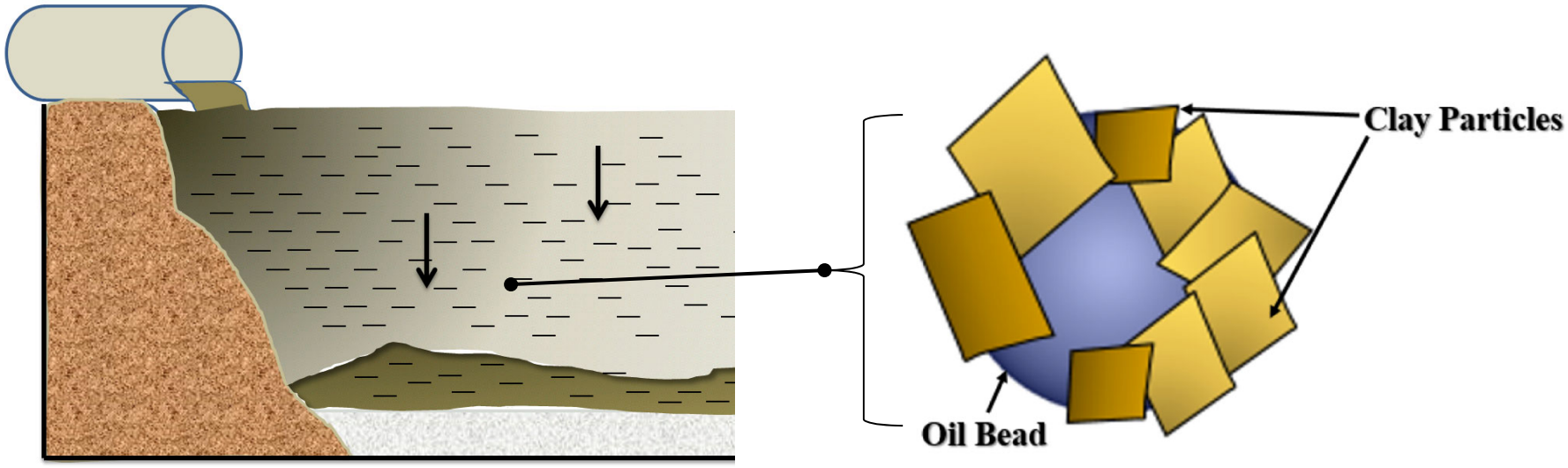
In situ Deposited Non-Aqueous Phase (IDN Sediments: A Conceptual Model for NAPL Emplacement

Jeffrey A. Johnson, Ph.D. (NewFields LLC - Houston)
Irina Mamonkina, P.E. (NewFields LLC – Houston)
Deborah A. Edwards, Ph.D. (ExxonMobil Environmental & Property Solutions)
Douglas Blue, Ph.D. (Imperial Oil Environmental & Property Solutions)
Sara J. Morey (ExxonMobil Research & Engineering)

Processes of LNAPL Emplacement in Sediments

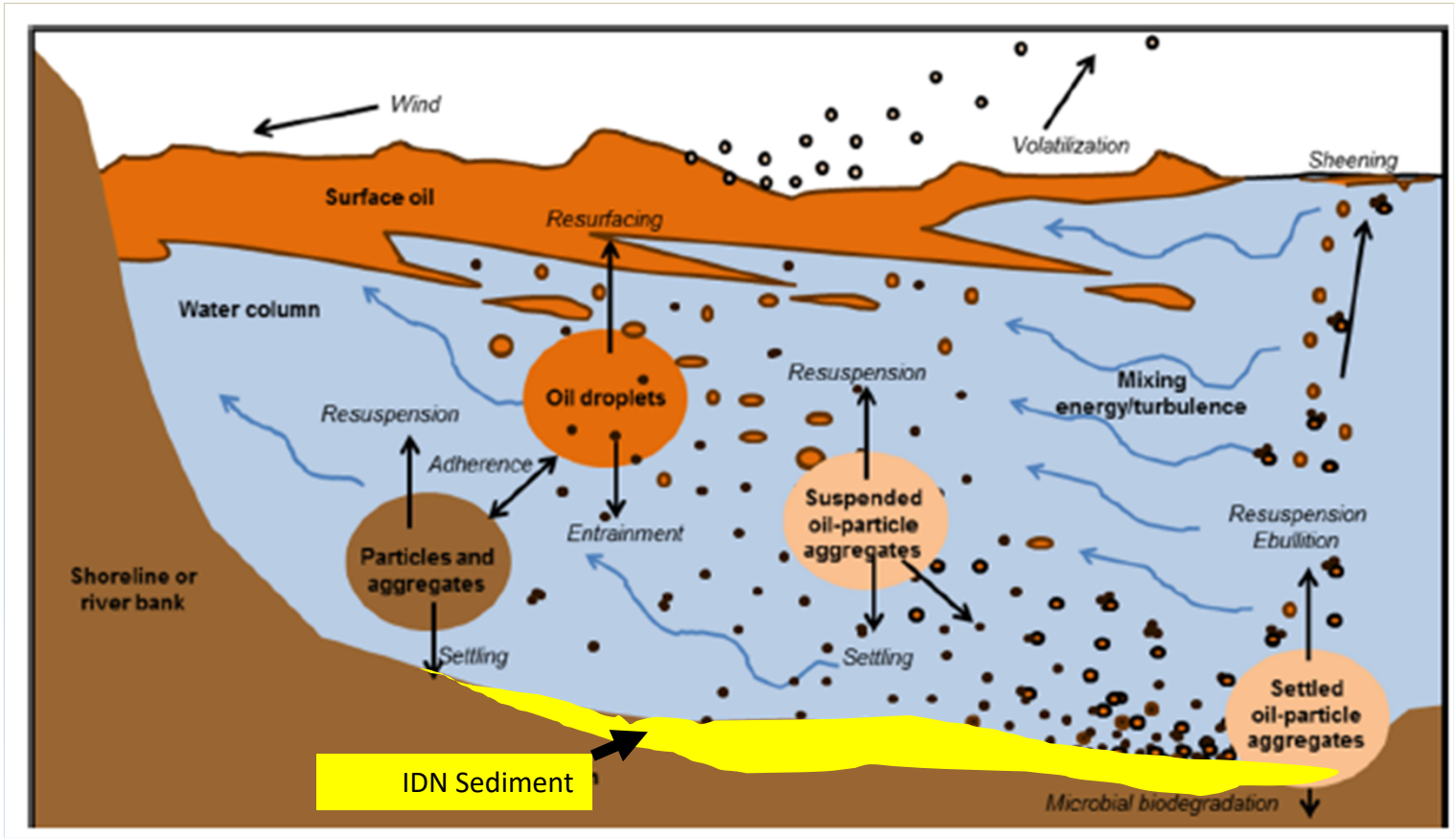
- Two general Conceptual Models describe the emplacement of petroleum hydrocarbons as LNAPL within the sediment regime
  - Advective Transport from a Land-based Source
  - *In situ* Deposition through the Water Column
- These two processes of emplacement produce different physical conditions
- "*In situ* deposition" is of particular importance due to the extent of potential impacts and history of discharges into surface water bodies

OPA Depositional Emplacement



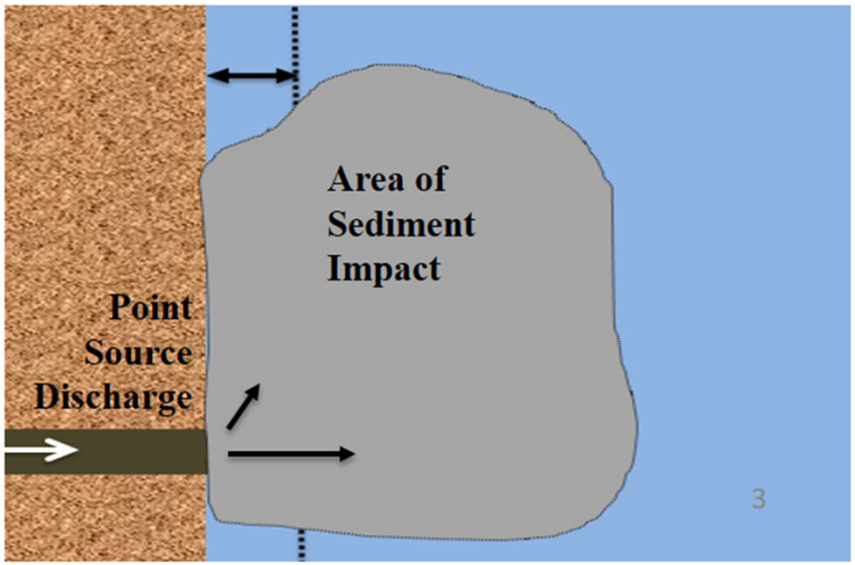
- Release of separate phase product occurs via a discharge directly to the surface water
  - Discharges via pipes or other point source
- With agitation, LNAPL forms "beads" that accumulate solid particles
- Oil-Particulate Aggregates (OPAs) become dispersed in the water column and are deposited *with* other particulates
- The resulting sediment consisting of OPAs forms as a layer at the base of the water column – along the existing sediment interface

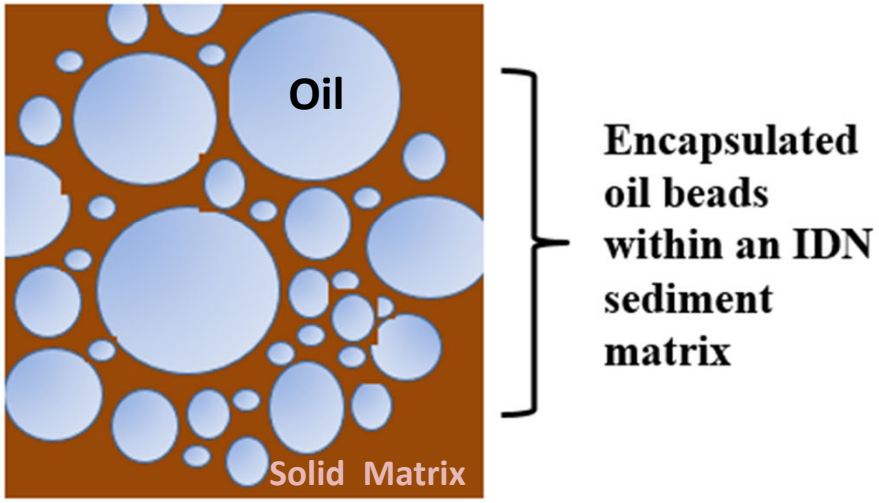
Conceptual Model for IDN Formation



- Oil + Particles = OPAs
- OPA's > 1.0 (1.02) g/cc induces deposition
- OPA Deposition = *In situ* Deposited NAPL Sediment (IDN)
- Oil emplacement by deposition

IDN Sediments

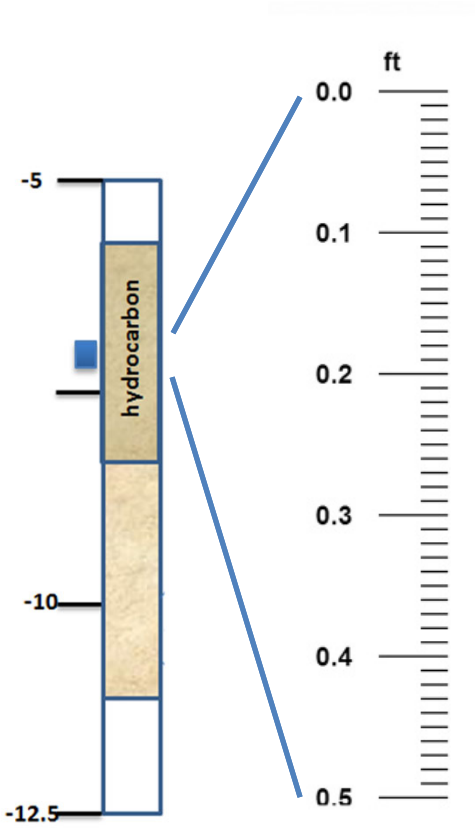


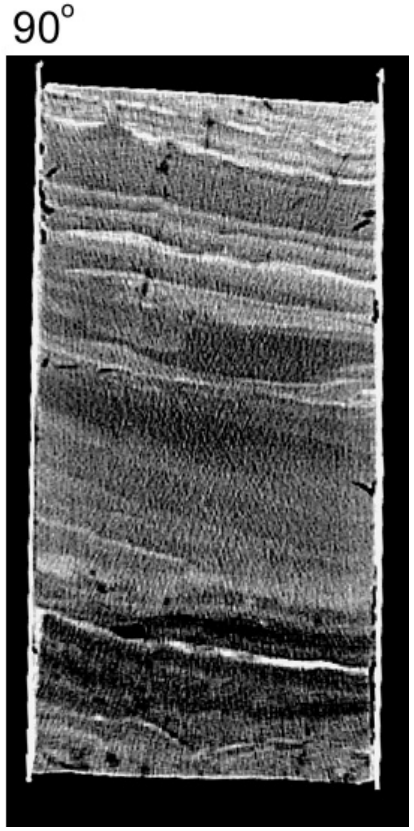


- IDN Sediments:
  - form discrete stratigraphic layers
  - reflect the depositional conditions
  - may cover large areas (several acres)
  - are composed of discrete beads of NAPL that are separated by solid particles – NAPL is retained within the solid matrix
- The degree of encapsulation by the solid particles affects the potential for NAPL mobility and interaction with the porewater

IDN Structure

- IDN sediments are typically stratified, documenting depositional origin
- Laminations vary in thickness ranging from millimeters to inches
- Once deposited IDN sediments become buried
- No evidence to indicate NAPL is released, unless pore structure is disturbed





CT Scan of IDN Sediment

IDN Investigations

- Physical conditions of IDN sediments were investigated at two sites
- Both sites are brackish and tidally influenced
- Historical discharges of NAPL have occurred
- Sediments range in grain size from gravel to clay, but clays and silt are dominant
- Previous investigation documented presence of NAPL through various screening technologies

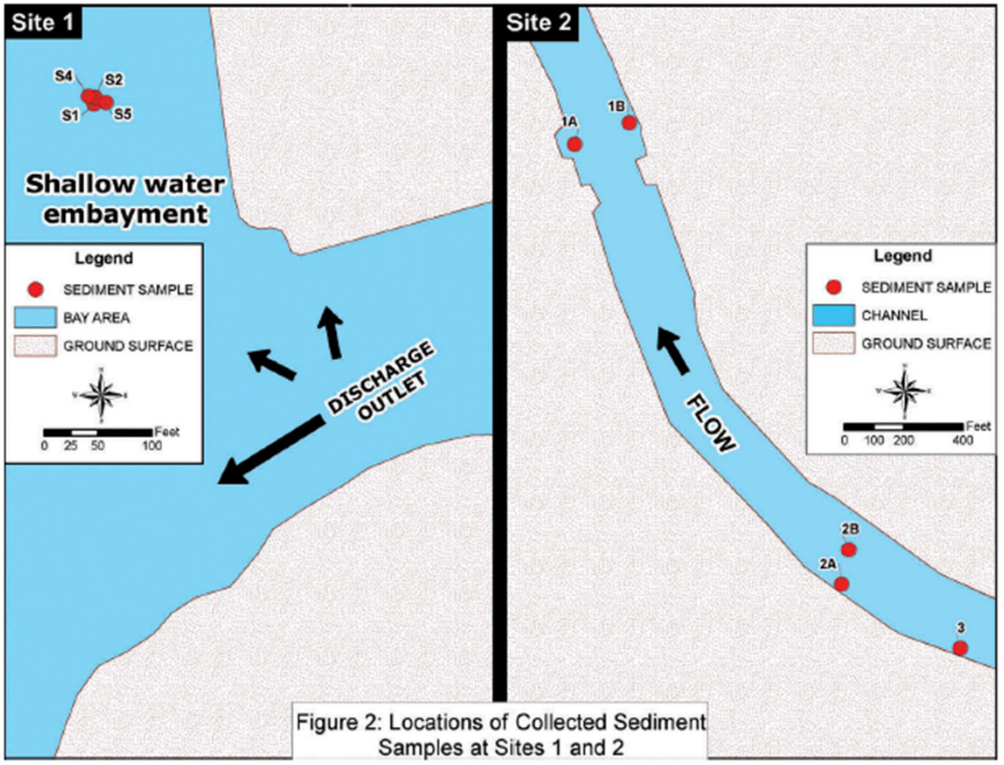


Figure 2: Locations of Collected Sediment Samples at Sites 1 and 2

Methods and Approach

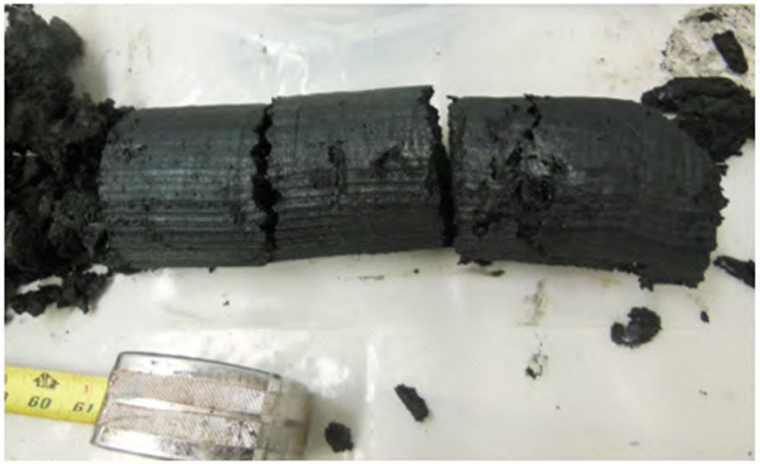
- Multiple cores collected at both sites by vibracore
- Initial core extruded and characterized: visual observations, texture, PID, UV light, sheen tests
- Selected sediment intervals from co-located cores were forwarded intact for chemical and physical testing
- Testing included:
  - Particle size
  - Porosity
  - Bulk Density
  - Fluid Saturation
  - Hydraulic Conductivity
  - Fraction organic content
  - Centrifuge Analyses
  - X-ray tomography

TPH Impacts

- TPH analyses at both sites documented mid-range C_{12}-C_{28} hydrocarbons
- TPH concentrations in the sediments typically ranged from 30,000 to 115,000 mg/kg
- No observed free flowing oil from sediments
- UV and sheen tests did indicate the presence of separate phase

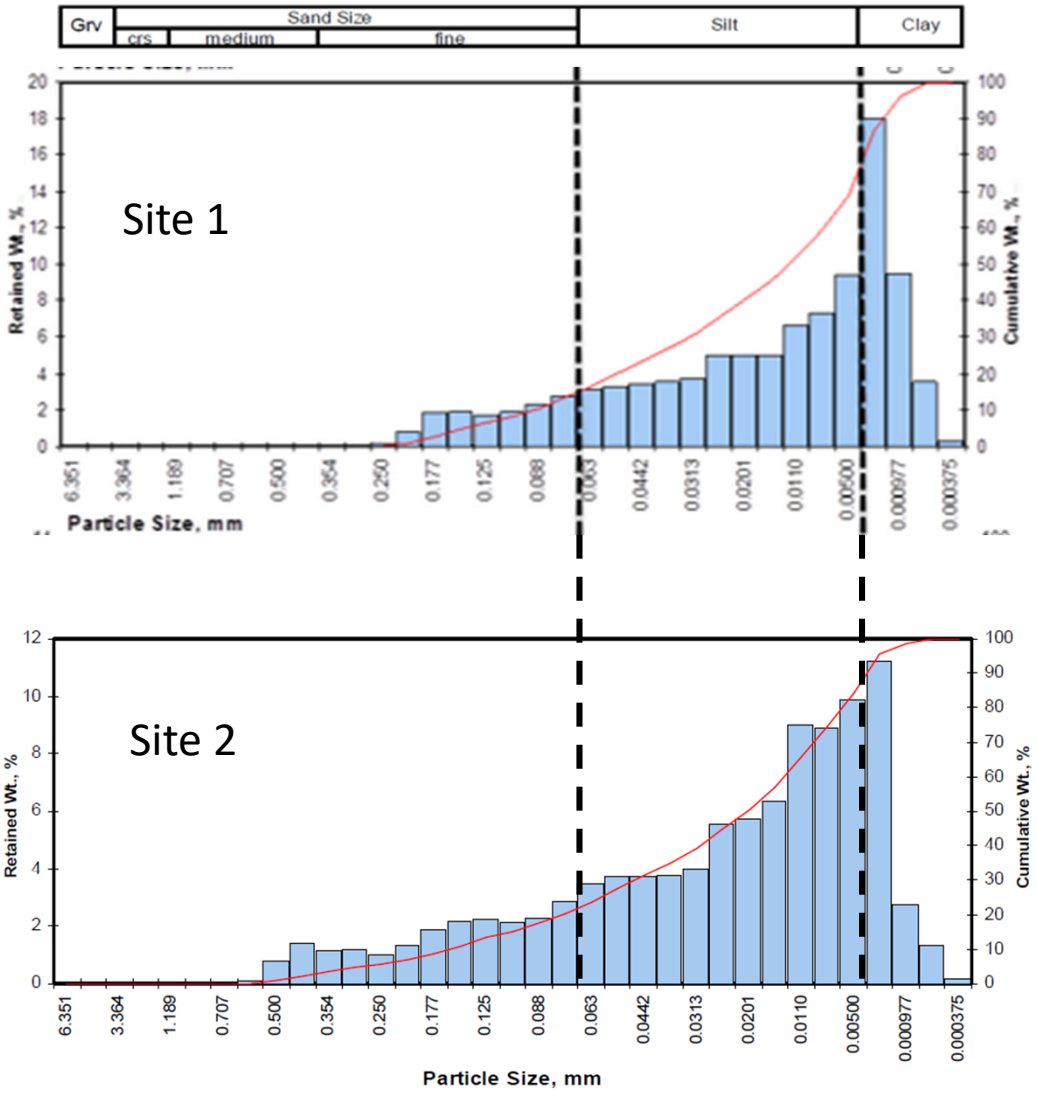
Site 1 Sediment

Site 2 Sediment



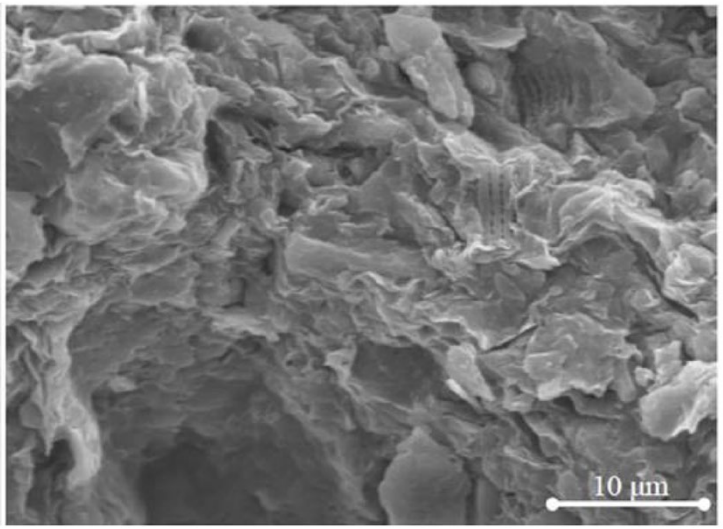
Particle Size

- Grain size analyses documented that fine silt and clay were the dominant particle size for the majority of the IDN sediment strata
- Over 50% of the particles were less than 0.02 mm in size
- Finer particle sizes enhance the capability of an OPA to become fully encapsulated, since more particles are required to adhere to the oil bead to produce deposition

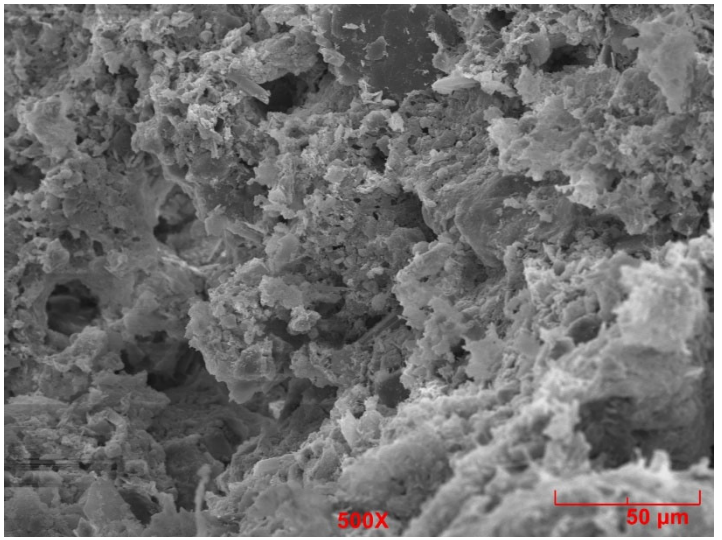


IDN Pore Structure

- Site 1 dominated by smectite clays
- Site 2 composed primarily of chlorite and illite clays
- Pore structure also varied between sites based on SEM micrographs
  - Site 1 dominated by laminated structure
  - Site 2 pore structure was more open, with more visible pore openings



Site 1. Laminated smectite clay

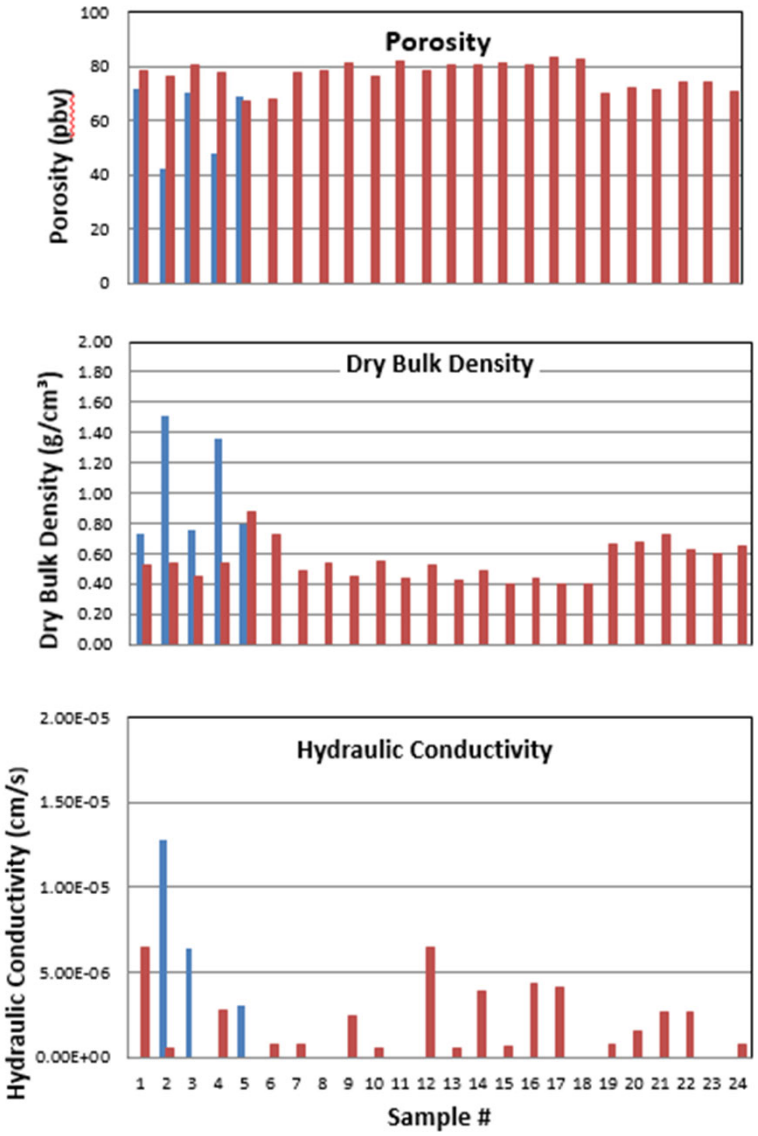


Site 2. Open structure composed of chlorite / illite clays

IDN Physical Measurements

IDN Sediments are typically characterized by:

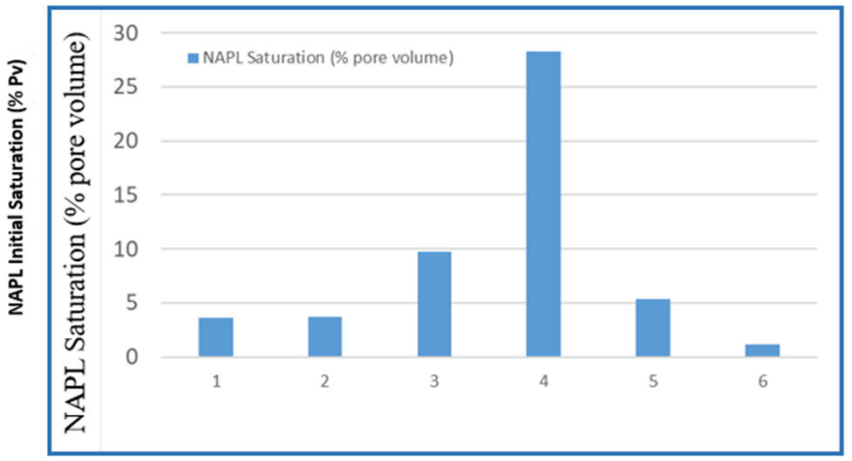
- High Porosity
  - 50-80 % porosity
- Low Bulk Density
  - <1.0 mg/cm^3
- Low Hydraulic Conductivity
  - < 10-5 cm/sec



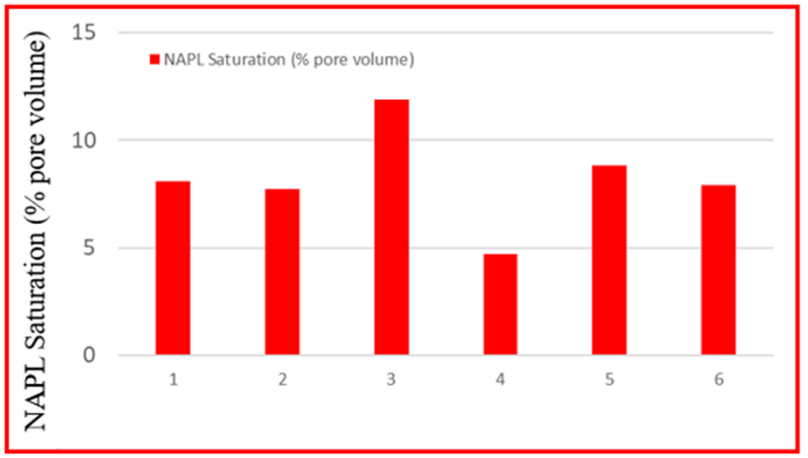
NAPL Saturation

- NAPL saturation values range from 1 to 28 % by vol.
- Majority of LNAPL saturations are below 10 % by volume
- Higher saturations correspond to larger grain size

Site 1



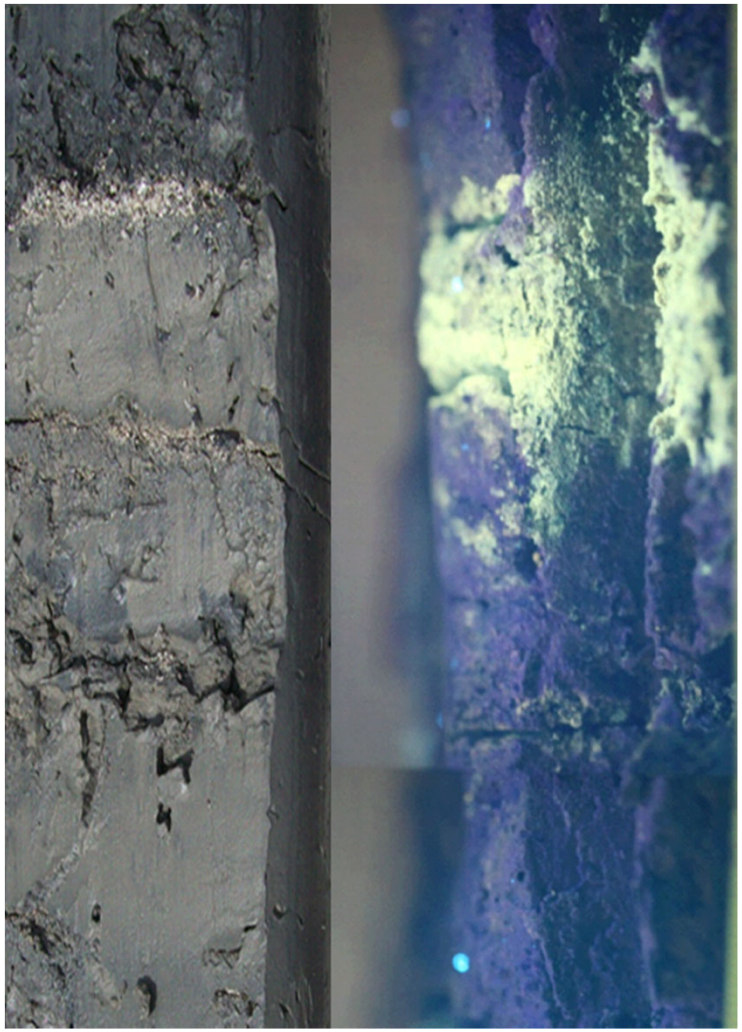
Site 2



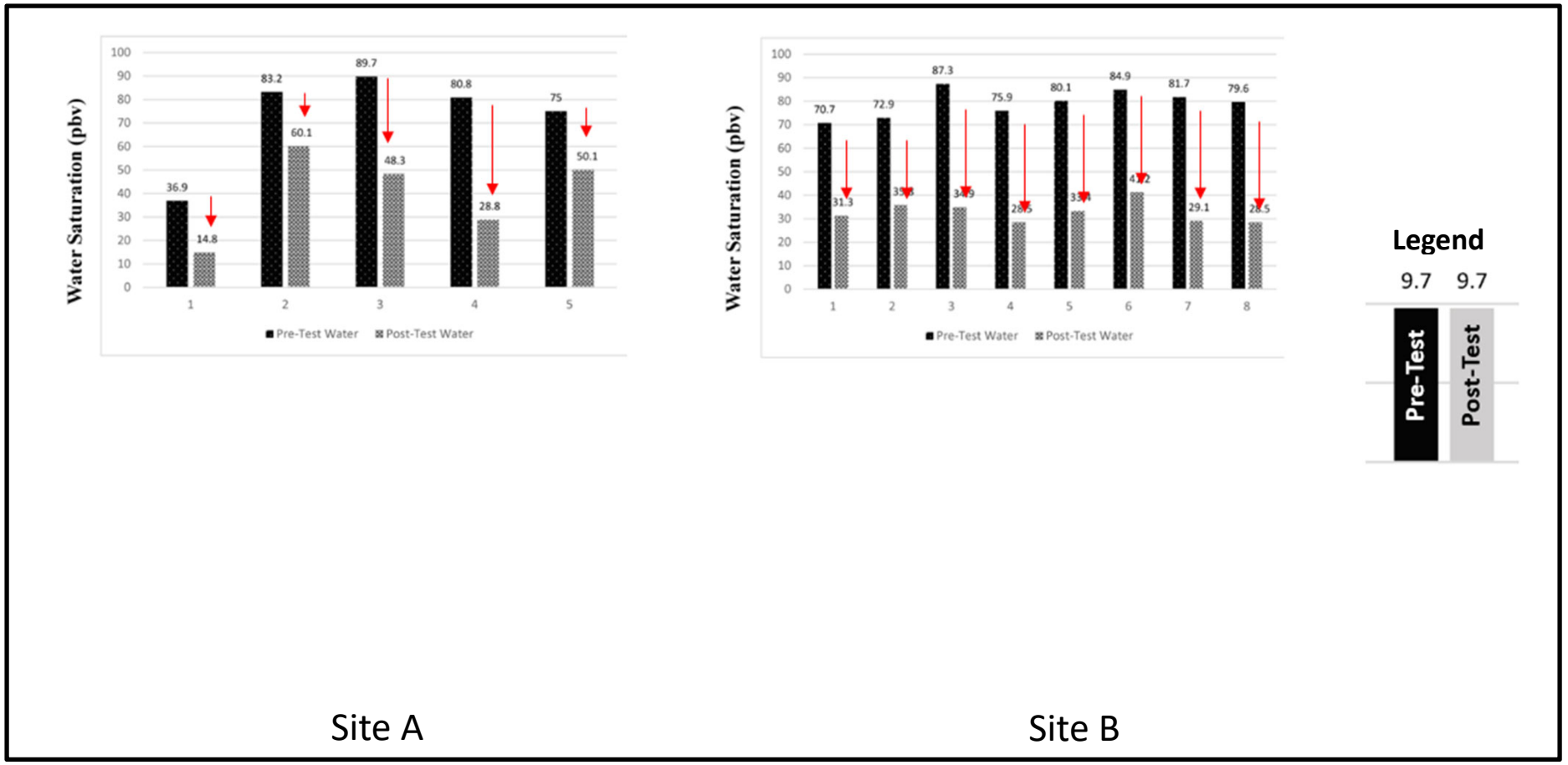
Fluid Mobility

- Fluid mobility was evaluated via centrifuge technology

- Applied standard upland approaches
  - NAPL Mobility
    - x1000G
  - Capillary pressure curve analysis

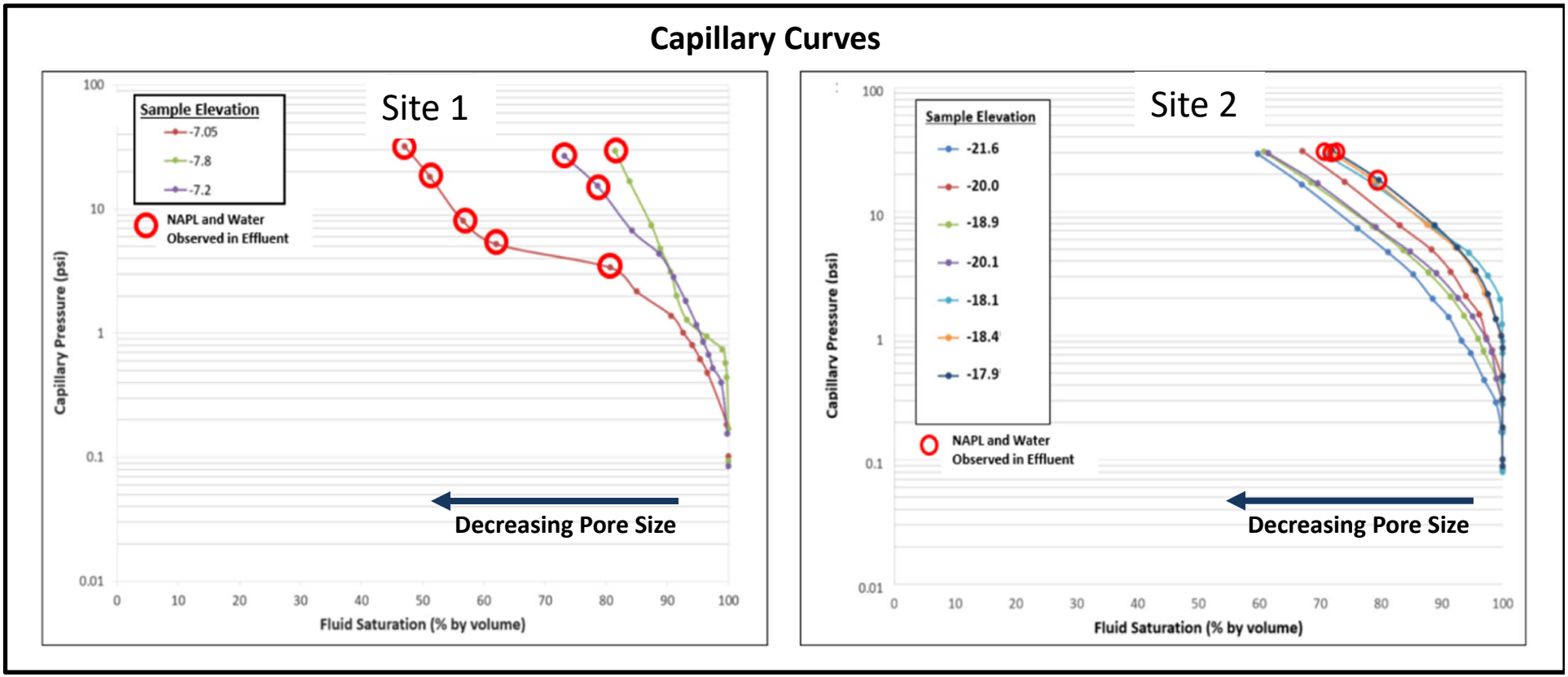


IDN: Centrifuge Fluid Mobility Studies



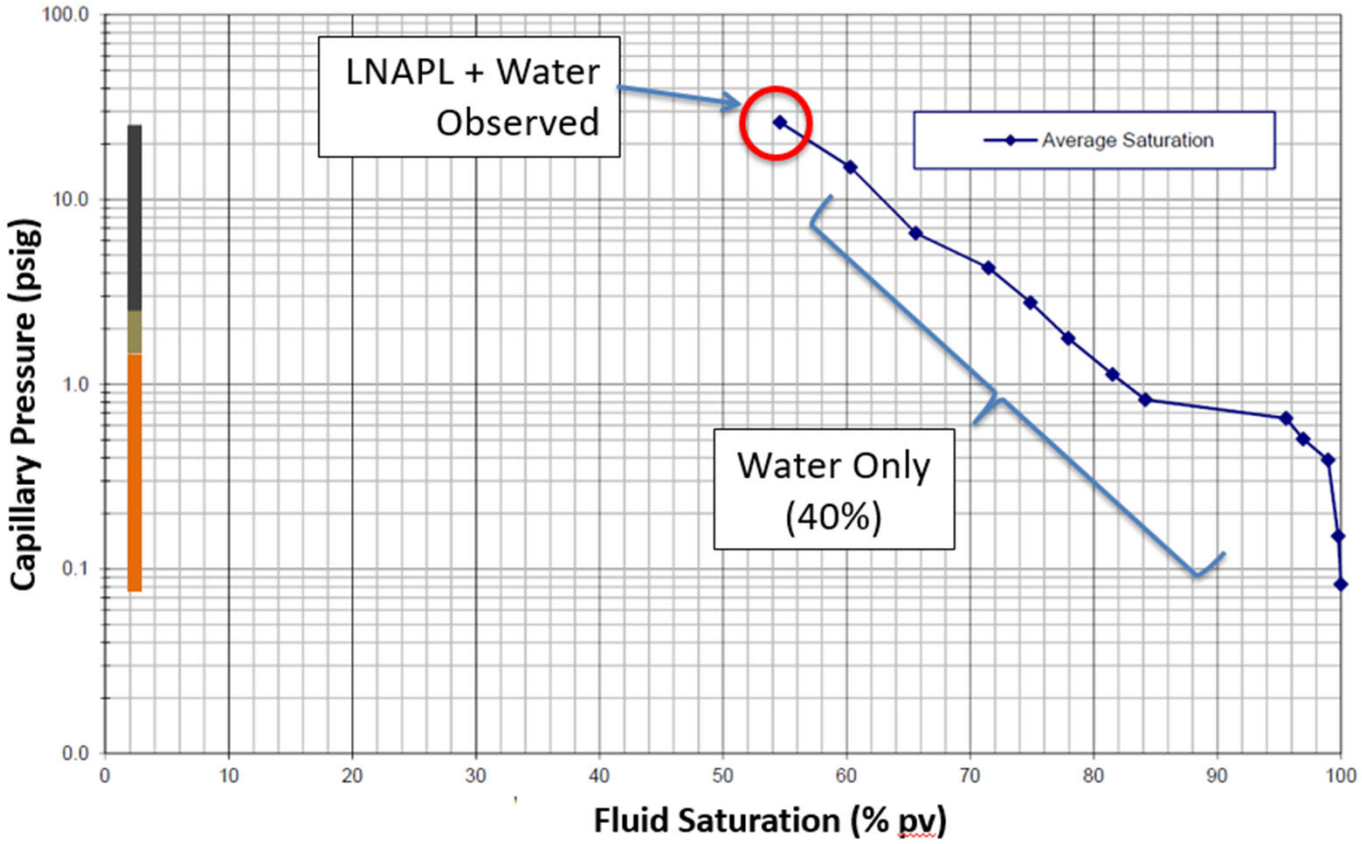
- Water is readily displaced under 1000G of induced pressure
- Centrifuge studies indicate NAPL is not readily mobile
- NAPL is retained within pore network

IDN: Centrifuge Capillary Pressure Studies



- Centrifuge studies document NAPL, if evacuated, is a secondary fluid
- NAPL released only after 20 to 30 % of water saturation is evacuated
- Centrifuge results demonstrate NAPL is present in smaller pores

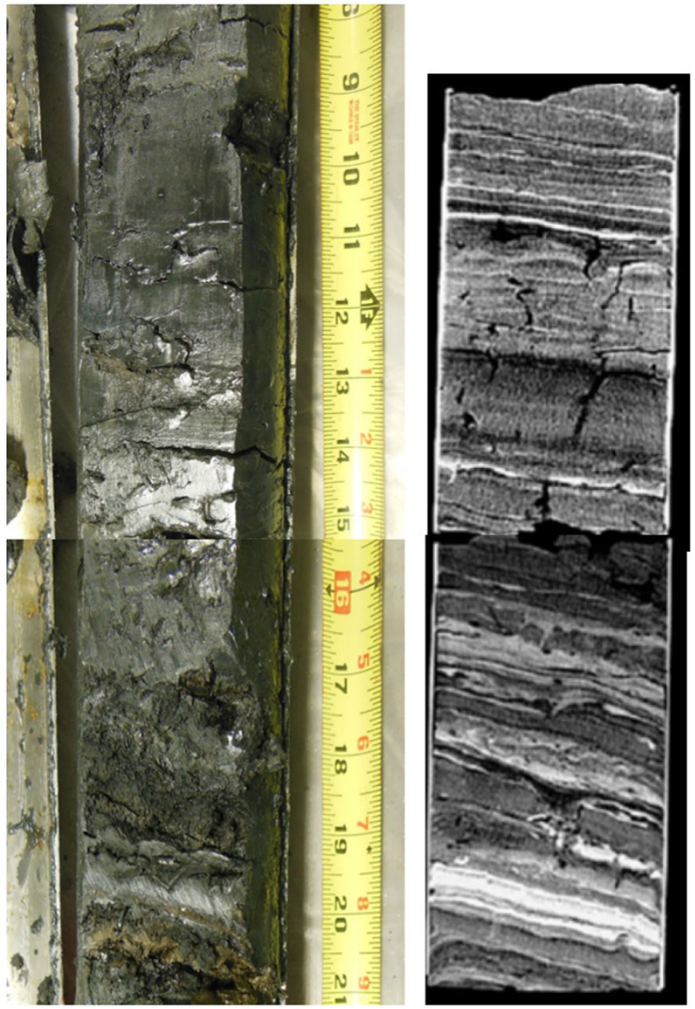
Capillary Pressure Curve: Effluent Composition



- LNAPL distribution retained in smaller sediment pores
- Even in sandy sediments, LNAPL is not released until 20% of water is expelled from pores
- Results indicate LNAPL, when encapsulated, is immobile under natural conditions

Summary: *In Situ* Deposition

- Two primary LNAPL emplacement processes in sediments
  - Groundwater Transport
  - *In Situ* Deposition from OPAs
- *In situ* deposition produces petroleum hydrocarbon as LNAPL entrained and encapsulated within the sediment matrix: IDN Sediments



Summary: IDN Sediments

- IDN sediments cover large areas
- IDN sediments and are derived from long-term historic discharges and contain large volumes of NAPL
- NAPL is encapsulated as a result of the OPA formation process
- OPA structure is retained upon deposition
- Encapsulation mitigates NAPL mobility and NAPL – pore water interactions
- Research is on-going to measure the encapsulation process and the effects of the process on the environment
- Additional field investigations needed to further characterize IDN sedimentary environments

OPA – IDN Literature Resources

Fitzpatrick, F.A., Boufadel, M.C., Johnson, Rex, Lee, Kenneth, Graan, T.P., and others, 2015, *Oil-particle interactions and submergence from crude oil spills in marine and freshwater environments—Review of the science and future science needs*: U.S. Geological Survey Open-File Report 2015–1076, 33 p., http://dx.doi.org/10.3133/ofr20151076.

Johnson, J. A., Edwards, D. A., Blue, D. and Morey, S. J. 2018. *Physical Properties of OPA Containing Sediments*. Soil and Sediment, Contamination: An International Journal. https://doi.org/10.1080/15320383.2018.1506425

Johnson, J. A., Edwards, D. A., Blue, D. and Morey, S. J. 2018. *NAPL mobility of OPA-containing sediments*. Soil and Sediment, Contamination: An International Journal. https://doi.org/10.1080/15320383.2018.1513990