Secondary Migration by Stokesian Flow of Metastable Clusters and Microdroplets of Petroleum in Water*

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Abstract

The popular hypothesis for secondary migration of petroleum as a continuous separate phase flow has many problems. To circumvent these, I proposed (Stainforth, 2012) that secondary migration of petroleum mainly occurs as colloidal clusters in water in the metastable region between true solution and continuous separate phases. The governing law is Stokes' rather than Darcy's, and the controlling viscosity is that of the pore water rather than the petroleum. As a result, the mechanism works equally well for all petroleum mixtures from the heaviest to the lightest and is generally much faster than Darcy flow of a separate phase. So long as the clusters are smaller than the pore throat size, there is no capillary resistance. At any one time, the volume fraction of petroleum in the pore water in the secondary migration pathways is very small (0.001 or less), and the losses of petroleum are negligible. Another enormous advantage of the mechanism is its ability to self-adjust the flux rates over at least six orders of magnitude, which is required by the focusing of flow in secondary migration systems.

In this paper, I combine drainage area analysis with fractal stream laws to compute petroleum mass fluxes in different parts of a secondary migration system. This allows the sizes of the petroleum clusters, and thus the minimum pore throat sizes in the carrier beds, to be computed. These pore throats sizes are translated into Darcy permeabilities for reference purposes, even though the controlling flow law is not Darcy. The mechanism points to the lithological and diagenetic limits for adequate carrier beds in secondary migration systems.

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SECONDARY MIGRATION BY STOKESIAN FLOW OF METASTABLE CLUSTERS & MICRODROPLETS OF PETROLEUM IN WATER

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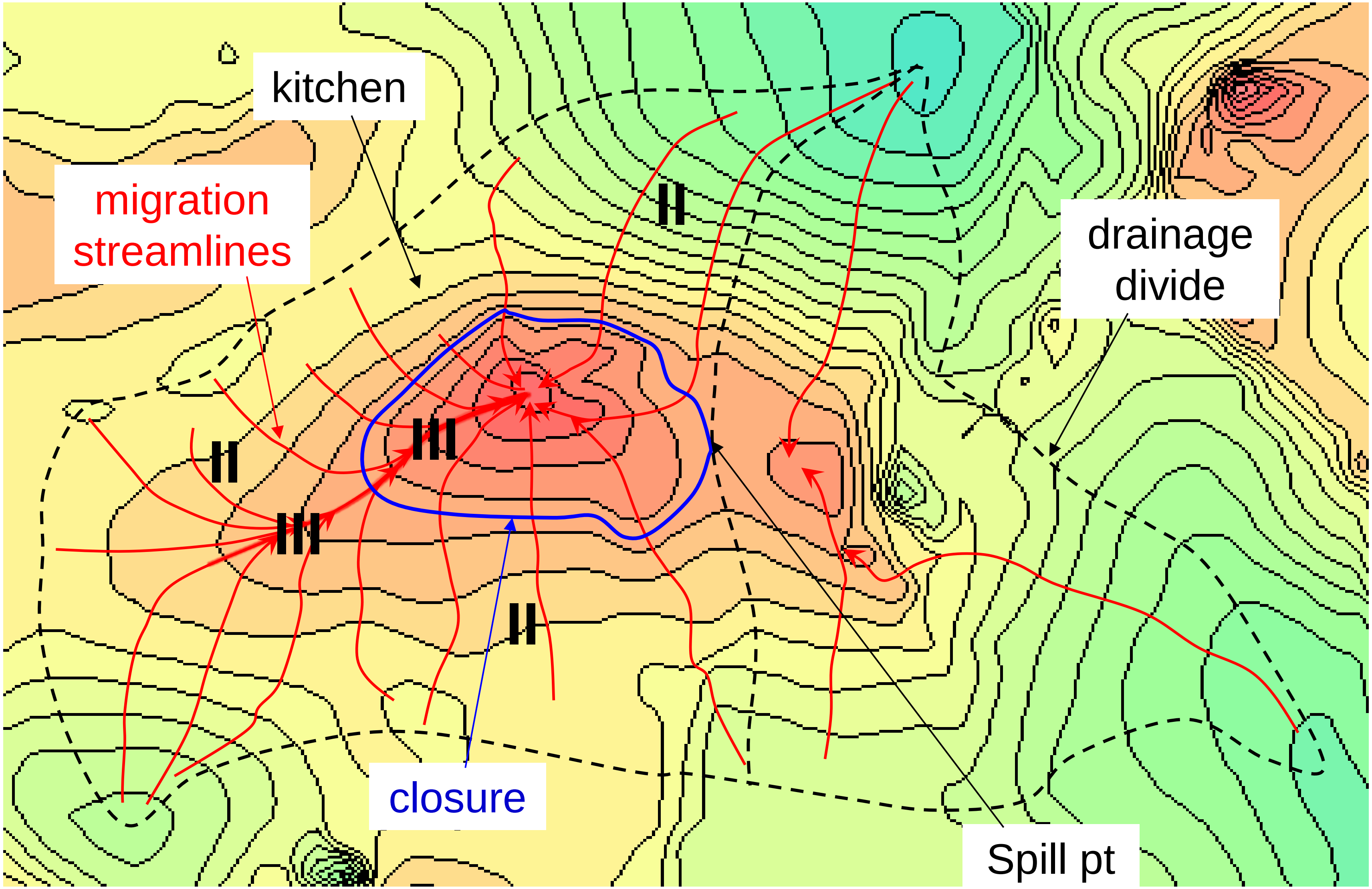
INTRODUCTION

- **Problems with the industry-favored hypothesis**:
  - Continuous phase or 2-phase Darcy flow with capillary entry pressures
- **Conceptual model of proposed alternative hypothesis**
  - Tracing petroleum molecules from source to trap
- **Preliminary numerical model**
  - Not very precise but "roughly right rather than precisely wrong"
  - Certainly good within an order-of-magnitude
  - Shows the strength of the hypothesis

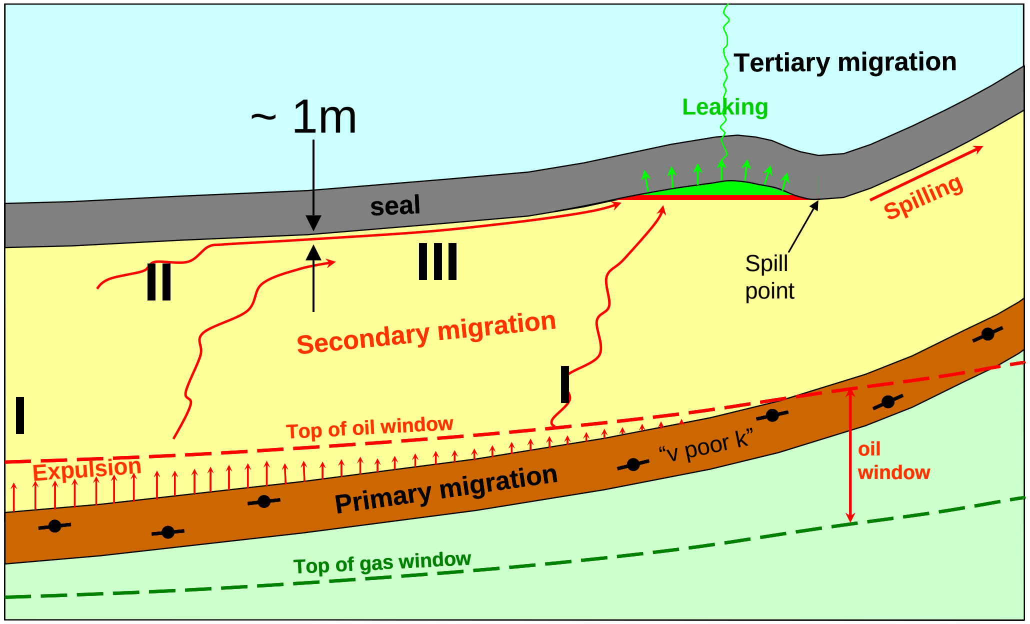
CURIOUS FEATURES OF SECONDARY MIGRATION

- **Petroleum "shows" in carrier beds are very minor**
  - Only ubiquitous HCs are those in pore water in true or colloidal solution
- **Works well with a wide range of carrier properties**
  - Carrier beds either "work" or "not work", as long as ~ 1mD or better
- **Works well for all petroleum types**
  - Gas, oil, light, heavy, low and high viscosity
- **Secondary migration is very efficient…**
- **… and not (usually) the rate-limiting step of migration**
  - That is petroleum generation & primary migration in the source rock
- **Petroleum systems are driven by very low expulsion flux rates**
  - Peak rates ~ 100 kg/m^2/My ~ 0.1 m^3/m^2/My ~ 1 nm/day
- **3D focusing of flow is very significant**
  - Lateral focusing into anticlines and structural noses
- **Secondary migration fluxes are highly variable**
  - Focussing must increase fluxes by orders of magnitude
- **T & P vary very gradually**
  - ~ 1 nC/day & ~ 10 nbar/day: extremely well controlled "lab"

FOCUSING INTO ANTICLINAL NOSES WITH ENORMOUS INCREASE IN FLUXES



FOCUSING ⇒ WIDE RANGE OF MIGRATION FLUXES



Flux has to increase ~ 6 to 7 orders

⇑

X-sectional area ⊥ To flow varies ~ 6, 7 orders

~ 10^8 m²

~ 10^4 m²

~ 10 - 100 m²

- **STAGE I: vertical cross-stratal migration**
  - Across carrier bed to top seal (only for expulsion↑): v slow
- **STAGE II: lateral drainage beneath a top-seal**
  - Over entire area with active SR's
  - Focusing into rivulets and streams
- **STAGE III: highly focused lateral flow in "streams" & "rivers"**
  - Focusing into 1 or 2 major "rivers"
- **Analogous to (1) rainfall, (2) run-off, & (3) stream flow in hydrology**

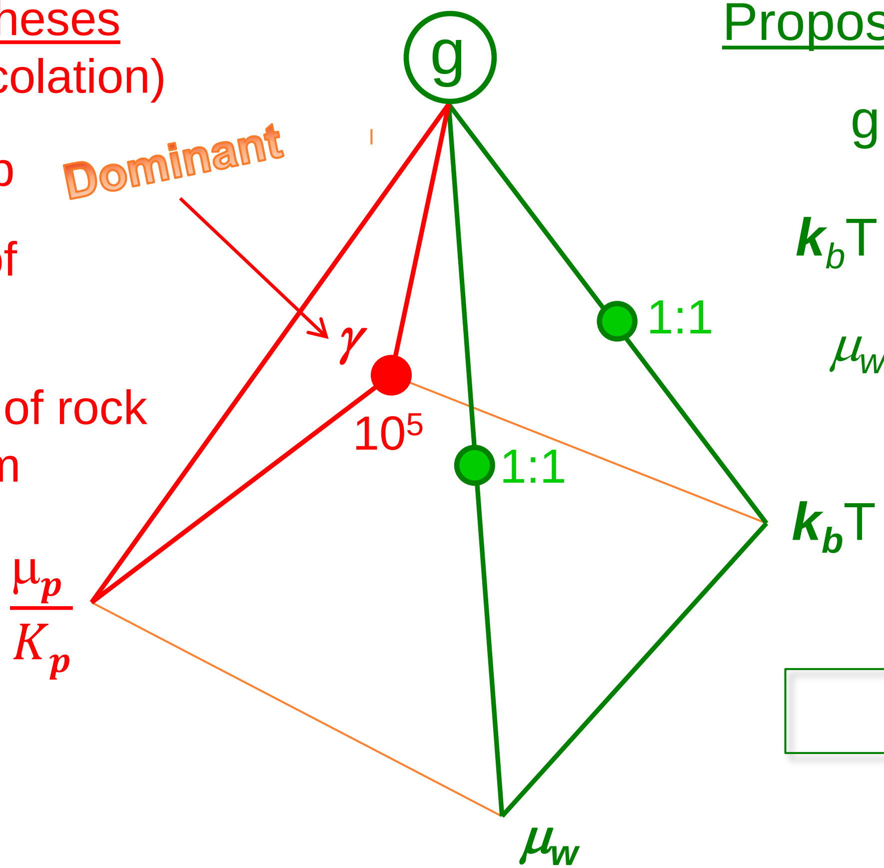
SECONDARY MIGRATION IS DRIVEN BY GRAVITY: BUT WHICH FORCES DOMINATE?

Popular hypotheses
(Darcy flow, percolation)

γ = cap entry p

μ_p = viscosity of *petroleum*

K_p = permeability of rock to petroleum



Proposed mechanism

g = gravity **Unavoidable**

k_bT = thermal **Unavoidable**

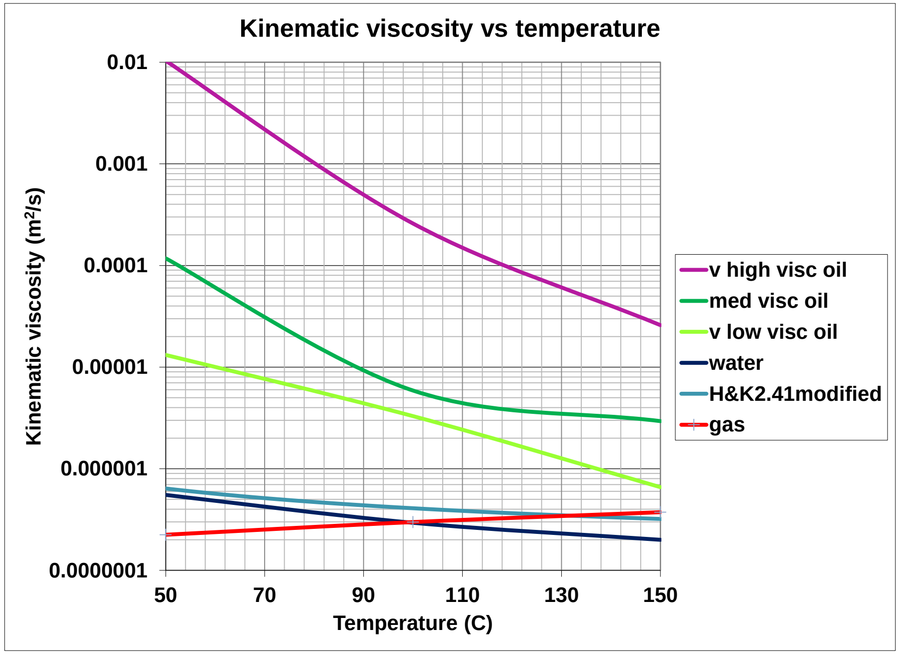
μ_w = viscosity of *water*

…utterly different

- **Popular hypotheses: capillary pressures are dominant**
  - BUT cap pressures, *petroleum* viscosity and rock permeability are ***all avoidable***!
- **Proposed hypothesis built around unavoidable forces**
  - Gravity (PE) in precise balance with viscous drag of *water* and with thermal energy

PROBLEMS WITH DARCY FLOW MECHANISM FOR SECONDARY MIGRATION

- **How can different petroleum types migrate with similar ease with Darcy flow?**
  - Petroleum viscosities vary by 5 orders
  - Petroleum viscosity generally >> water viscosity



Darcy flux

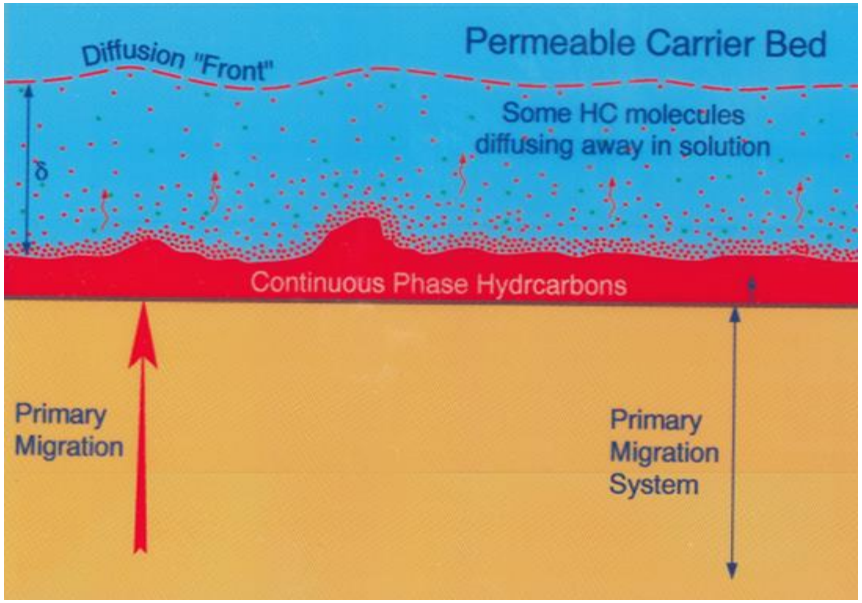
$$J_d = \frac{k_p}{\mu_p} g \Delta \rho$$

- **Why don't we see influence of carrier bed permeability**
  - Carrier bed permeability *k* varies by > 6 orders!
  - SM should be v sluggish(!) for viscous petroleum, particularly in poor carriers
- **Yet SM works equally well for all petroleum and carrier bed types**

PROBLEMS WITH DARCY FLOW MECHANISM FOR SECONDARY MIGRATION

- **How can Darcy flow rates increase by orders of magnitude to cope with focussing of flow?**
  - Darcy *fluxes* ~ fixed by the petroleum viscosities & rock permeabilities
  - ⇒ Darcy *flow rates* can only be increased by increasing the X-sectional area of the flow, i.e., by increasing the thickness of the migrating petroleum slugs

- **Why do we never see petroleum stringers or slugs?**
  - Requires buoyancy > capillary entry pressures
  - Continuous phase petroleum waiting to take off – NEVER seen!



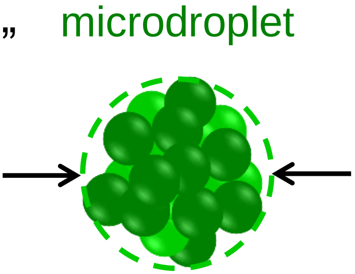
MIGRATION OF PETROLEUM IN COLLOIDAL DISPERSIONS (EMULSIONS) OF MICRODROPLETS

Emulsions: microdroplets of petroleum in water

- Parks (1924) microdroplets
- Meinschein (1959): droplets or emulsions
- Baker (1962): two sizes of micelles ~ 6 and 500 nm
- Welte (1965): "colloidally dispersed; later…emulsion-like form"
- Peake and Hodgson (1966, 1967) colloidal "accommodations" of n-alkanes in water ~ 3 to 4 orders > true solubilities

Today's hypothesis more specific and detailed

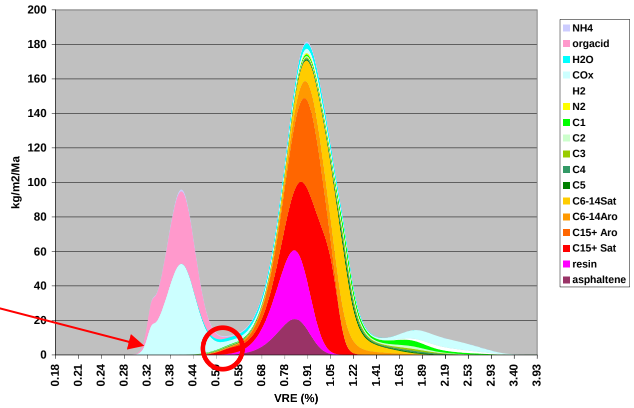
- migration of petroleum molecules in "clusters"/"microdroplets"
- roughly spherical ~ 10 nm →10 μm in diameter
- Many new aspects



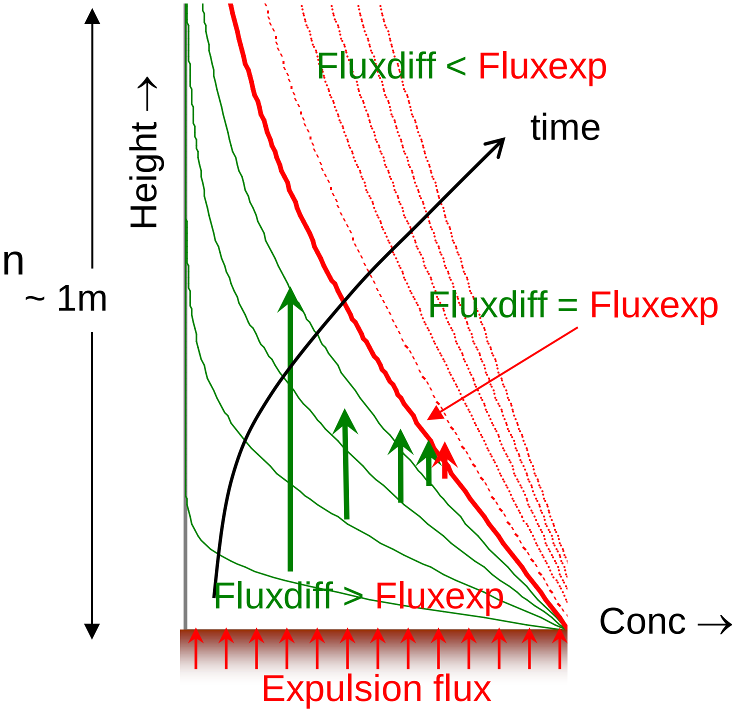
Diameter 10's nm → 10's μm

SECONDARY MIGRATION THOUGHT EXPERIMENT: INITIAL "GESTATION" PERIOD

- Initially petroleum expulsion fluxes are extremely low << 1 kg/m²/my
  - Initially petroleum passes directly into water solution at $10^{-6} \rightarrow 10^{-5}$ part per volume or mass
  - ⇒ NO continuous phase ever forms



- Transient "gestation" period
  - At first, diffusive flux faster than expulsion flux
  - But after a short gestation period (~ 100 y), diffusion can not keep up with expulsion flux



STOKESIAN RISE OF METASTABLE CLUSTERS OF MOLECULES OR MICRODROPLETS

- **Pore-water becomes saturated/supersaturated with petroleum**
  - Causes petroleum molecules to exsolve…
  - ... & form meta-stable clusters/microdroplets ~ 1 - 100 nm

- **Buoyant rise of clusters**
  - buoyancy balanced by viscous drag

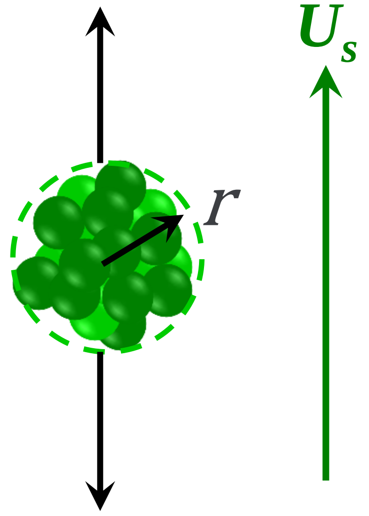
$$\boxed{U_s = \frac{2r^2}{9\mu_w}\Delta\rho g = \frac{d^2}{18\nu_w}\frac{\Delta\rho}{\rho}g}$$

Stoke's law

  - inertia is negligible cf viscosity (*Re* < 10^{-6})

- **Stokesian velocity**
  - ✓ $\propto$ **radius *r*²** or **diameter *d*²**, i.e. strong size dependence
  - ✓ $\propto$ 1/**viscosity of *water* (μ_w)** <u>not</u> petroleum
  - × Does <u>not</u> depend on rock **permeability**
  - × <u>No</u> **capillary entry pressure** if droplet size < pore throat

$$F_{buoy} = \frac{\pi}{6}d^3\Delta\rho g$$



$$F_{drag} = 3\pi d\mu_w U_s$$

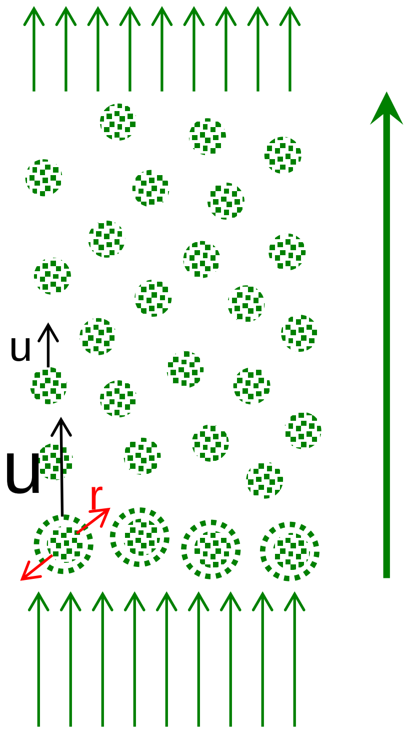
SECONDARY MIGRATION - STAGE I: X-STRATAL MIGRATION of CLUSTERS/MICRODROPLETS

- **Cluster sizes ∝ supersaturation of petroleum in water**
  - If petroleum influx > efflux anywhere in migration pathways
    - supersaturation increases…
    - … microdroplets to increase in size…
    - … increase in vertical speed
    - until petroleum fluxes are balancec
    - and v.v.

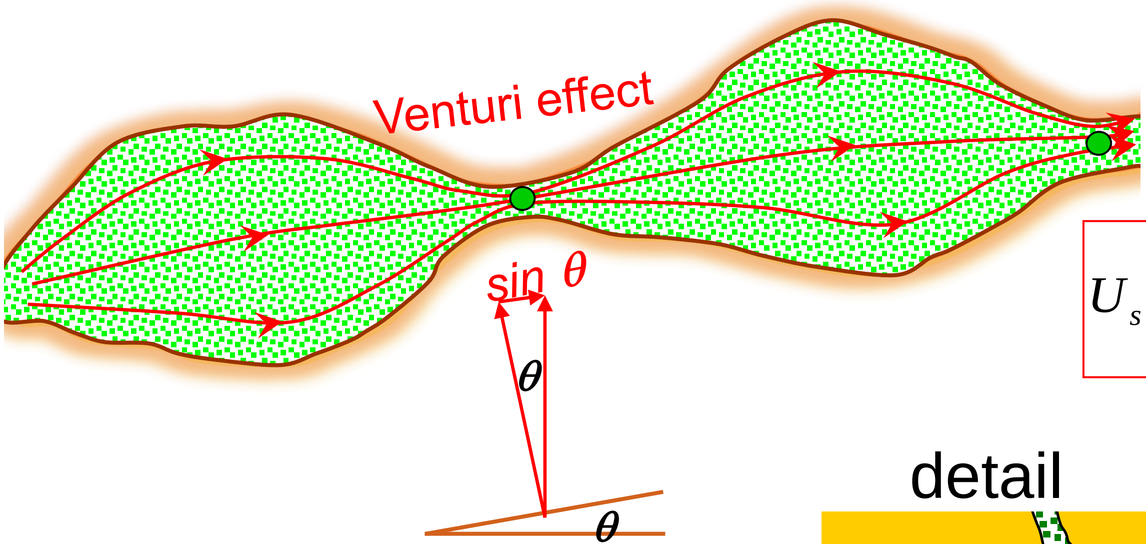
⇒ **Flow rate of clusters/microdroplets is self-adjusting**

- Mass flow rate is balanced everywhere in the secondary migration system …
- … to match the rates of petroleum expulsion integrated over the whole SR kitchen area

$$U_s \propto \frac{r^2}{\mu_w} g \Delta \rho$$



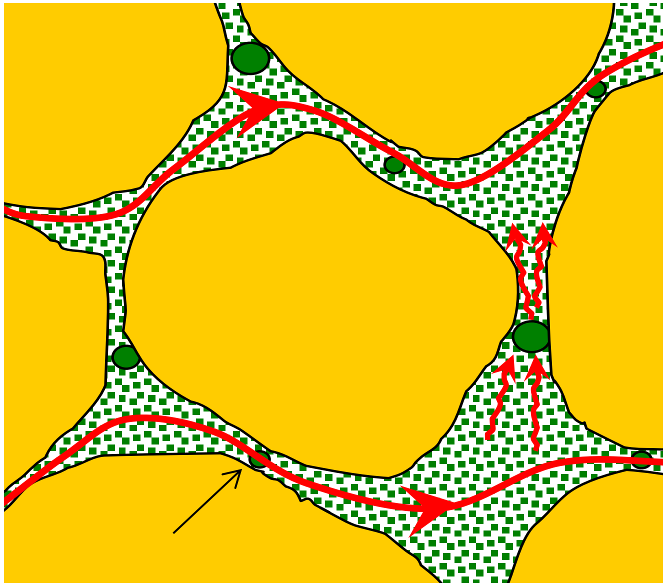
LATERAL MIGRATION OF MICRODROPLETS BENEATH DIPPING TOP SEAL



$$U_s \propto \frac{r^2}{\mu_w} g\Delta\rho \sin\theta$$

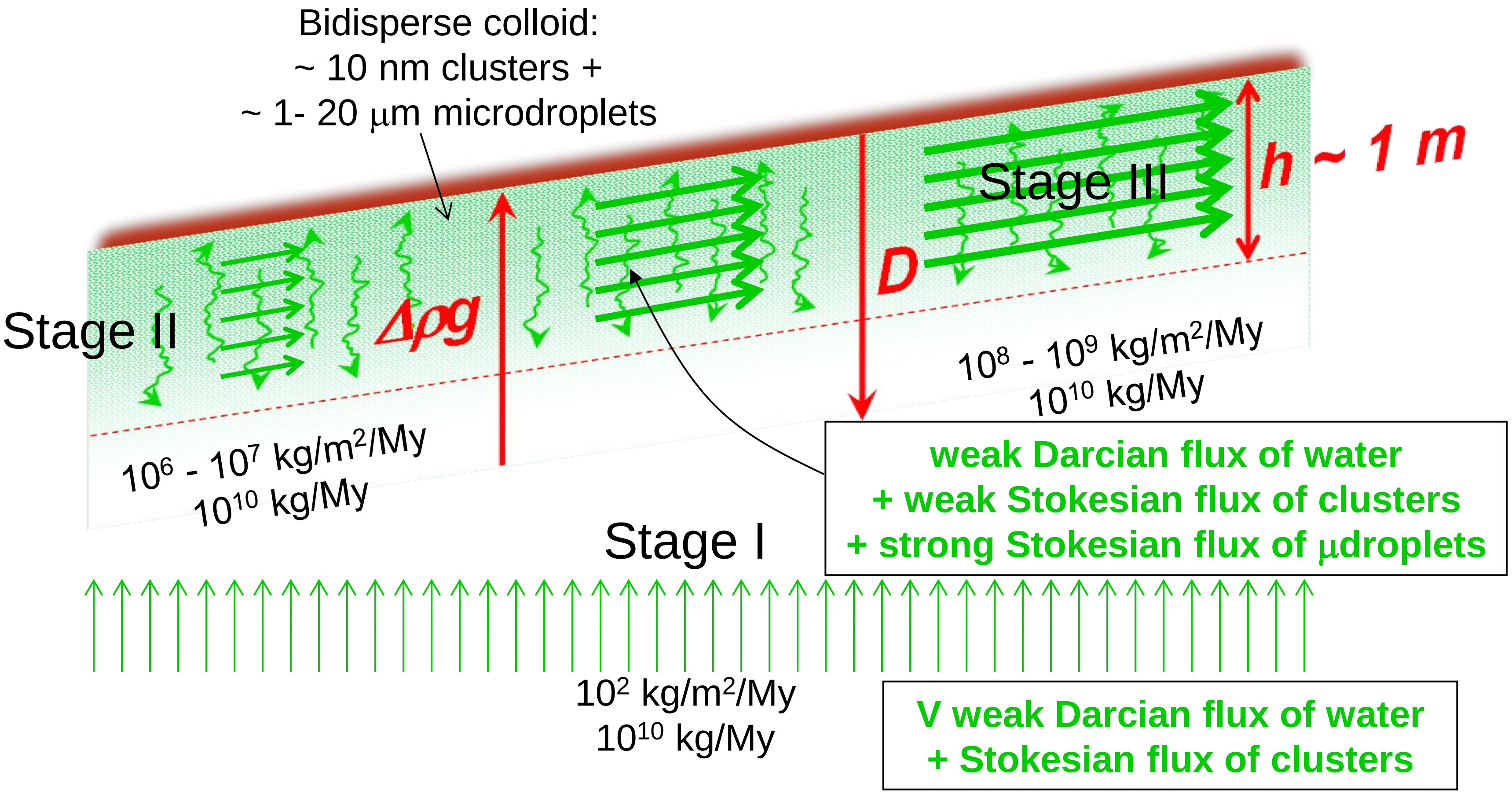
- <u>Preferential lateral pathways</u>
  - Microdroplet size relates to porethroat size
  - Flow is heterogeneous and anisotropic
  - Faster laterally than vertically
- <u>Trapping</u>
  - No lateral flux
  - μdroplets coalesce
  - Buoyancy > cap pressures etc

detail



STEADY STATE PETROLEUM MIGRATION RATE (kg/y) ⇒INCREASING MIGRATION FLUXES (kg/m^2/y)

- **Equilibrium between vertical & lateral fluxes**
- **Fluxes increase orders of magnitude during lateral migration**



Bidisperse colloid:
~ 10 nm clusters +
~ 1- 20 μm microdroplets

Stage III

10^8 - 10^9 kg/m^2/My
10^{10} kg/My

Stage II

10^6 - 10^7 kg/m^2/My
10^{10} kg/My

weak Darcian flux of water
+ weak Stokesian flux of clusters
+ strong Stokesian flux of μdroplets

Stage I

10^2 kg/m^2/My
10^{10} kg/My

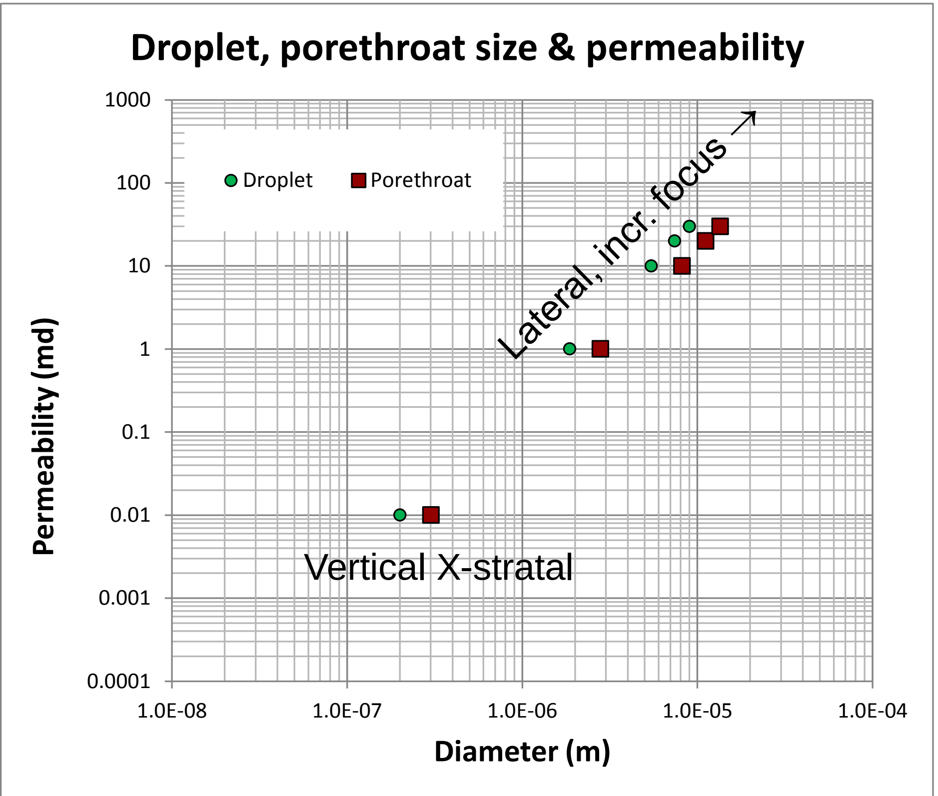
V weak Darcian flux of water
+ Stokesian flux of clusters

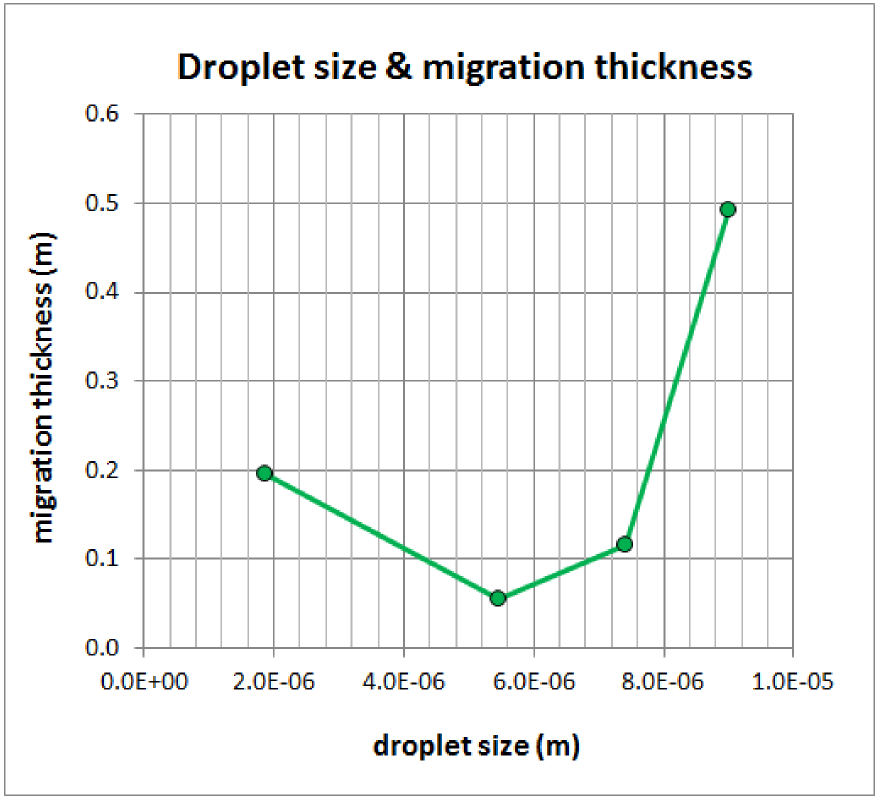
SIMPLE NUMERICAL MODEL

- **Input parameters: first case**
  - Drainage area: 100 km^2, hemispherical geometry, top seal dips < 6° to 0°
  - Carrier beds:
    - thickness 10 m (for X-stratal migration)
    - Choose permeabilities from μD → 10’s mD
    - Aspect ratio of pores (pore size/throat size) ~ 5 → 10
    - Minimum pore throat size = 1.5 x microdroplet size
    - ~ 1 microdroplet/pore at any one time ⇒ vol/vol petroleum in pores ~ $10^{-5} \rightarrow 10^{-3}$
  - Burial rate: 100 m/My, heat flow 50 mW/m^2
  - Source rock: SPI 10 tonne HC/m^2 → ~ 3 10^9 bbl over 30 My
    - peak expulsion flux ~ 60 kg/m^2/My, API 35, GOR ~ 0.1,

DROPLET SIZES & THICKNESS OF THE ZONE OF LATERAL MIGRATION TOP SEAL

- **Input**
  - Permeabilities e.g. 1, 10, 20, 30 mD
- **Output**
  - Microdroplet size: ~ 200 nm for X-stratal migration, 2 → 10 μm for lateral migration
  - Thickness of migration zone to keep up with expulsion fluxes: 10’s cm → 0.5 m

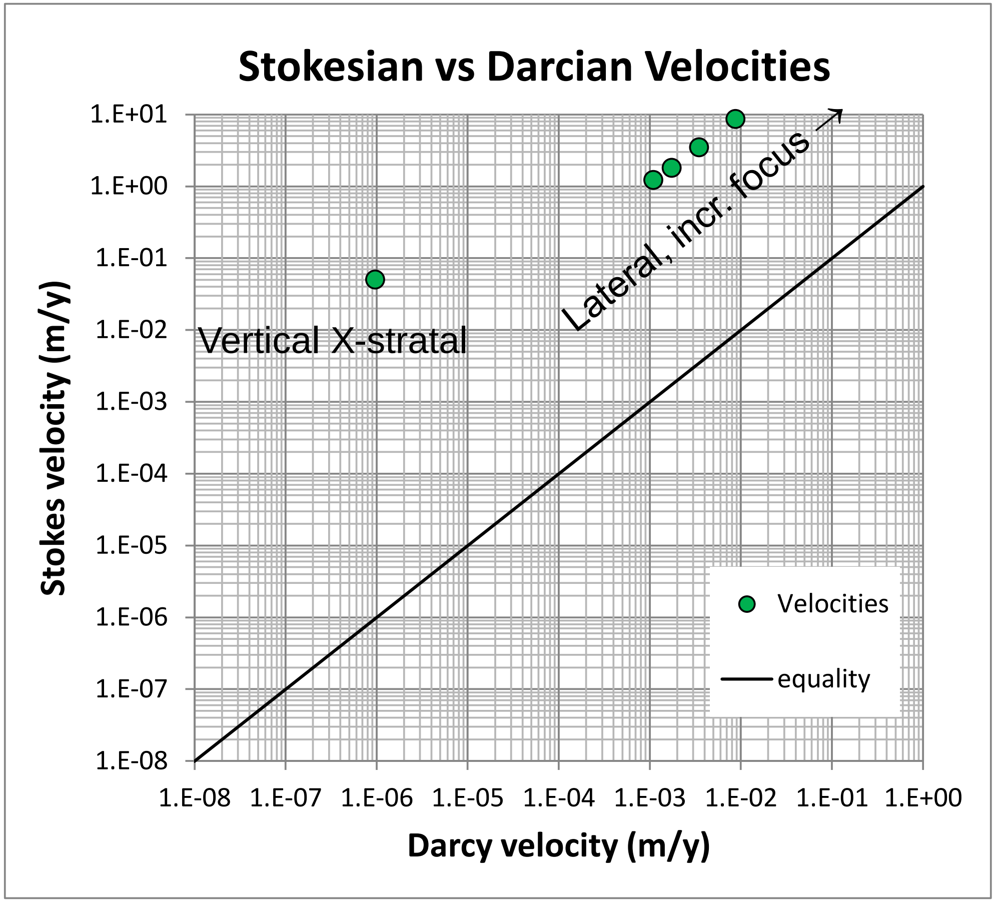




MIGRATION VELOCITIES: STOKESIAN VS DARCY FLOW

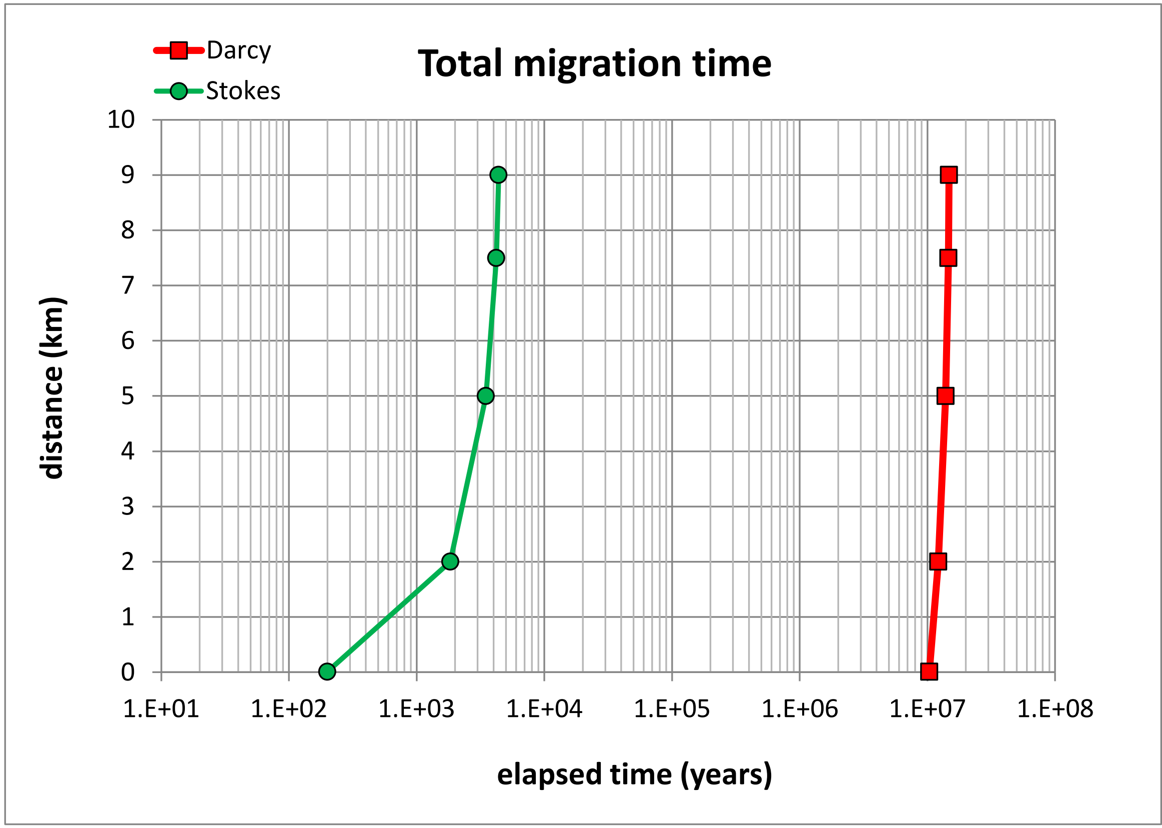
- **Migration velocities**
  - Stokesian velocities of microdroplets are ~ 3 → 5 orders faster than Darcy velocities of slugs

- **Because of**
  - Lack of hindrance by rock grains
  - Stokesian drag is caused by the (low) viscosity of water
  - Cf Darcy drag is caused by much higher viscosity of petroleum



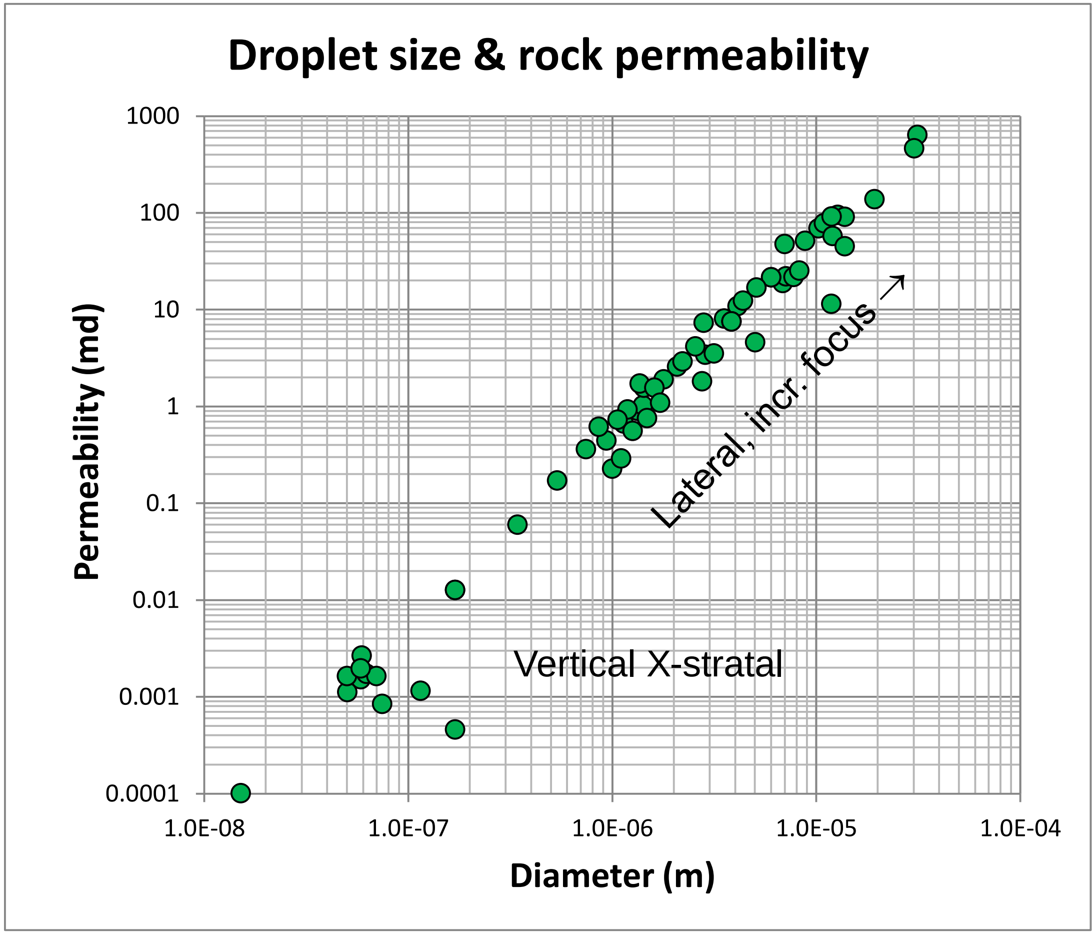
TOTAL MIGRATION TIMES: STOKESIAN VS DARCY FLOW

- **Stokesian droplet flow**
  - X-stratal migration ~ 200 y
  - Total migration ~ 4000 y
- **Darcy slug flow**
  - X-stratal migration ~ 10 My
  - Total migration ~ 15 My
  - Duration of main phase petroleum generation~ 30 My
- **Darcy much slower**
  - V slow for X-stratal migration
  - Even with this 35 API gravity oil with moderate viscosity
  - Hopeless with heavy viscous oil: 100’s My!



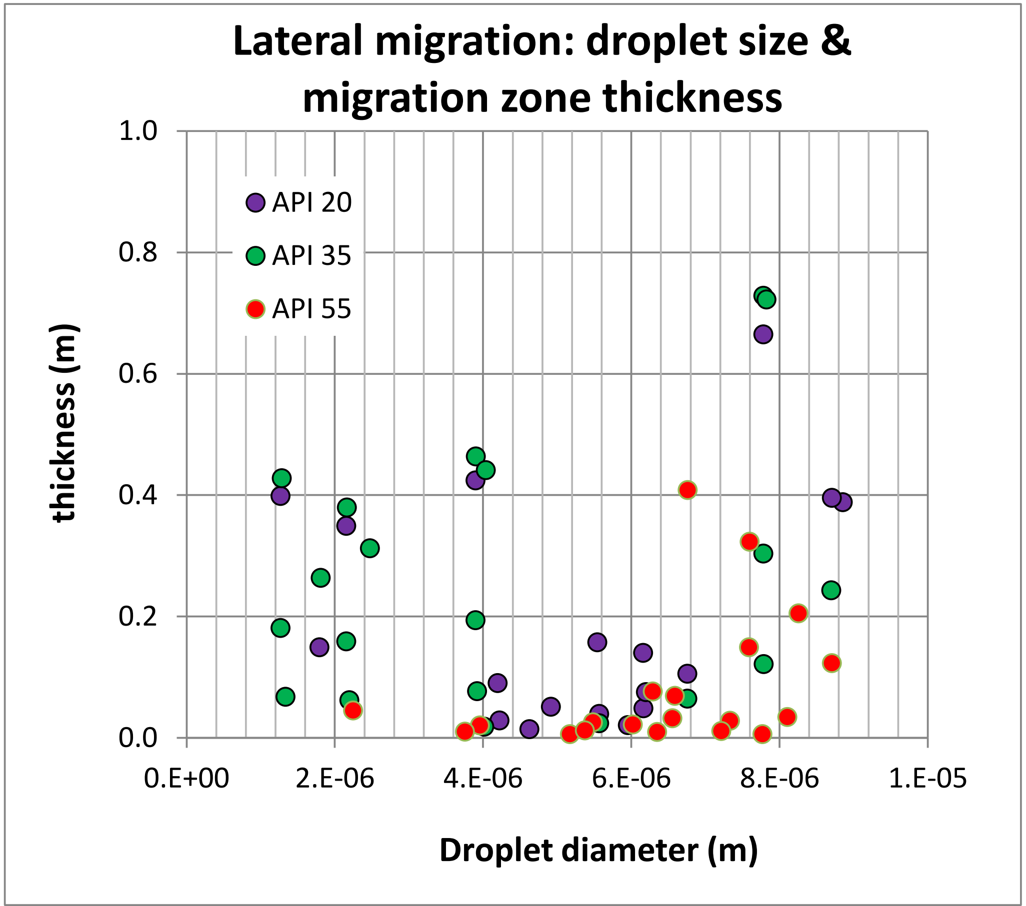
MICRODROPLET SIZES FOR GIVEN PERMEABILITIES OF CARRIER BEDS (MULTIPLE CASES)

- **Vary all input parameters**
  - Carrier bed permeabilities
  - Drainage area size, shape
  - SR type & quality
  - Oil from 15 → 60 API gravity
  - Viscosities 0.1 → 100 cP
  - GOR 0.01 → 10 kg/kg
- **Predicted droplet sizes**
  - X-stratal mig ~ 10's → 100's nm
  - Lateral mig ~ 100's nm → 10's μm



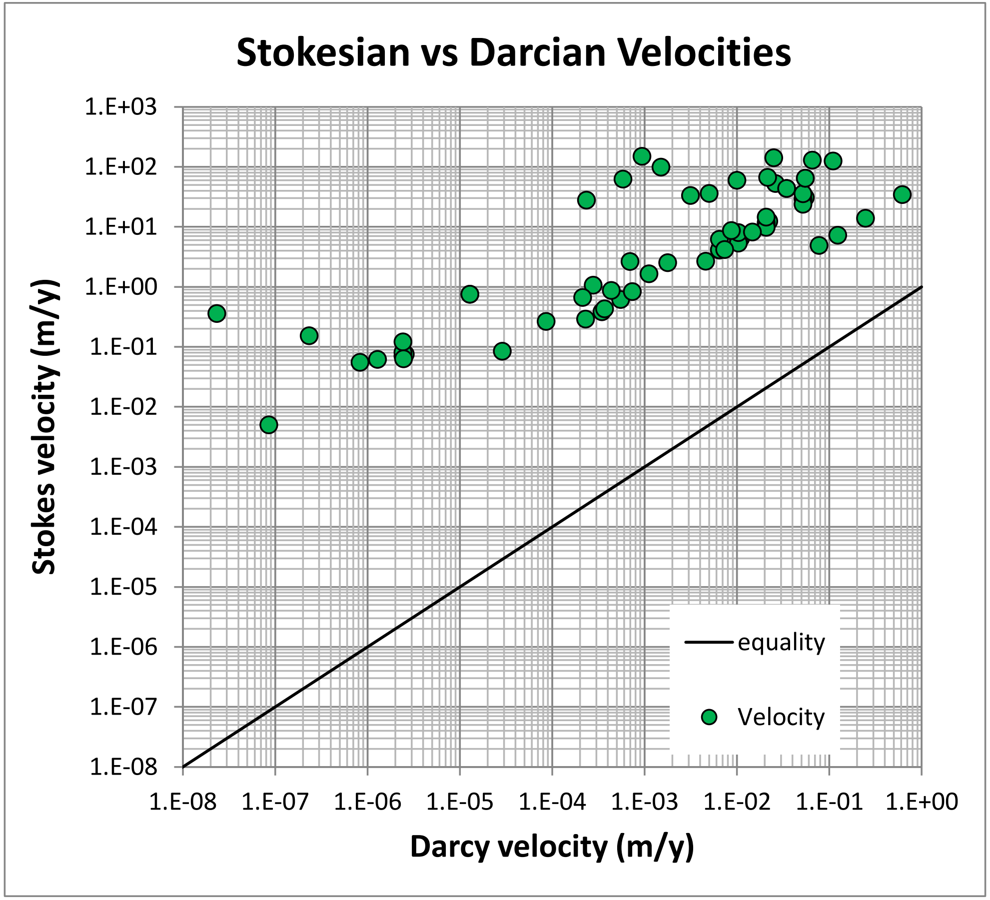
AND THICKNESSES OF LATERAL MIGRATION ZONE BENEATH TOP SEAL (MULTIPLE CASES)

- **Output**
  - Droplet diameters 1 → 10 μm,
  - Thickness of lateral migration zone < 1m (mainly cm's → 10's cm)



MIGRATION VELOCITIES: STOKESIAN VS DARCY MODELS

- **Stokesian velocity of microdroplets 2 to 5 orders > Darcy slugs**
  - cm/yr → 100’s m/y



- **Proposed mechanism is highly effective & plausible**

PRINCIPLES OF LEAST ENERGY DISSIPATION & MAXIMUM RATE OF HEAT DISSIPATION

Principle of least energy dissipation

- Viscous dissipation (heat) = $E = F_d L = 3\pi d \eta_w U_s L$
- Creeping Stokesian flow is a minimum dissipation flow
- Equations for dissipation are v complicated, <u>but</u> total dissipation equals…

….PE lost in migrating petroleum of mass *m*, density contrast $\Delta\rho$, through height *h*

$$PE = F_b h = mg \frac{\Delta\rho}{\rho} h$$

- No particular size of droplet is favored wrt dissipation

Principle of maximum rate of energy dissipation (entropy production)

- Rate of energy dissipation dE/dt = drag force x velocity

$$dE/dt = F_d U_s = fU_s^2 = 3\pi d \eta_w U_s^2$$

- This is also equal to buoyant force x velocity, which = rate of loss of PE

$$dE/dt = F_b U_s = mg \frac{\Delta\rho}{\rho} U_s = d(PE)/dt$$

- Analogous to electrical power dissipation = $VI = RI^2$
- Highest possible flow rates (low viscosity of water) → maximum dE/dt

IMPLICATIONS

- **Secondary migration of petroleum occurs mainly in microdroplets**
  - as a colloidal dispersion/emulsion of petroleum μdroplets in pore water
- **Dispersion/emulsion is dynamically metastable**
  - NO emulsifiers required
  - Droplet sizes in equilibrium with petroleum fluxes & expulsion rates
- **The velocities of microdroplets are self-adjusting**
  - Focusing of secondary migration increases fluxes by ~ 6 orders
  - Achieved by changing droplet sizes ~ 3 orders
  - Generally much faster than Darcy flow of continuous phase “slugs”
- **Works similarly for all petroleum types regardless of their viscosity**
  - Flow rates are controlled by the viscosity of *water,* which is low & ~ constant
  - NOT by the highly variable and greater viscosity of petroleum
- **Carrier beds either “work” or “not work”: cut-off is pore-size constraint**
  - NO effect of permeability of carrier beds
  - NO capillary entry pressures
- **Volume fraction petroleum in migration pathways is low ($<10^{-4} – 10^{-2}$)**
  - Very little petroleum in pathways
  - Secondary migration by this mechanism is extremely efficient (> 99.99%)
- **Least energy dissipation & maximum rate of dissipation principles**
  - All PE of migrating petroleum is dissipated as heat at maximum possible rate

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