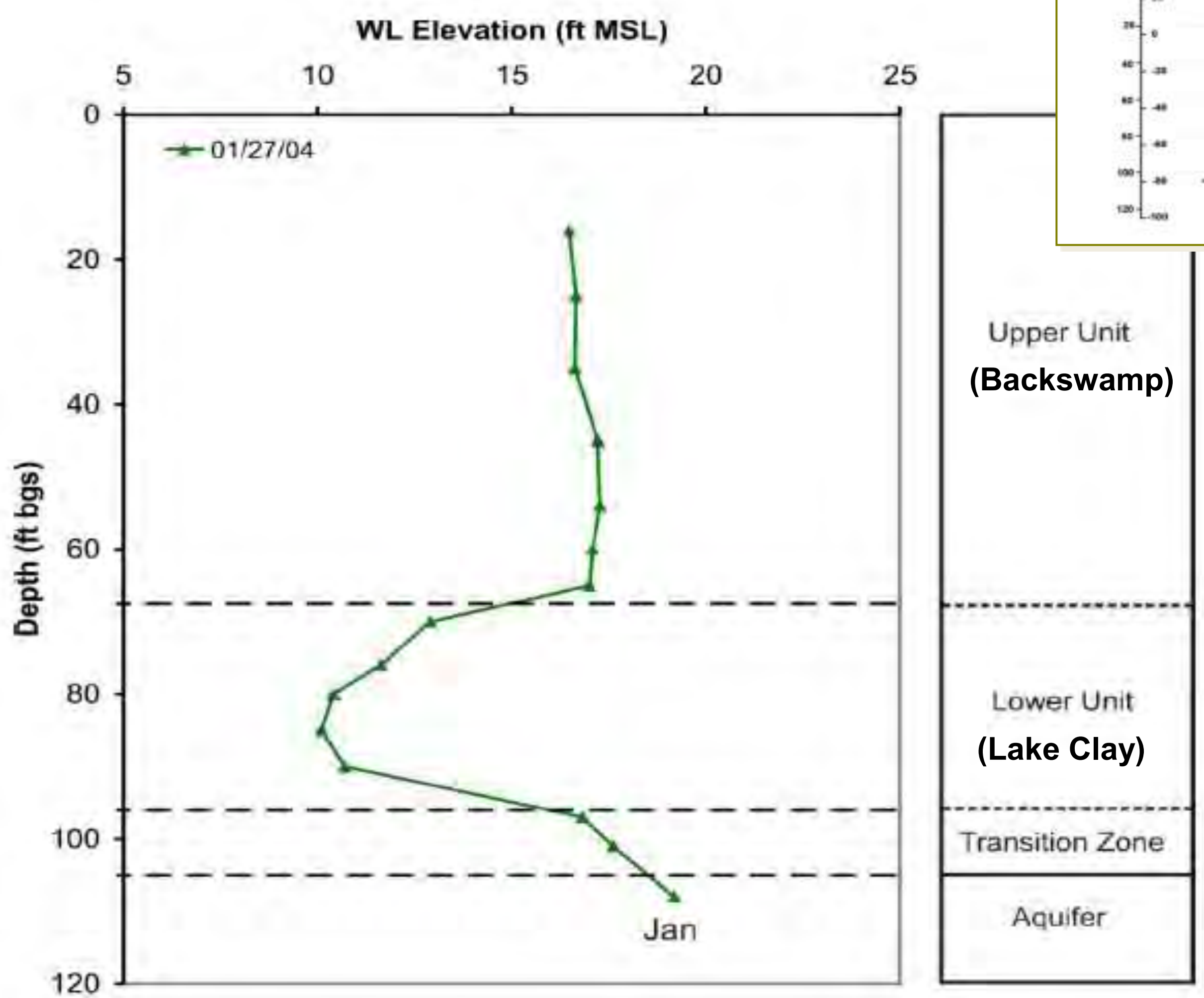
Stable isotopes and chloride profiles show diffusion control suggesting excellent aquitard integrity

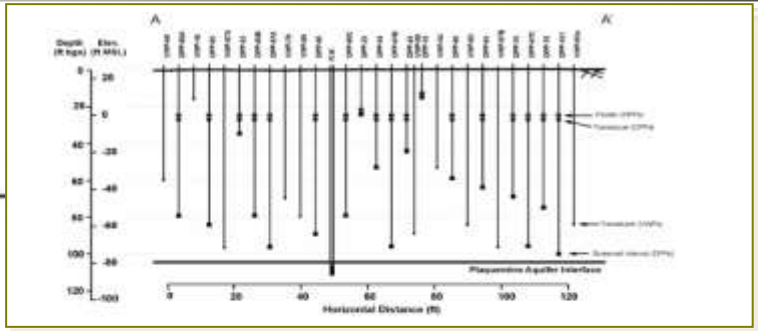




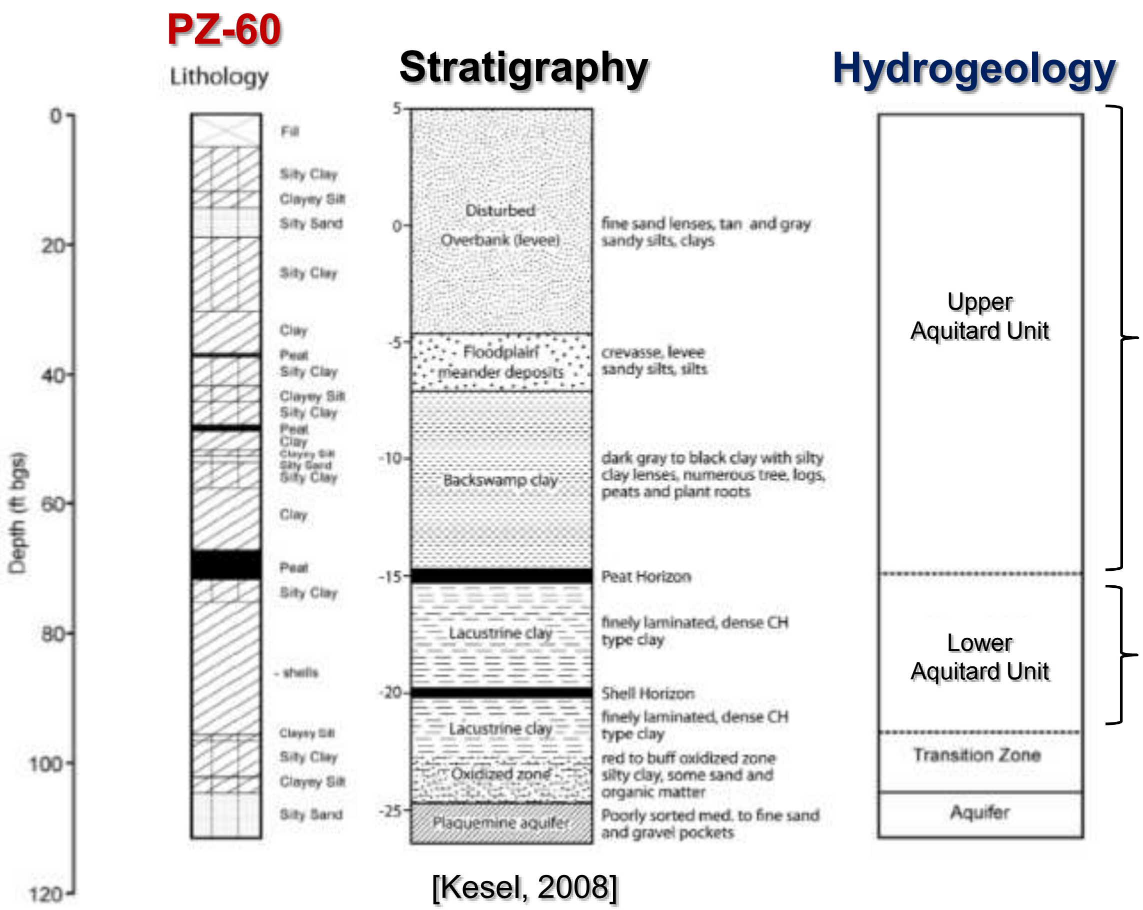
Contaminants did not go through the aquitard

Head profiles also show diffusion control suggesting excellent aquitard integrity





Bottom zone in aquitard is of lacustrine origin



[Kesel, 2008]

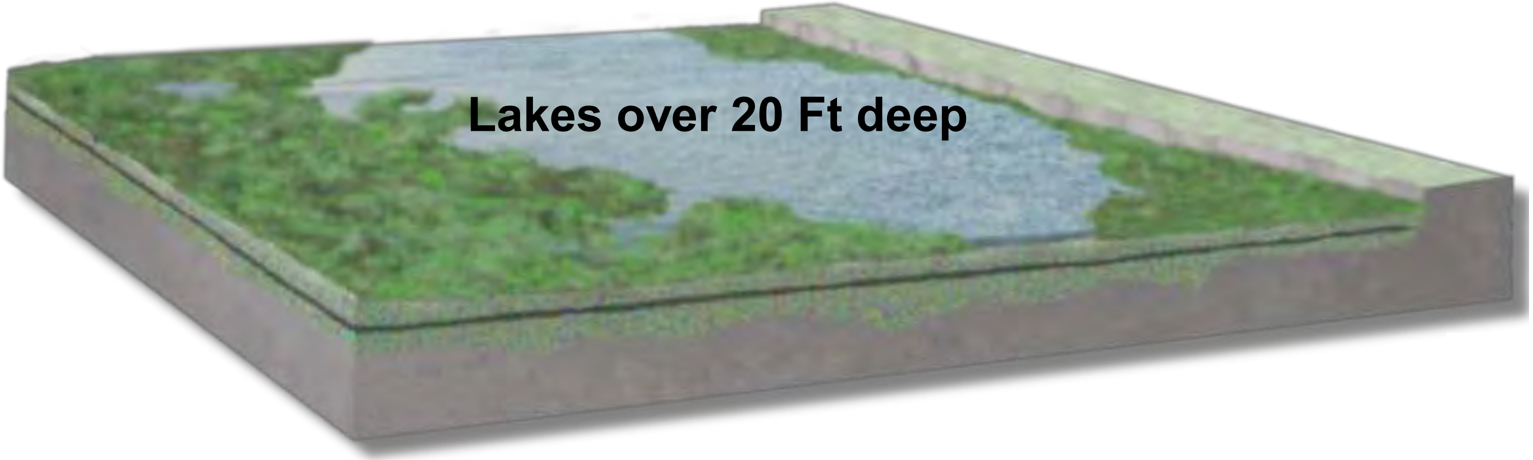
Backswamp deposits: higher vertical K due to fractures, rootholes animal burrows and weathering

Lacustrine deposits: No evidence of secondary permeability features and weathering

1927 Mississippi Flood Carries Large Load of Mud deposited widely

11,000 – 8,000 Years Ago (Holocene Time)

Larger Lakes Created by Frequent Flooding of Ancient Mississippi River



Key Points: Geology is most important

The aquitard has high integrity due to nature of both aquitard units:

- High DNAPL storage capacity by sandy layers and organic matter in fractured backswamp deposits prevents DNAPL from descending to top of lacustrine unit

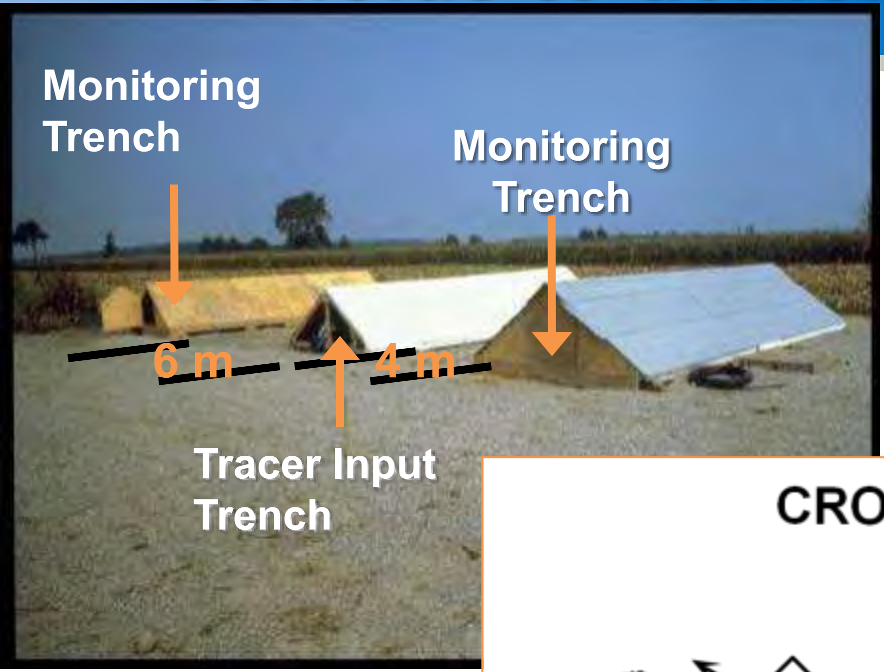
- Deep lacustrine unit: diffusion controlled

Contaminants have not moved through aquitard to aquifer

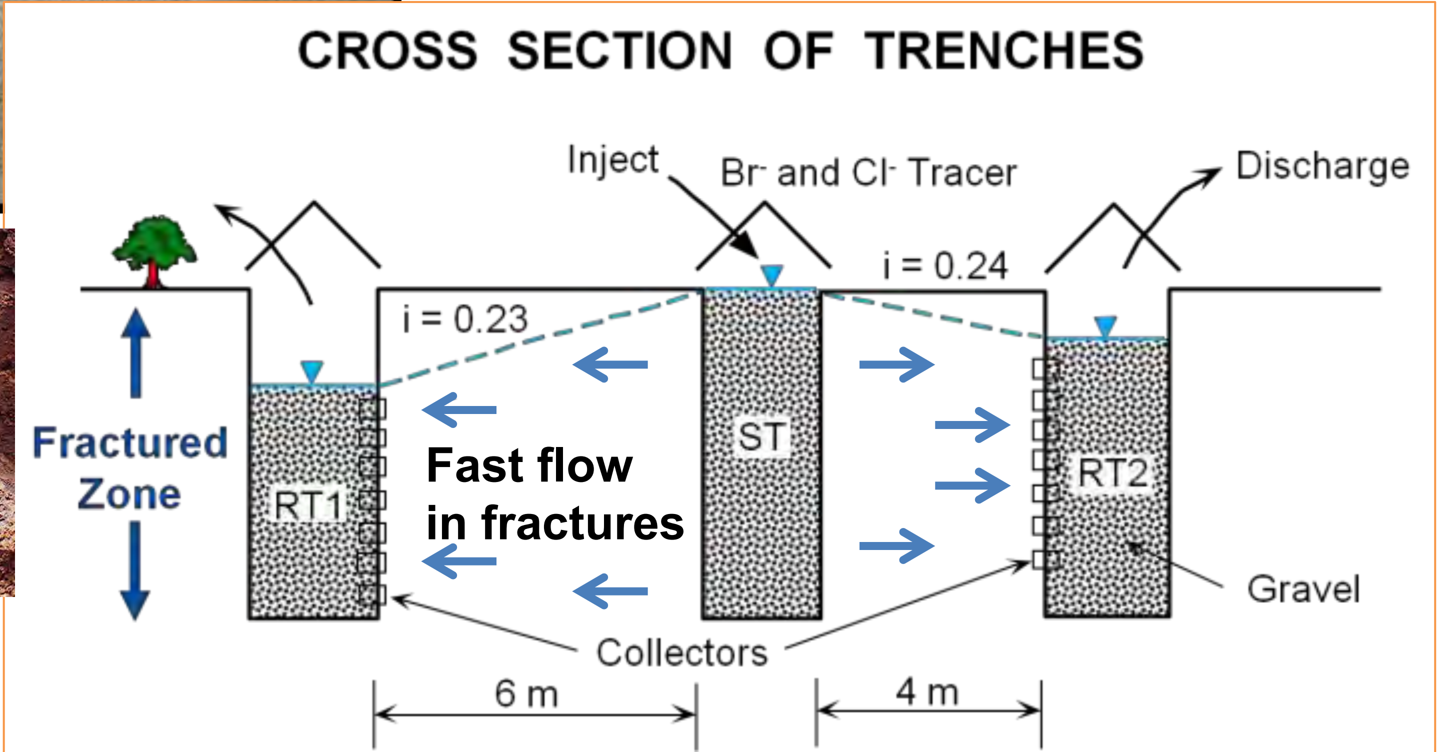
Viruses, Fractures and Aquitards

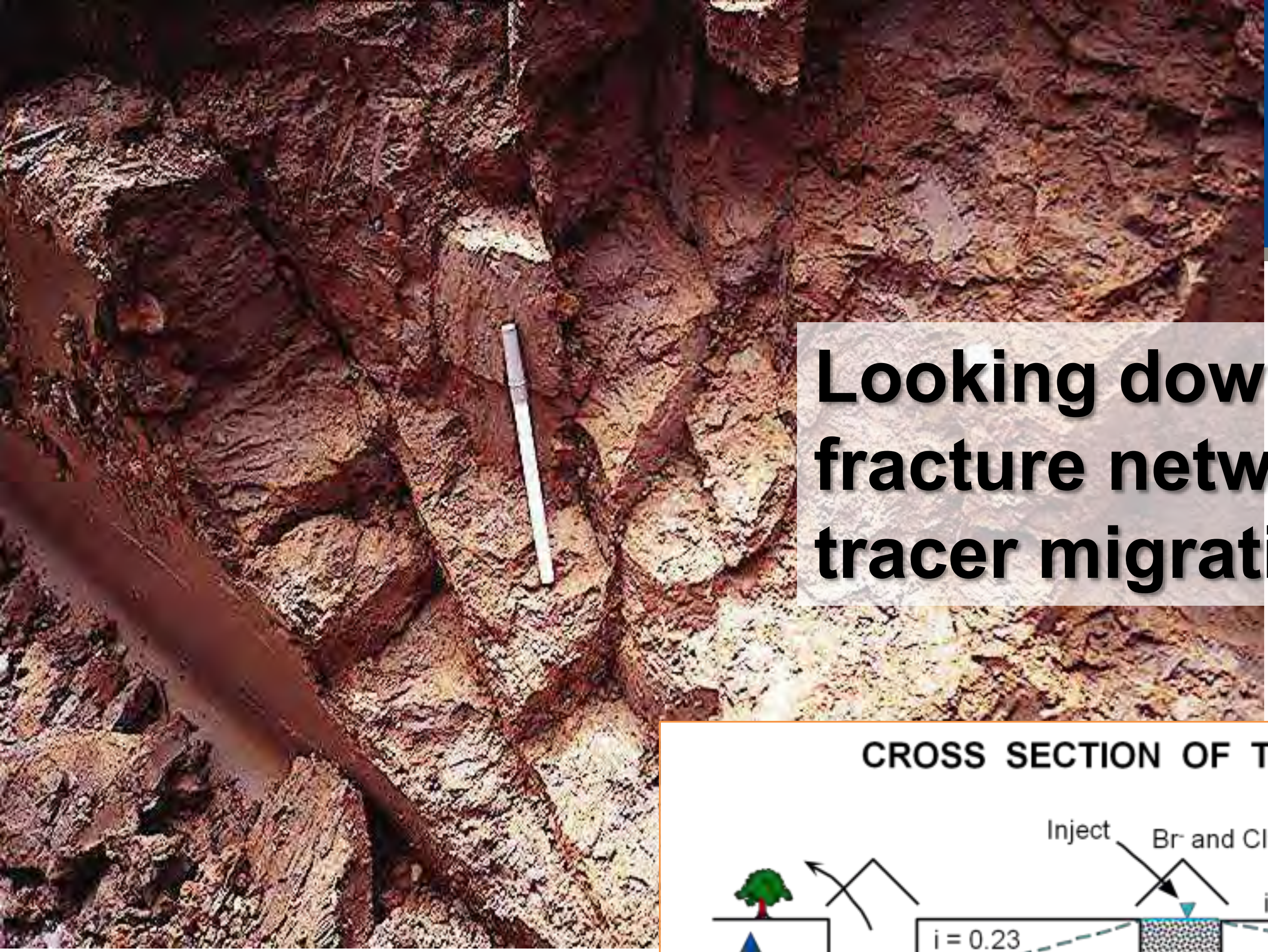
Viruses are colloid sized and have a life span less than ~2 years in the subsurface

Field experiment using solutes and colloids to demonstrate matrix diffusion

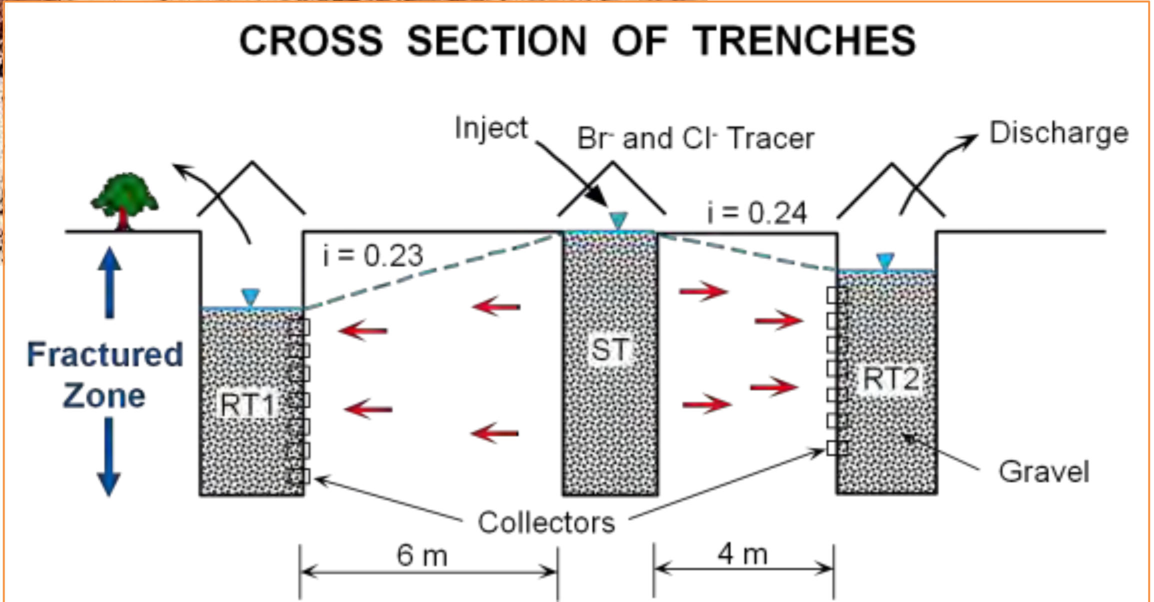


Larry McKay, PhD Thesis
Papers Published in WRR and ES&T 1993





Looking downward at fracture network in tracer migration zone



Fracture Apertures

5 to 30 microns

Installing Seepage Collectors On Trench Walls

Tracer trench being instrumented with vertical seepage meters on wall

Predicted Rapid Calculated Linear Groundwater Velocity in Horizontal Direction in Vertical Fractures

$$\bar{v} = \frac{\textit{Darcy Flux}}{\textit{Bulk Effective Porosity}}$$

Bulk K ~10^{-6}

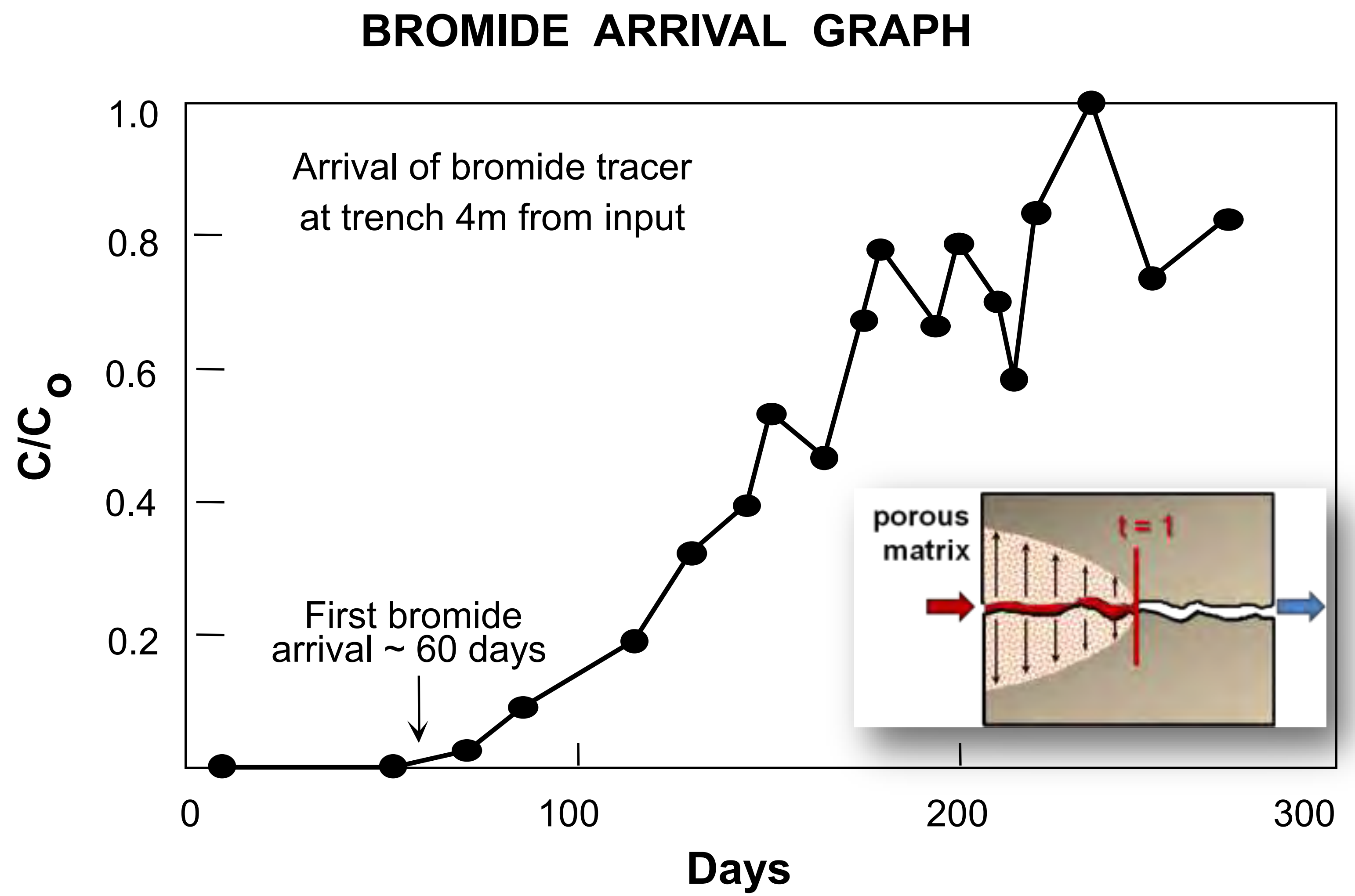
$$\bar{v} = \frac{K_b}{\phi_f}\frac{\Delta h}{\Delta L} = \text{ A few meters / day}$$

where ϕ_f = fracture porosity

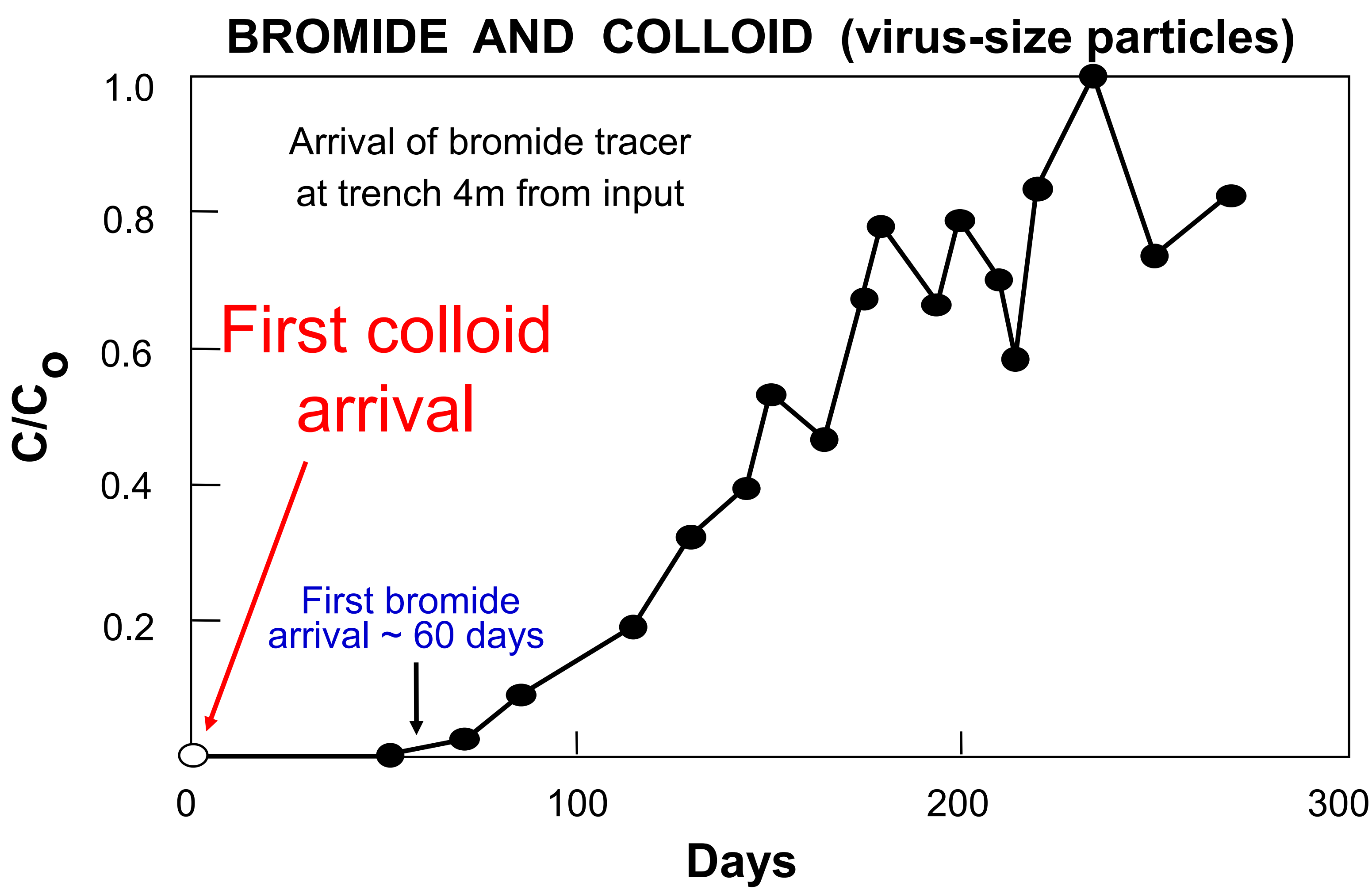
~ 10^{-3} to 10^{-4}

(calculated from the cubic law)

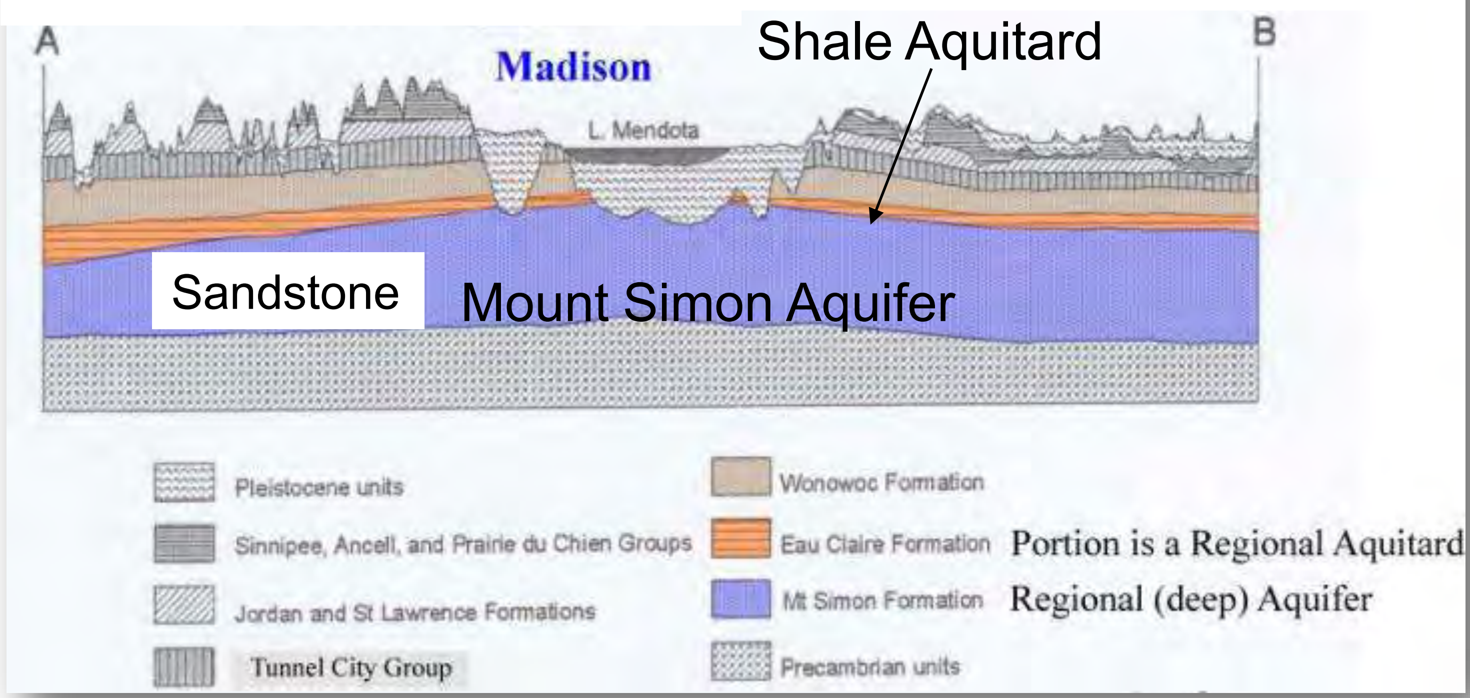
Diffusion Causes Strong Retardation of Bromide Arrival Relative to Calculated $\overline{v}$



Colloids do not diffuse and therefore arrived much faster than bromide
Virus-sized particles moved fast through very small fractures

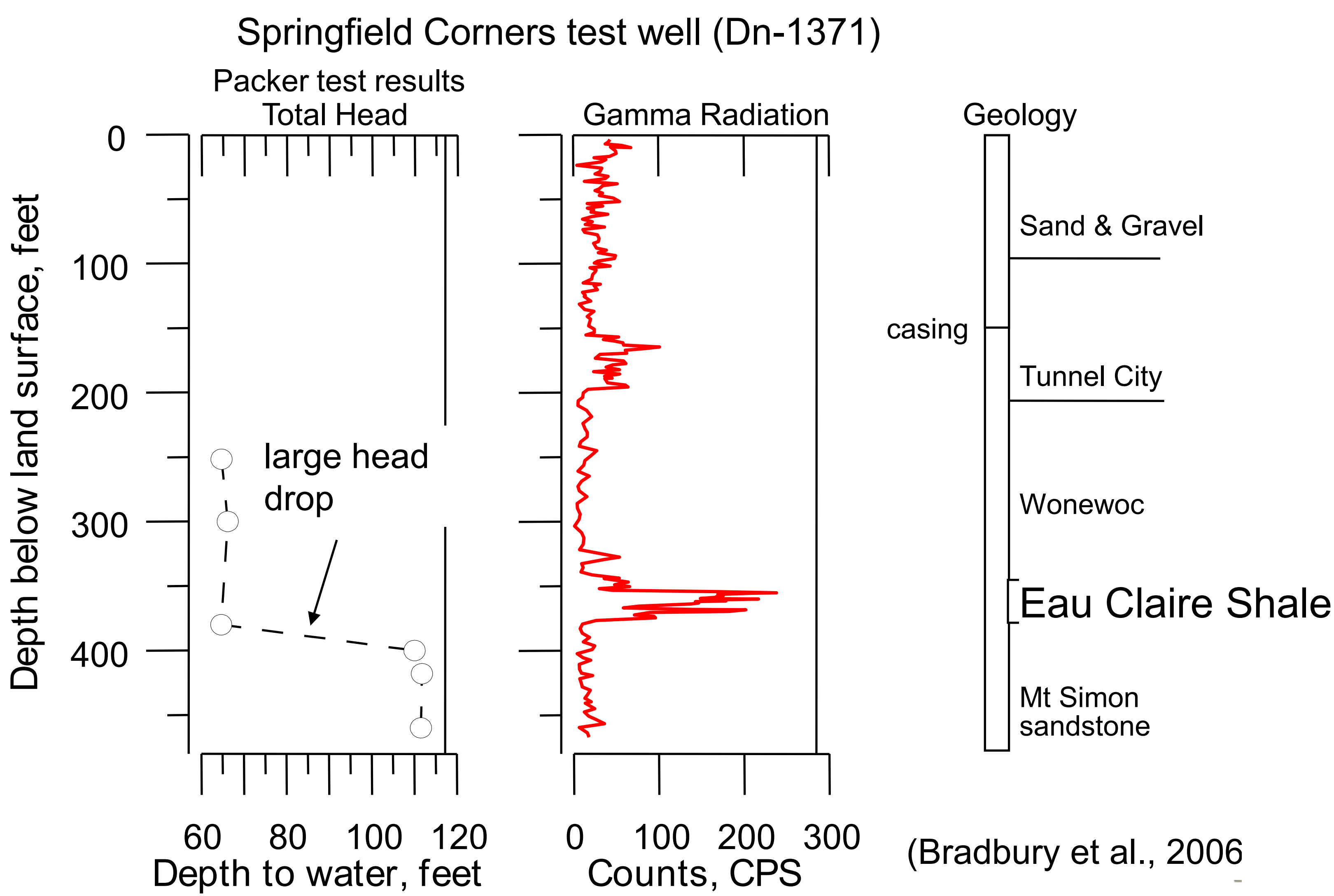


Municipal Water Supply: Mt. Simon Aquifer, Beneath the Shale Aquitard



From Massie-Ferch 1997

Aquitard Thickness Indicated by Head Profile and Gamma Log



(Bradbury et al., 2006

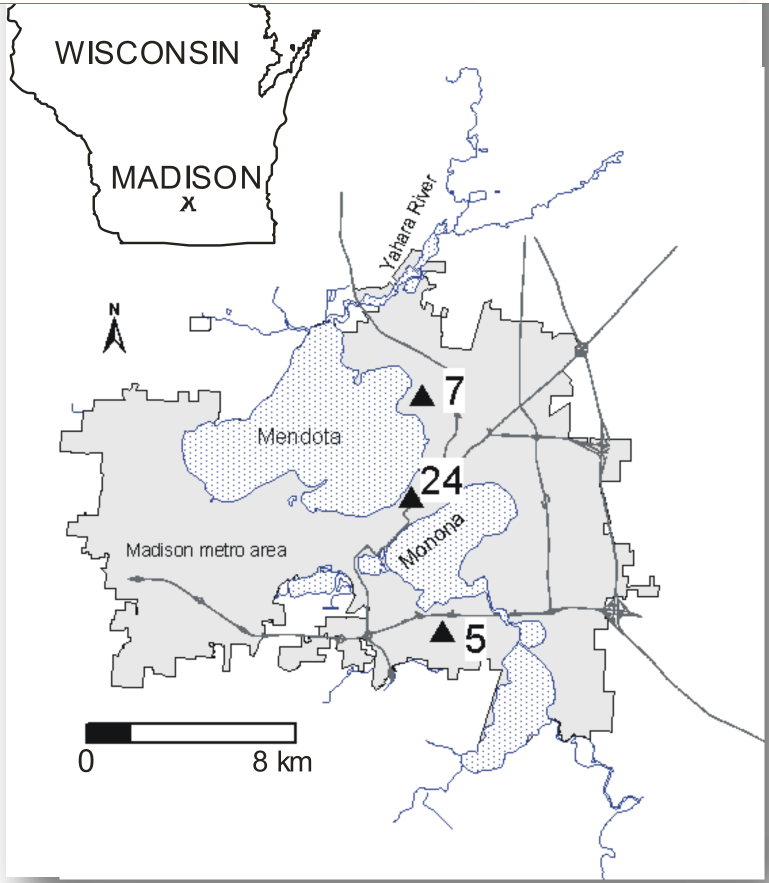
Human Viruses from Leaky Sewers Found in Municipal Wells Madison, WI, 2005

Human Enteric Viruses in Groundwater from a Confined Bedrock Aquifer

Mark A. Borchardt, Kenneth R. Bradbury, Madeline B. Gotkowitz, John A. Cherry, and Beth L. Parker

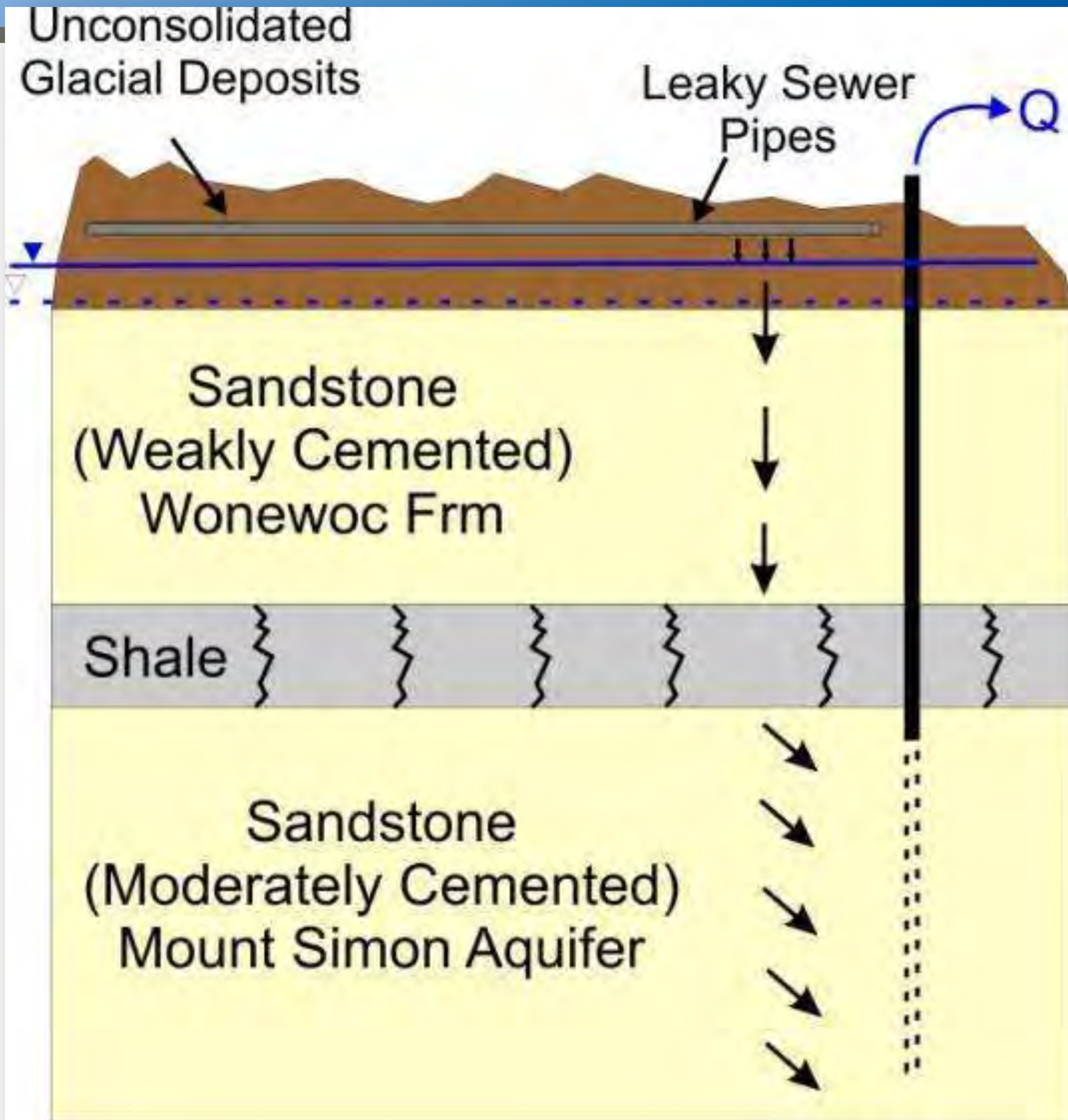
Environ. Sci. Technol., **2007**, 41 (18), 6606-6612 • DOI: 10.1021/es071110+

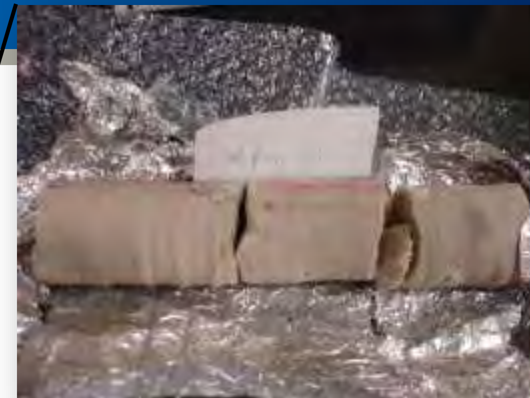
Downloaded from http://pubs.acs.org on February 3, 2009



- ~ 220,000 people in Madison
- 30 million gallons of water pumped per day, primarily from Mt. Simon aquifer from 21 municipal wells
- Wells 5, 7, and 24 each pump between 1 and 2 million gallons per day

Lithologies Along Likely Virus Transport Path





Aquitard Travel Time: Flow in Fractures Through Aquitard

$$\bar{v} = \frac{K_{bulk-vertical} \dfrac{dh}{dl}}{\phi_{fracture}}$$

Flow in Idealized Parallel Plate Fractures

$$\bar{v} = \frac{(2x10^{-7}\, cm/s)(1.8)}{3x10^{-6}} = 104\ \mathrm{m/d}$$

32 μm fractures spaced 10 m apart

$$t = \frac{\text{thickness (m)}}{\bar{v}\ \text{(m/d)}} = \frac{9m}{104m/d} = \boxed{2.1\ \text{hours}}$$

Travel time through aquitard

Key Points

- Groundwater travel times in networks with even small fractures can be fast
- Virus research concerning groundwater is still in its infancy

Commercially Available Multilevel Systems

CMT

Solinst

Waterloo

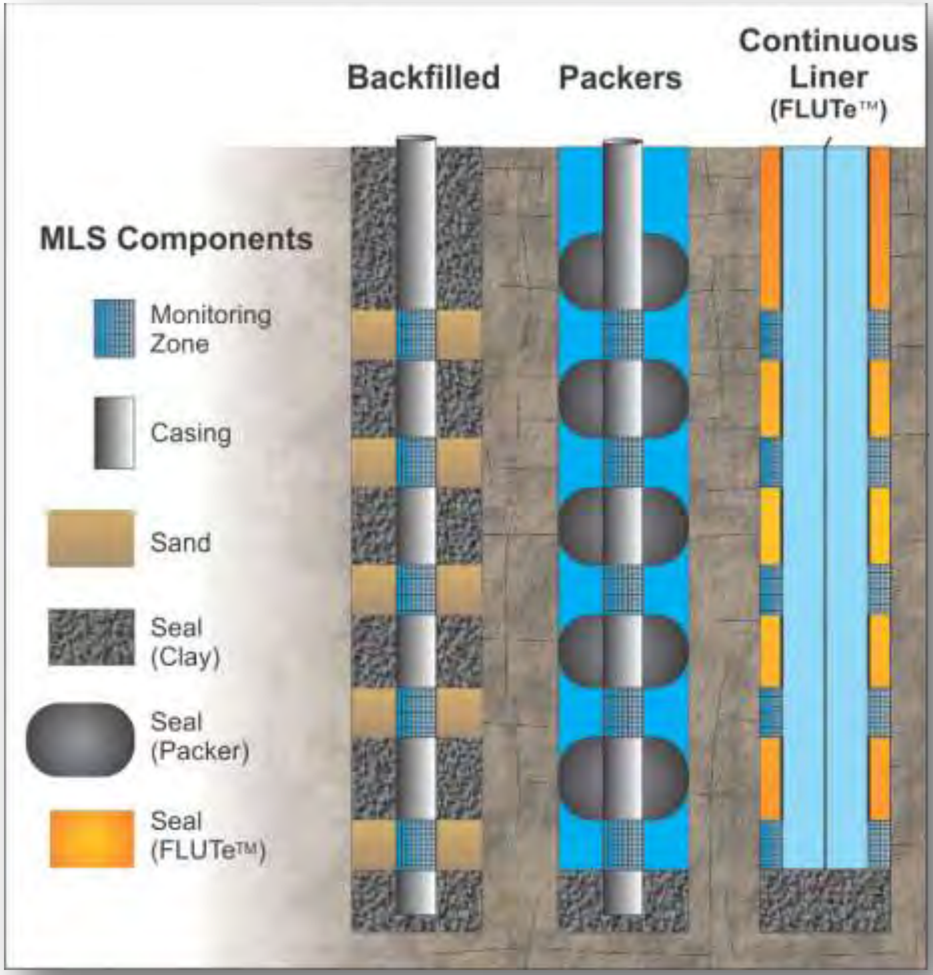
Solinst

FLUTe
Flexible Liner Underground Technologies, Ltd. Co.

Westbay

Schlumberger
WATER SERVICES

Depth Discrete Multilevel Monitoring



adapted from Cherry 2000

Multilevel System (MLS)

A single device installed into a borehole that divides the hole into many separate intervals for depth-discrete monitoring

Problem Statement

- Midwestern communities commonly rely on groundwater from sedimentary rock aquifers
- Water quantity and quality issues are co-mingled
- Powerful numerical models are needed for decision-making

High resolution field data are essential

Site Located in South Central WI

Model Domain
2003 Plume

Village of Cottage Grove

- 2010 population ~ 6,200

Dane County, Wisconsin

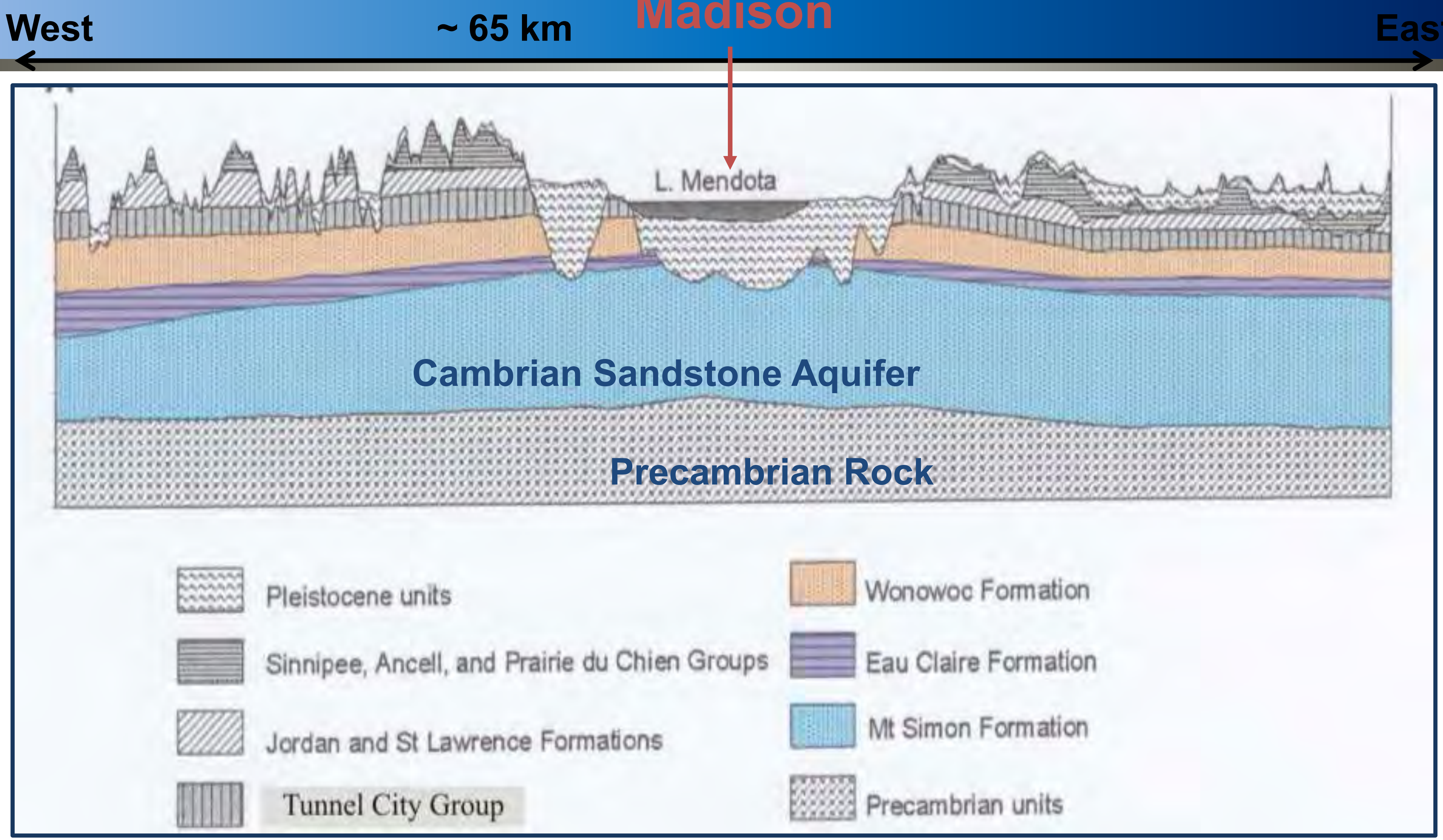
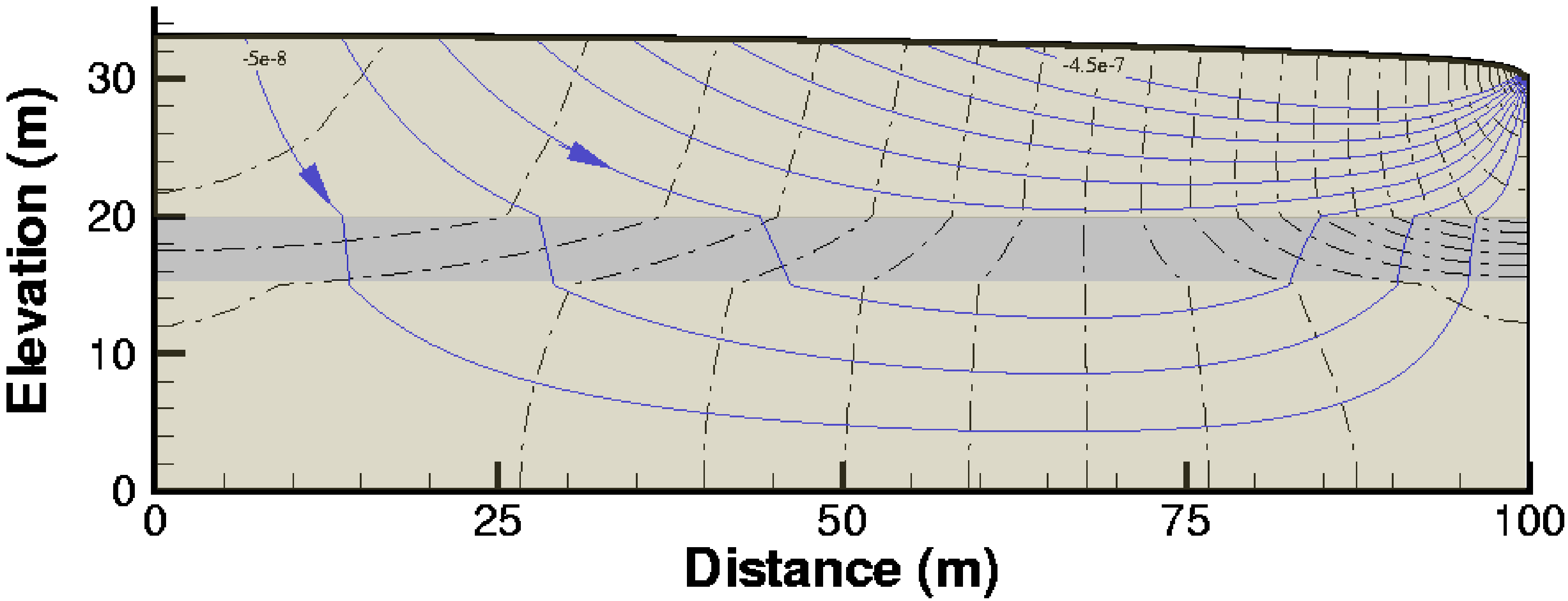
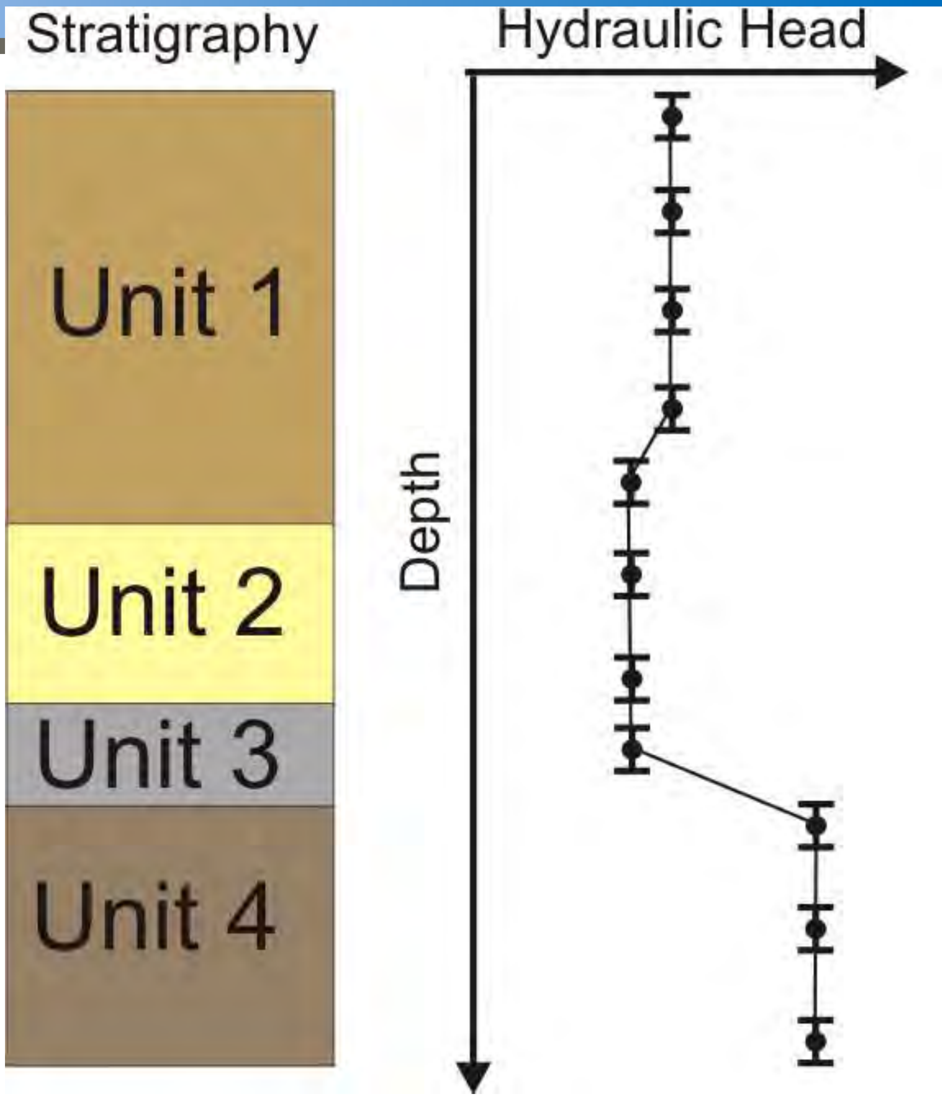


Figure modified from Bradbury et al. (1999), WGNHS OFR 1999-04
based on information from Massie-Ferch et al. (1997), GSA Abstracts with Programs

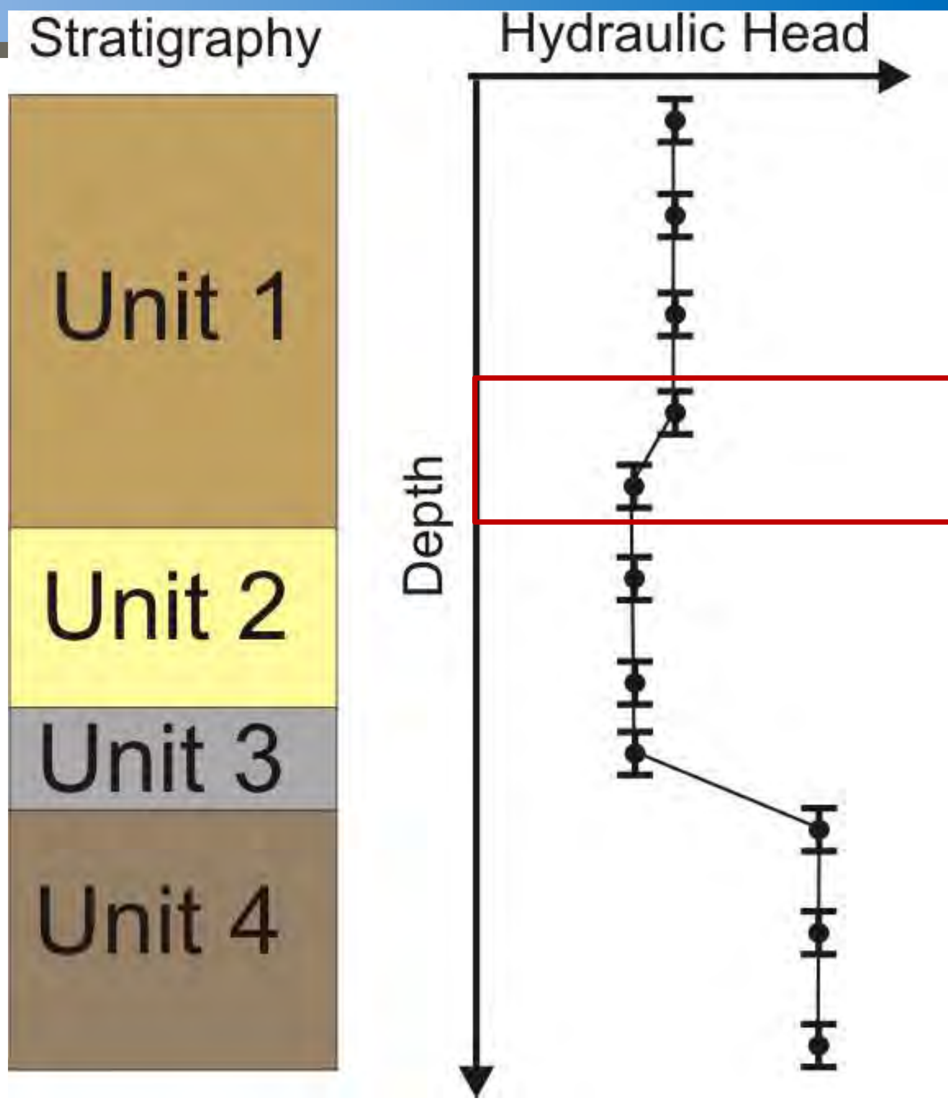
Aquitards in Flow Systems



Schematic Head Profile

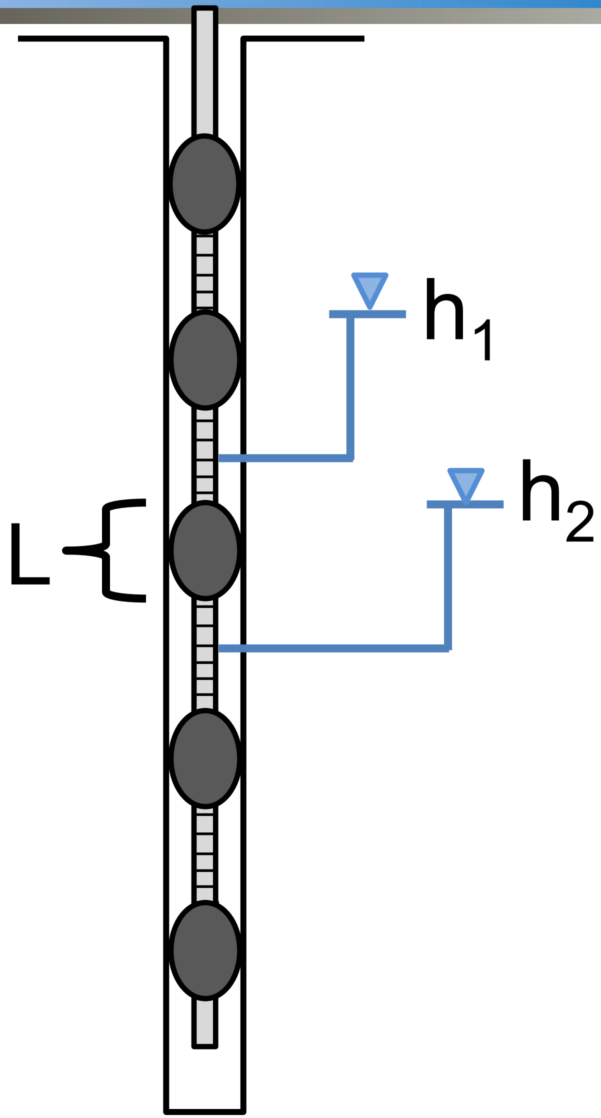


Inflections Are . . .



Discrete change in head with depth

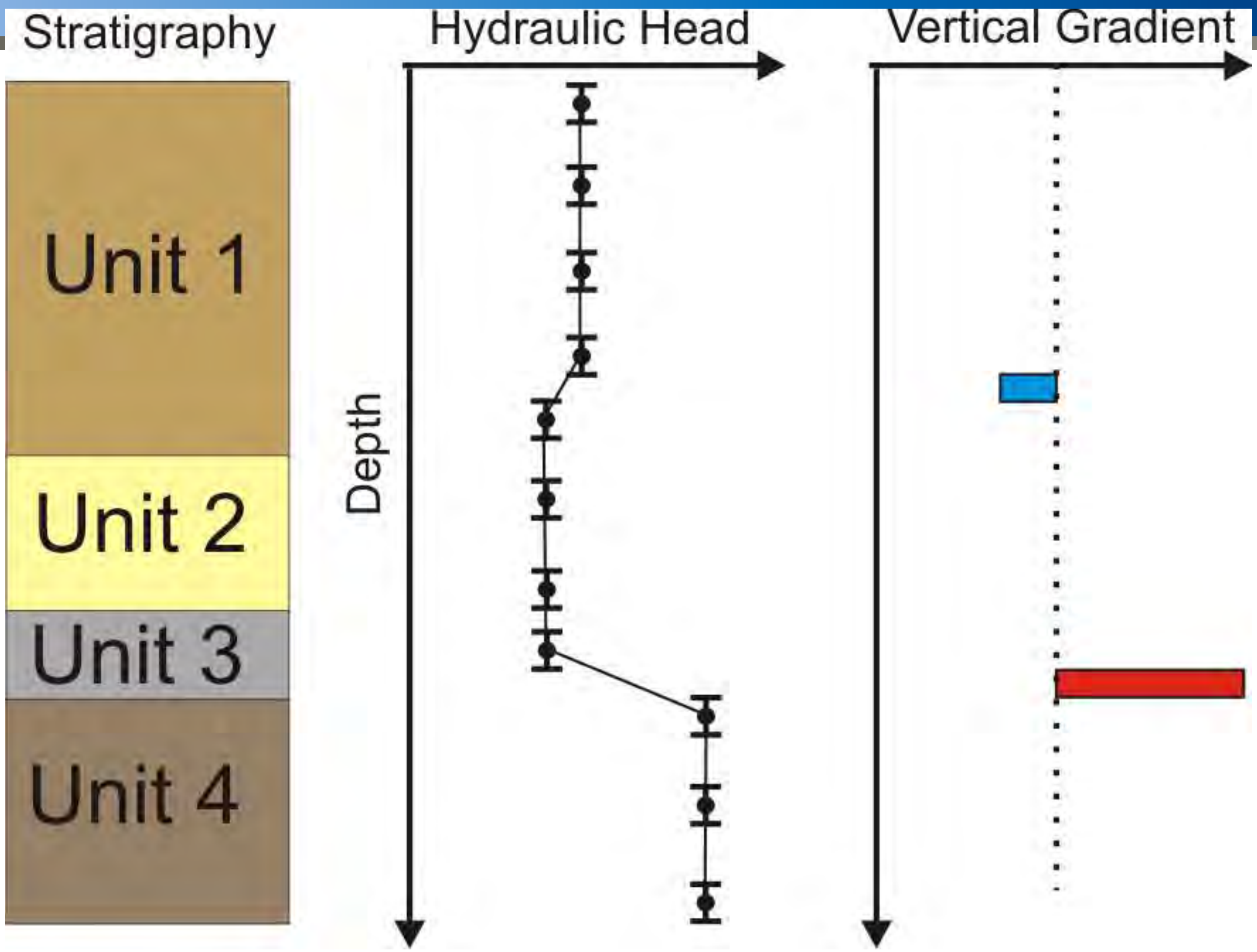
Vertical Component of Hydraulic Gradient



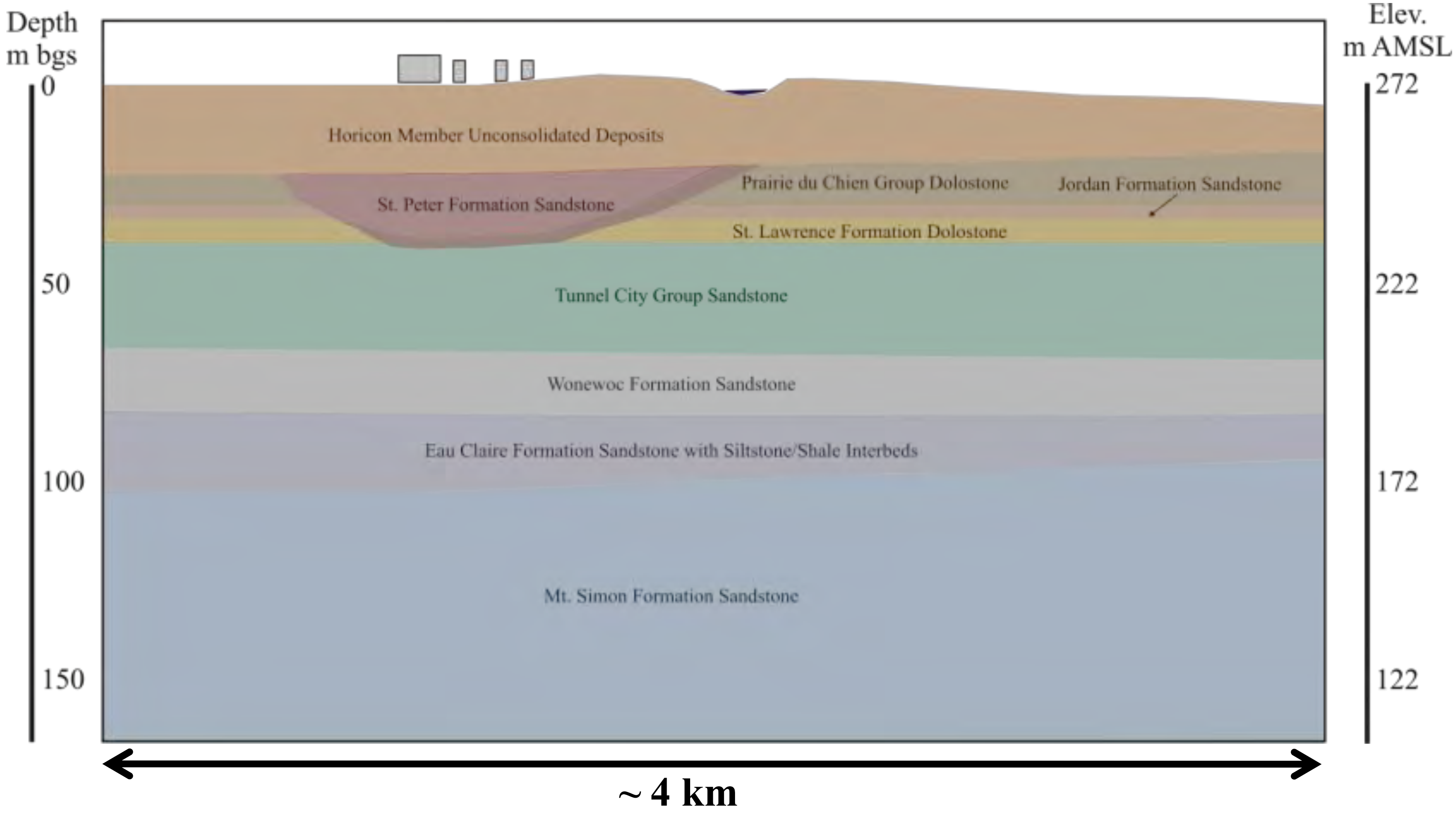
Maximum Vertical Gradient $= \dfrac{h_1 - h_2}{L}$

Vertical gradients across lower K layers are commonly greater than 1

Schematic Head Profile



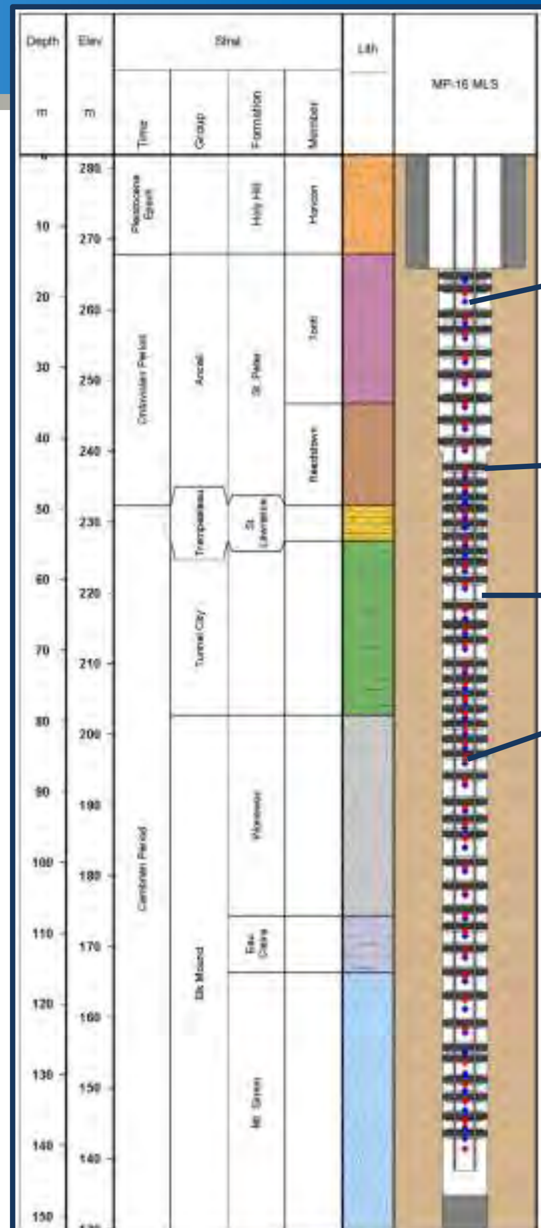
Geologic Conceptual Model



Detailed Westbay Multilevel System Wisconsin Site

Multilevel System

- ✓monitors 129.5 m of bedrock
- ✓46 monitoring zones
- ✓83% of monitoring zones are < 2.5 m long



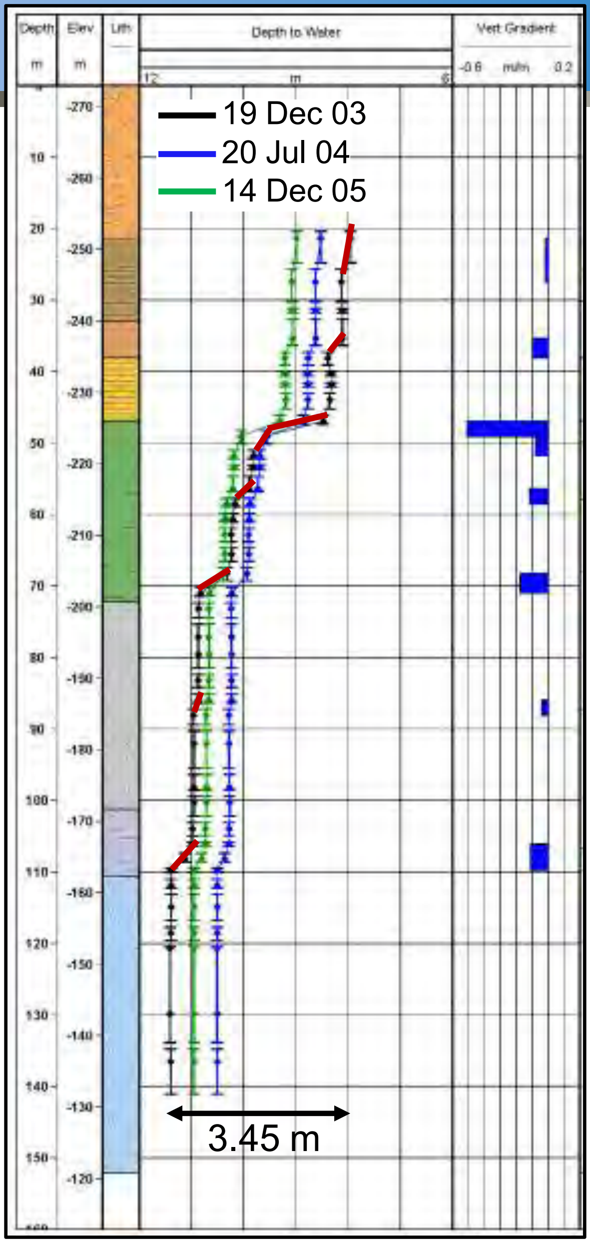
Measurement Port

Packer

Monitoring Interval

Pumping Port

Head Profile Characteristics



- Large vertical gradients at inflections

- Inflections do not always correlate with stratigraphy

Meyer et al., 2008, Envir. Geology, v. 56, p. 27-44

Head Profiles from Westbay Systems Used to Delineate Hydrogeologic Units

Meyer, Parker & Cherry, 2008
Environ. Geol., 2008, Vol. 56, No. 1, pp. 27-54

Environ Geol (2008) 56:27–44
DOI 10.1007/s00254-007-1137-4

ORIGINAL ARTICLE

Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock

Jessica R. Meyer · Beth L. Parker · John A. Cherry

Received: 15 September 2007 / Accepted: 12 November 2007 / Published online: 7 December 2007
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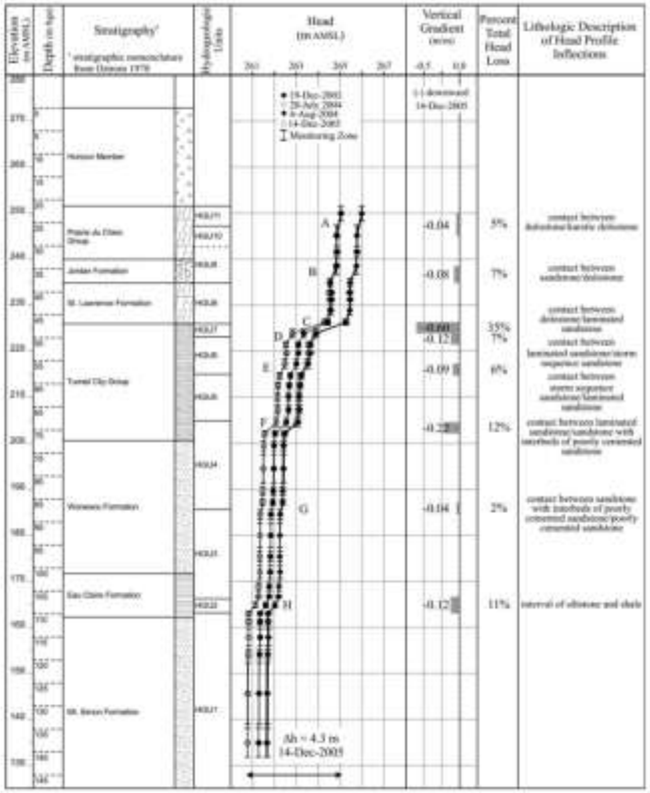
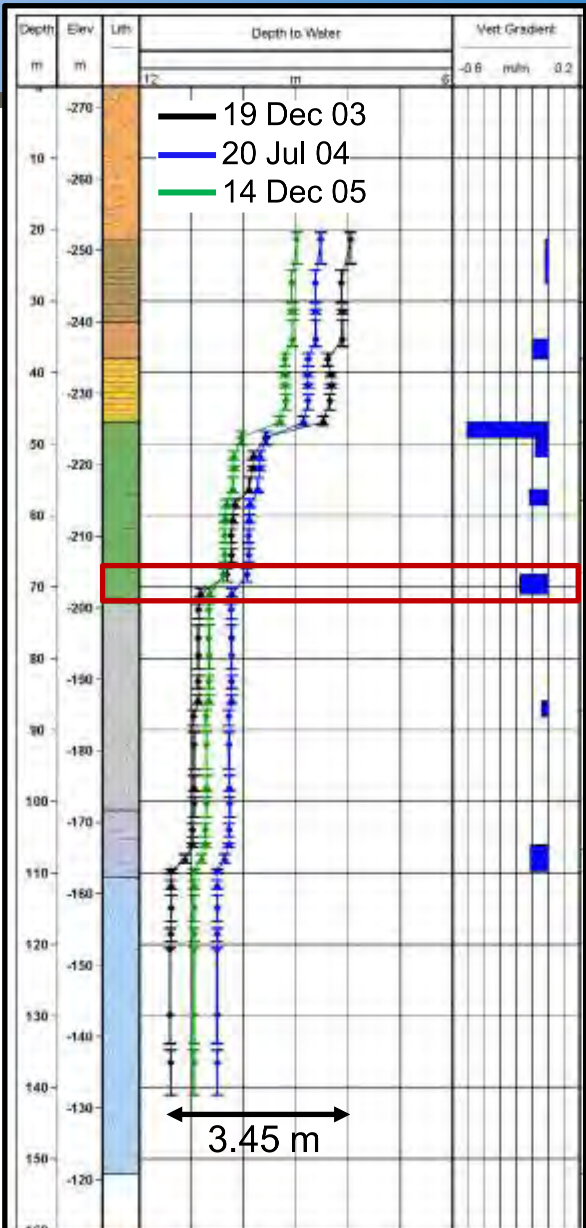
Abstract This paper describes a study in southern Wisconsin where vertical hydraulic head profiles measured in exceptional detail provided the key data for defining hydrogeologic units (HGUs) in a layered sequence of sandstone, siltstone, shale, and dolostone. The most important data were obtained from corehole MP-6 which was cored 131 m into bedrock and instrumented using a Westbay® multilevel system with 36 depth discrete monitoring intervals. The resulting head profile is consistant over time and shows eight distinct inflections in hydraulic head. Several of the inflections occur between adjacent permeable units and are likely due to poor vertical connectivity of fracture sets rather than distinct lower permeability layers or aquitards in the conventional sense.

Introduction

In the 1960s, the focus of groundwater research turned to analysis and modeling of regional scale flow systems (Toth 1962, 1963; Freeze and Witherspoon 1966, 1967). For example, Toth (1963) demonstrated the influence of topography on flow paths which led to the definition of regional, intermediate, and local groundwater flow systems. Toth's (1963) research was expanded on by Freeze and Witherspoon (1966) who introduced a numerical model to investigate idealized regional groundwater flow patterns. Later, Freeze and Witherspoon (1967) showed vertical 2D cross-sections from numerical simulations where lines of equal head are refracted at the interfaces

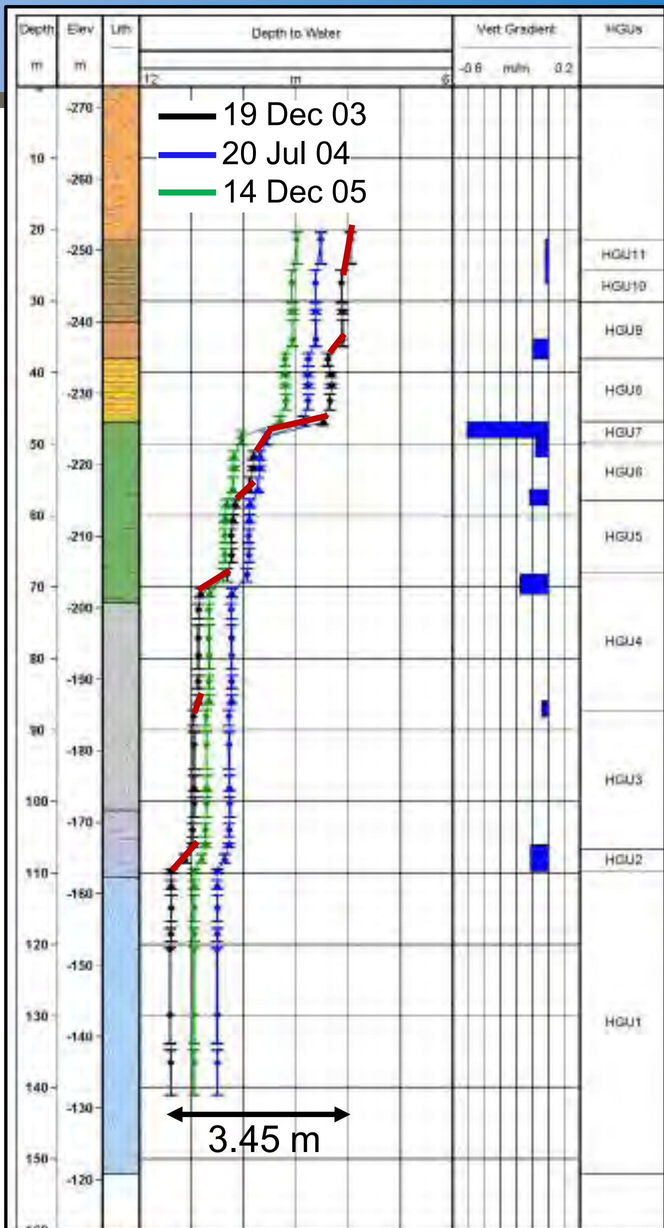


Example Inflection – No Shale Bed



Meyer et al., 2008, Envir. Geology, v. 56, p. 27-44

Defining HGUs Using Head Profiles



- Head profiles indicate 11 HGUs
- HGUs don't correlate with stratigraphy

Meyer et al., 2008, Envir. Geology, v. 56, p. 27-44

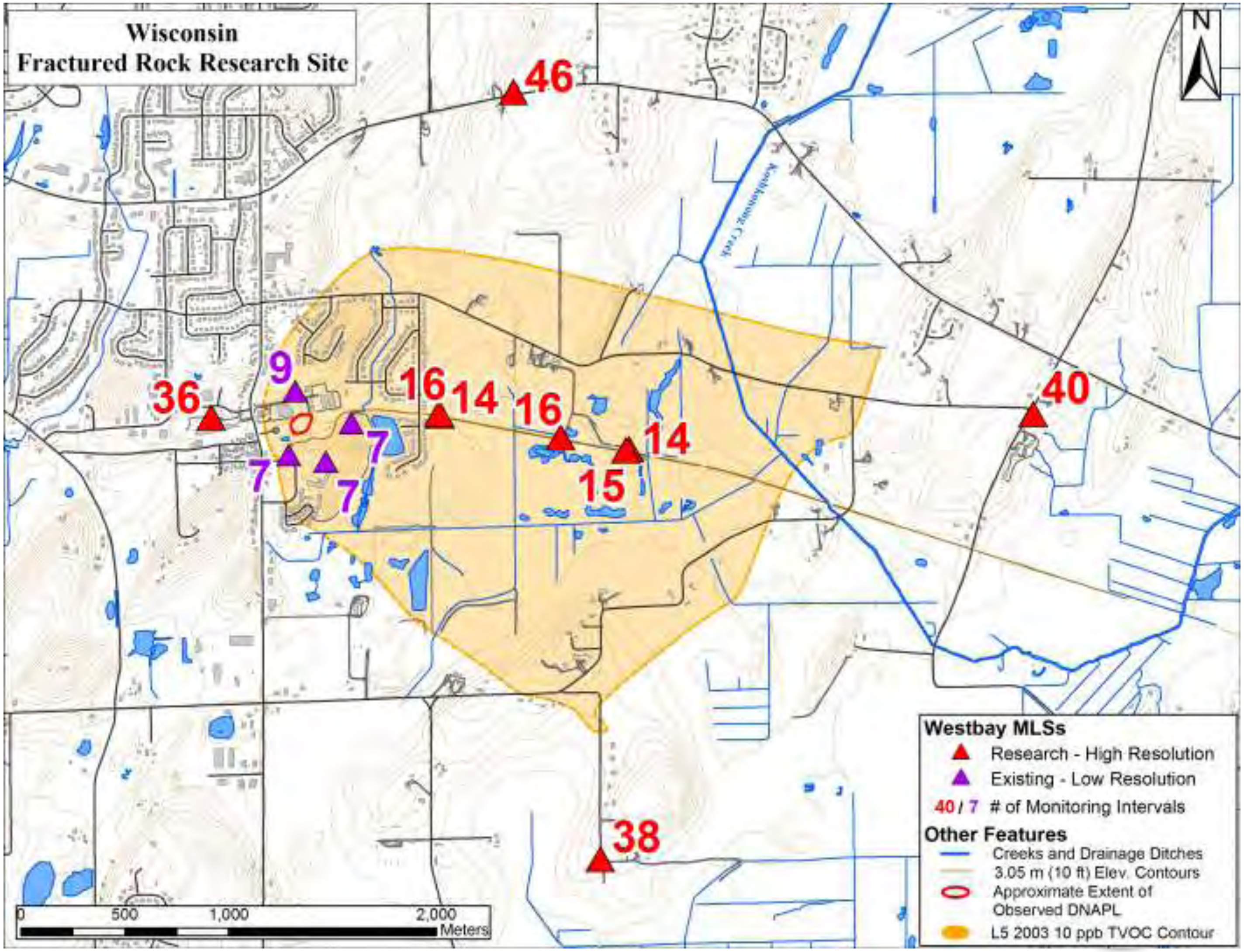
13 Bedrock Westbay Systems

Total of 265 Monitoring Intervals

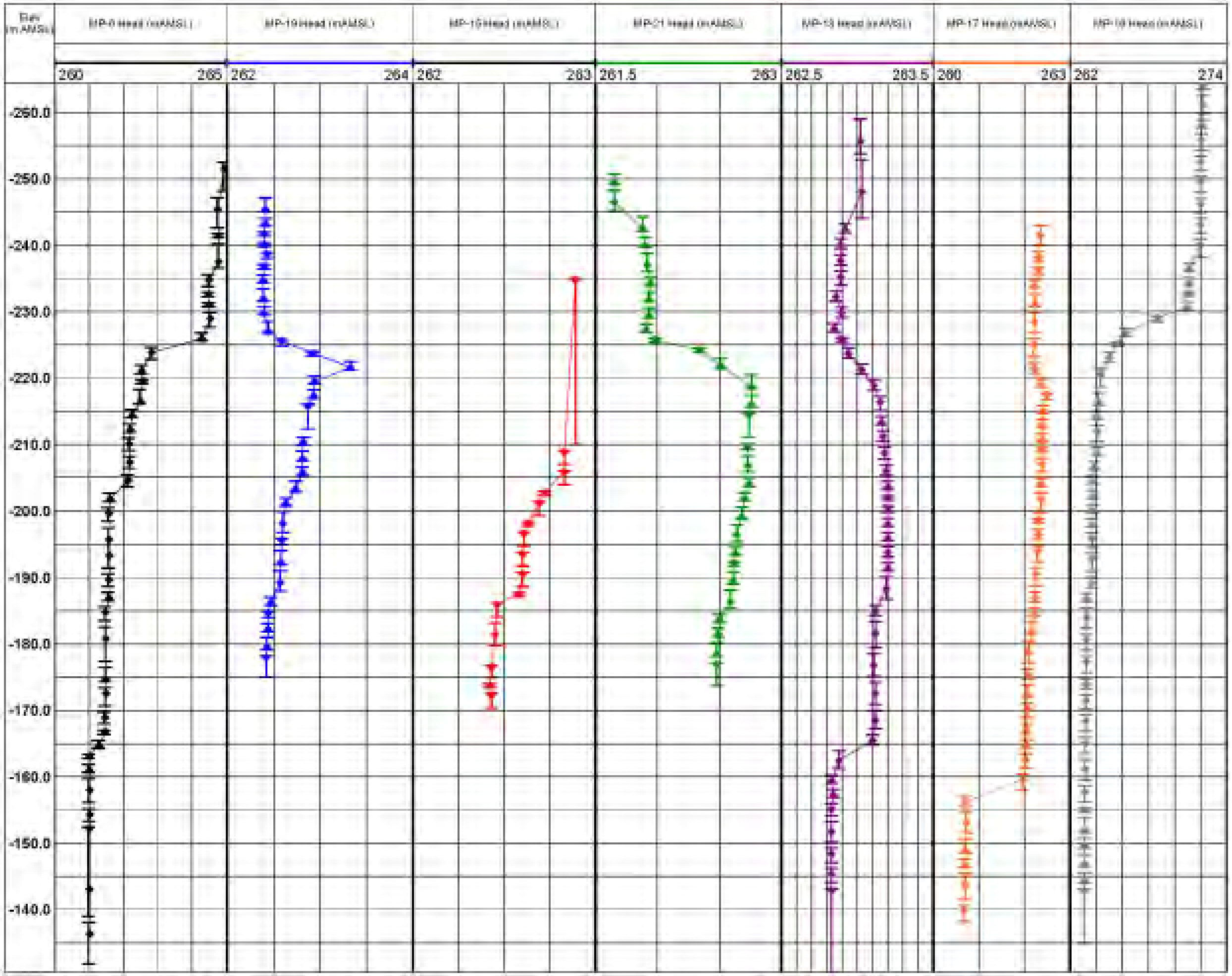
High Resolution Westbay MLS Since 2003

Low Resolution Westbay MLS Since 1993

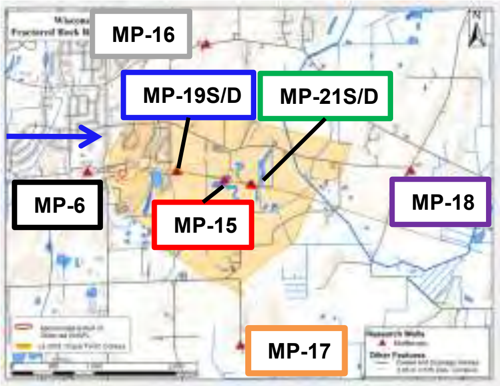
46/7 # of Monitoring Intervals



Head Inflections Correlate

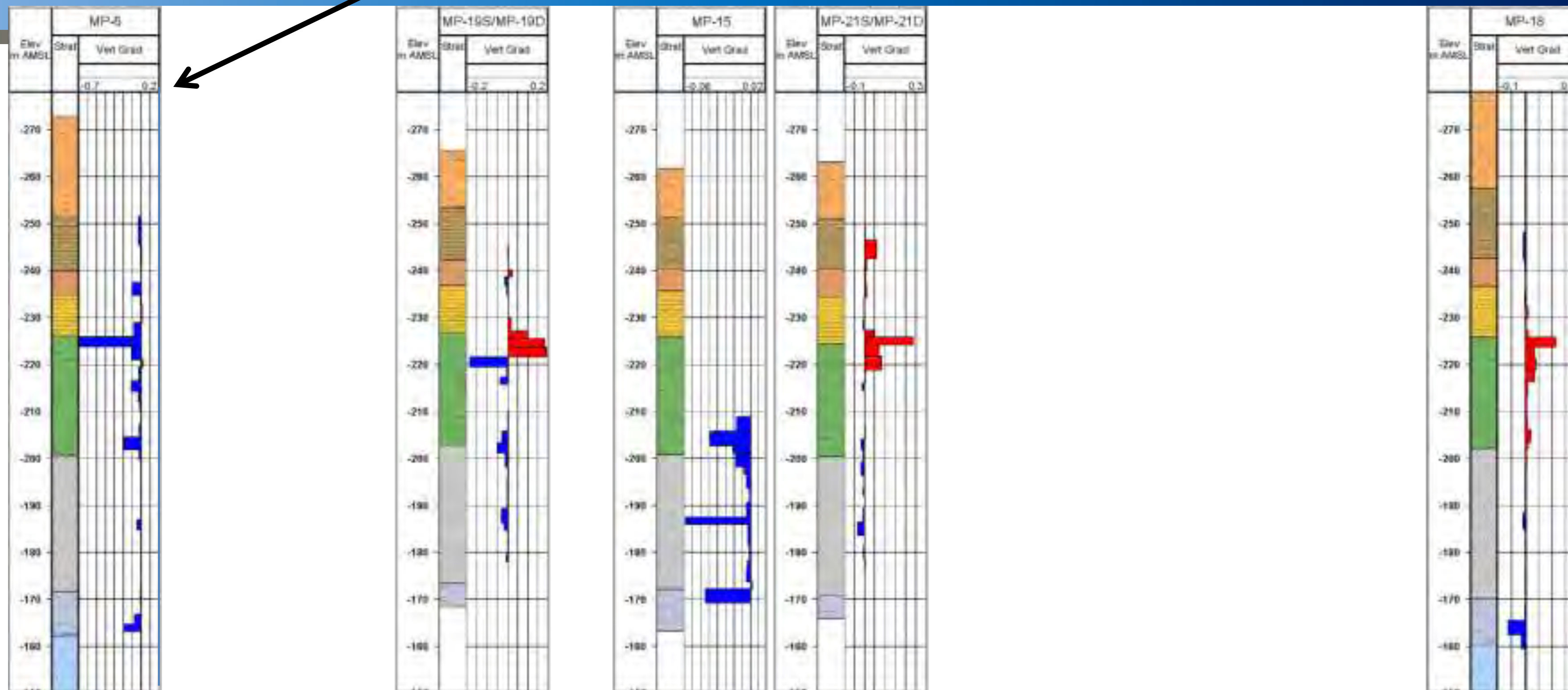


- Smooth geometrical head profiles
- Inflections correlate across the site

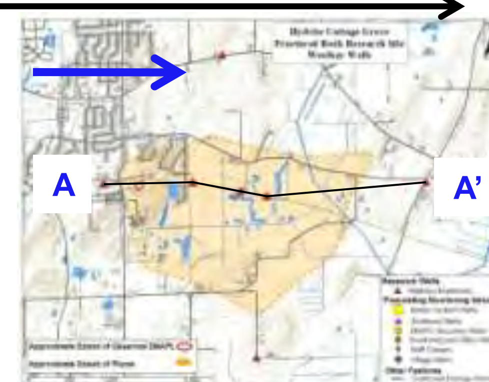


Vertical Gradients Correlate Across Site

A Recharge Area Discharge Area A'

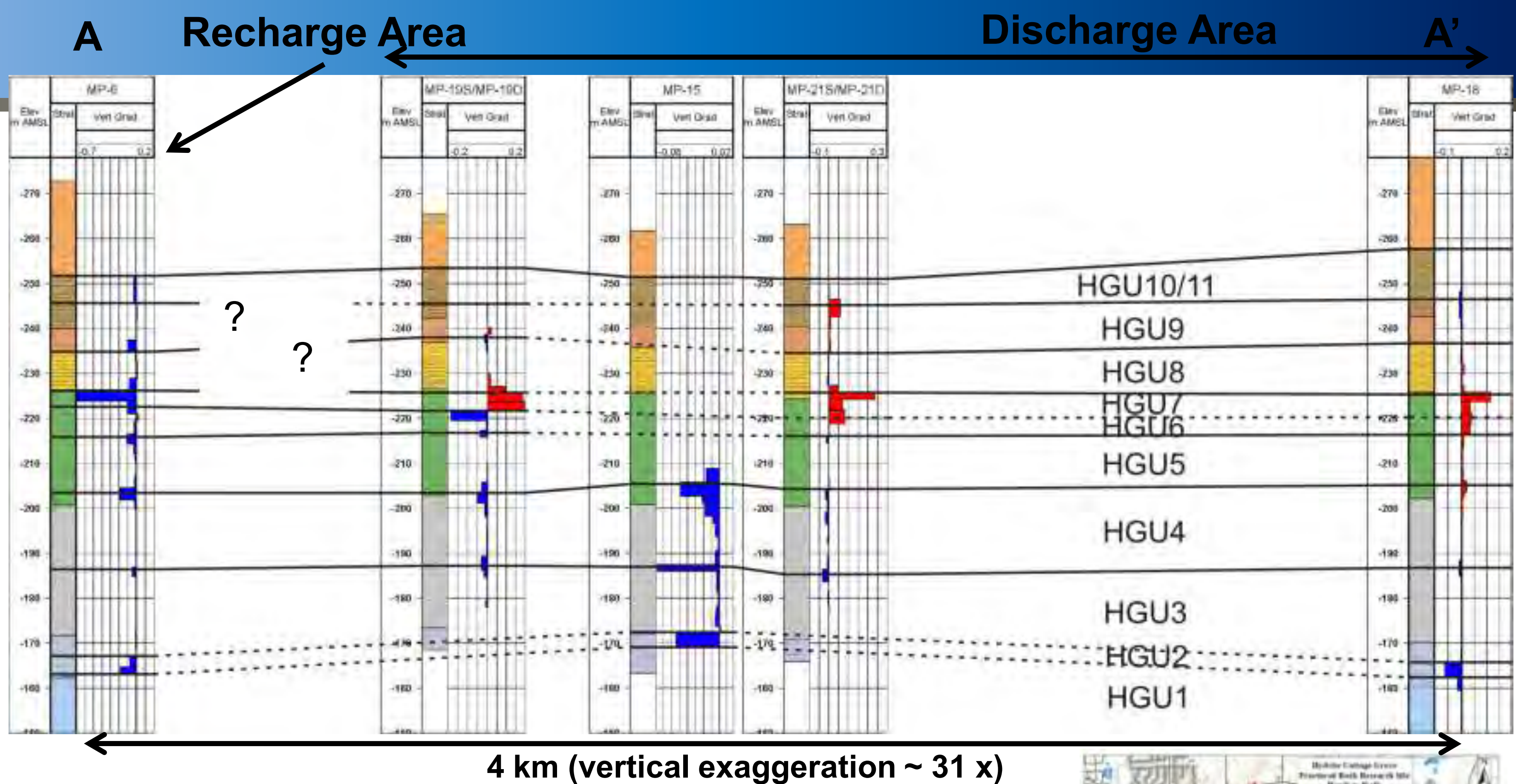


4 km (vertical exaggeration ~ 31 x)



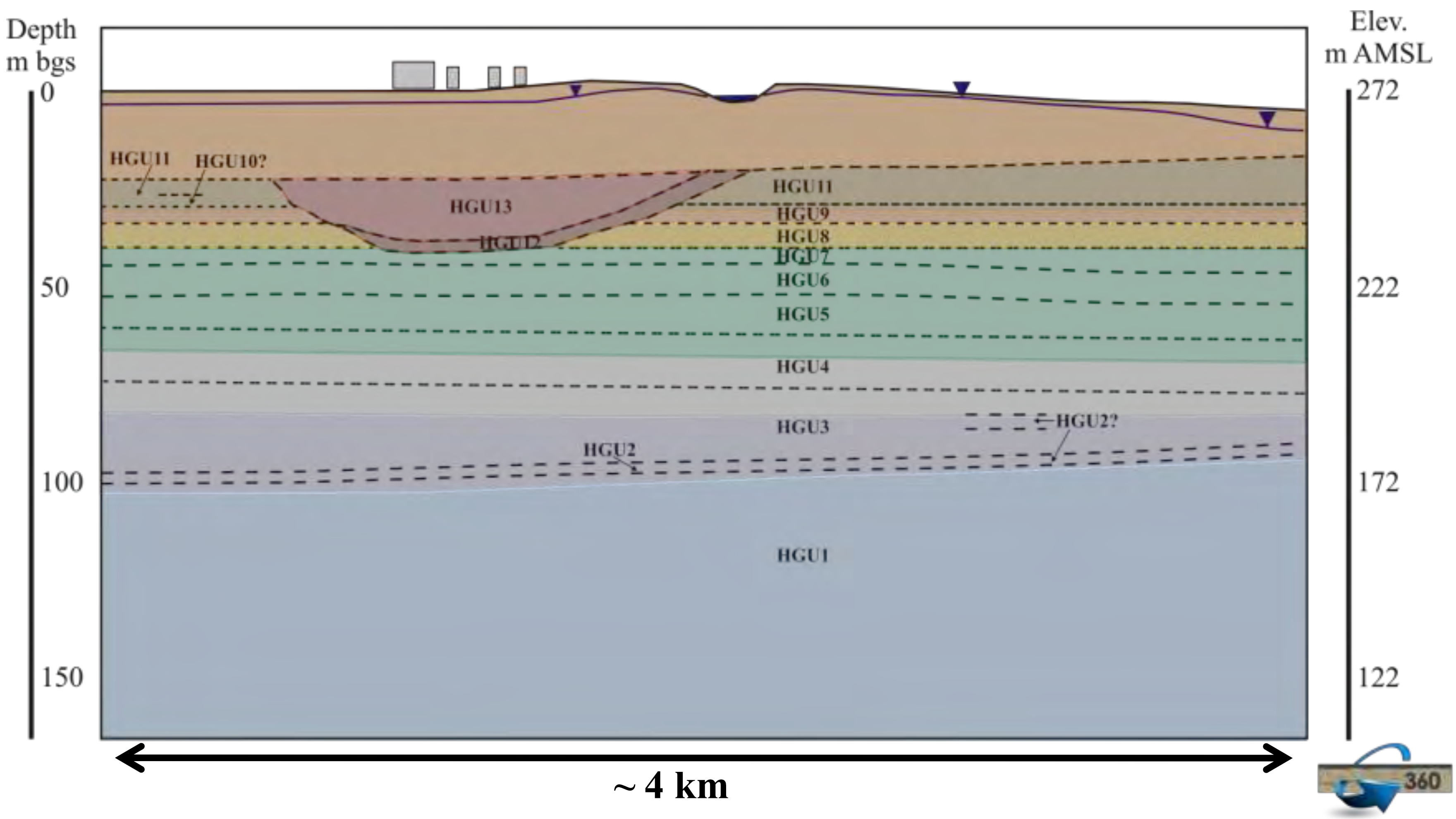
Vertical gradients indicate position in flow system

Defining the 3D Hydrogeologic Framework

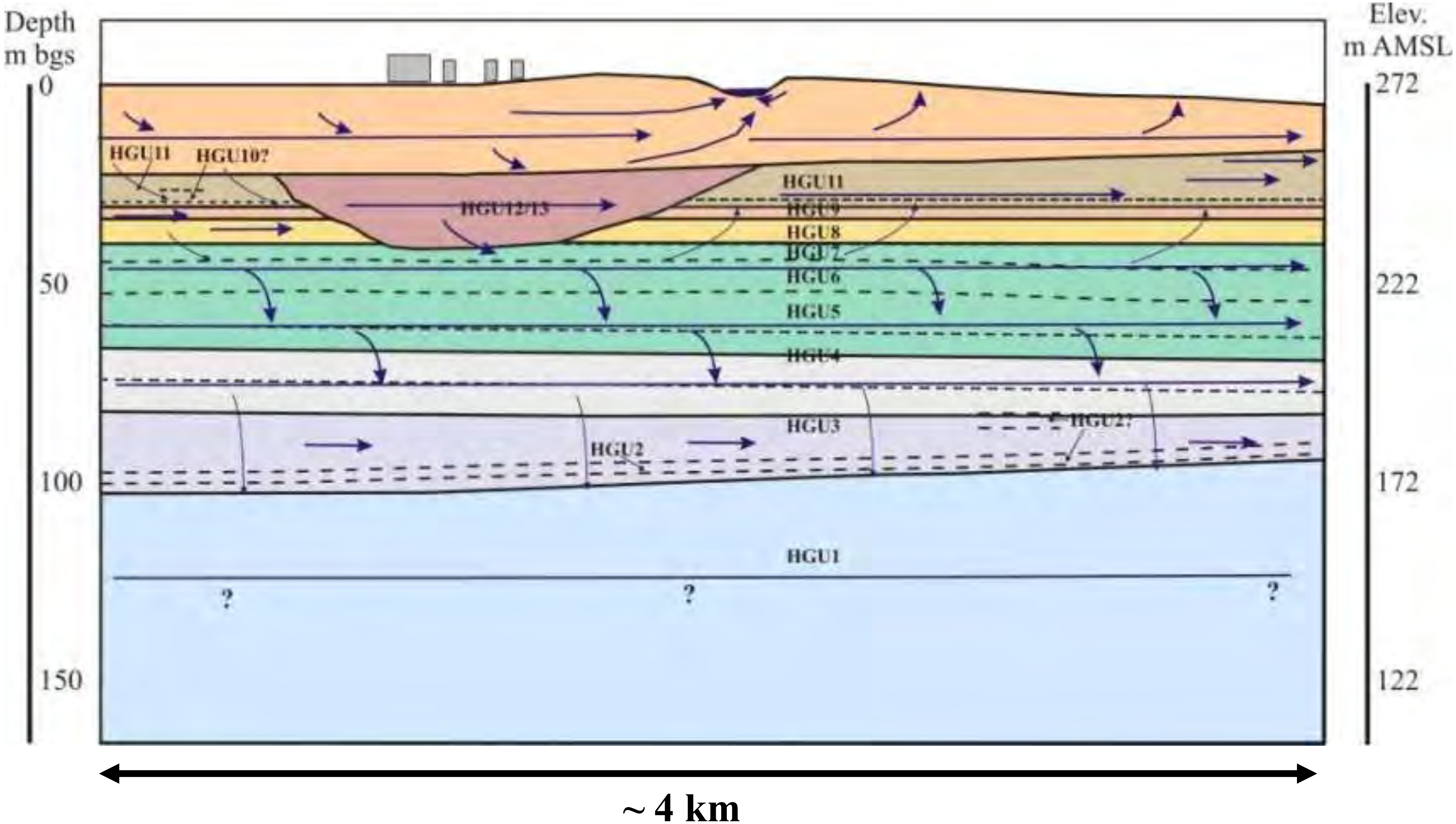


- HGUs are generally laterally extensive
- St. Peter formation unconformity disrupts the HGUs

Comprehensive Definition of 13 Bedrock HGUs



Schematic Flow System



Key Findings

- Detailed hydraulic head profiles are essential evidence for defining hydrogeologic units in fractured sedimentary rock
- Conventional approach using stratigraphic units to define hydrogeologic units is invalid

Summary of Aquitard Literature – AWWARF (2006)

1. Cherry, J.A., B.L. Parker, K.R. Bradbury, T.T. Eaton, M.G. Gotkowitz, D.J. Hart and M.A. Borchardt, 2005. Contaminant Transport Through Aquitards: A "State of the Science" Review. AWWA Research Foundation, Denver, Colorado.

2. K.R. Bradbury, M.G. Gotkowitz, D.J. Hart, T.T. Eaton, Cherry, J.A., B.L. Parker, and M.A. Borchardt, 2005. Contaminant Transport Through Aquitards: Technical Guidance for Aquitard Assessment. AWWA Research Foundation, Denver, Colorado.

Summary

- **Aquitards generally govern aquifer-aquitard systems**
- **Aquitard studies typically need profiles of:**
  - Hydraulic Head
  - Water Isotopes
  - Major Ions
- **Aquitards commonly show evidence of paleohydrology**
- **Fractures must be assumed to be present until sufficient evidence is gathered to show otherwise**

Thank you for your attention.

Questions?

Comments?