Permeable Reactive Barriers for Groundwater Remediation

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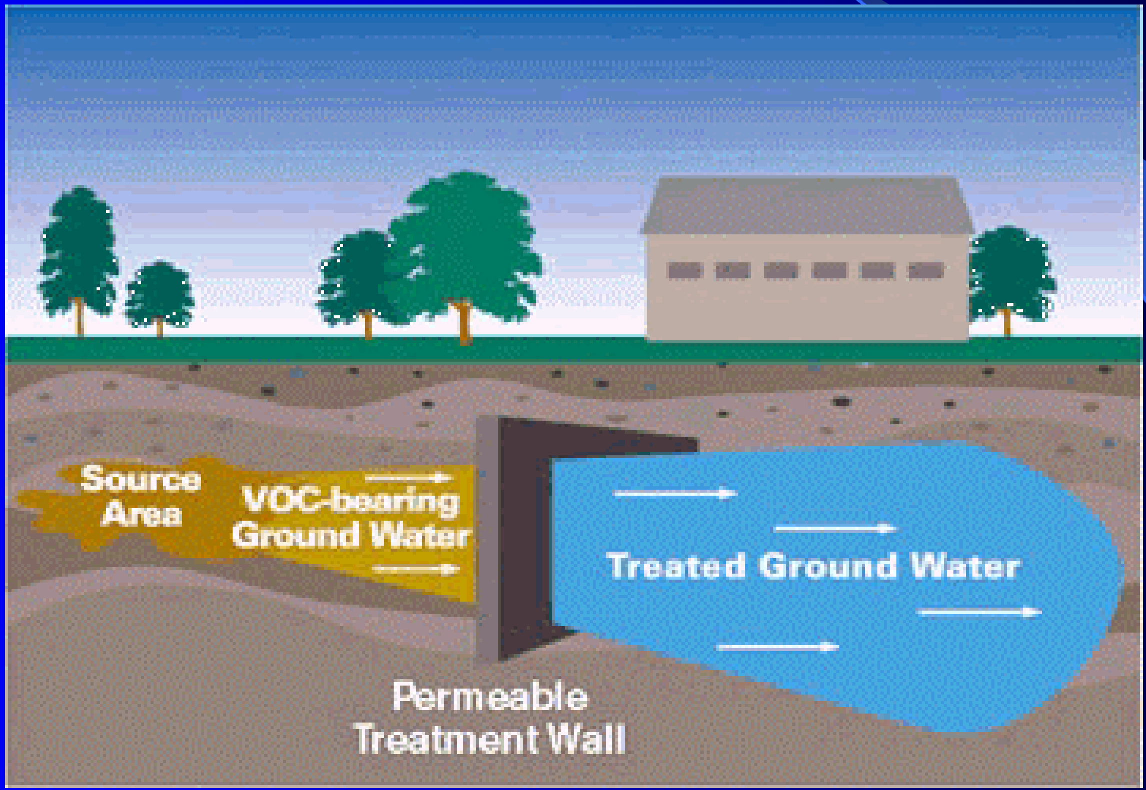
What?

A Permeable Reactive Barrier (PRB):

- A permeable zone containing or creating a reactive treatment area oriented to intercept and remediate a contaminant plume
- Removes contaminants from the groundwater flow system by physical, chemical, or biological processes

A PRB for VOC Remediation



Source: General Electric Company

Why Use a PRB?

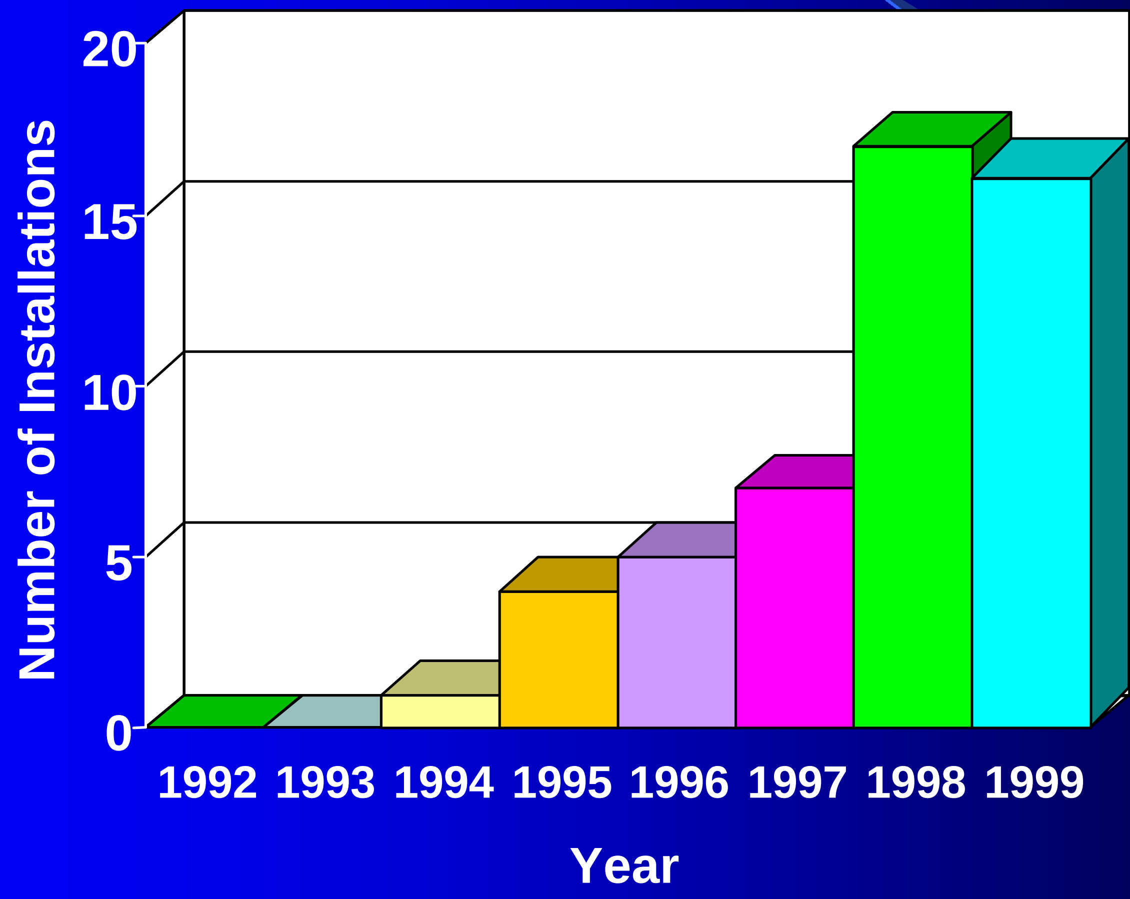
- Treatment occurs in the subsurface
- Typical treatment is passive
- Lower costs than conventional methods
- Allows full economic use of a property
- Robust
- Monitoring can be focused

PERMEABLE REACTIVE BARRIERS

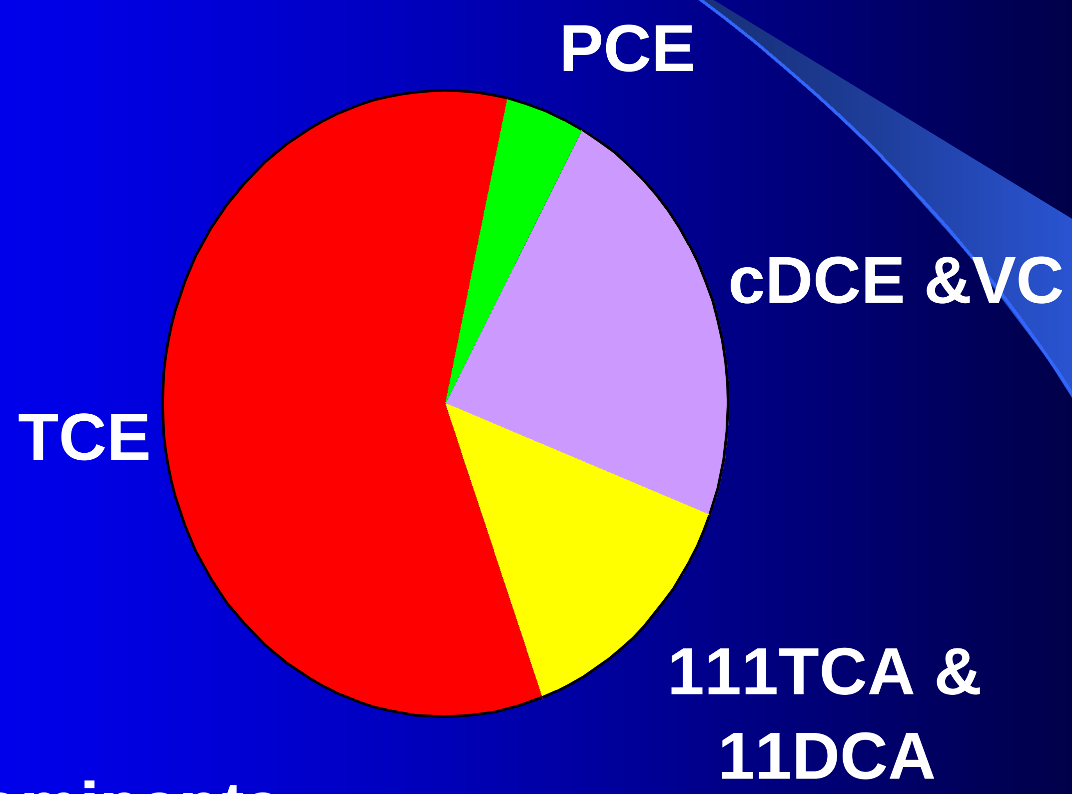
- Permeable Reactive Barriers may be appropriate for more than 500 sites in the next 10 years

- The potential cost savings for using PRBs instead of a conventional technology may collectively range from $500 million to greater than $1 Billion.

Technology Acceptance



Primary Contaminants Treated



Other contaminants:
Cr, U, As, Pb, ARD

Trends in Field Applications

- Decrease in reactive media costs
- Increase focus on plume characterization to minimize installation costs, optimize performance
- Combined PRB/natural attenuation remedies

Treatment Matrix

- Zone or material that promotes treatment
- Focus on zero-valent iron [Fe^0]
  - to treat groundwater affected by
    - chlorinated ethenes
    - chlorinated ethanes
    - chlorinated methanes (some)
    - dissolved metals

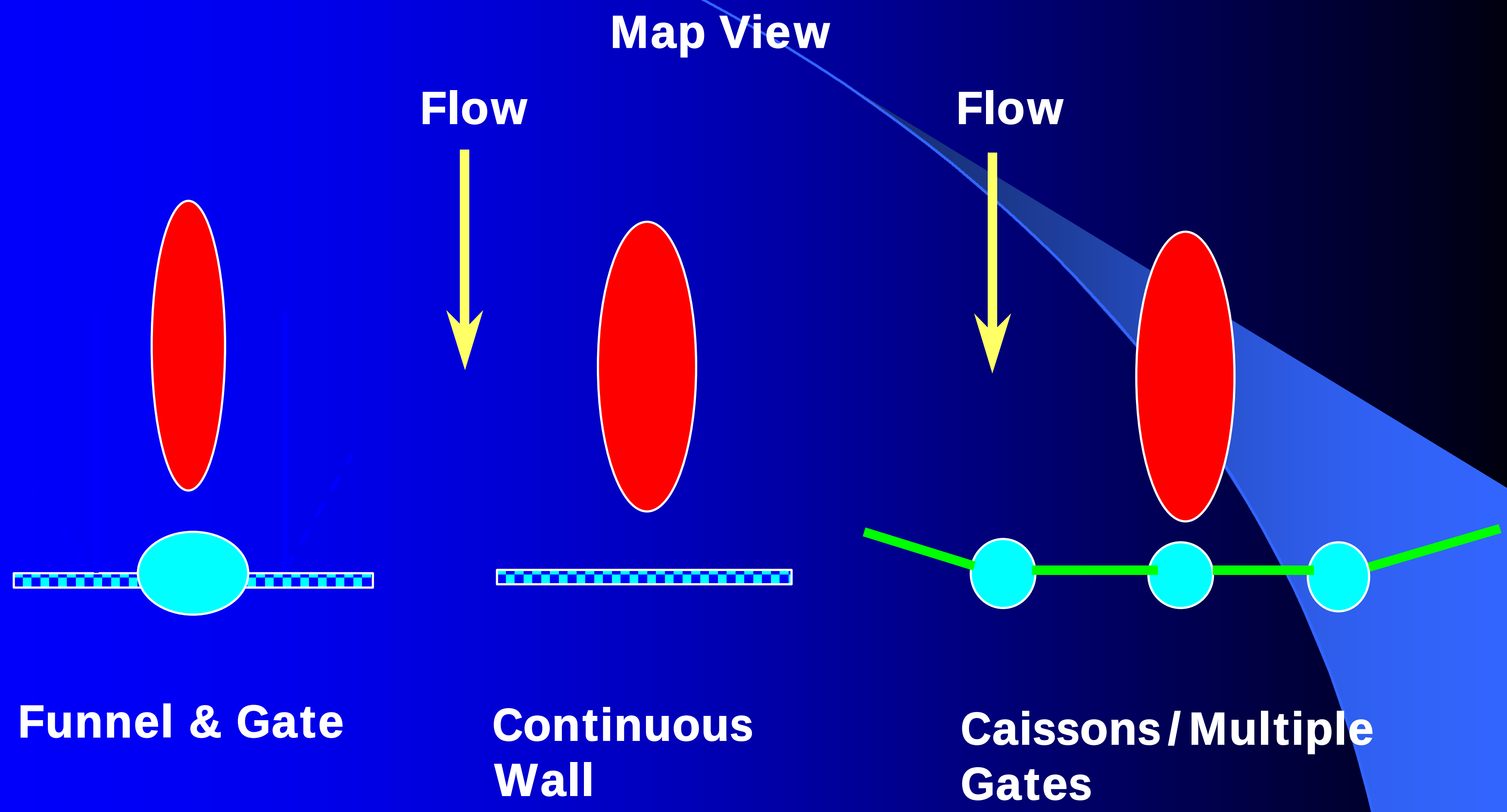
Treatment Materials & Treatable Contaminants

Treatment Material	Target Contaminants
Zero-valent iron	Halocarbons, reducible metals
Reduced metals	Halocarbons, reducible metals
Limestone	Metals, acid water
Sorptive agents	Metals, organics
Reducing agents	Reducible metals, organics
Biologic electron acceptors	Petroleum hydrocarbons
Biologic electron donors	Halocarbons

Hydraulic Control Systems

- Controls velocity through the reactive media
- Routes affected groundwater through the treatment zone (horizontal and vertical)
- Prevents migration around treatment zone
  - funnel and gate
  - continuous wall

Hydraulic Control Systems

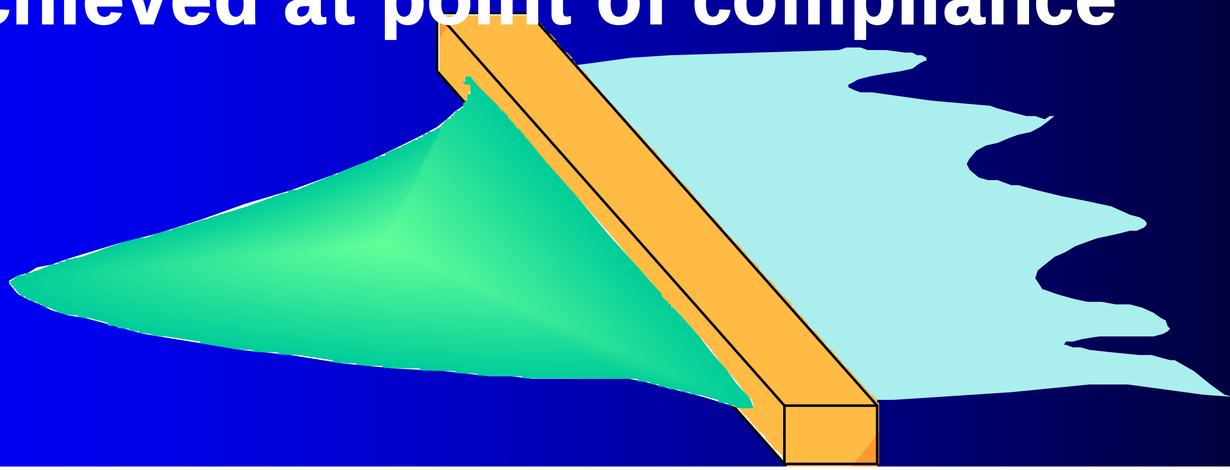


Current Applications

- Full-scale installations
  - >40
- Pilot-scale demonstrations
  - >50
- Laboratory-scale tests
  - >100
- Feasibility assessments
  - >1000 (likely)

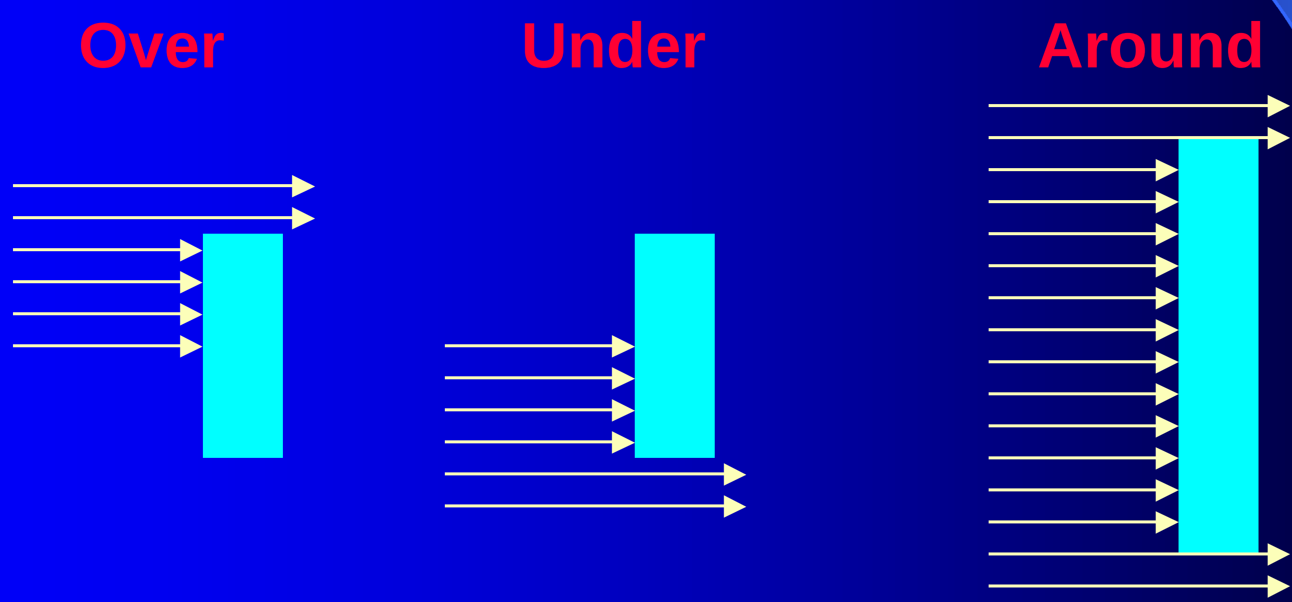
Goal = Passive Remediation System

– The plume enters under the natural gradient
– The entire plume is captured by the system
– Regulatory concentration goals are achieved at point of compliance



Potential Problems

- The plume could pass over, under, or around the barrier
- The groundwater flow direction or velocity might change
- Incomplete remediation as higher concentrations reach the barrier
- Loss of surface reactivity—precipitate coatings, etc.
- Barrier plugging, decreased permeability



Side Views *Plan View*

Site Characterization Issues to Address to Achieve Goal

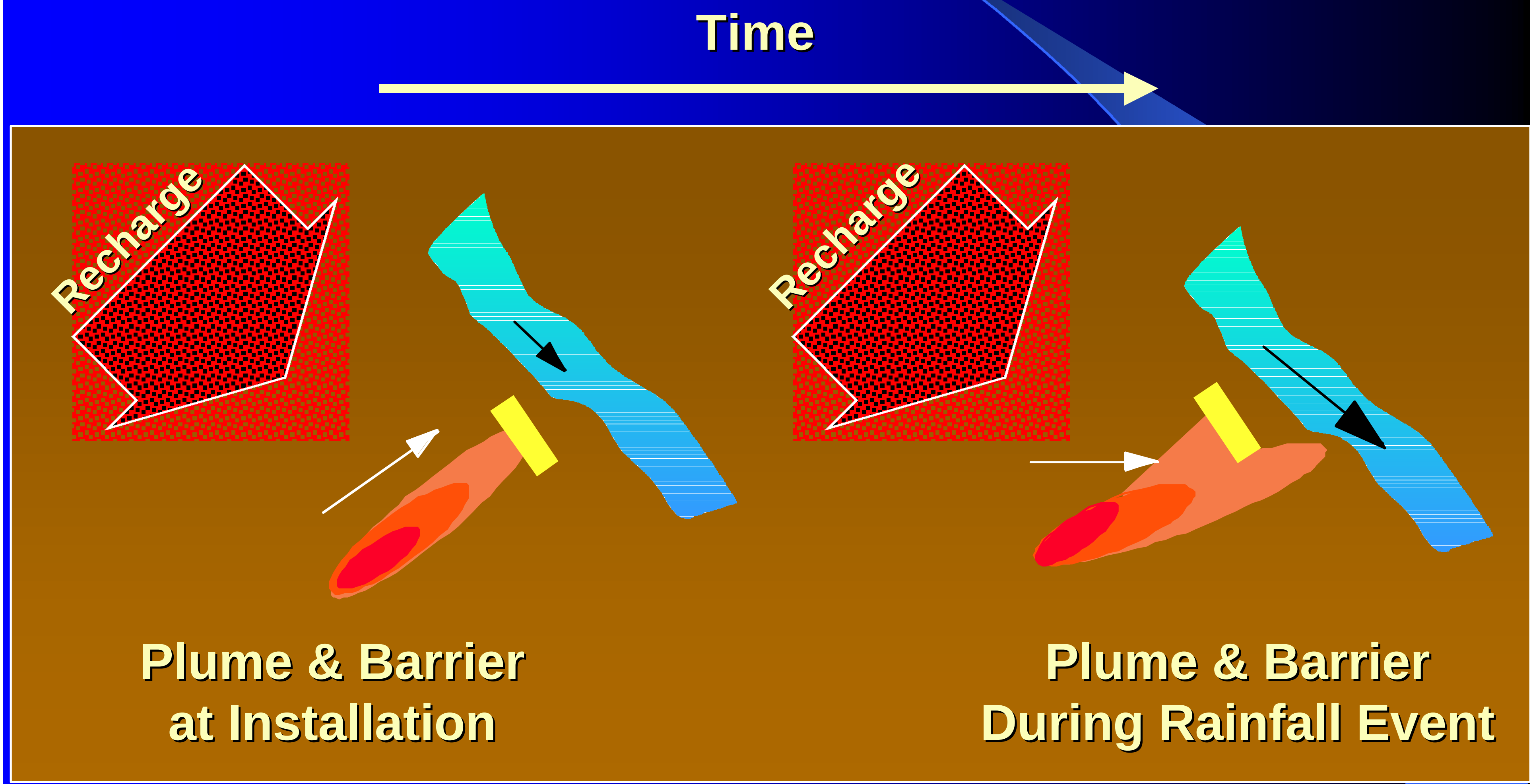
- **Hydrology**
- **Geology**
- **Contaminant distribution within the aquifer**
- **Geochemistry**
- **Microbiology**

These parameters are not discrete, but highly interactive.

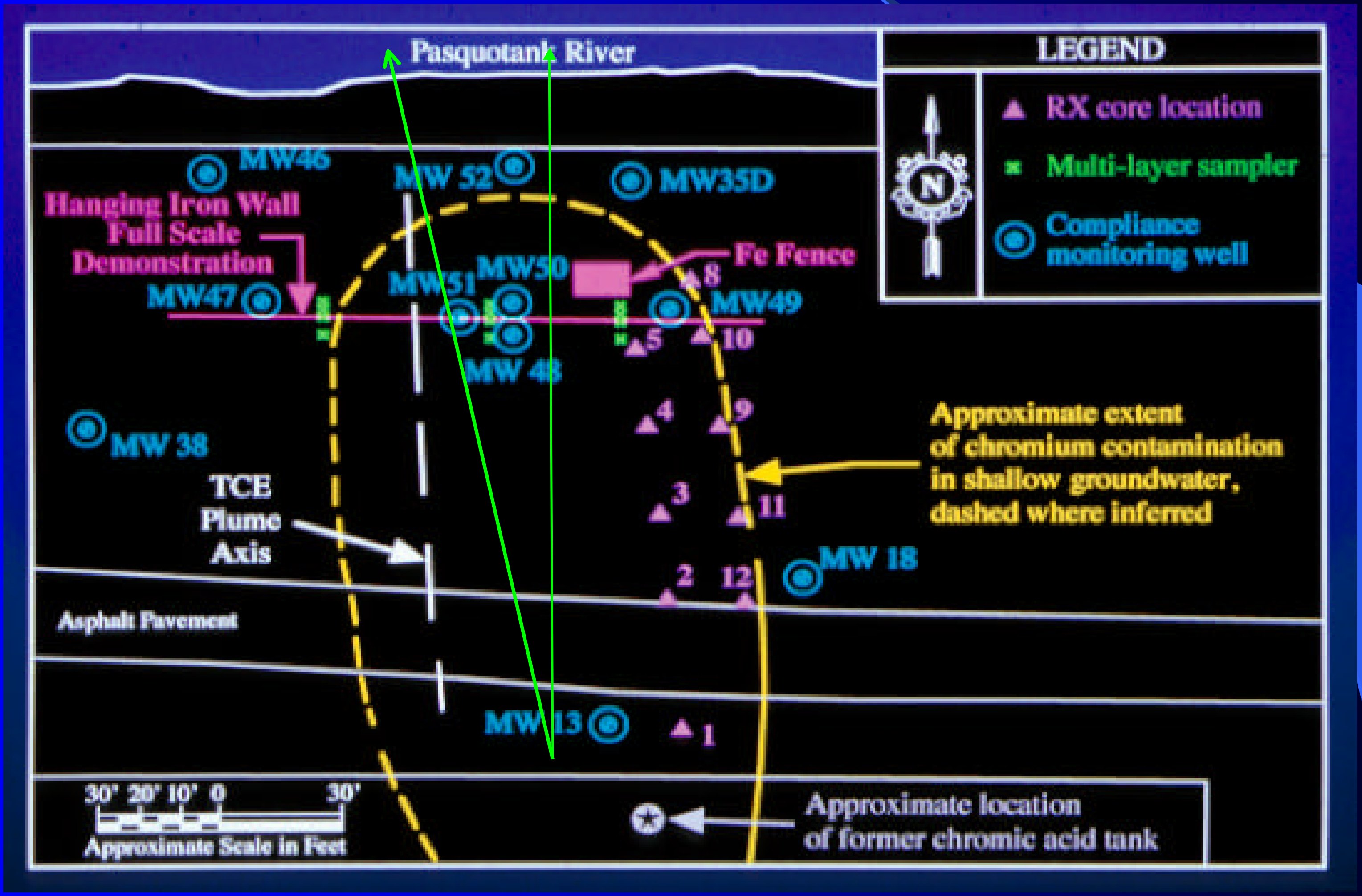
Hydrology

- Groundwater flow
  - direction (gradient)
  - velocity
  - flux
- Seasonal changes in groundwater flow velocity, direction (e.g. due to recharge events)
- Effects of nearby intermittent pumping
- Provide data for construction of groundwater flow model

Changes in GW Flow Direction



Elizabeth City - GW Flow Direction



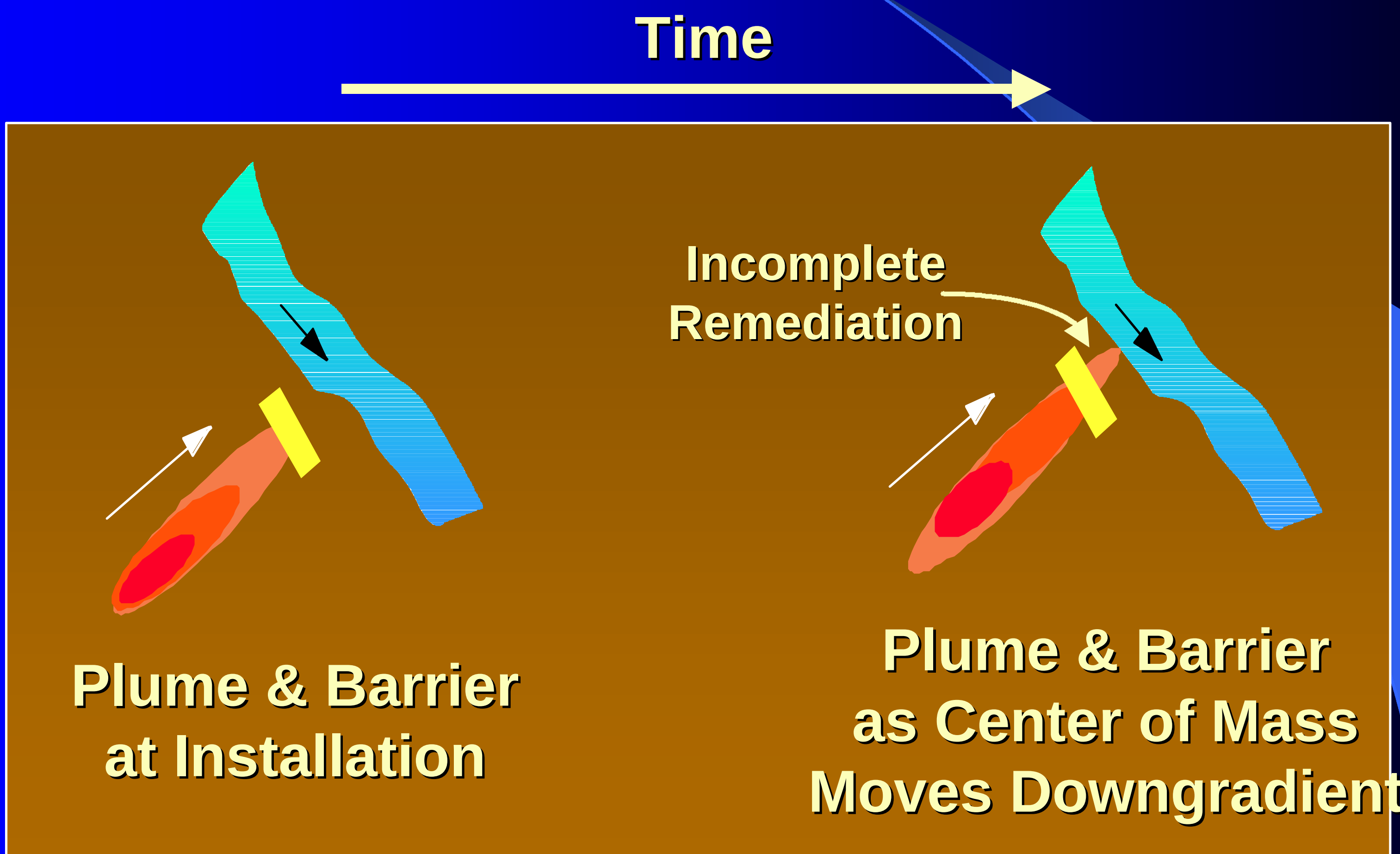
Geologic Setting

- Depositional environment
  - type, mineralogy, TOC
- Stratigraphy
  - depths and continuity of sand layers, clay layers, bedrock
    - keyed barrier or hanging wall
    - zones of water/contaminant movement
    - degree of fracturing

Contaminant Distribution

- Identify contaminants and degradation products
- Plume location in all dimensions
  - x, y, z, concentrations and time
  - Is natural attenuation occurring?
    - Has steady state been reached?
    - Are the high concentration zones moving?
    - What concentrations will reach the wall?

Dynamic/Unstable Plume

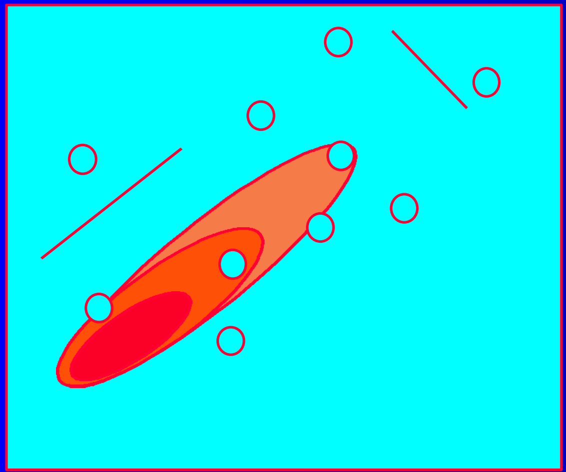


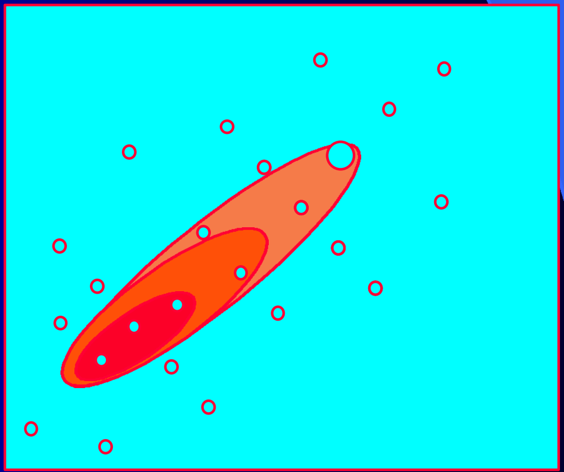
Geochemistry Considerations

- Oxygen concentration
  - O_2 is preferred electron acceptor
  - high O_2, increased $Fe(OH)_3$ precipitation
- Carbonate alkalinity
  - precipitation of $Fe(CO)_3$ (siderite)
  - precipitation of $Ca(CO)_3$ (calcite)
- Sulfate concentration
  - possible sulfide formation

Rapid Site Characterization Methods

- Use push tool technologies where appropriate
  - Geoprobe® and Hydropunch®
  - cone penetrometers
  - more samples can be collected, allowing:
    - denser coverage of the area
    - evaluation of a larger area





Summary – Site Characterization

- A thorough site characterization is needed for the immediate and continued success of a reactive barrier installation
  - The “passive” nature of the technology makes this critical
- Good hydrologic characterization essential to remedial effectiveness
- Current conditions must be known and future conditions predicted

Emplacement Methods

- Conventional excavation
- Trenching machine
- Deep soil mixing
- Biopolymer trenching
  - Trench excavation
  - High-pressure jetting
  - Vertical hydraulic fracturing

Biopolymer Construction Methods

Emerging Technology

Biopolymer Trench

- Excavated trench
- Biopolymer provides trench stability
- Cost effective compared to other methods
- Biopolymer breaks down allowing groundwater to move through the wall

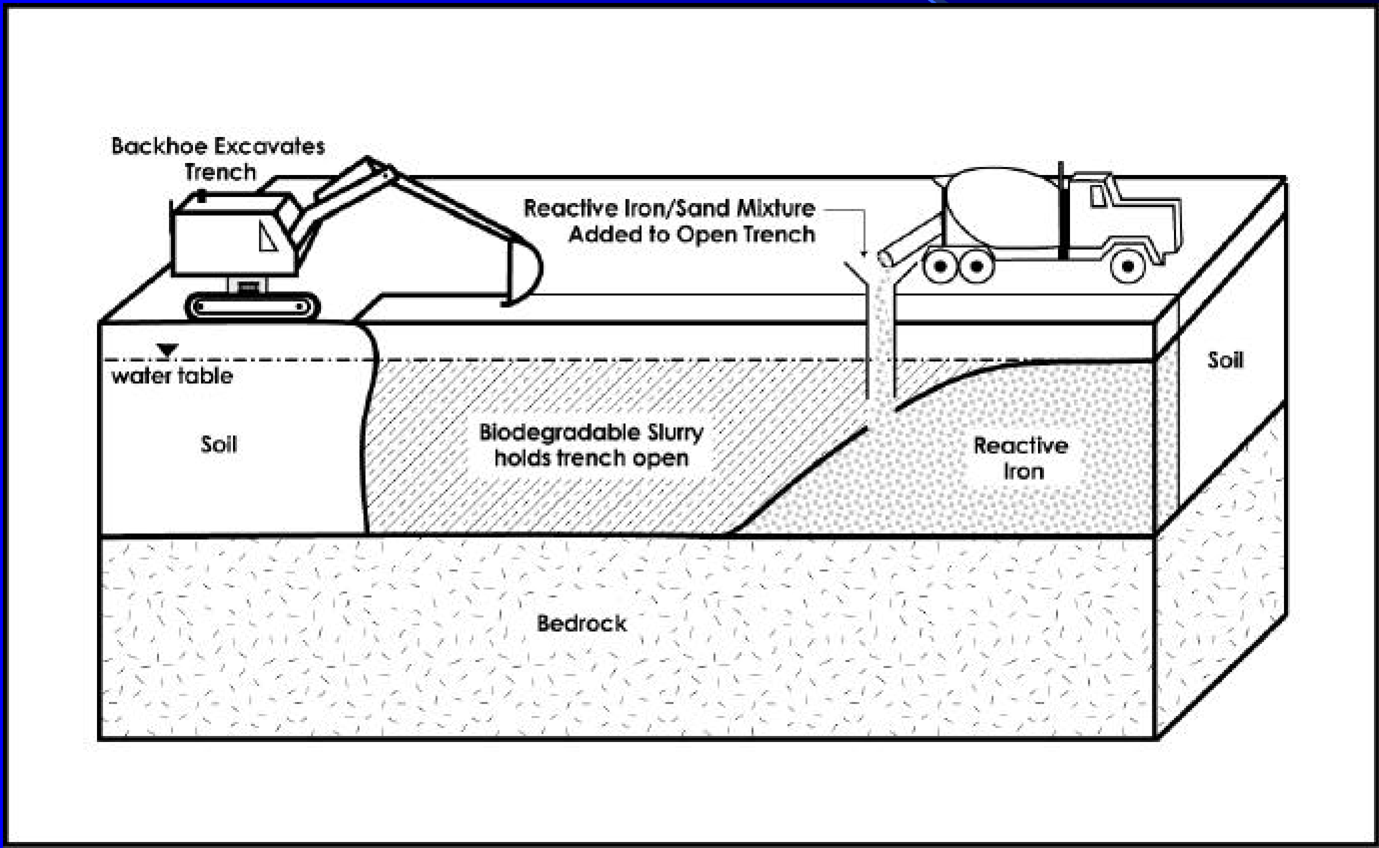
BIOPOLYMER

- **Guar Gum (Galactomannan)**
  - **powder milled from specially grown beans**
  - **long chain carbohydrate**
  - **forms a viscous solution in water**
- **Alternatives are polyacrylamide and xanthan gum**

Emplacement Methods

- Trench Excavation
  - Guar Gum (60 lb/1,000 gal or 7.2 g/L)
  - pH Adjustment (soda ash to pH » 9.0 to 9.5)
  - High pH Enzyme Breaker

Trench Excavation



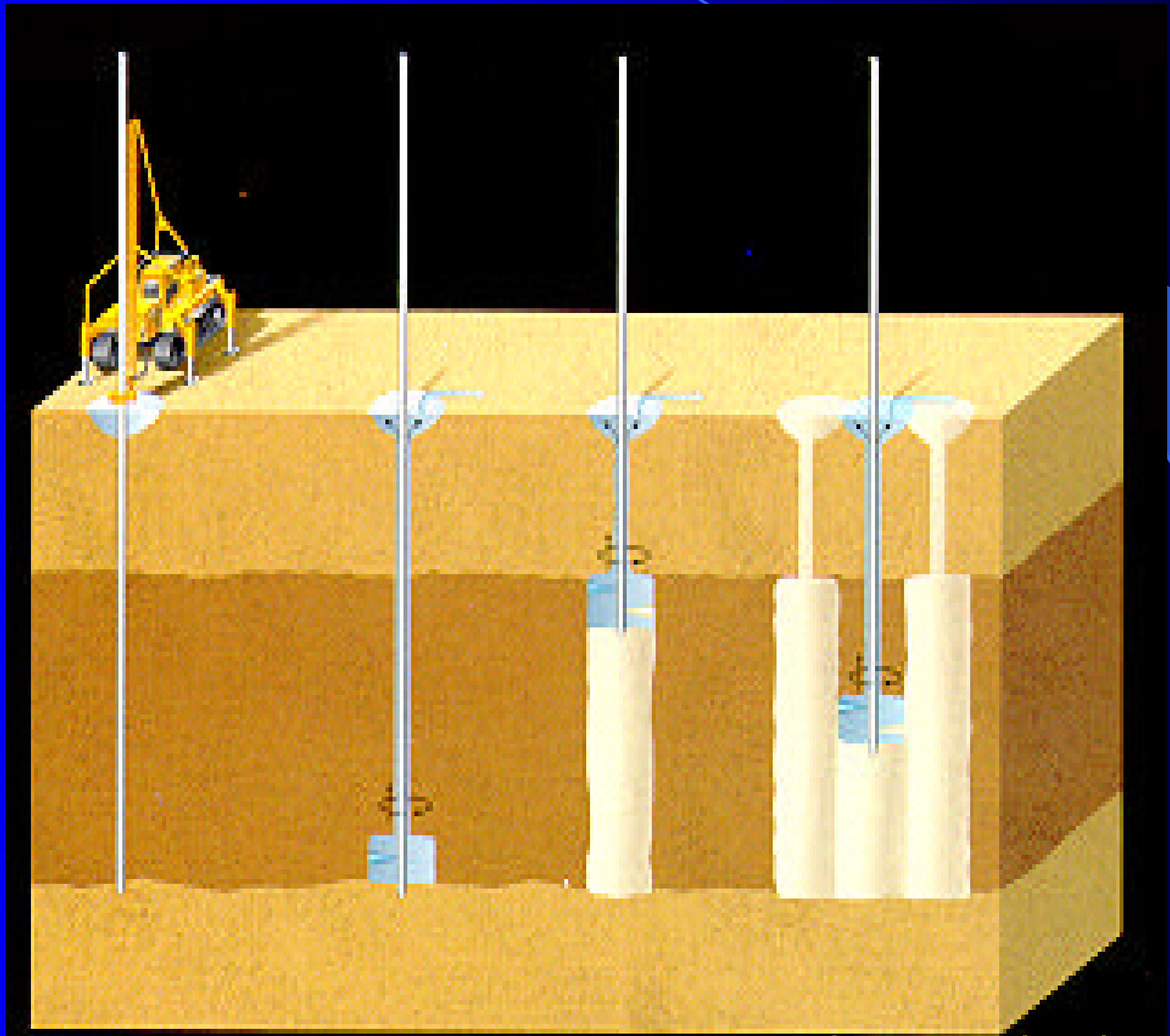
Other Emplacement Methods

- Jetting
  - Guar Gum
  - pH Adjustment
    (10% Acetic Acid Vinegar to pH » 4.0)
  - Enzyme Breaker
  - 50% by Weight Granular Iron
- Vertical Hydrofracturing
  - Proprietary (Guar Gum, Cross-Linker, Breaker, Granular Iron)

Jetting

- Iron suspended in bio-degradable guar based slurry
- Iron slurry injected at high pressure and flow rate
- Jetting is initiated from boreholes on 2-3 m centers
- Jetting creates either columnar or panel type structures in the sub-surface

Jetting Process

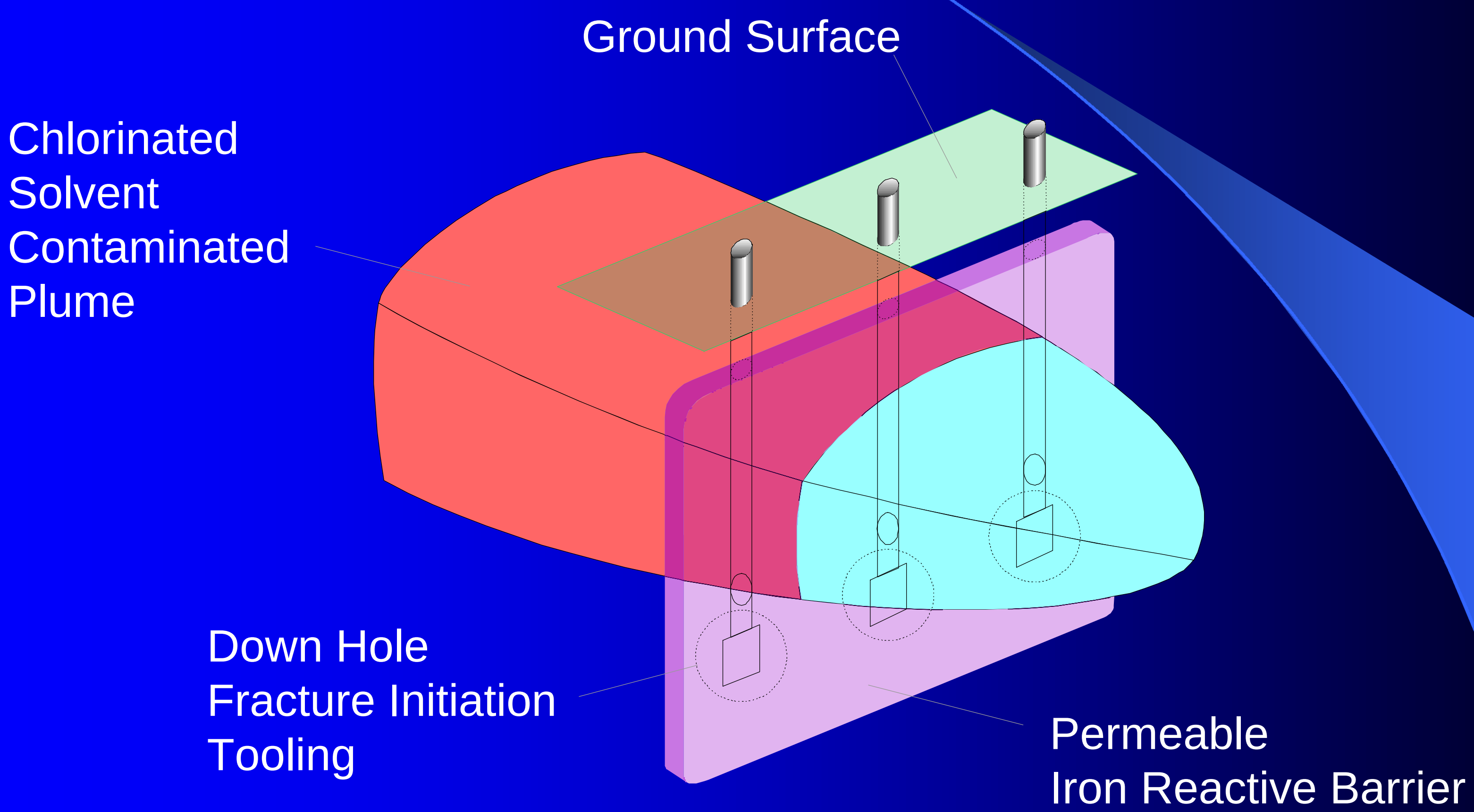


Courtesy of Hayward Baker

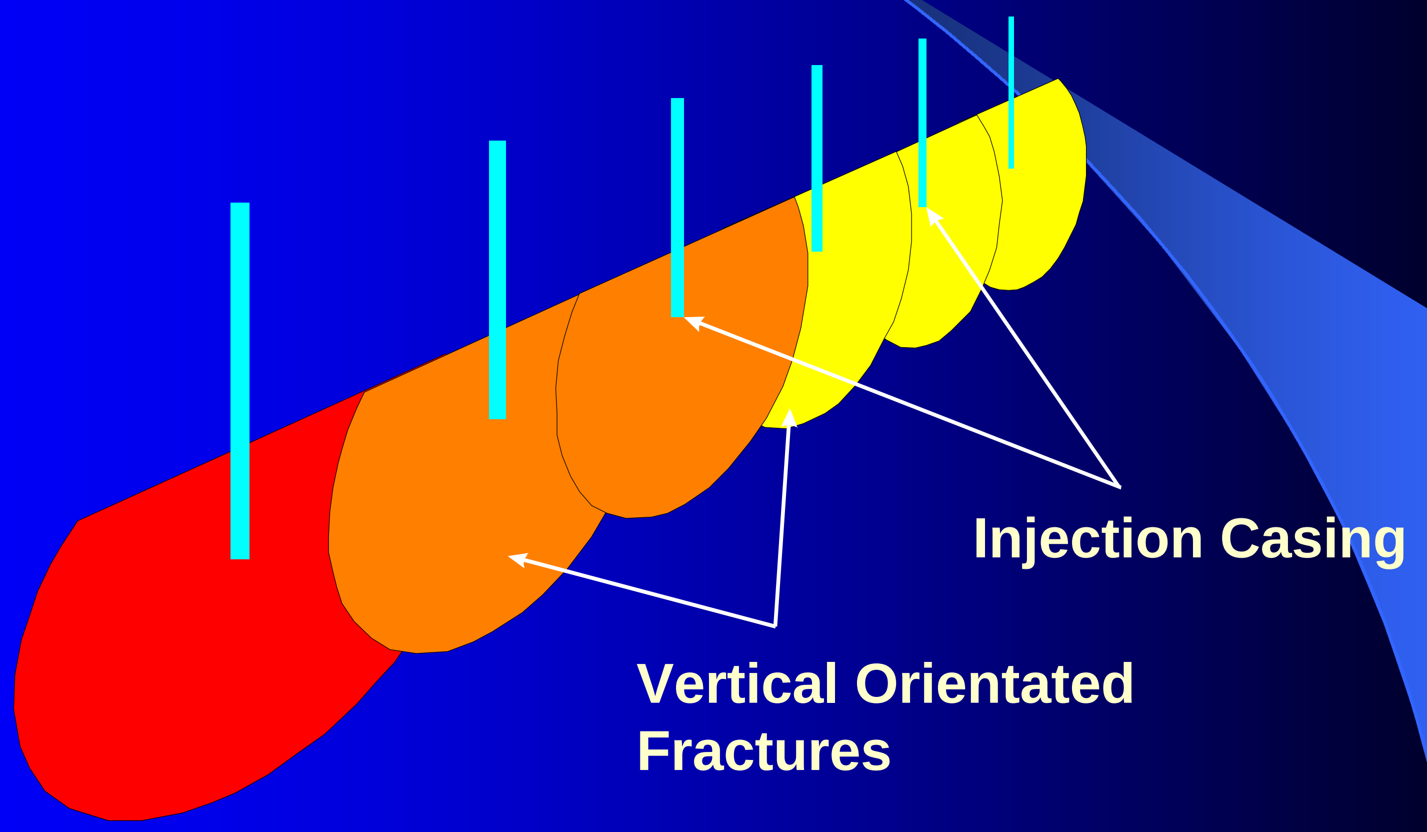
Hydraulic Fracturing

- A process that uses a low pressure stream of viscous fluid carrying a propping agent to separate the soil matrix.
- Emplace in the soil matrix desired materials such as granular iron and create overlapping panels to form continuous wall.

Vertical Hydraulic Fracturing

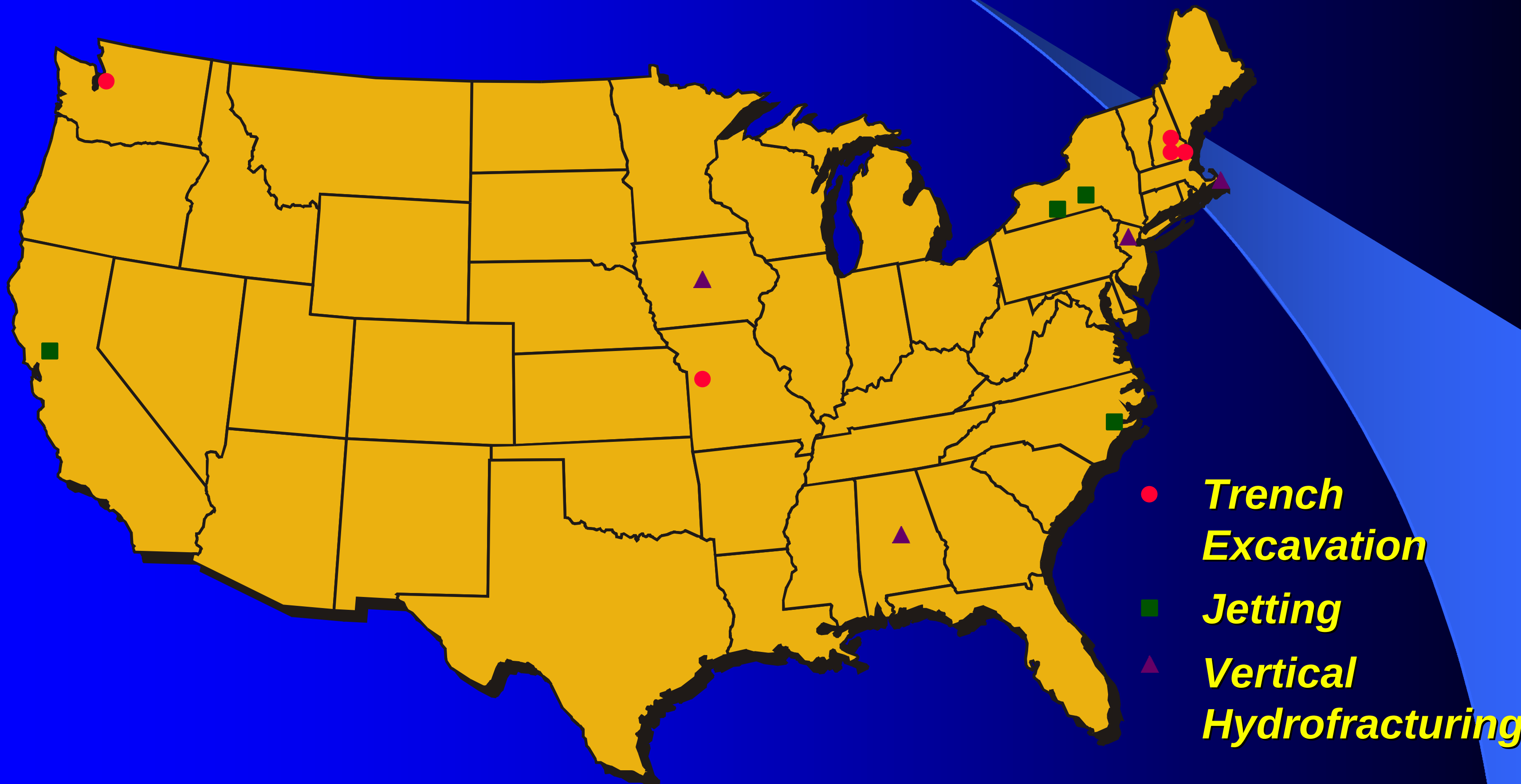


Overlapping Fractures



Panel Emplacement

BP Construction Sites to Date



Pilot Scale BP Trench Site Somersworth, NH

Full-scale BP Trench Somersworth, NH, Sep 2000

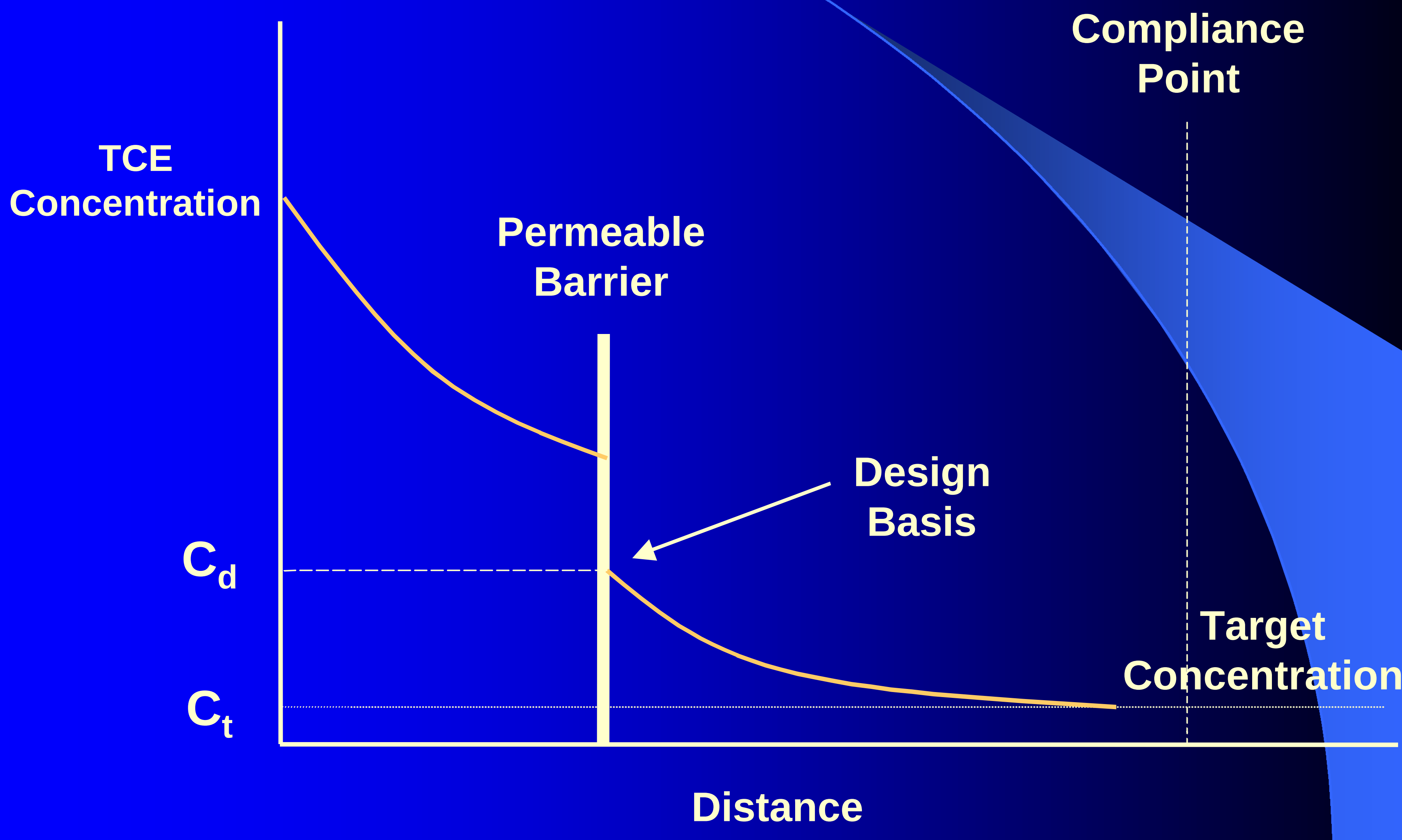
Emplacement Summary

- Recent advances in PRB emplacement technology are viable and cost effective
- Depth limitations are significantly reduced with recent developments
- Thin and thick PRBs can be emplaced
- Recent advancements allow PRB emplacement where excavation would be problematic

PRB Synergy with Natural Biodegradation Processes

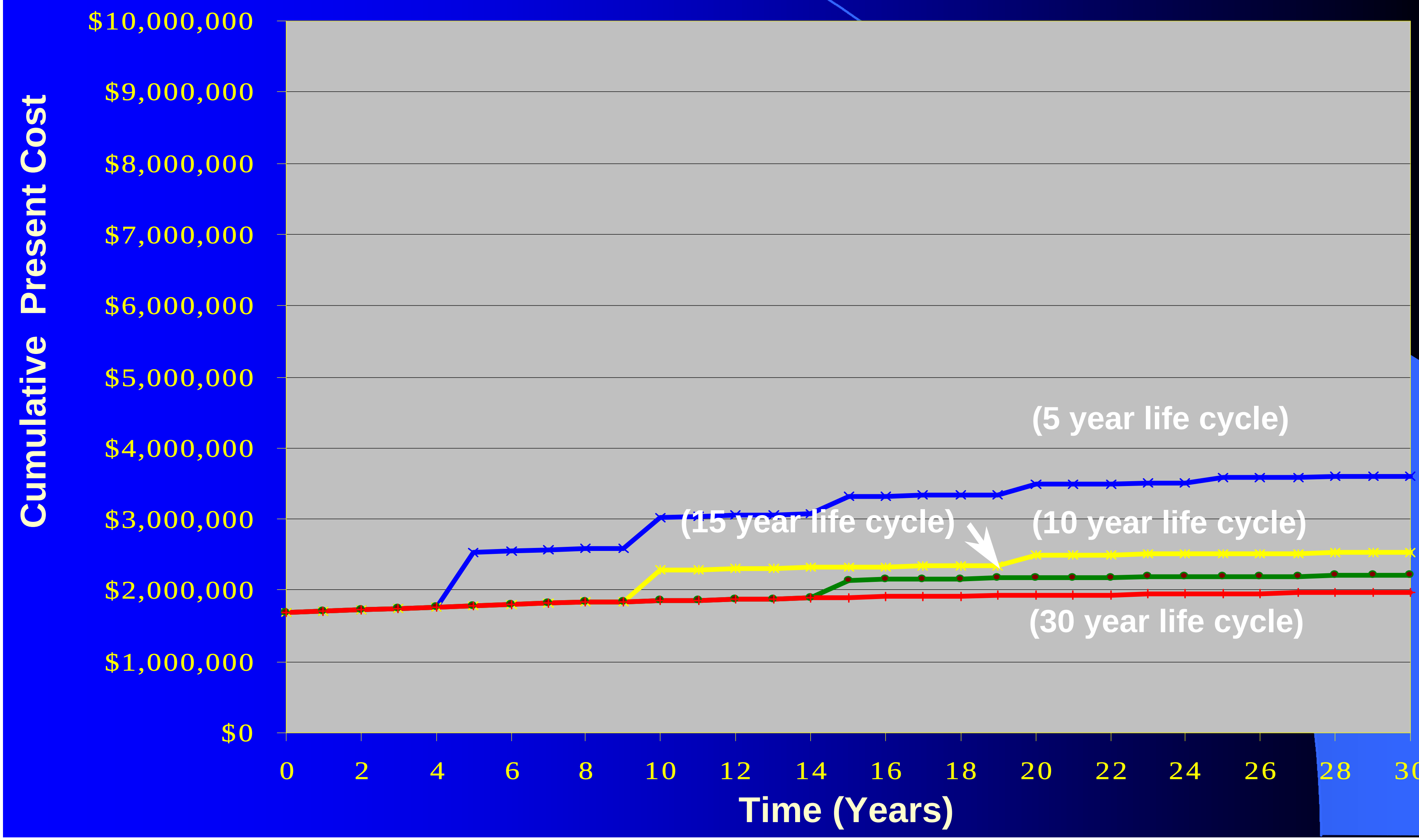
- Both are reductive processes
- PRB enhances reducing environment
- Understand processes and incorporate into design
- Barrier location relative to source and compliance point
- Take advantage of available space and residence time for natural biodegradation

Combining PRBs with Natural Biodegradation Processes



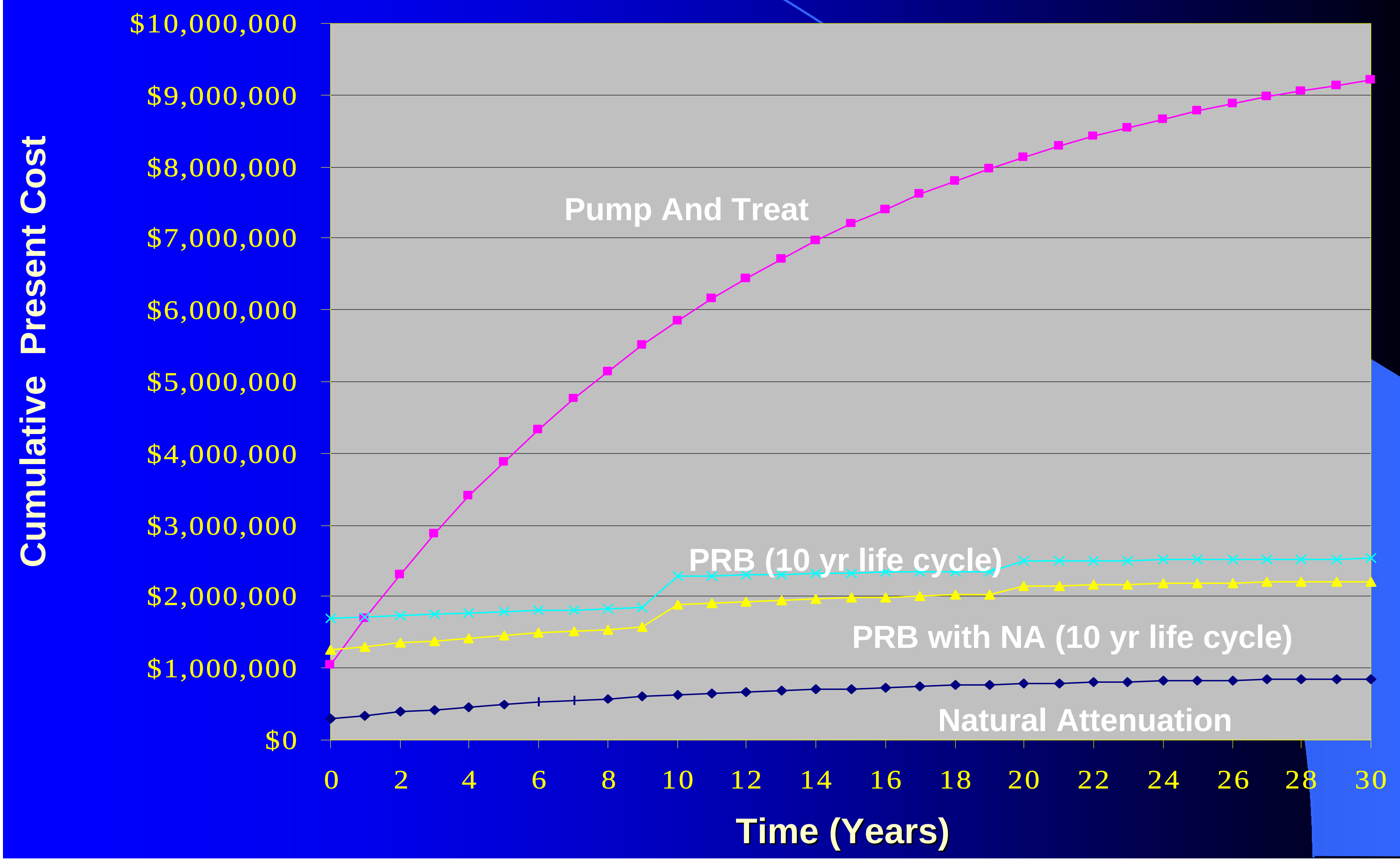
PRB Cost

PRB Summary



Cumulative Present Cost
$10,000,000
$9,000,000
$8,000,000
$7,000,000
$6,000,000
$5,000,000
$4,000,000
$3,000,000
$2,000,000
$1,000,000
$0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Time (Years)
(5 year life cycle)
(15 year life cycle)
(10 year life cycle)
(30 year life cycle)

Overall Cost Comparison



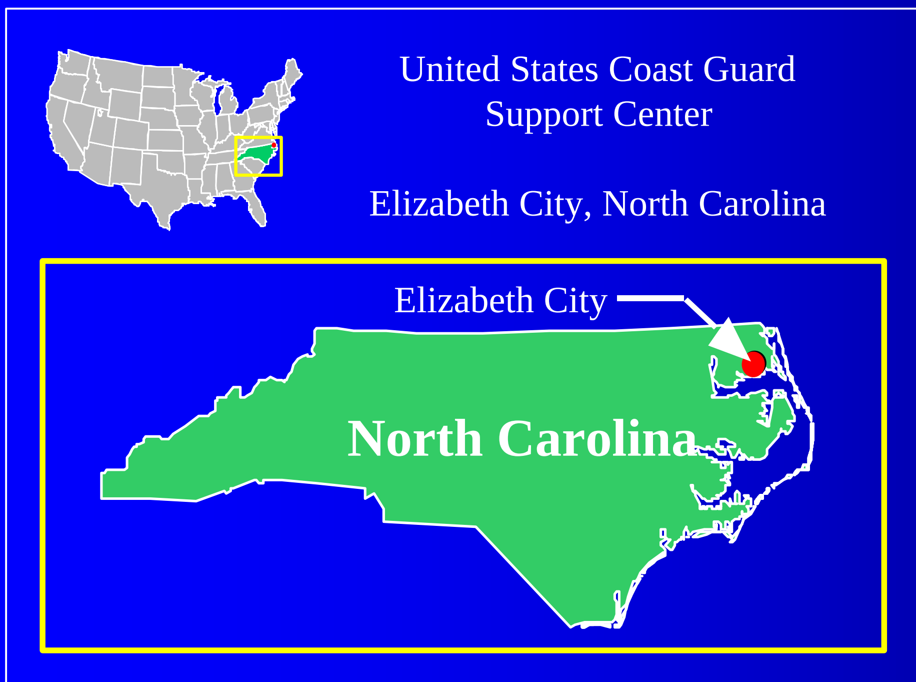
Cost Summary

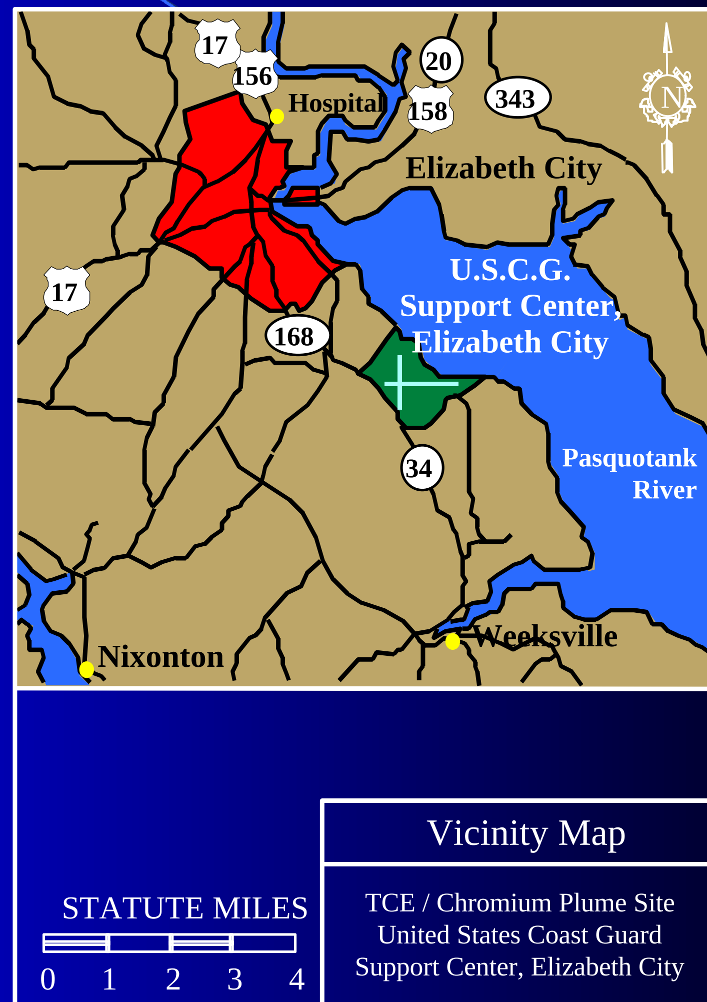
- Permeable reactive barriers are cost-effective compared to P&T systems
- Zero O&M is the major advantage for PRBs
- Emplacement and media drive costs for PRBs
- Capital costs for P&T systems and PRBs are similar
- PRB payback is quick whereas O&M for P&T continues to add up
- Synergy with natural biodegradation processes should be considered during PRB design stage

PRB Case Study

USCG Support Center
Elizabeth City, NC

Elizabeth City PRB Site

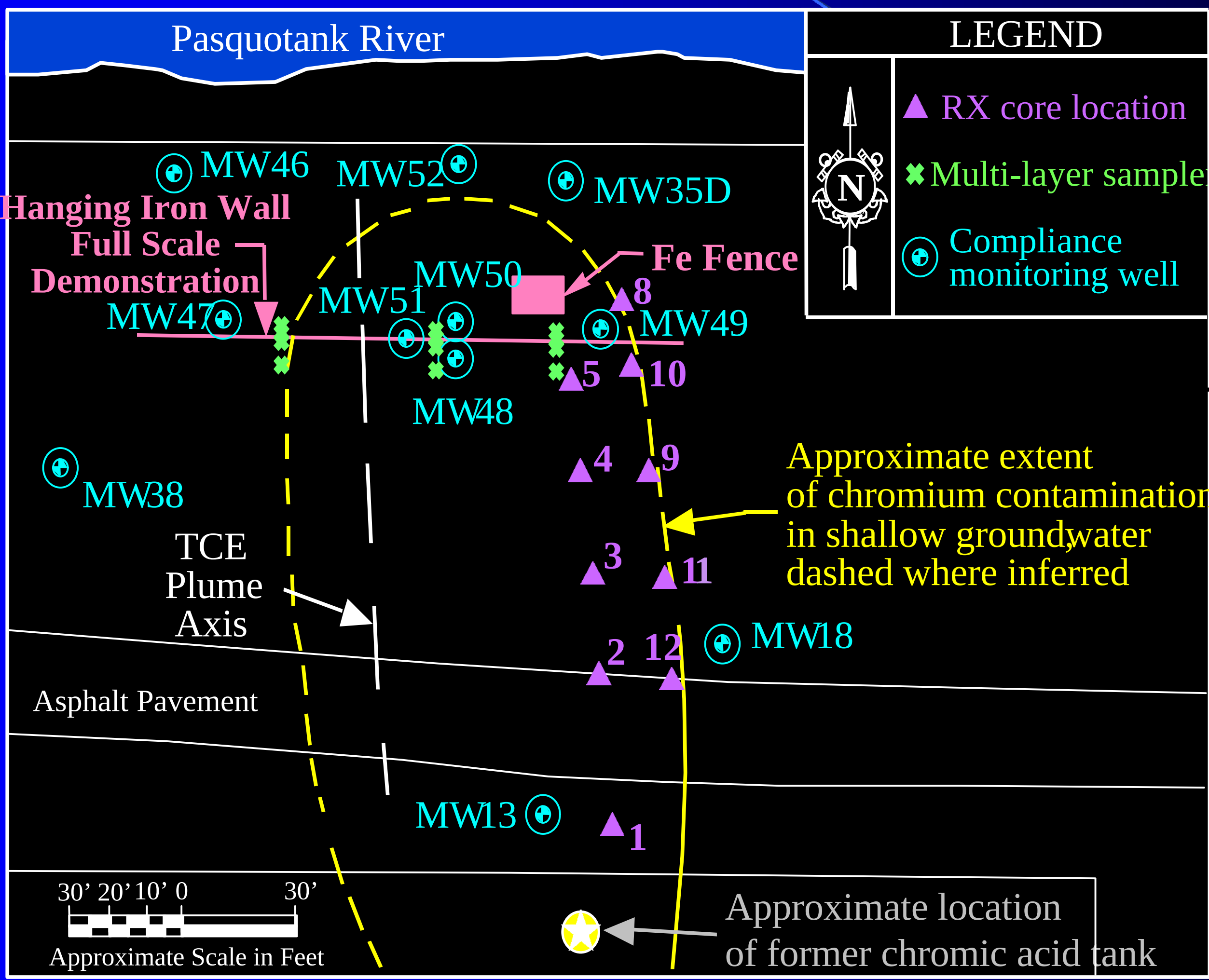




USEPA - USCG PRB RESEARCH SITE
Elizabeth City, NC

Trencher Used at Elizabeth City, NC for Continuous Wall Installation

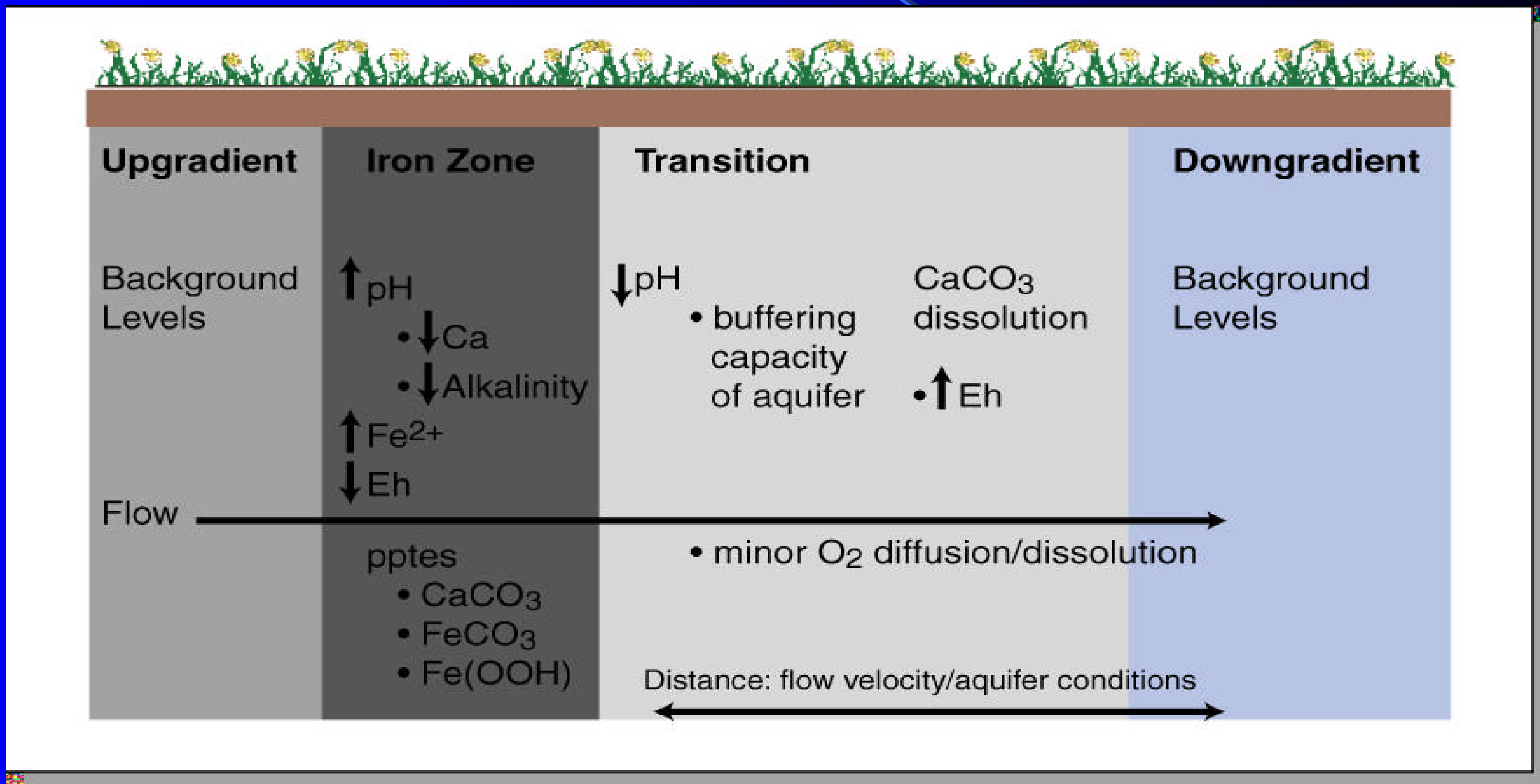
Elizabeth City Site Plan View



Performance Monitoring

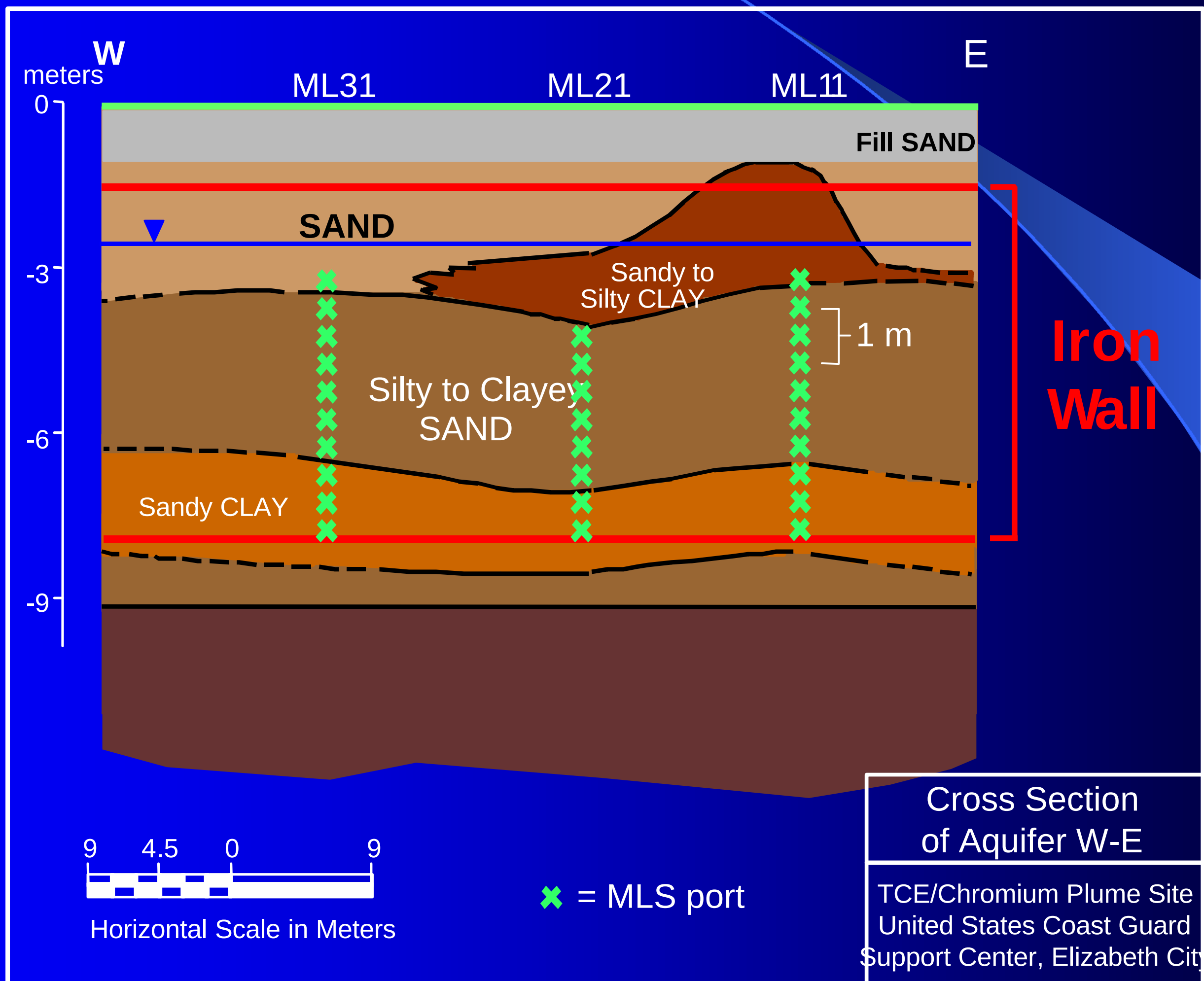
- For PRB's - emphasis on plume capture (passive technology) and contaminant treatment
- FOCUS
  - changes in system reactivity over time,
  - changes in site and reactive wall hydraulics over time.

System Geochemistry

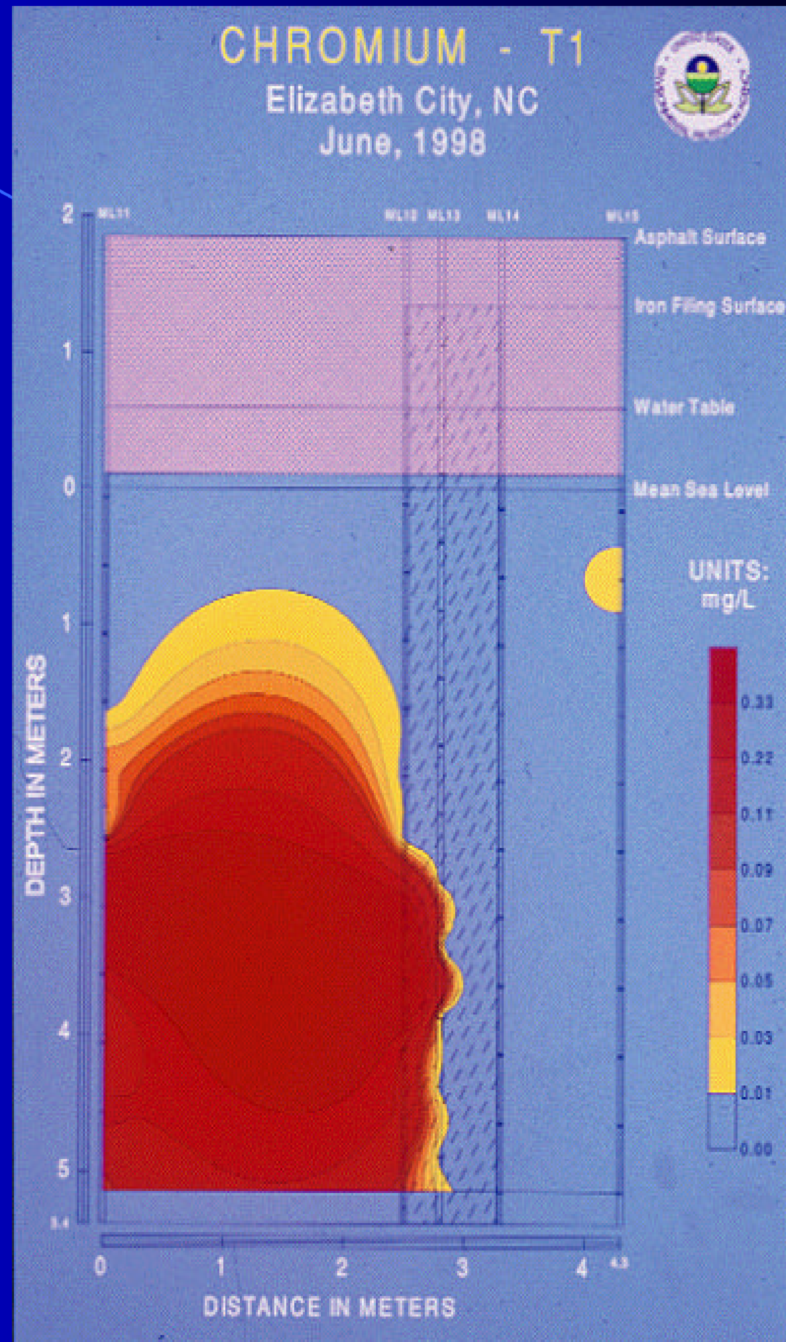


enviro**metal** technologies inc.

Multi-Level Samplers

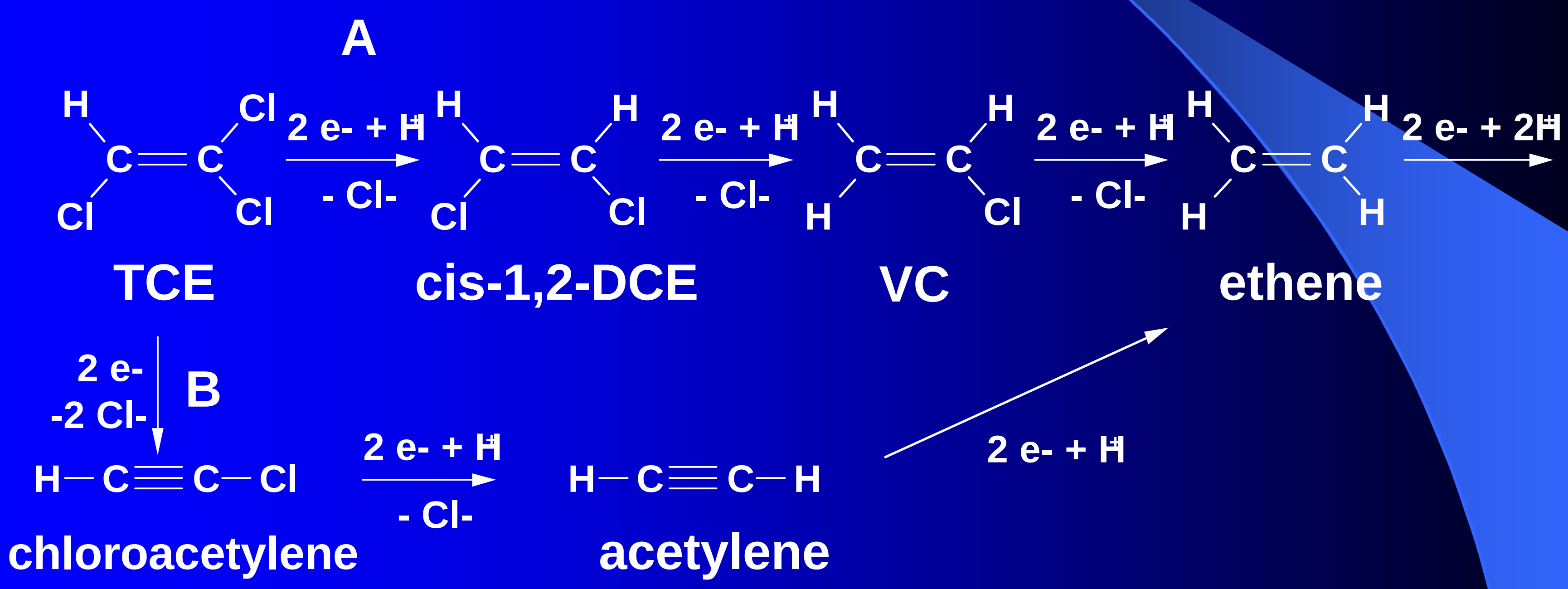


Cr-2D Cross-Section

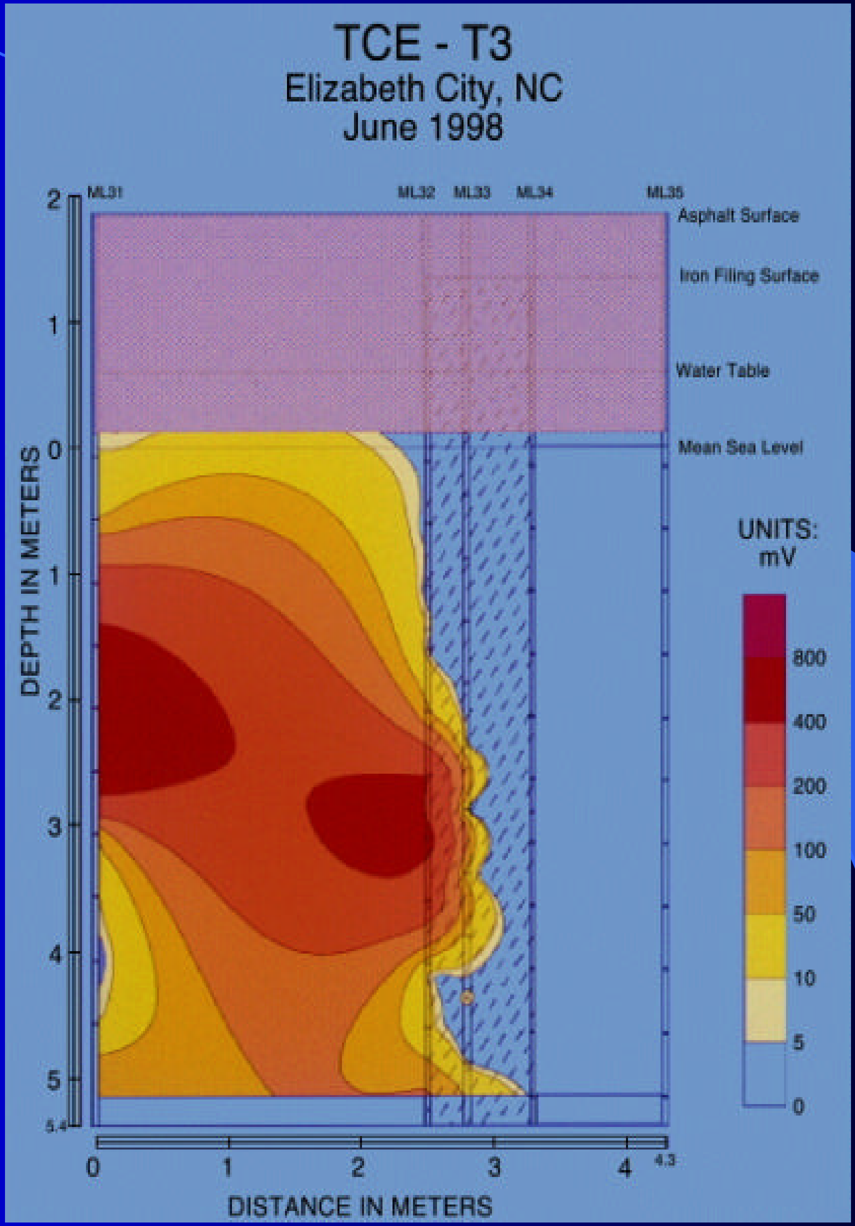


Contaminant Degradation

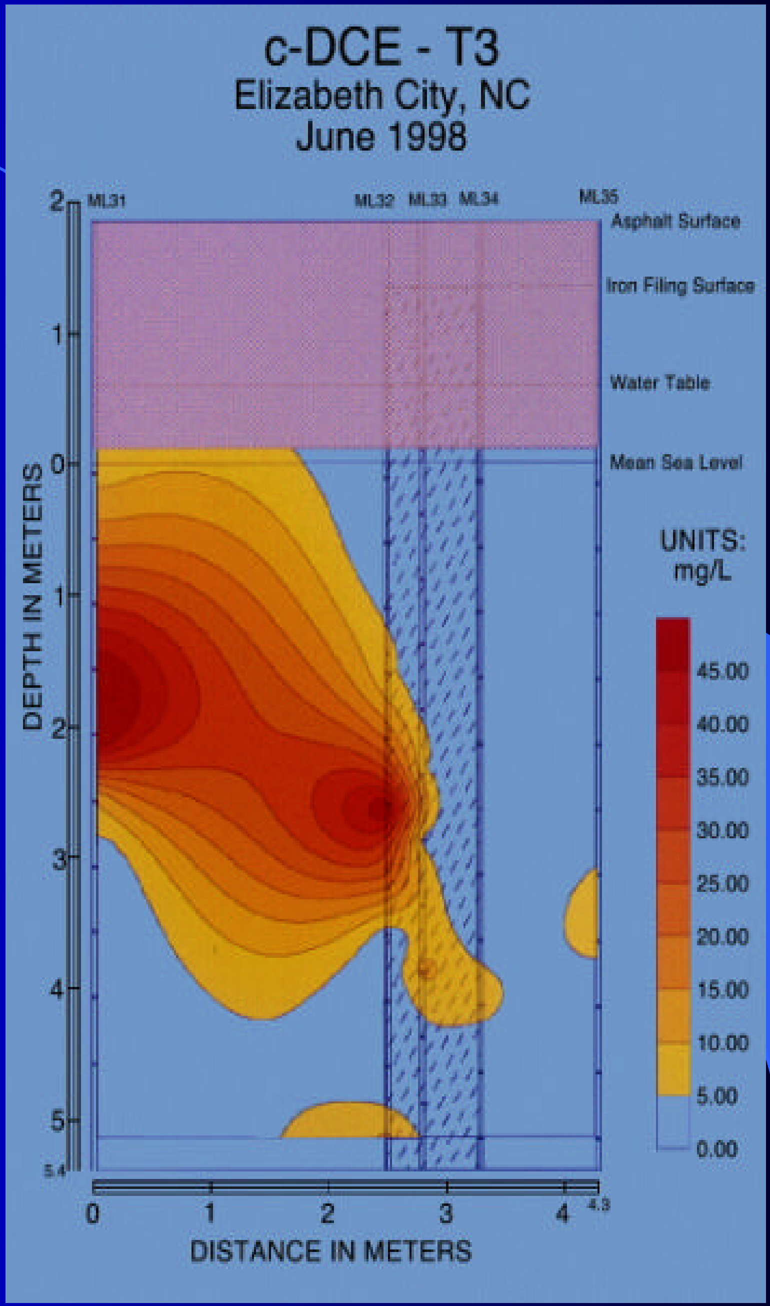
TCE



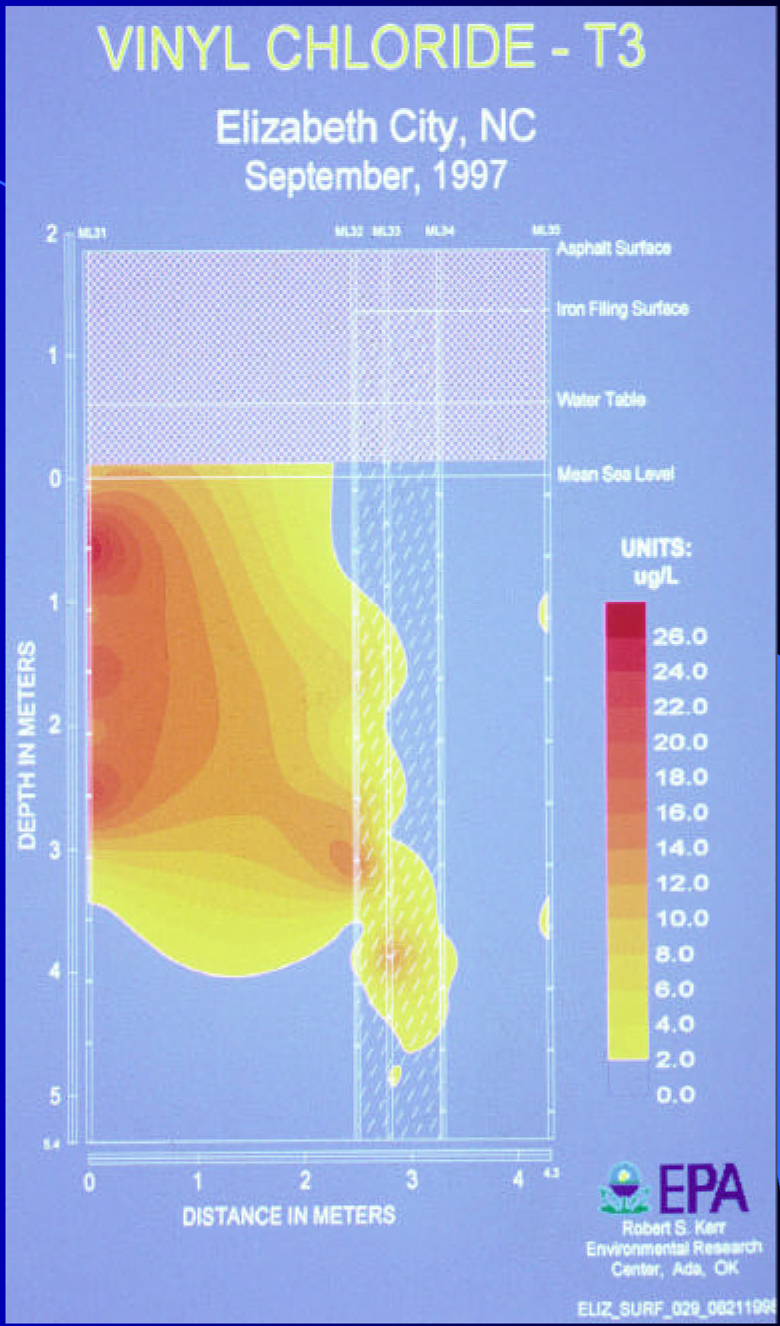
TCE-2D Cross-Section



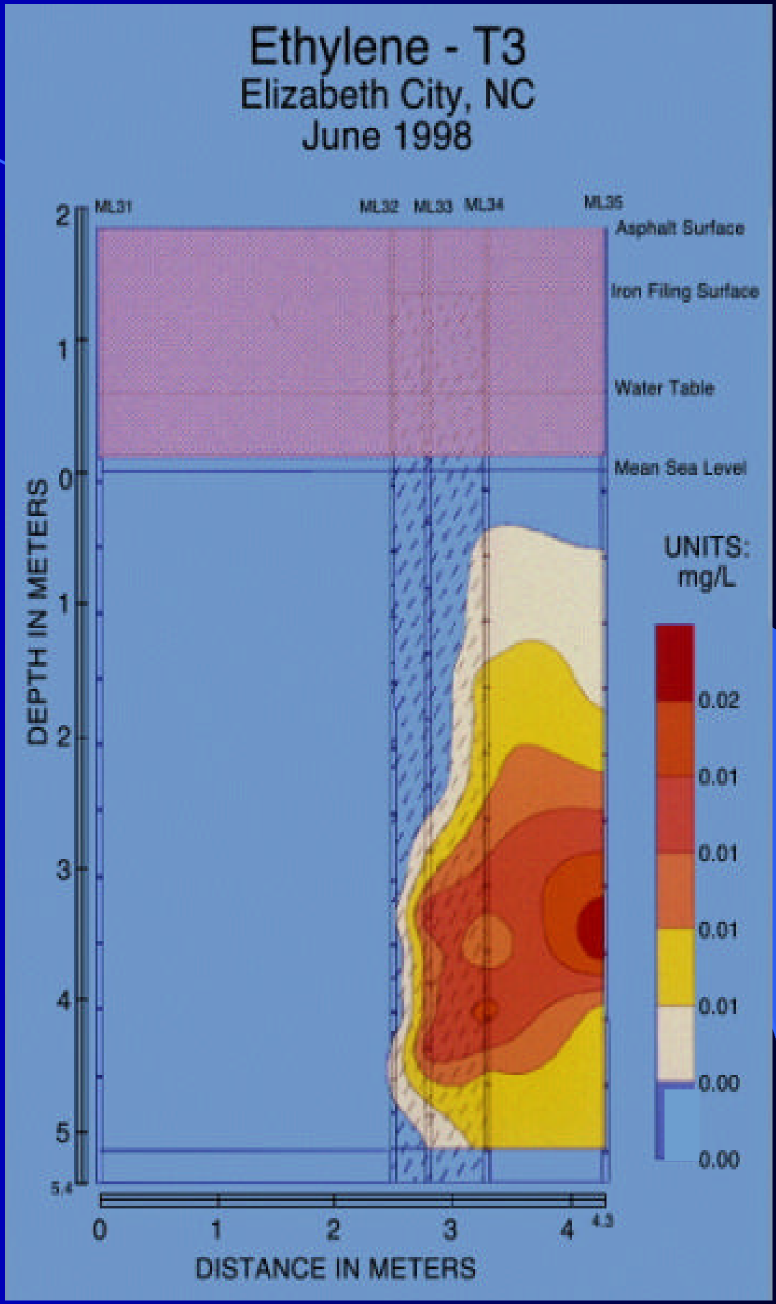
c-DCE-2D Cross-Section



Vinyl Chloride-2D Cross-Section



Ethylene-2D Cross-Section



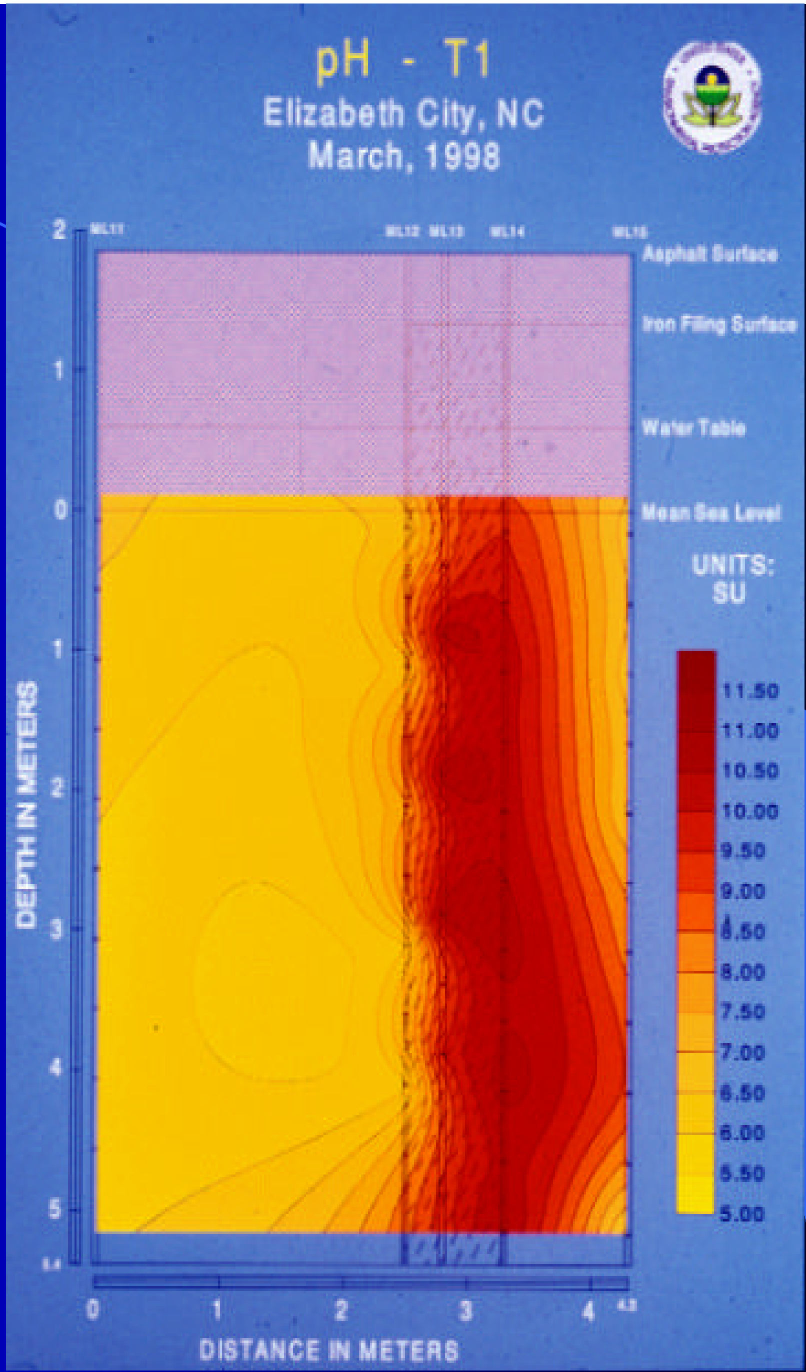
Iron Corrosion in Subsurface Systems

$Fe^0 + 2H_2O \rightarrow 2FE^{2+} + H_2 + 2OH^-$

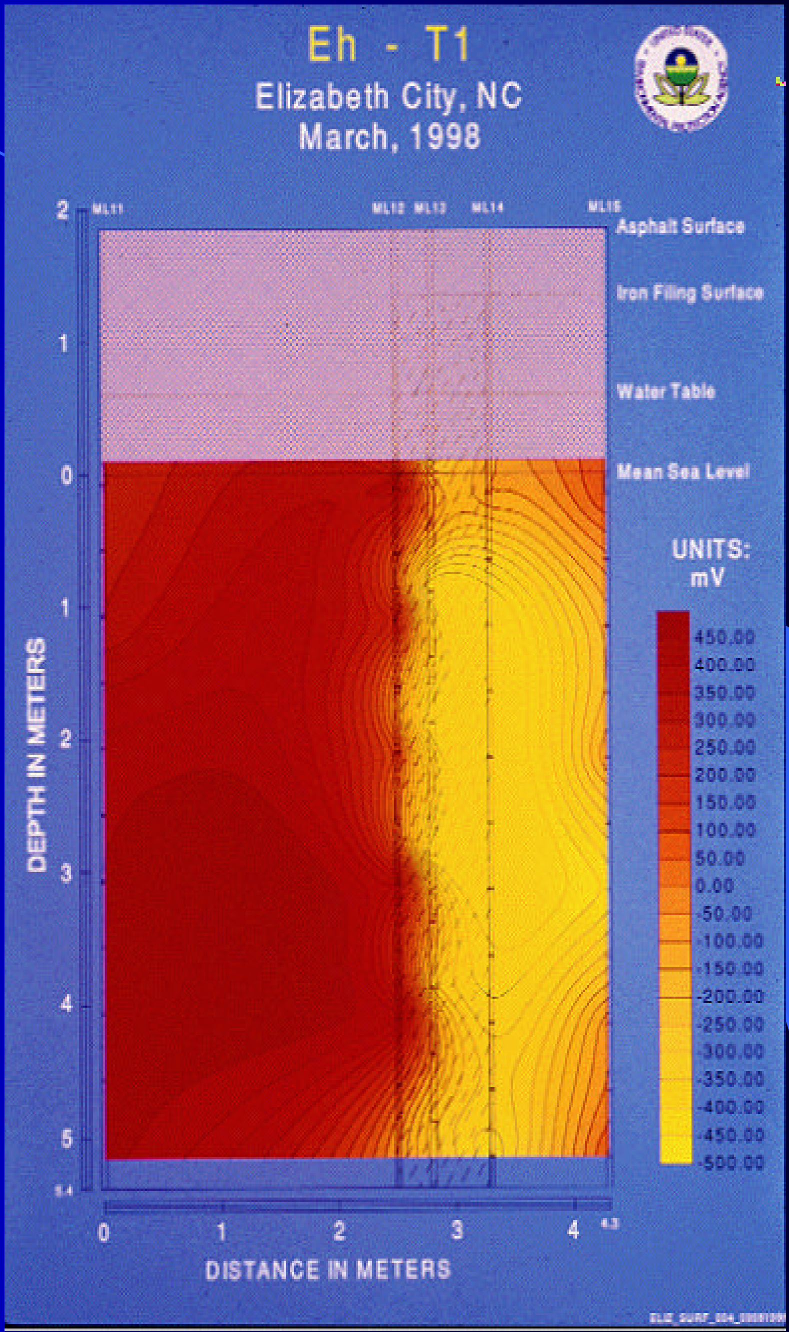
$Fe^0 + O_2 + 2H_2O \rightarrow 2FE^{2+} + 4OH^-$

$\uparrow$ pH Fe^{2+} $\downarrow$ Eh

pH-2D Cross-Section



Eh-2D Cross-Section



EPA/USCG Full-Scale Demonstration Results

- First site to use continuous wall design
  - more cost effective
  - more efficient at plume capture
- After 4.5 years continues to meet remedial objectives
- No evidence of decrease in performance
- First wall to remediate both chlorinated solvents and chromium

Long-term Performance

- Potential Loss of reactivity, permeability
  - Surface geochemistry
  - Microbiology
  - Hydrology

Long-term Performance SUMMARY

- Accumulation of precipitates over time *may* cause porosity/permeability loss
- Consistent degradation/removal of contaminants
- Microbial Biofouling may occur under limited conditions