LNAPL Saturation Concepts

How and Why of Aquifer LNAPL Flow

September 7, 2016

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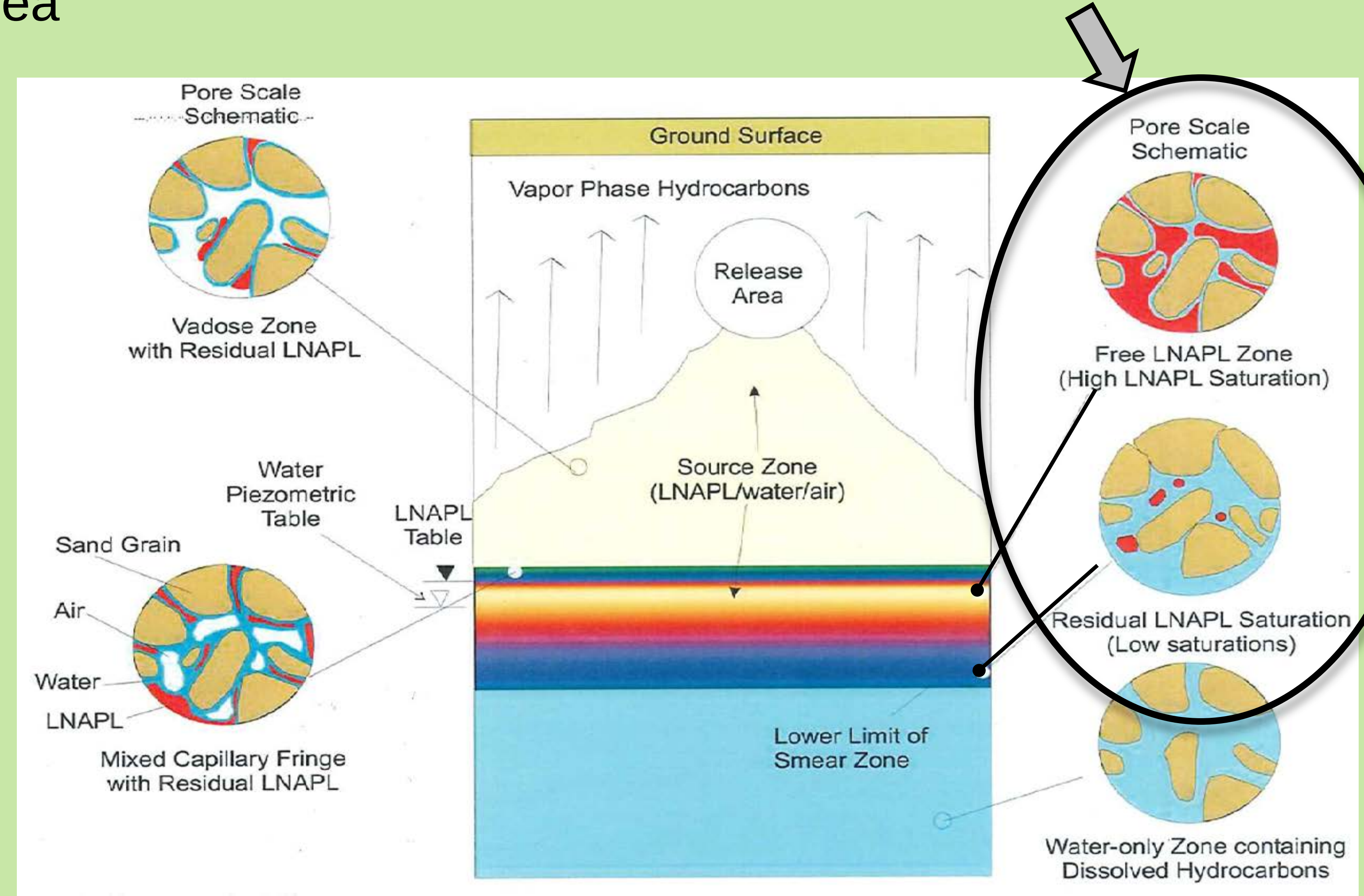
LNAPL Saturation Distributions Across Source Area

Emphasis (herein):
<u>Saturated Zone (Aquifer)</u>



ASTM, 2006

Darcy's Law for Dual Phase Flow:

Water flow component
wetting fluid (w)

$$Q_w = \frac{-k_{rw} k_i \rho_w}{\mu_w} A \frac{dh_w}{dl}$$

Q_w = volume of water flowing
k_{rw} = relative permeability of water in the presence of the nonwetting fluid
k_i = intrinsic permeability of the rock
ρ_w = density of the water
μ_w = dynamic viscosity of the water
A = cross-sectional area of flow
dh_w/dl = gradient of the head of the water

LNAPL flow component
non-wetting fluid (nw)

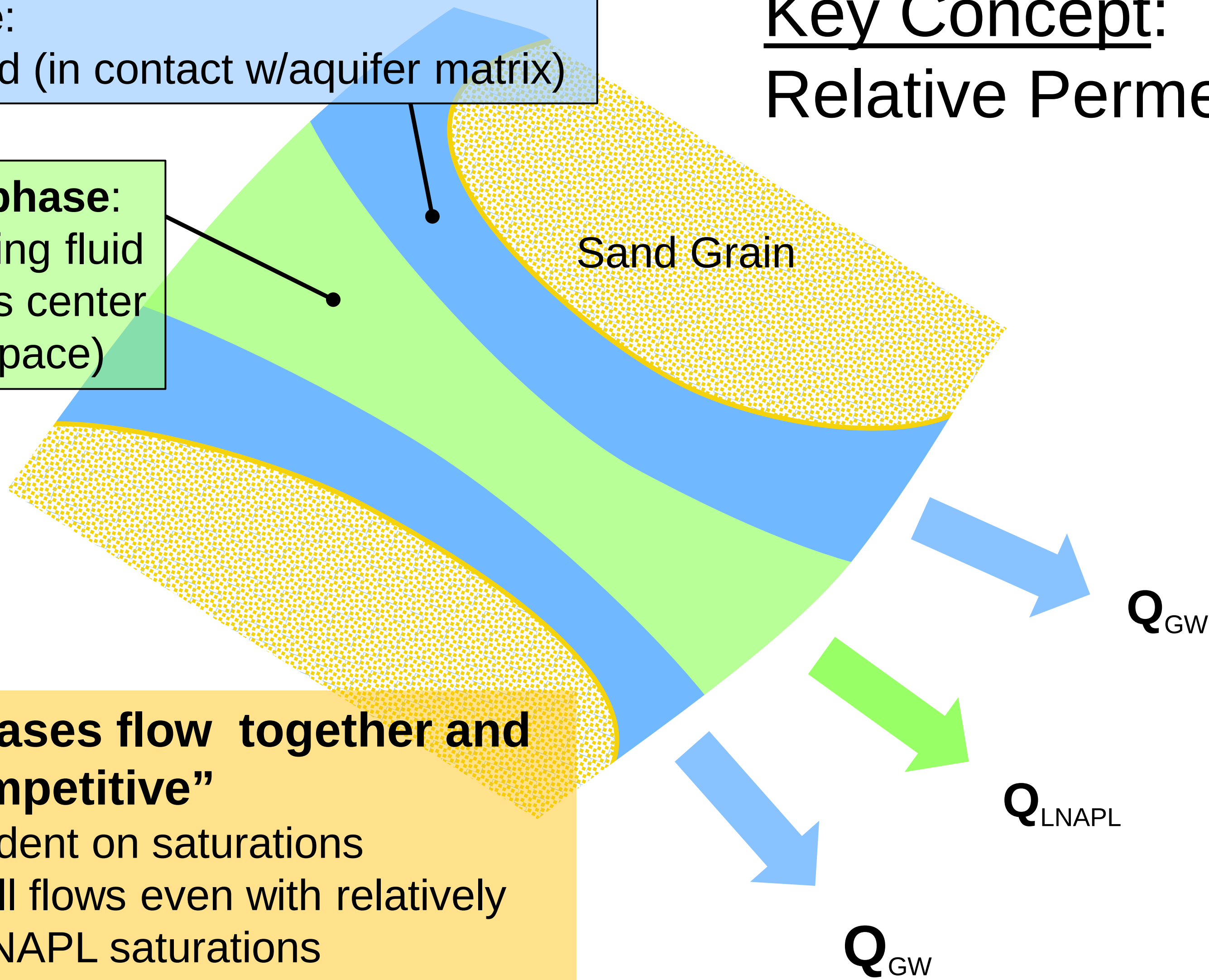
$$Q_{nw} = \frac{-k_{rnw} k_i \rho_{nw}}{\mu_{nw}} A \frac{dh_{nw}}{dl}$$

(Fetter, 1993)

Key Concept: Relative Permeability

GW phase:
wetting fluid (in contact w/aquifer matrix)

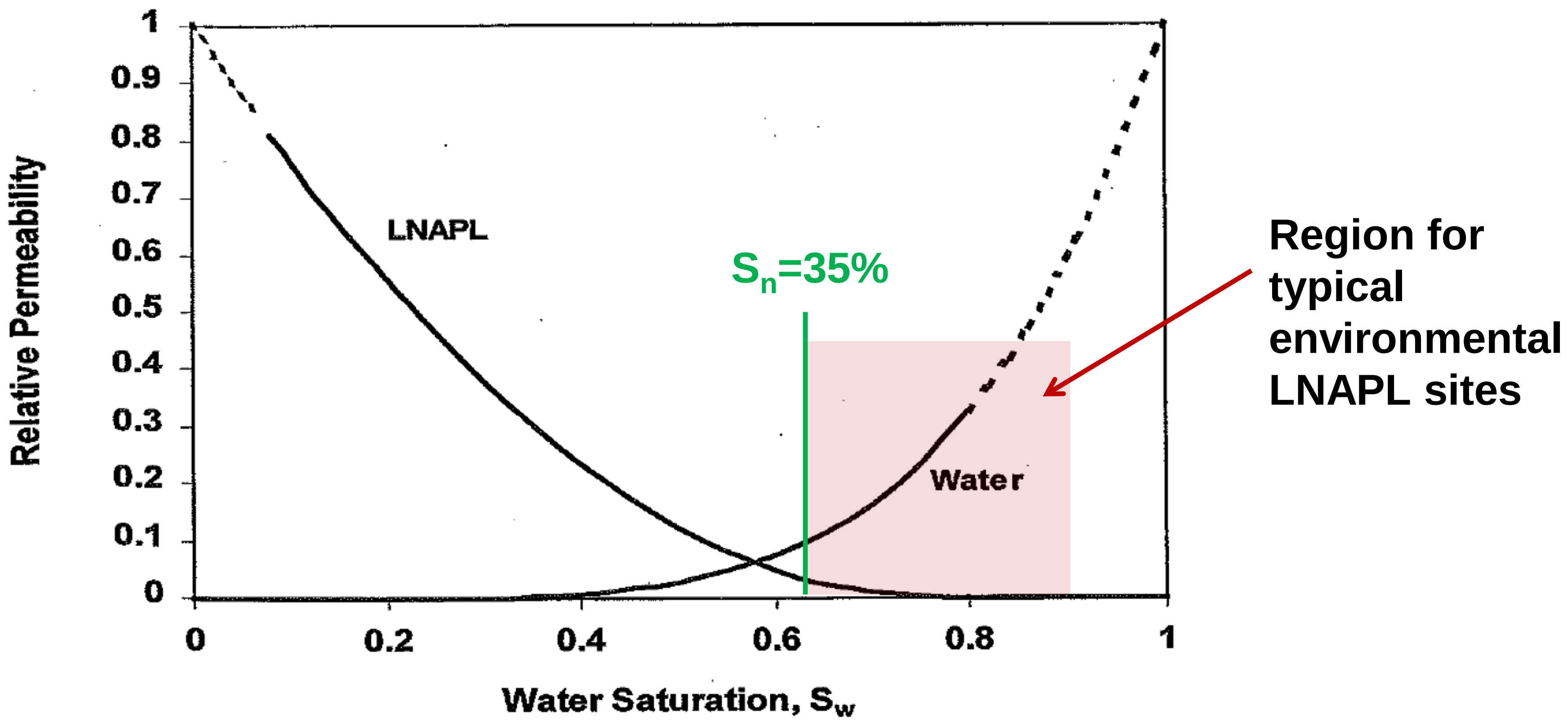
LNAPL phase:
non-wetting fluid (occupies center of pore space)



Both phases flow together and are "competitive"

- Dependent on saturations
- GW still flows even with relatively high LNAPL saturations

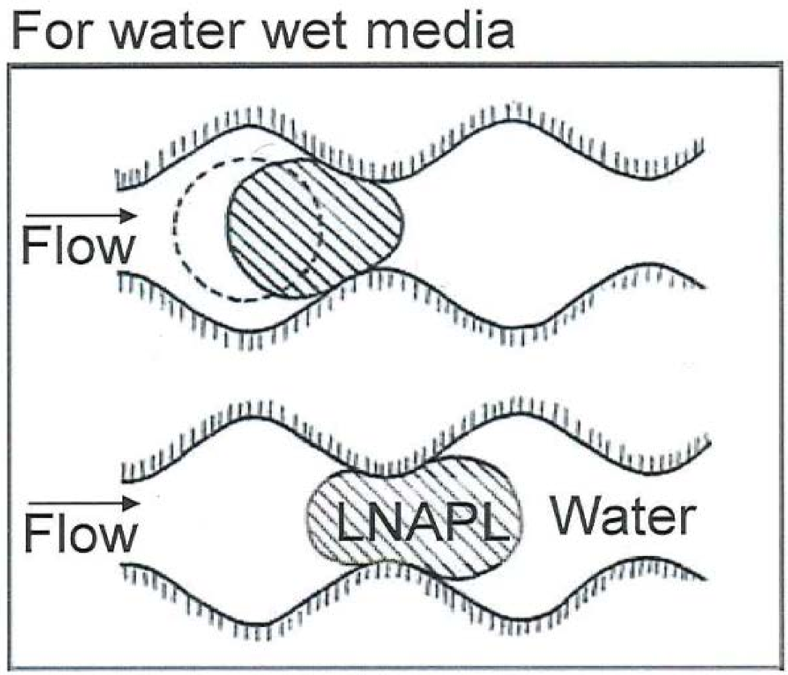
Relative Permeability:
Defines flow competition (relationship) between water and LNAPL



Note: overall LNAPL Saturation is (1-Sw)

(Charbeneau, 1999)

More details concerning LNAPL flow……



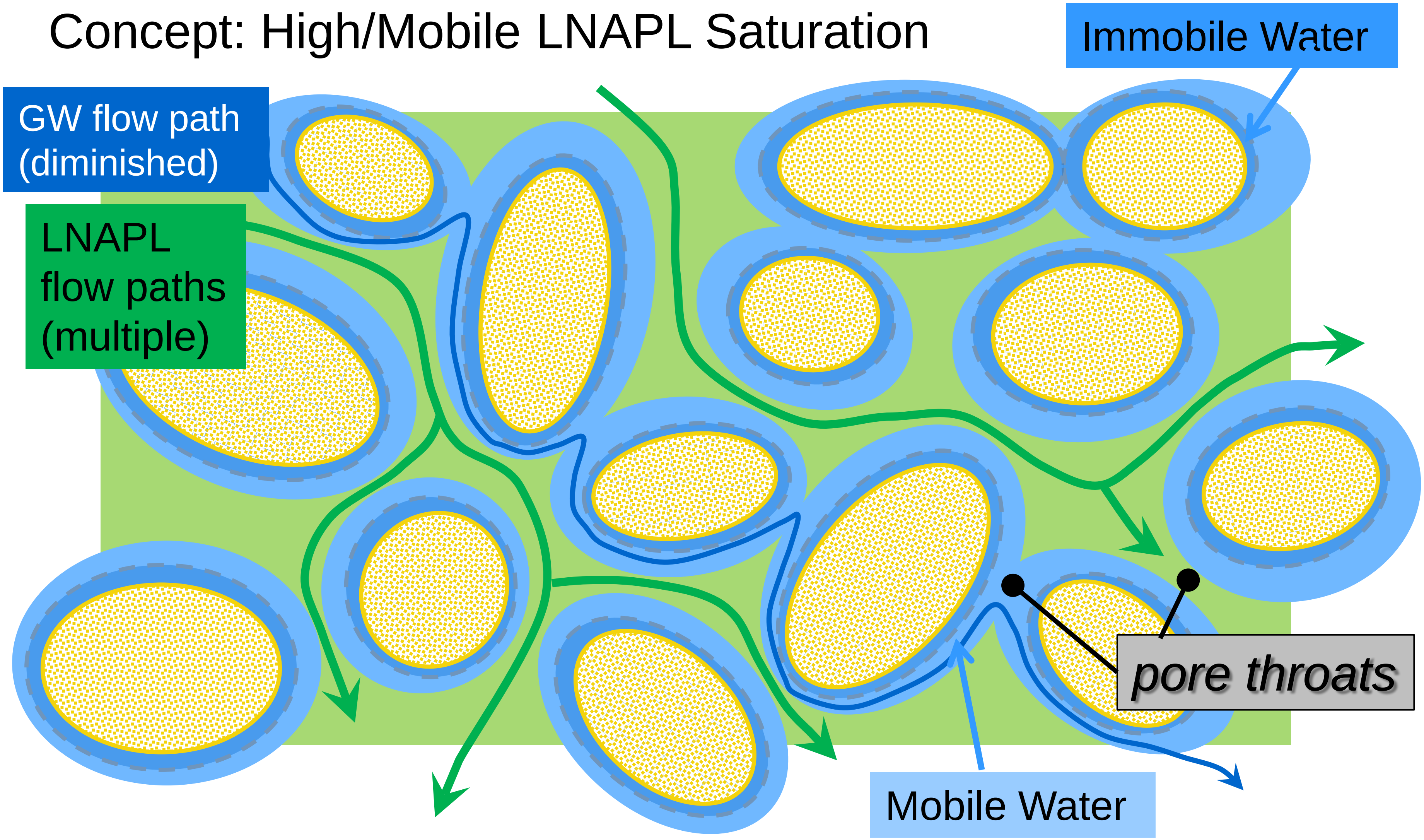
(ITRC Training Part 1, Slide 24)

Misconception:

Suggests LNAPL flows as if a plunger were pushing (or pumping well drawing or GW gradient pushing)……let's examine in more detail, and revisit this illustration later (hint: it's more complicated/nuanced).

Dual Phase (Groundwater & LNAPL) Flow

Concept: High/Mobile LNAPL Saturation



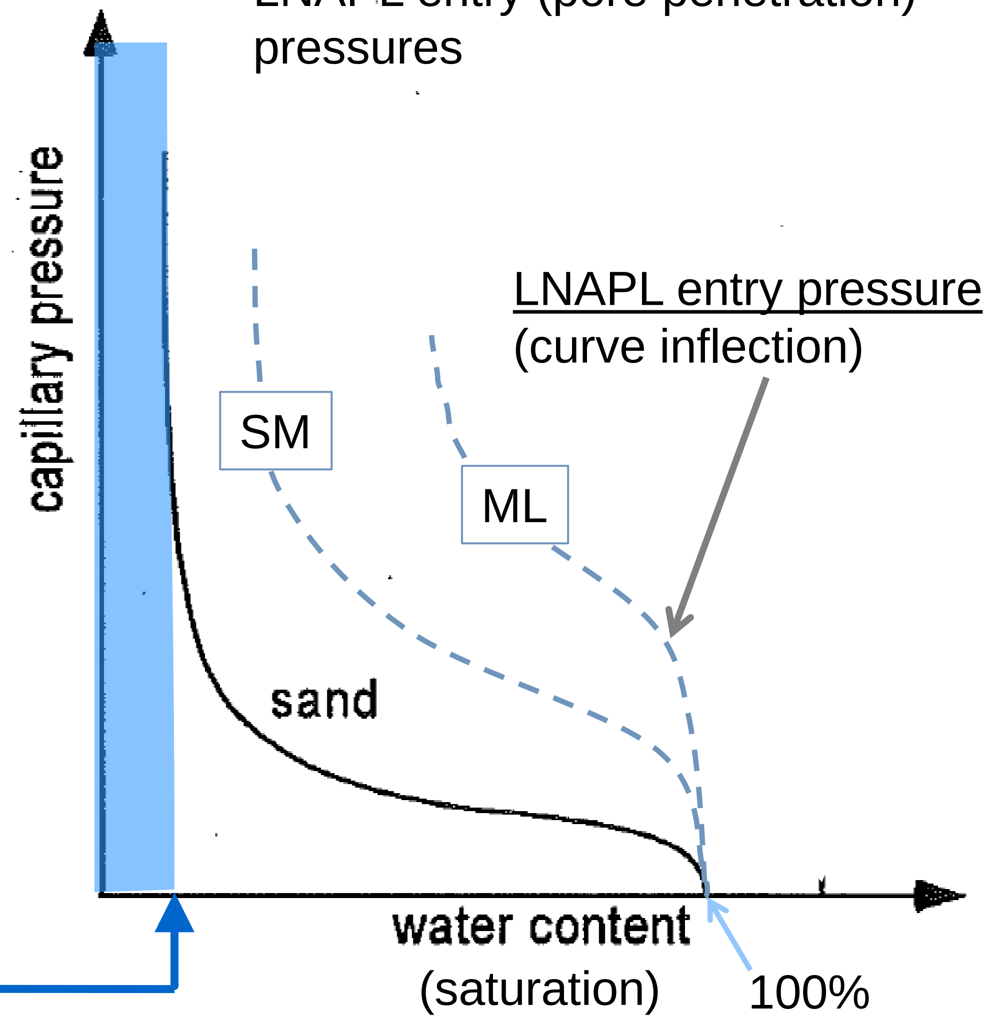
Lab-Determined (Core) Moisture Retention Curves (aka: Drainage curve)

i.e., will not move (reduce) under any pressure regime

Irreducible (Immobile) Water Saturation

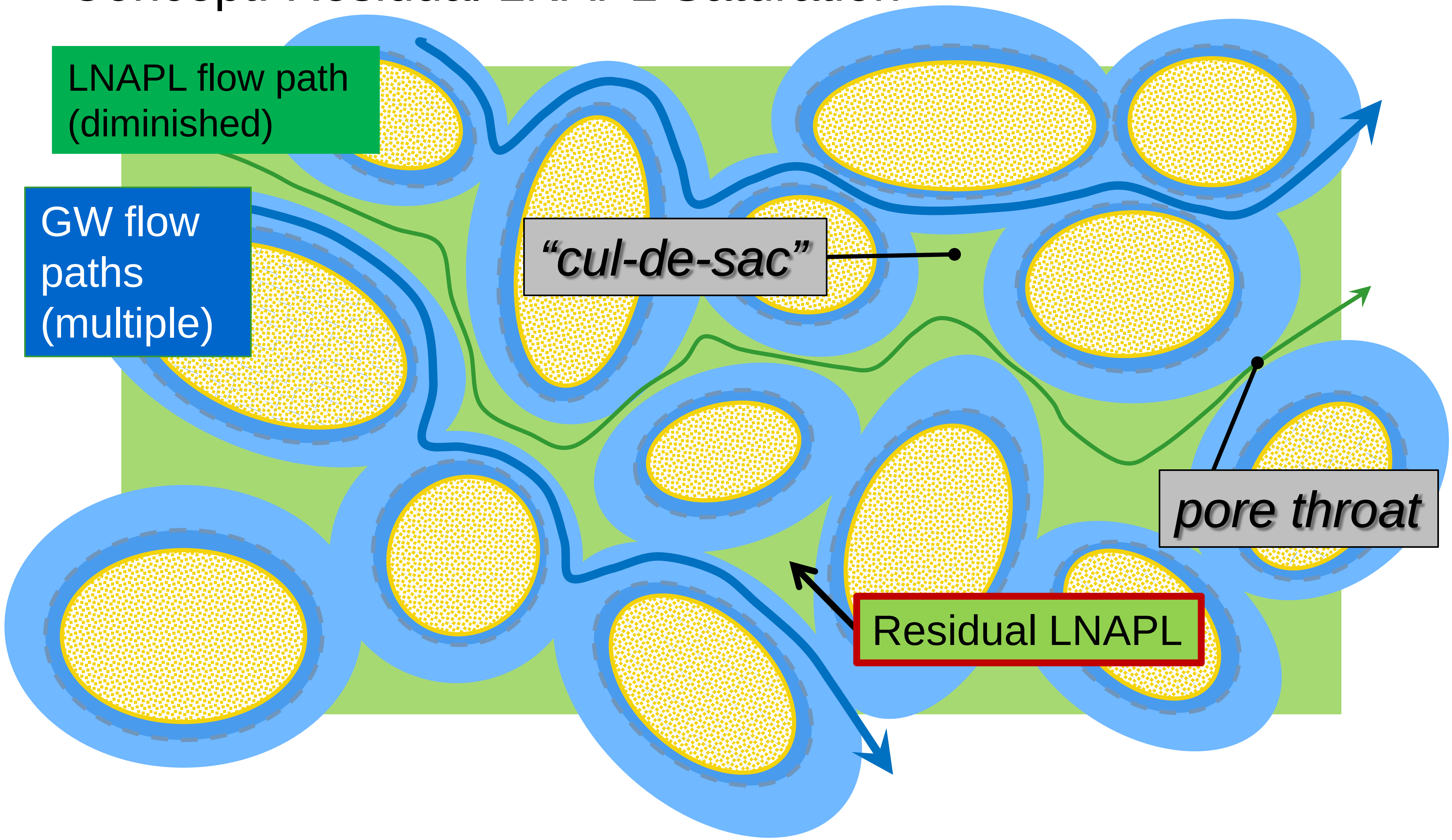
8-12% for clean, well sorted (poorly graded) sand

Key concept:
More permeable soils have lower LNAPL entry (pore penetration) pressures

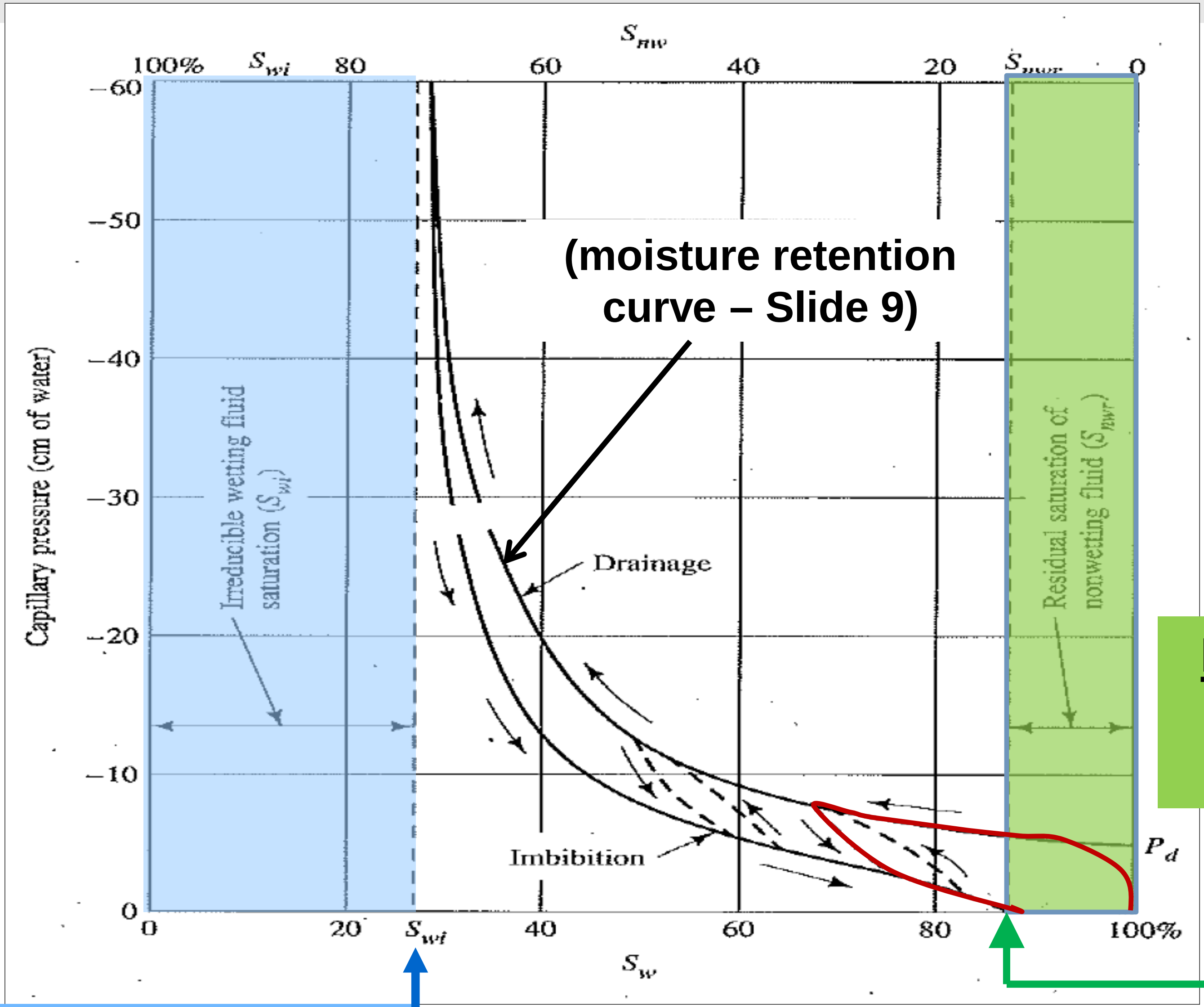


Dual Phase (Groundwater & LNAPL) Flow

Concept: Residual LNAPL Saturation



Lab-Derived, Drainage & Imbibition Curves (aka, Hysteresis)



i.e., will not move (reduce) – retained by the formation

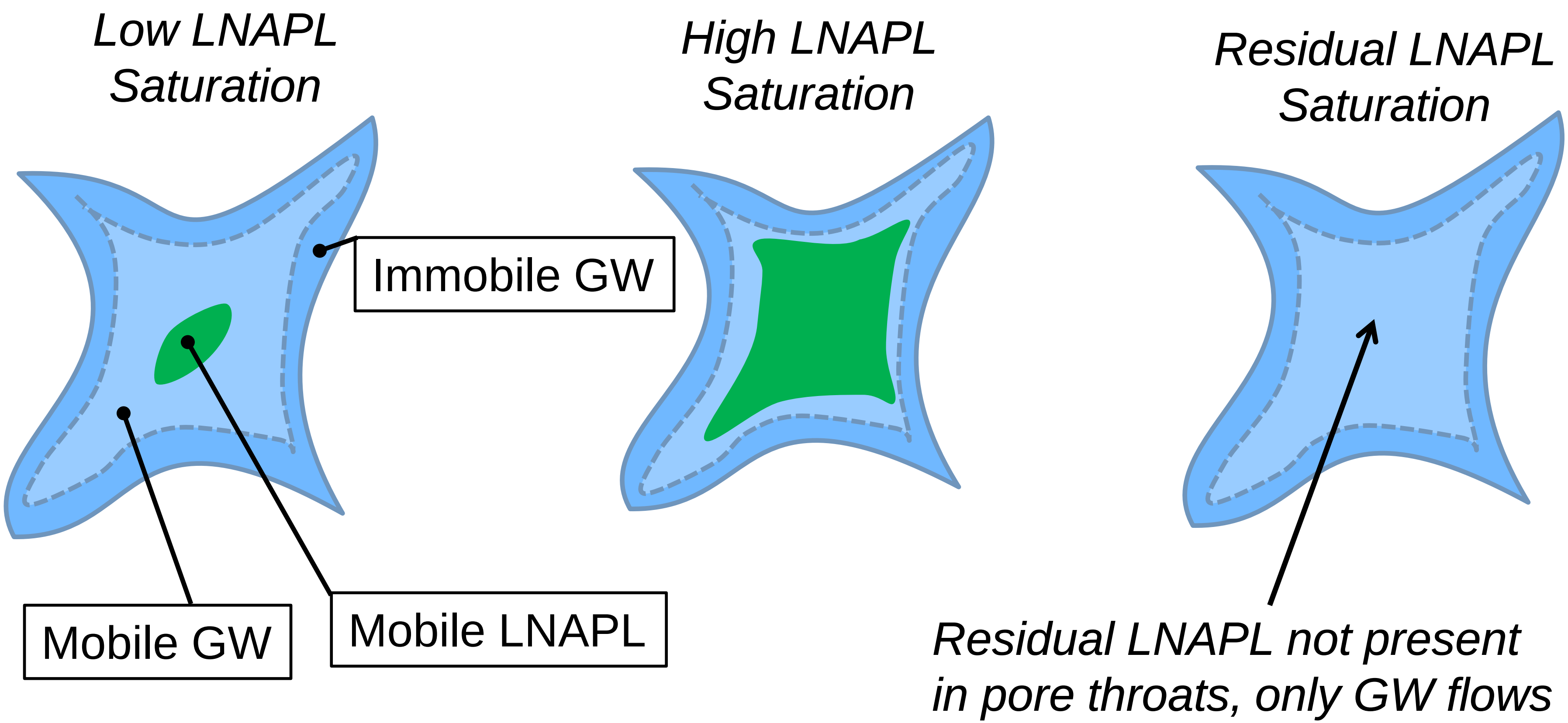
<u>Irreducible LNAPL</u> Saturation (Residual)

Immobile GW Sat.

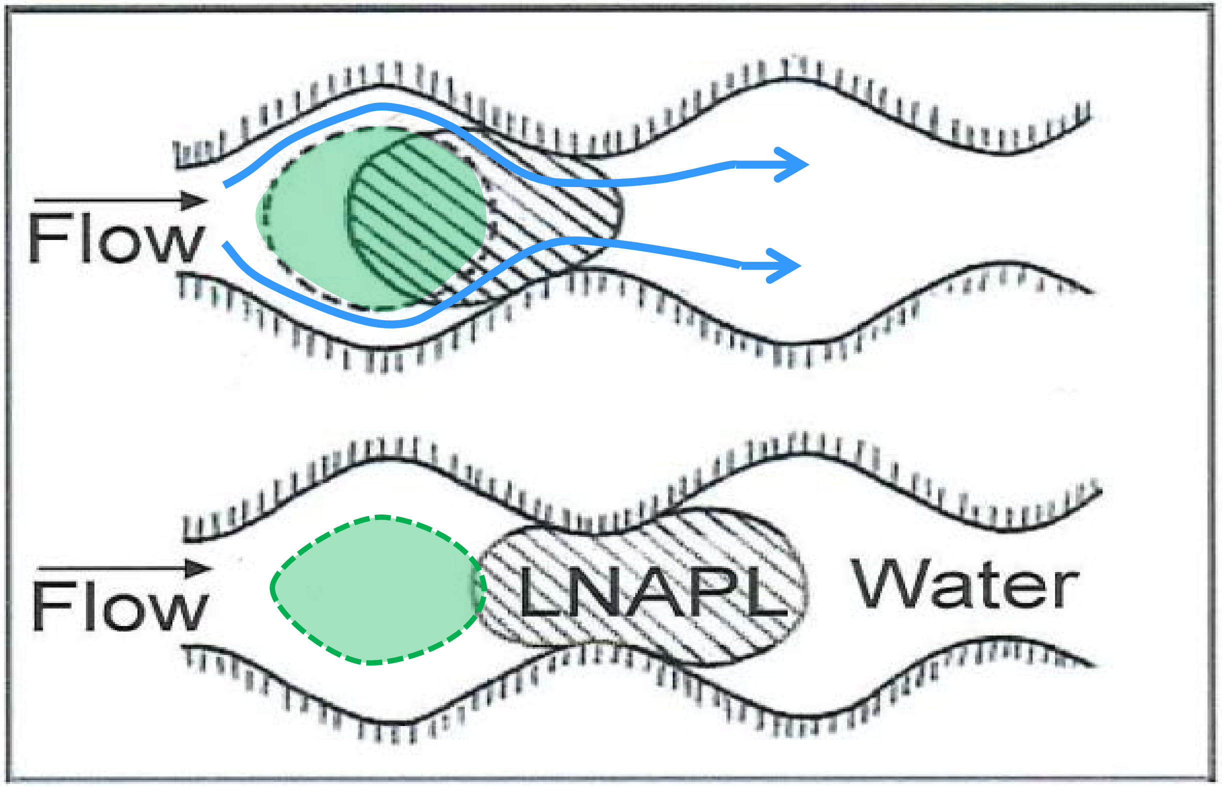
(Fetter, 1993)

Pore Throats Control Flow

(flow from pore-to-pore is out of plane of illustration)



As shown, initial LNAPL position (dashed) would only be residual, so there would be no LNAPL flow, only GW flow around it



In the case of actual LNAPL flow, a significant proportion of the "mobile" LNAPL would remain as residual in the center of 1st pore

Summary:

- Dual phase flow reflects competition between GW & LNAPL
- For most sites permeability to GW > permeability to LNAPL, some >>
- Irreducible GW saturation coats matrix, reduces effective porosity and *increases with finer grained soils and heterogeneous mixtures*
- Residual LNAPL saturation reflects fraction that is not mobile, *increases with finer grained soils and heterogeneous mixtures*
- For most sites overall LNAPL saturations are low due to low pressure environment. Consequently, mobile < residual saturations, some << (even before remedial removal of mobile LNAPL)
- Pore throat size/distribution (porosity architecture) determines LNAPL flow and degree of residual LNAPL saturation; *throats diminish in finer grained soils and generally diminish in heterogeneous mixtures, thereby increasing residual LNAPL saturations.*

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Sorting & Heterogeneity *(cont.)*:

Optimal: well-sorted, isotropic sands w/no fines, and best-case packing (uniformly rounded grains):

- Uniform pore and pore throat sizes – max. mobile LNAPL flow and min. residual LNAPL
- Why its ideal as "frac" proppant

Poorly-sorted mixtures (common glacial sediments) and more angular grains allow for denser packing:

- Pore throats vary in size and can be plugged w/fines – reduces mobile LNAPL flow and increases residual LNAPL
- Variable pore size – increases residual LNAPL

Grain size and sorting distributions are bedding-related
(i.e., horizontal anisotropy):

Most efficient hydraulic LNAPL removal:

- Take advantage of horizontal bedding most transmissive to LNAPL
- Take advantage of horizontal geometry of LNAPL accumulation
- ***Design extraction so it is literally opposite from how LNAPL migrated into the formation***

More pertinent today than ever…..

Reason: recent improvements in geophysical imaging -
LIF surveys and associated tools detail the extent of LNAPL accumulations and the soils within which they are trapped

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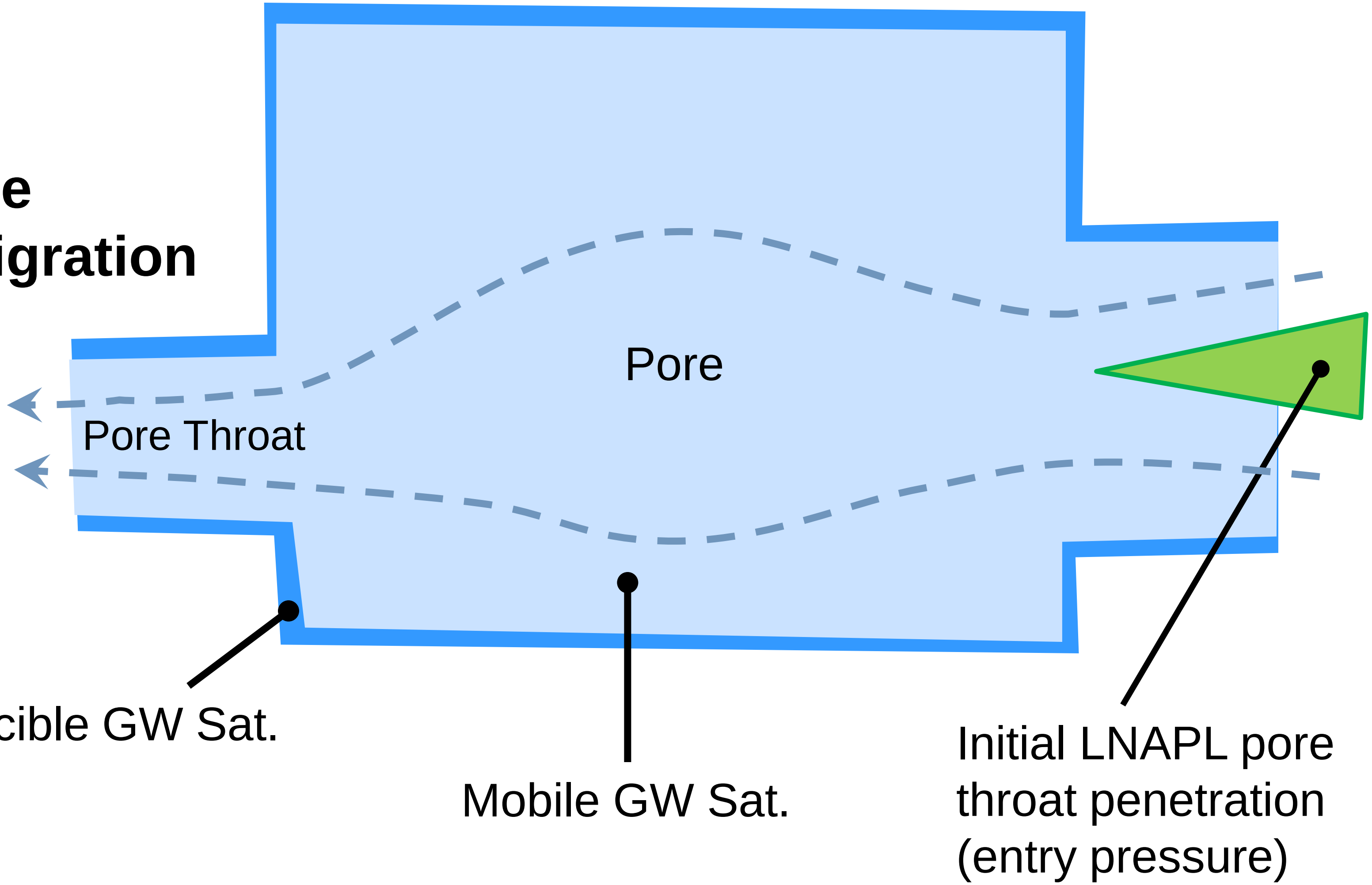
Pore-Scale LNAPL Migration



Note that pore throat on left is smaller than on right

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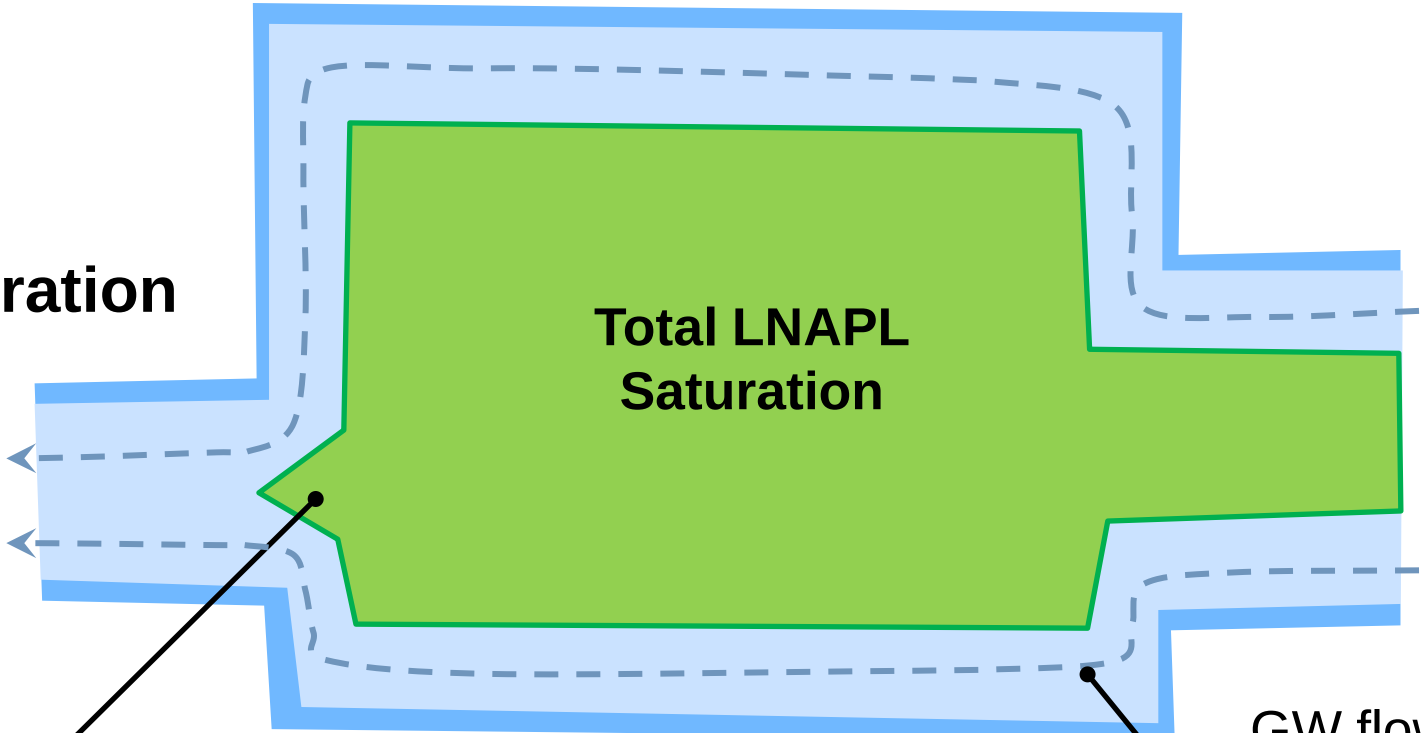
Pore-Scale LNAPL Migration (cont.)



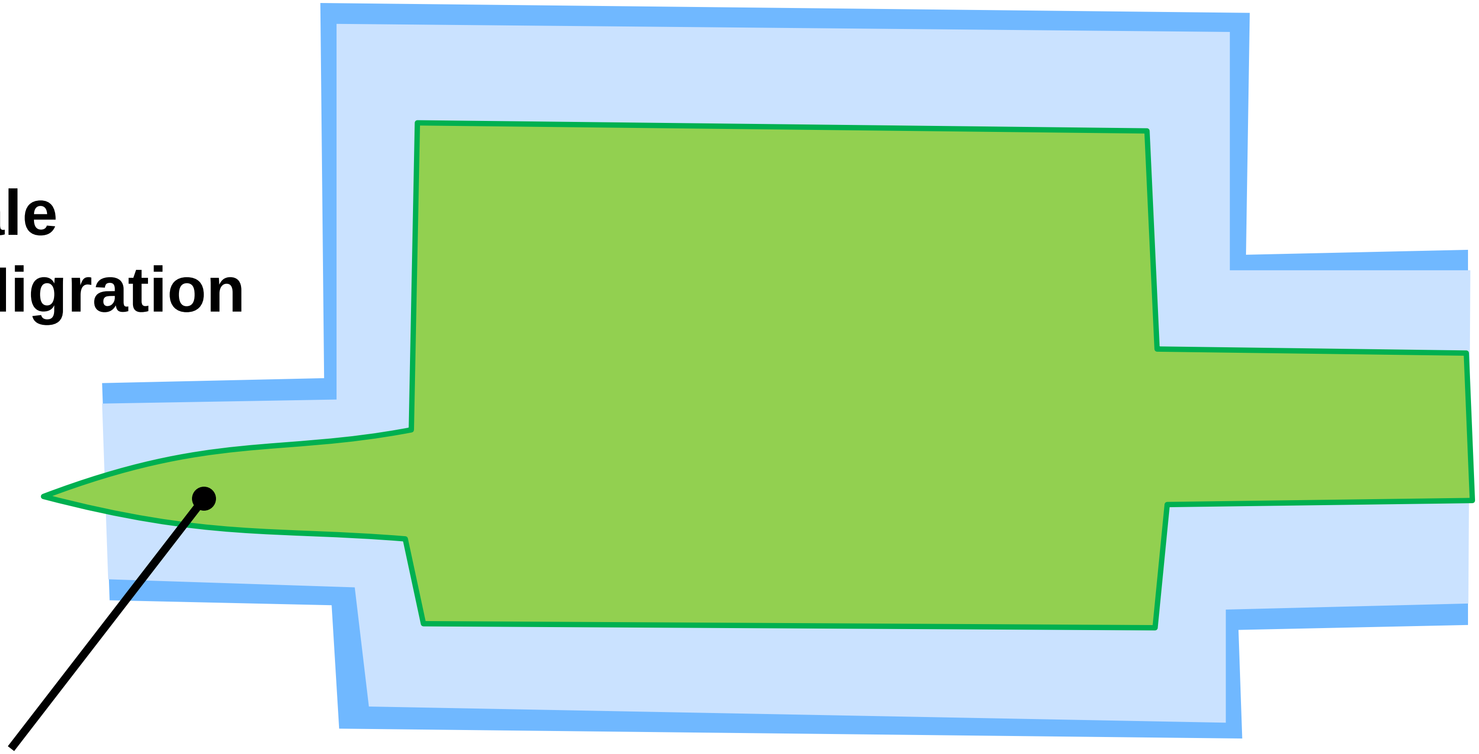
LNAPL progressively fills pore until saturation is near entry pressure for smaller (exit) pore throat

GW flows at diminishing rates as LNAPL saturation increases

Note: Residual LNAPL is not yet defined by this illustration

3

Pore-Scale LNAPL Migration (cont.)



Increment of additional LNAPL Saturation overcomes entry pressure for smaller pore throat

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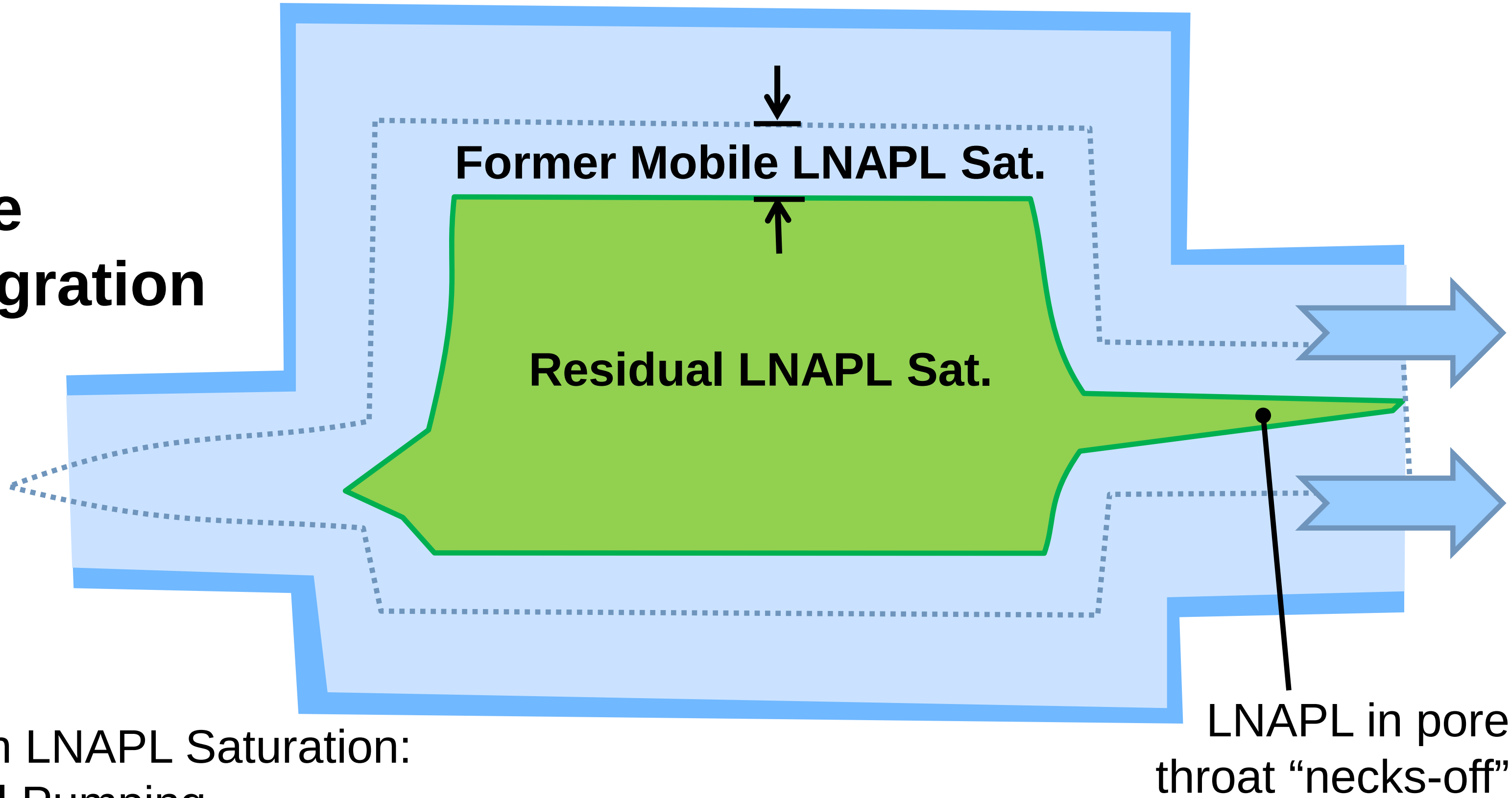
Pore-Scale LNAPL Migration (reversal)



Reduction in LNAPL Saturation:
- Remedial Pumping
- Vertical smear zone re-distribution

Key Concept: once LNAPL migrates into a new pore space, a residual volume will be retained thereafter (i.e., hysteresis)

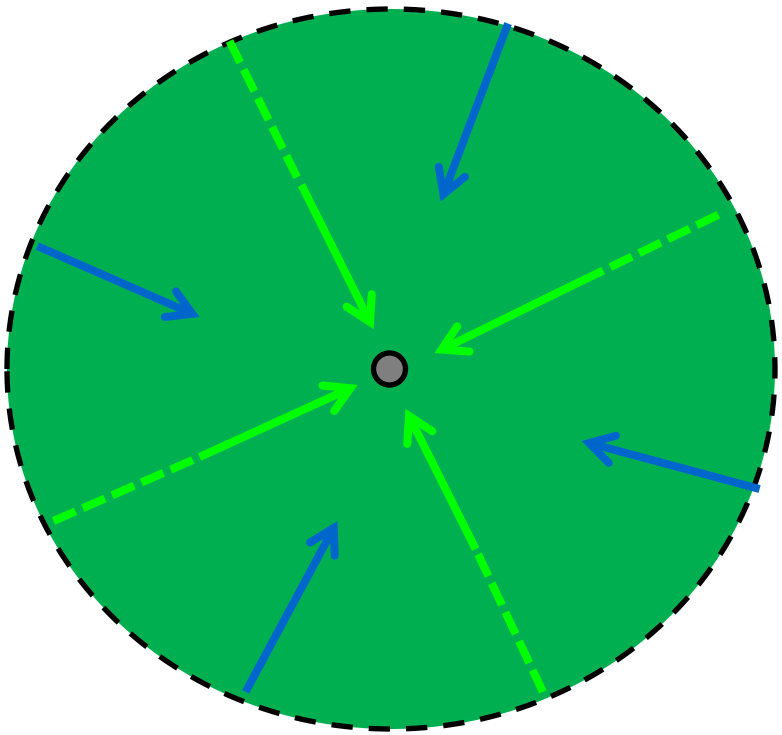
Questions?

LNAPL Saturation Concepts

Practical Implications

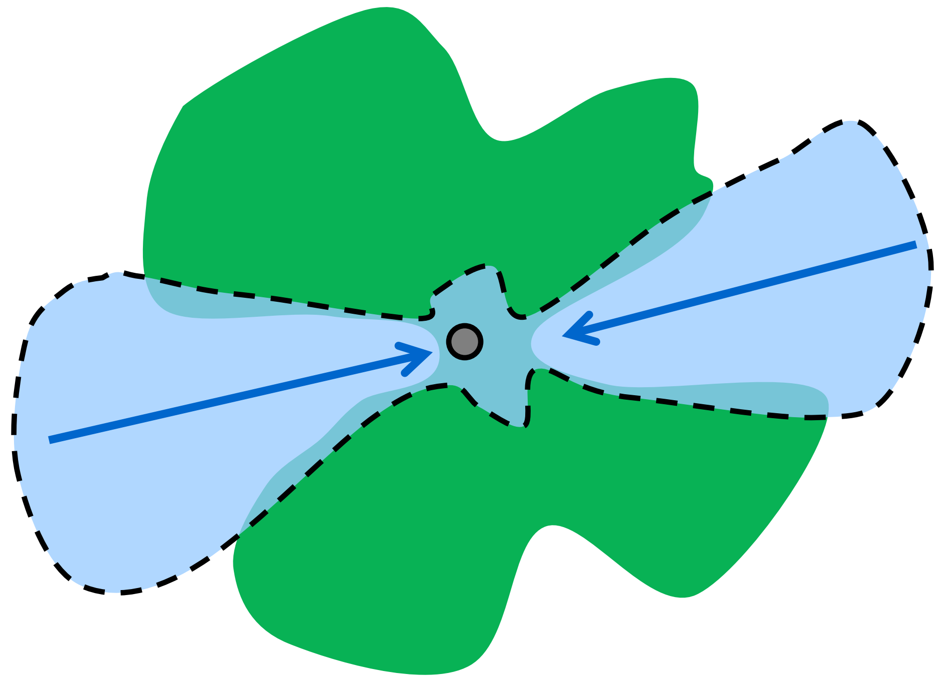
Hydraulic Capture Zones (Horizontal)

Idealized – isotropic media



Radial flow w/LNAPL & GW flow to center extraction well

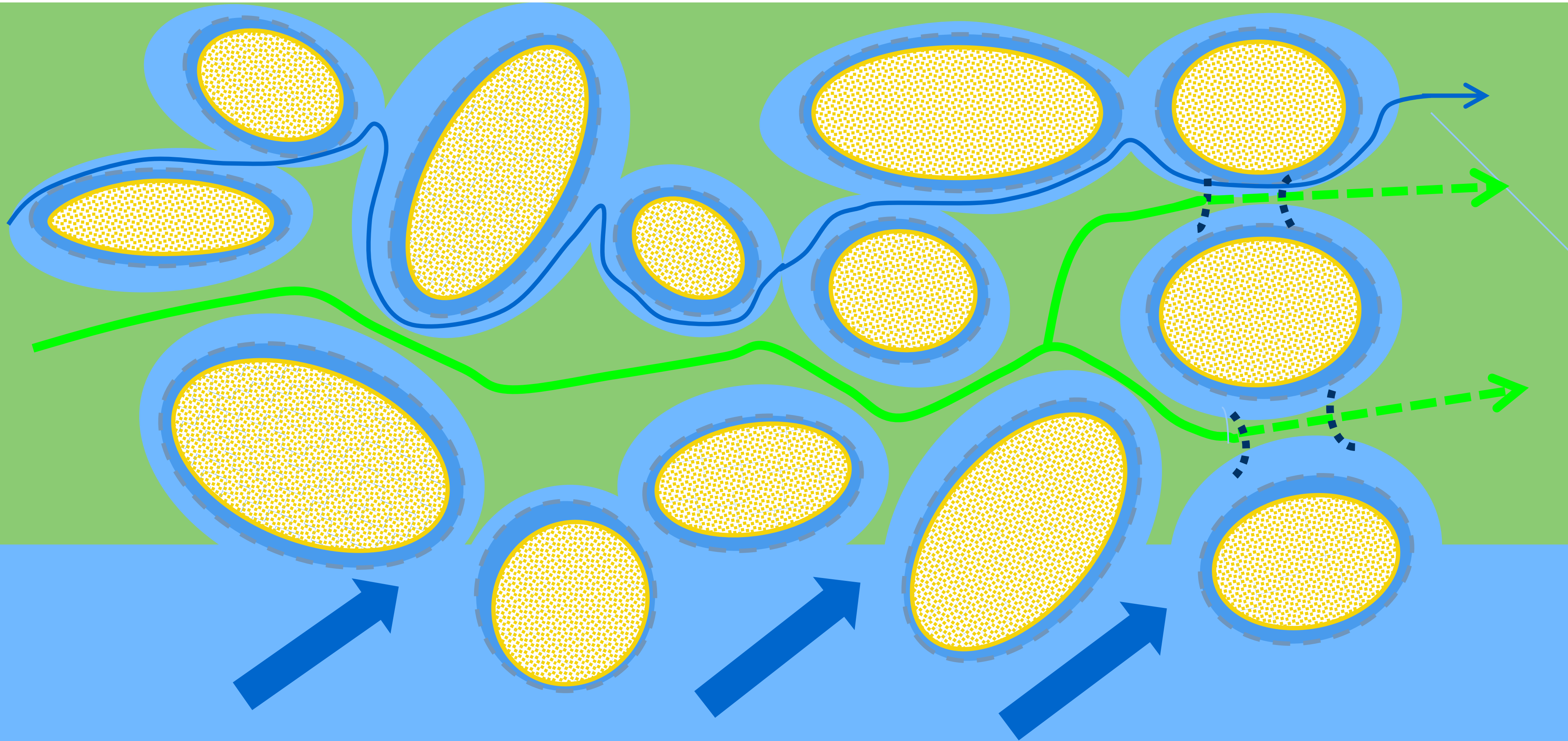
Actual – heterogeneous media



Preferential flow/greater perm to GW causes “breakthrough”

- LNAPL capture zone very limited
- LNAPL recovery always disappoints

Hydraulic Recovery - **Thin** LNAPL Accumulations

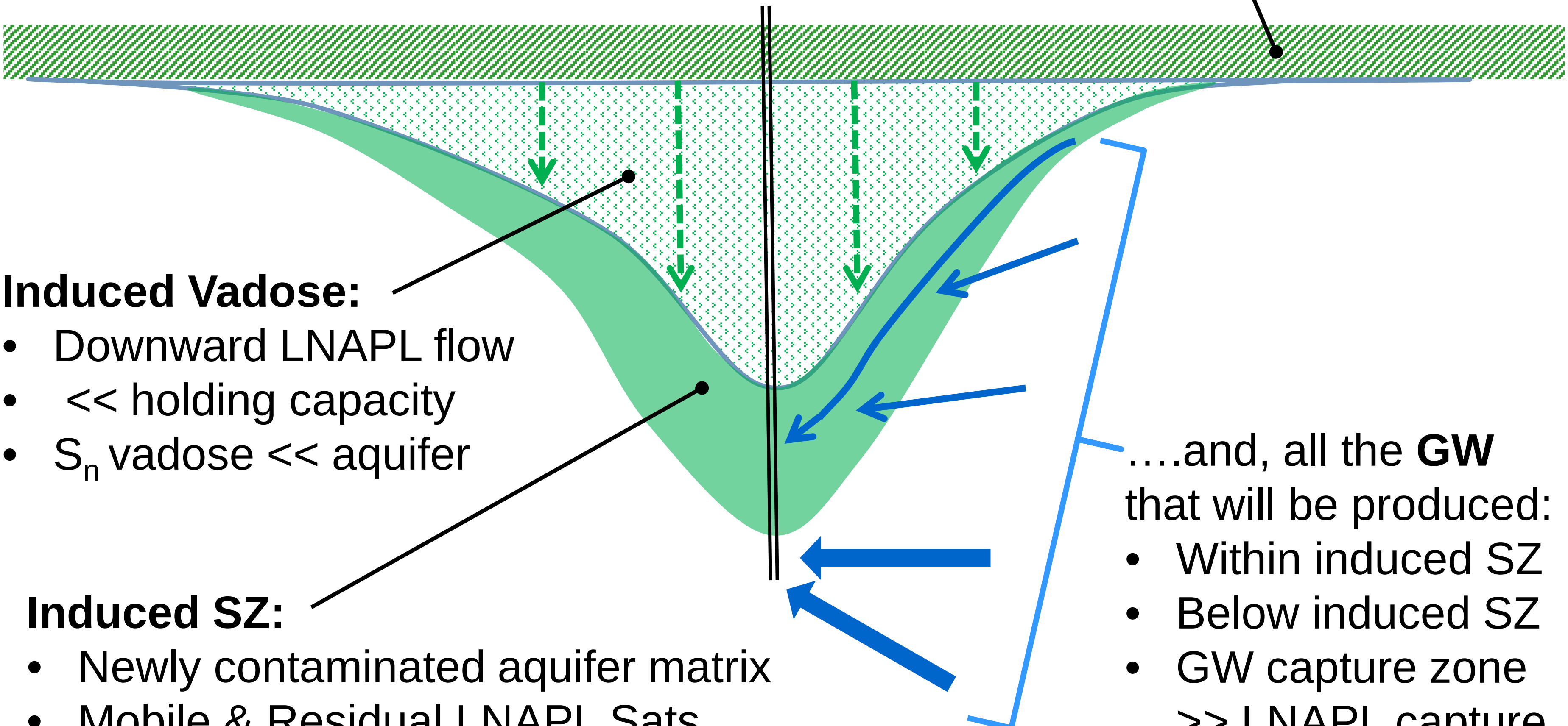


Higher *induced* S_W causes LNAPL pore throat connections to close (i.e., “neck-off’) - defines effective edge of capture zone

- Higher pumping rates cause earlier “necking-off”
- High GW flux from below accentuates

Hydraulic Capture Zones (Vertical)

LNAPL Smear Zone (SZ):
- Mobile & Residual LNAPL Sats.
- Natural vertical redistribution

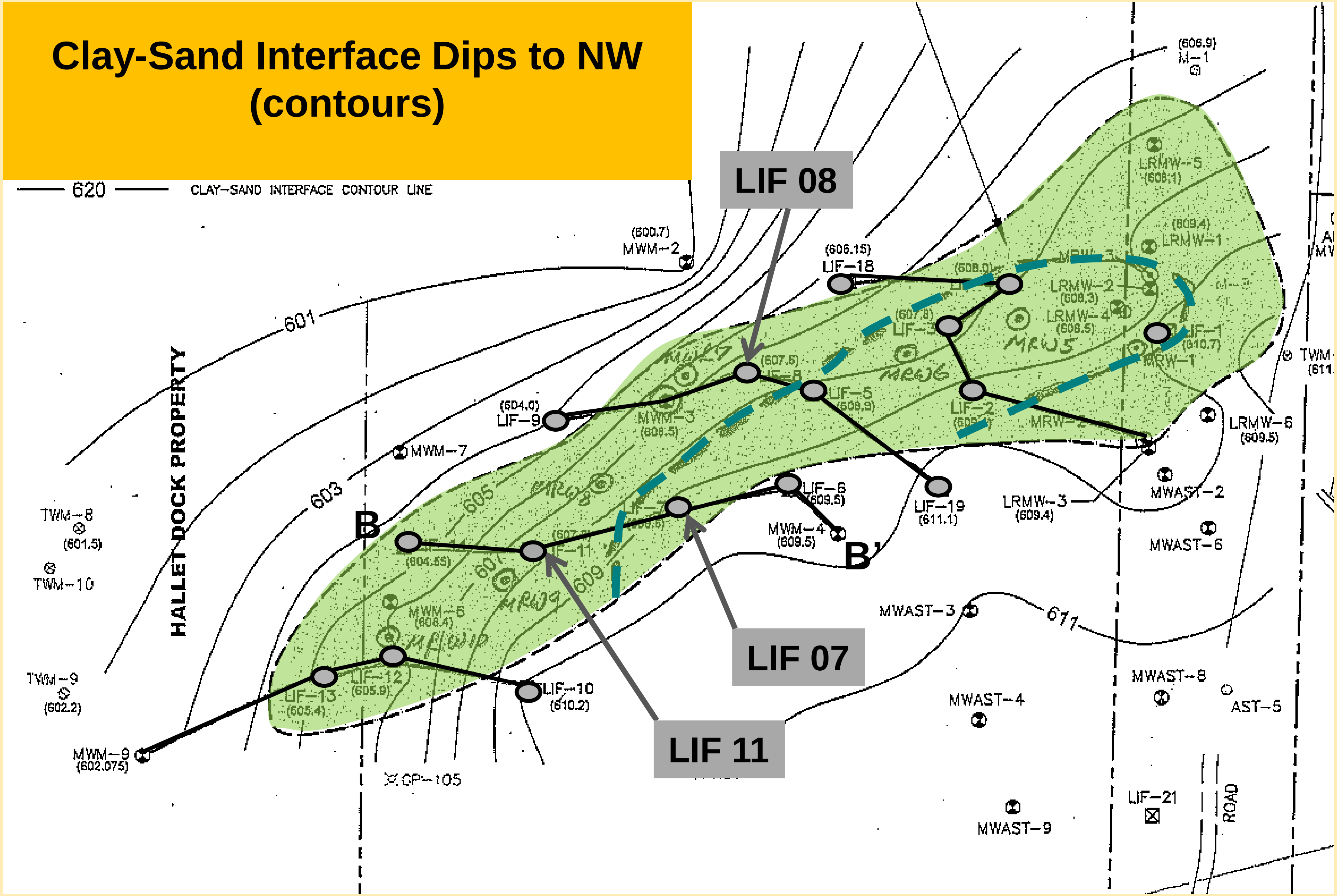


Induced Vadose:
- Downward LNAPL flow
- << holding capacity
- S_n vadose << aquifer

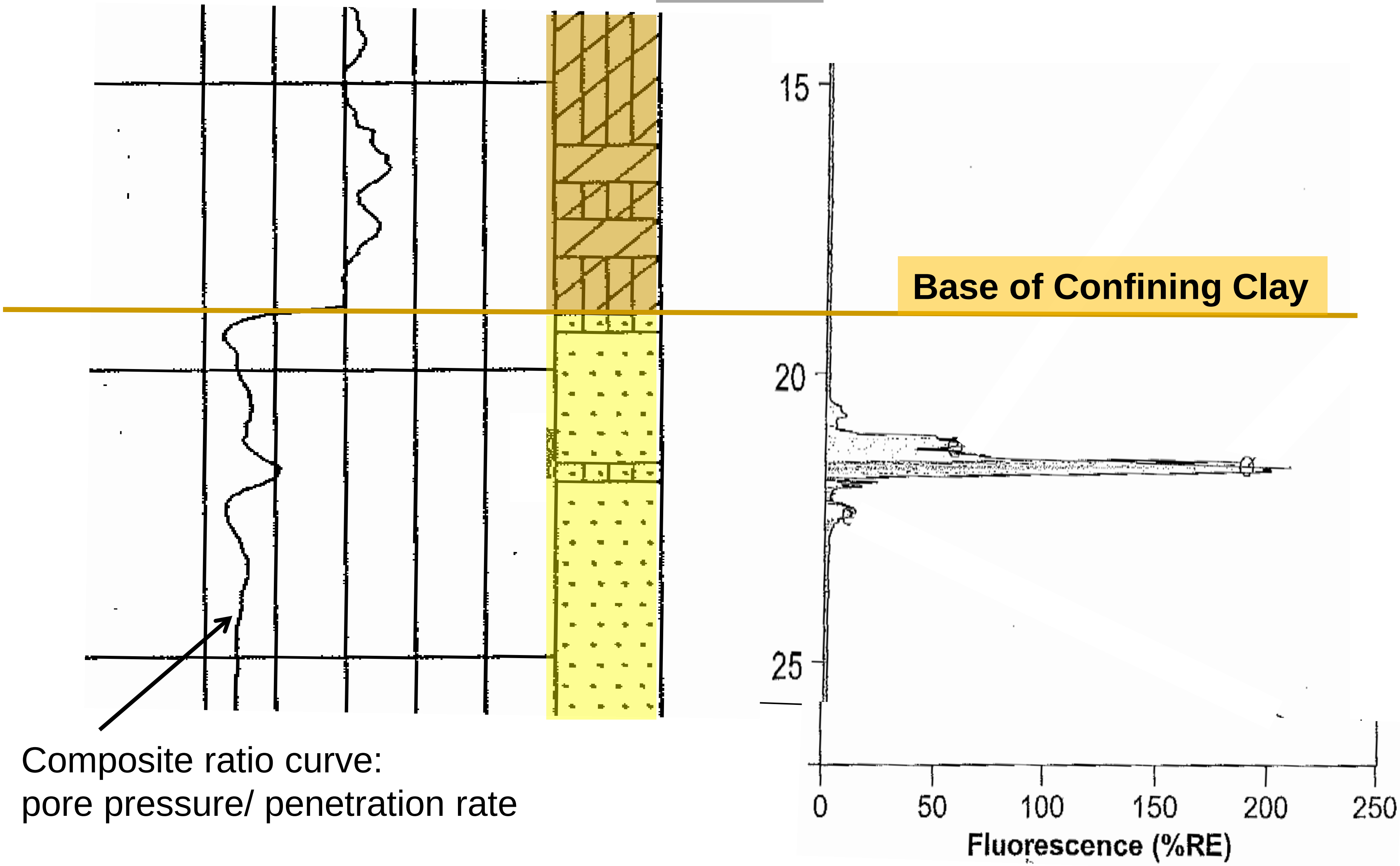
Induced SZ:
- Newly contaminated aquifer matrix
- Mobile & Residual LNAPL Sats.
- After pumping, significant residual mass below water table
- S_{nr} tends to be >> S_{nm}

….and, all the **GW** that will be produced:
- Within induced SZ
- Below induced SZ
- GW capture zone >> LNAPL capture

Site With Confined LNAPL Accumulation

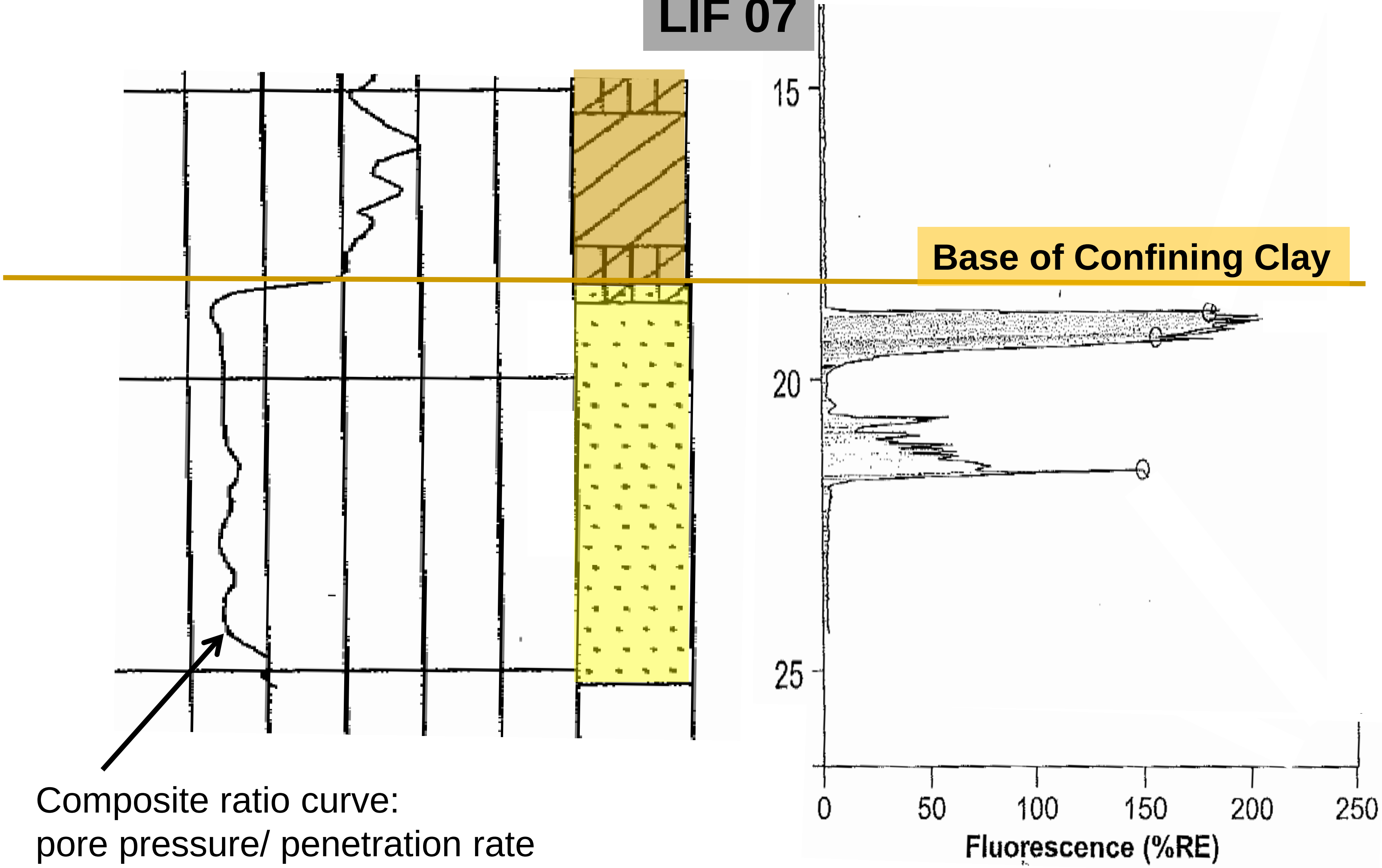


LIF 11



Composite ratio curve:
pore pressure/ penetration rate

LIF 07



Composite ratio curve:
pore pressure/ penetration rate

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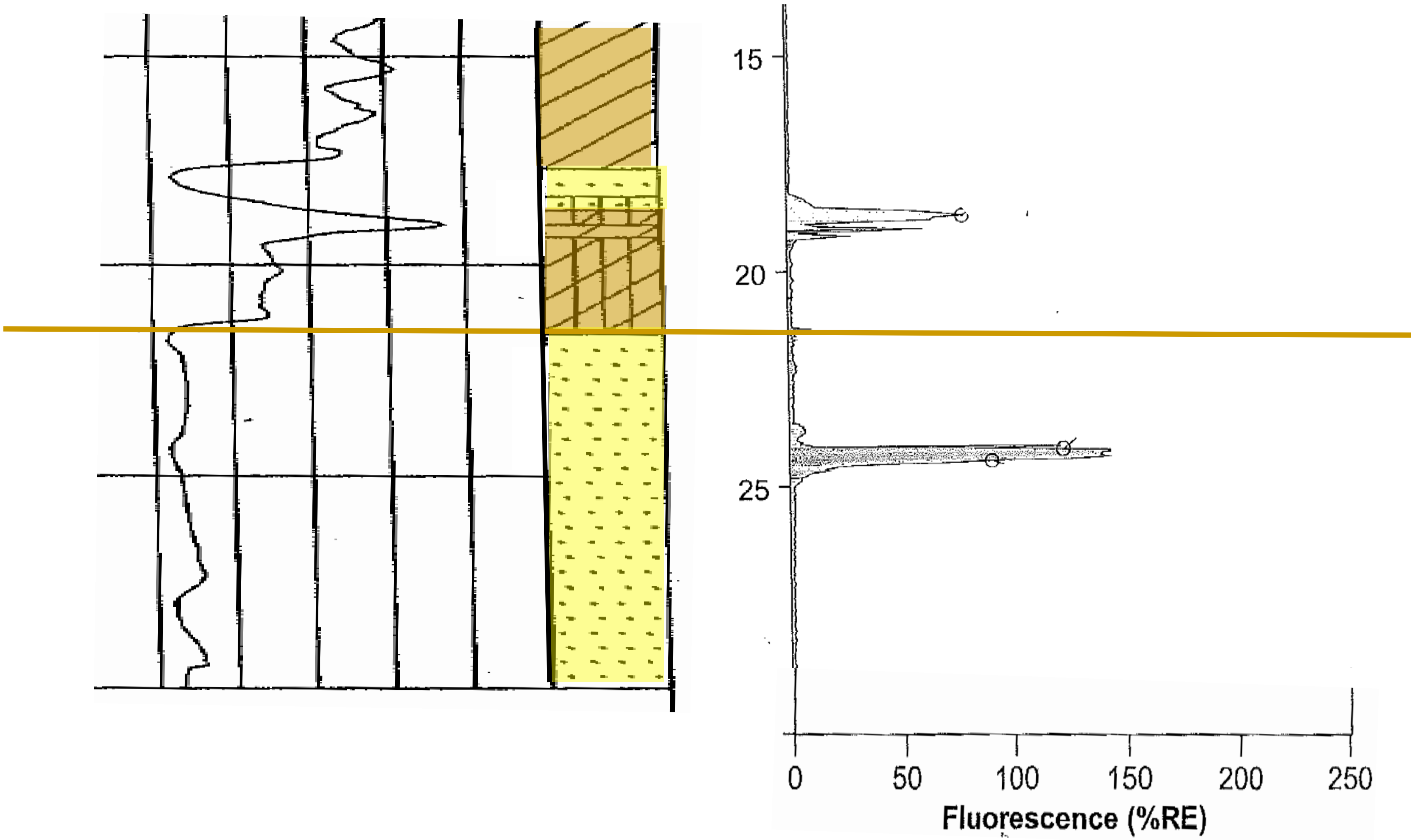
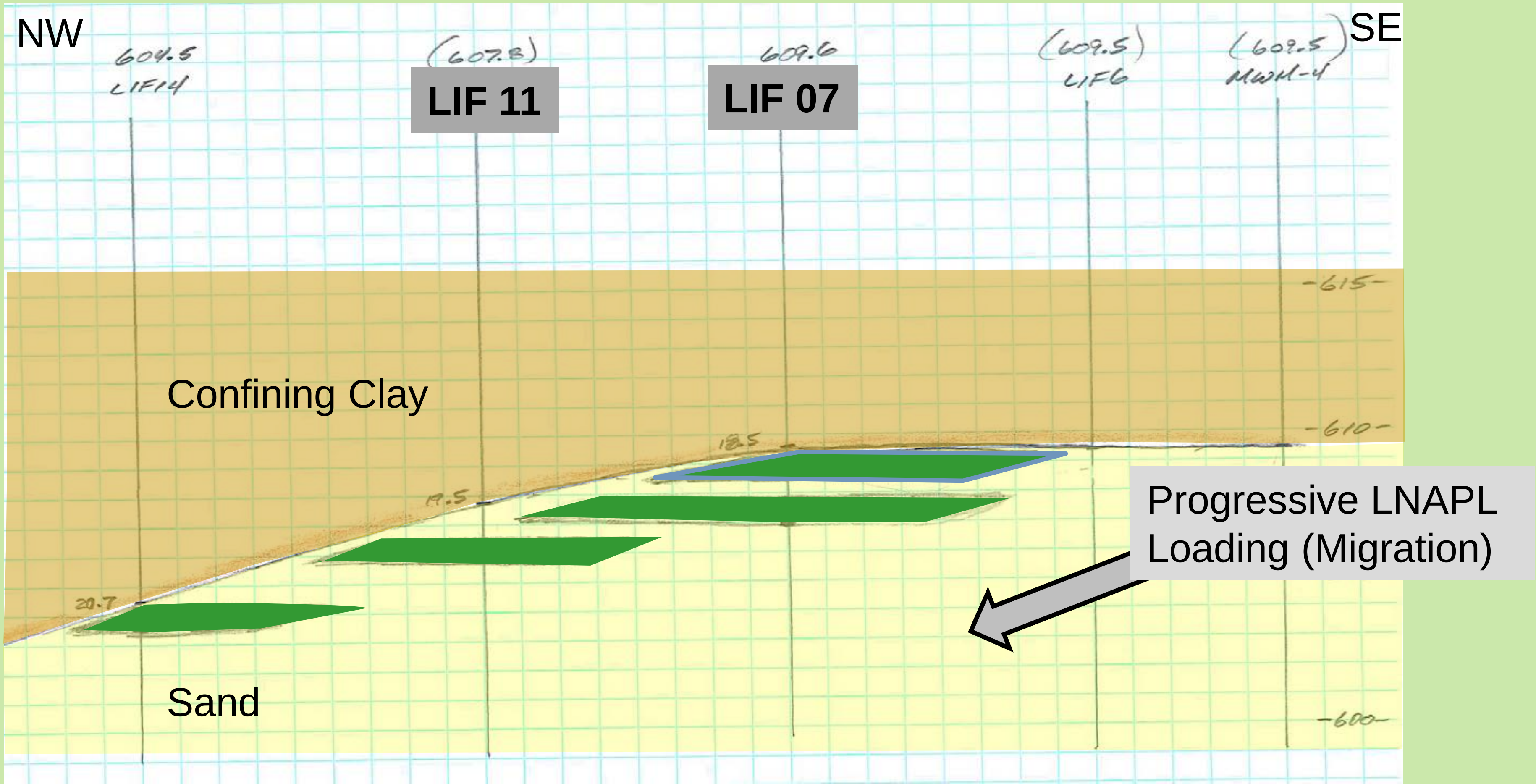
LIF 08

Base of Confining Clay

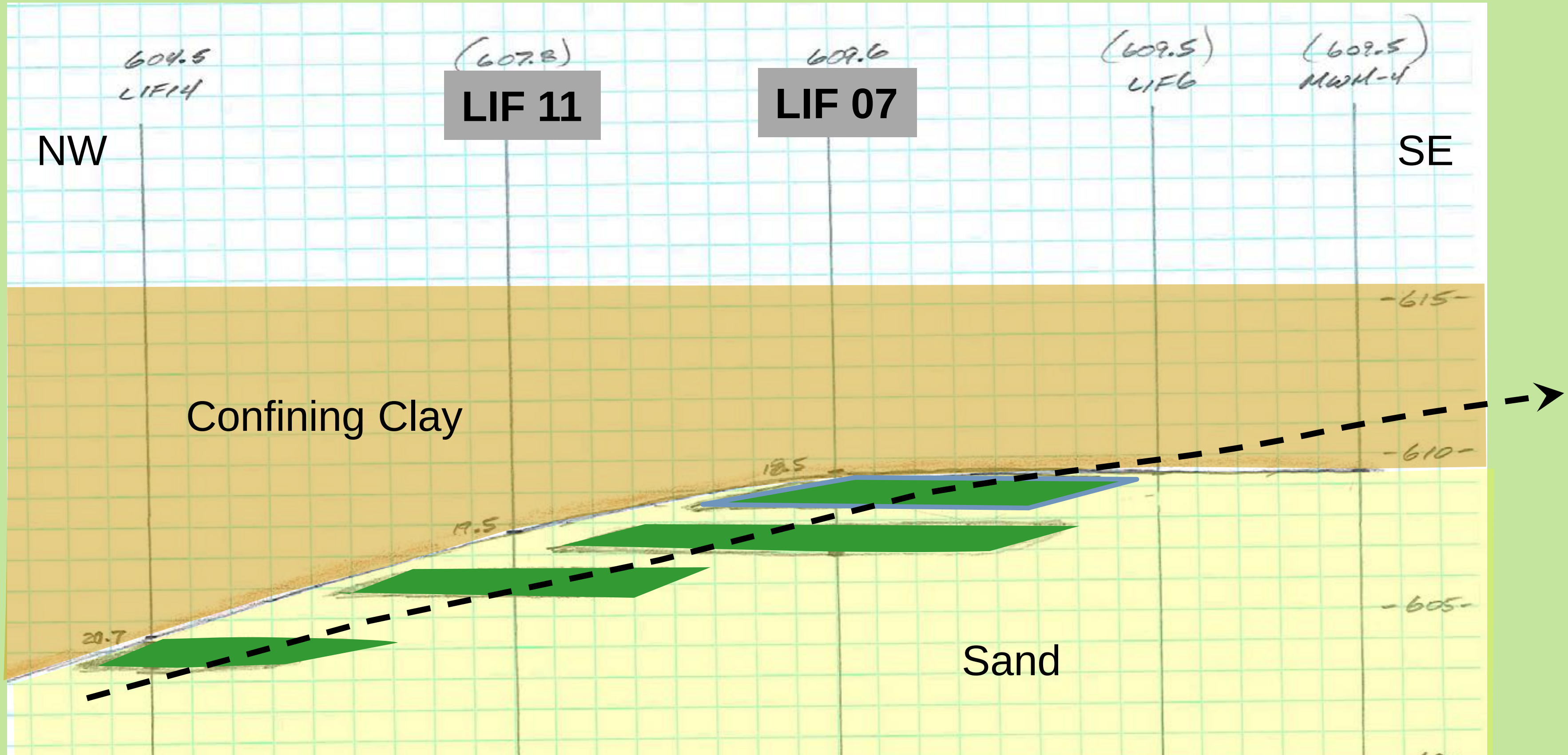


Section B - B’



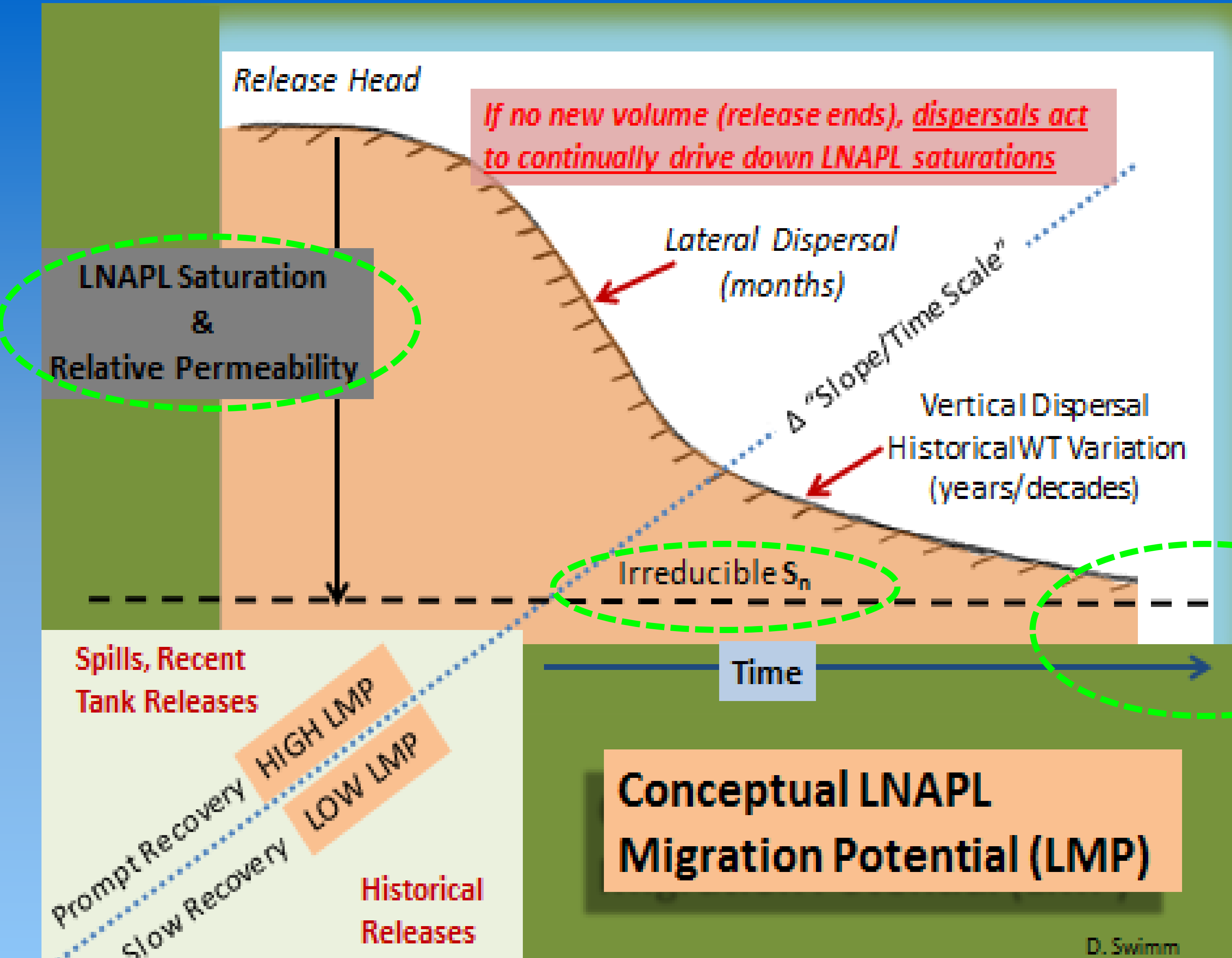
NW
SE
604.5
LIF14
(607.8)
LIF 11
609.6
LIF 07
(609.5)
LIF6
(609.5)
MWM-4
-615-
-610-
-600-
Confining Clay
18.5
19.5
20.7
Sand
Progressive LNAPL Loading (Migration)

Horizontal Extraction?



LNAPL "extraction sinks"

- Low head differentials (slow pumping)
- Using engineered screens to distribute the low differential across the most advantage LNAPL saturations



Most historical release sites

Questions?