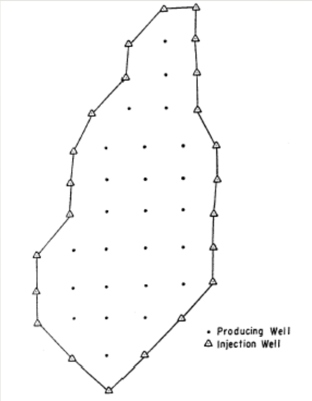
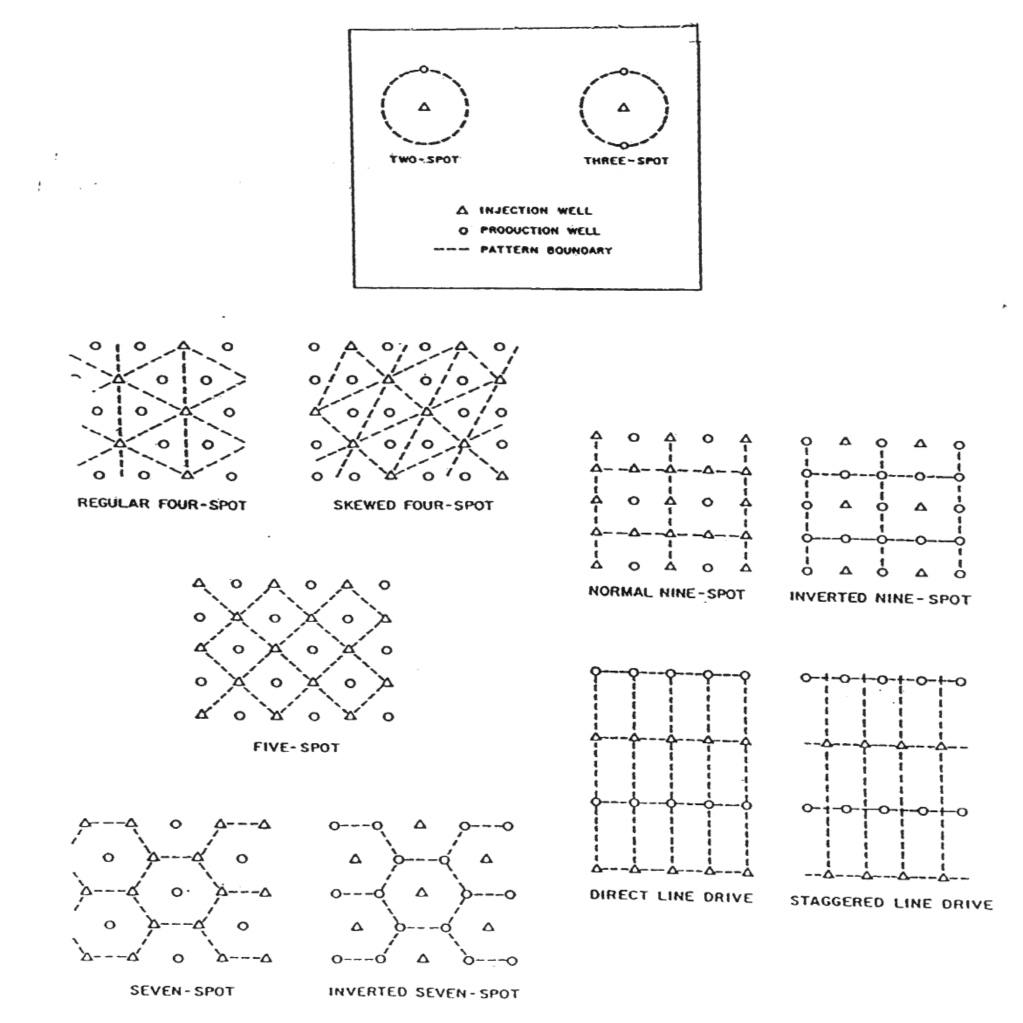
# LECTURE 13-14
# INTEGRATED WATERFLOOD

*PATTERN SELECTION & WELL SPACING*

# PATTERN SELECTION - IMPACTS

- Sweep efficiency
- Injectivity
- Flexibility to modify
- Regulators





TWO-SPOT
THREE-SPOT
INJECTION WELL
PRODUCTION WELL
PATTERN BOUNDARY
REGULAR FOUR-SPOT
SKEWED FOUR-SPOT
NORMAL NINE-SPOT
INVERTED NINE-SPOT
FIVE-SPOT
DIRECT LINE DRIVE
STAGGERED LINE DRIVE
SEVEN-SPOT
INVERTED SEVEN-SPOT

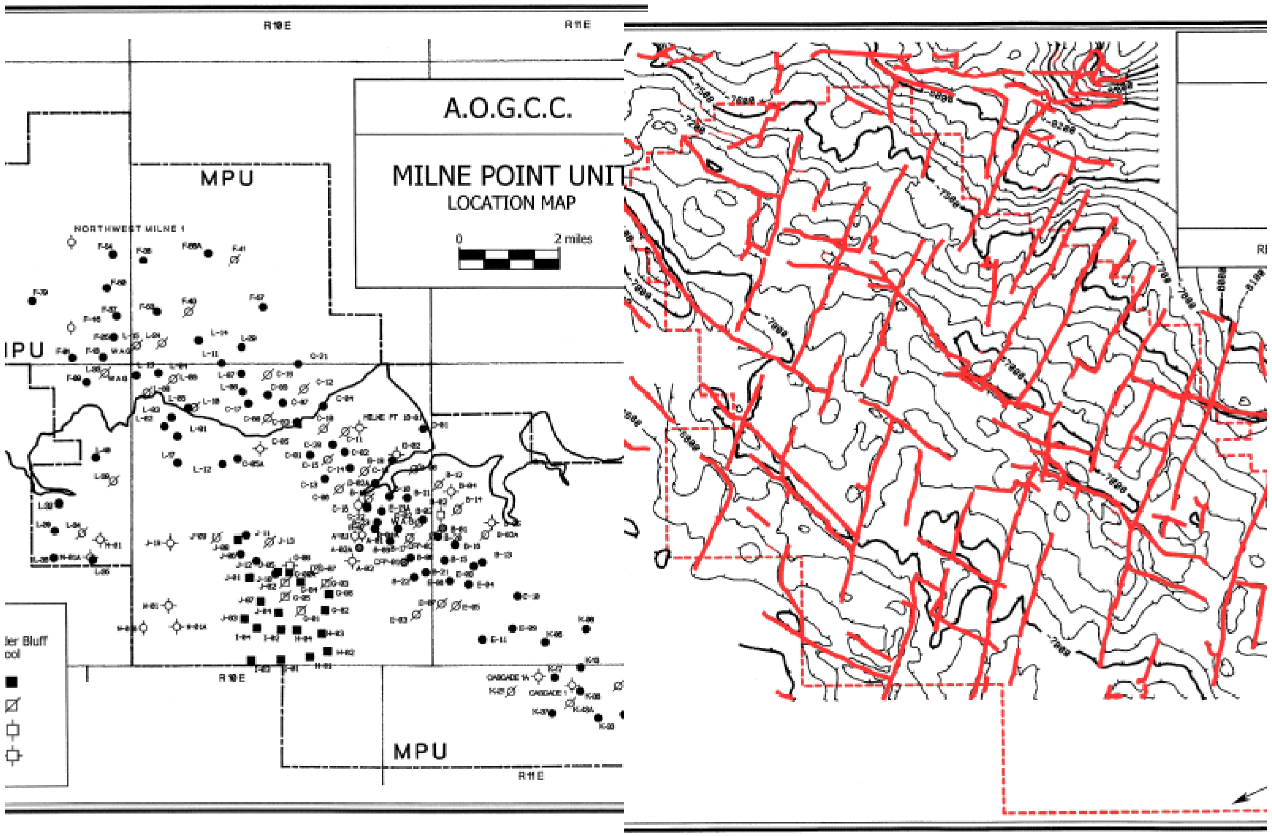
# PATTERN SELECTION – PERIPHERAL

- Injectors placed to supplement aquifer
- consider rock property variations near OWC
- Best when vertical communication and/or dip is high (gravity stable)
- Common for Shell offshore Gulf of Mexico
- Aquifer influx models
- Schilthuis - 1936 (steady-state)
- van Everdingen & Hurst - 1949 (un-steady-state)
- Carter-Tracy - 1960 (un-steady-state)
- Fetkovitch – 1971 (pseudo-steady-state)
- neglects the transient period
- popular
- fairly accurate
- Coats, Allard & Chen for bottom-water drive
- see Chapter 8 Craft, Hawkins & Terry for example calculations
- Strongly consider using numerical simulation

# PATTERN SELECTION – PATTERN

- Lack of natural water drive
- Low dip
- Implies some degree of control
- Simple analytical models are available
  - various mobility ratios and well skins
  - simplifying assumptions
  - restricted on range of sensitivities
- Example of non-repeating patterns
  - Milne Point Field

# PATTERNS - MILNE POINT FIELD (KUPARUK A-SAND)



# PATTERN SELECTION – PATTERN (CONTINUED)

- Ensure reasonable hydraulic connectivity between the injector and producer
- Avoid short-circuits through fractures, thief zones and conductive faults
- Consider injector rows along axis of maximum horizontal stress
  - reduce short circuit via induced fractures
- Balance productivity & injectivity
- Additional considerations
  - fault/fractures
  - areal heterogeneity
  - reservoir anisotropy
  - mobility ratio (show streamlines)
  - pattern conversion flexibility needs
- SPE 75140 Producer to Injector Ratio by Hansen

# WELL SPACING

- Economics!
- Hydraulic connectivity
- Permeability (effective)
- Anisotropy
- Stimulation techniques
  - acid stimulations
  - fracturing
- Well design & trajectory

# WELL SPACING

- Injection above the fracturing gradient
  - increase water injectivity
  - reduce the number of injectors
  - monitor and control fracture growth
  - reduced sweep efficiency?
  - injection loss into non-target zones
  - proppant & proppantless injector fractures
  - thermal fracturing
  - many waterfloods operate under fracture conditions
- Recovery mechanisms
- Phased development with infill drilling

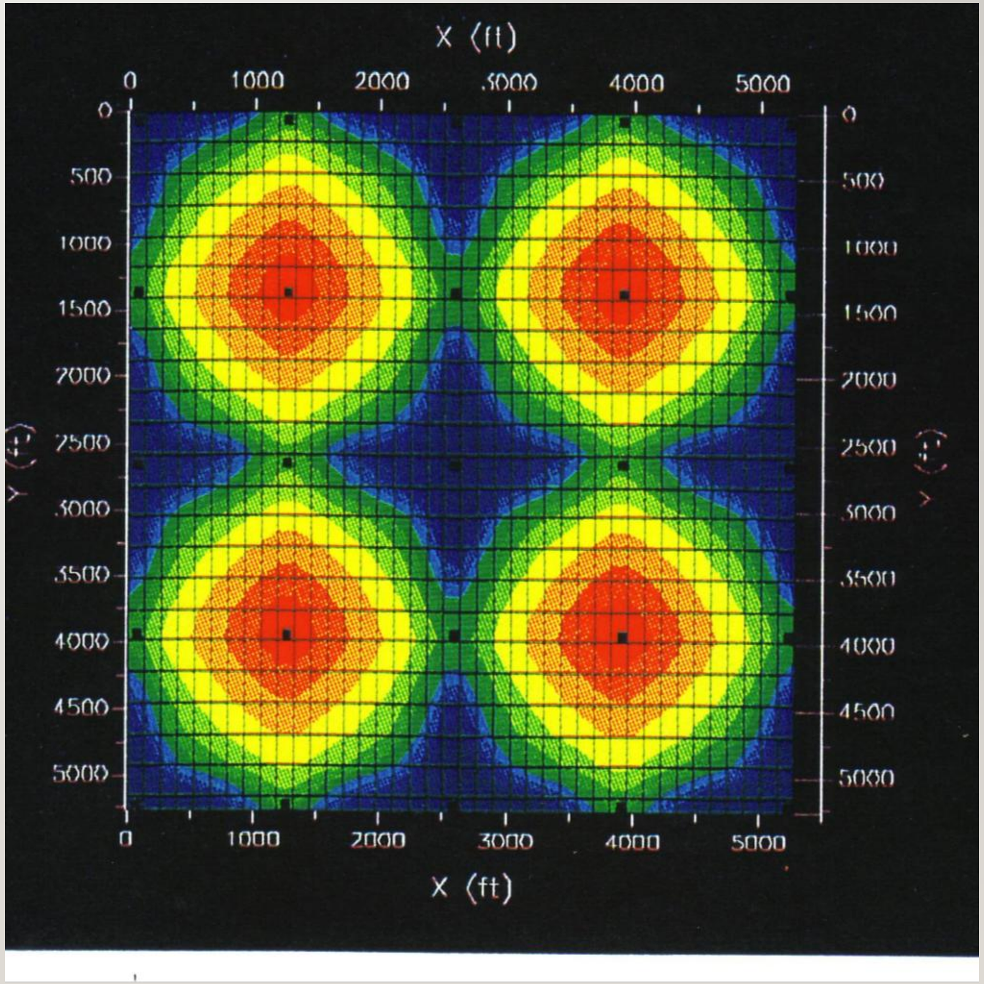
# WELL PATTERNS, SPACING, & SWEEP EFFICIENCY

- Injector & producer
  - shortest streamline
  - highest pressure gradient
  - breakthrough only a fraction of the area has been swept
  - analytical solution for unit mobility
  - physical experiment for non-unit mobility
  - numerical simulation
    - finite difference
    - finite element (streamline simulation)
    - generates recovery efficiency value
    - show example

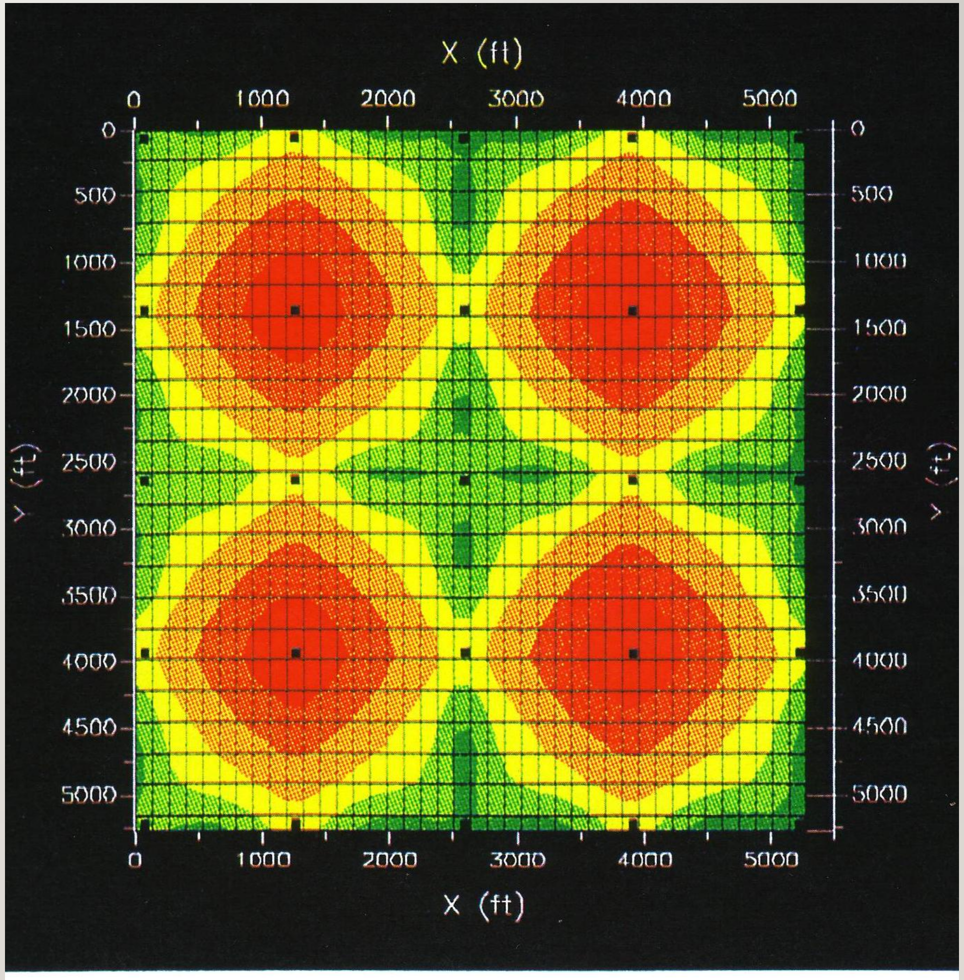
# WELL PATTERNS, SPACING, & SWEEP EFFICIENCY

- Depleted for 6 years, then waterflood for 44 more years
- Inverted 9-Spot (injector & 8-producers)
- Effect of areal heterogeneity
  - Case 1 – porosity (12%) and permeability (100 md.)
  - Case 2 – porosity and permeability vary randomly
- Water saturation plots
  - red for maximum
  - blue for minimum

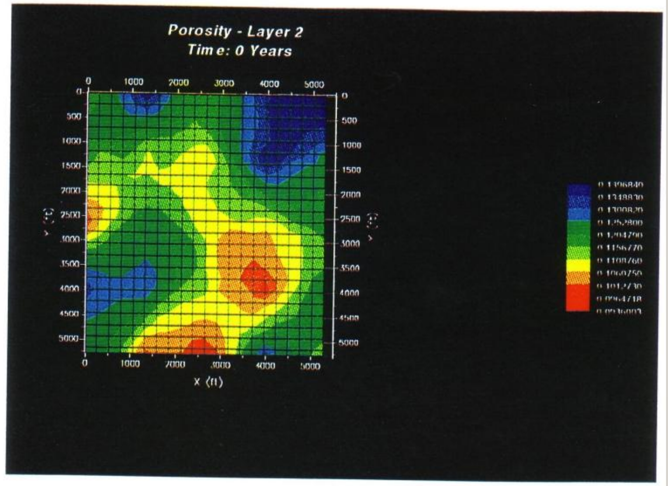
# 20 YEARS & CONSTANT PROPERTIES

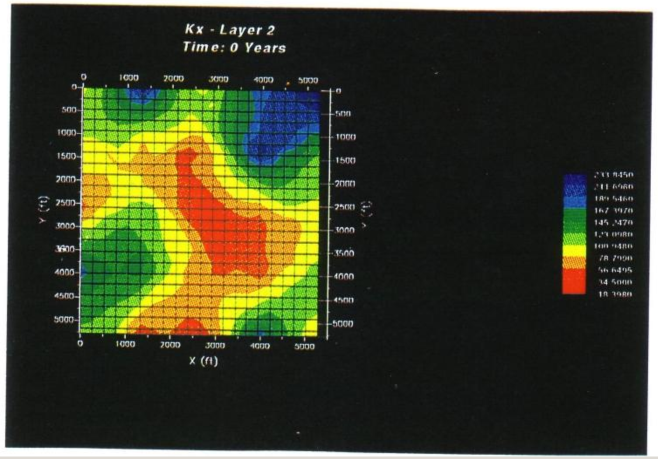


# 50 YEARS & CONSTANT PROPERTIES



# NON-CONSTANT PROPERTIES



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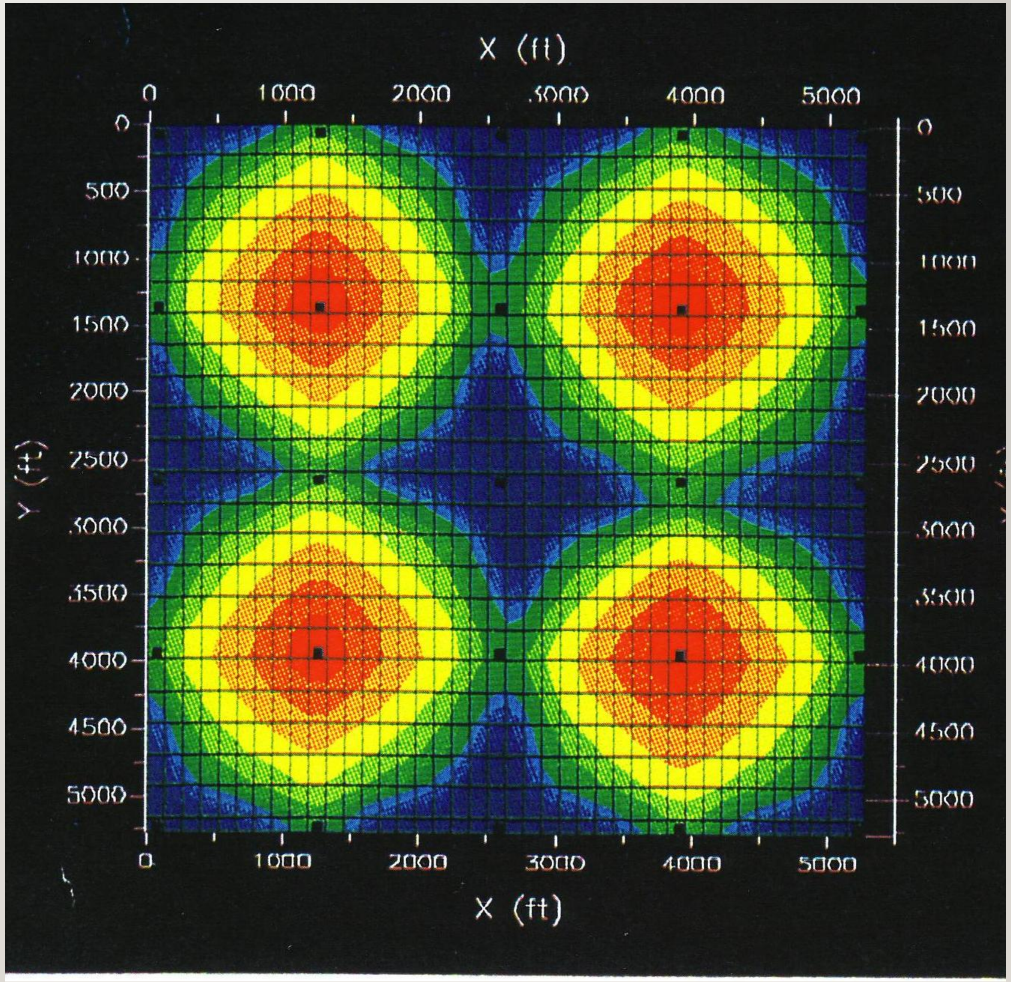

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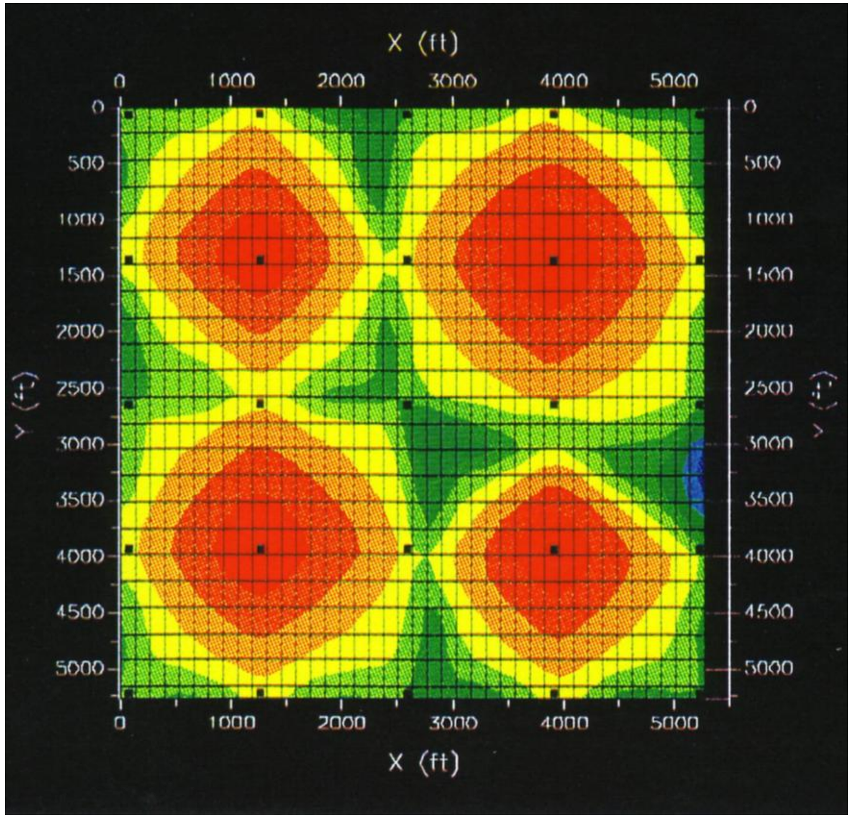


# WELL PATTERNS, SPACING, & SWEEP EFFICIENCY

- Simulation results quite idealized
- Heterogeneity in static properties still resulted in only slight skew in saturations
- Well operations were fixed
  - how realistic is this?
- History match model to account for differences
- Comfort in choosing new well locations?

# WELL PATTERNS – ADDITIONAL INFLUENCES

- Existing well stock
  - a sidetrack may also provide a additional capabilities
- Surface & subsurface topography
- Well types
  - vertical, high slant, horizontal, designer
- Reservoir characteristics
  - gas cap
- Boundary conditions
  - subsurface (GDWFI)
  - surface
- Influenced primary recovery performance
  - detection of faults/fractures

# INTEGRATED WATERFLOOD COURSE

- Analytical Performance Predictions

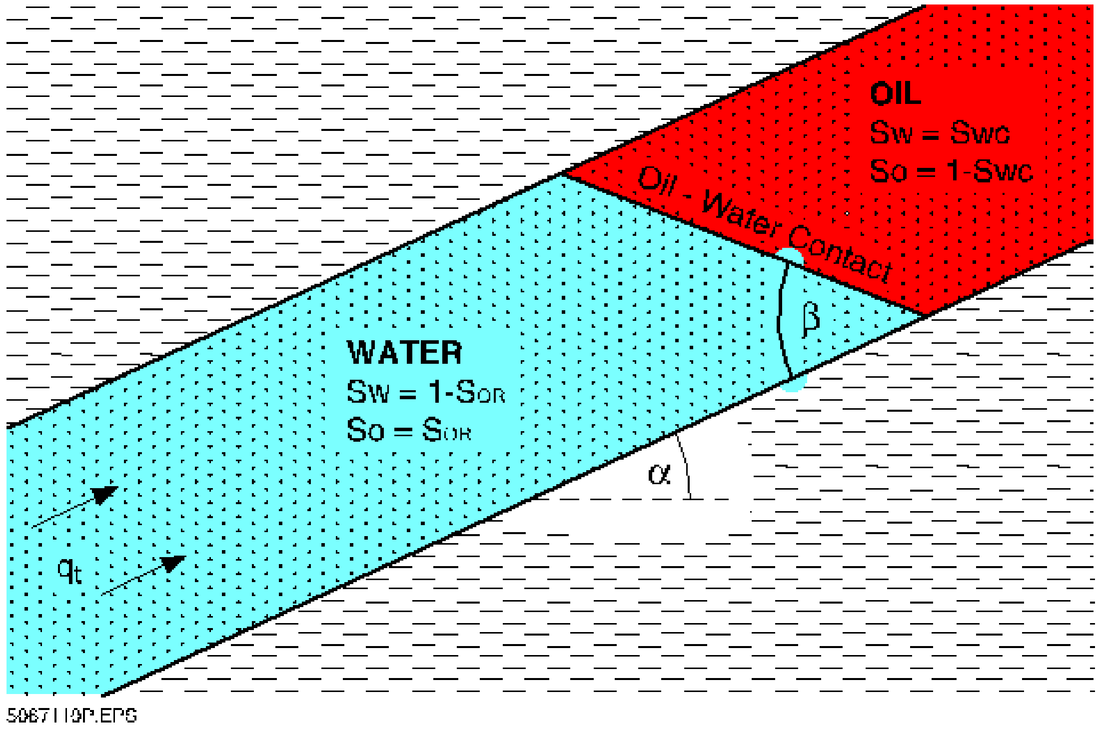
# WATERFLOODING – ANALYTICAL METHODS

- Buckley-Leverett Model
  - best suited for:
    - small-scale applications
    - moderately permeable
    - relatively light oil
    - reservoir layer is thinner than the capillary transition zone
    - flow instability due to viscous fingering is not present
  - key findings:
  - $S_{orw}$ impacts ultimate recovery
  - relative permeability curves shapes are important
  - oil-wet reservoir: more injection needed to achieve ultimate recovery
  - higher oil viscosity: higher the water cut at breakthrough and the slower the oil recovery
    - large amount of water recycling even in homogeneous reservoir

# WATERFLOODING – ANALYTICAL METHODS

- Dietz Model
  - Given small capillary pressures (e.g., high permeability sandstone) gravity segregates oil from injected water
  - formula for calculating the tilt angle of the displacement front relative to the bedding of the reservoir
  - a function of:
    - dimensionless gravity number
    - dip-angle
    - mobility ratio
  - calculates the critical injection rate above which injected water will under-run the oil and form a tongue
  - key finding: displacement is stable in a tilted reservoir when the mobility ratio is less than or equal to one

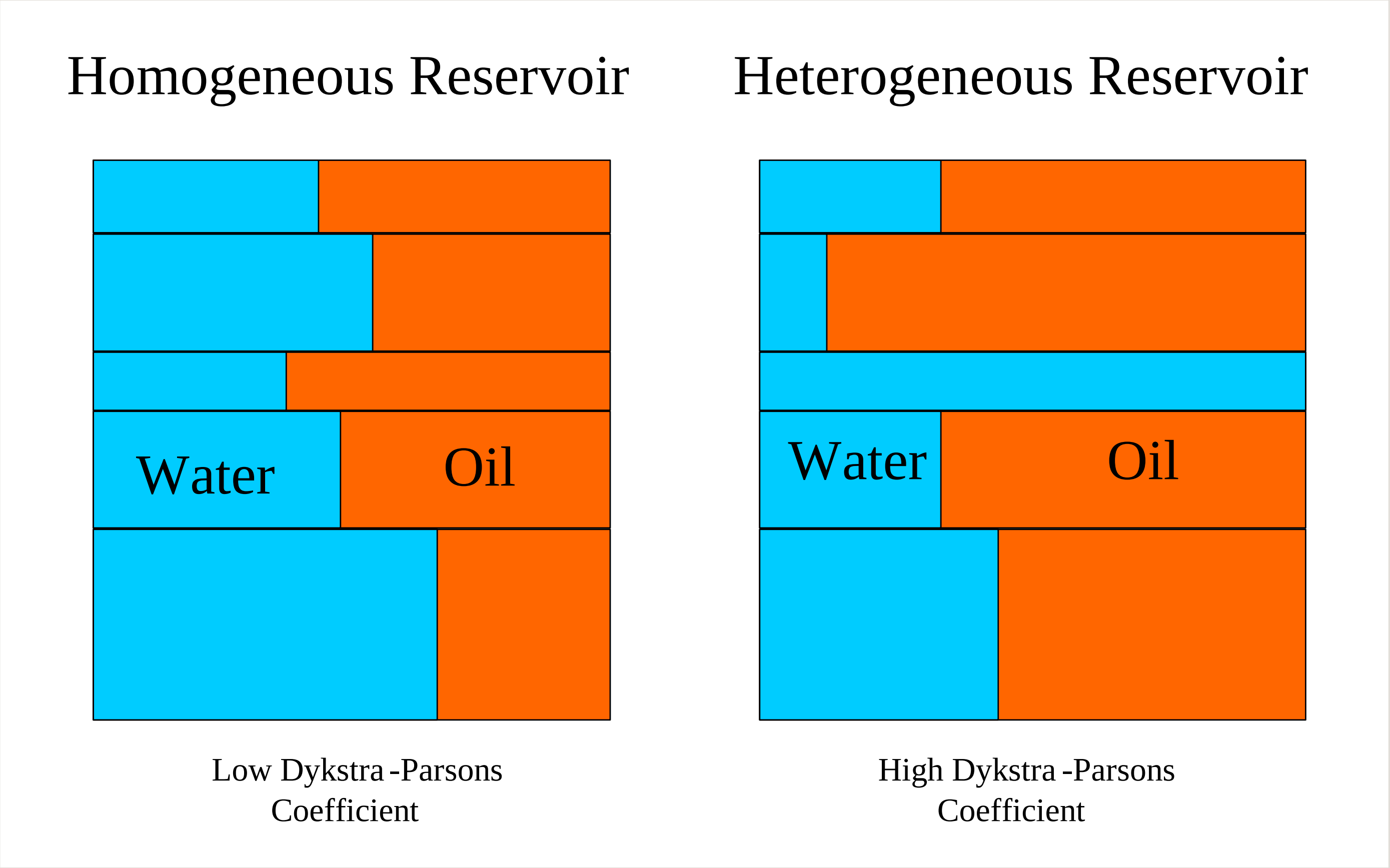
# WATERFLOODING – DIETZ MODEL



# WATERFLOODING – ANALYTICAL METHODS

- Stiles and Dykstra-Parsons Models
  - first generation analytical technique useful for forecasting waterflood recovery in a layered reservoir
  - piston-like displacement
  - non-communicating layers.
  - rarely used in their original forms
    - recent adaptation replaced linear flow by radial flow in a 5-spot
  - key findings:
    - sensitive to permeability contrast between layers
      - Dykstra-Parsons coefficient
      - Lorentz coefficient

# WATERFLOODING – STILES AND DYKSTRA-PARSONS



# WATERFLOODING – BUCKLEY-LEVERETT WITH GRAVITY

- Gravity along the bedding plane is considered
- Capillary pressure gradients in this direction are ignored
- Can be no saturation change over the height - the length of the capillary transition zone greatly exceeds the height of the formation
- Can be no "viscous fingering“
- Worked example in Shell Production Handbook Vol. 4

# WATERFLOODING – DIETZ W/ SATURATION TRANSITION

- Combines Dietz with Buckley-Leverett
- Calculates shape of the displacement front together with the saturation transition behind the front
- Unstable displacements do not always occur even if the endpoint mobility ratio is unfavorable
- When calculating conditions of stable displacement and displacement front angles, the validity of simple models such as Dietz should first be verified

# WATERFLOODING – STILES MODEL FOR 5-SPOT PATTERN

- Gardner's technique replaces the piston-like displacement of Stiles
- Radial frontal displacement in a pattern-flood situation
- Quick forecasts of oil recovery of a waterflood
- 5-spot pattern
- Uniform reservoir properties
- "Shell's Waterflood Spreadsheet"
- Variables:
  - Dykstra-Parsons coefficient
  - water-oil relative permeabilities
  - viscosities
  - initial gas saturation
- Shell Report EP 93-2361

# INTEGRATED WATERFLOOD COURSE

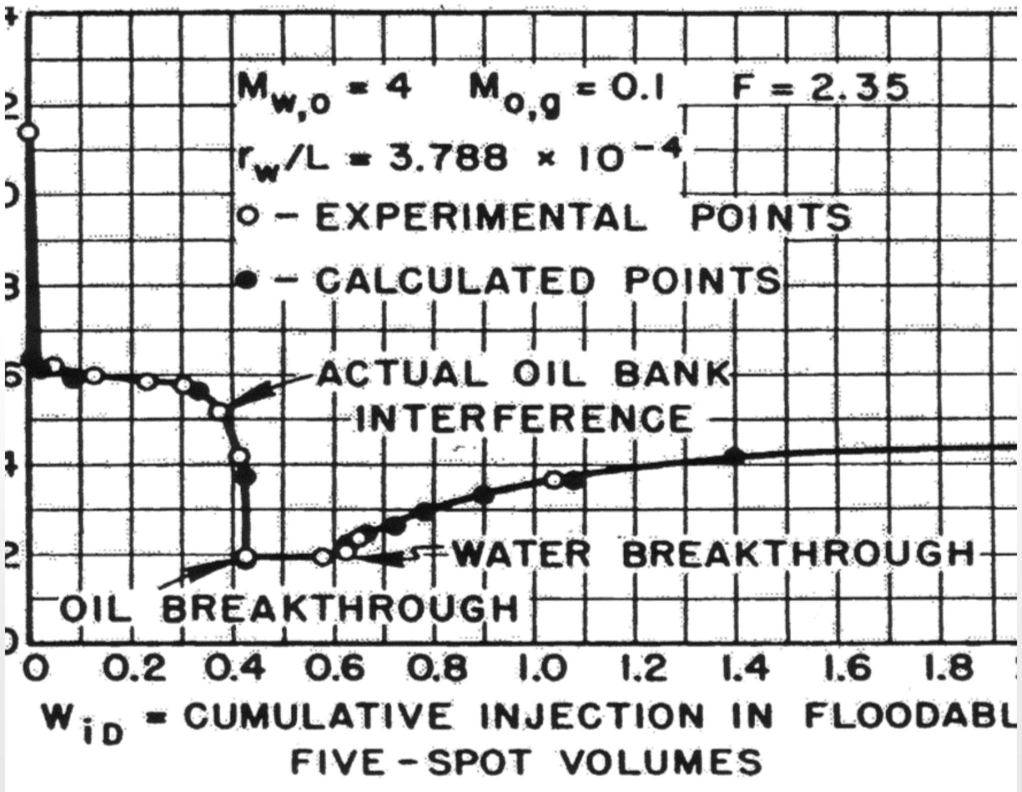
- Water Injectivity

# WATER INJECTIVITY

- Injectivity: injection rate per unit pressure drop
- Analogous to productivity index for a producer
- Function of:
  - permeability
  - thickness
  - skin
  - pattern geometry
- Assuming unit mobility ratio, injectivity is independent of:
  - sweep efficiency
  - time
- Assuming non-unit mobility ratios the injectivity changes as the displacement progresses:
  - improves if $M>1$
  - degrades if $M<1$

# WATER INJECTIVITY

- Theoretical change in injectivity M=4



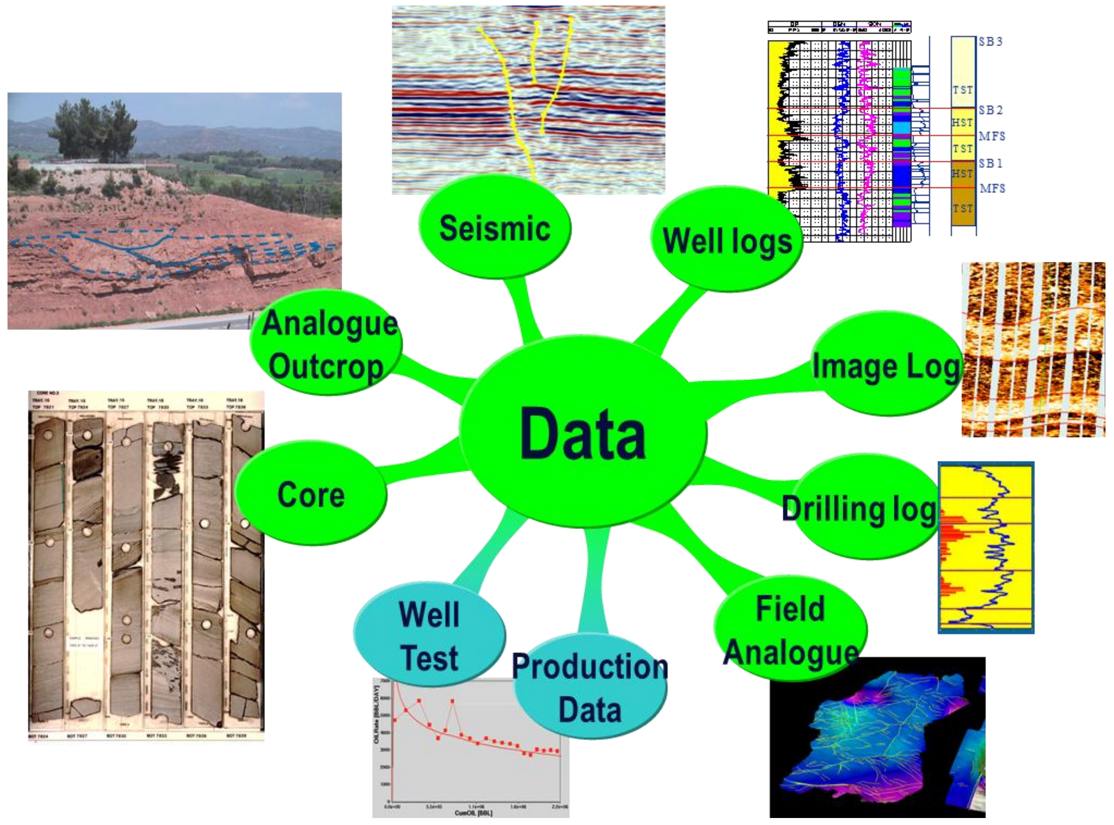
# WATER INJECTIVITY

- Analytical methods are over-simplified
- Severe limitations in their use
- Physical modelling would provide a more robust solution
- Analytical & physical models assume constant rock properties
- Fine-scale simulations
  - more complexities
  - variable properties
- History match field performance data

# INTEGRATED WATERFLOOD COURSE

- Integrated Reservoir Modeling

# INTEGRATED RESERVOIR MODELING



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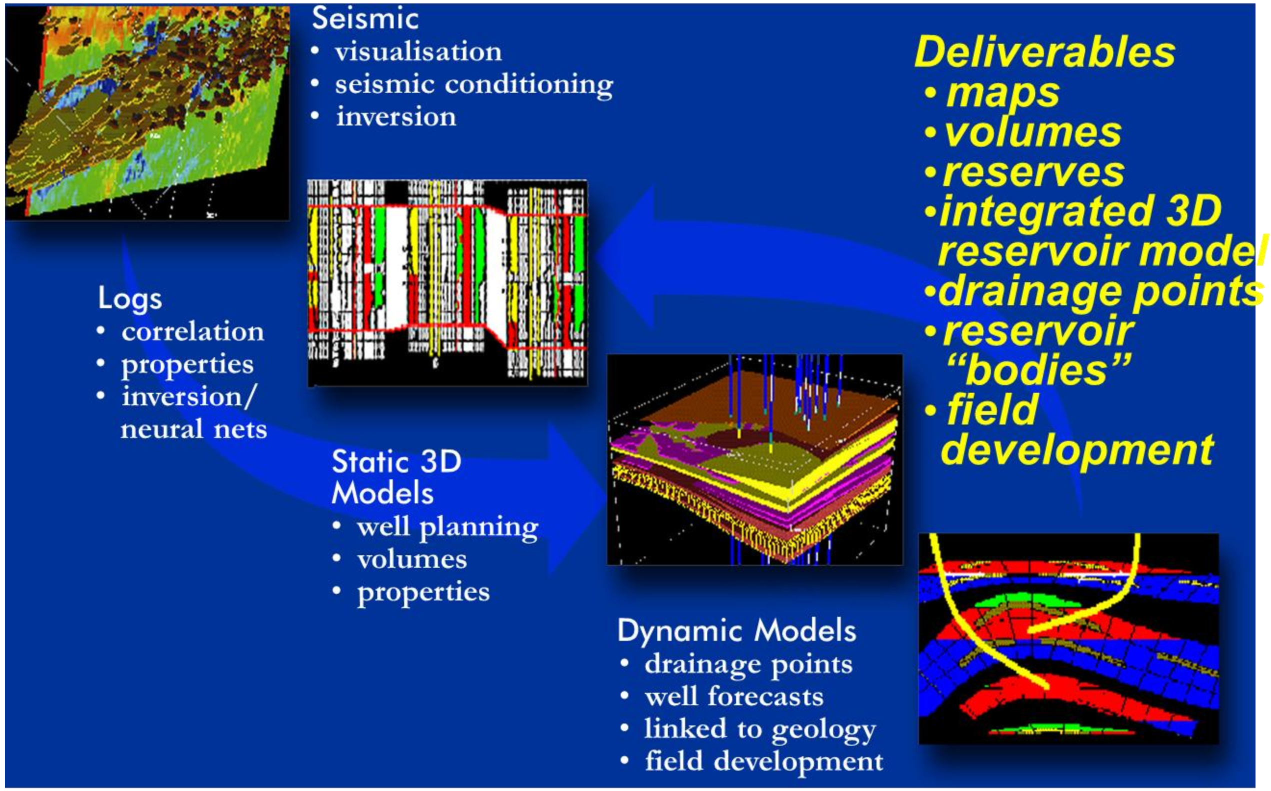

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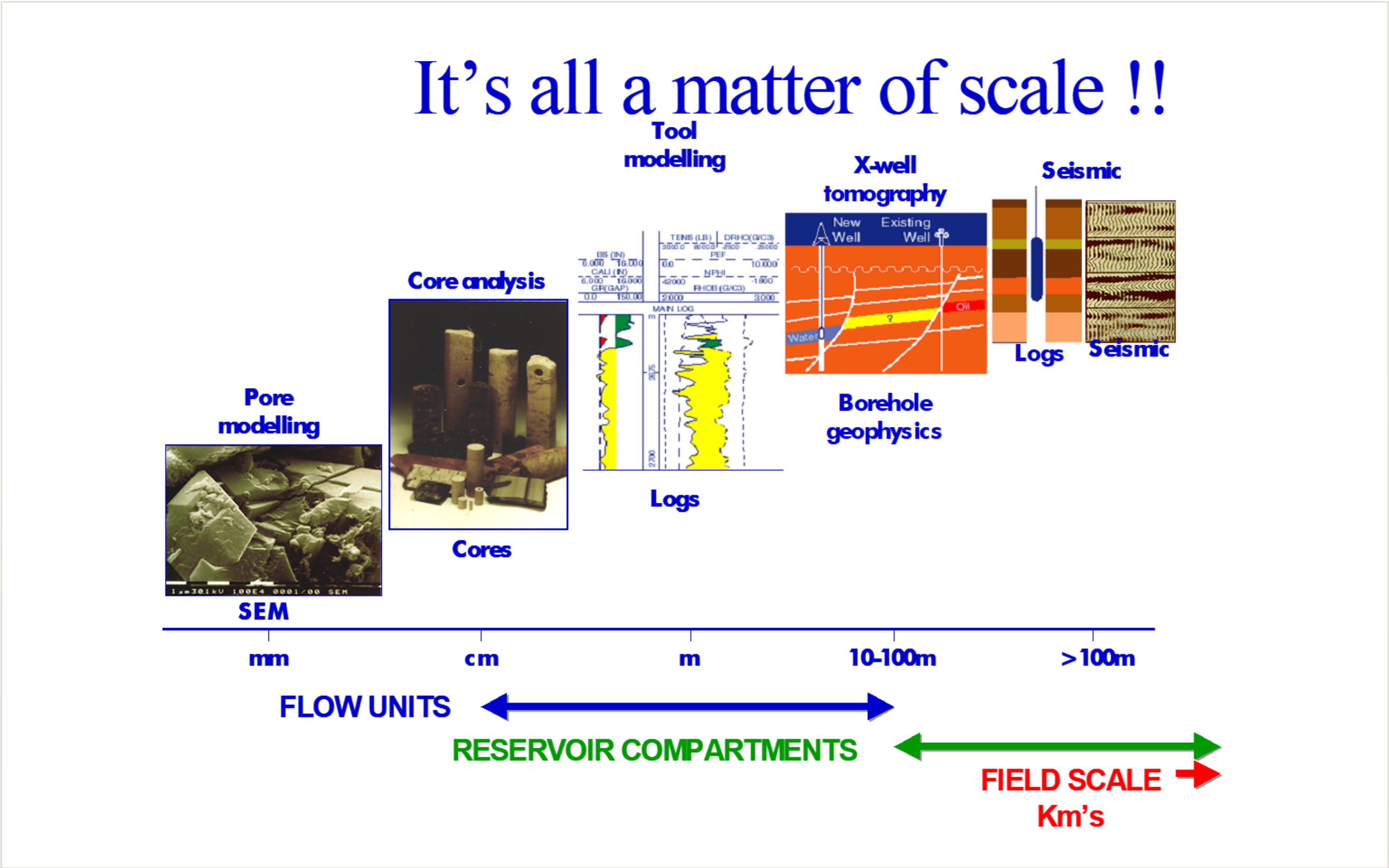

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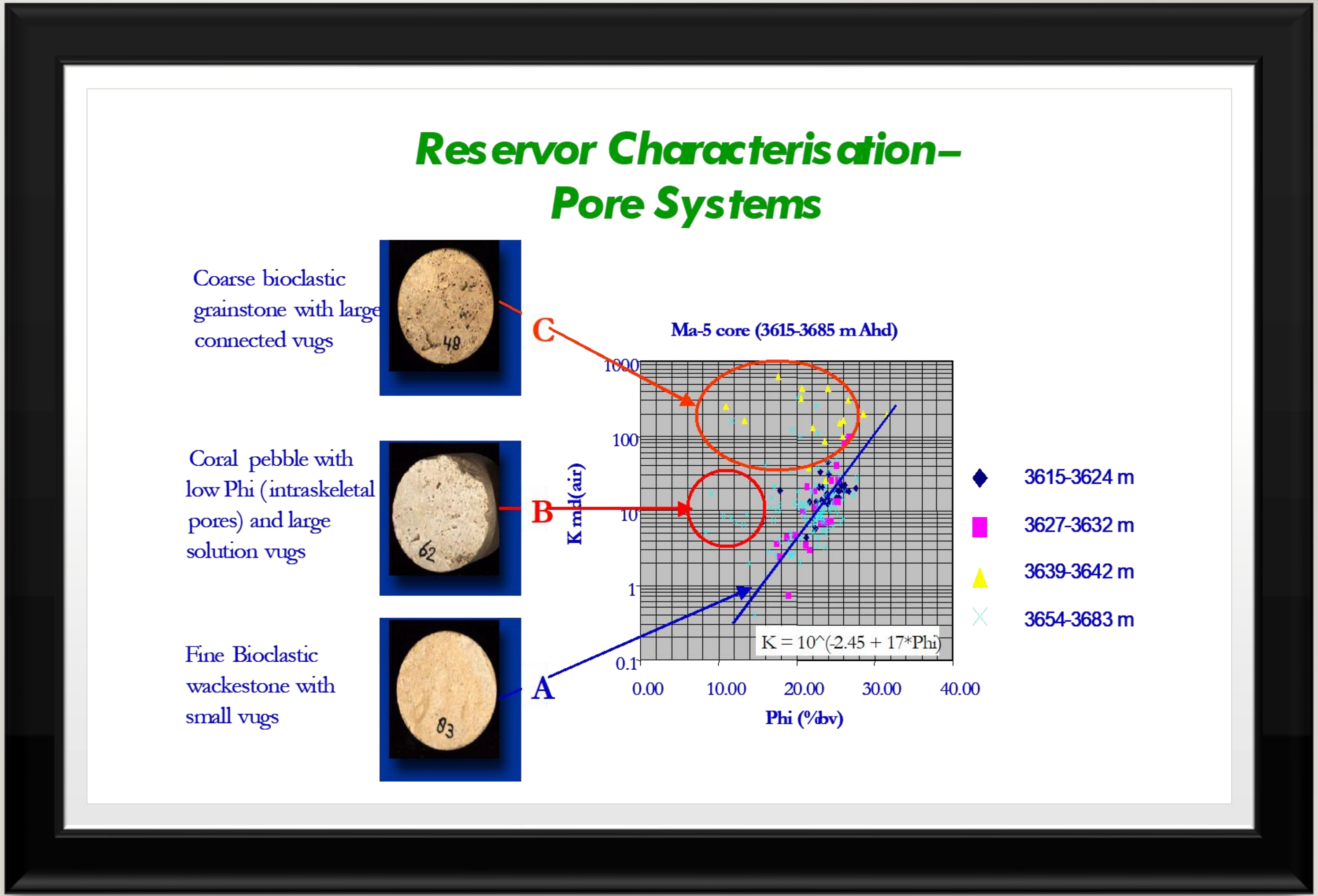

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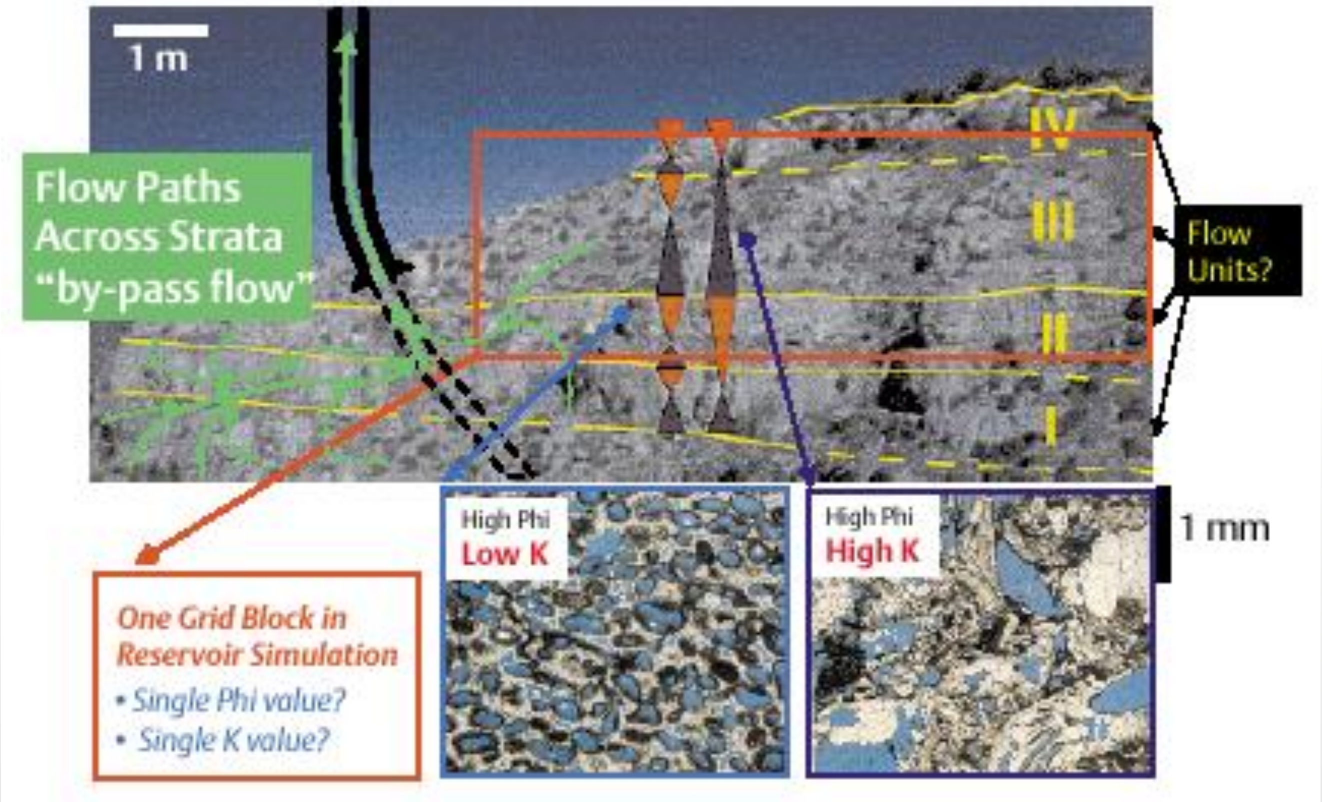
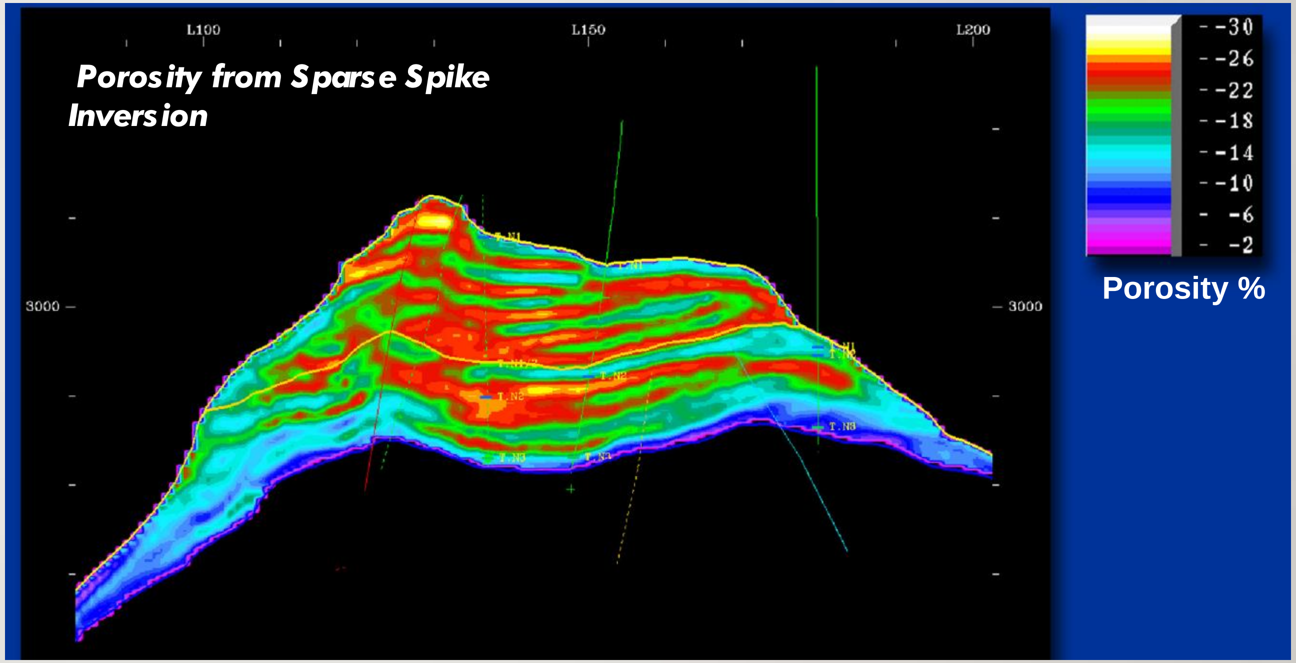


# INTEGRATED RESERVOIR MODELING

## Reservoir Properties from Seismic



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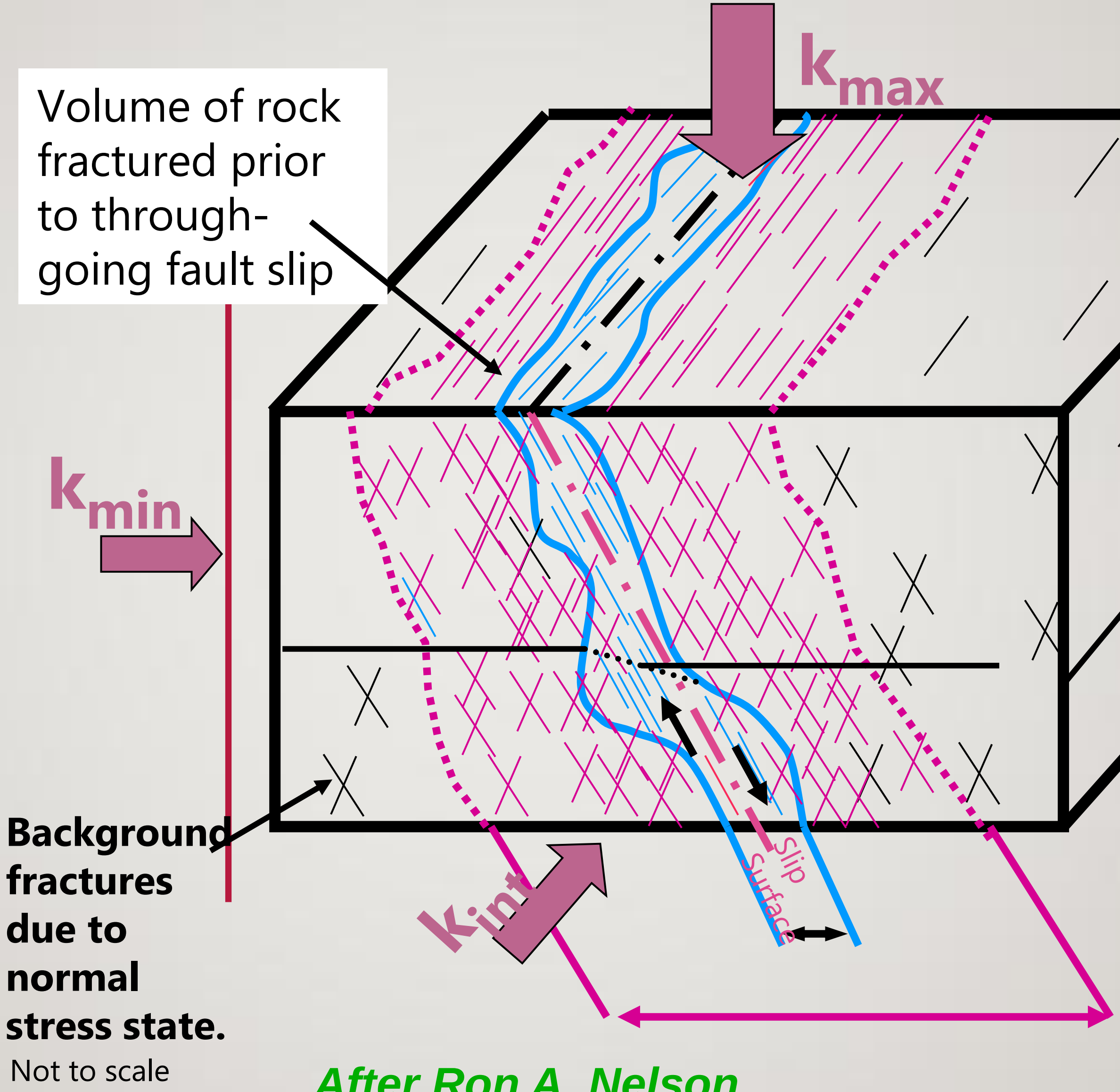
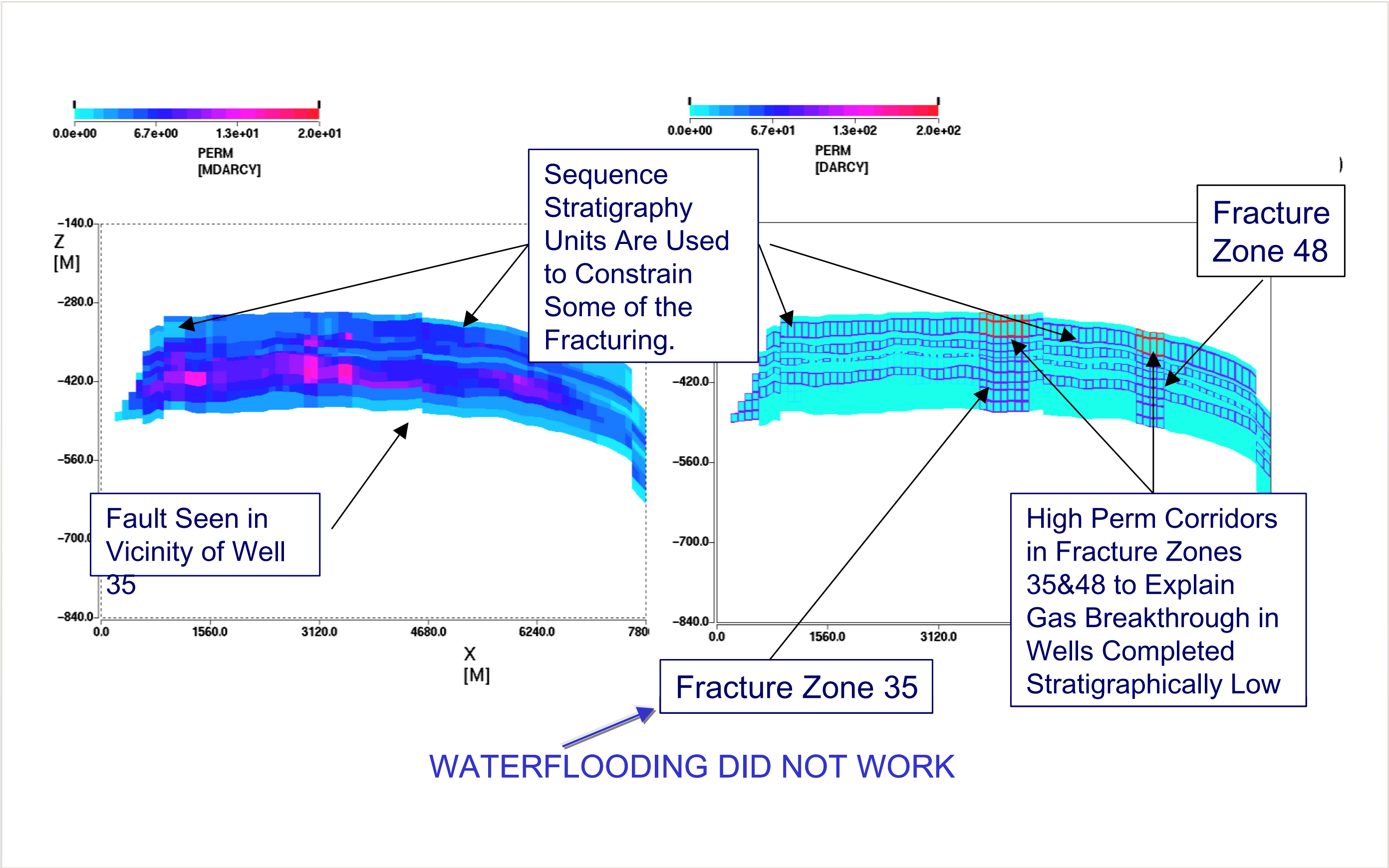



**Damage zone** ***(c. a few feet*** **is usually low in permeability.**

**Effective process zone** ***(a few hundred feet)*** **is the zone that is significantly greater than matrix flow.**

***After Ron A. Nelson, 2002***

# INTEGRATED RESERVOIR MODELING



# INTEGRATED RESERVOIR MODELING