# Section 8.a

# Modeling Leachate Natural Attenuation

## Vejen Landfill, Vejen, Denmark

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# Overview

- landfill MNA - a new perspective
- detailed case study
  - Vejen landfill site - leachate natural attenuation
- BioRedox reaction schemes for modeling:
  - Cr(VI) attenuation
  - permeable reactive barriers (PRBs)
  - ORC for bioremediation of BTEX and MTBE

# Landfill MNA

- researchers studying leachate natural attenuation since the 1970's
- older municipal landfills
  - typically unlined, uncovered for decades
  - organic solvents discarded with refuse
  - biodegradation in landfill
  - bioattenuation of leachate plumes below LF
  - sometimes natural attenuation has effectively mitigated plume migration for decades

# Landfill MNA

- favorable conditions for biostabilization
  - refuse: moisture, high temp., rich in OM
  - aquifer:
    - organic-rich leachate
    - sequential anaerobic-aerobic zones
- remediation of old municipal landfills
  - permeable caps --> bioreactor
    - "biofilter" caps - methanotrophic co-metabolism
      - filter out VOCs in landfill gas
    - destroy pollutants through biodegradation
    - continued bioattenuation of leachate below landfill

# Landfill MNA

- remediation of old municipal landfills
  - low-permeability caps --> entombment
    - contain pollutants for hundreds of years
    - technology lifespan uncertain
- movement towards allowing LF MNA in some cases
  - long-term monitoring critical
  - integrated processes between components:
    - cap --> landfill --> aquifer

# Landfill MNA

- may need predictive tool to assess long-term effectiveness of landfill MNA
  - integrated remediation alternatives
    - landfill caps
    - landfill gas collection
    - natural attenuation or enhanced bio in groundwater
- reactive transport models
  - insight into effects of integrated technologies

# Vejen Landfill Site

- Vejen, Denmark
- unlined landfill over shallow aquifer
- stable leachate plume
- extensive redox zone delineation (t=15 yrs)
- Thomas Christensen et al. (Technical University of Denmark)
  - landfill hydrology
  - hydrogeology, biogeochemistry in aquifer

# Vejen Landfill Site

- Monitoring program:
  - 9 borings along a transect (370 m long)
    - 13 to 31 samples collected from each boring (0.5 meter intervals)
      - 10 cm-long iron screens fitted onto 1-inch iron pipes
  - additional borings placed within 130 meters of landfill
    - temporal fluctuations in redox parameters

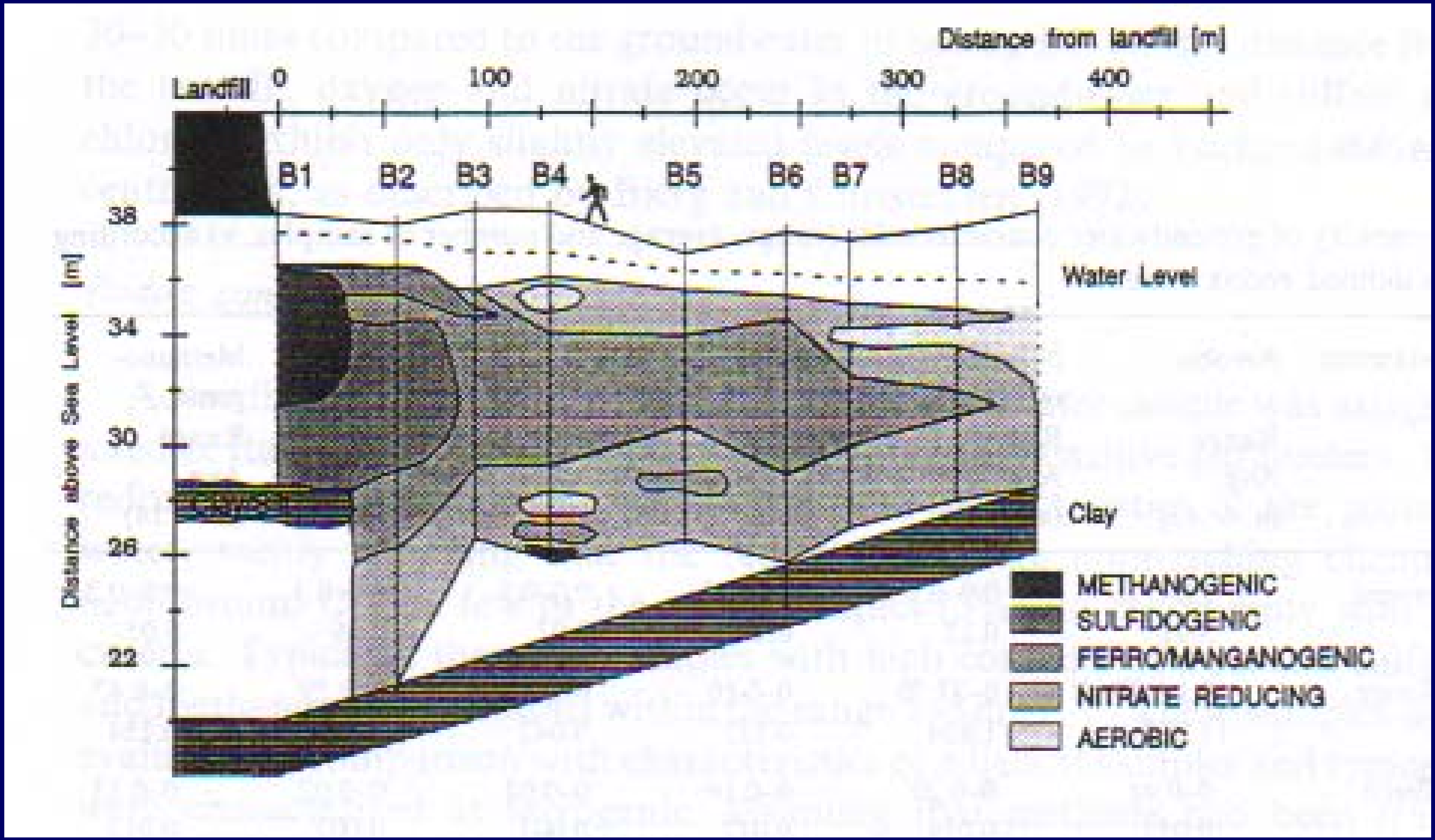
# Conceptual Model

- homogeneous shallow aquifer
- leachate source model (TOC)
- groundwater velocity: 500 to 650 ft/year
- 2D cross-section model
  - groundwater flow:  MODFLOW
  - solute transport:  *BioRedox*

# Conceptual Model

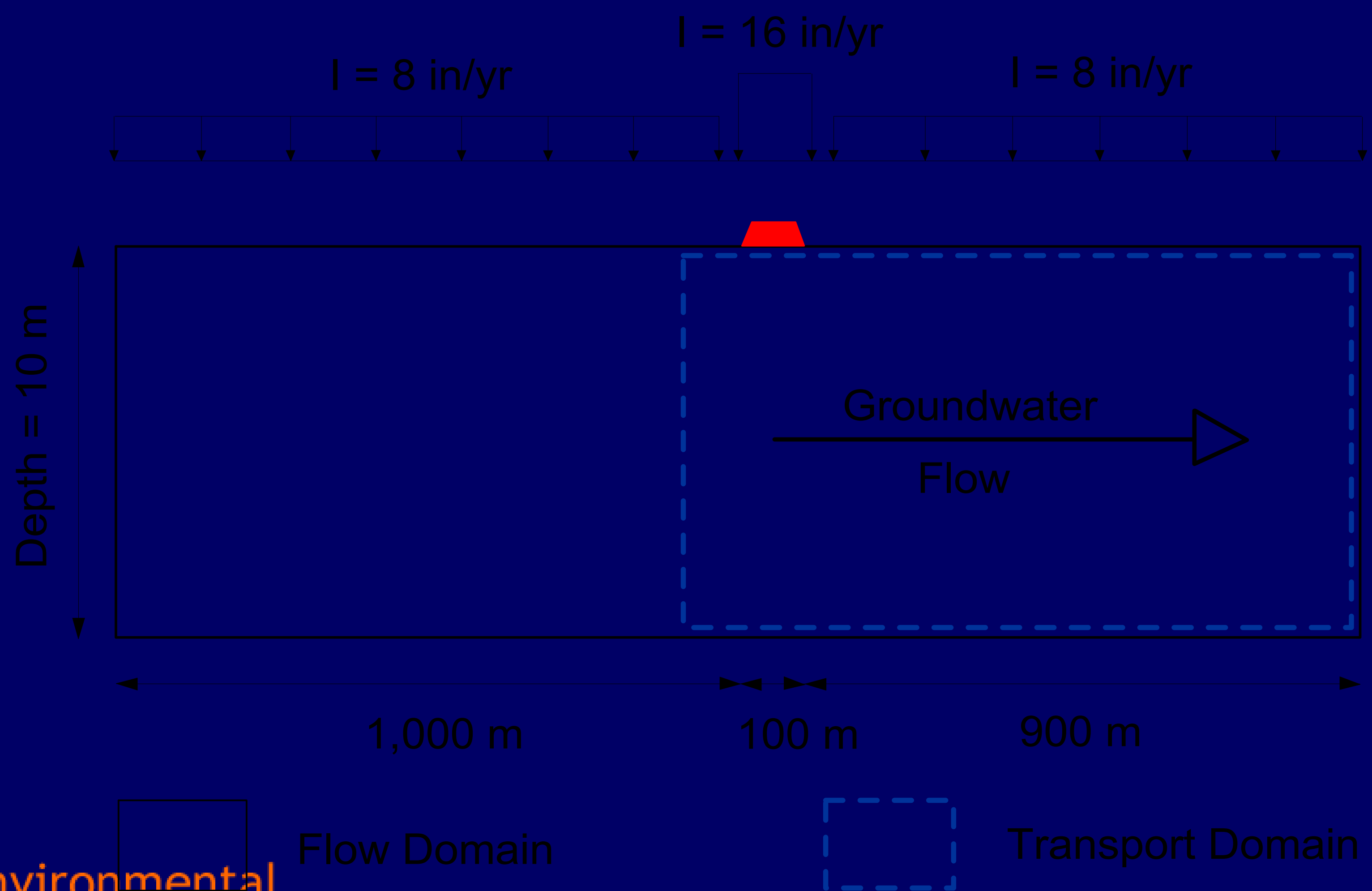
- *BioRedox* represents:
  - leachate source
  - TOC oxidation
  - electron acceptor reduction ($O_2$, $NO_3$, $Fe(OH)_3$, $SO_4$, and $CO_2$)

# Redox Zones in Groundwater




Source: Lyngkilde and Christensen, 1992

# Model Domain

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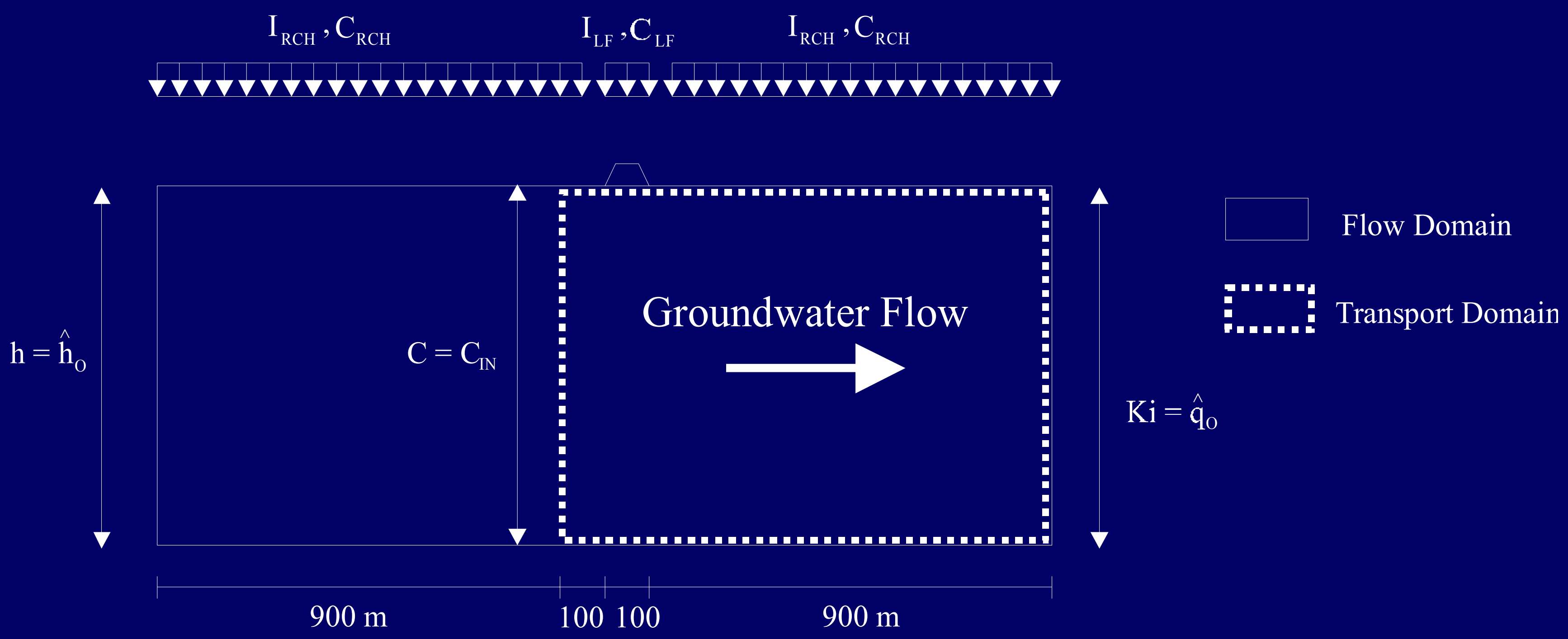
# Boundary Conditions



# Solute Properties

| ***Solute*** | ***Molecular Weight (g/mol)*** | ***$K_{oc}$ (mL/g)*** | ***Units of Concentration*** | ***Boundary and Initial Conditions*** | | | |
|---|---|---|---|---|---|---|---|
| | | | | ***$C_{IN}$*** | ***$C_{RCH}$*** | ***$C_{LF}$*** | ***C(x,t=0)*** |
| TOC | 12 | 0 | mg/L | 0 | 0 | (a) | 0 |
| PCE | 166 | 364 | ug/L | 0 | 0 | 250 | 0 |
| TCE | 131.5 | 126 | ug/L | 0 | 0 | 250 | 0 |
| DCE | 97 | 49 | ug/L | 0 | 0 | 250 | 0 |
| Vinyl Chloride | 62.5 | 57 | ug/L | 0 | 0 | 250 | 0 |
| Oxygen | 32 | 0 | mg/L | 7 | 7 | 0 | 7 |
| Nitrate | 62 | 0 | mg/L | 25 | 25 | 0 | 25 |
| Ferric Hydroxide | 55.85 | N/A | mg/g | N/A | N/A | N/A | 5 |
| Sulfate | 96.1 | 0 | mg/L | 40 | 40 | 400 | 40 |

(a) $C = 14000e^{-0.26t}$, $t \le 10$ years; $C = 1040$ mg/L, $t > 10$ years

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# Solute Reactions

| *Solute* | *Type* | *Half-Reaction* |
|---|---|---|
| TOC | Oxidation | $CH_2O + H_2O \text{ --> } CO_2 + 4H^+ + 4e^-$ |
| Vinyl Chloride | Oxidation | $CH_2CHCl + 2H_2O \text{ --> } CH_3COOH + 3H^+ + 3e^-$ |
| Oxygen | Reduction | $O_2 + 4H^+ + 4e^- \text{ --> } 2H_2O$ |
| Nitrate | Reduction | $NO3^- + 6H^+ + 5e^- \text{ --> } 0.5N_2(g) + 3H_2O$ |
| Ferric Hydroxide | Reduction | $Fe(OH)_3(s) + 3H^+ + e^- \text{ --> } Fe^{2+} + 3H2O$ |
| Sulfate | Reduction | $SO_4^{2-} + 9H^+ + 8e^- \text{ --> } HS^- + 4H_2O$ |

| ***Organic Solute*** | ***Redox Zone Biodegradation Rate*** | | | | |
|---|---|---|---|---|---|
| | ***$CH_4$*** | ***$SO_4$*** | ***Fe(III)*** | ***$NO_3$*** | ***$O_2$*** |
| TOC | $k_{TOC}$ | $k_{TOC}$ | $k_{TOC}$ | $k_{TOC}$ | $k_{TOC}$ |
| PCE | $k_{RD}$ | 0.75 $k_{RD}$ | 0.5 $k_{RD}$ | 0 | 0 |
| TCE | $k_{RD}$ | 0.75 $k_{RD}$ | 0.5 $k_{RD}$ | 0 | 0 |
| DCE | $k_{RD}$ | 0 | 0 | 0 | 0 |
| Vinyl Chloride | 0.75 $k_{RD}$ | 0 | $k_{OXD}$ | 0 | $k_{OXD}$ |

| ***Scenario*** | ***$k_{TOC}$ ($d^{-1}$)*** | ***$k_{RD}$ ($d^{-1}$)*** | ***$k_{OXD}$ ($d^{-1}$)*** |
|---|---|---|---|
| no cap | 7.6E-3 | 7.6E-3 | 7.6E-3 |
| high-K cap | 7.6E-3 | 7.6E-3 | 7.6E-3 |
| low-K cap | 7.6E-3 | 1.9E-3 | 7.6E-3 |

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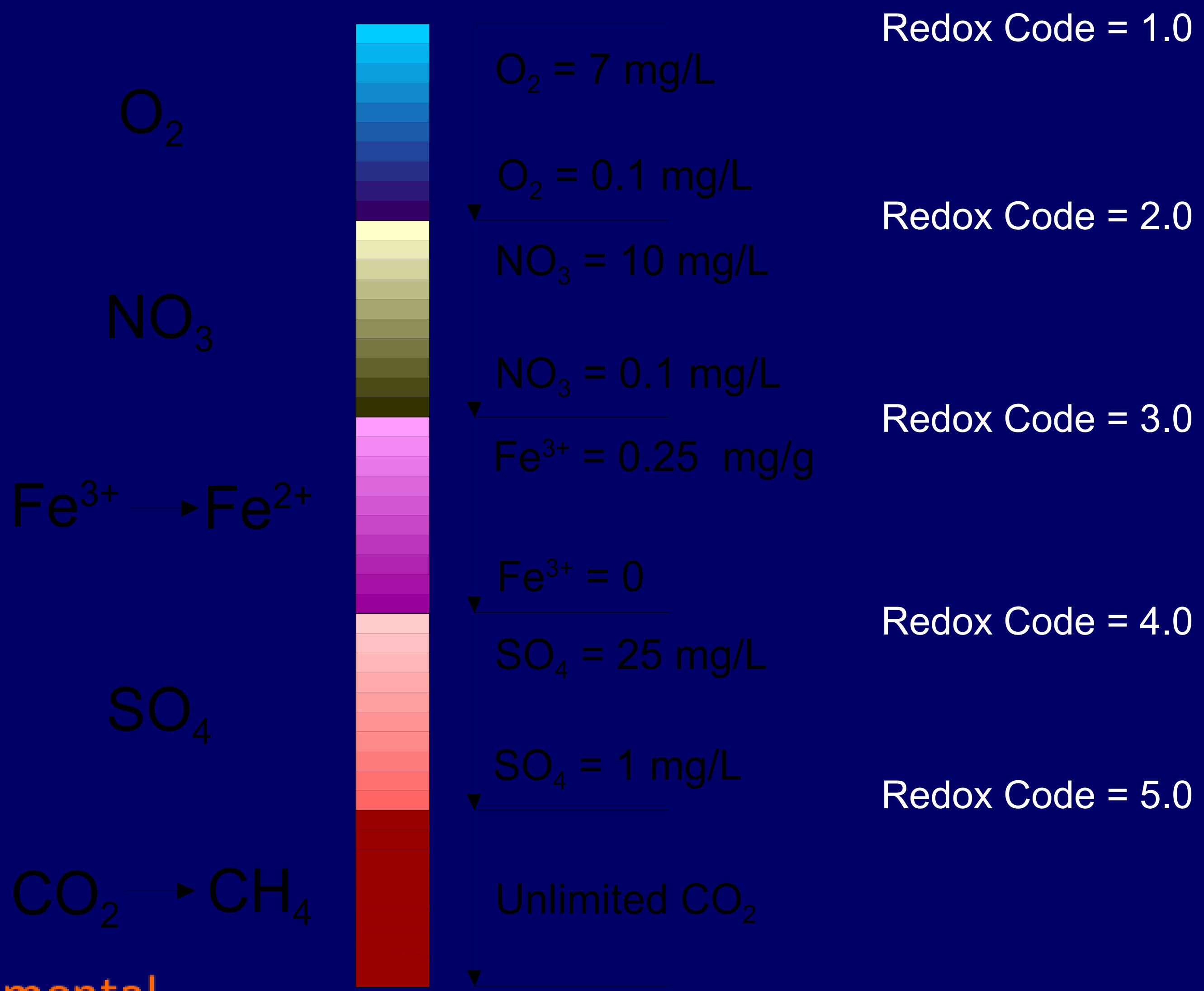
# Redox Zone Visualization

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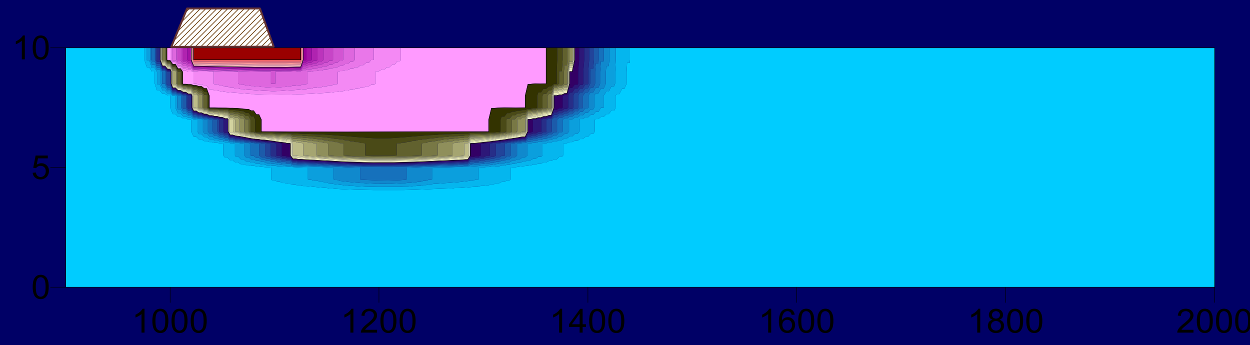
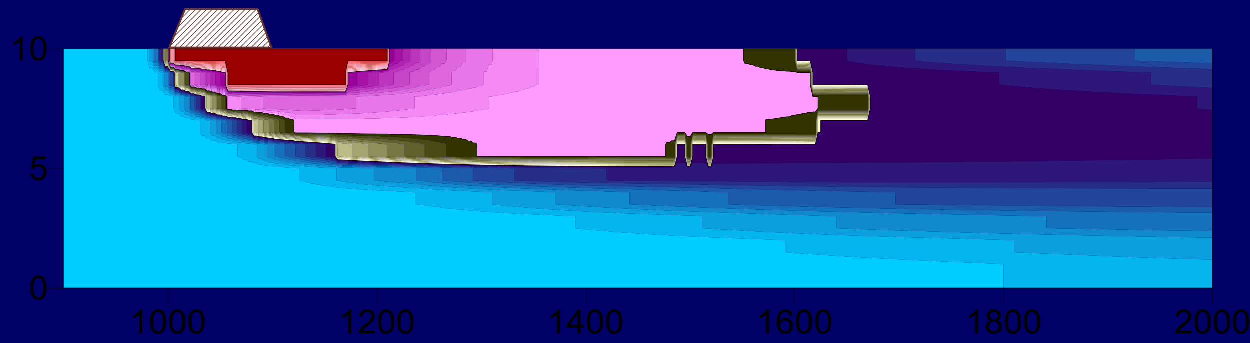
# Transient Bioattenuation Capacity

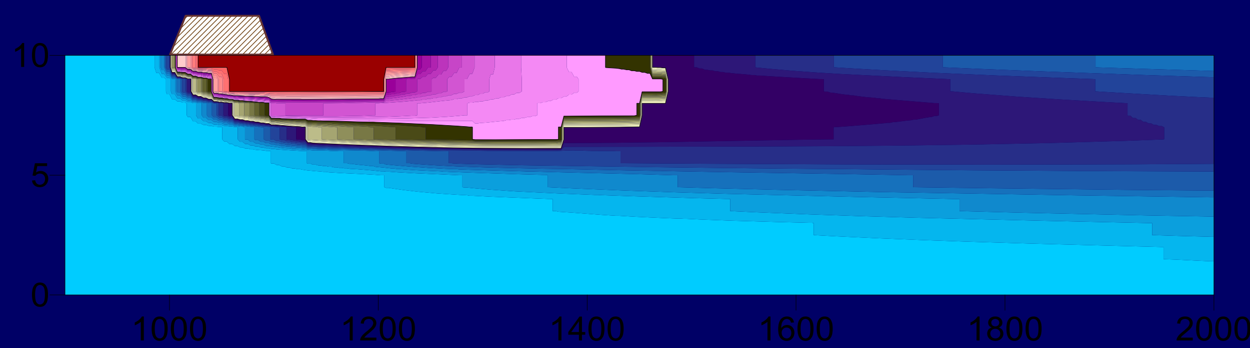
t =1 year




t = 5 years




t = 15 years

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# Vejen Landfill Comparison

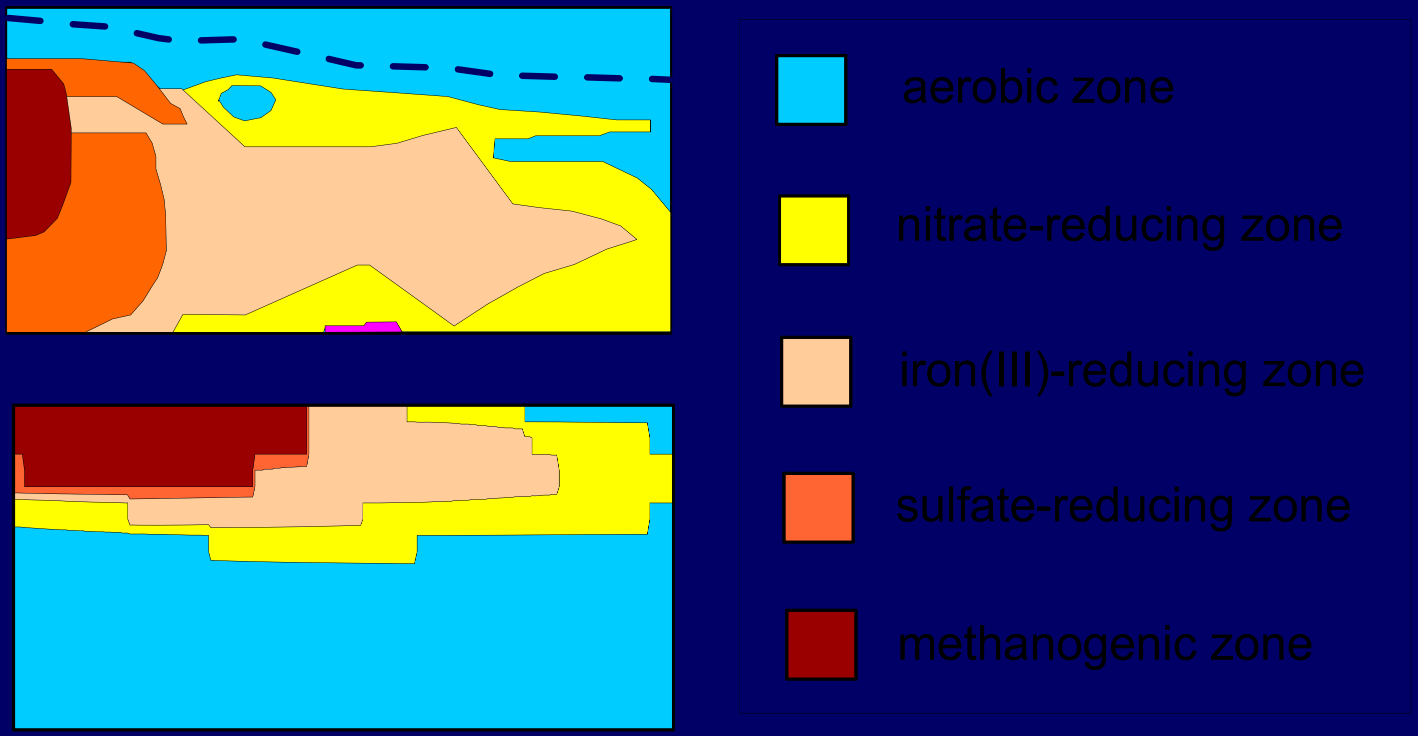
| *Redox Zone* | *Observed* * | *Simulated* |
|---|---|---|
| **Methanogenic / Sulfate-Reducing** | **75 metres** | **100 metres** |
| **Ferrogenic / Manganogenic** | **250 metres** | **250 metres** |
| **Nitrate-Reducing** | **25 metres** | **5 metres** |

* Lyngkilde and Christensen, 1992, J. Contam. Hydrol., 10: 273-289.

Vertical dispersivity = 0.003 m
rate = 1.0e-2 per day
TOC degrades when TOC > 0

Observed:

Model:

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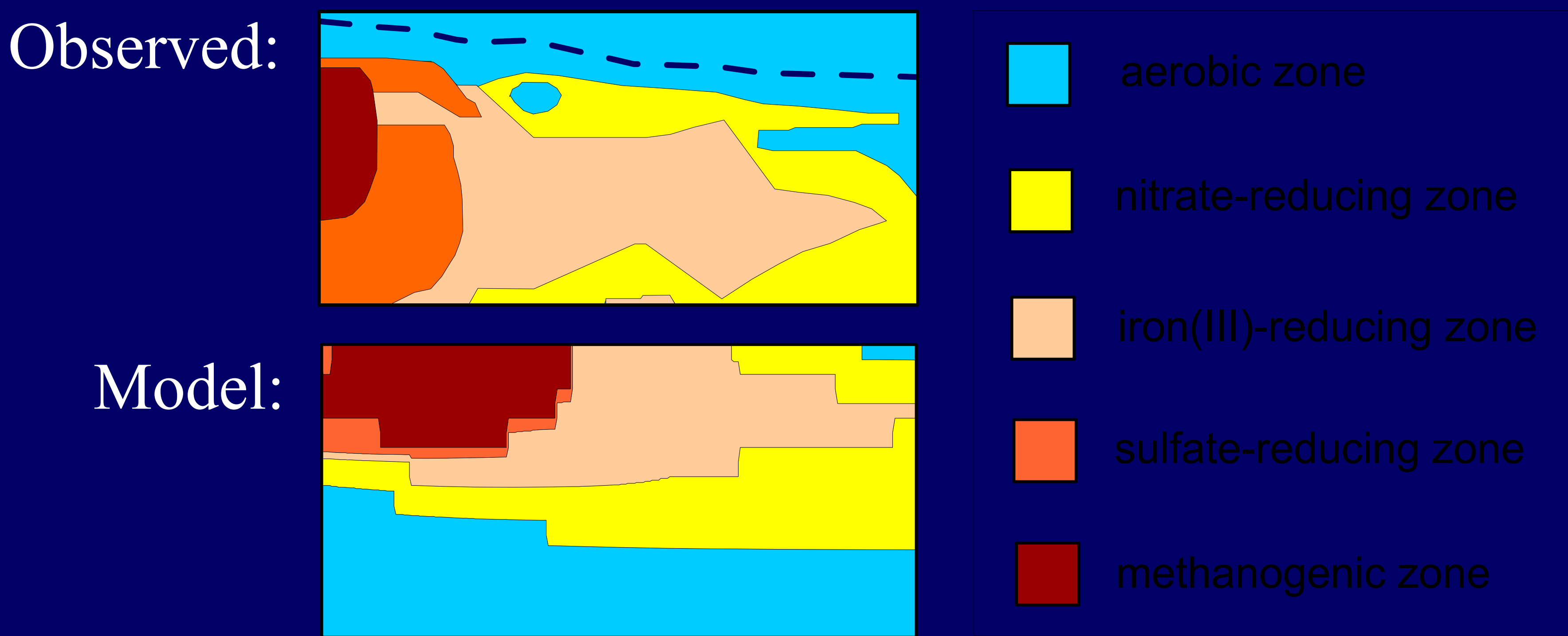
Vertical dispersivity = 0.008 m
rate = 7.6e-3 per day
TOC degrades when TOC > 0.1 mg/L

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# *Hypothetical CAH Model*

# Biodegradation Kinetics

| | ***Redox Zone*** | | | | |
|---|---|---|---|---|---|
| | ***$CH_4$*** | ***$SO_4$*** | ***Fe(III)*** | ***$NO_3$*** | ***$O_2$*** |
| **TOC** | | | | | |
| **PCE** | | | | | |
| **TCE** | | | | | |
| **DCE** | | | | | |
| **VC** | | | | | |

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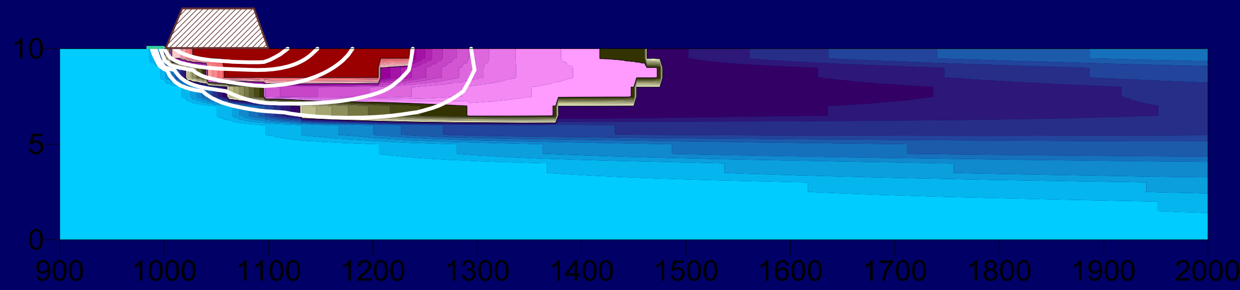
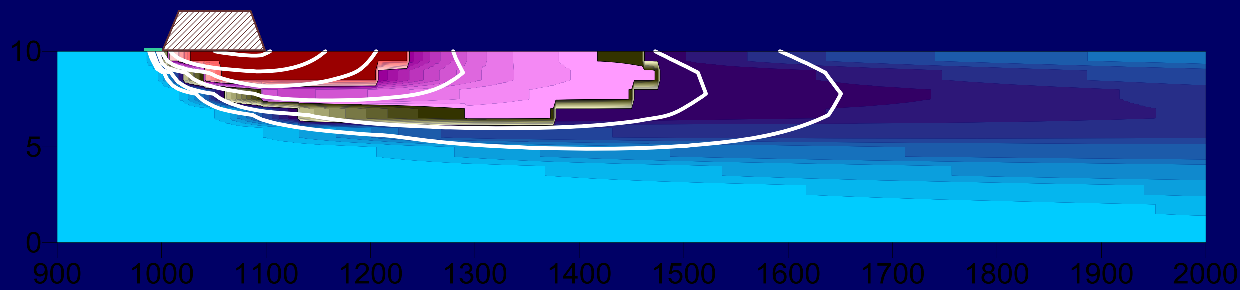
# Without Methane Transport:

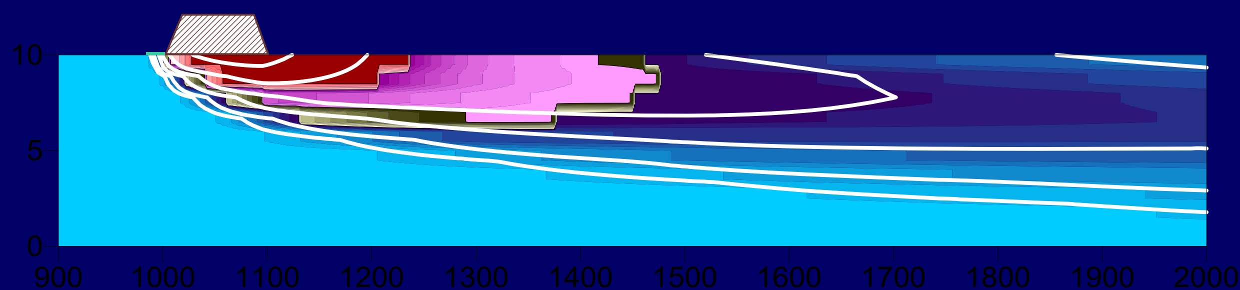
PCE




TCE




DCE




(CAH concentration contours of 1, 2, 5, 10, 20, 50, and 100 ug/L)

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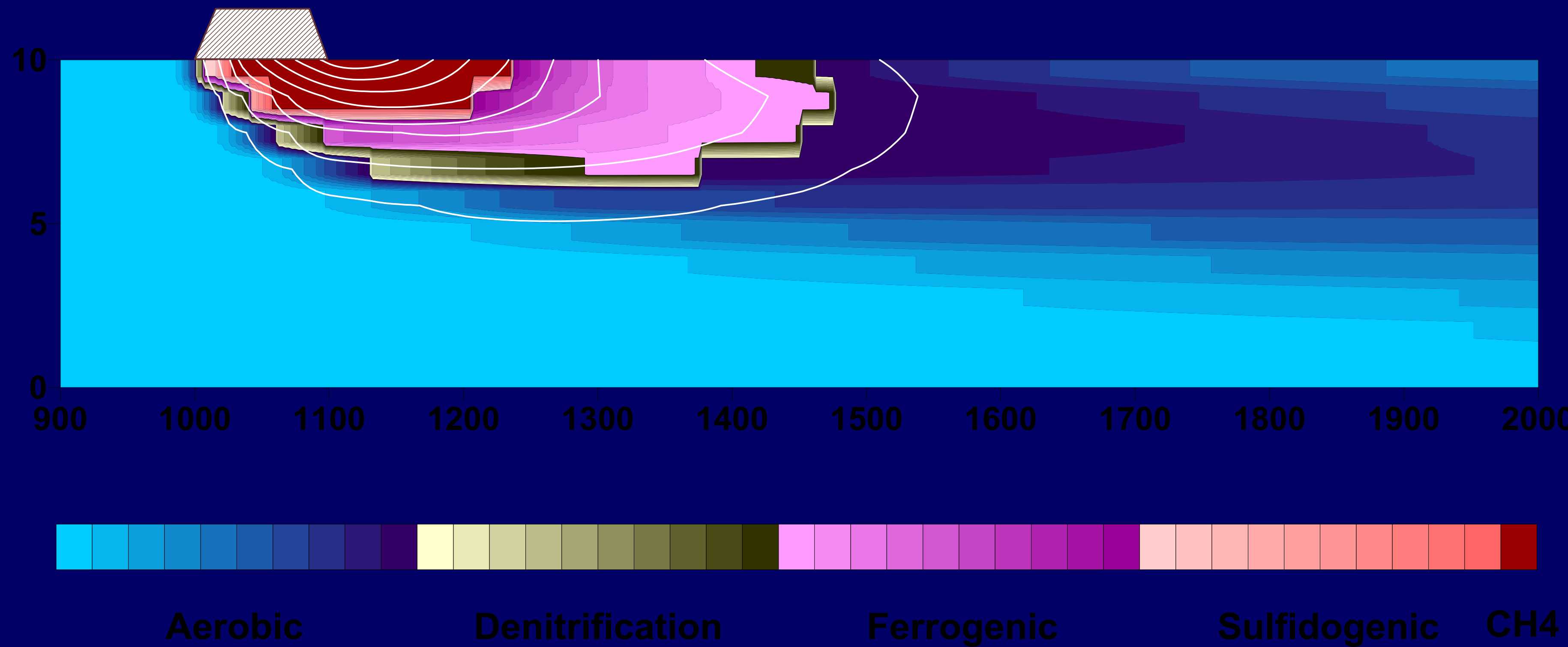
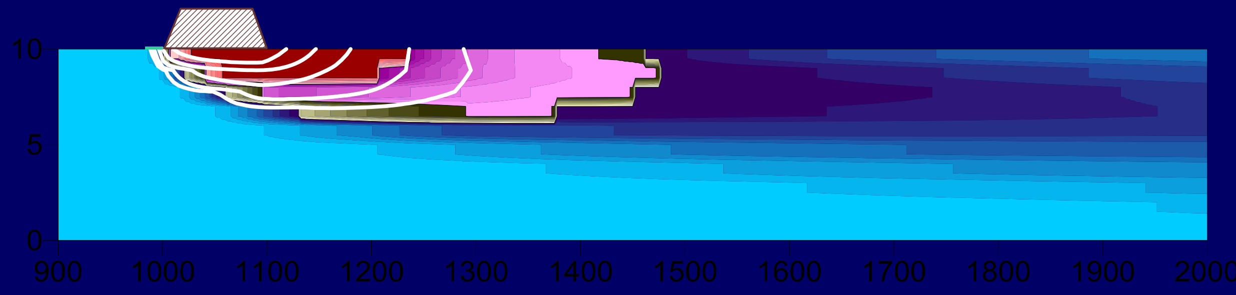
# Methane Simulation:



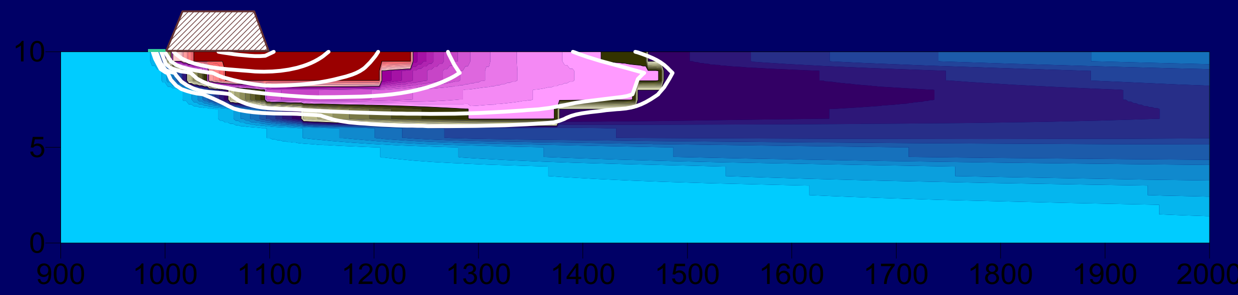

(Methane concentration contours of 0.1, 1, 5, 10, 20, 30, 40, and 50 mg/L)

# Methanotrophic Biodegradation:

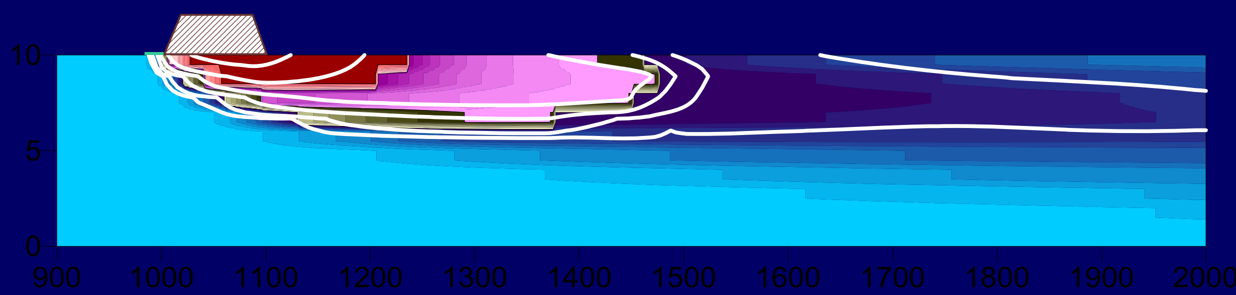
PCE




TCE




DCE




(CAH concentration contours of 1, 2, 5, 10, 20, 50, and 100 ug/L)

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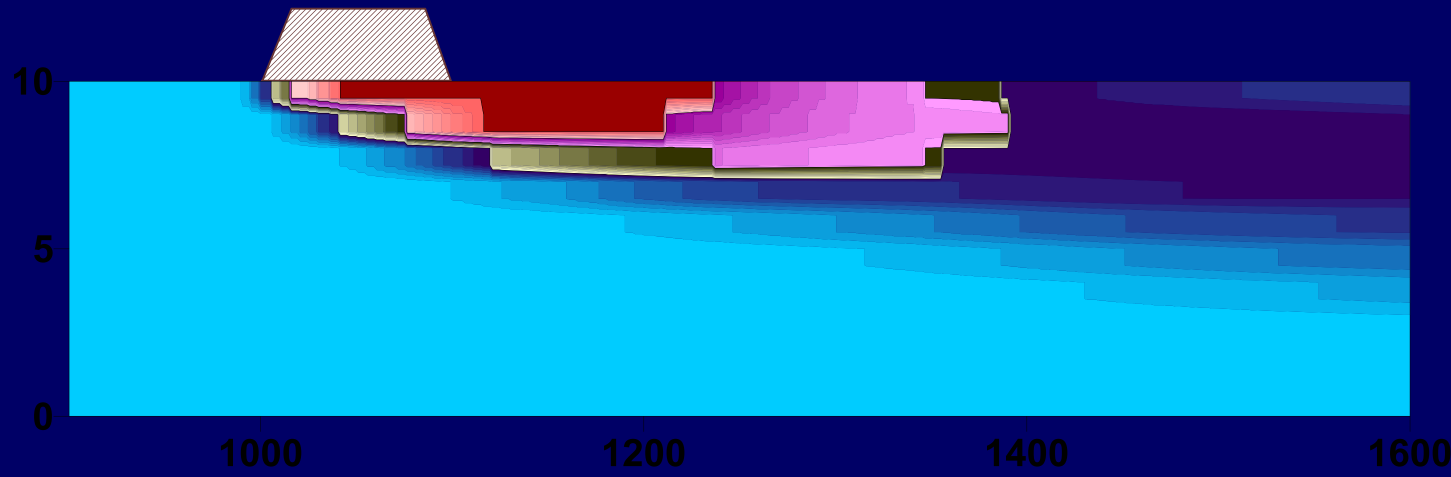
# *Cap Performance Comparison (t=15 to 30 years)*

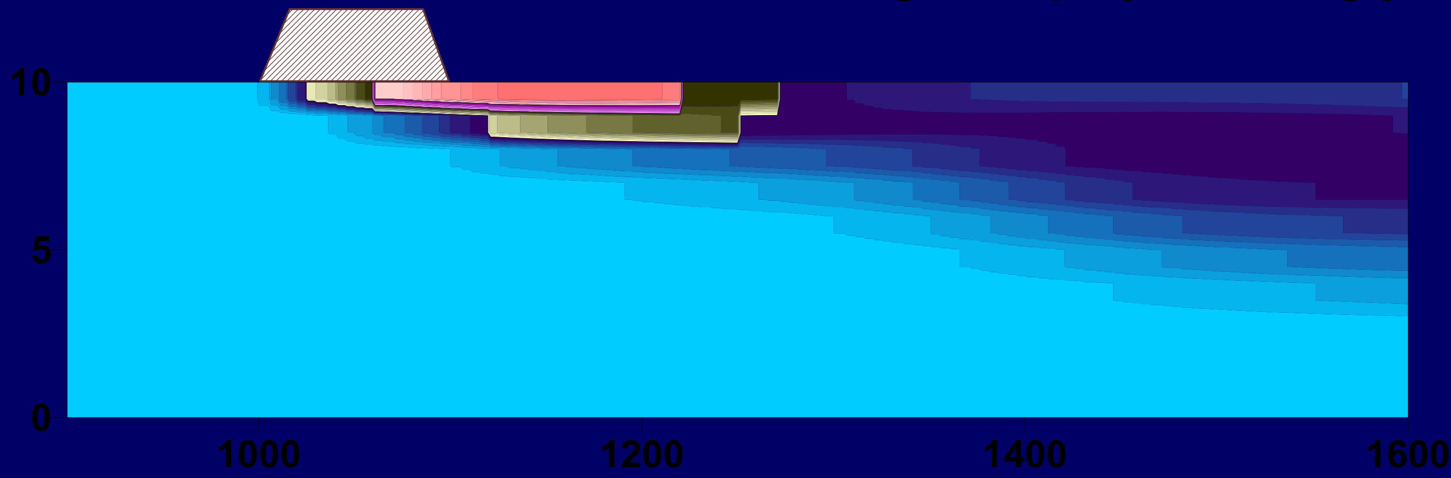
# Cap Performance Comparison

- cap placement (t=15 to 30 years)
- two scenarios:
  - Permeable cap: I = 6 in/yr
  - Clay Cap: I = 1 in/yr
- compared effects on groundwater impact
  - TCE criteria is 5 ug/L

# Permeable Cap (t =17 y)




# Clay Cap (t = 17 y)

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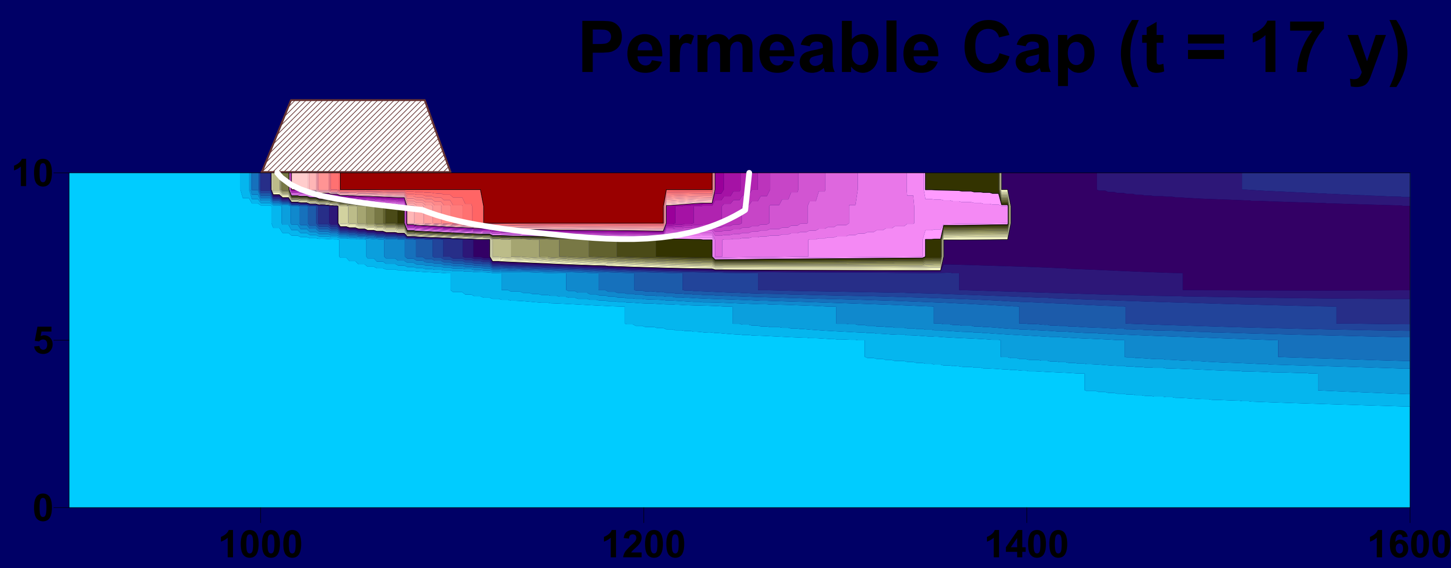


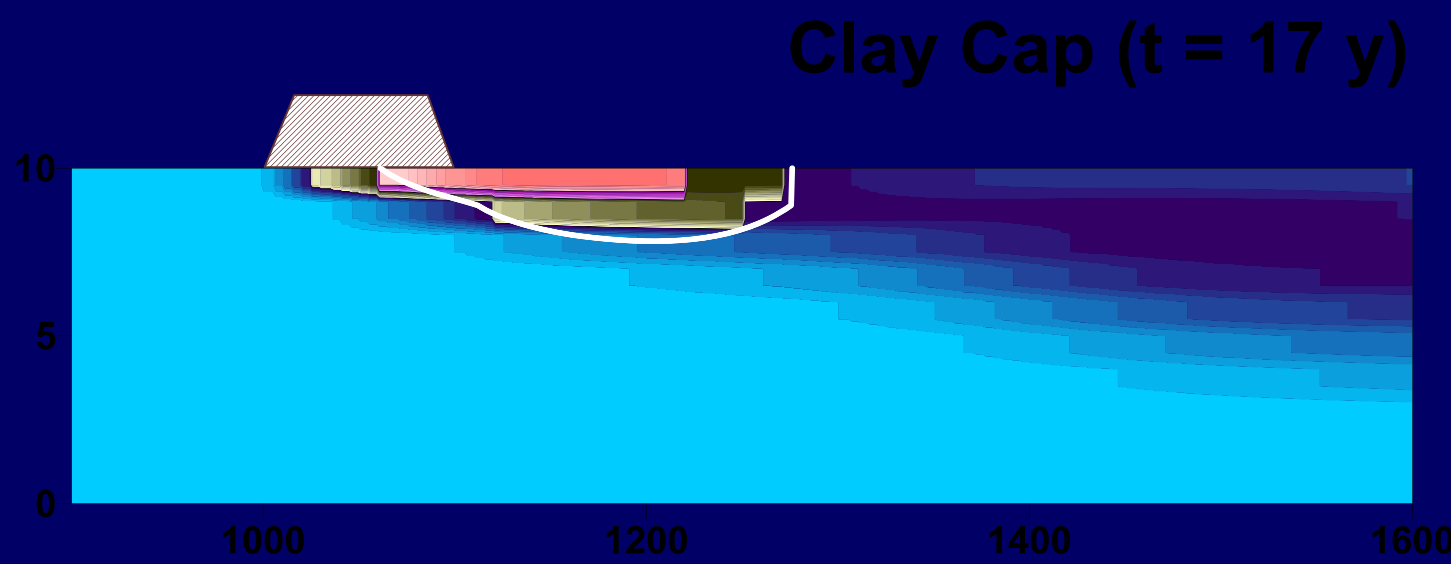


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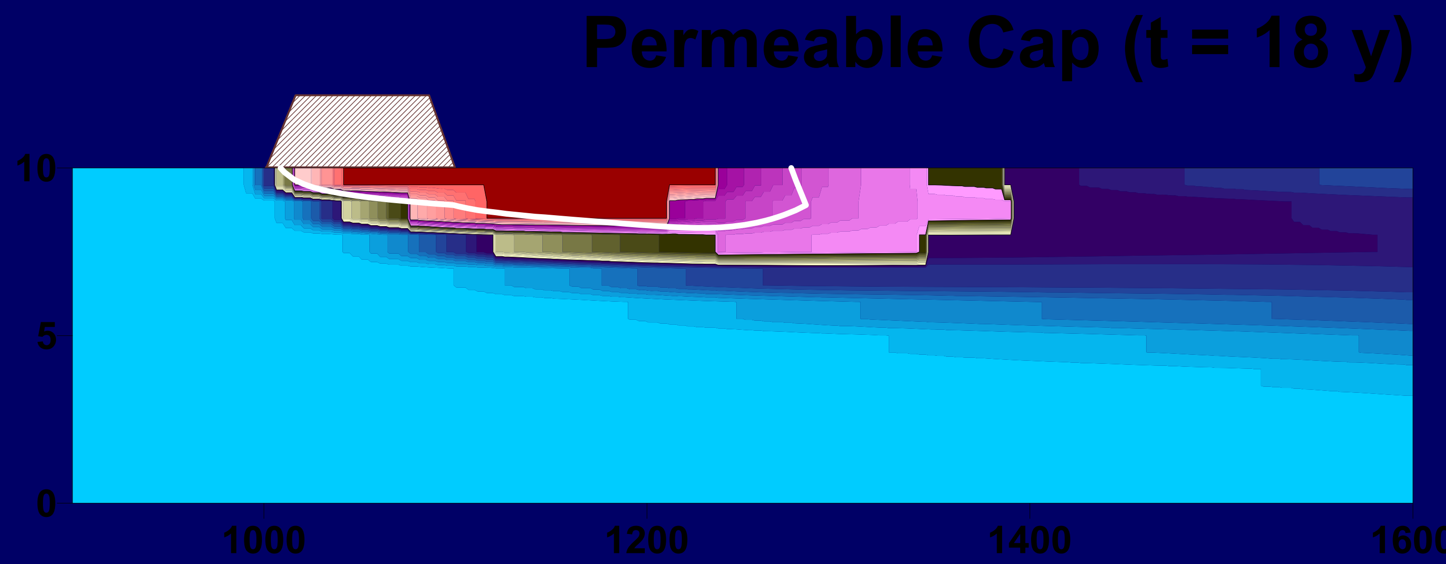


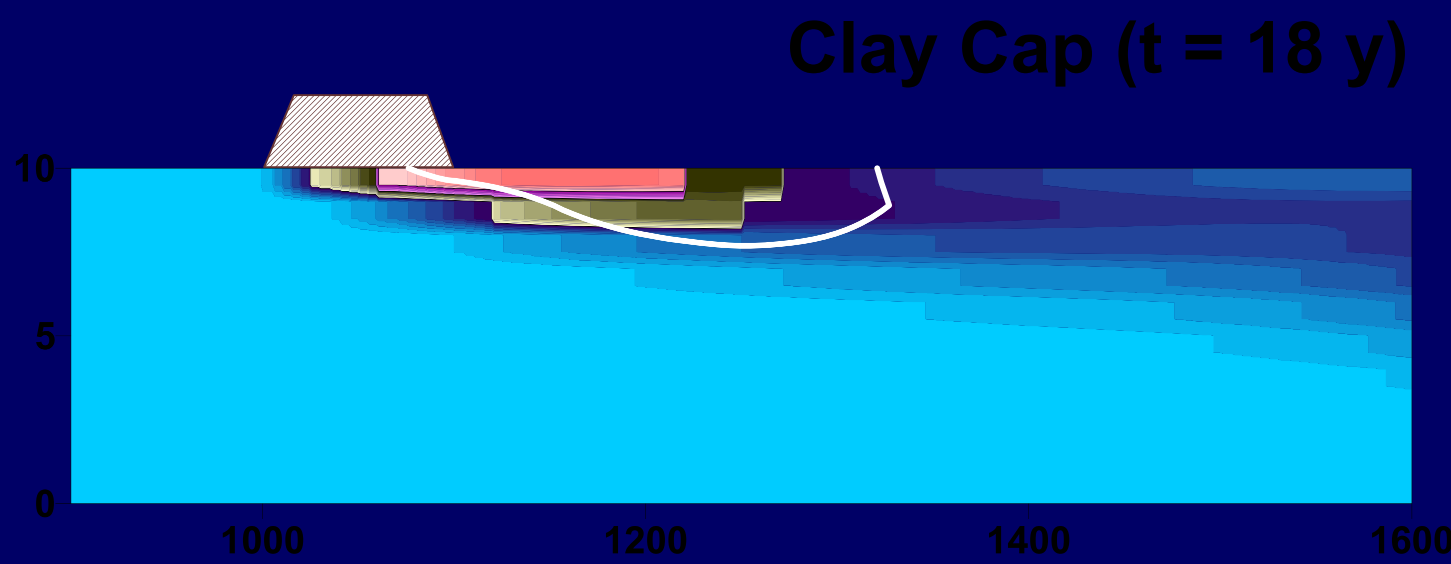


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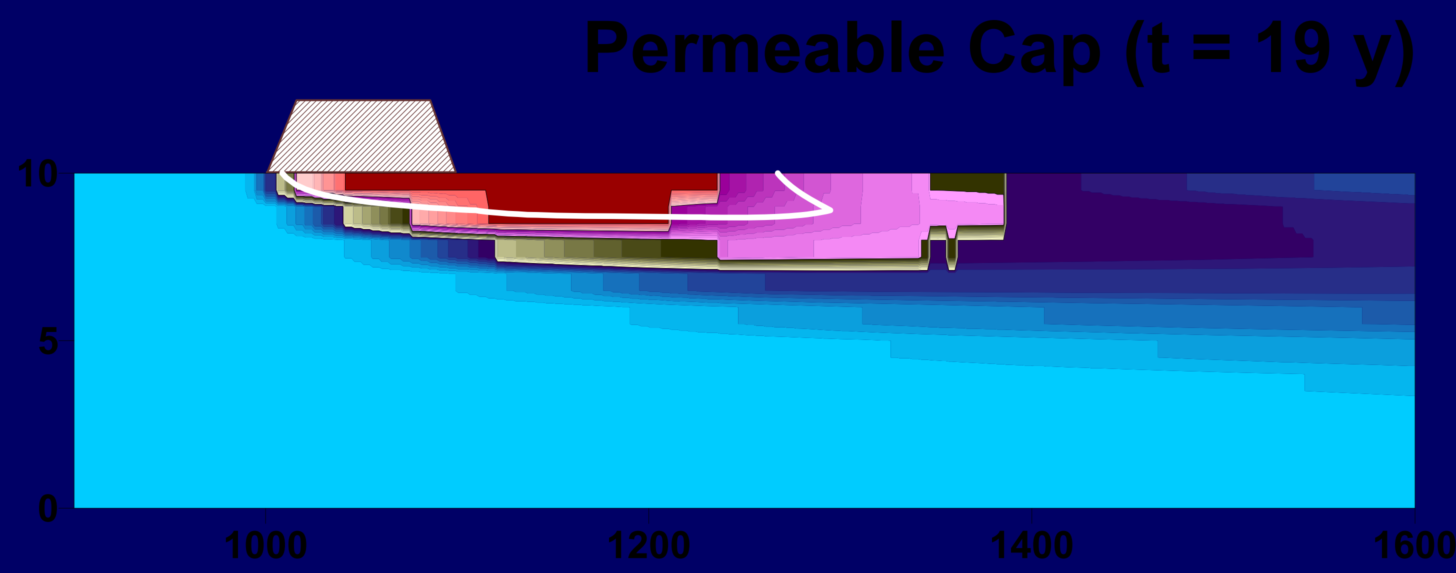


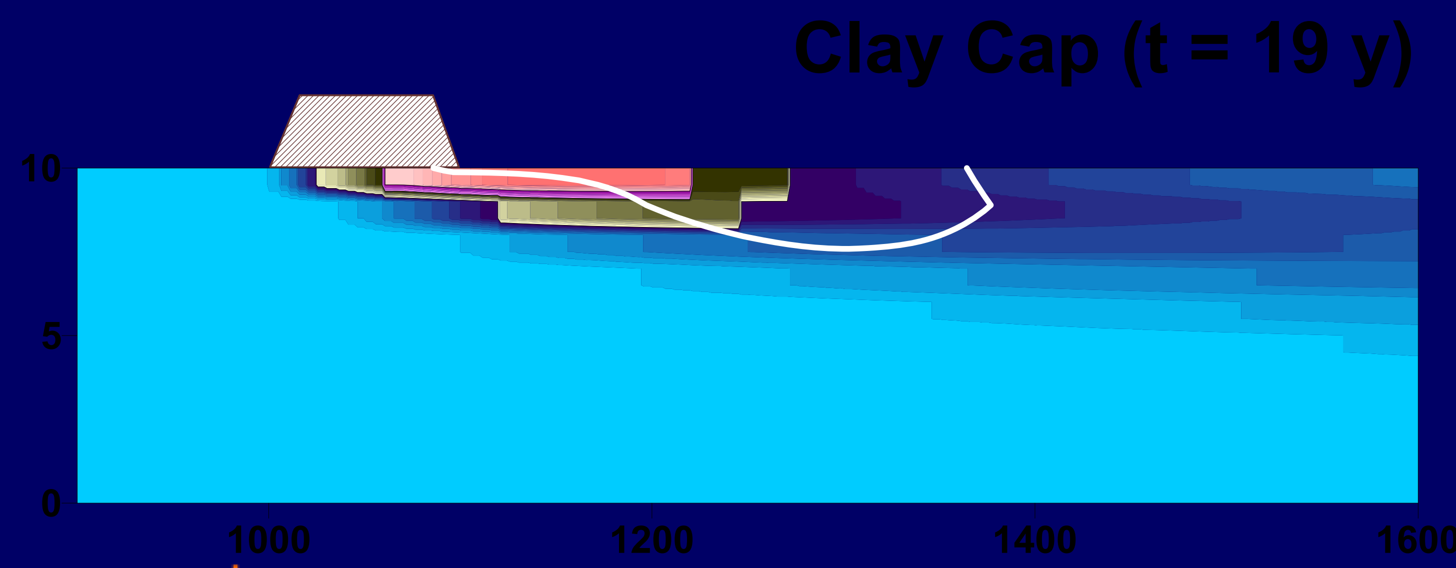


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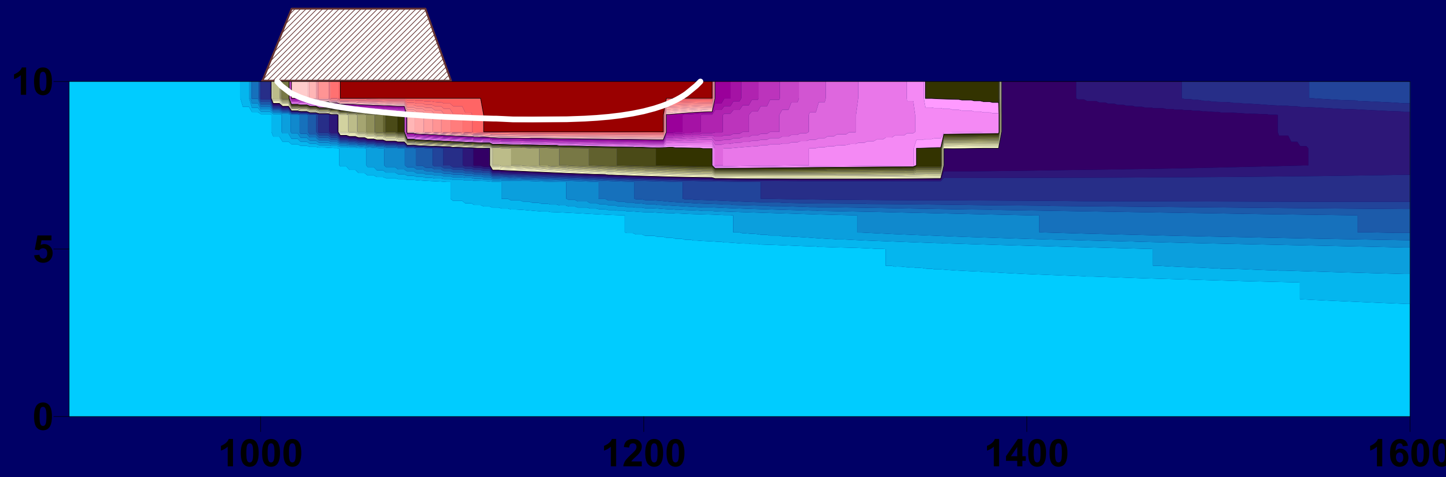
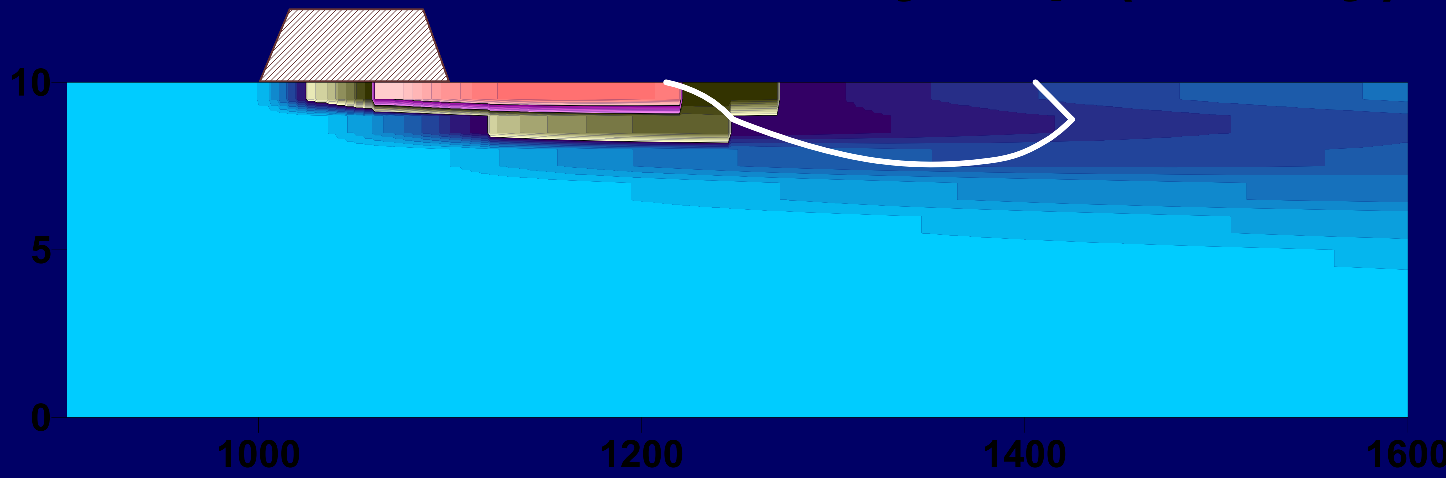
# Permeable Cap (t = 20 y)




# Clay Cap (t = 20 y)

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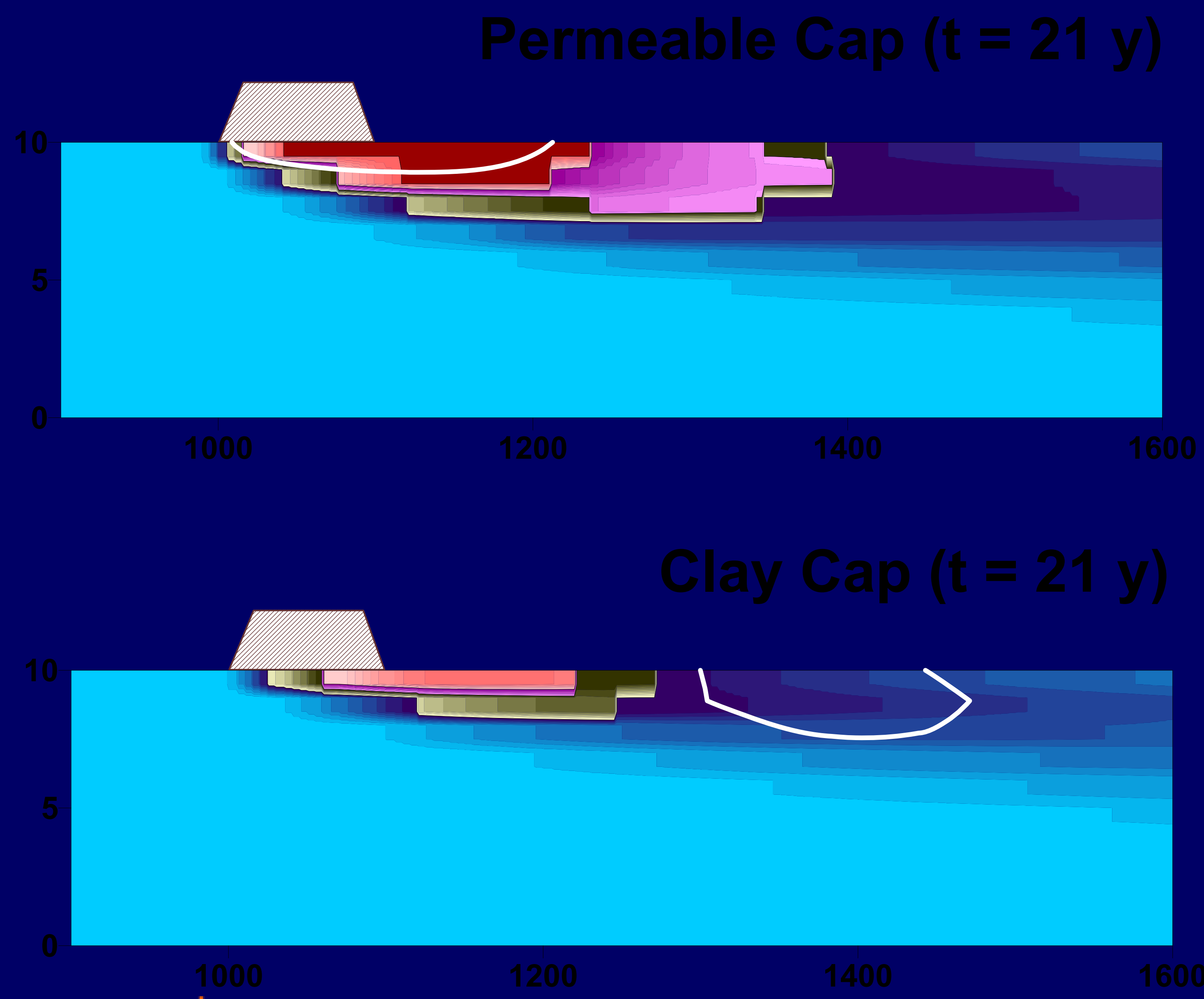


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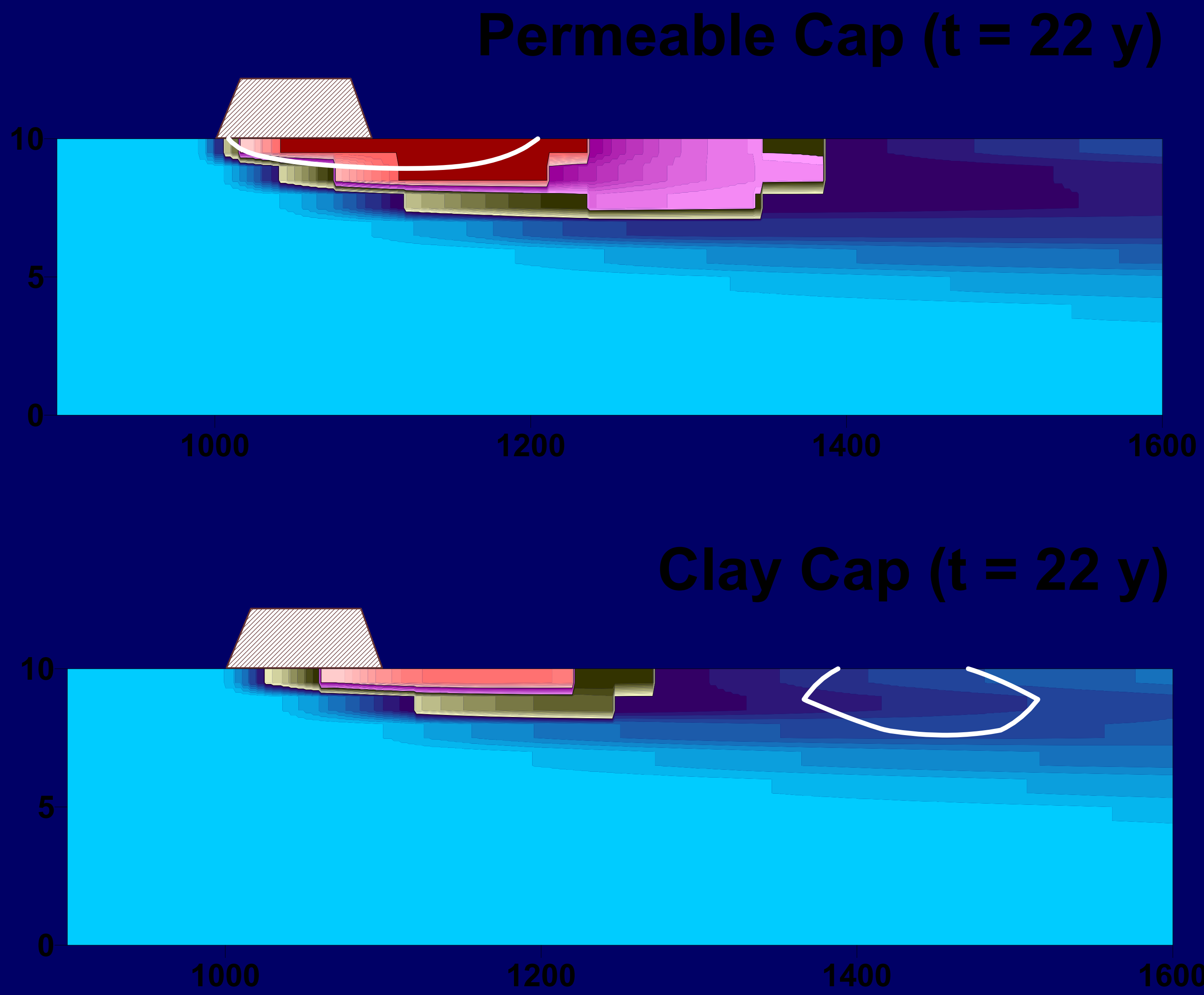


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