Reservoir Management

Dan Arnold

Learning objectives

1. Provide a formal Management Process
2. Reservoir Management tools
3. Review some examples of Management Strategy
    1. Clastics
    2. Carbonates
    3. Oil
    4. Gas
4. Develop a knowledge of Reservoir Management techniques and applications
5. Reservoir Management best practice

"The purpose of reservoir management is to control operations to obtain the maximum possible economic recovery from a reservoir on the basis of facts, information and knowledge"

Thakur, 1996 - Chevron

"The marshalling of all appropriate business, technical and operating resources to exploit a reservoir optimally from discovery to abandonment"

"Through-life, ongoing process"

Al-Hussainy and Humphreys, 1996 - Mobil

"There are probably as many different definitions as there are perceptions of the process"

"Integrated approach...key consideration..."

"The judicious use of the various means available to a business to maximise its benefits/profits from the reservoir"

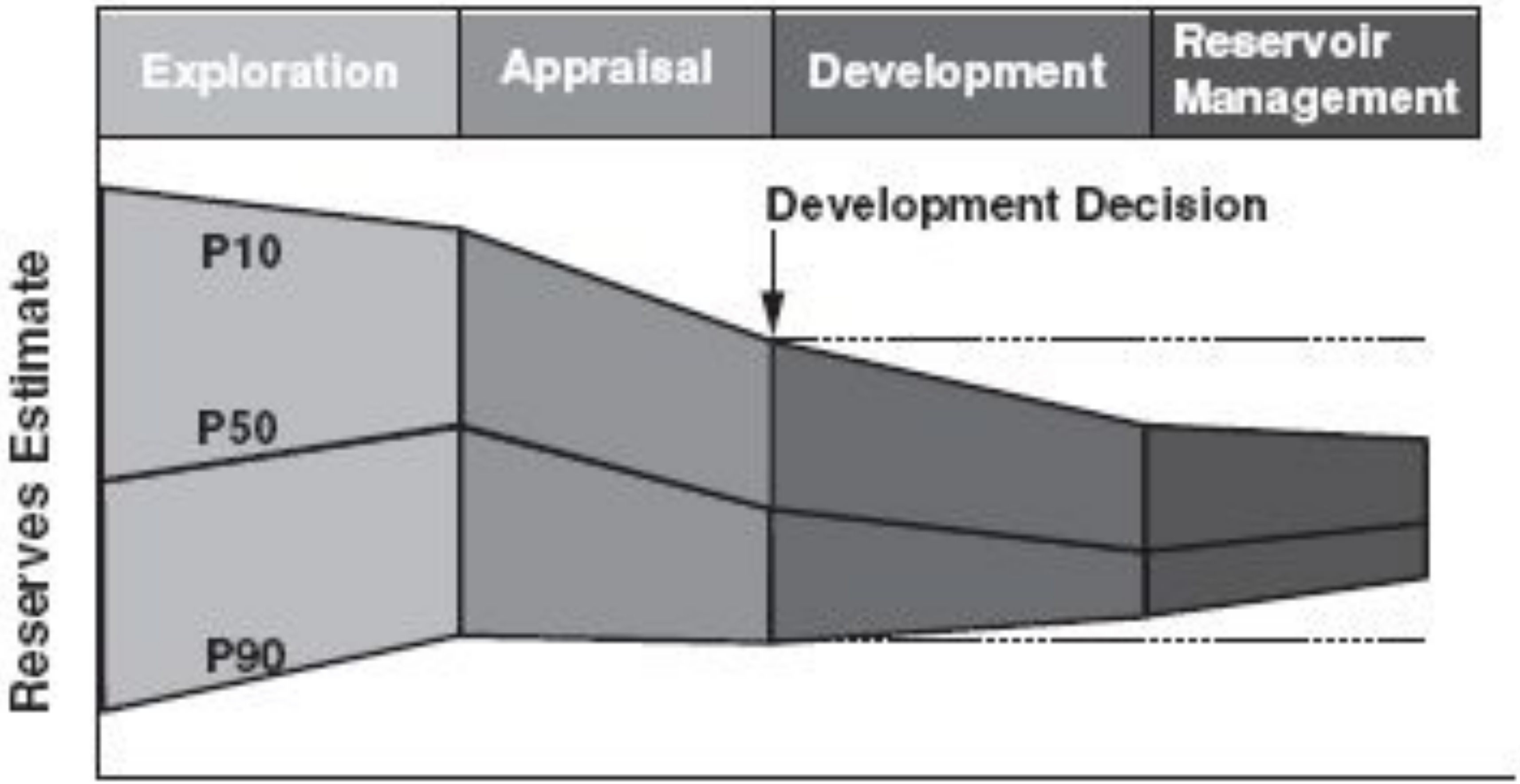
Egbogah, 1996 - Petronas

What is reservoir management? - Summary

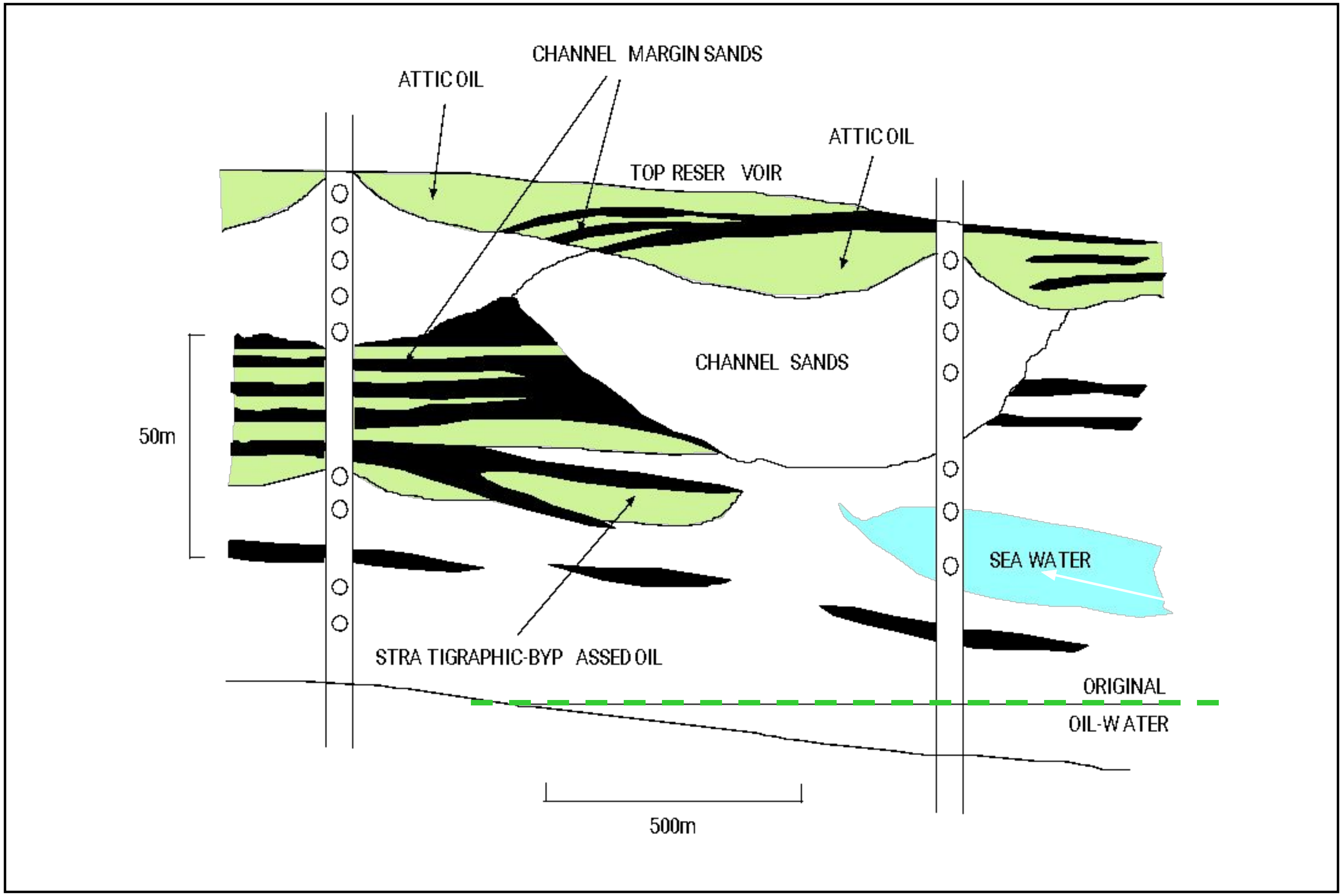
Integrated approach:

1. to control operations
2. to maximise benefits/profits (value) from the reservoir (asset)
3. to obtain the maximum possible economic recovery from a reservoir

A lifetime of reservoir models



Forties field – habitat of remaining oil



(from Brand et al., 1996; Scott, 1997)

Monetary value of an asset

- Recoverable resources (i.e. reserves)
- Rate of production
- Cost of production
- Oil price
- Fiscal regime

Aim

MAXIMISE VALUE

MINIMISE COST

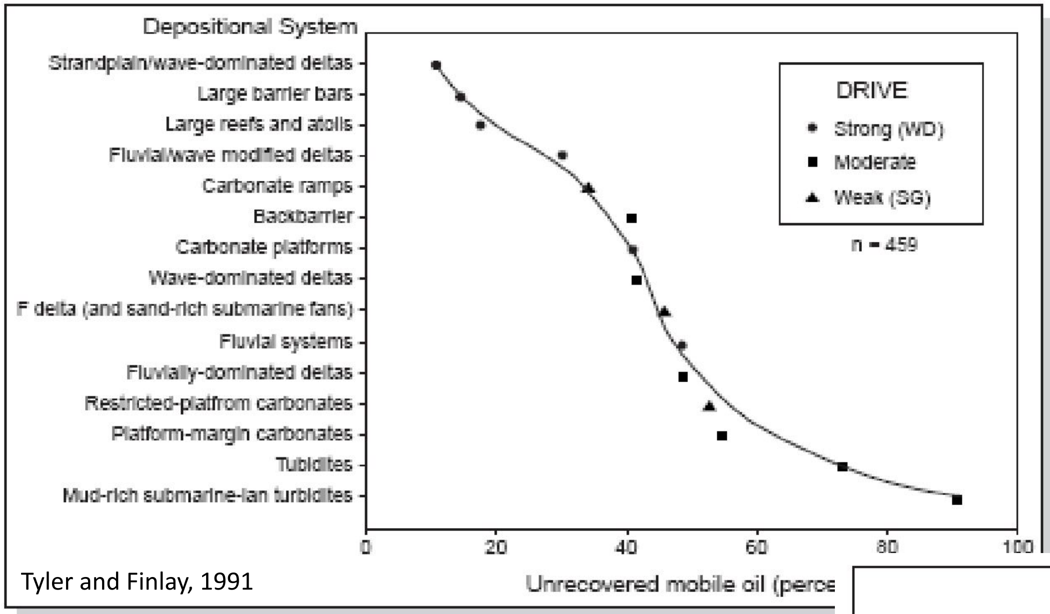
- Maximise recovery
- Recovery Technology (speed up)
- People/Team
- Reservoir Knowledge/analysis

- CAPEX
- OPEX
- Tax
- Depreciation

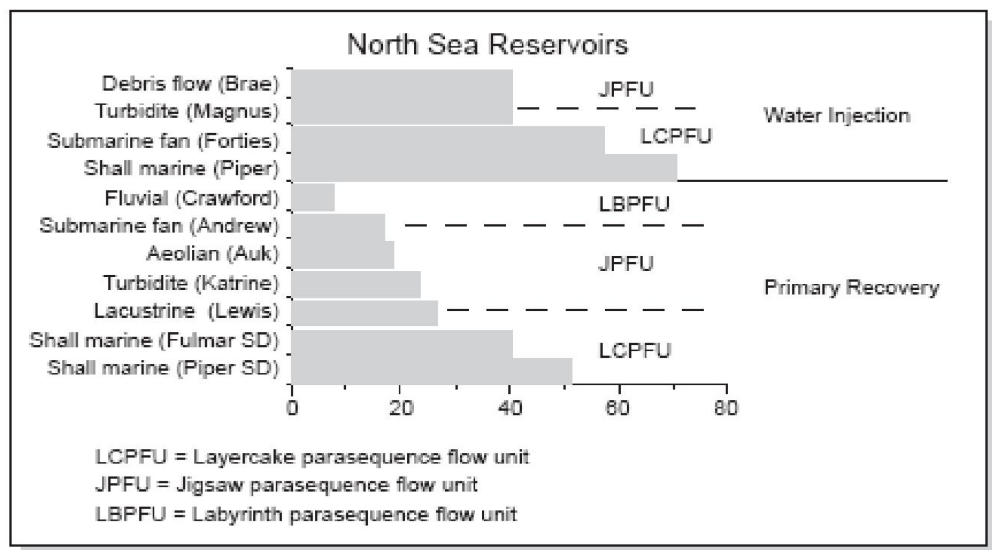
Maximise value through…

RECOVERY

Recovery Factors



Depends on Geology



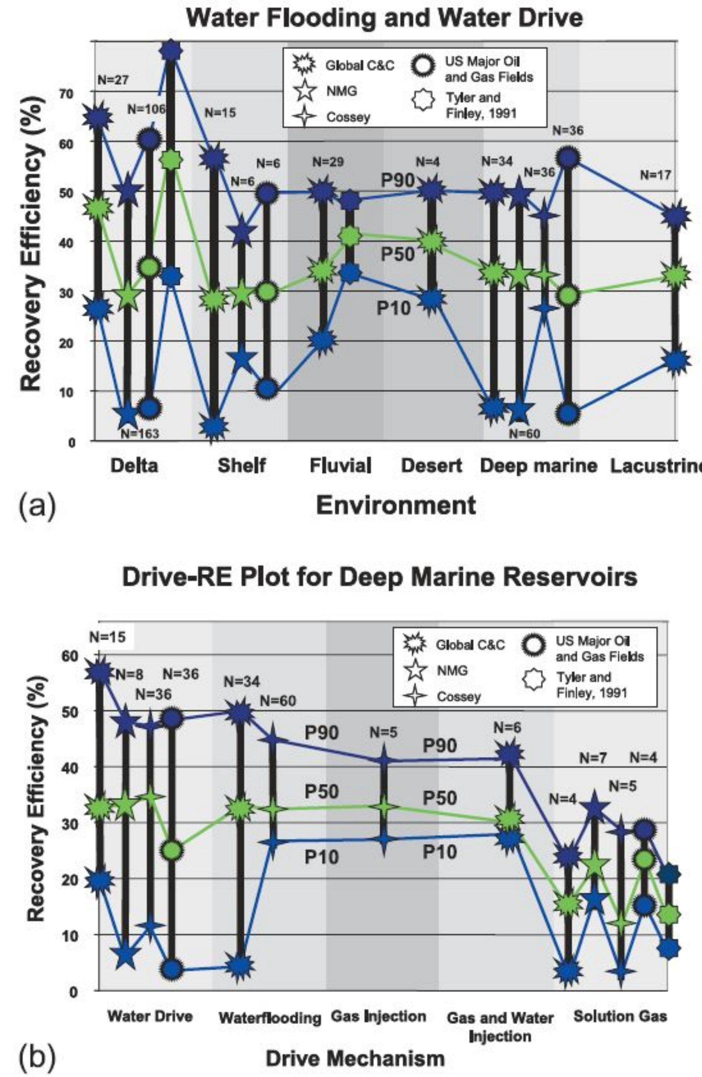
and Drive Mechanism

Solution gas drive	5-30%
Gas cap drive	20-40%
Water drive	35-75%
Gravity drainage	5-30%

(after Sills, AAPG Methods 10, 1992)

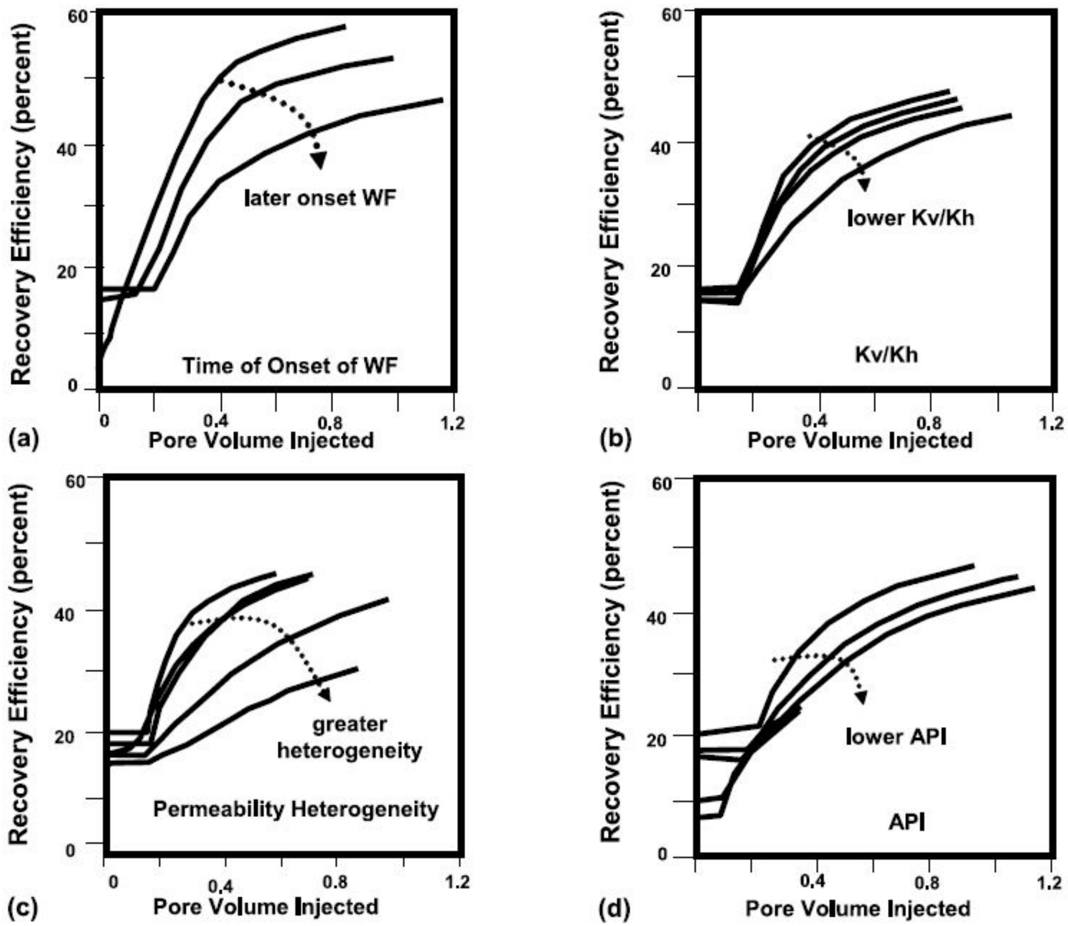
Depositional Environment vs Drive Mechanism

- Environment type has less of an impact on recovery efficiency
- Primary vs secondary recovery has a bigger impact
  - Primary recover average = 20% recovery vs 40% for secondary recovery mechanisms



Larue and Friedman, 2005

Recover efficiency impact from various reservoir features

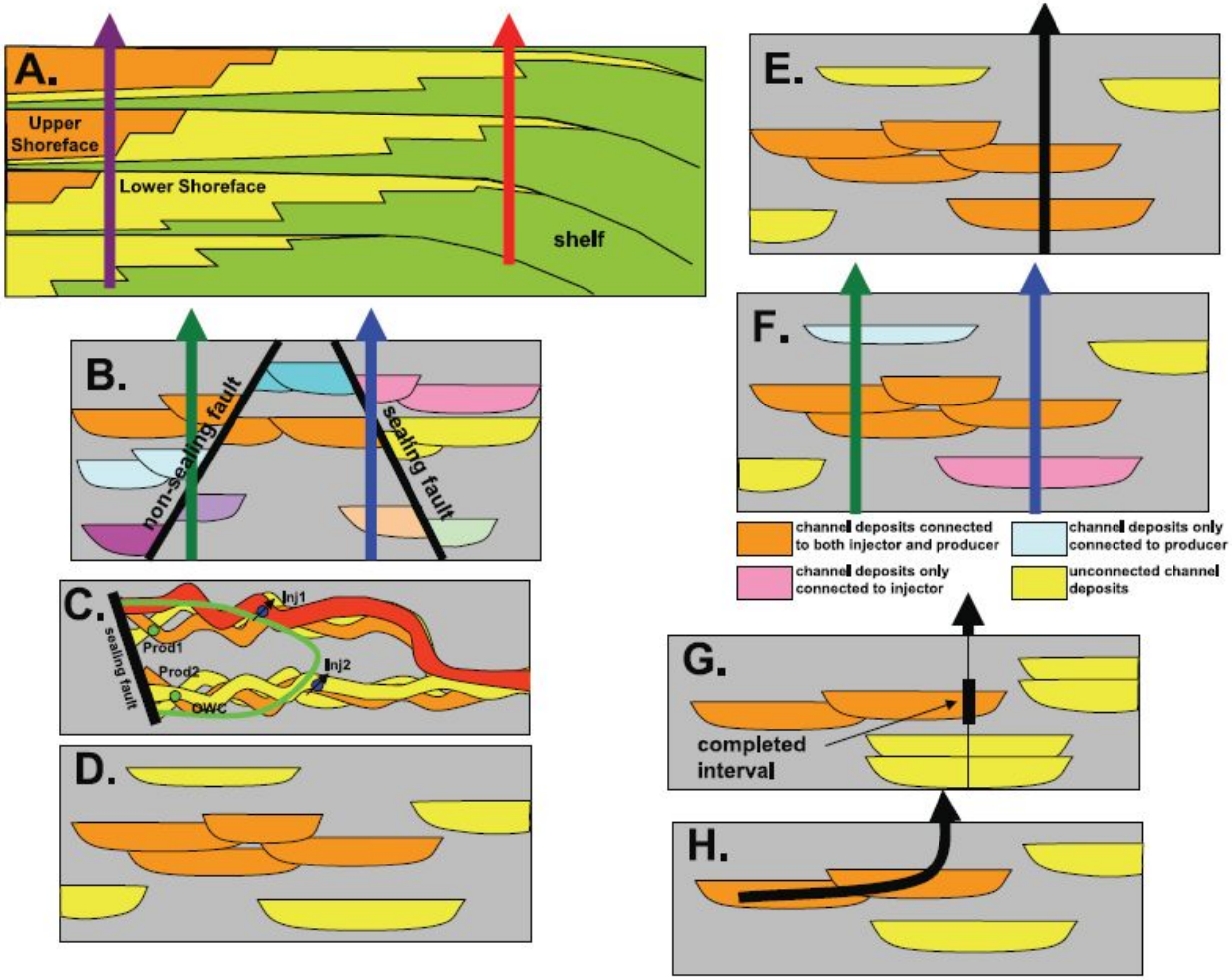


Does connectivity influence recovery?

What is connectivity?

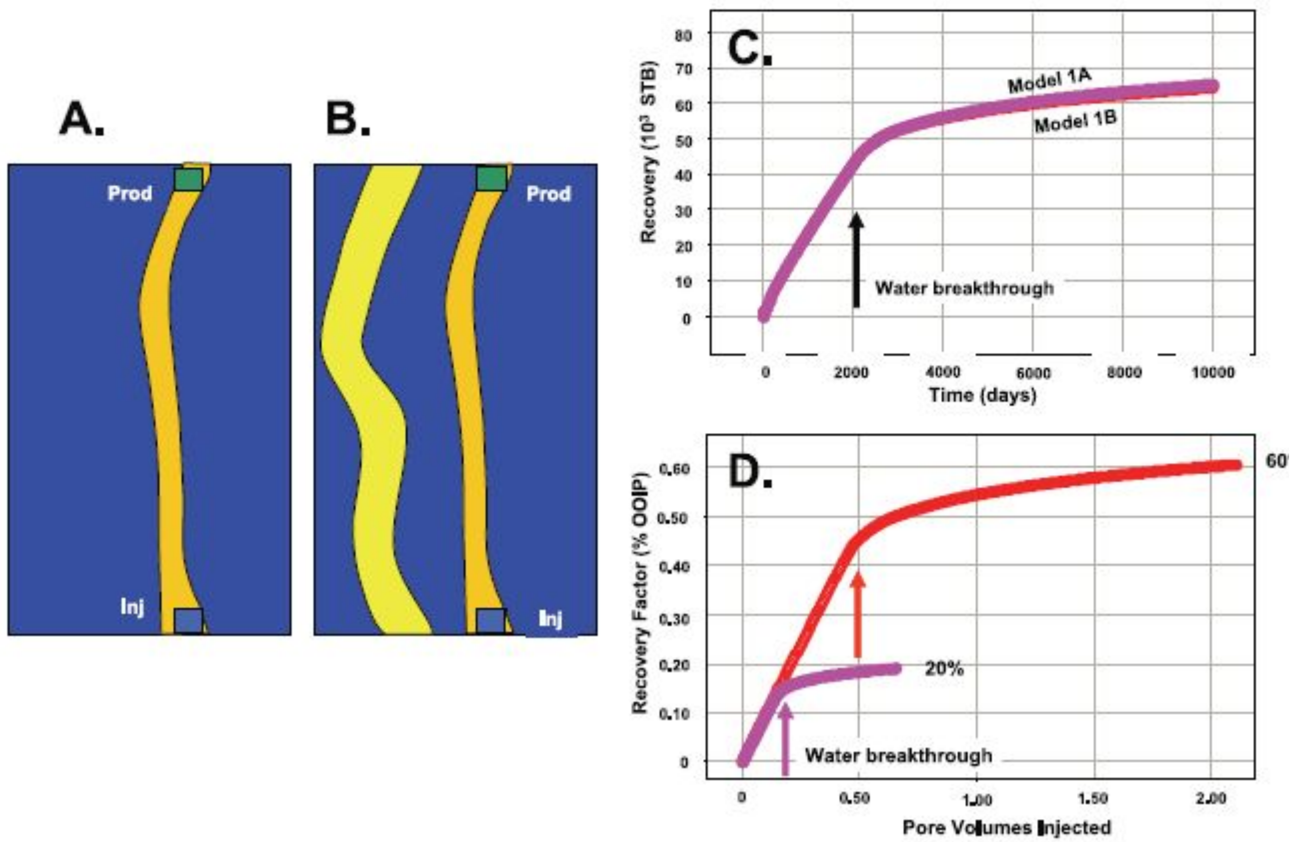
- **Sandbody connectivity**
  - % of sand bodies that are connected to each other
- **Reservoir connectivity**
  - % of sand connected to the wells
  - Producer, producer/injector, completions/laterals
- **Static** and **Dynamic** connectivity
  - How long will it take to produce the connected volume
  - Bypassing?
  - Multiple connections?

Examples of connectivity?



Larue & Hovadik, 2006

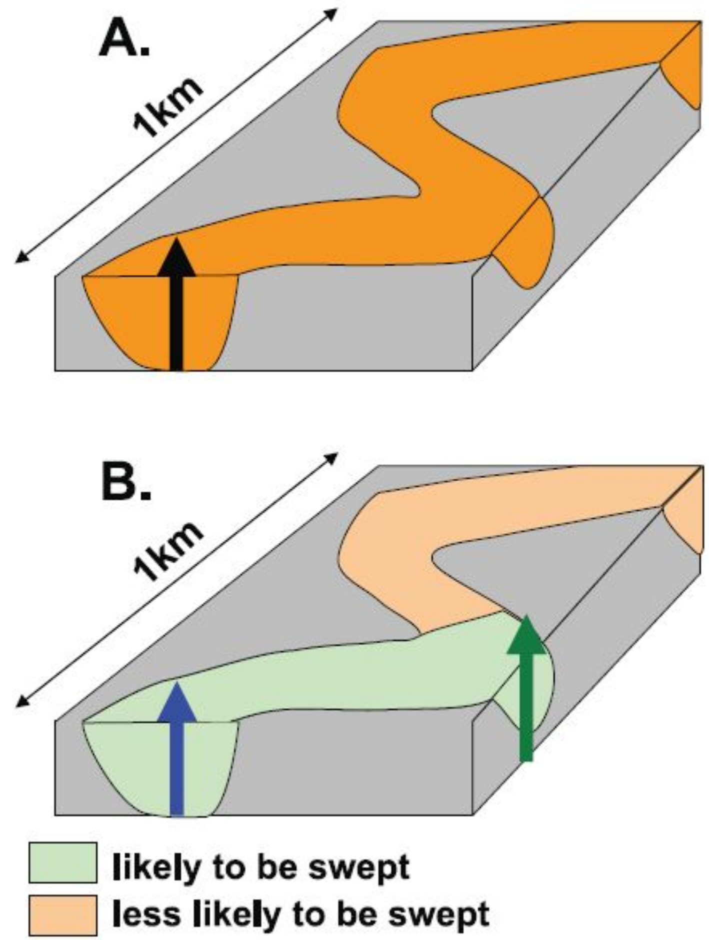
Relationship between connectivity and recovery



Larue & Hovadik, 2006

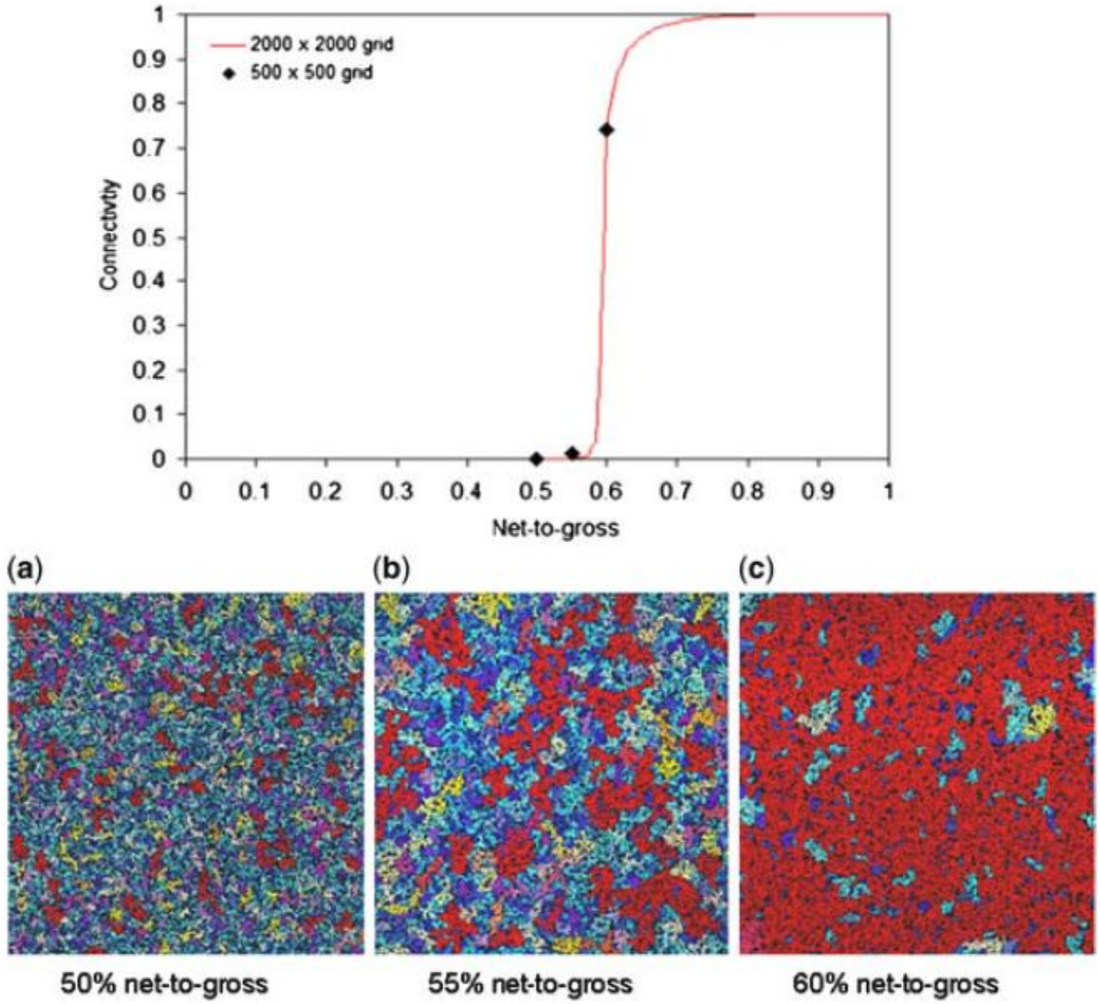
Static vs dynamic well connectivity

- Reservoir recoveries significantly below percolation prediction of connected sand bodies
  - Static inter-body connectivity
  - Producer sand connectivity
  - Producer-injector connectivity
  - Dynamic recovery efficiency is different



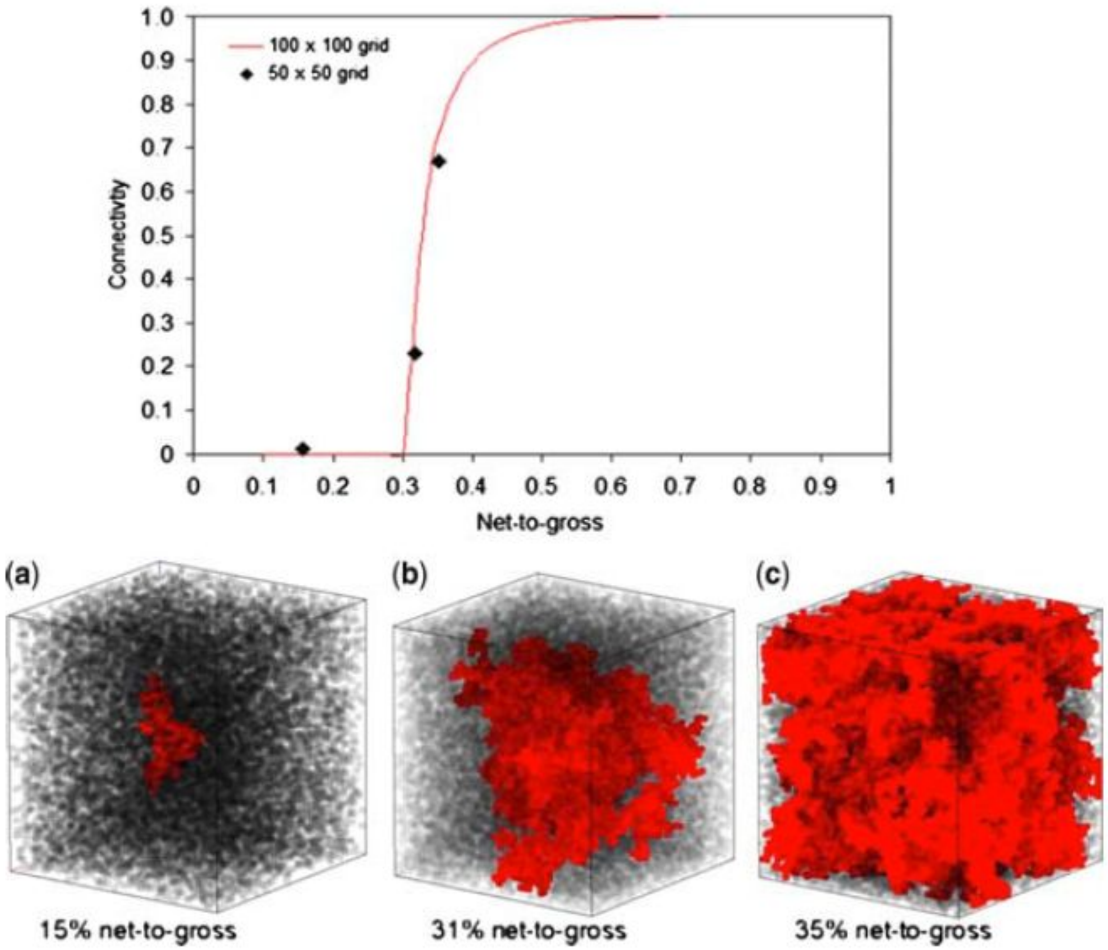
Larue & Hovadik, 2006

2D Connectivity



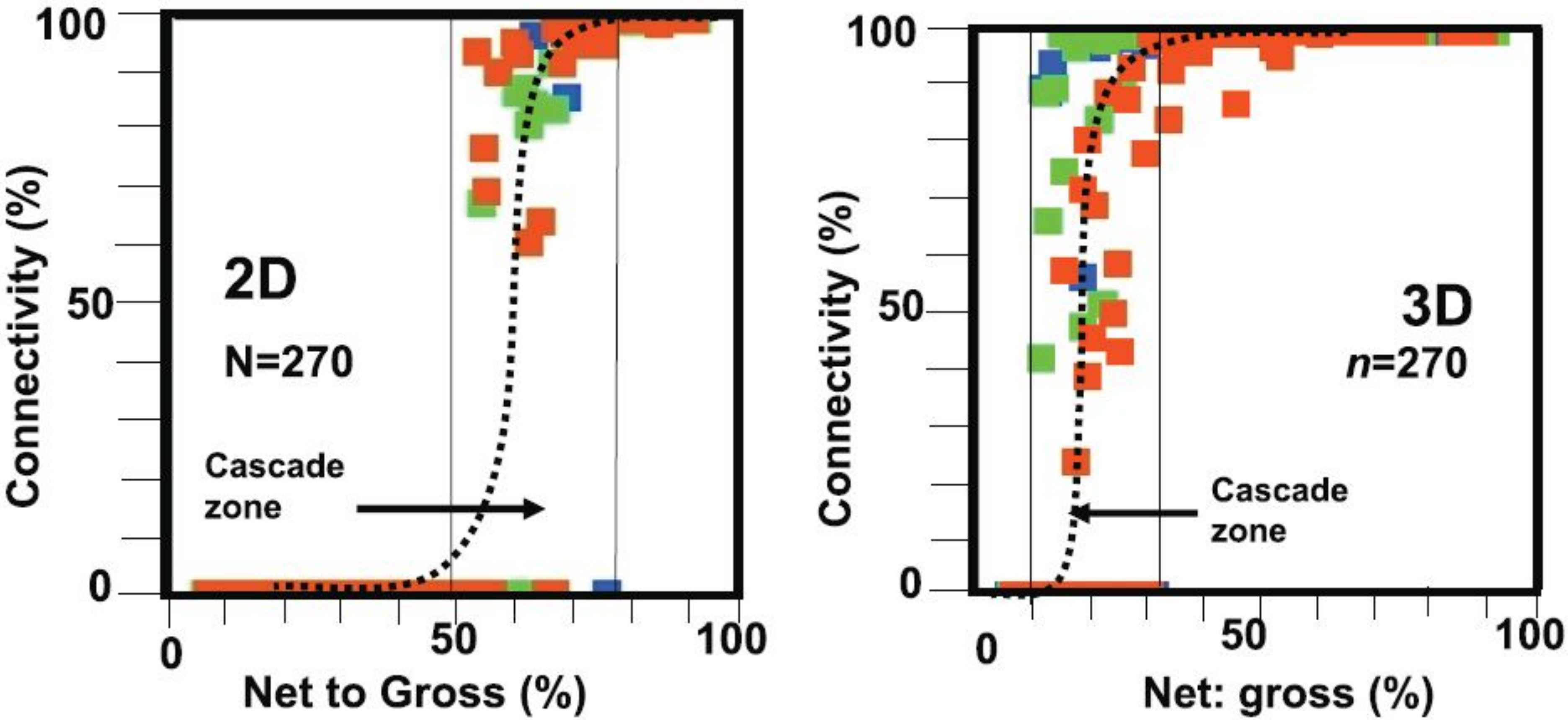
Hovadik & Larue, 2010

3D percolation connectivity



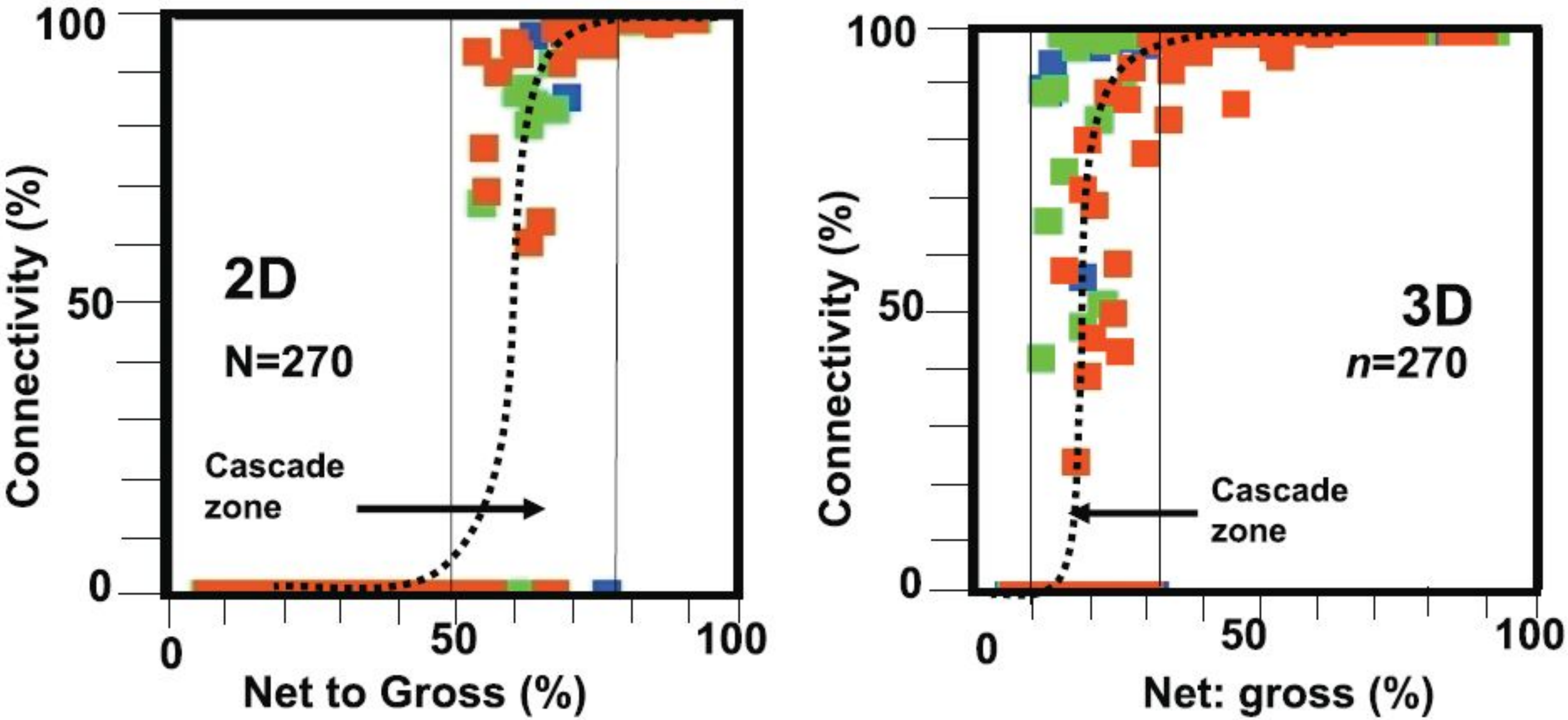
Hovadik & Larue, 2010

2D vs 3D connectivity



Larue & Hovadik, 2006

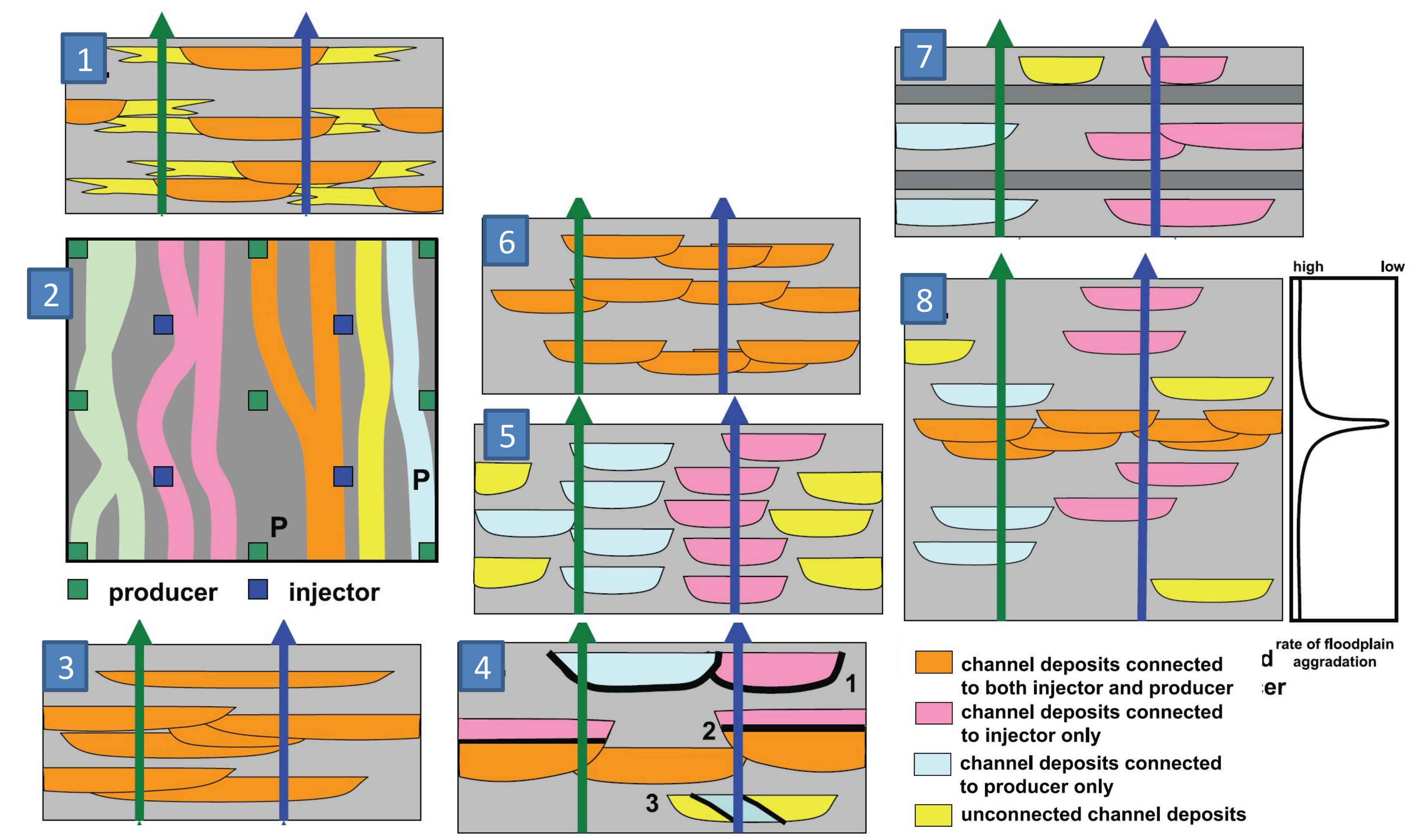
Shifting the S-Curve



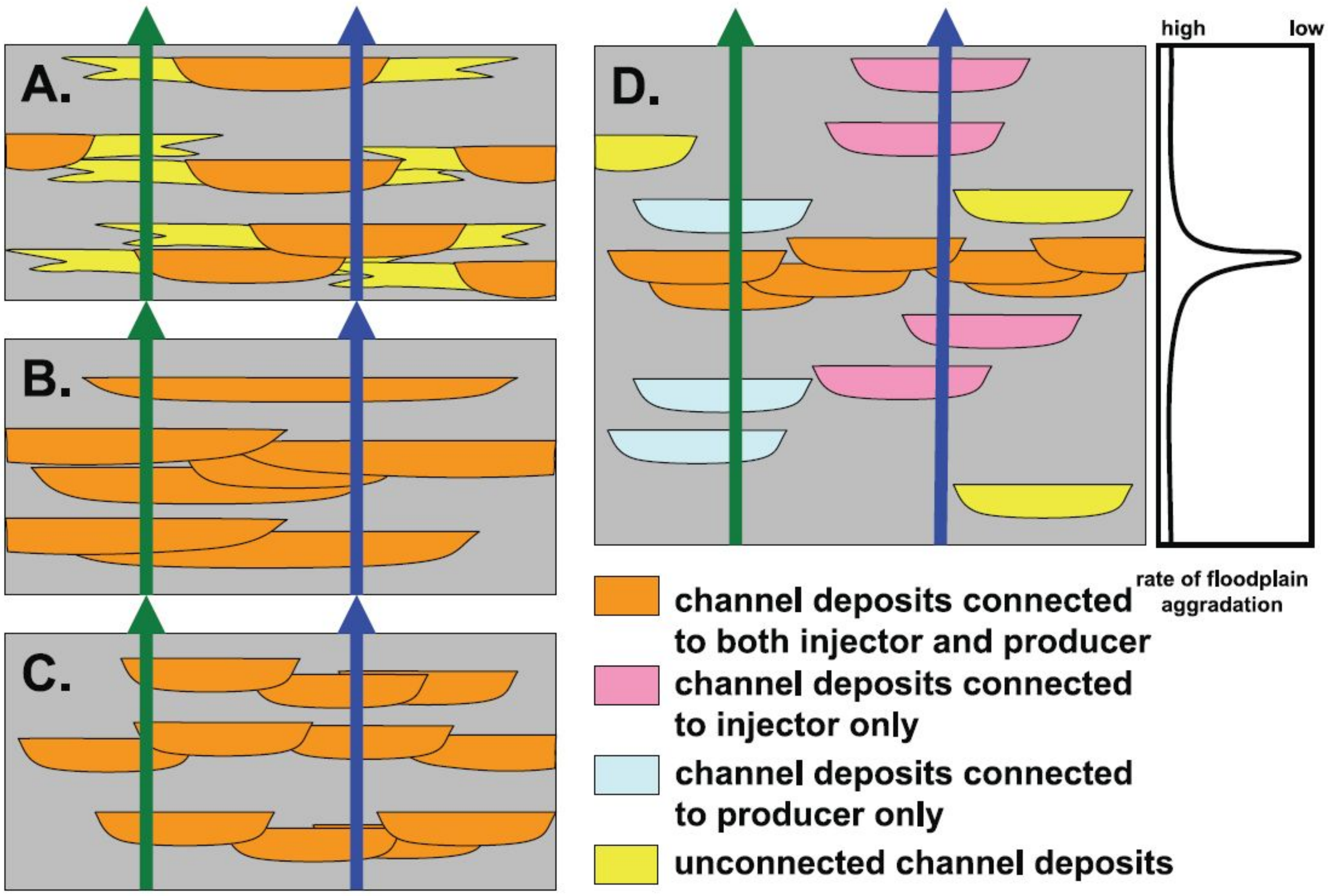
Larue & Hovadik, 2006

Larue & Hovadik, 2006

Shifting the S-Curve Left or Right?

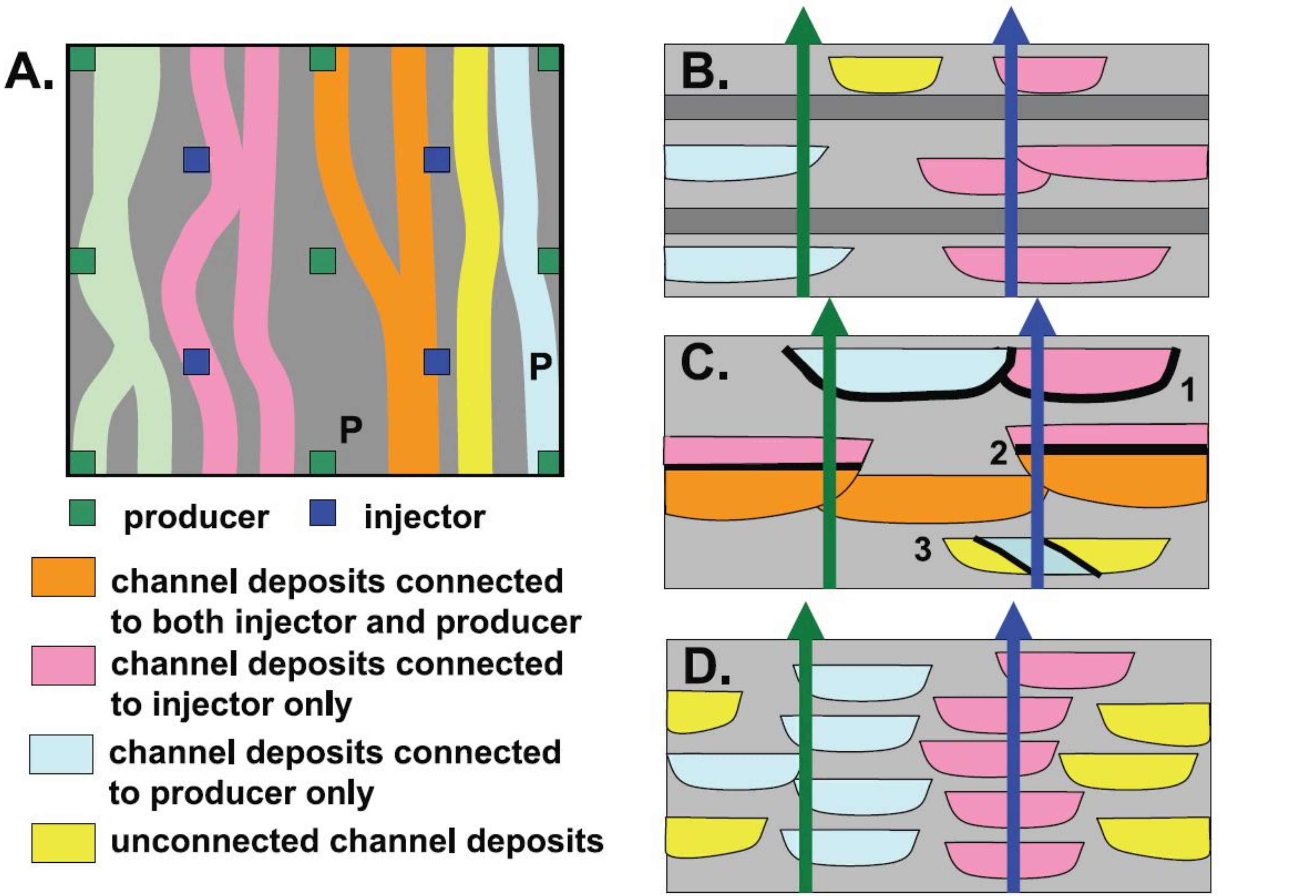


Geology that shifts the S-Curve Left



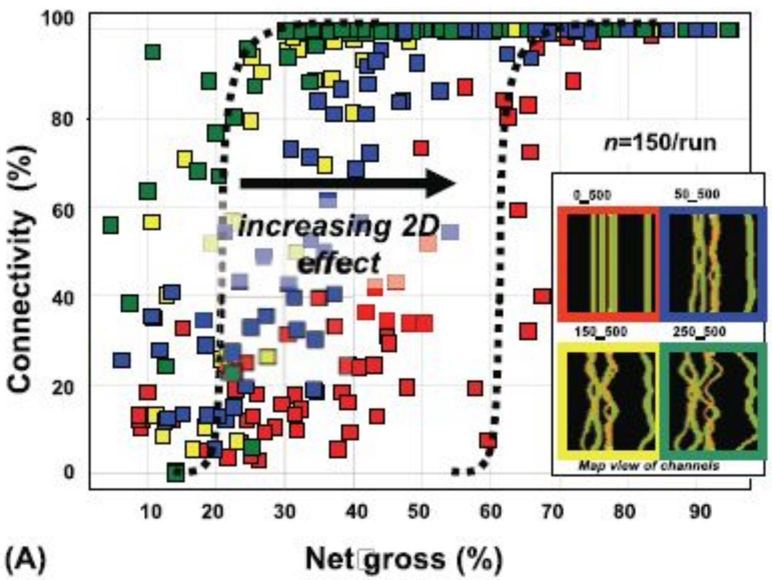
Larue & Hovadik, 2006

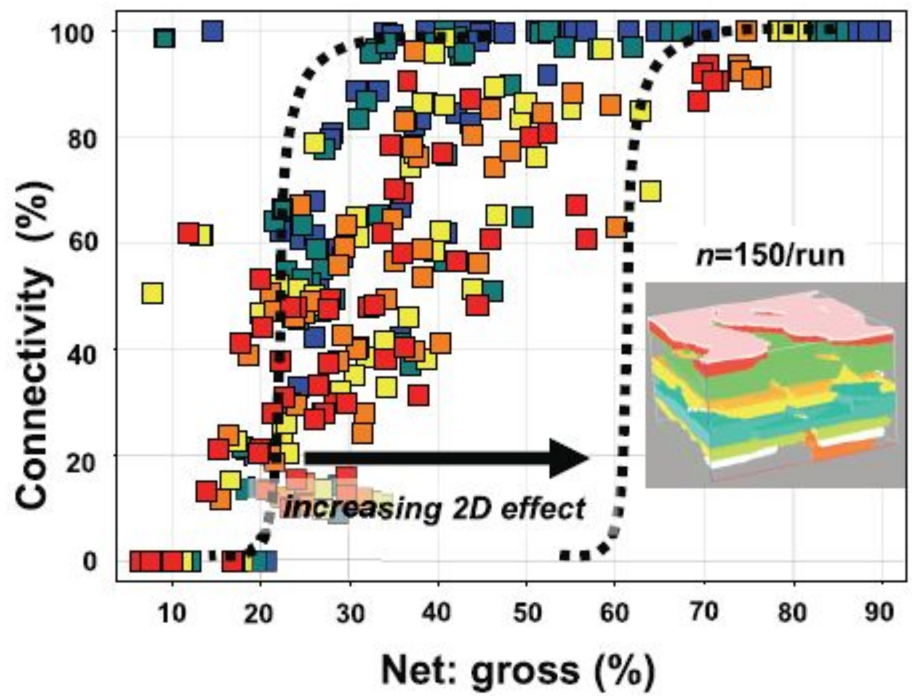
Geology that shifts the S-Curve Right



Larue & Hovadik, 2006

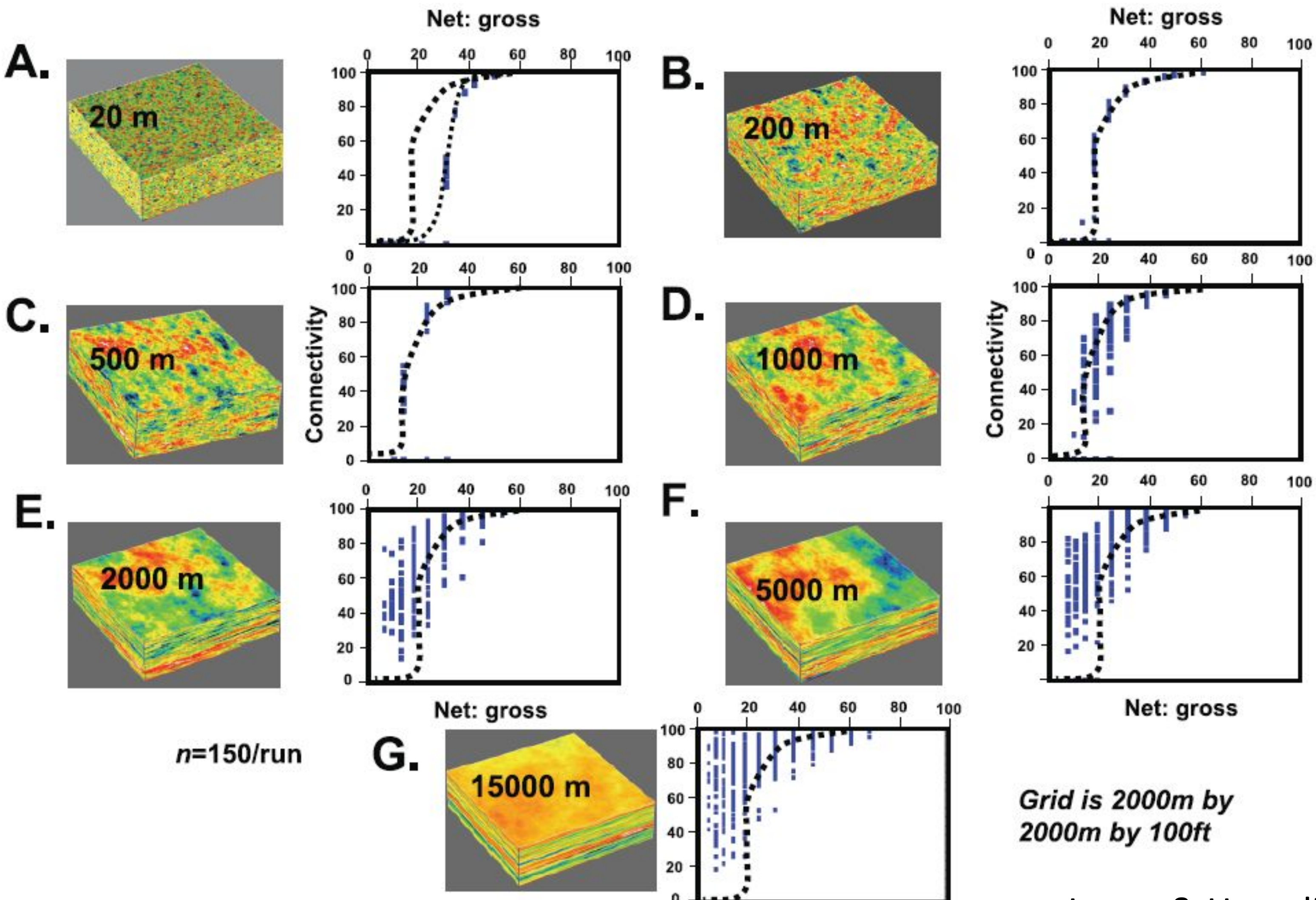
Increasing 2D effect (shift to Right)





Larue & Hovadik, 2006

Volume support and the cascade zone



Larue & Hovadik, 2006

Geobody Anisotropy

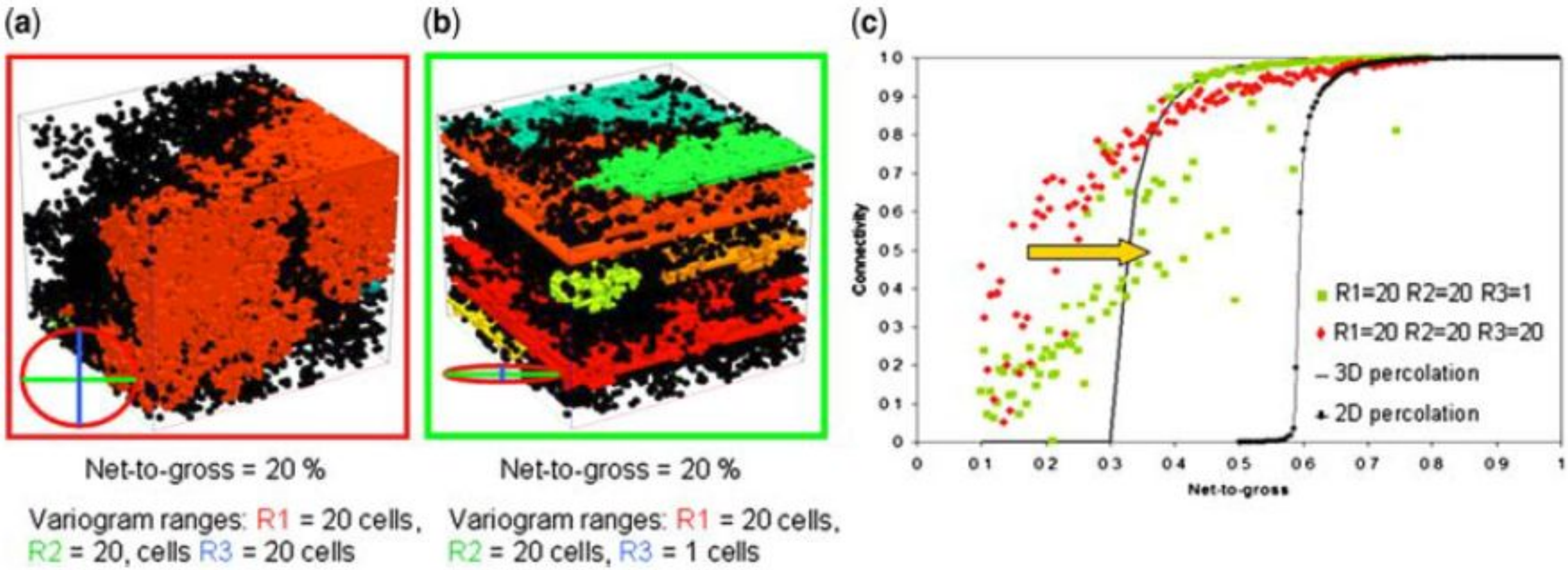
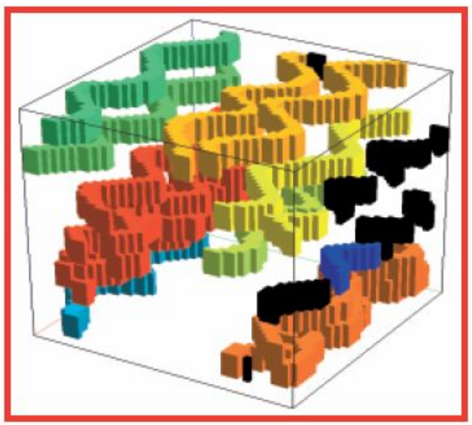


Fig. 7. From Hovadik & Larue 2007. Effect of an anisotropic variogram on the connectivity v. net-to-gross 'S-curve' in a random stationary and anisotropic system. (**a**) Isotropic variogram. An anisotropic variogram (**b**) shifts the 'S-curve' to the right (**c**).

Hovadik & Larue, 2010

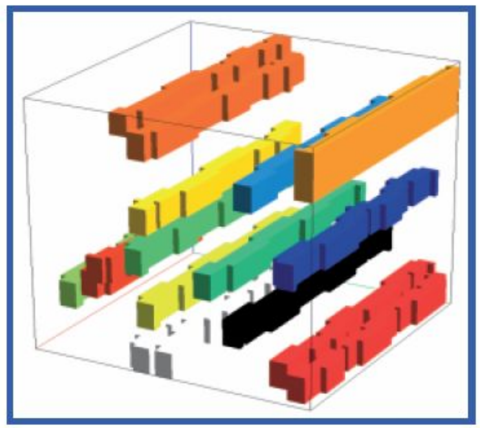
Sinuosity



(a) Net: gross = 10 %

Channel width = 3 cells

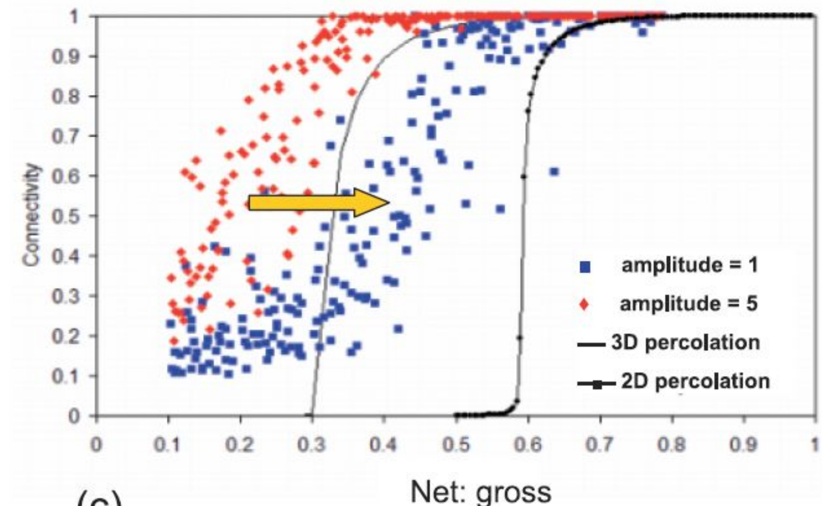
Sinuosity amplitude = 5 cells



(b) Net: gross = 10 %

Channel width = 3 cells

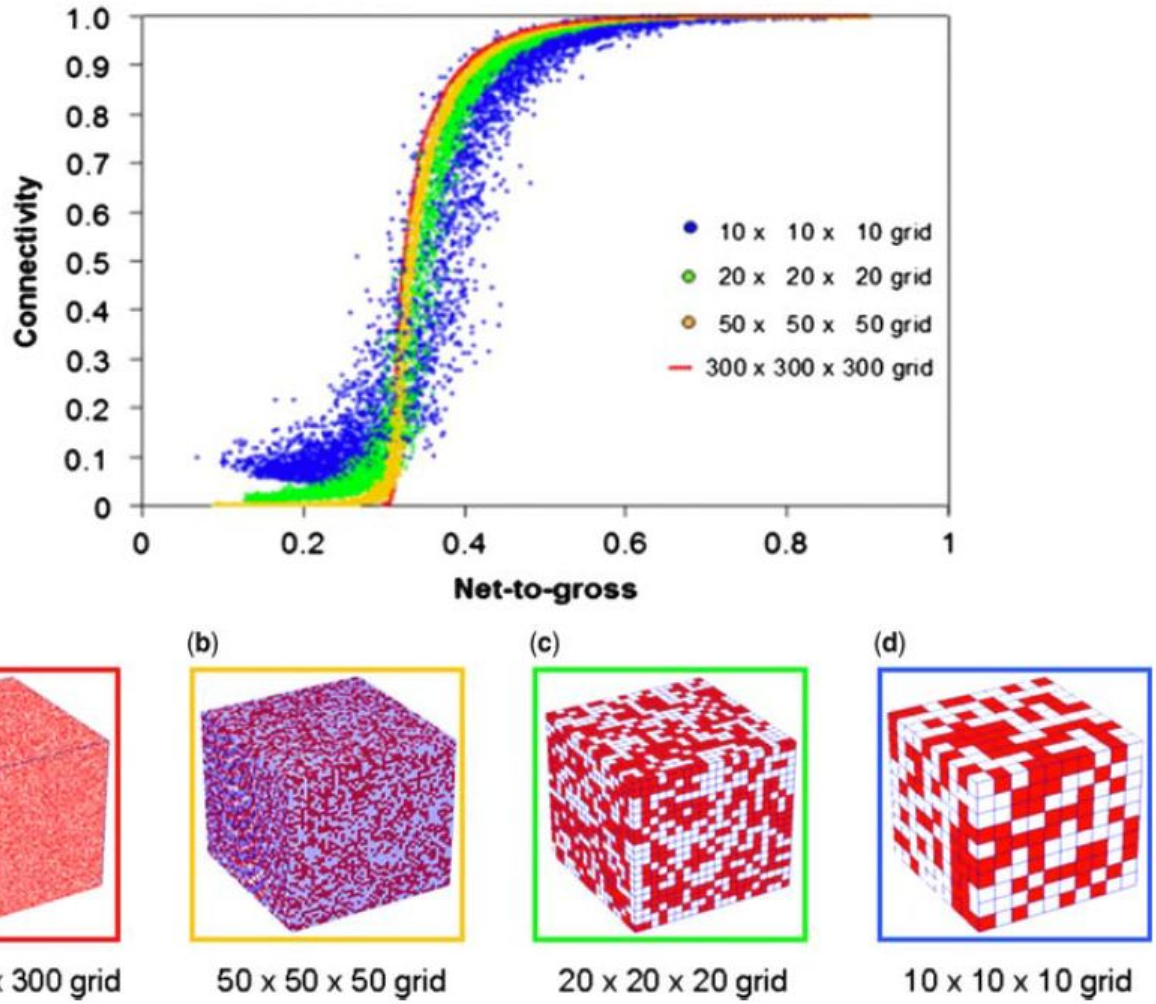
Sinuosity amplitude = 1 cell



(c)

Hovadik & Larue, 2010

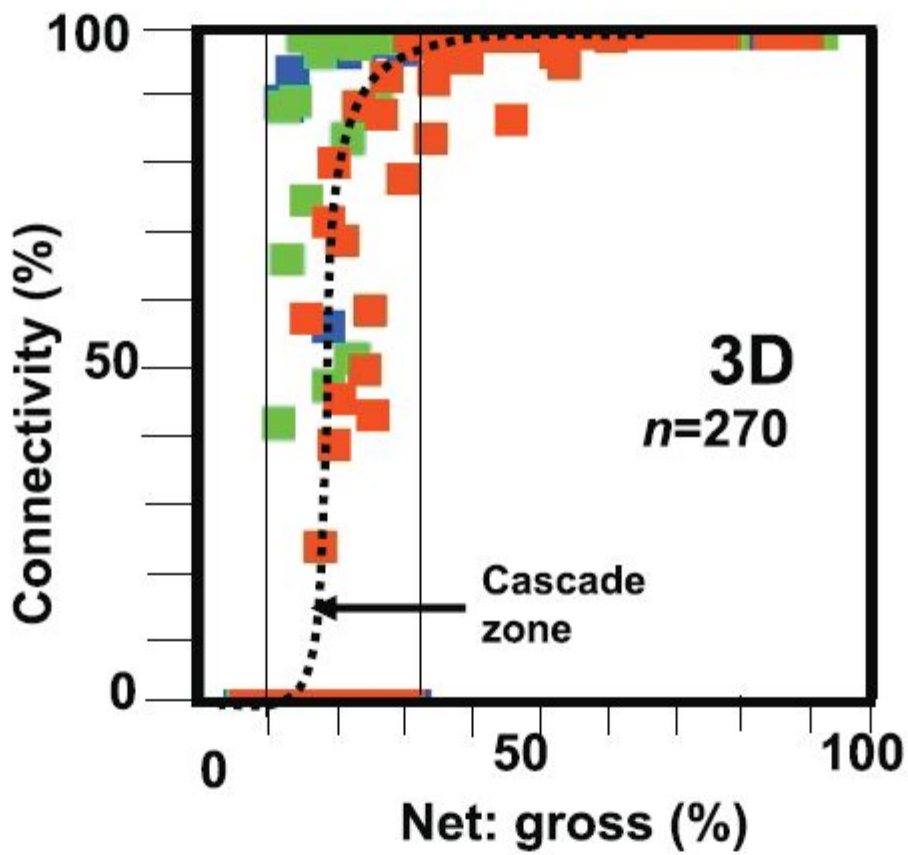
Grid dimensions – volume support



Hovadik & Larue, 2007/2010

Overview

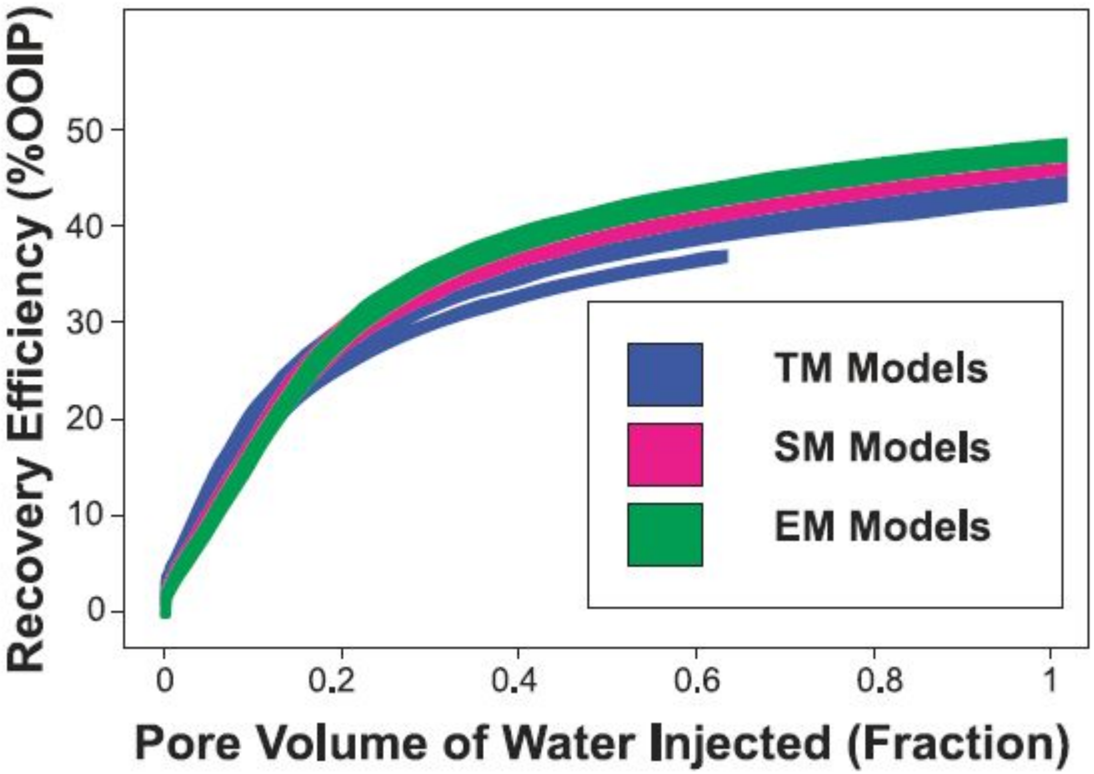
- Increased volume support **increases width** of cascade zone
- Decreasing "dimensionality" moves curve to **right**
- Increasing dimensionality shifts curve to the **left**



Which impact?

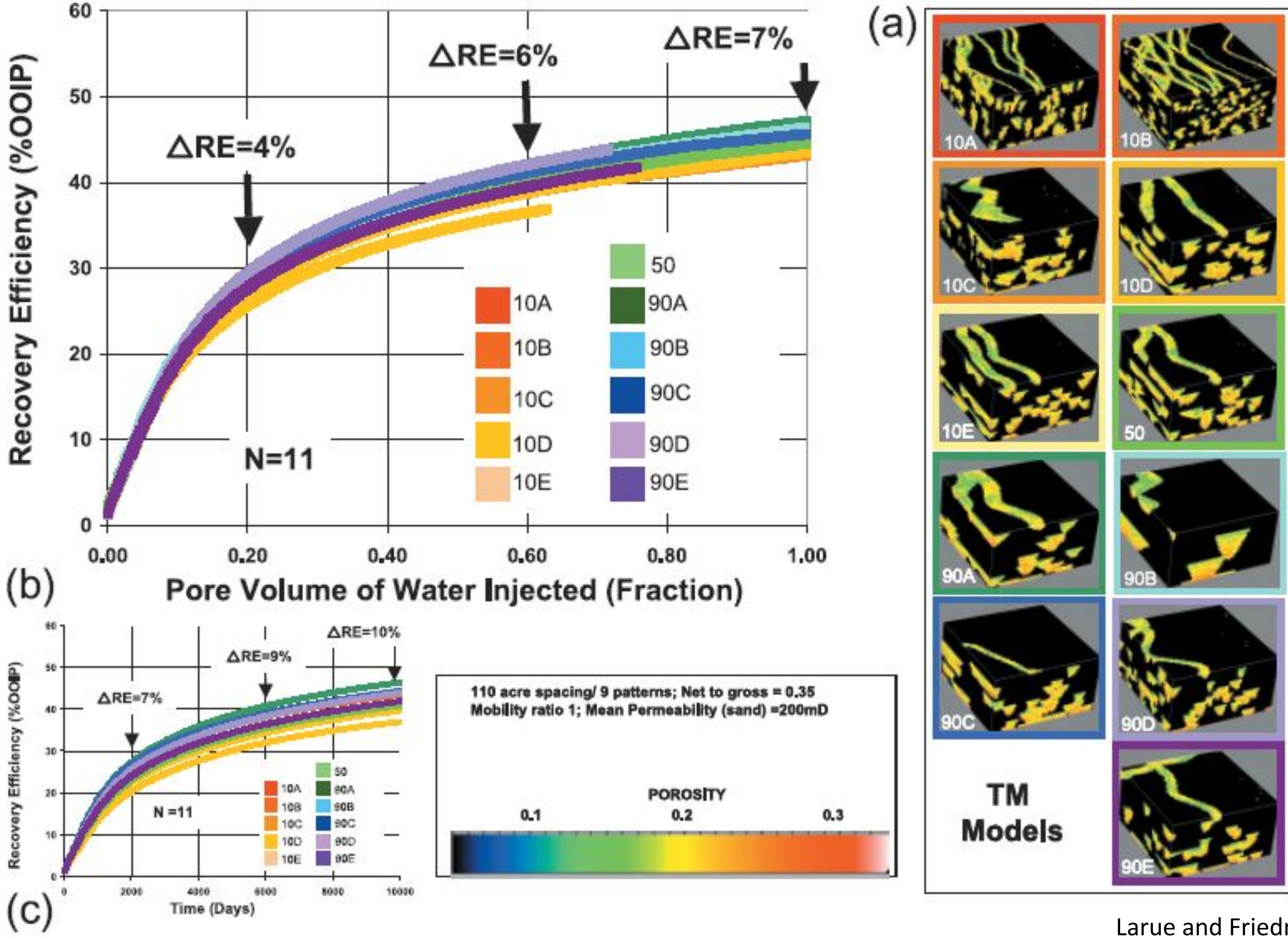
Geological Factor	Dimensionality (S-curve shift)	Volume support (dispersion)
Variogram Range		X
Variogram Anisotropy	X	
Channel width and thickness		X
Channel width/thickness ratio	X	
Channel Parallelism	X	
Channel deviation	X	
Continuous mudstone bed %		X
Local mudstone drapes	X	
Channel clustering		X
# sealing faults		X
Fault block size		X
Fault offset		X
Fault length		X

Is connectivity the biggest factor affecting recovery?



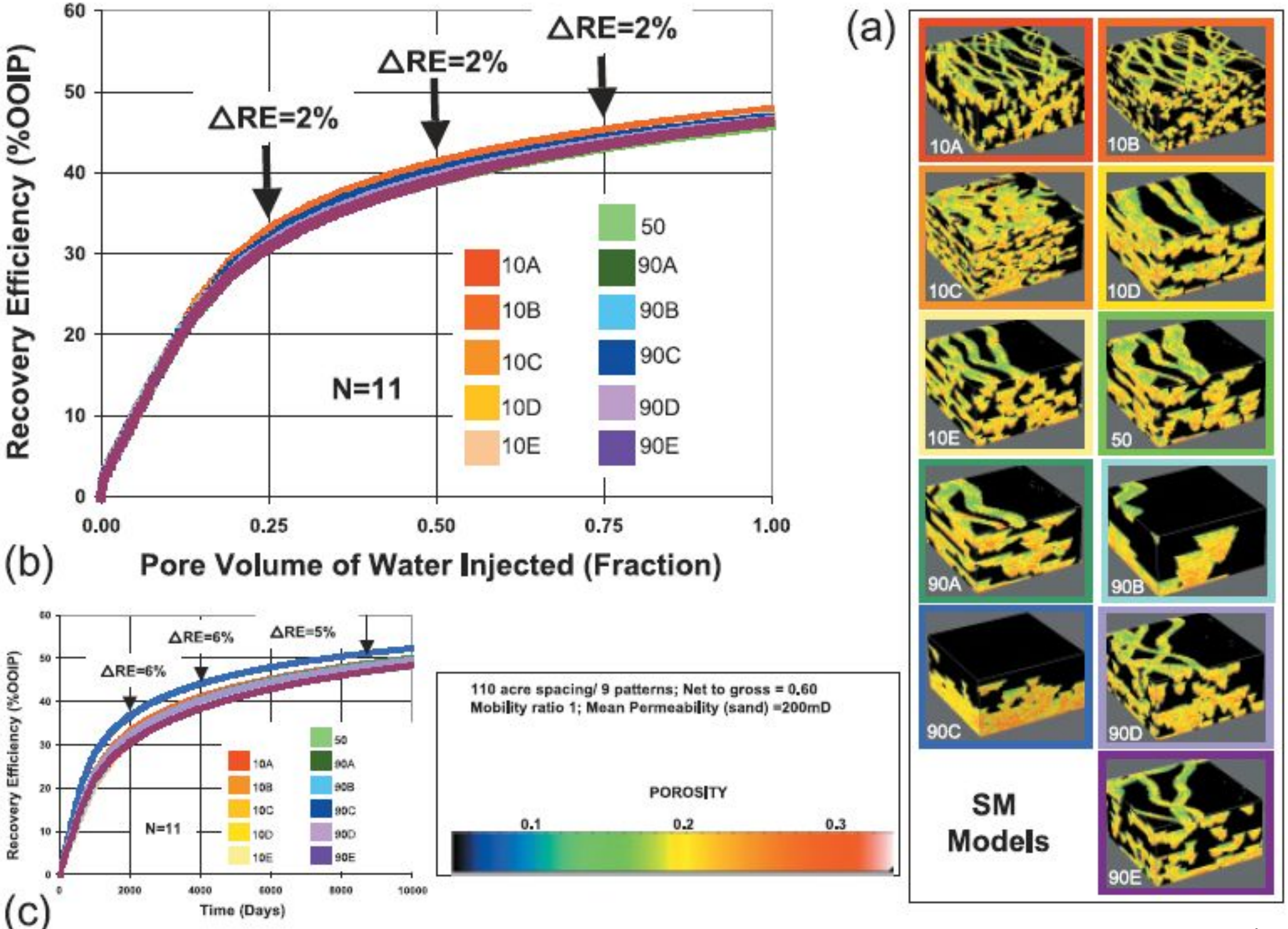
Larue and Friedman, 2005

30% NTG



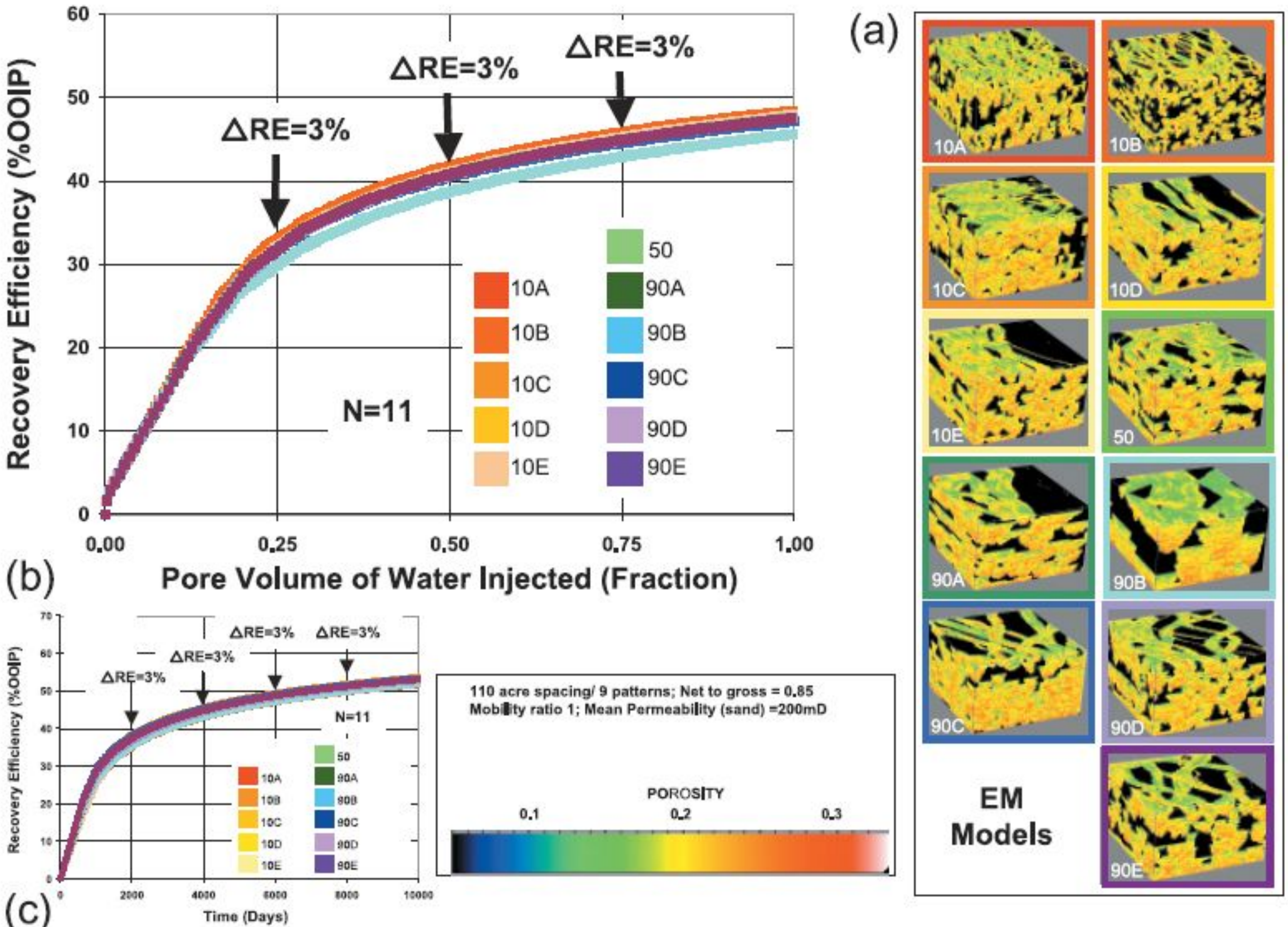
Larue and Friedman, 2005

60% NTG



Larue and Friedman, 2005

80% NTG

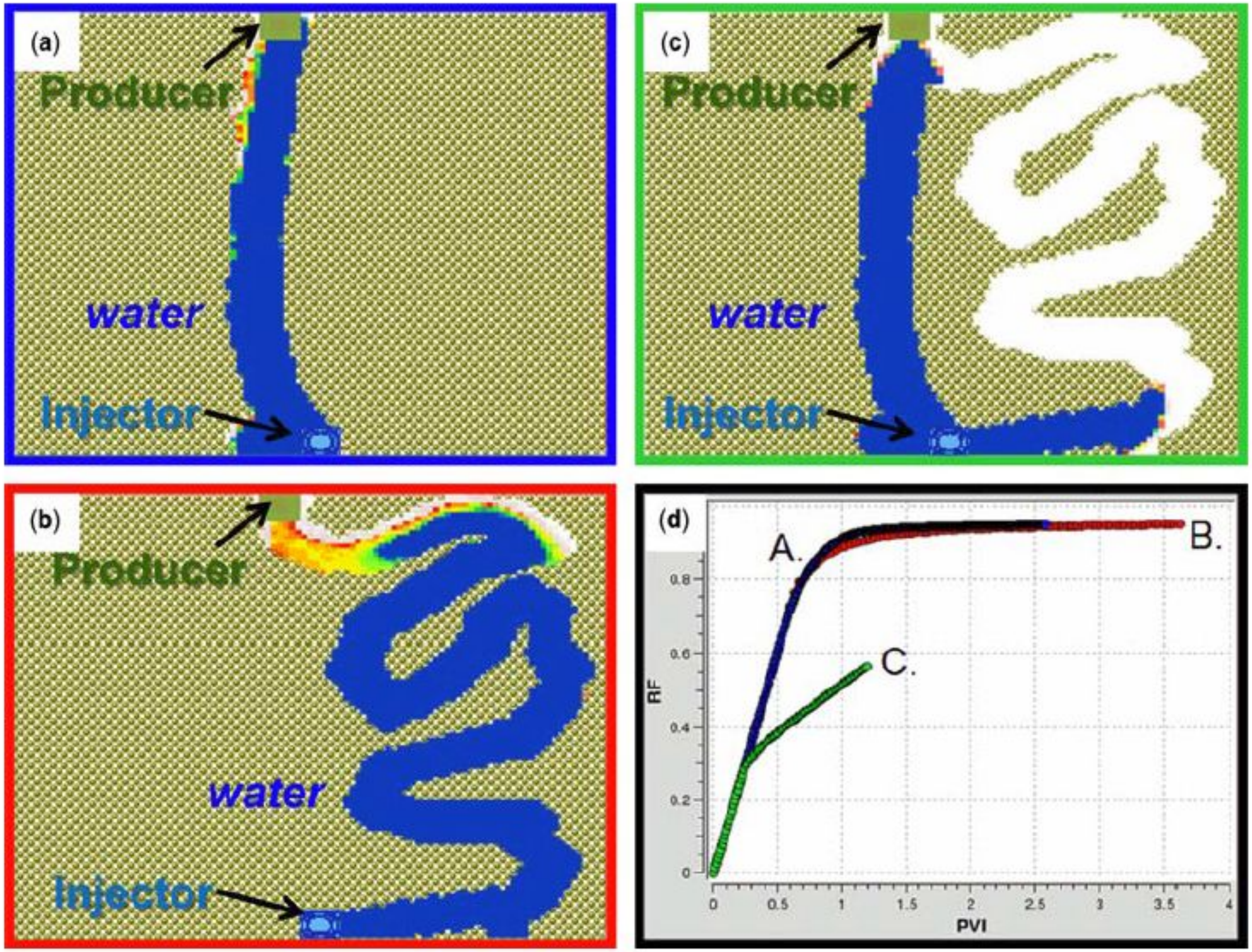


Larue and Friedman, 2005

Key factors affecting dynamic recovery

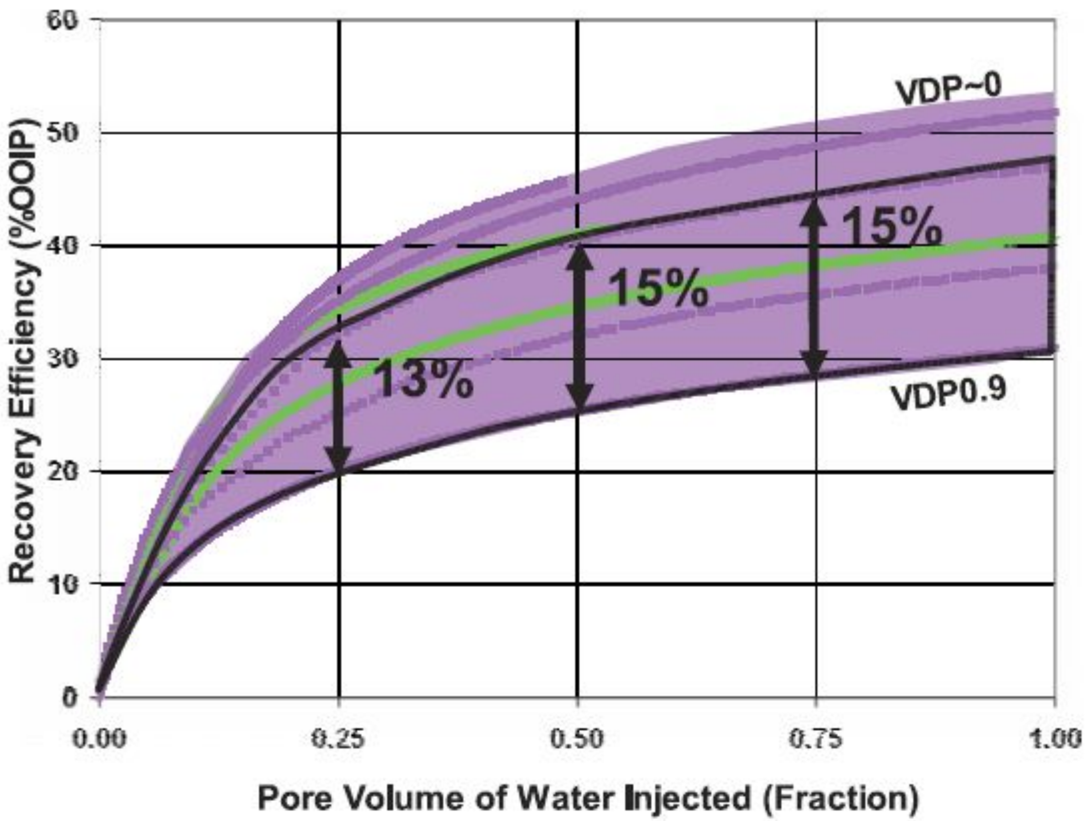
- Static connectivity
  - SHAPE OF S-CURVE
- Dynamic “addons”
  - Tortuosity
  - Permeability Heterogeneity
  - Inter-well distance
  - Fault connectivity
  - Fluid

Impact of tortuosity



Larue & Hovadik, 2006

Impact of permeability heterogeneity



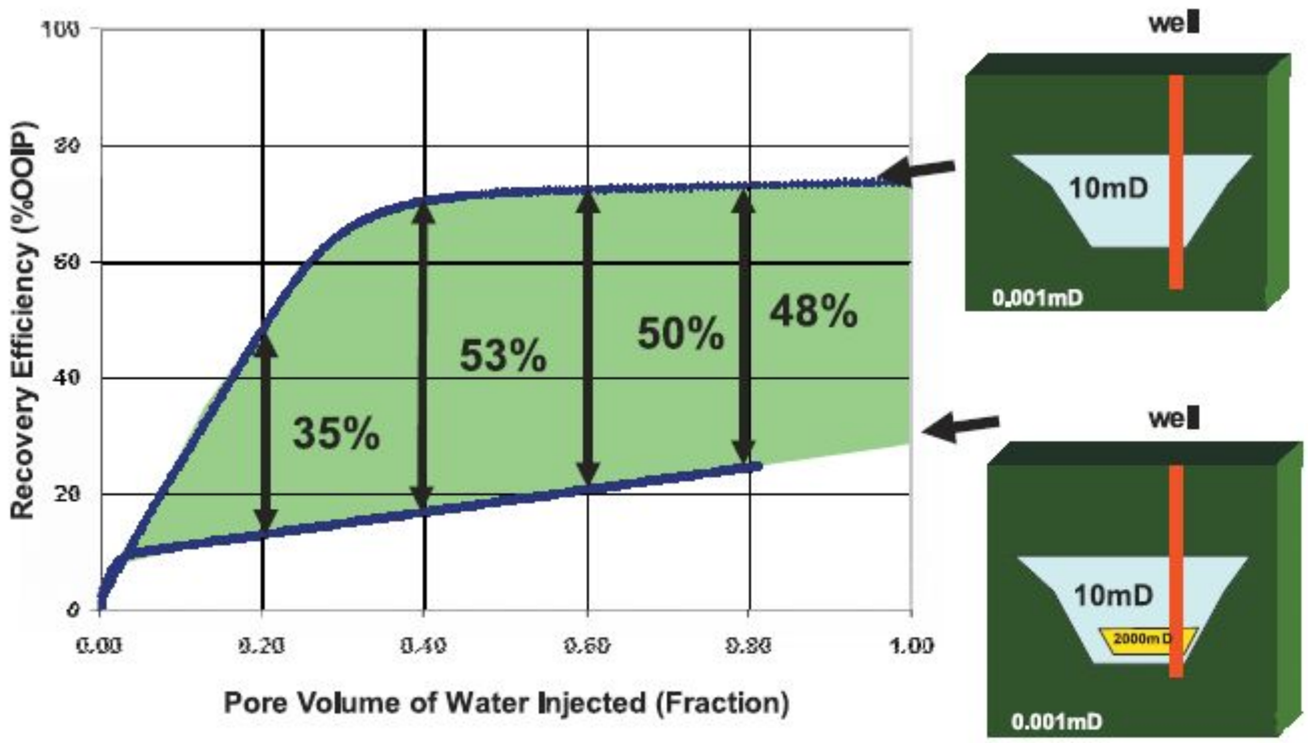
$$V_{dp} = (k_{50} - k_{84.1}) / k_{50}$$

where k_{50} is median permeability and

$k_{84.1}$ is the 84.1 percentile

Larue and Friedman, 2005

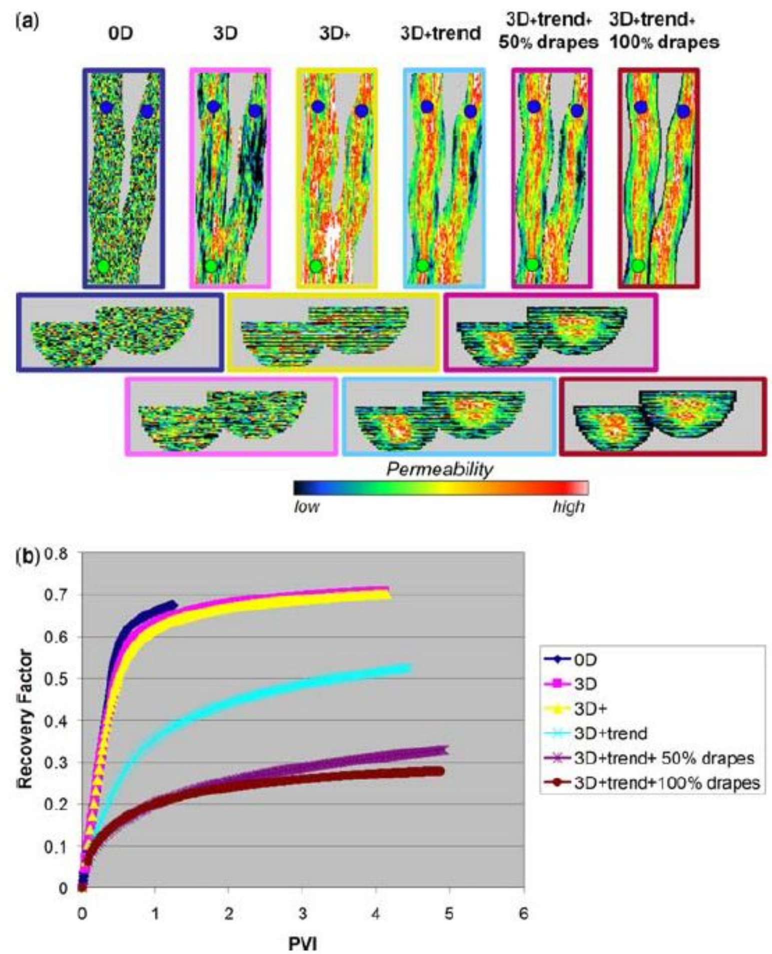
Thief zone impact on recovery



Larue and Friedman, 2005

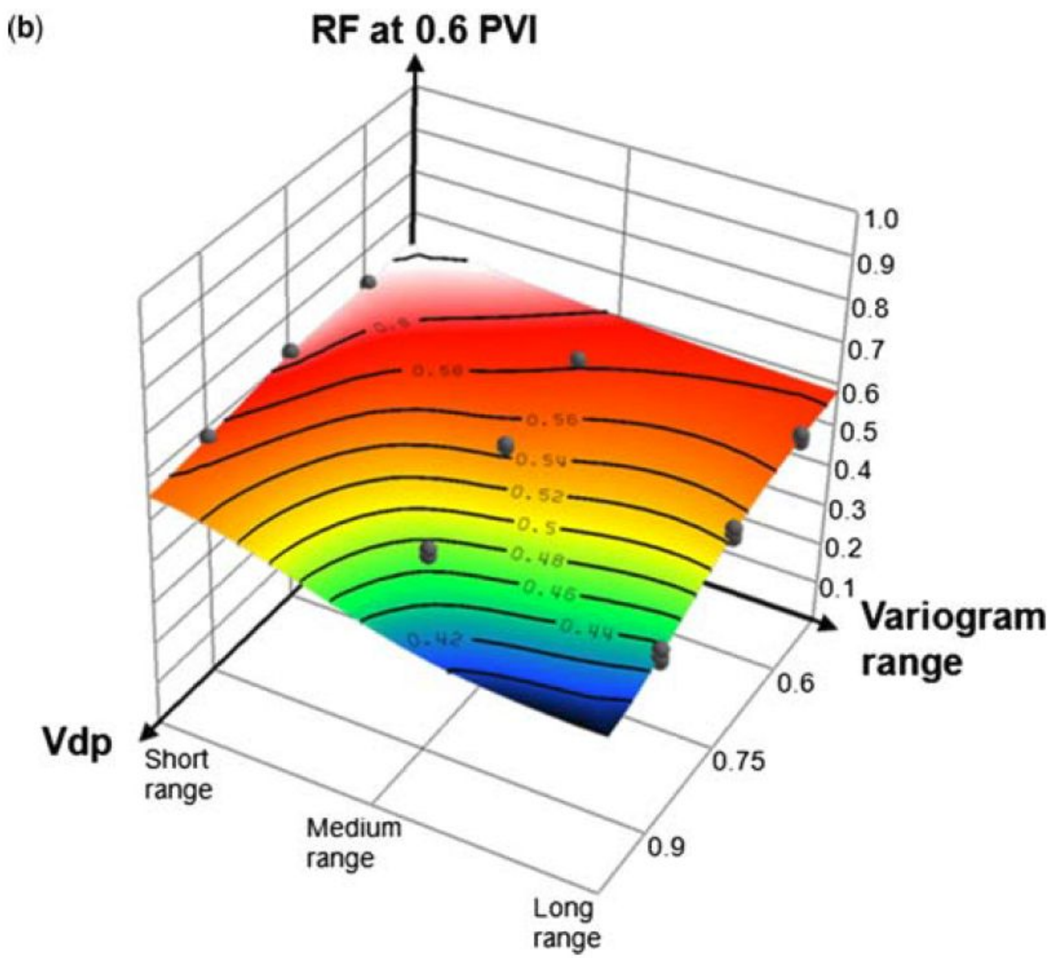
Permeabilty heterogeneity impact

- Small difference between 0D (nugget) and 3D (variogram) models
- Add trend to increase K at centre = reduced recovery
- Add drapes and both K variability and tortuosity increase
- Compartmentalisation from mud drapes Further reduces recovery



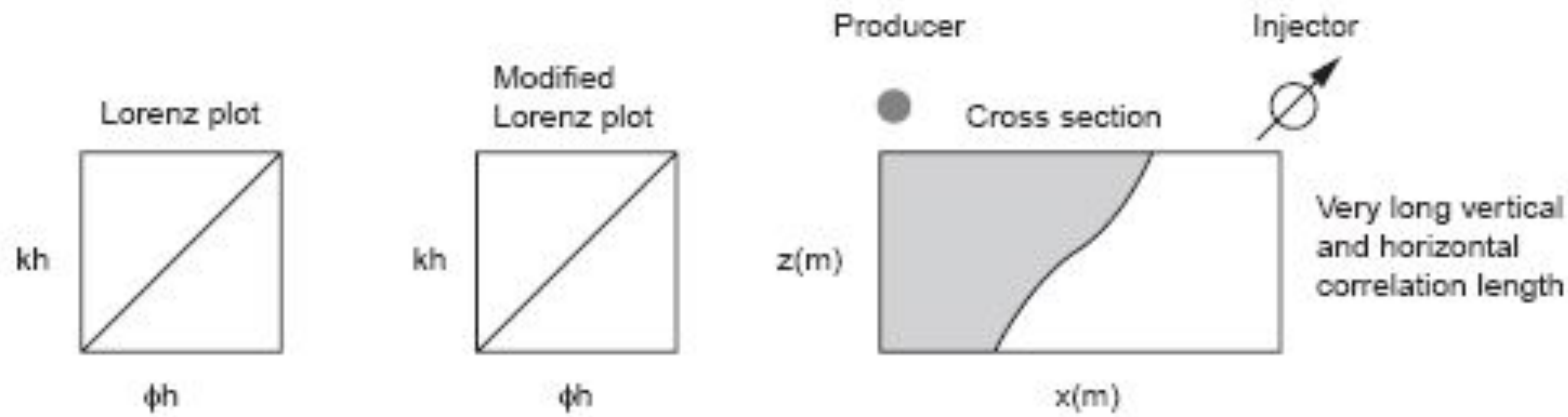
Hovadik & Larue, 2010

Variogram range and Vdp combined

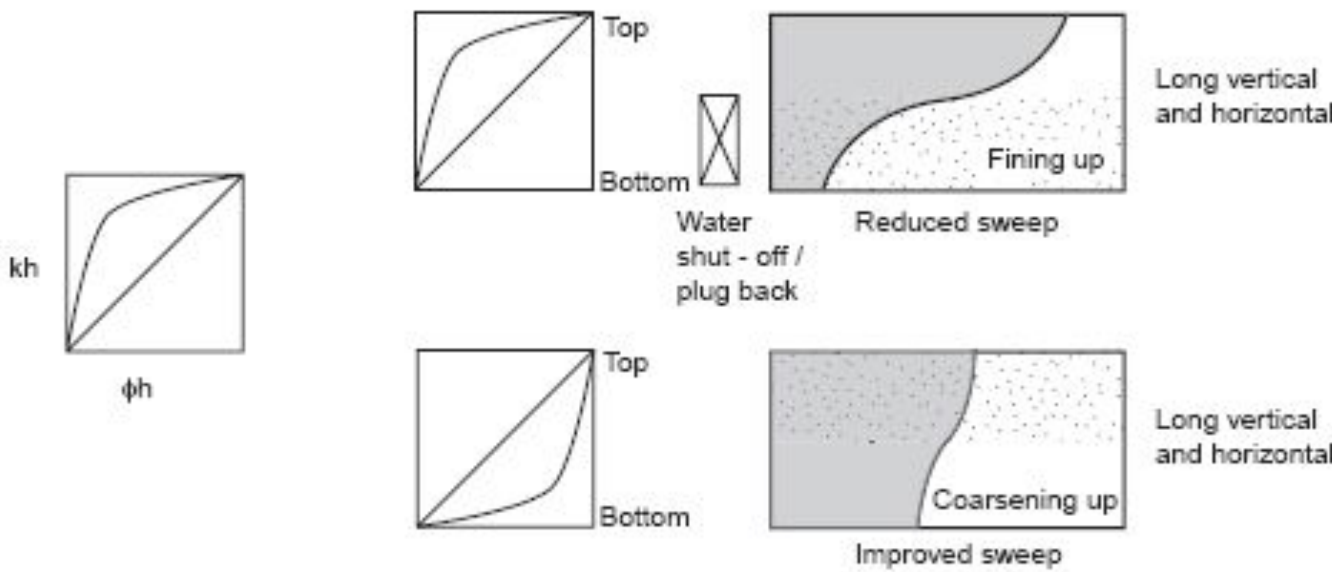


Hovadik & Larue, 2010

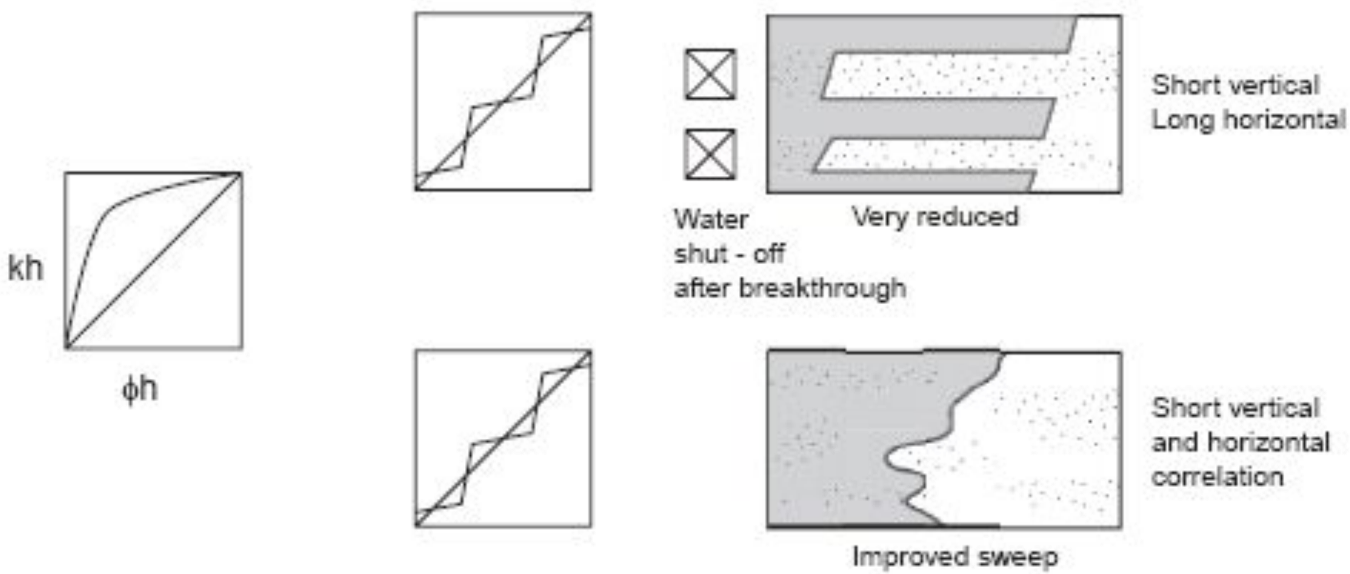
Reservoir Sweep



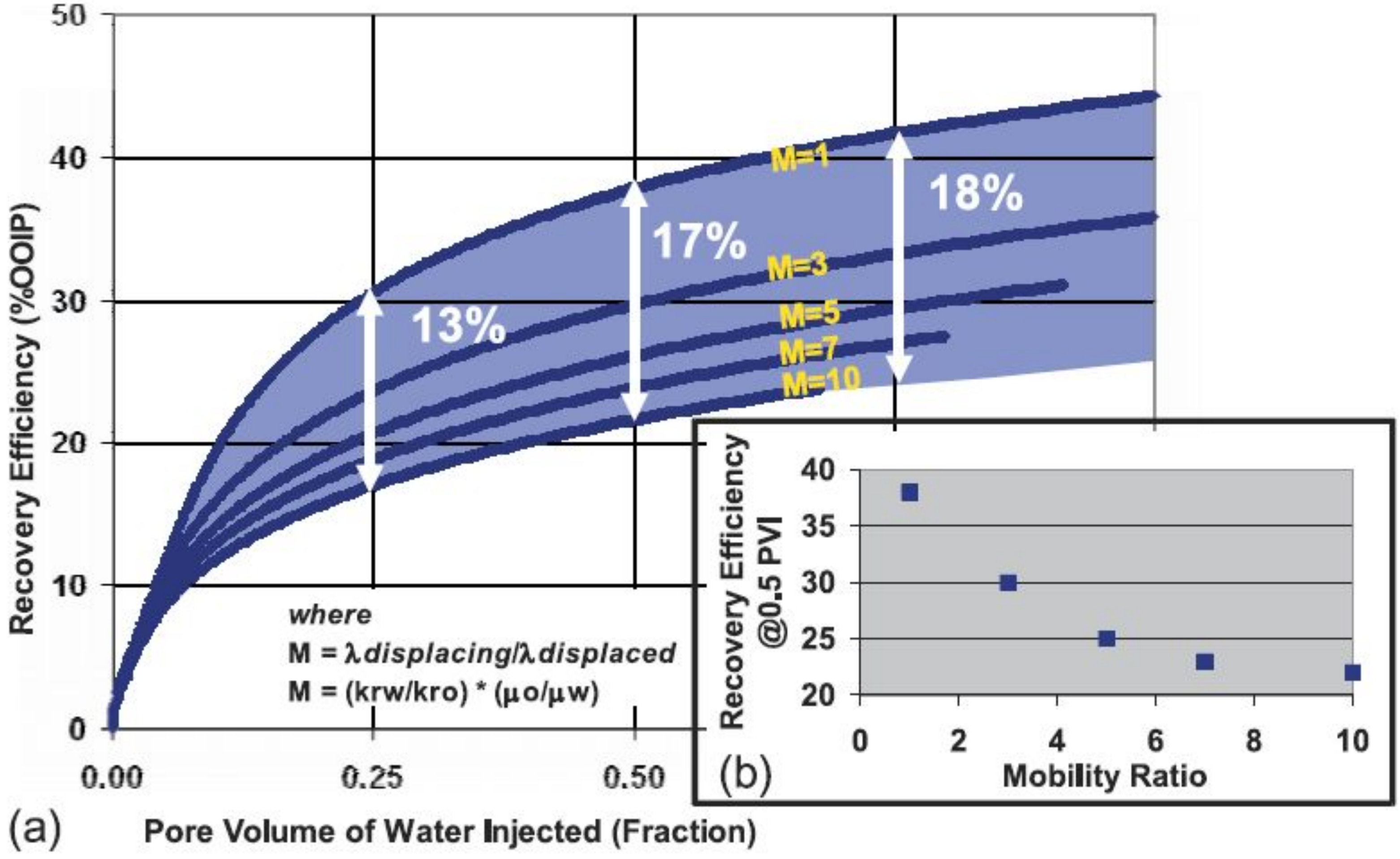
Reservoir Sweep



Reservoir Sweep

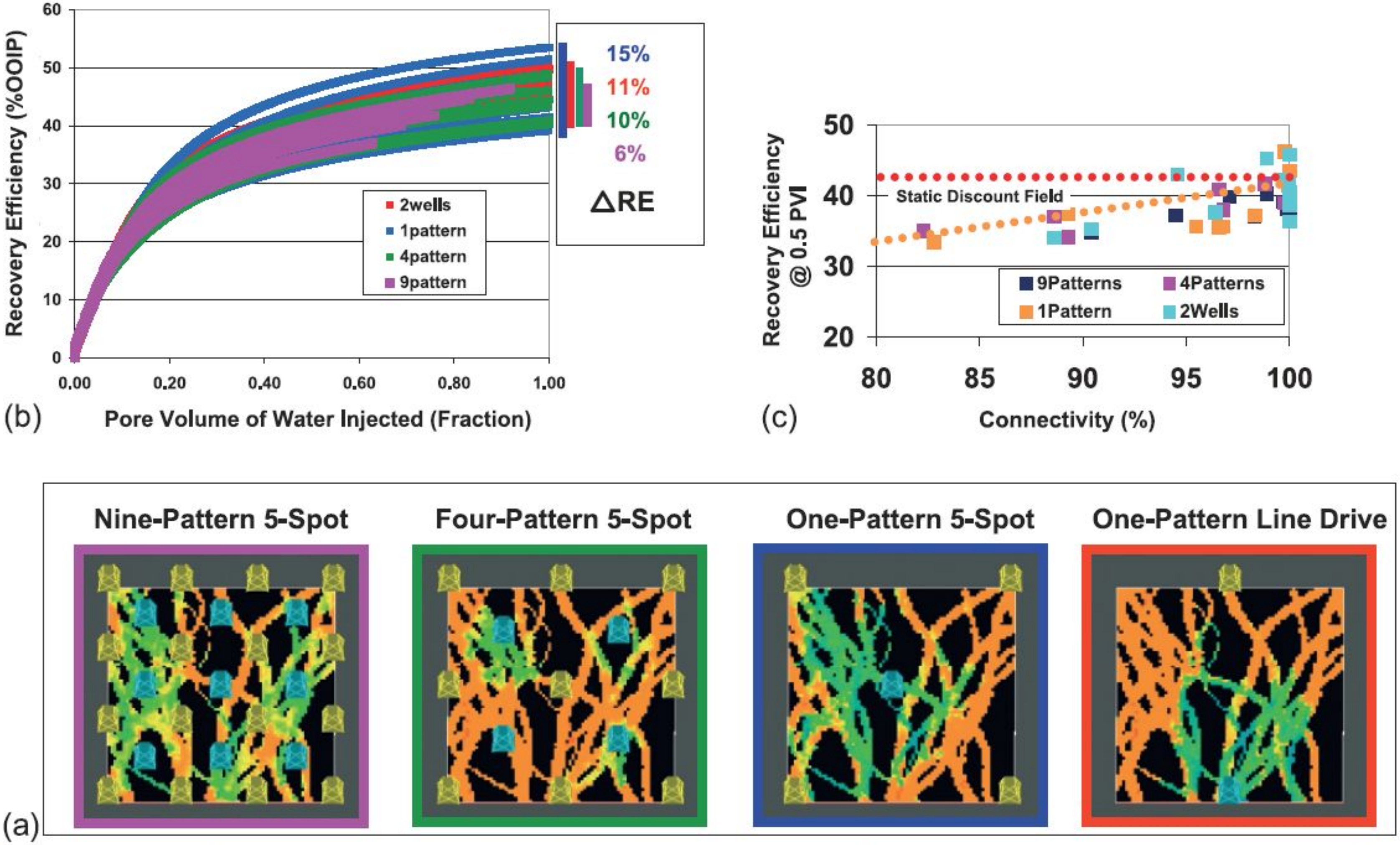


Impact of mobility ratio



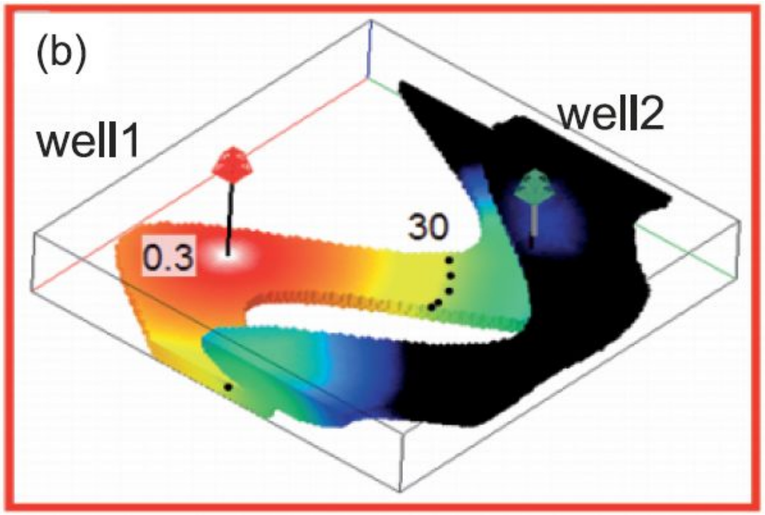
Larue and Friedman, 2005

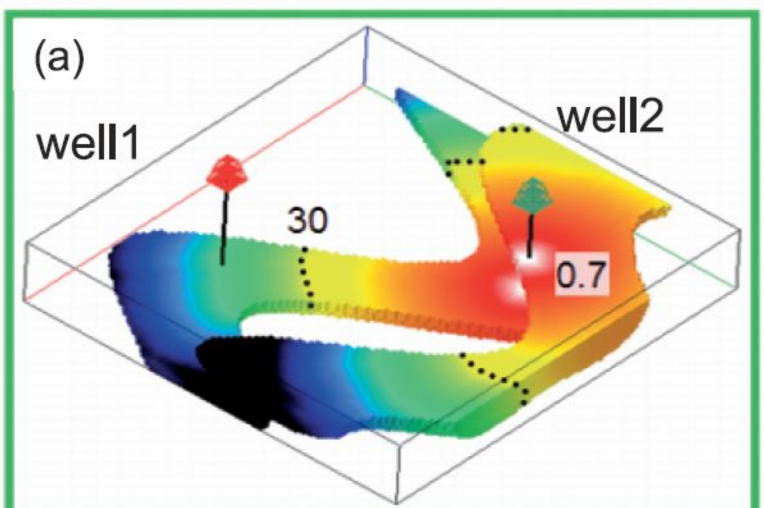
Impact of well pattern

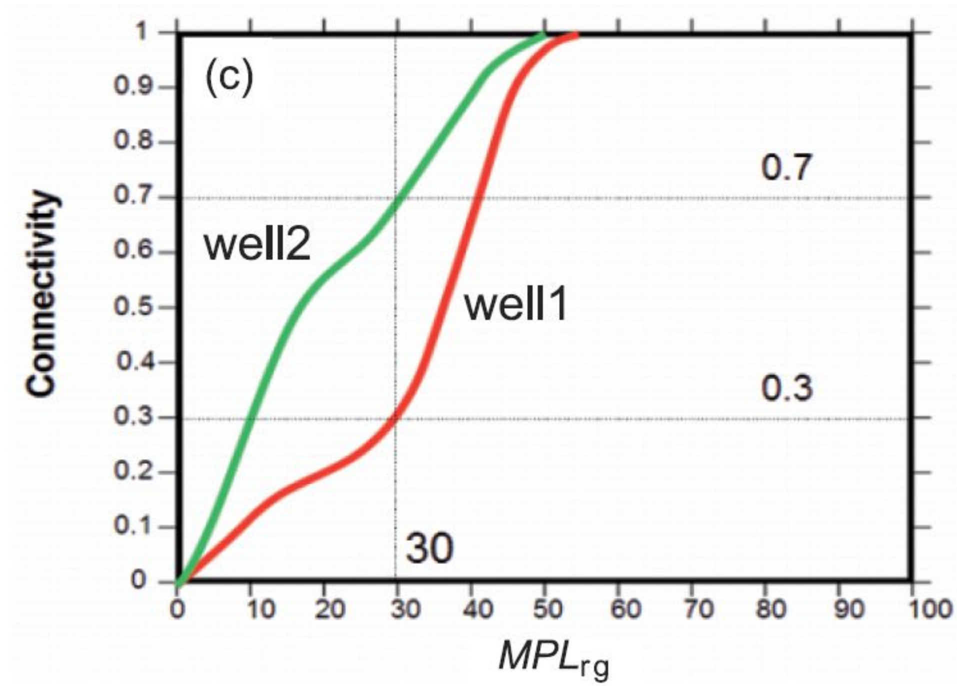


Larue and Friedman, 2005

Well distance impact on recovery (dynamic connectivity)

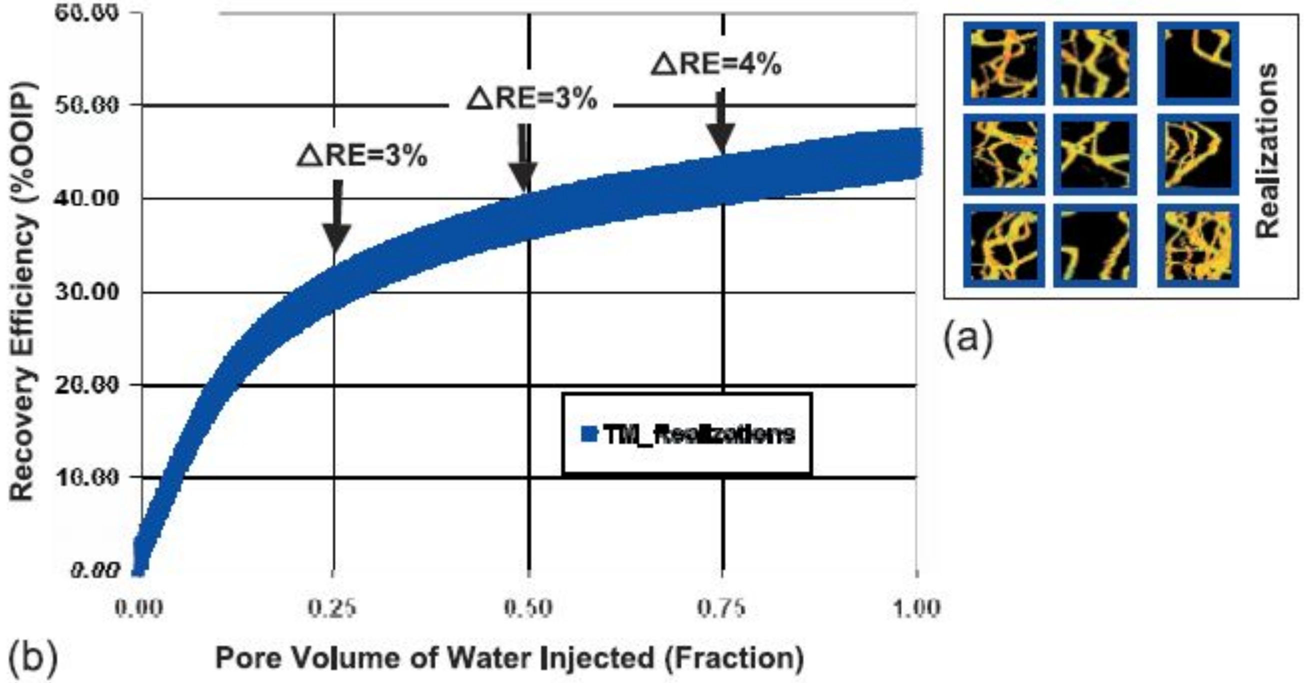






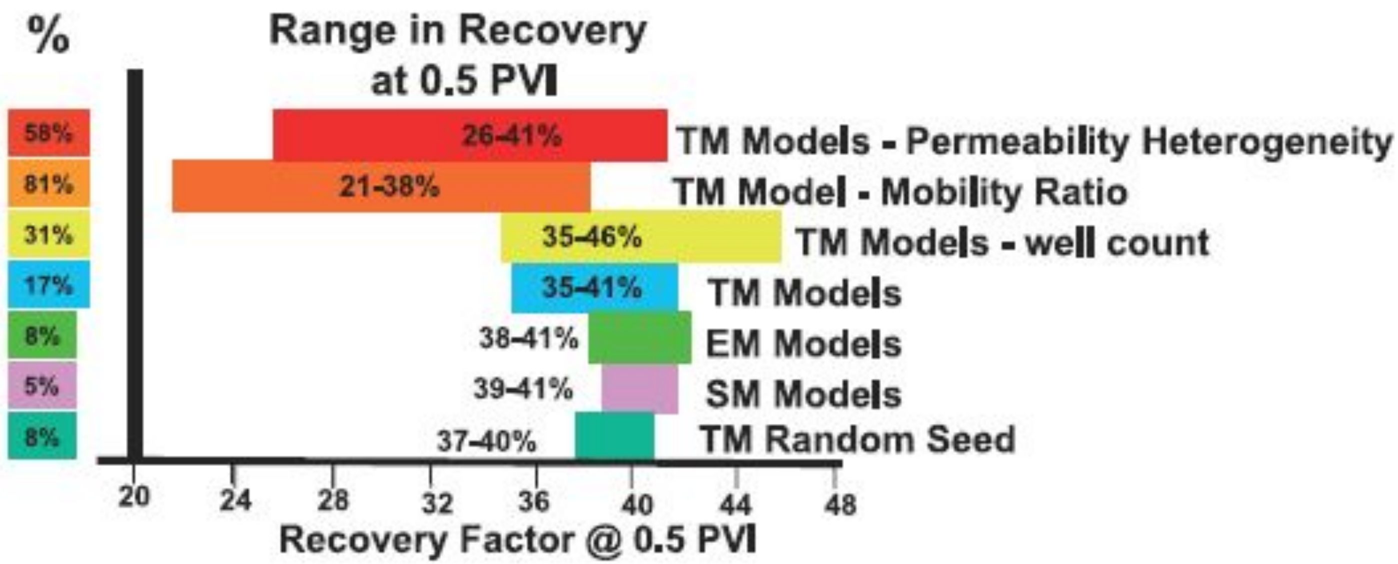
Hovadik & Larue, 2010

Does seed really account for uncertainty?



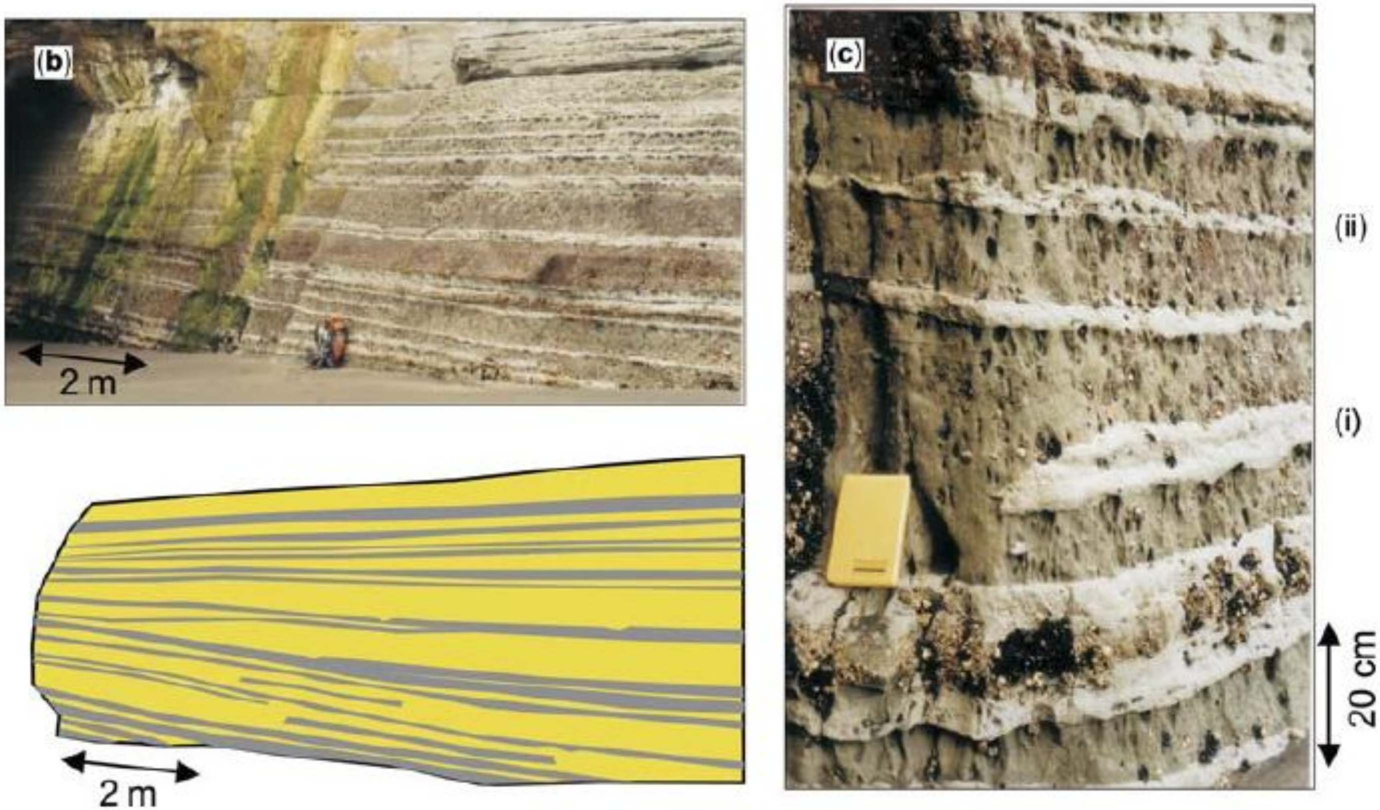
Larue and Friedman, 2005

What matters in your reservoir?



Larue and Friedman, 2005

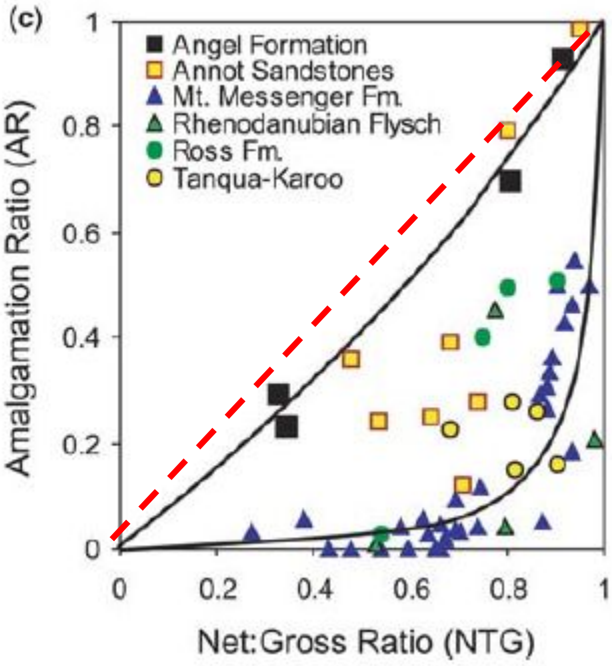
Extreme edge cases: High NTG + Low Connectivity



Manzocchi et al, 2007

NTG vs Amalgamation Ratio

- NTG and Amalgamation ratio do not corellate in real systems (e.g. turbidites)
  - High NTG vs Low AR
- Object models



Manzocchi et al, 2007

How will NTG correlate with AR in an Object model?

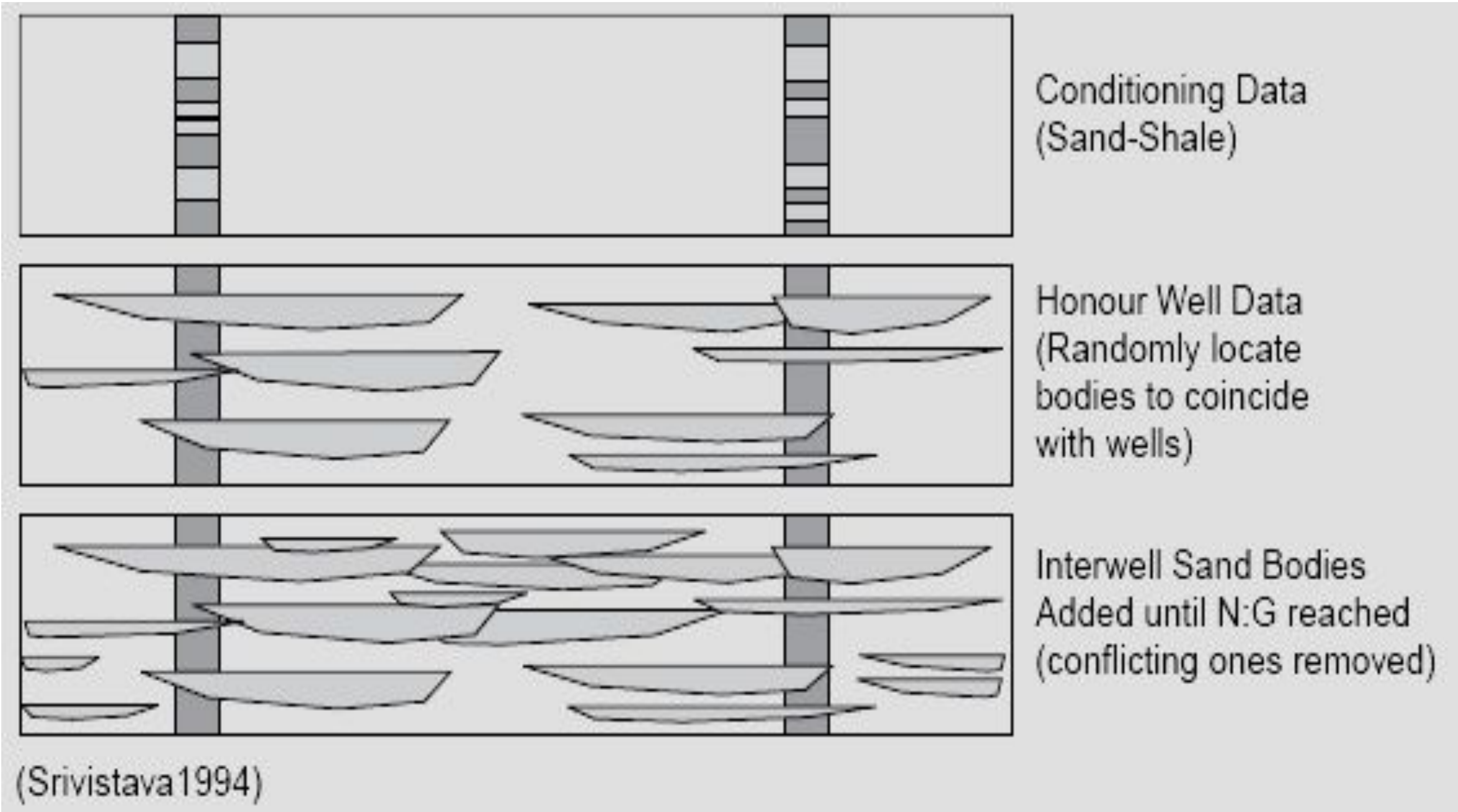
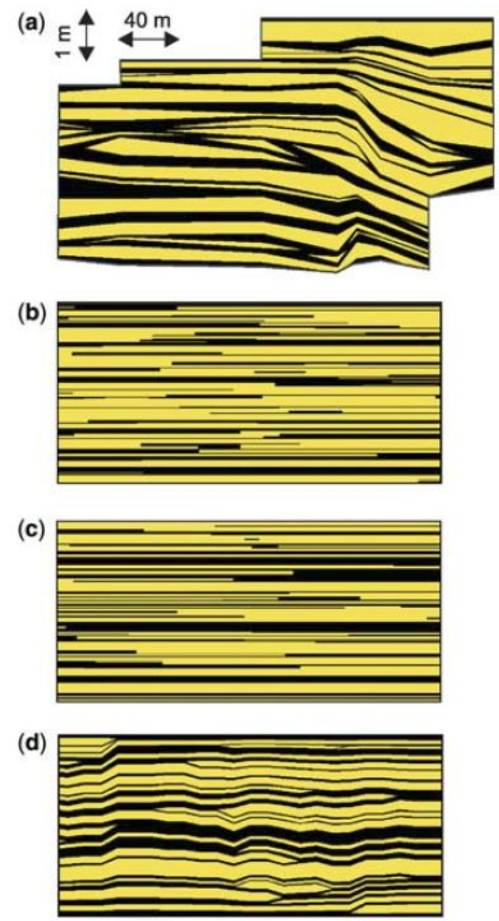


Illustration of Sequential
Object Based Algorithm (Srivastava 1994)

Geostatistical modelling conditioned to NTG

- High NTG system has short continuity of sandbodies vertically and laterally (<20%)
  - Beds terminate early
  - Shales laterally extensive
  - LOW Amalgamation ratio
- Modelling using Objects
  - (b) sand in shale background
  - (c) shale in sand background
  - Neither honour AR of system
  - Need to model with additional AR parameter (d)
- Standard Geostats methods won't capture the shift to 2D connectivity due to low AR



Manzocchi et al, 2007

Overview of connectivity

NTG

30

The threshold at which a reservoir commonly starts to connect in 3D

NTG

60

The percolation threshold for a 2D model.

Impact of Geology

Geological features can shift curve to left or right, from 3D to 2D behaviour

Geobody size

The average recovery from reservoirs independent of geology

Total Recovery

A+B

Is the sum of the connected volume (A) and recovery factor (B)

More wells

Increases recovery by increasing the connected volume.

Lower Mobility

Lowers recovery as oil viscosity allows for faster water movement.

High Vdp

High permeability heterogeneity greatly reduces recovery.

NTG >35%

Has little impact on recovery factor above the percolation threshold

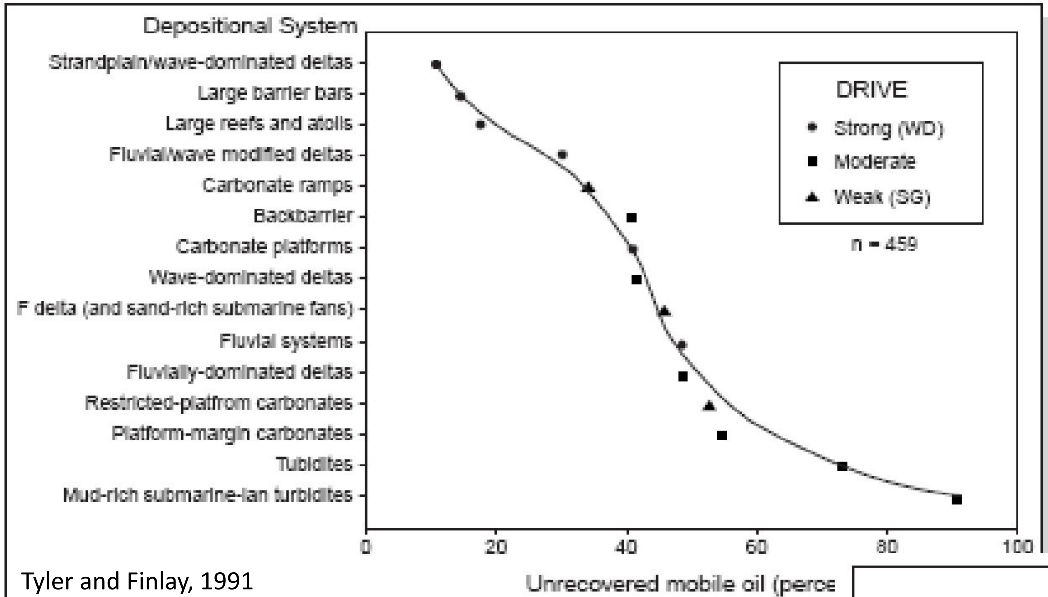
Seed

Has little impact on recovery globally, only local variations for wells.

Maximise value through…

IMPROVED RECOVERY

Recovery Factors



Tyler and Finlay, 1991

Depends on Geology

and Drive Mechanism

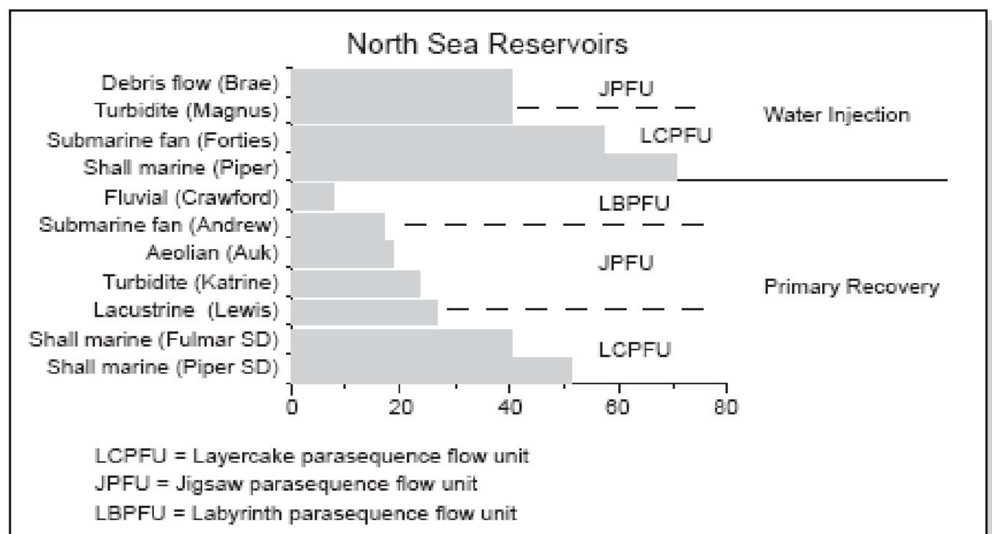
Solution gas drive 5-30%

Gas cap drive 20-40%

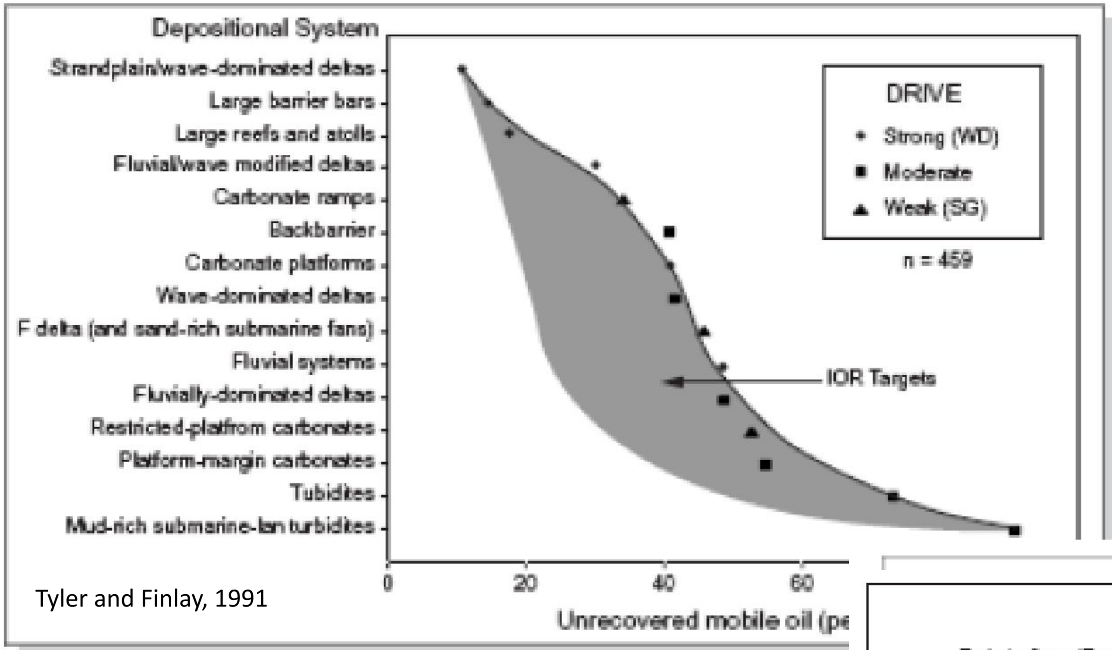
Water drive 35-75%

Gravity drainage 5-30%

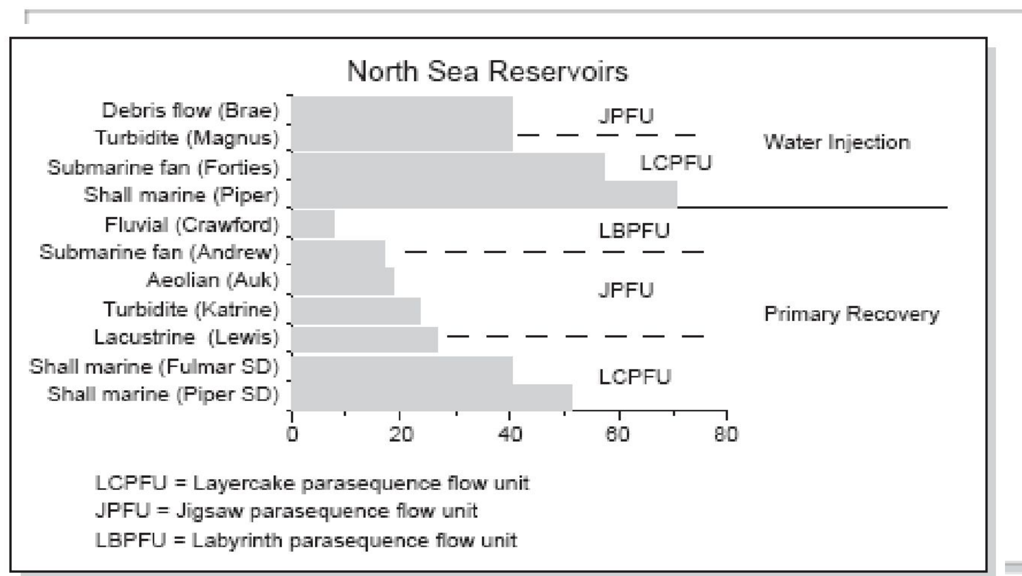
(after Sills, AAPG Methods 10, 1992)



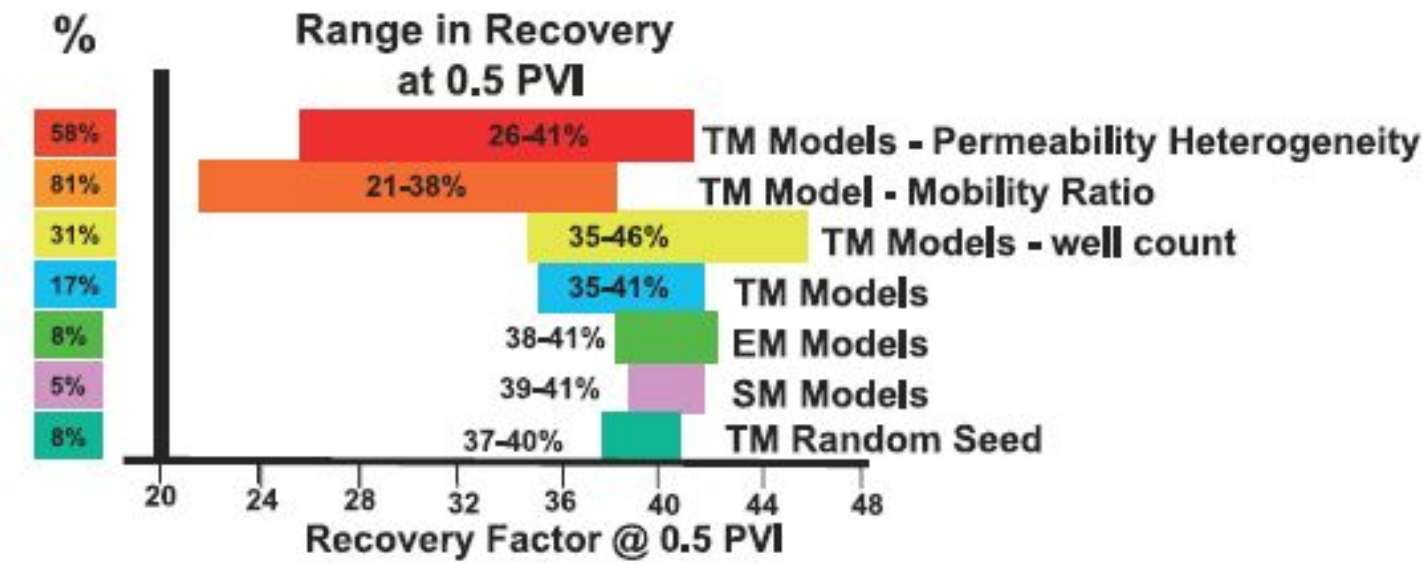
Improved Recover Factors



Tyler and Finlay, 1991

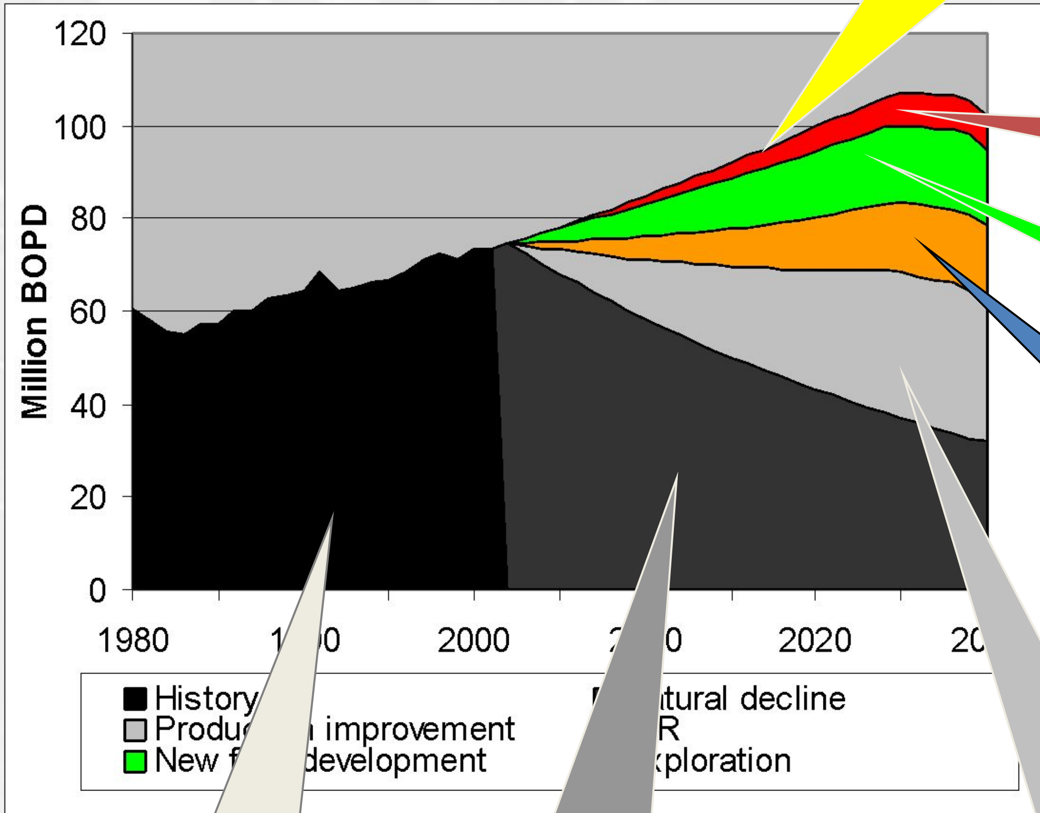


What can we adjust to improve recovery?



Petroleum Industry Drivers

STATOIL



Demand growth

Exploration success

New field developments

Reserve growth; IOR and EOR

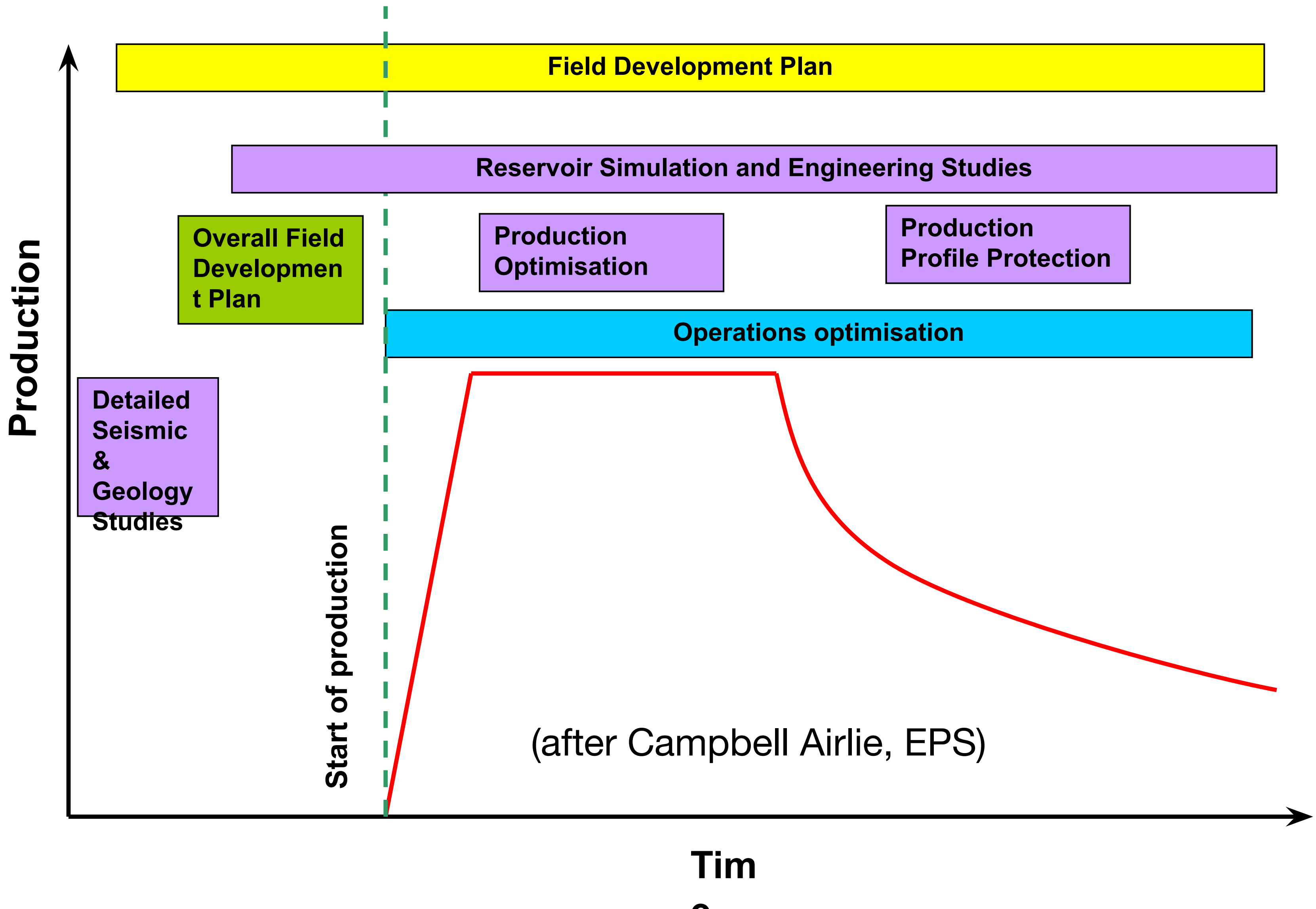
Evaluation of history, IHS data base

Natural decline “as is”

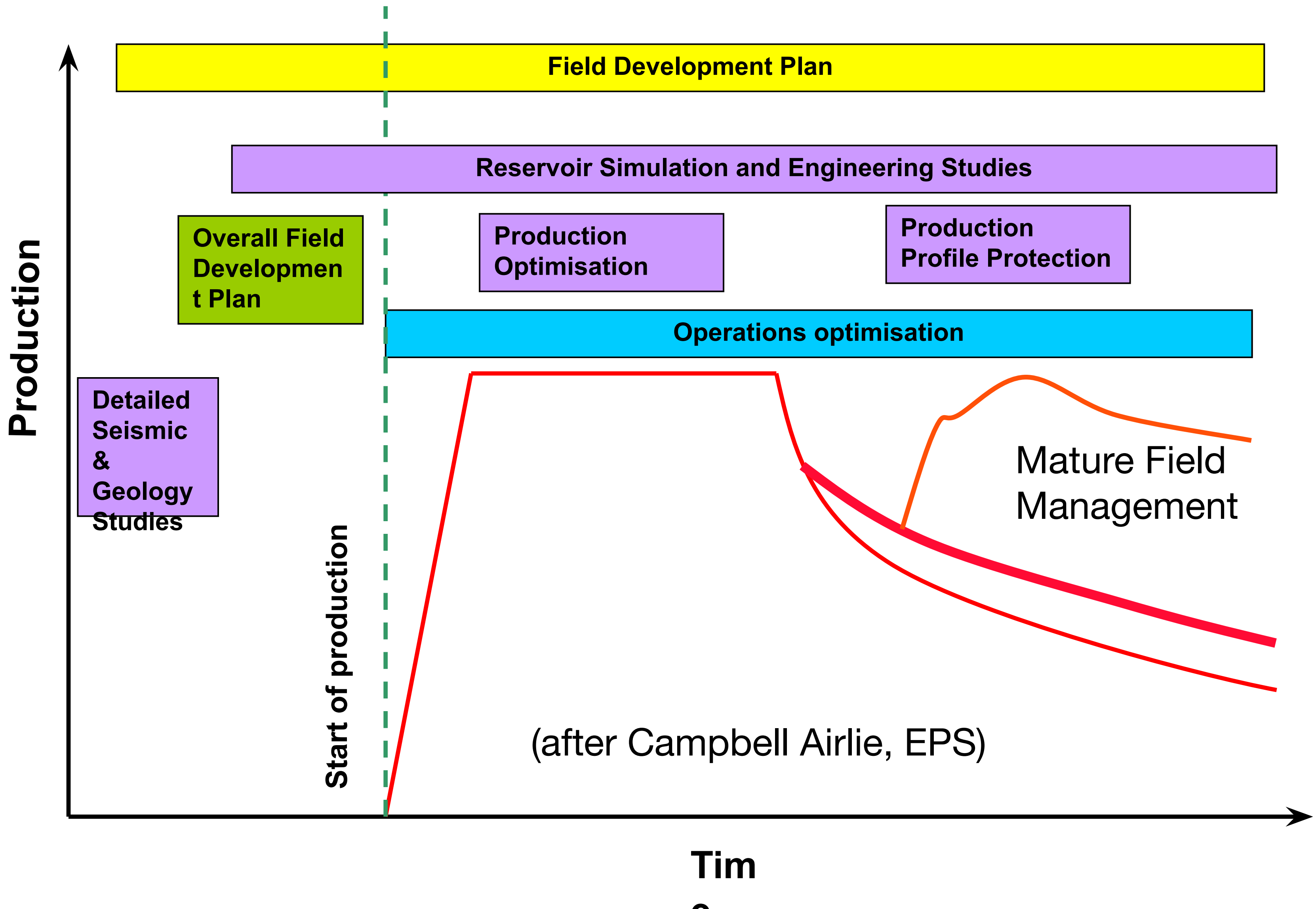
Production efficiency

From Meling, 2004

Production Capacity Increase in Mature Fields



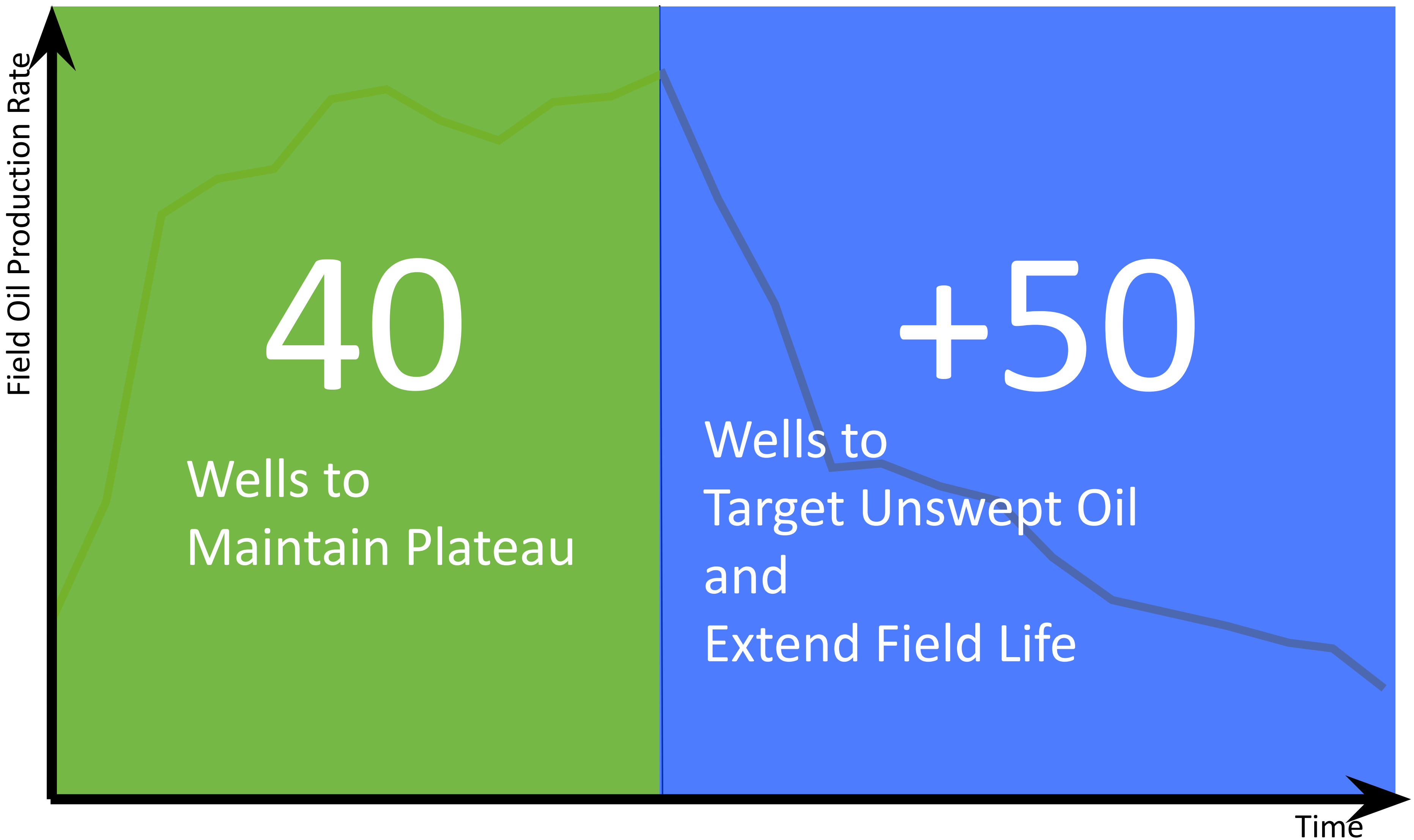
Production Capacity Increase in Mature Fields



Example of….

INFILL DRILLING

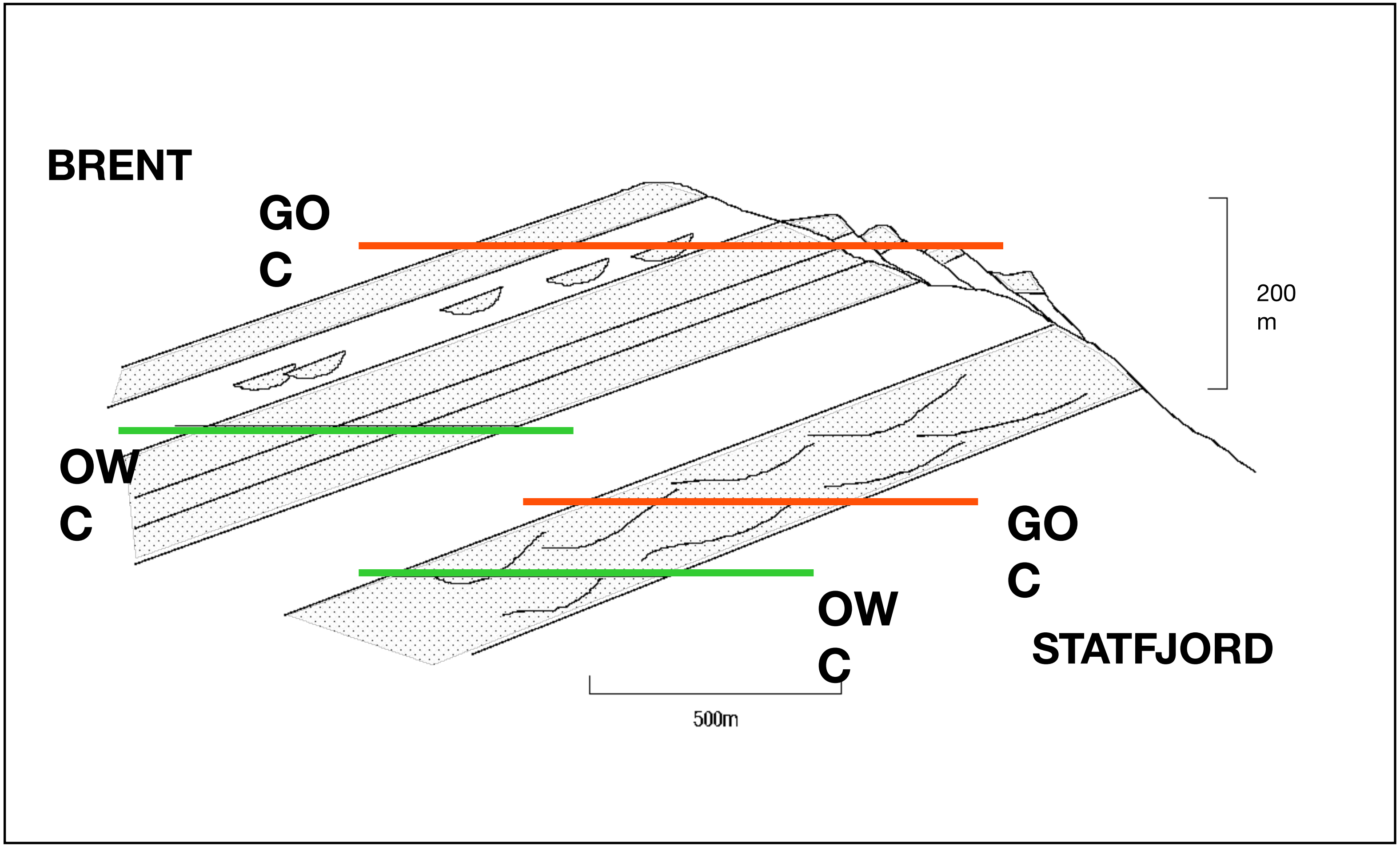
A typical example of the north sea



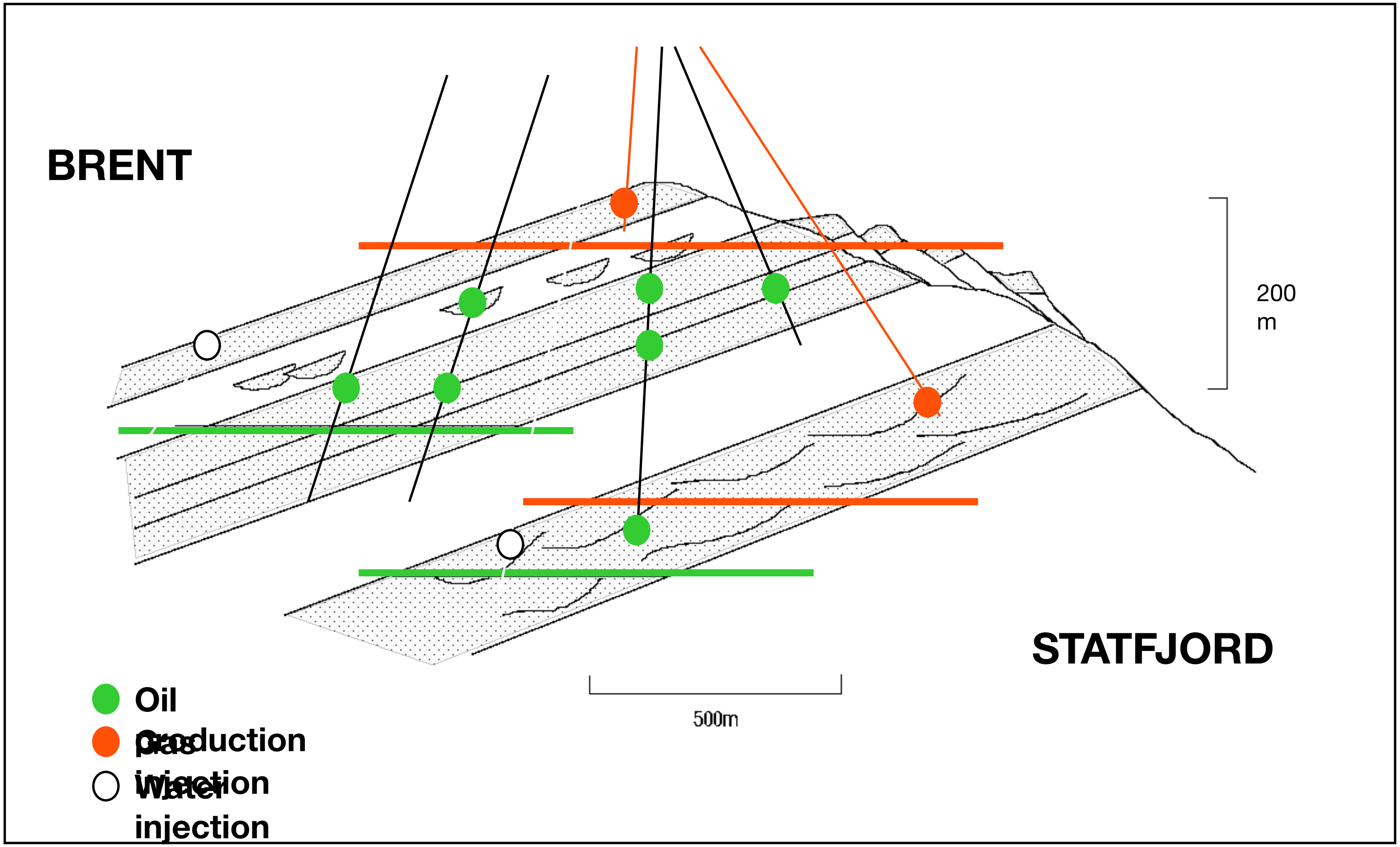
RM Example 1

- Strategy for Statfjord
  - Aadland et al., 1994
- High well activity
- Horizontal wells
- Reservoir simulation
- Proactive
- Investment for future

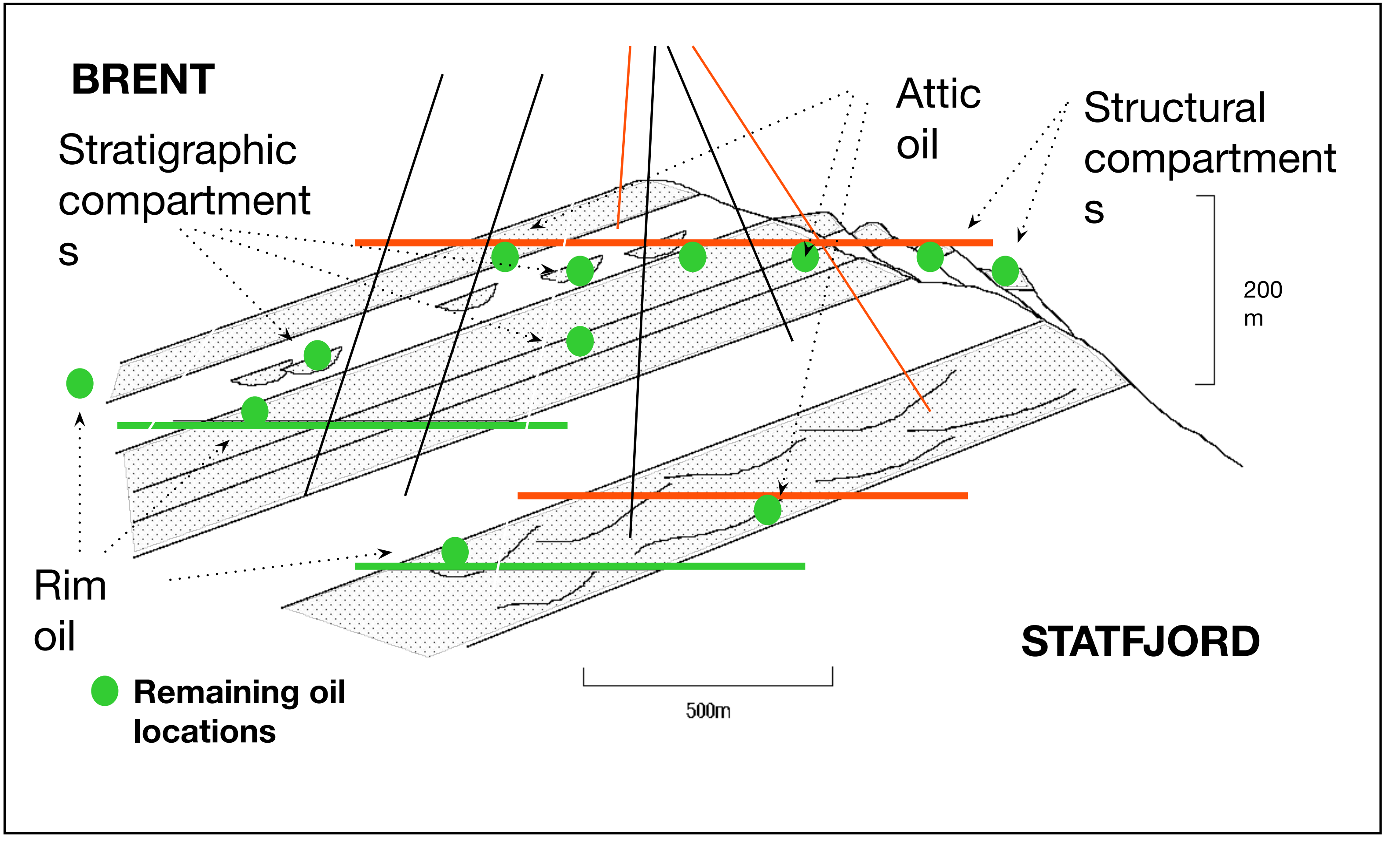
Statfjord Field - cross section



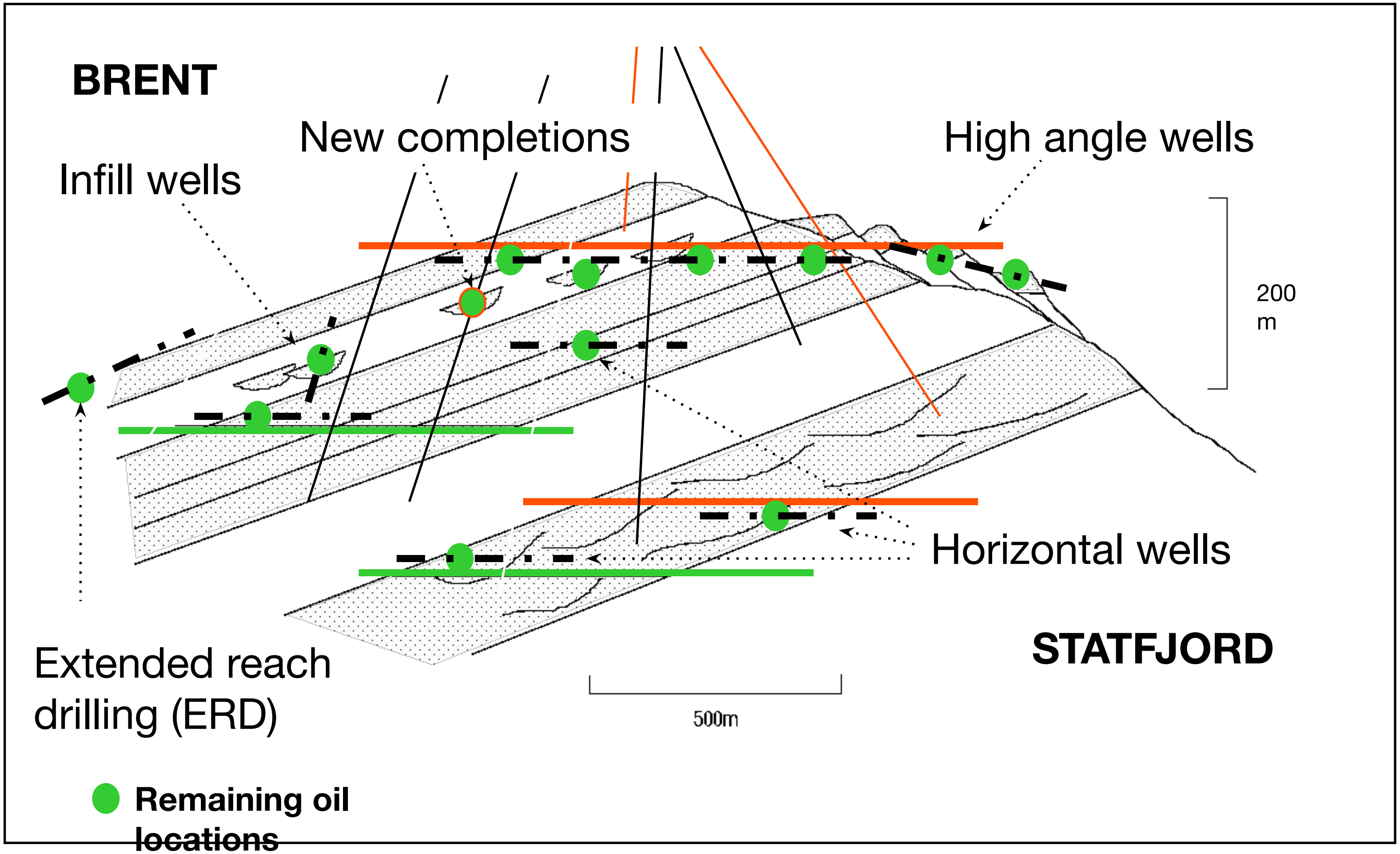
Statfjord Field - initial production plan



Statfjord Field - Remaining oil

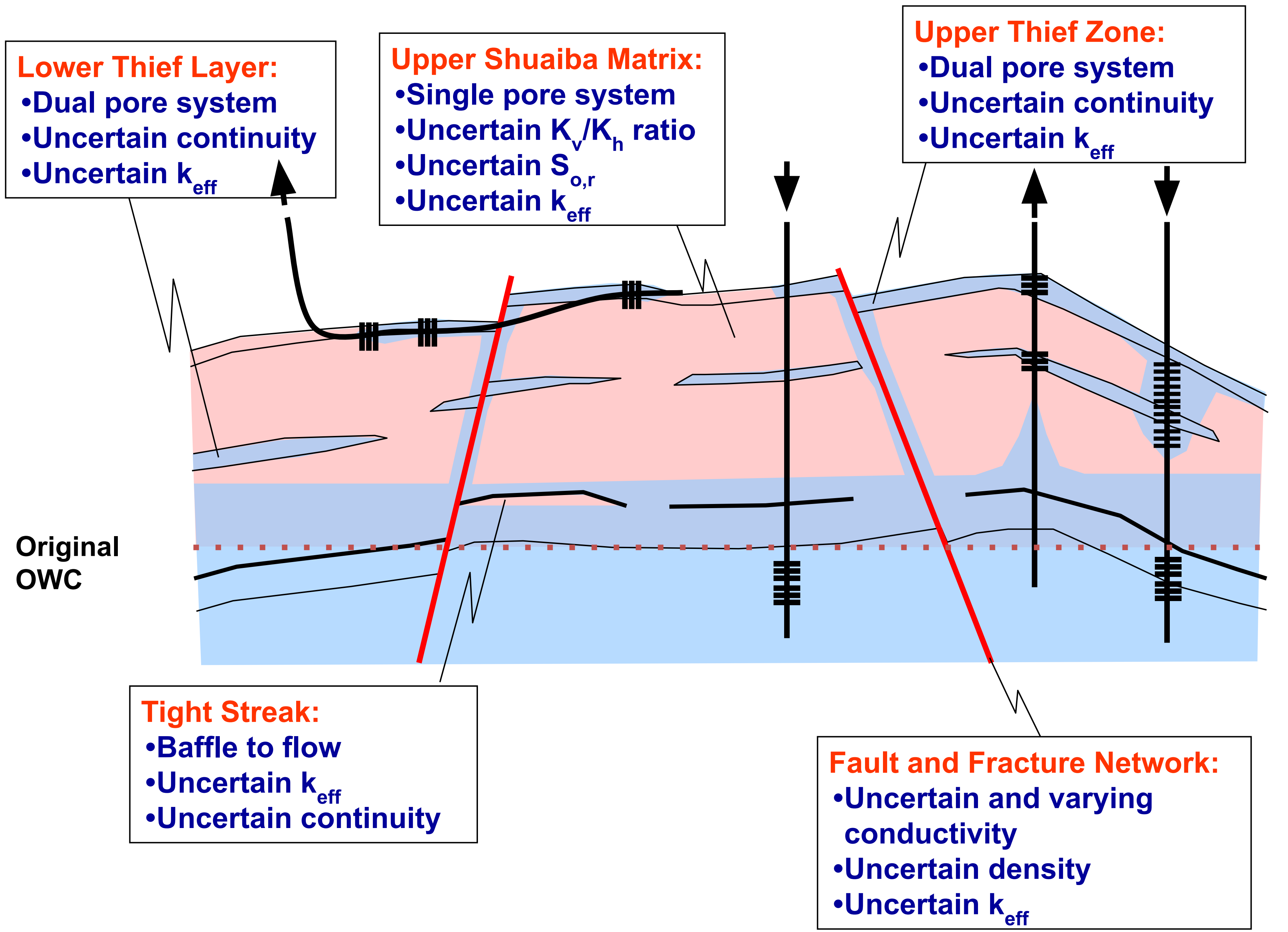


Statfjord Field - New opportunities



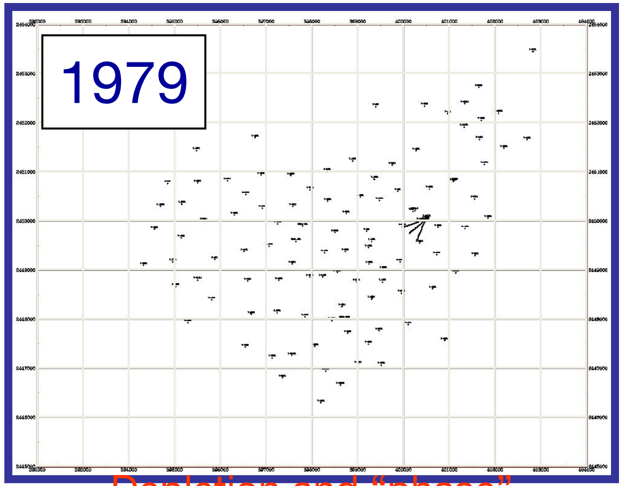
Example: Yibal Field, Oman

- Strategy for Yibal Field, Oman
- Horizontal wells
- Bypassed oil in a Carbonate

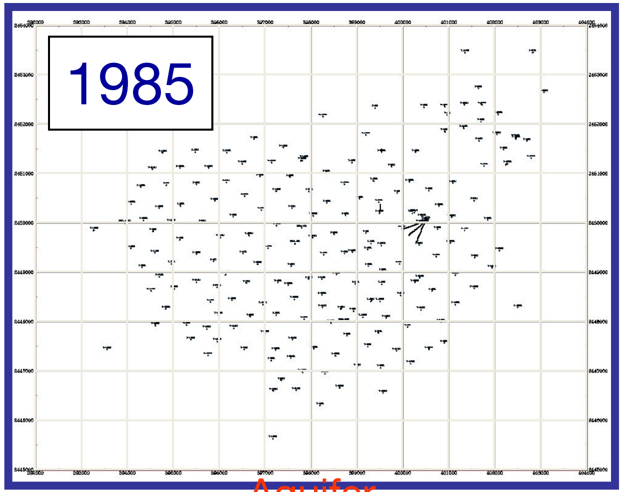


Lower Thief Layer:
•Dual pore system
•Uncertain continuity
•Uncertain k_{eff}
Upper Shuaiba Matrix:
•Single pore system
•Uncertain K_v/K_h ratio
•Uncertain $S_{o,r}$
•Uncertain k_{eff}
Upper Thief Zone:
•Dual pore system
•Uncertain continuity
•Uncertain k_{eff}
Original OWC
Tight Streak:
•Baffle to flow
•Uncertain k_{eff}
•Uncertain continuity
Fault and Fracture Network:
•Uncertain and varying conductivity
•Uncertain density
•Uncertain k_{eff}

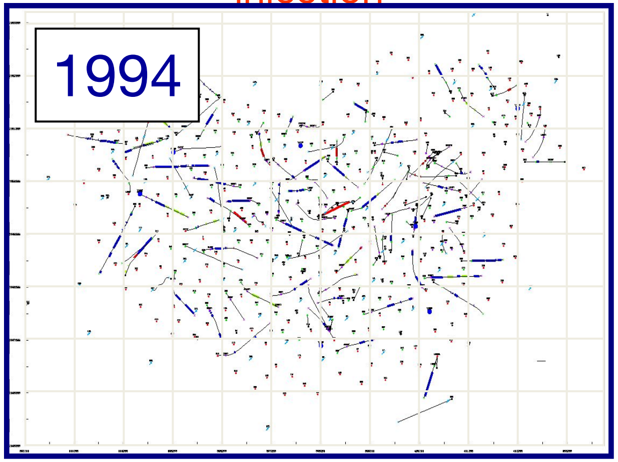
Yibal Field Development History



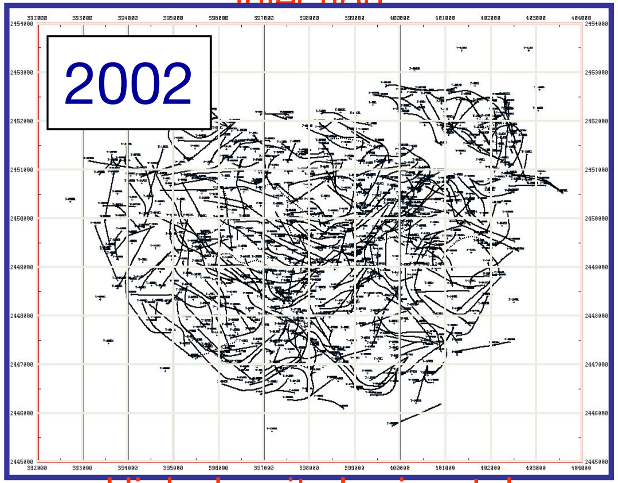
Depletion and "phase" injection



Aquifer injection



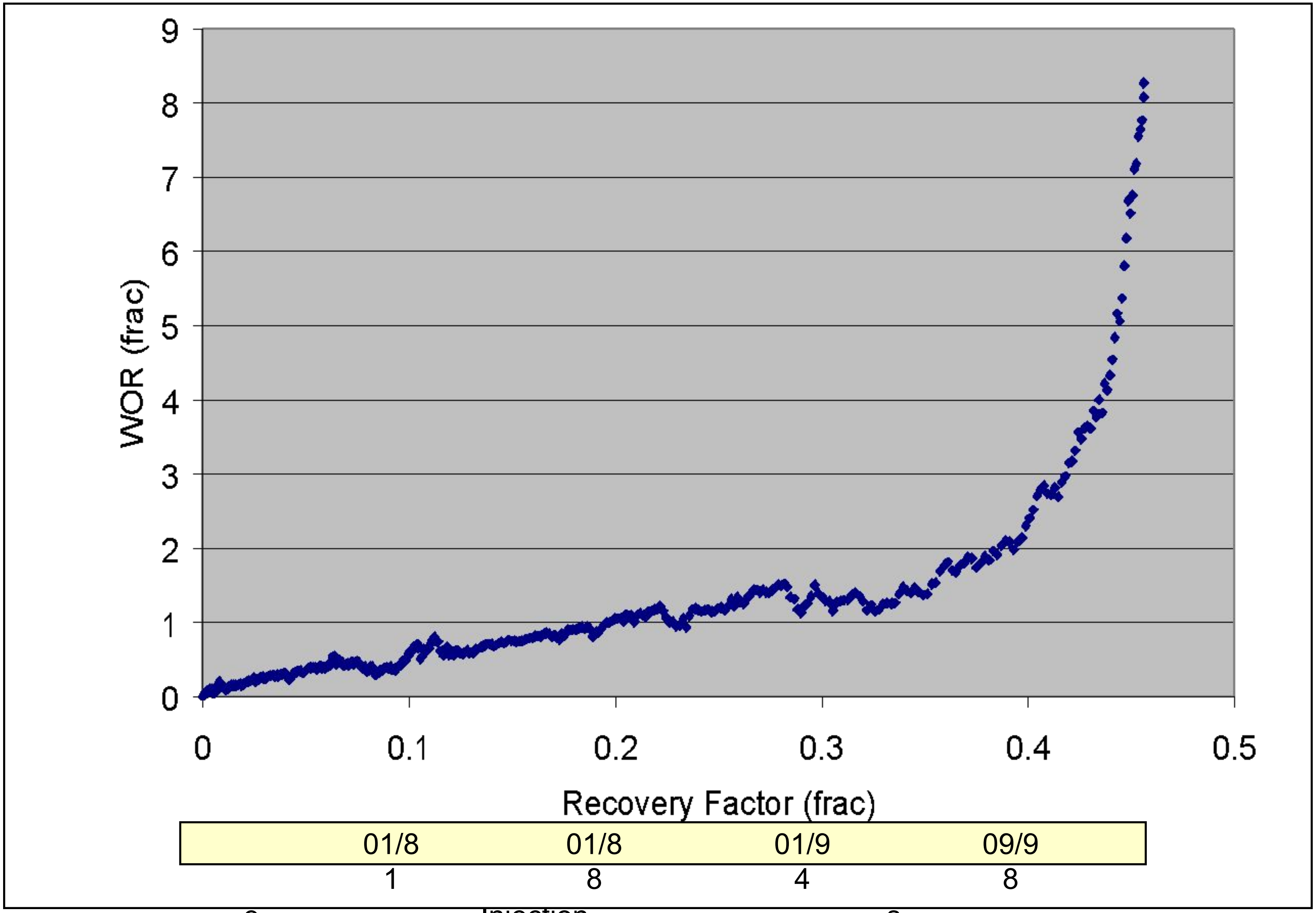
Onset of horizontal drilling



High density horizontal infill

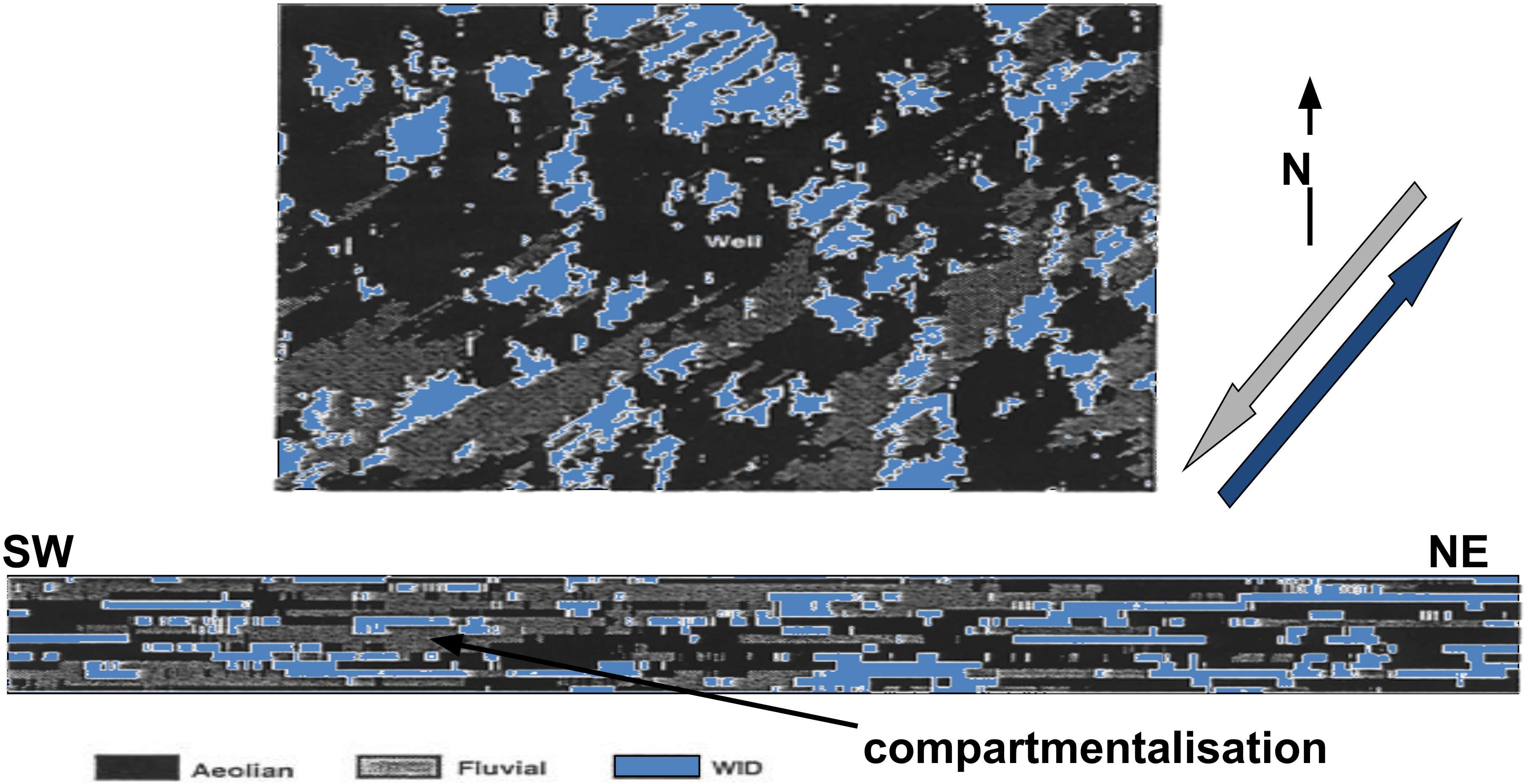
(from Mijnsen et al, 2005)

YIBAL FIELD: Water - Oil Rate vs RF



Impact of well placement

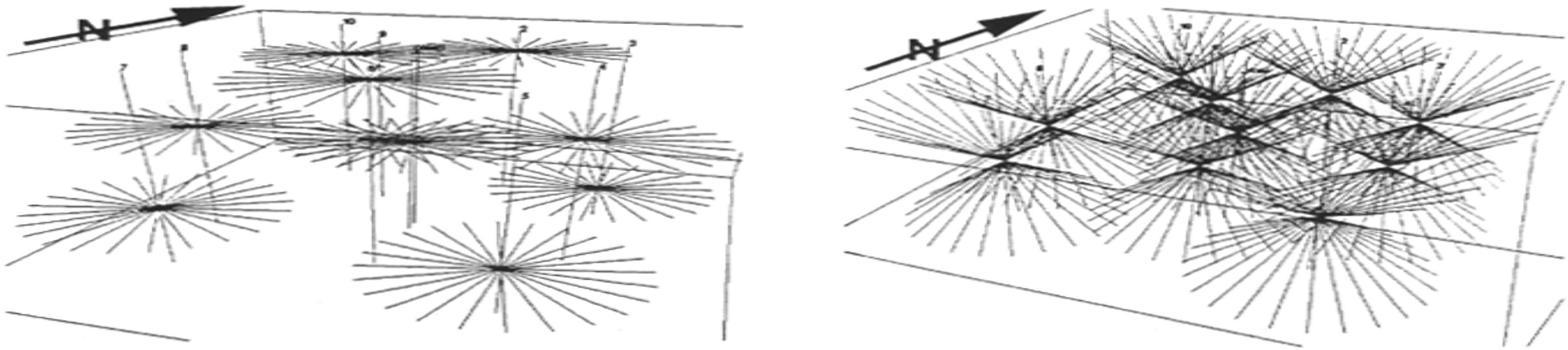
fluvial study



Seifert et al., 1996

Impact of well placement

fluvial study

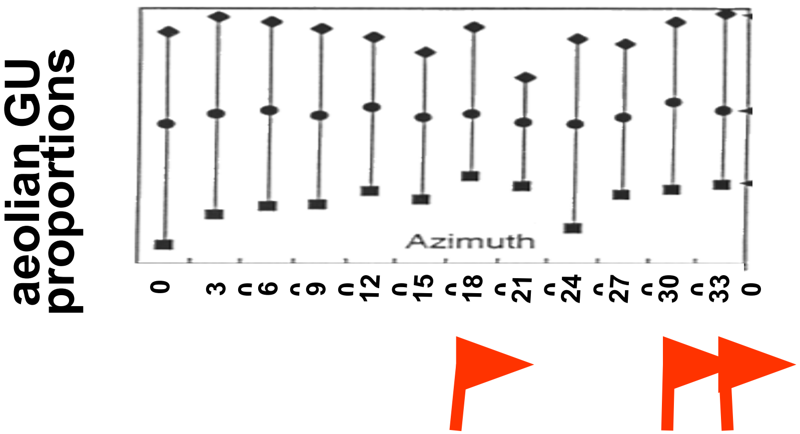


- find orientation of well trajectory most likely to
  - contain > aeolian GU proportions
    - maximise productivity
  - intersect > number of aeolian bodies
    - maximise drainage
- assess the likelihood of wells in this orientation intersecting high proportions of aeolian GUs

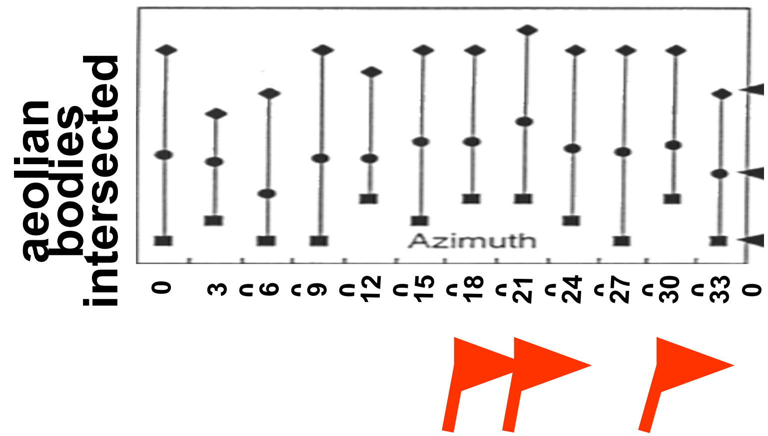
Seifert et al., 1996

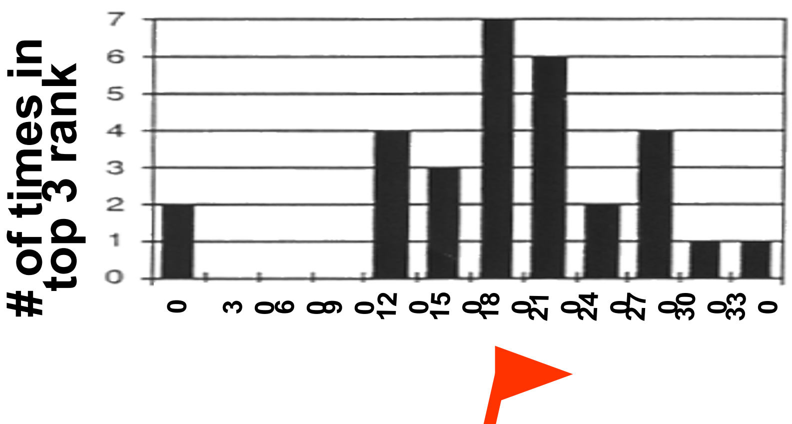
Impact of well placement

results

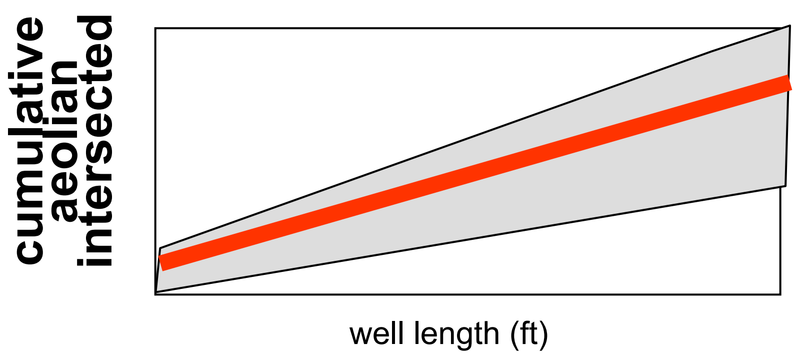


horizontal wells





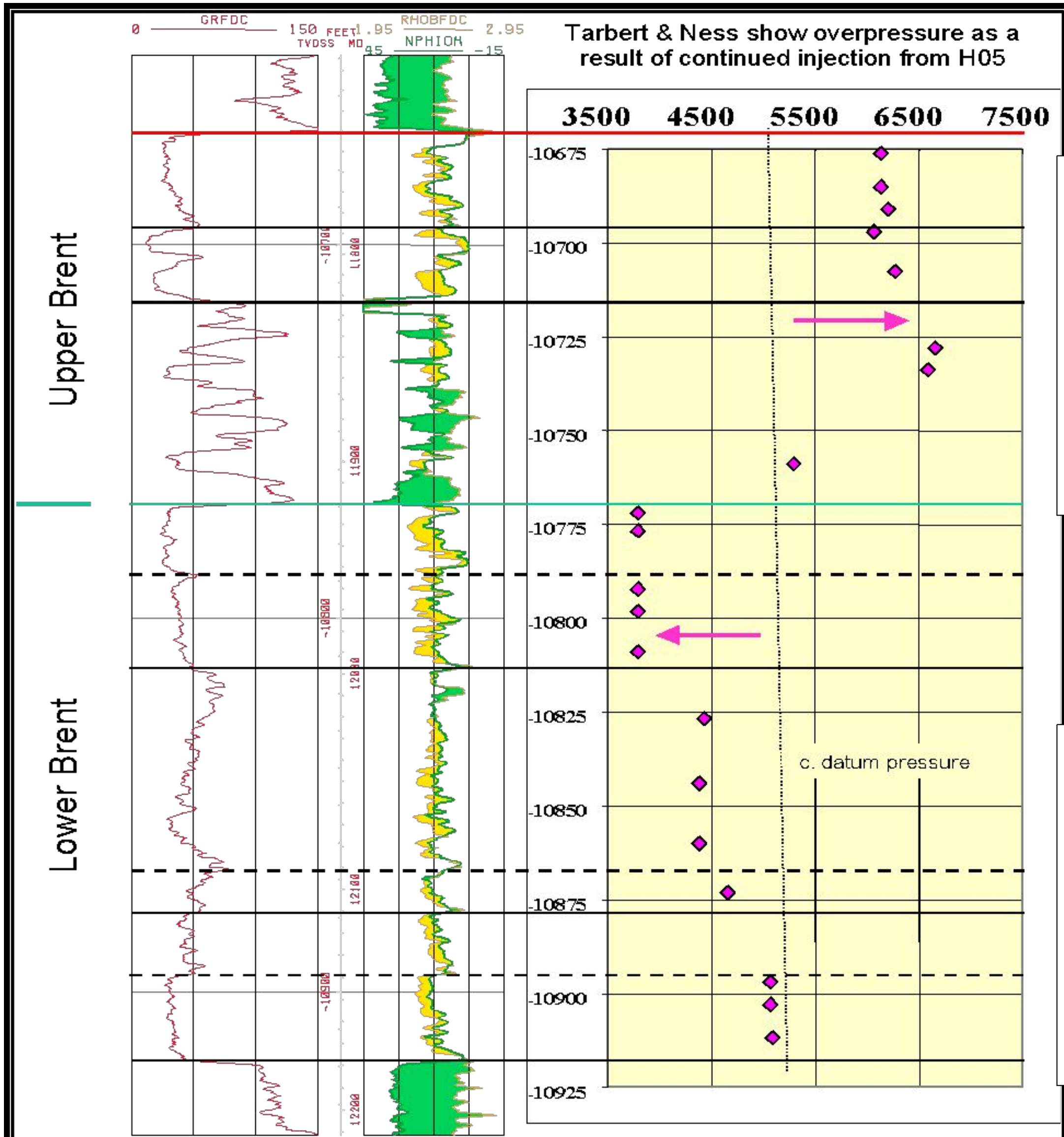
inclined wells

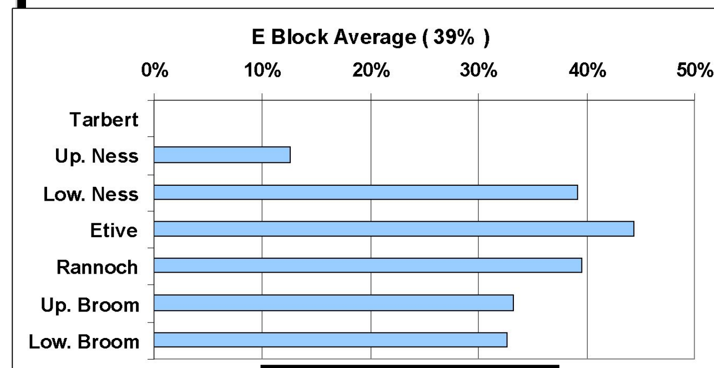


Seifert et al., 1996

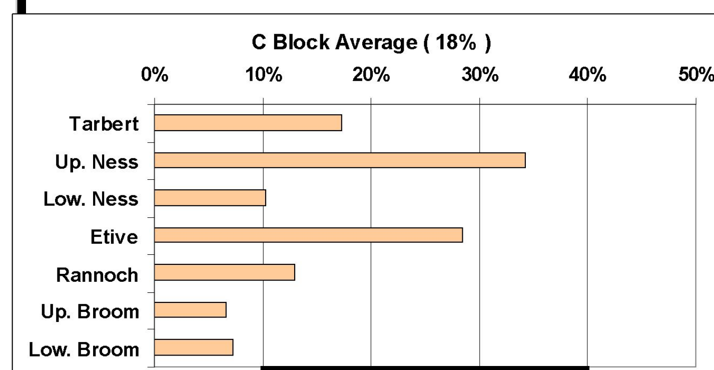
RM Example 3: Heather Field

Compartmentalisation and Variable Recovery



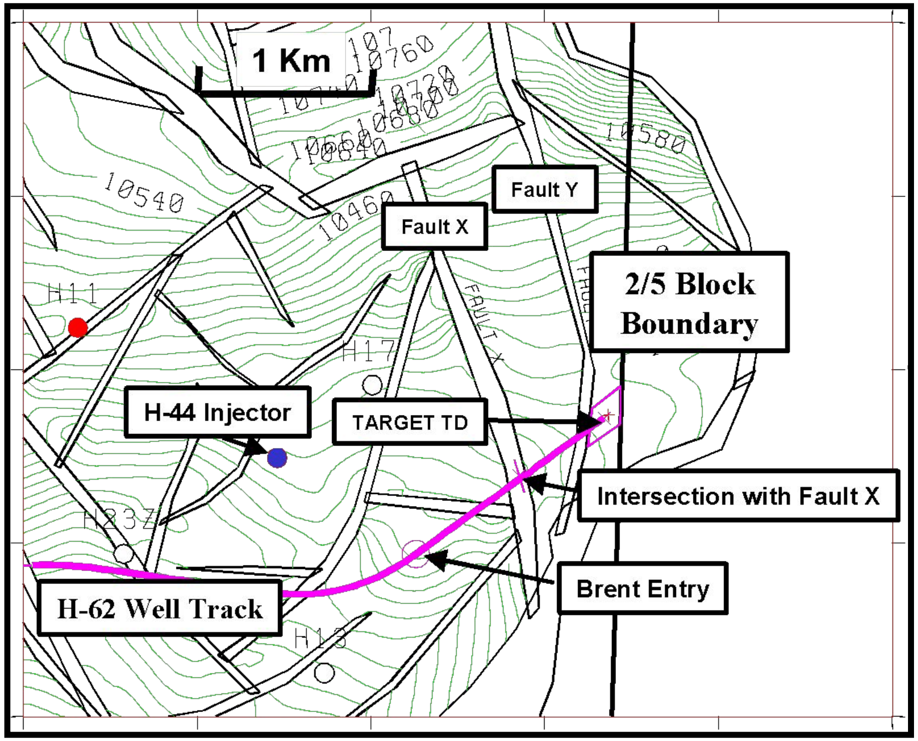


Crest



Flank

Infill Drilling – Heather Field



Fault compartmentalisation

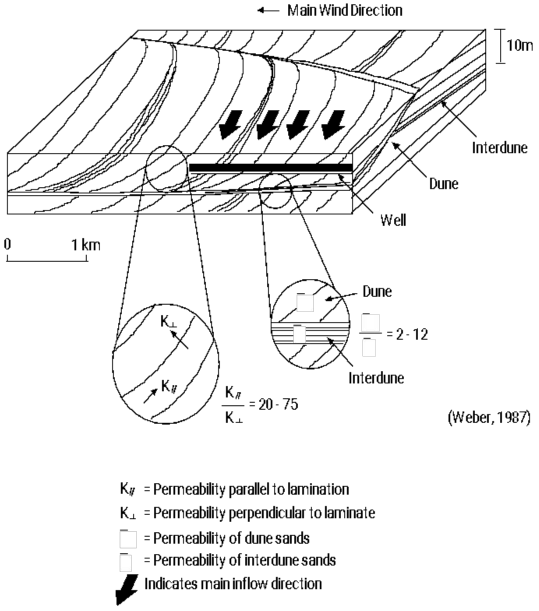
Example of….

FRACCING

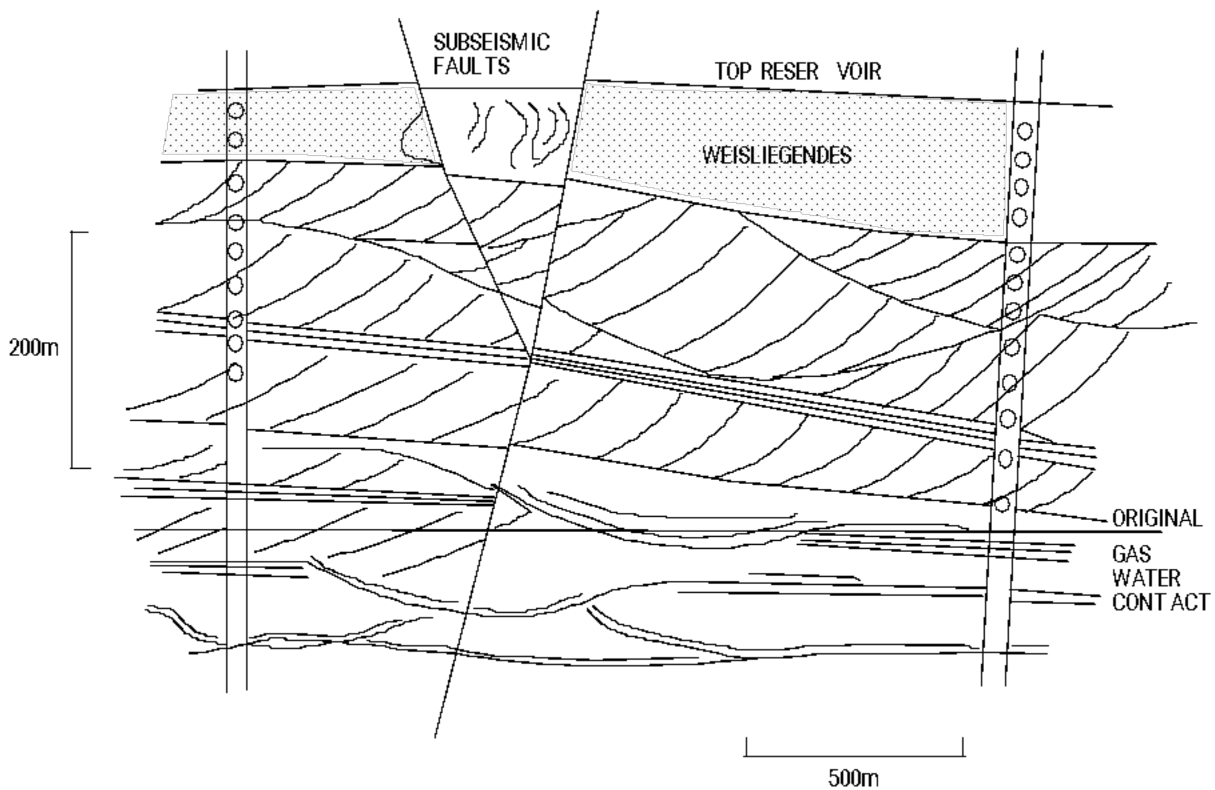
Example: Leman Field

- Strategy for Leman Field
  - Mijnsson and Maskall 1994
- Proactive hunt for gas
- Horizontal wells
  - Parallel to palaeowind

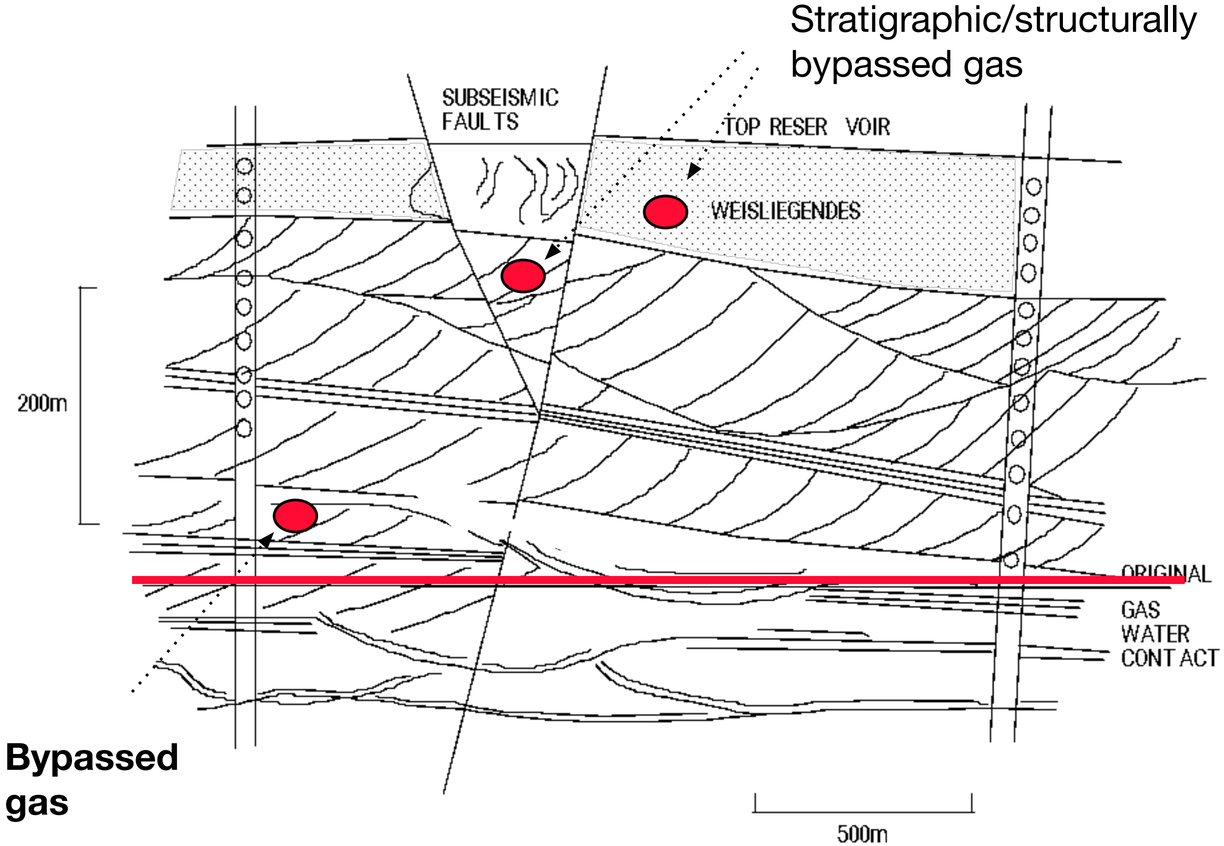
- Only part of the story



Typical Rotliegend reservoir section

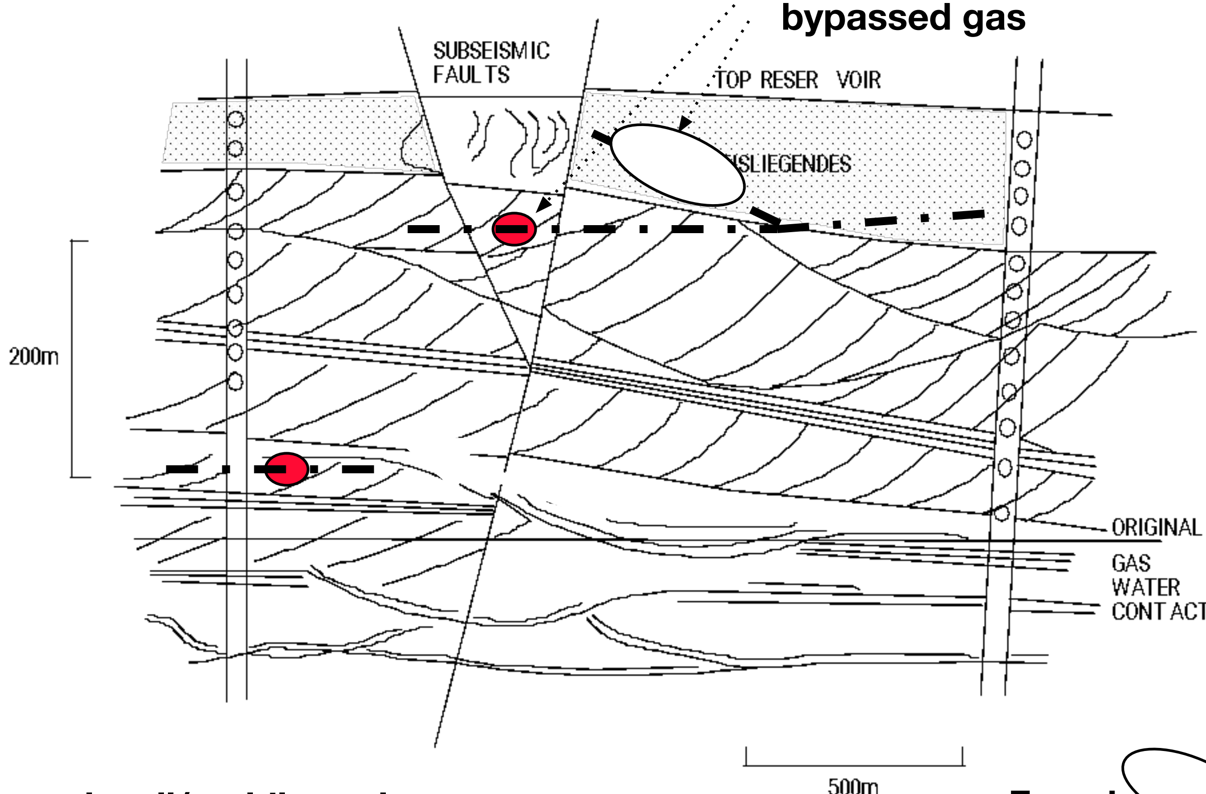


Typical Rotliegend reservoir section



Typical Rotliegend reservoir section

Stratigraphic/structurally bypassed gas



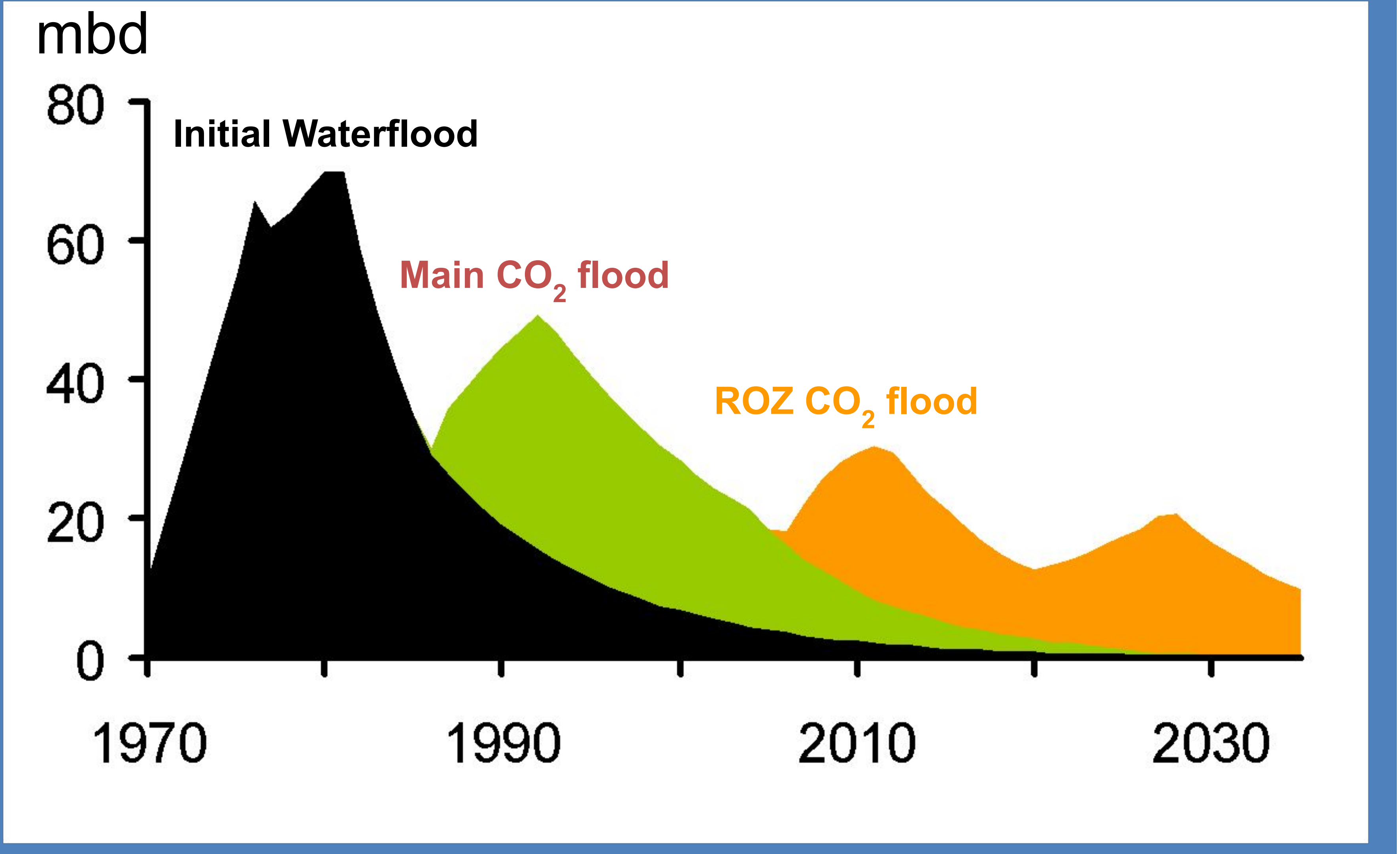
Horizontal well/multilateral opportunities

Fraccin g

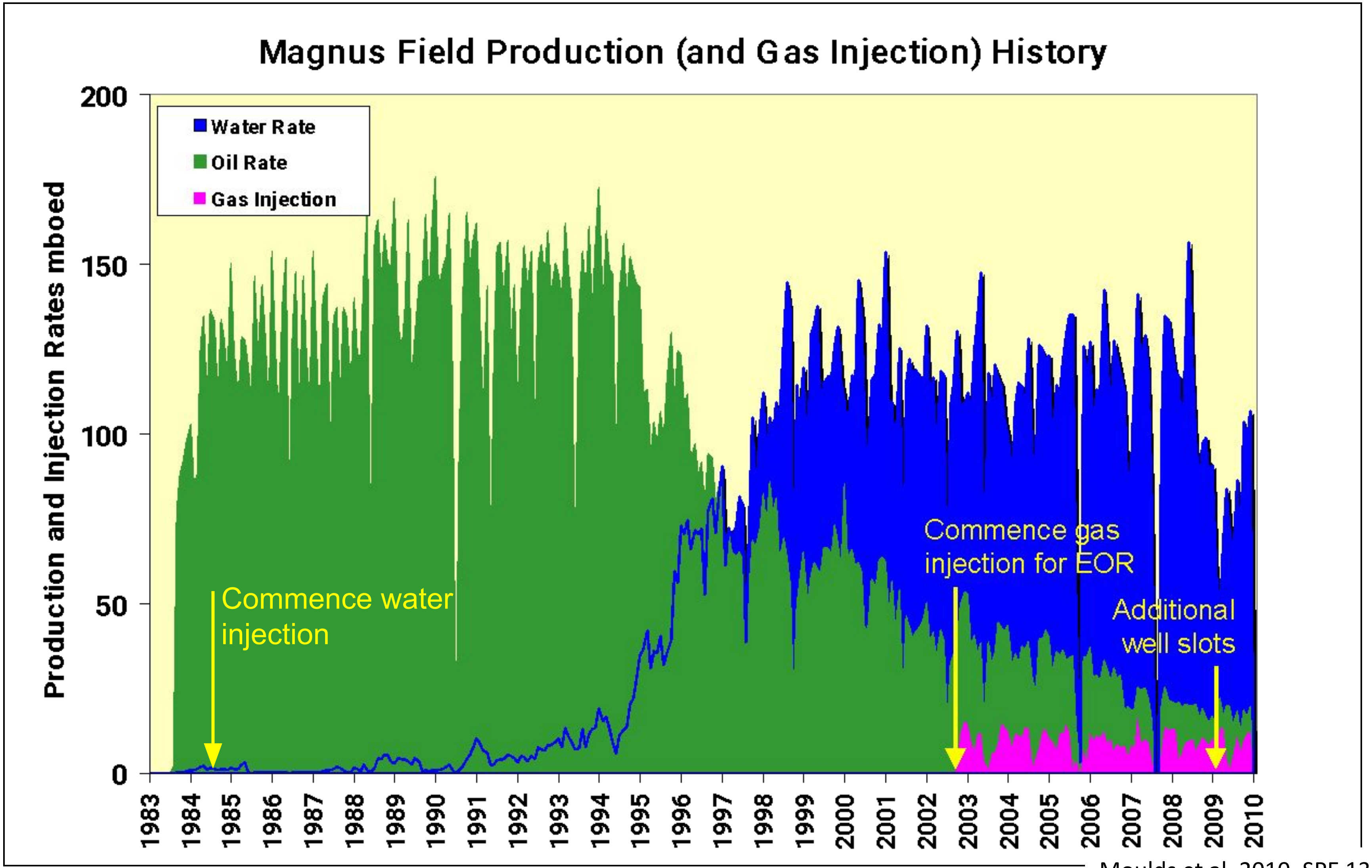
Example of….

EOR (WAG)

IOR: New opportunities with CO2

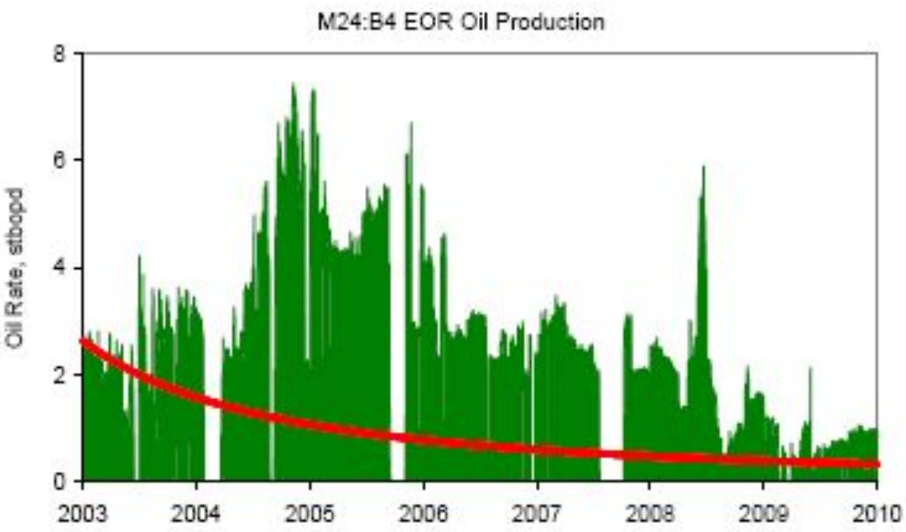


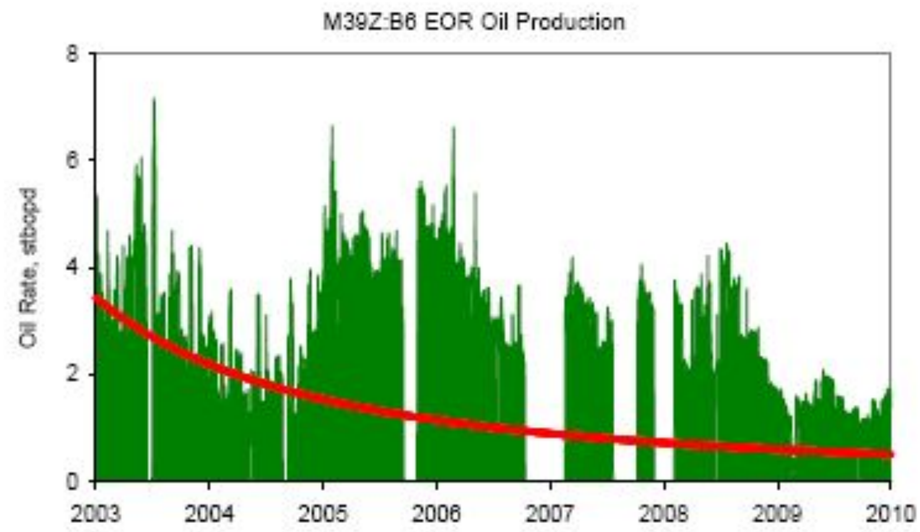
Example: Magnus Field
Production & Injection History



Moulds et al, 2010, SPE 134953

Improved oil recovery from EOR over waterflood

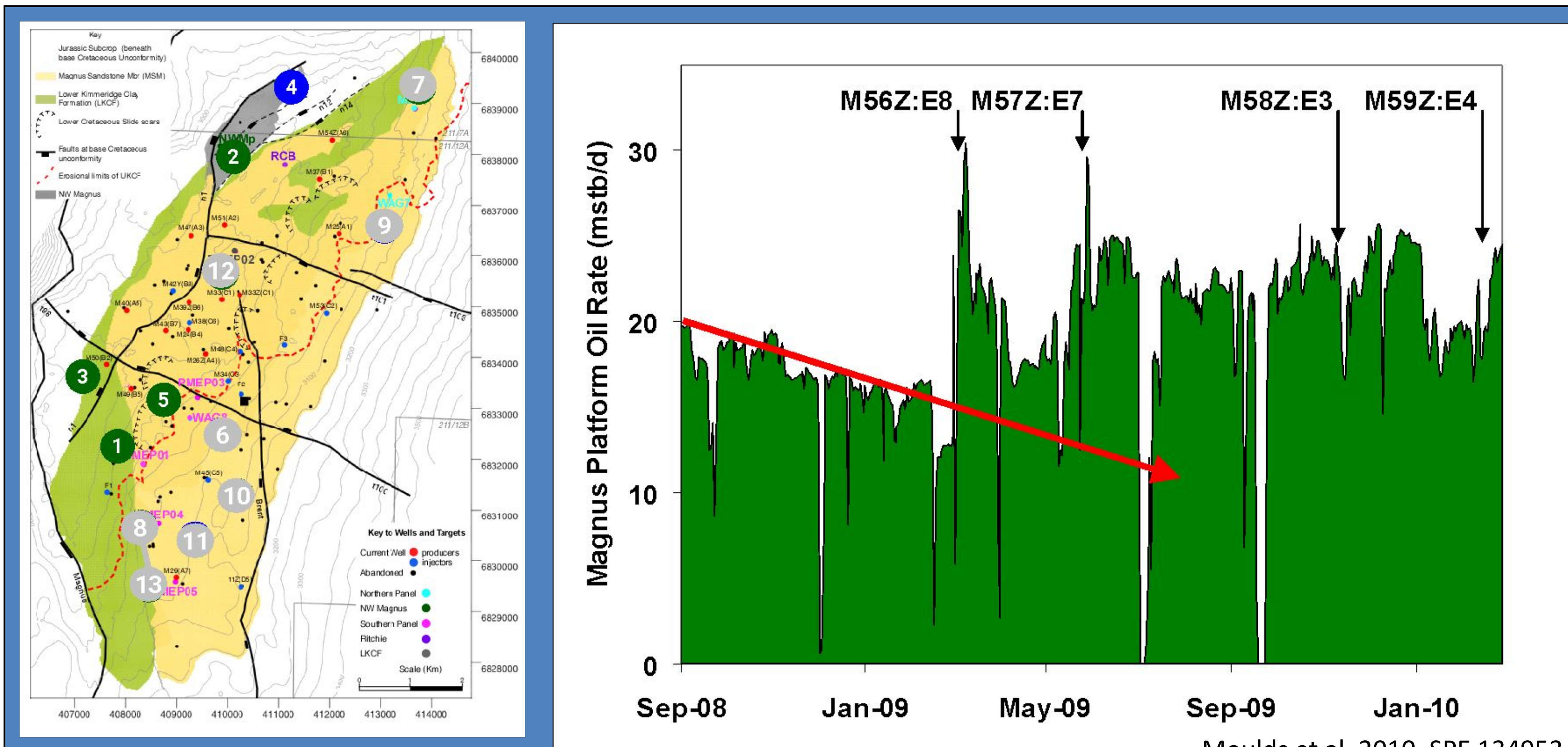




Moulds et al, 2010, SPE 134953

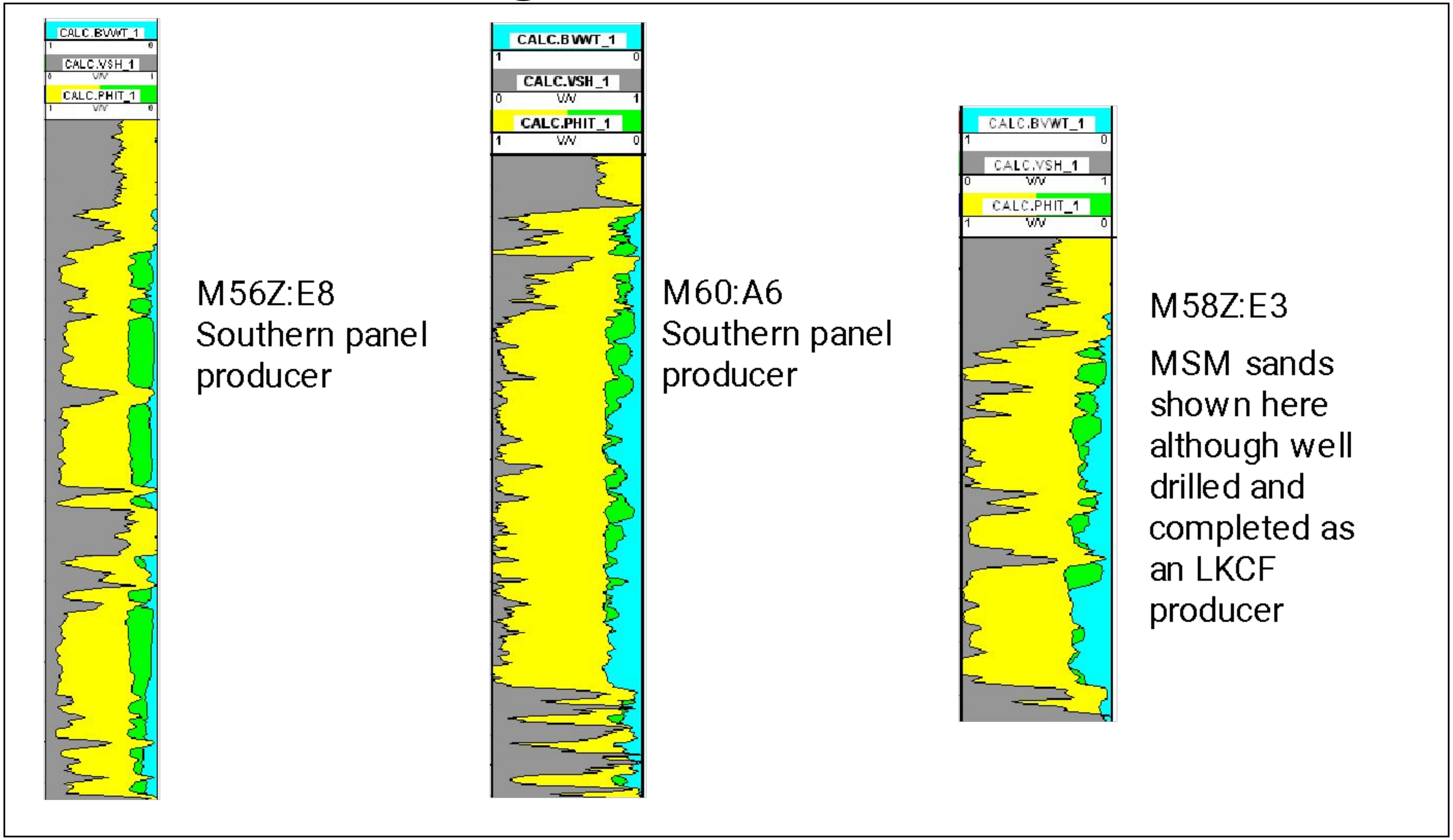
The Future – New Wells

- Magnus Extension Project
  - 4 new slots, slot splitter technology enables 2 wells from each slot
- 13 well drilling programme under-way



Moulds et al, 2010, SPE 134953

Target: Magnus Field
Oil Remaining after waterflood



EOR oil target: updip attic target and unswept oil under shales

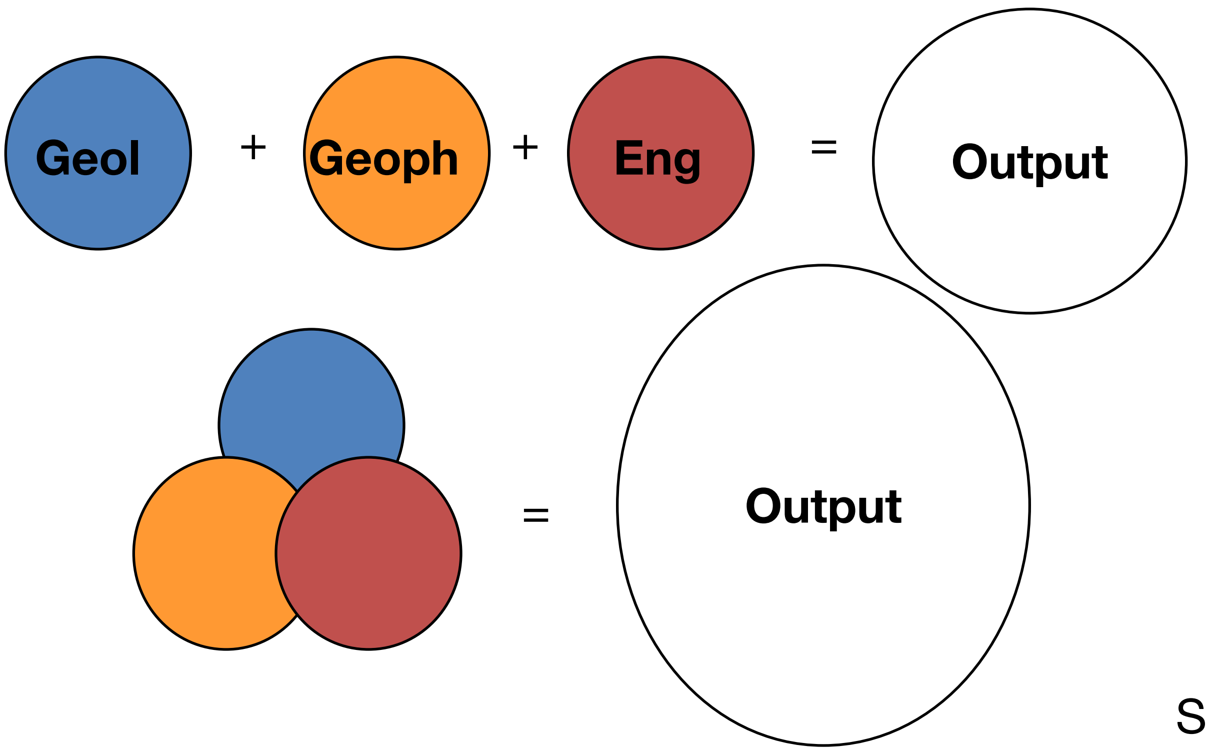
Moulds et al, 2010, SPE 134953

Maximise value through…

PEOPLE/TEAMS

Synergy

Output of a synergistic team is larger than the sum of the output of individuals….



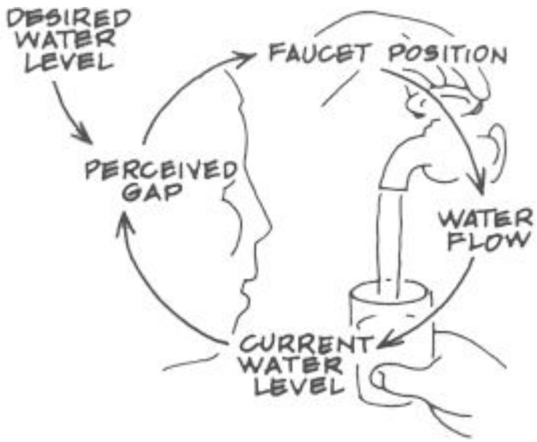
Sneider, 2000

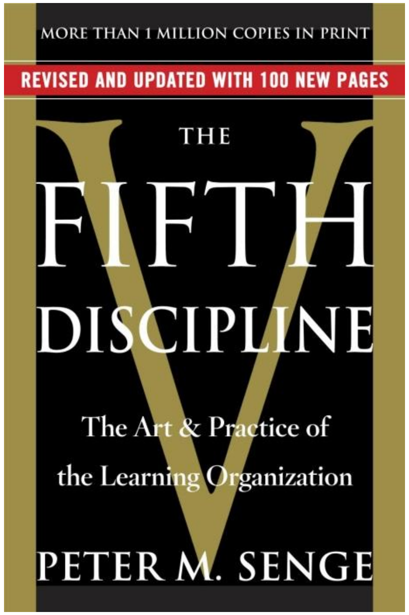
Synergy

- Is not:
  - Geoengineering
  - Any thing about multi-discipline work
  - Anything to do with Energy
- Synergy
  - Sum of the parts are greater than they are individually

REM is like Systems thinking

- System of interdependent processes
- Model Complexity of system rather than simplify
- People in parts of system need to work together and communicate





- Geology, petrophysics, geophysics, reservoir engineering, drilling, petroleum engineering, upstream/downstream, environment, local populations, governments….. The list goes on

Field Management Plan (UK DTI)

- Reservoir Management Strategy
- - detailing the principles and objectives that the operator will hold when making field management decisions and conducting field operations
- Reservoir Monitoring Plan
- - describing the data gathering and analysis proposed to resolve existing uncertainties and understand dynamic performance during development drilling and subsequent production
- Owen, 1998

RM Strategy

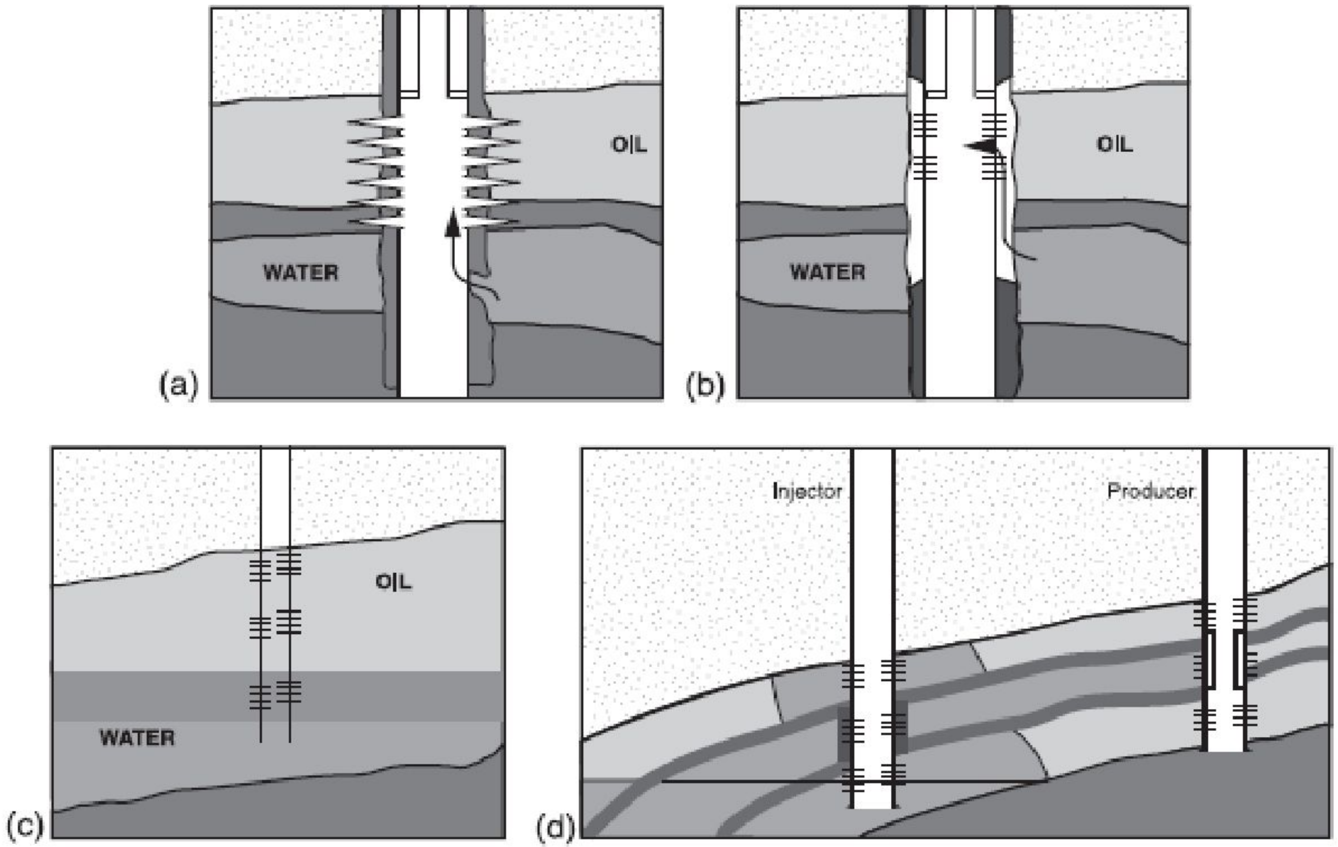
- Developing
- Implementing
- Monitoring
- Evaluating

- DIME - Satter and Thakur, 1994

Increase costs through…

WATER MANAGEMENT

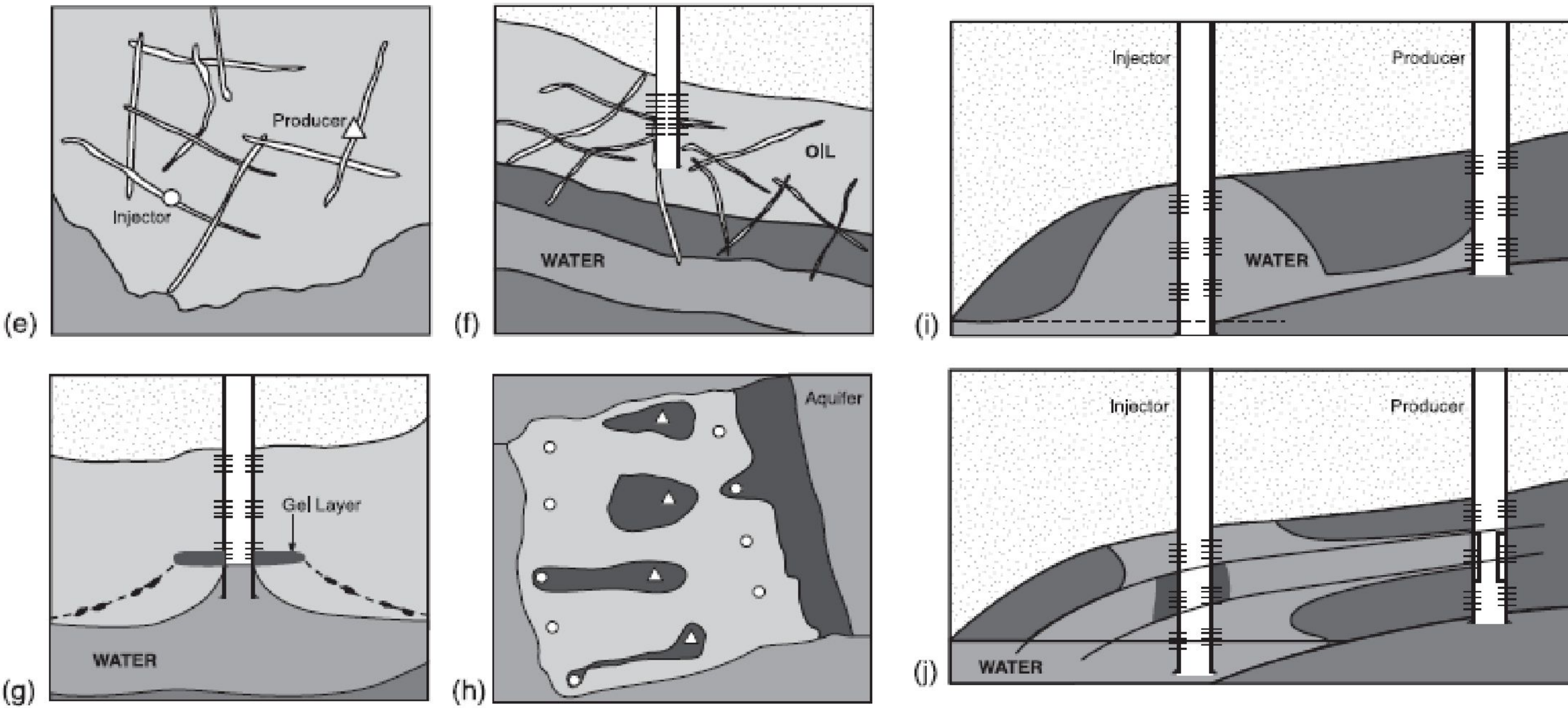
Reservoir Management Issues (1)



(From Arnold et al., 2004)

a- Mechanical leaks: b - Behind Casing flow
c - Oil-water contact: d – High perm zones

Reservoir Management Issues (2)



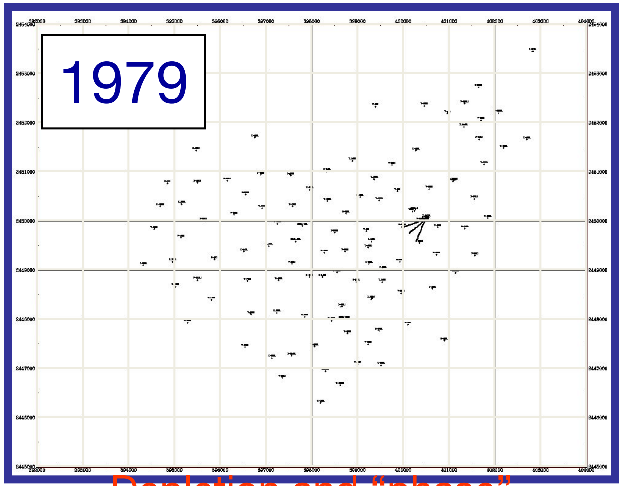
e- Fractures: f – Fractures to water
g - Coning: h – Areal sweep

i – Gravity segregation
j – High perm with crossflow

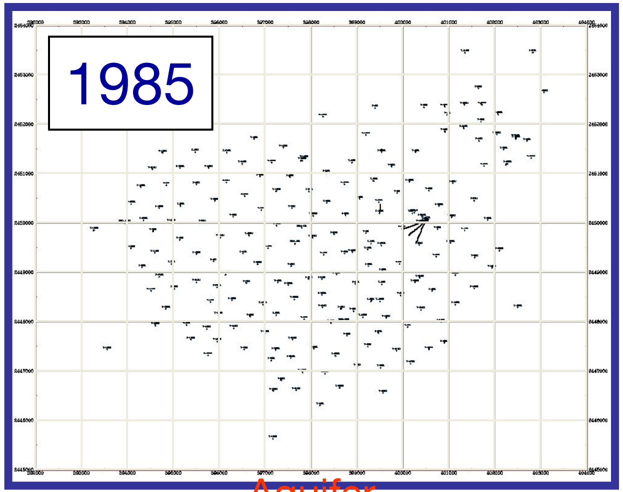
Example of….

WATER SHUTOFF

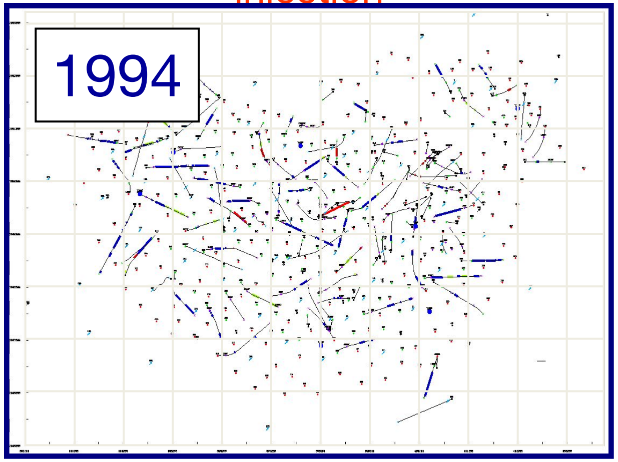
Yibal Field Development History



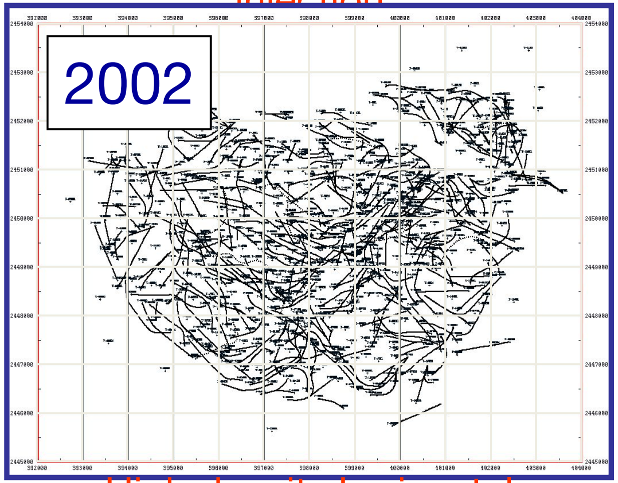
Depletion and "phase" injection



Aquifer injection



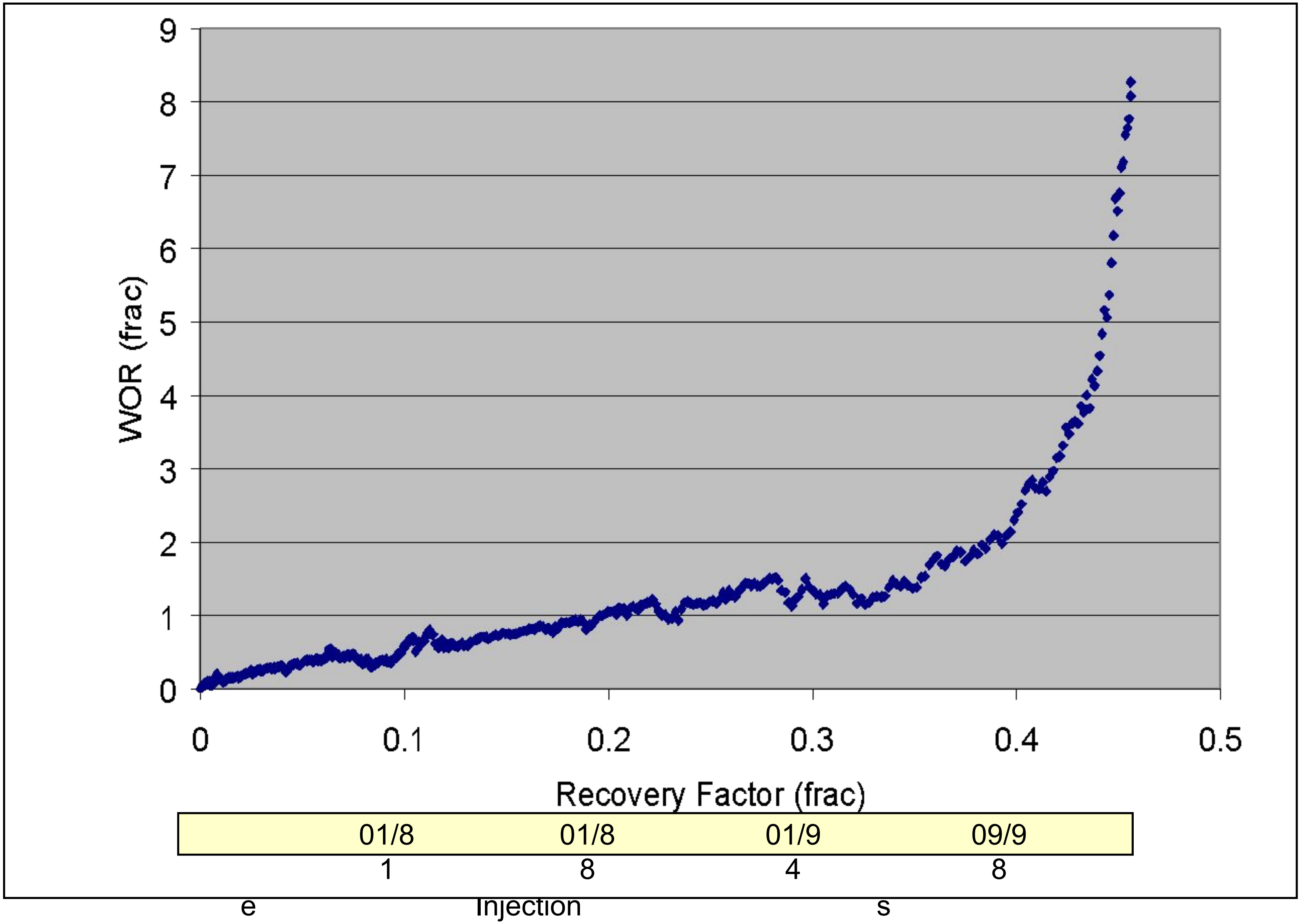
Onset of horizontal drilling



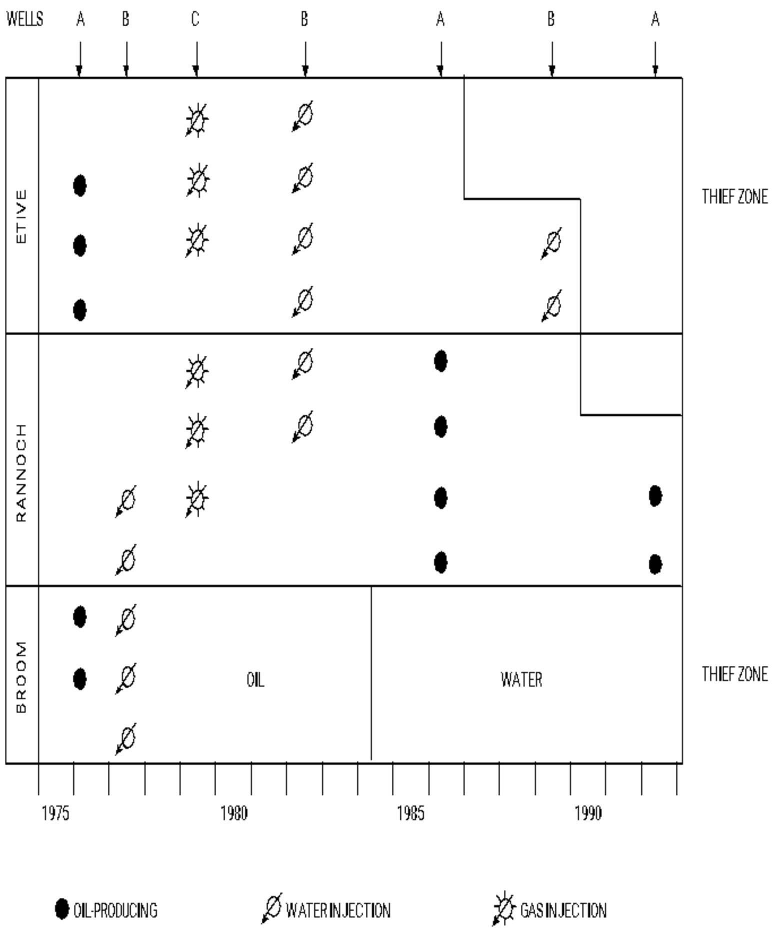
High density horizontal infill

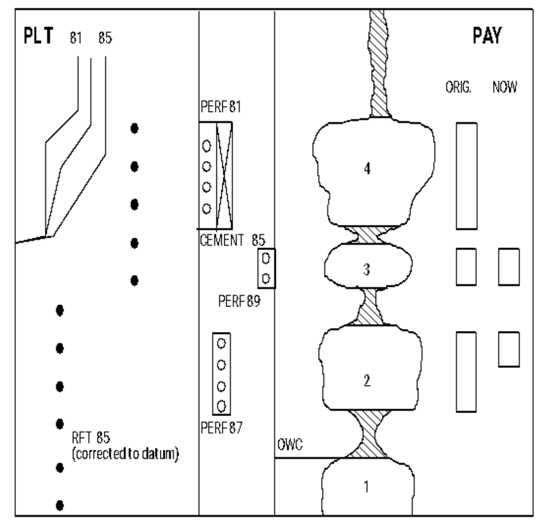
(from Mijnsen et al, 2005)

YIBAL FIELD: Water - Oil Rate vs RF



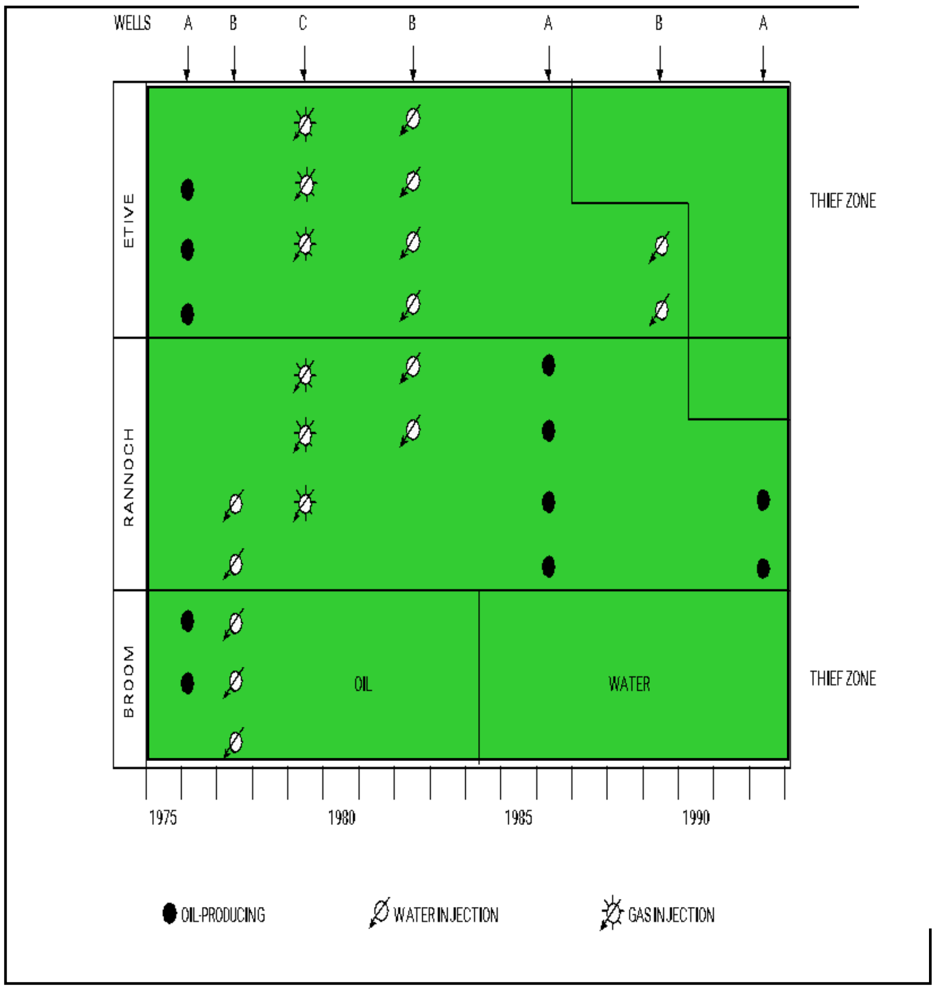
Brent Field Reservoir monitoring





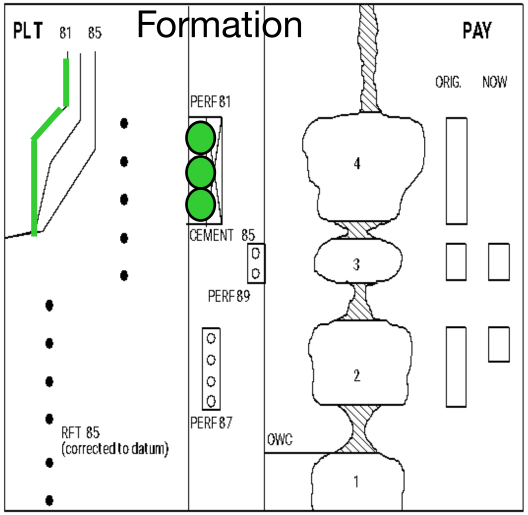
(Bryant and Livera, 1991)

Brent Field Reservoir monitoring



1. Initial Conditions

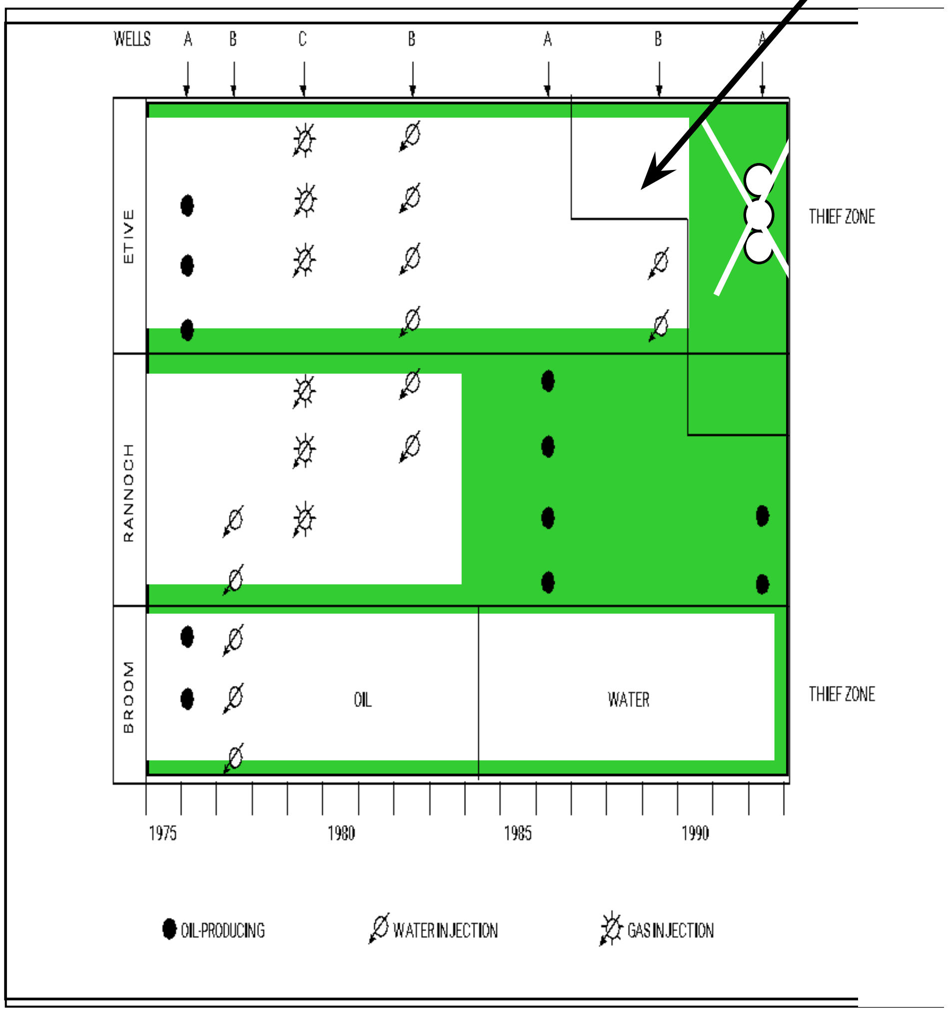
Ness Formation



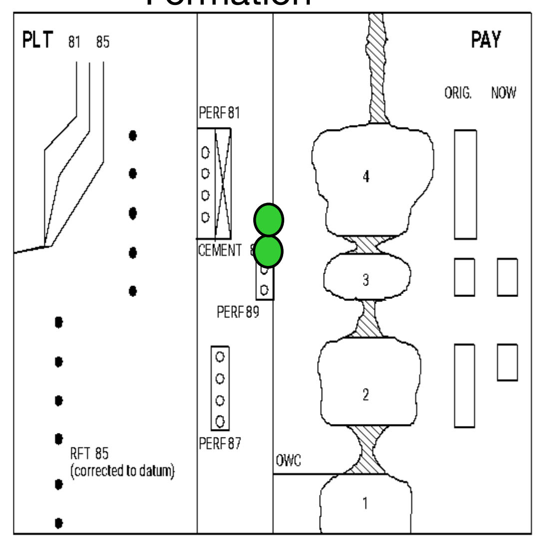
(Bryant and Livera, 1991)

Brent Field Reservoir monitoring

Water Shut-off



1. 1987 Conditions
   Ness Formation



New Perforations

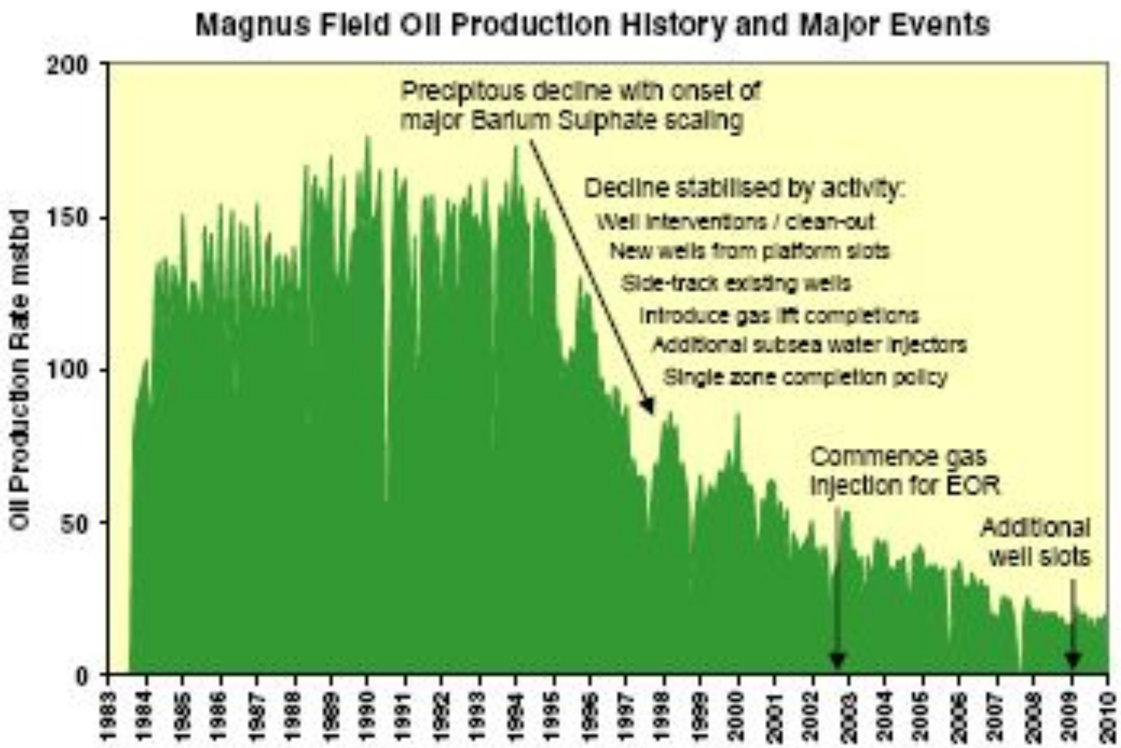
Profile Modification

(Bryant and Livera, 1991)

Increase costs through…

SCALE MANAGEMENT

Decline in Magnus production



Moulds et al, 2010, SPE 134953

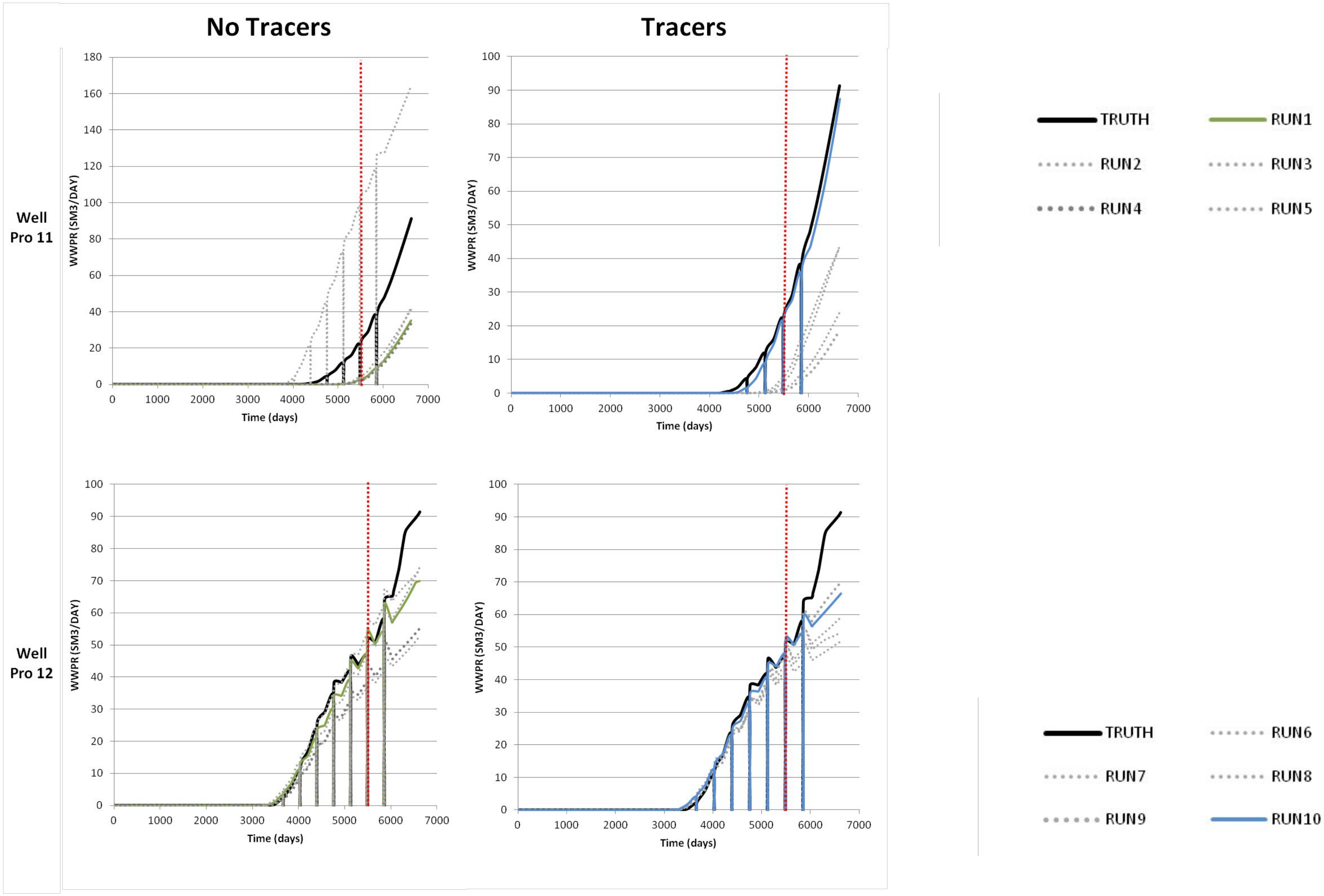
Examples - Flow Restriction

Examples - Facilities

separator scaled up

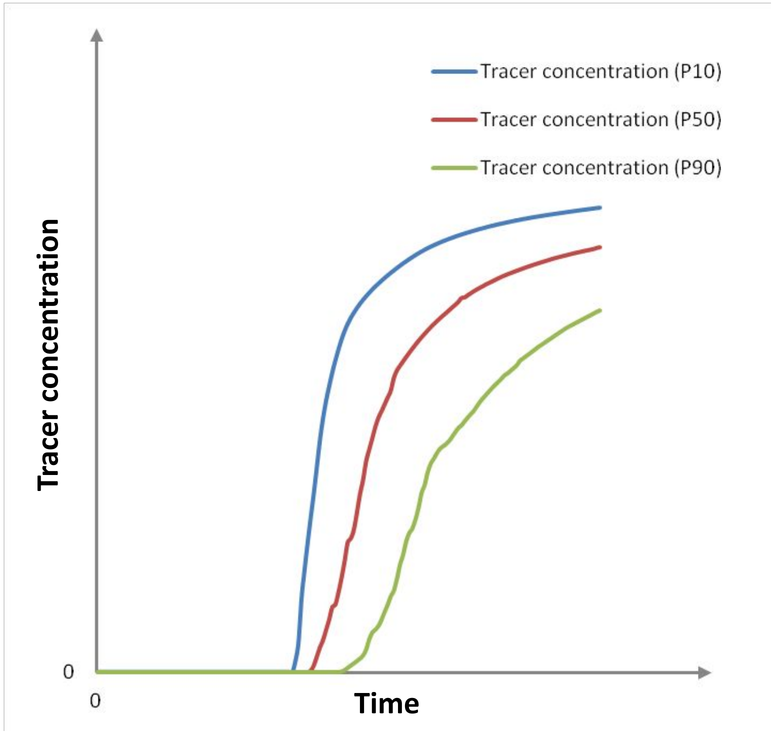
and after cleaning

Water chemistry history match

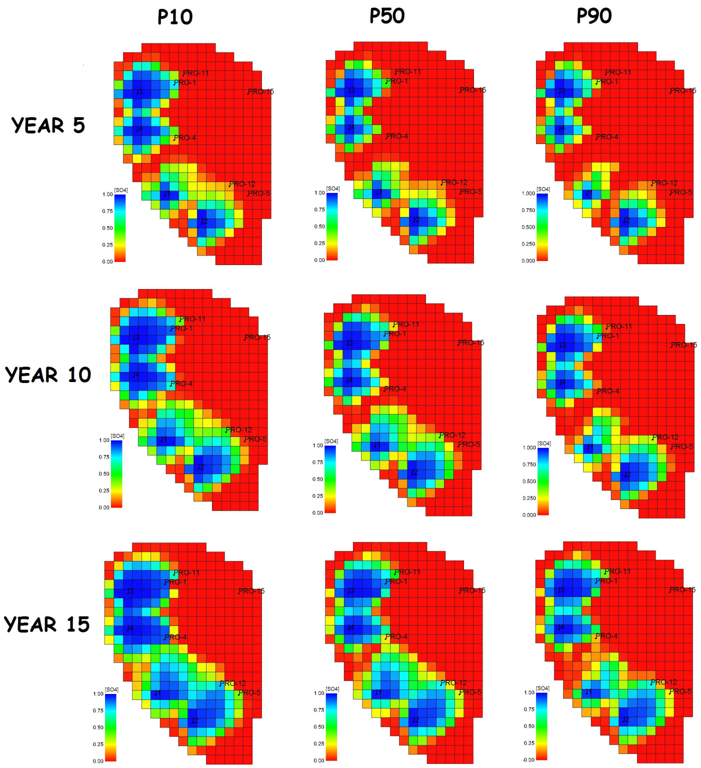


Probabilistic predictions of scaling in wells

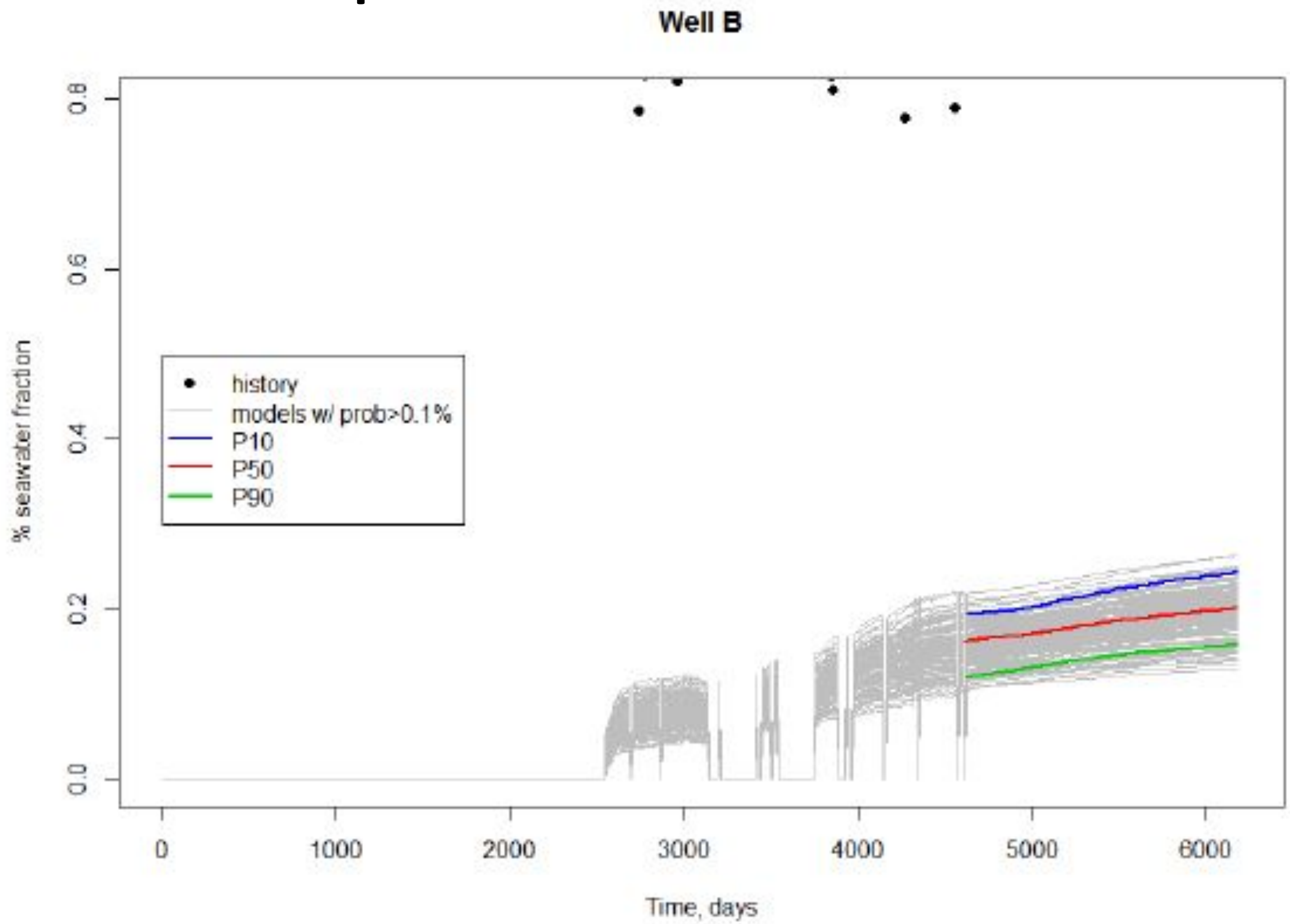
Well Forecasts



Spatial Probability Maps



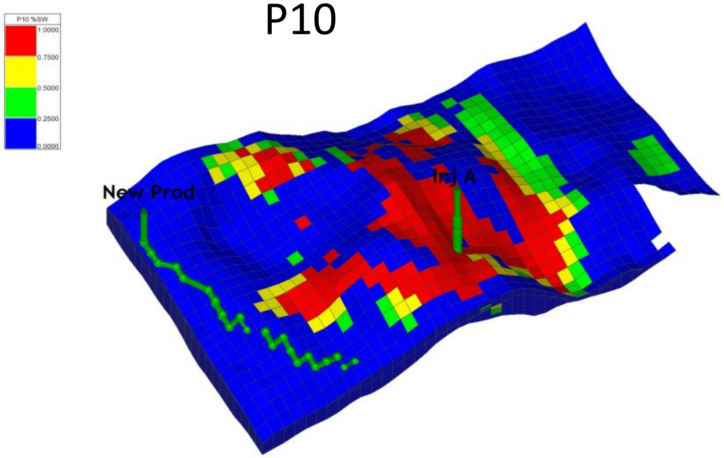
Predicting Seawater fraction in produced water



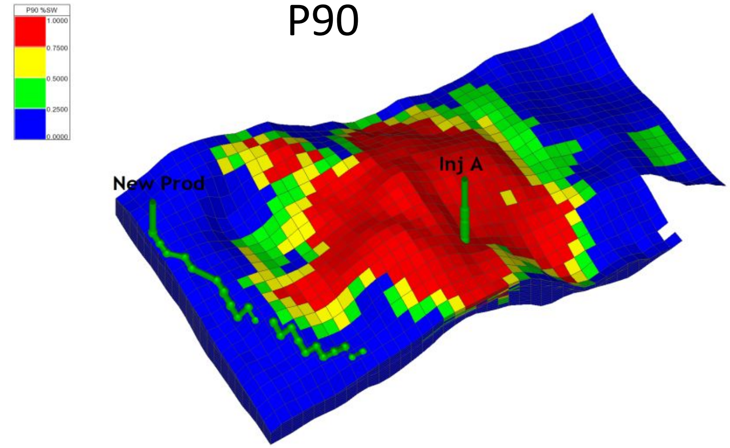
(Vasquez et al., 2013)

Probability maps of seawater fraction

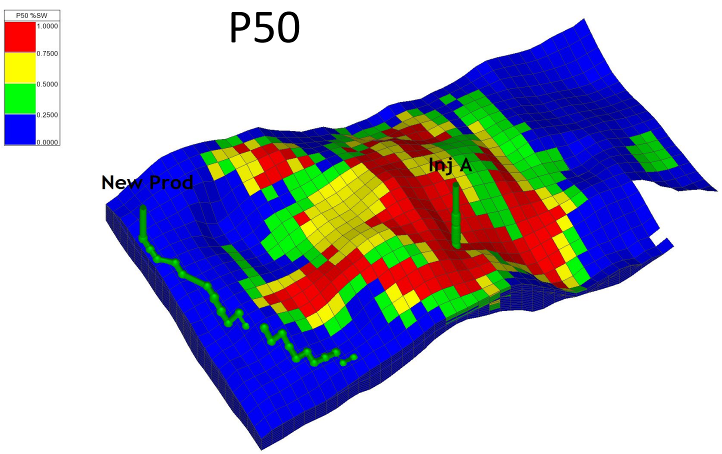
P10

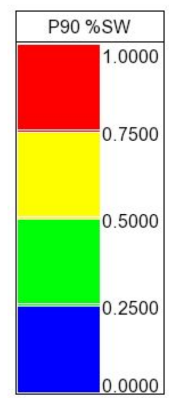


P90



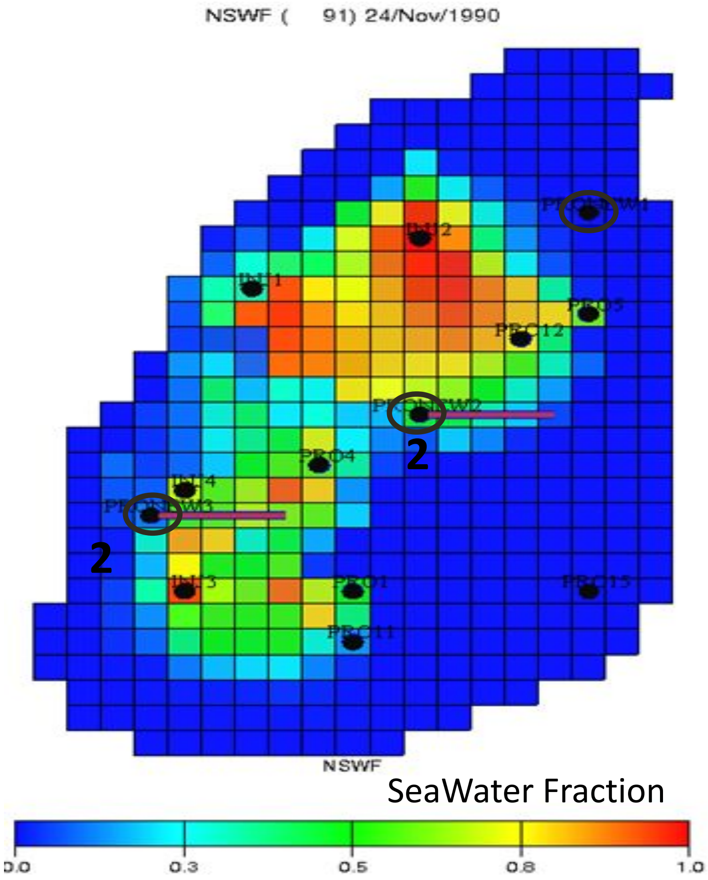
P50

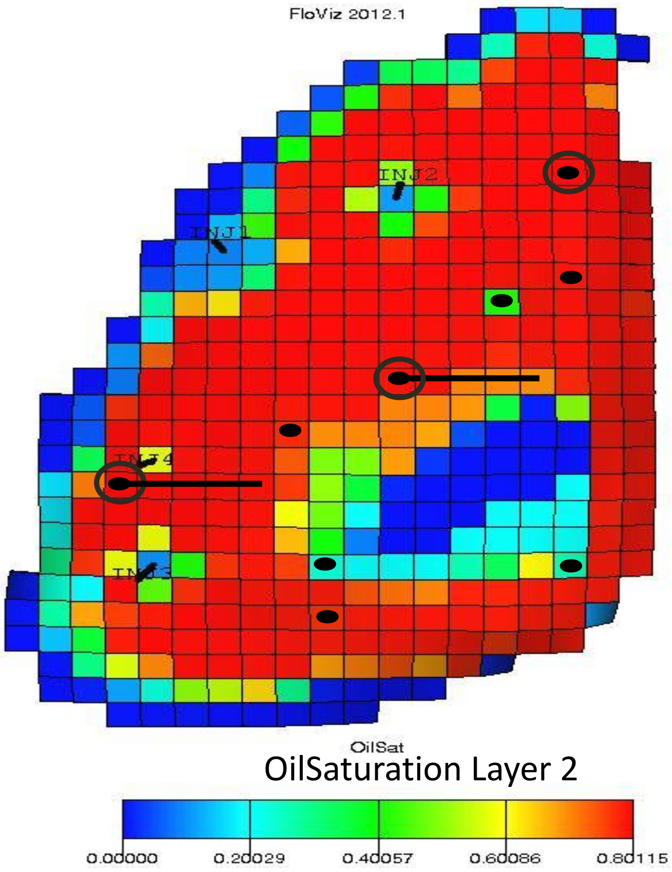




Results

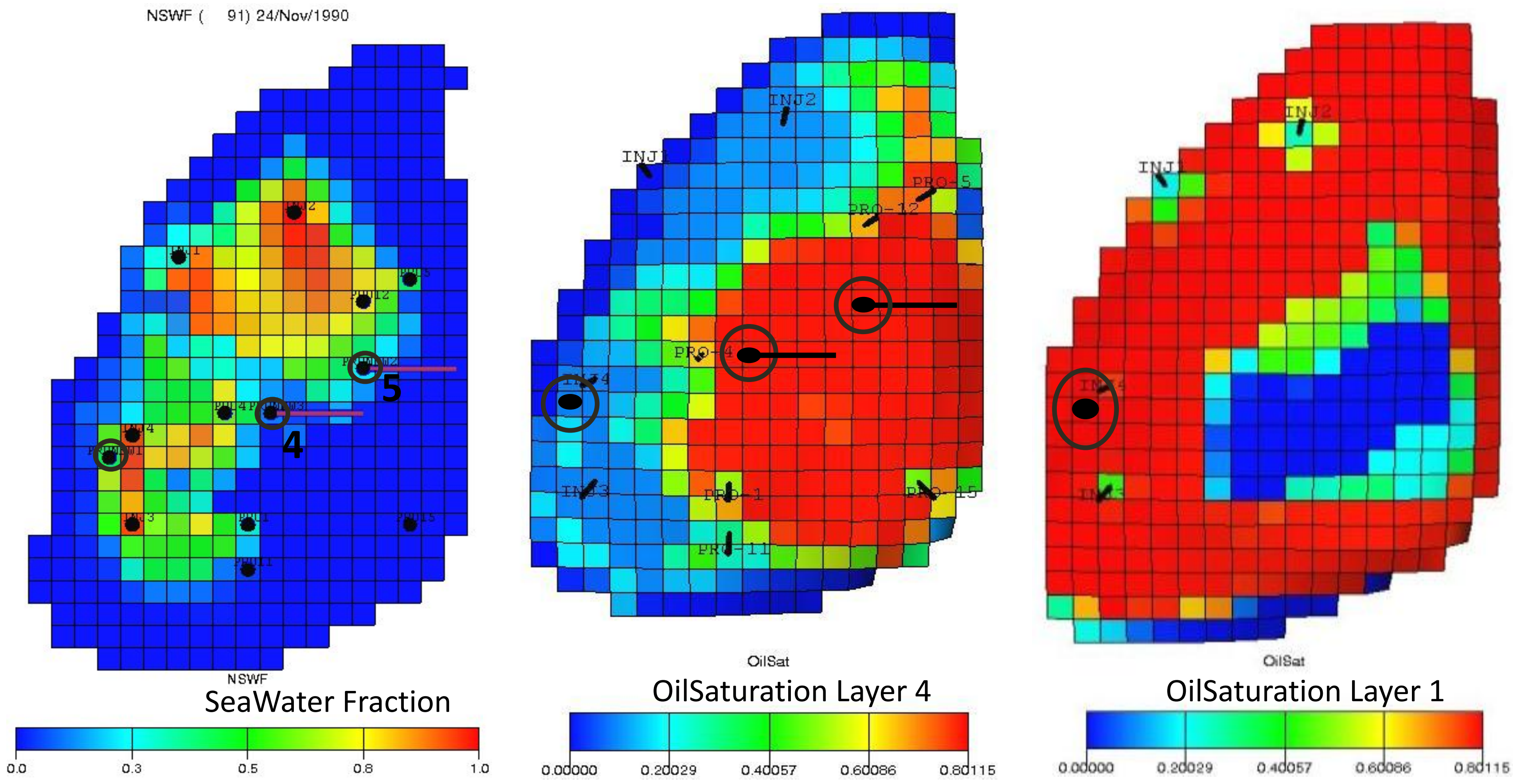
- Optimization w/o accounting scale risk





Results

- Optimization accounting scale risk

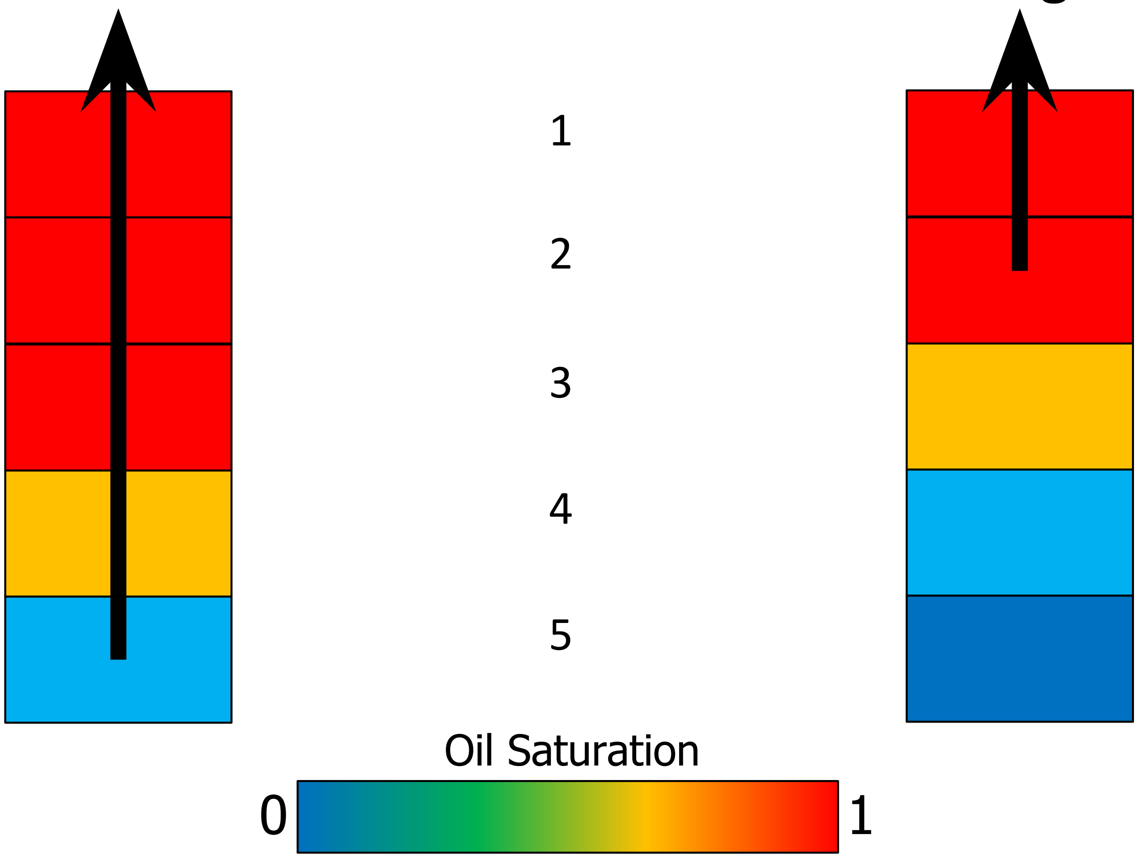


Results

Layer open/shut

- w/o accounting scale risk

- accounting scale risk



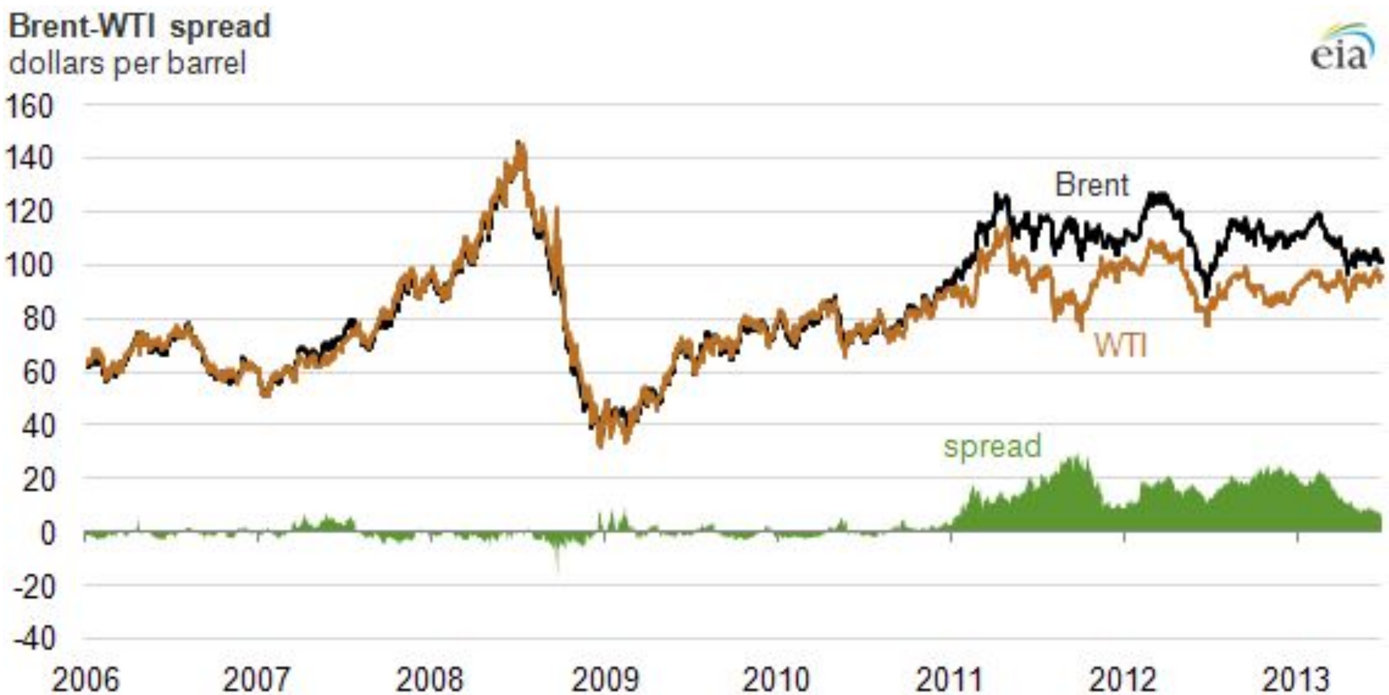
Impact in the value through…

VALUE OF YOUR OIL

Two key things you don't know

- How much oil you can extract
  - Reservoir uncertainty
  - Variations from different development plans
  - Ownership
- How much your oil is worth
  - Oil price
  - Lifting costs
  - CAPEX
  - Taxation/Royalty

All oil is not created equally priced...



Time value of money

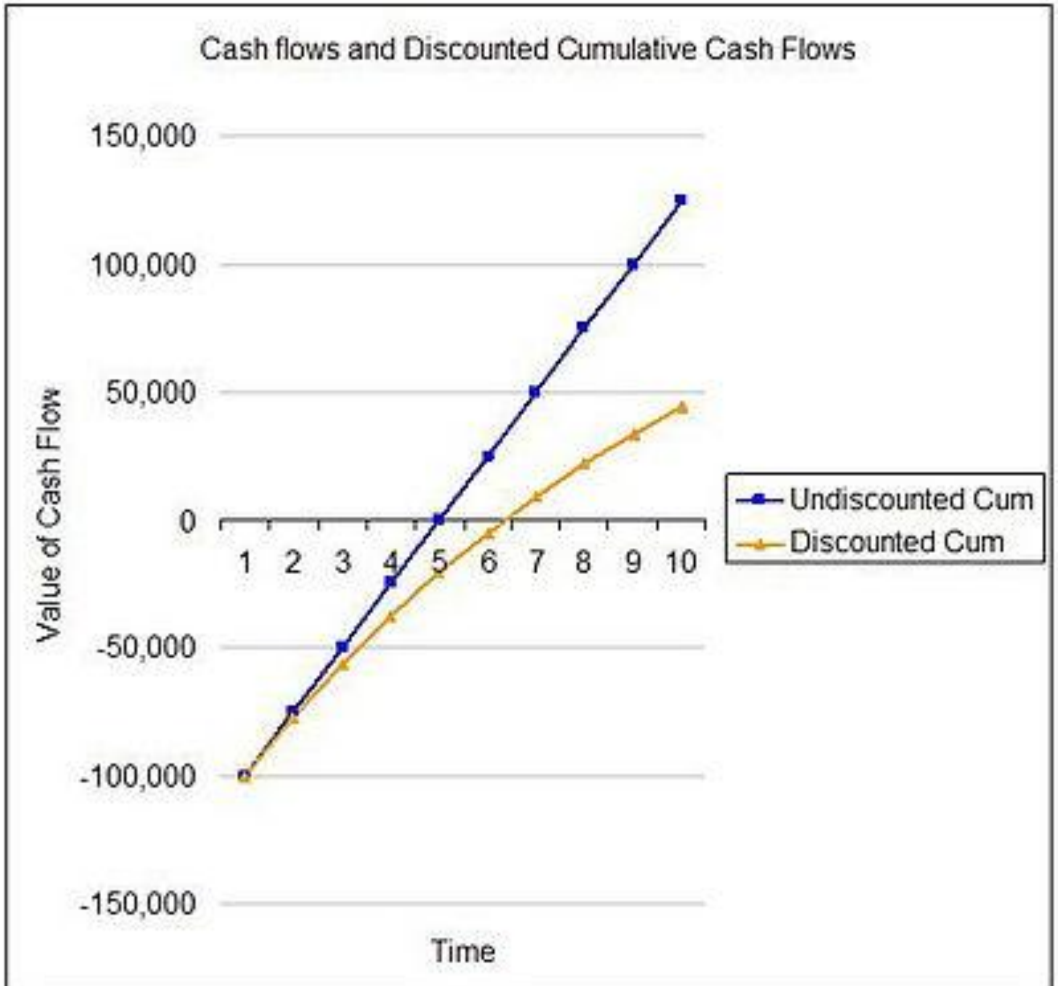
"how much money would have to be invested currently, at a given rate of return, to yield the cash flow in future."

$$DPV = \frac{FV}{(1+i)^n}$$

where

- *DPV* is the discounted present value of the future cash flow (*FV*), or *FV* adjusted for the delay in receipt;
- *FV* is the nominal value of a cash flow amount in a future period;
- *i* is the interest rate or discount rate, which reflects the cost of tying up capital and may also allow for the risk that the payment may not be received in full;[1]
- *n* is the time in years before the future cash flow occurs

Value of money decreases overtime (NPV)



From wikipedia

Compare value of companies

- Oil = 5,817 million barrels
- Gas = 24,948 billion cubic feet
- 1.75 million BOE per day

$6.8 billion net income

Market cap = 83.28bn

- Oil = 2,234 million barrels
- Gas = 3,810 billion cubic feet
- 753,000 BOE per day production

$4.6 billion net income

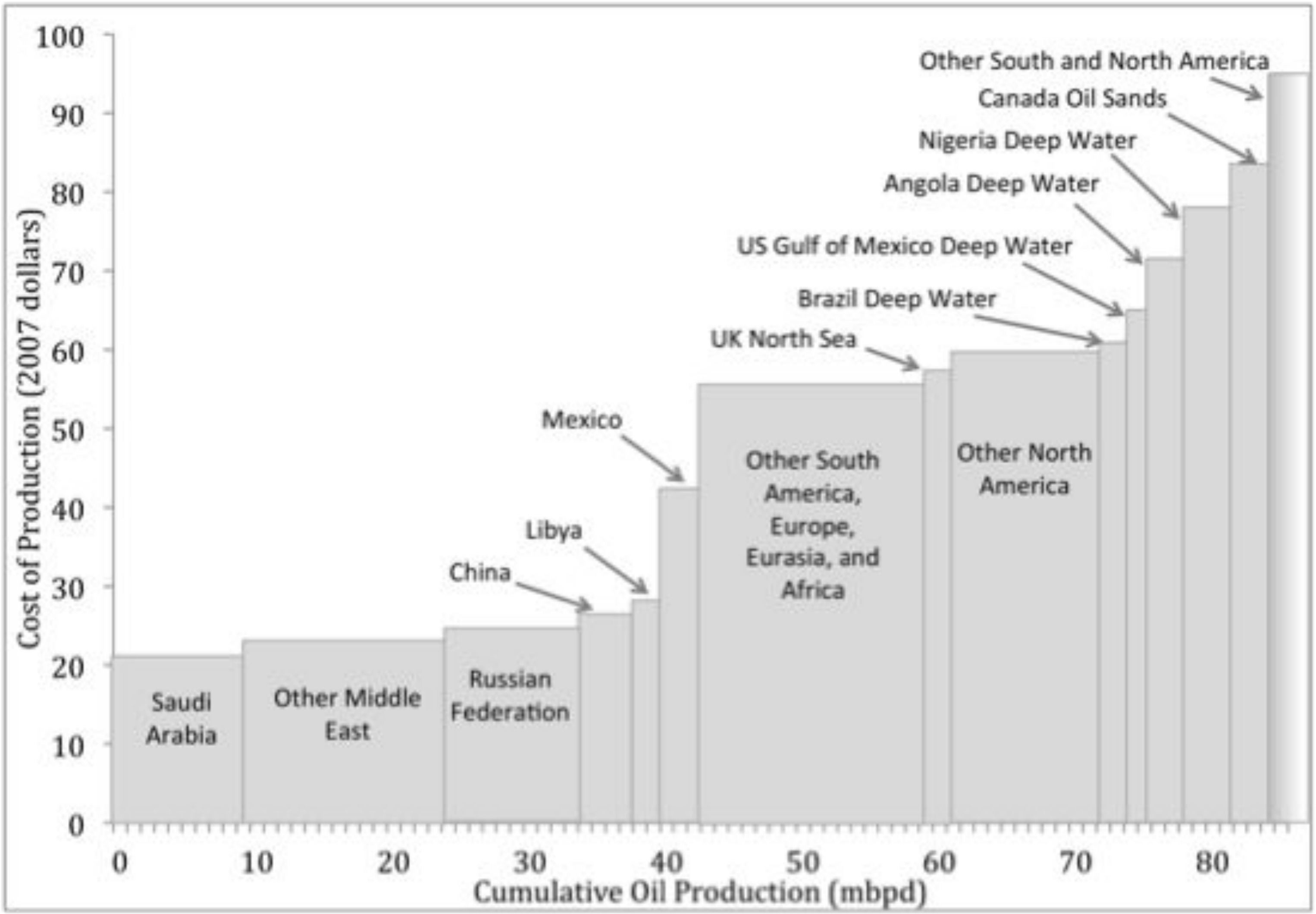
Market cap = 77.63bn

Compare strategy of companies

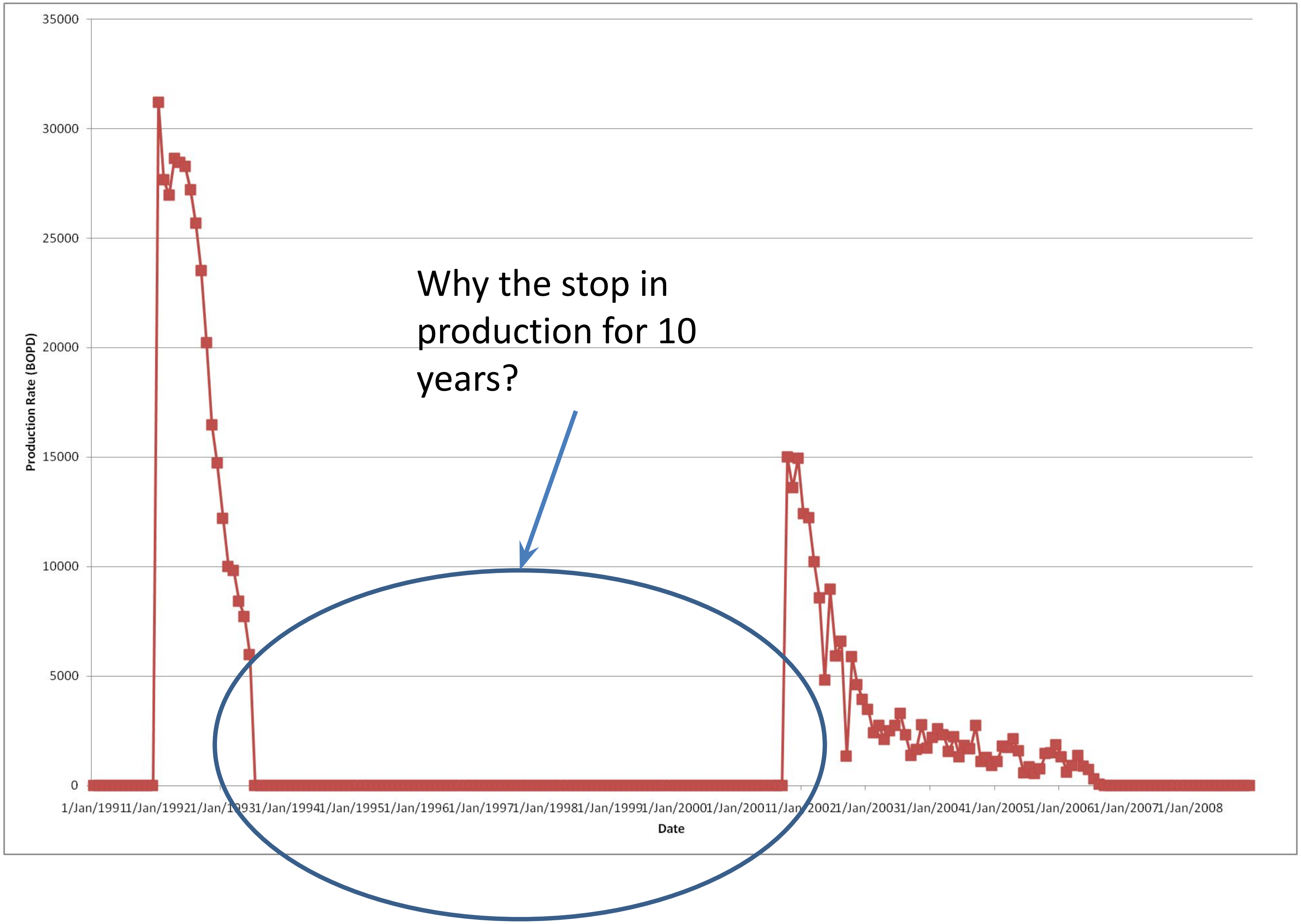
- **Offshore, deep water, complex fields**
- **Ultra high production (60,000 bpd + per well)**
- **High well costs ($150 million + per well)**
- **Ultra high CAPEX**
- **Long development cycles (6 years)**

- **Onshore, EOR, easy access, shallow**
- **Low production (500-1000bpd)**
- **Low CAPEX/high OPEX ($10/bbl)**
- **Low well cost ($2-4 million)**
- **Fast turn around times on wells (less than 1 year)**

Lifting cost of oil (worldwide)



Angus field NS



Aim

MAXIMISE VALUE	MINIMISE COST
• Maximise recovery • Speed up recovery • People/Team • Reservoir Knowledge/analysis • Recovery Technology	• CAPEX • OPEX • Tax • Depreciation

Aim

MAXIMISE VALUE

- Maximise recove
- Speed up recovery
- People/Team
- Reservoir Knowledge/analysis
- Recovery Technology

MINIMISE COST

- CAPEX
- OPEX
- Tax
- Depreciation

RISK

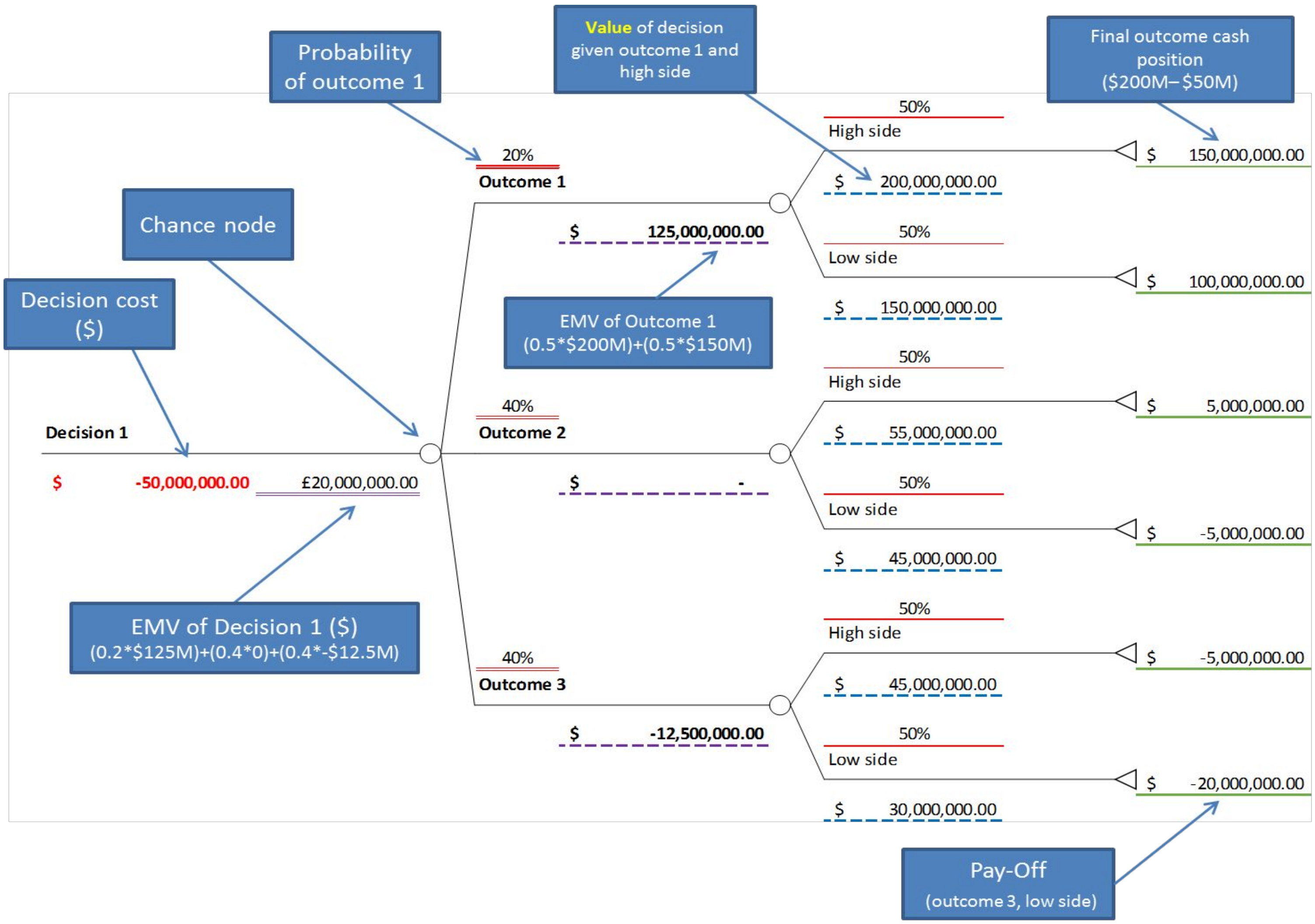
Value and Risk: Expected Return

- Expected loss/gain for an event is sum of probabilities*loss/gains for each event

$$E(R) = 0.5 \times £10 + 0.25 \times £20 + 0.25 \times (-£10) = £7.5$$

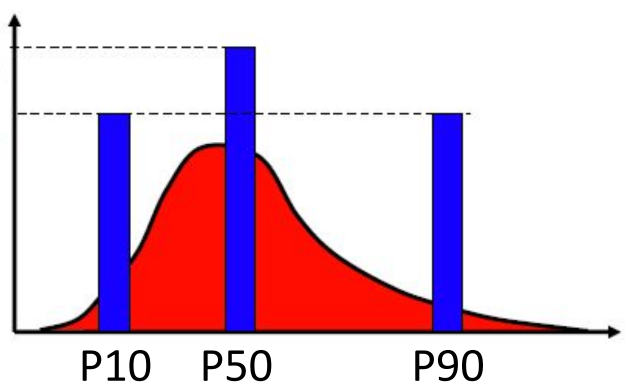
Loss/Gain	Probability
£10	50%
£20	25%
-£10	25%

Decision tree analysis



Discretisation of PDFs

- Convert continuous values into discrete to use in decision tree
- Several methods, such as:
  - Swanson's rule (P10/50/90 = 30%/40%/30%)
  - Pearson Tukey (P10/50/90 = 18.5%/63%/18.5%)
  - McNamee & Celona Shortcut (25%/50%/25%)



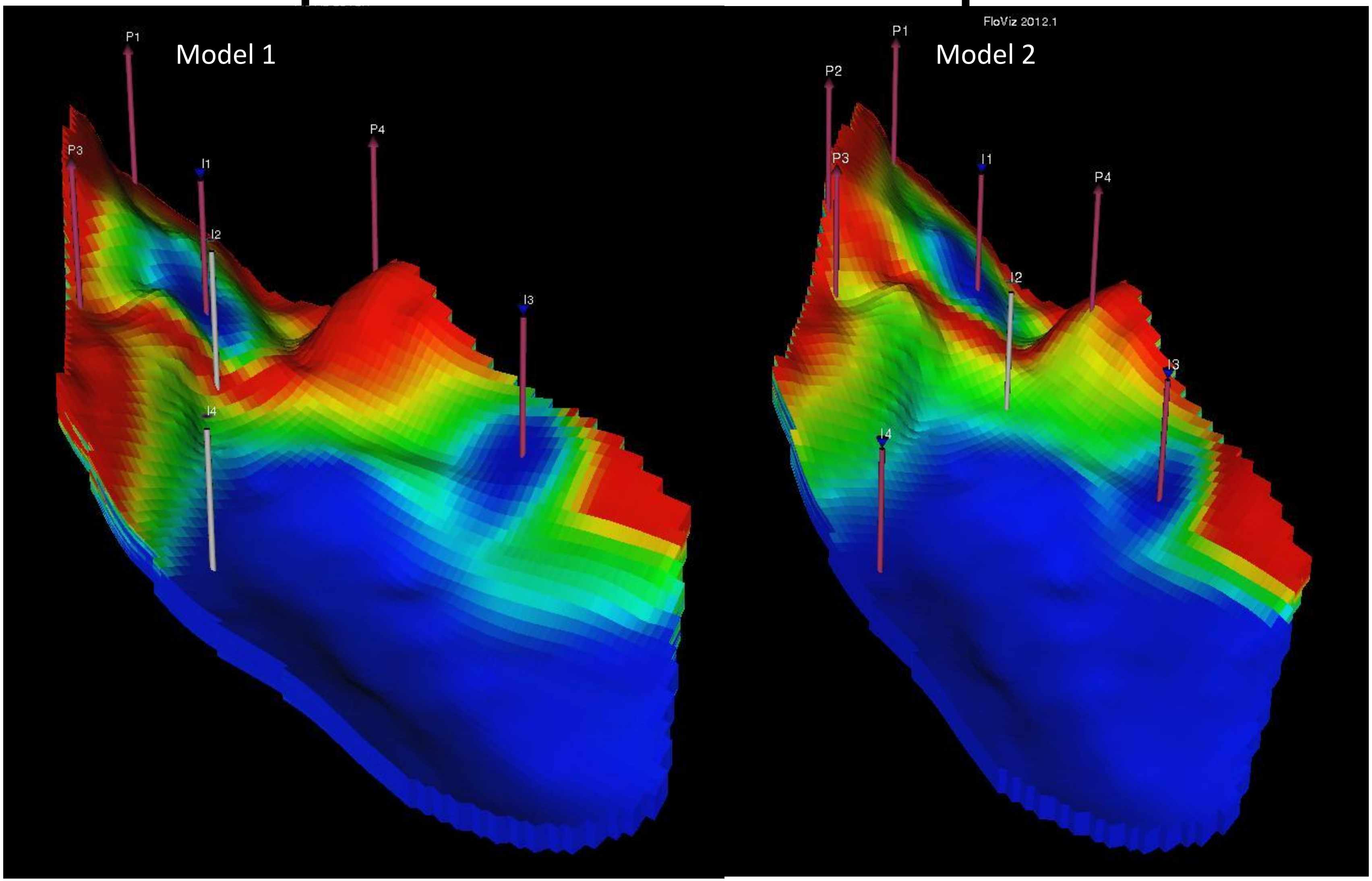
Maximise value through…

RESERVOIR DEVELOPMENT OPTIMISATION

What do we mean by optimisation

- Process of improving something
  - to find the best compromise among **several** often **conflicting requirements**
  - Constantly updating/improving process vs defined decision points
  - Maximising value, minimising risk/impact, lowering cost
  - Integrated solution in complex systems

Optimisation example



Optimisation often involves trade-offs

MAXIMISE VALUE

- Maximise recovery
- Speed up recovery
- People/Team
- Reservoir Knowledge/analysis
- Recovery Technology

MINIMISE COST

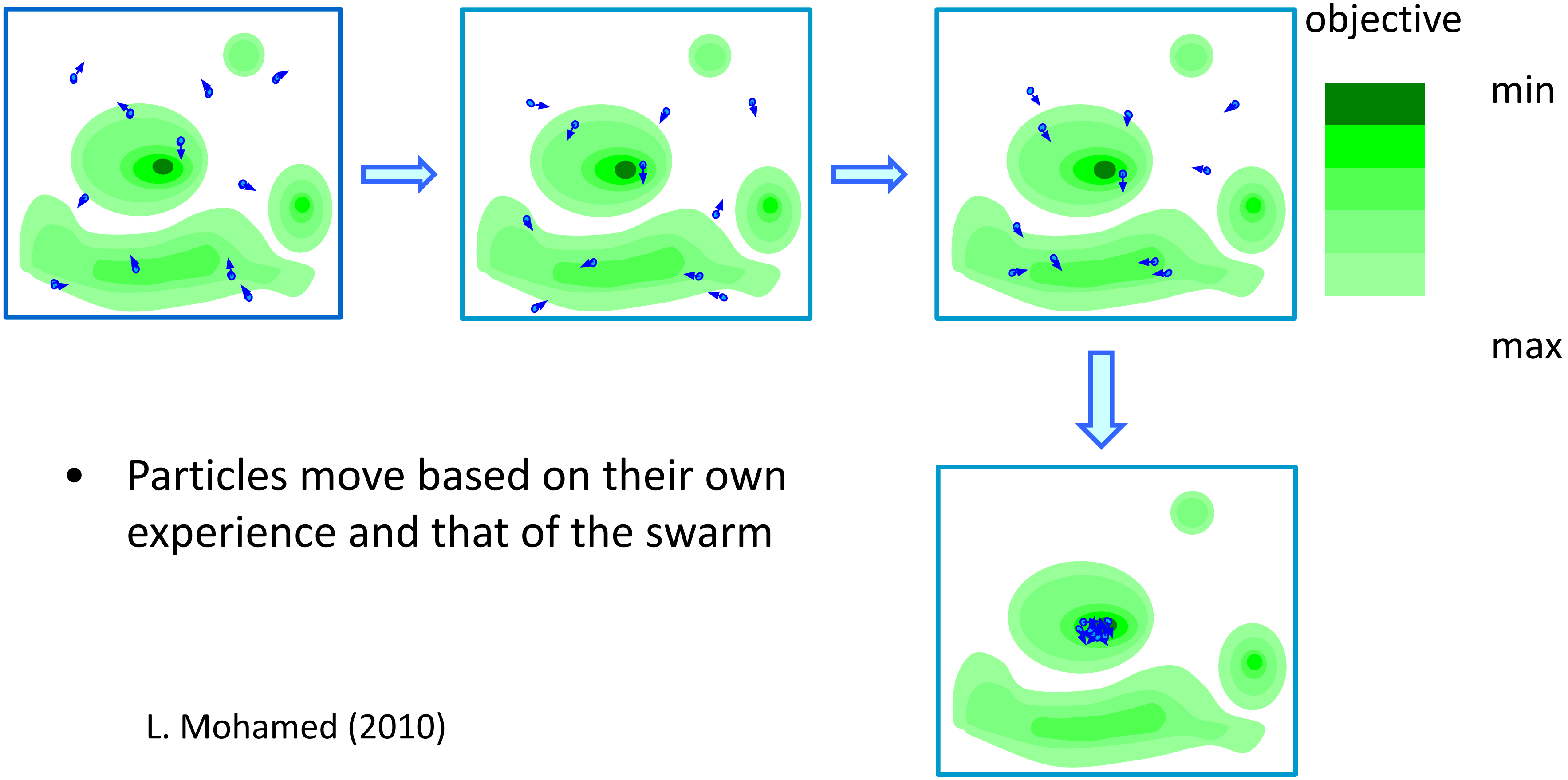
- CAPEX
- OPEX
- Tax
- Depreciation

Automated optimisation

- A set of algorithms available that can automate the optimisation process
- Define problem as a set of optimisation parameters in the model
- Algorithm adjusts these automatically to find “optimal solutions”
- Algorithm steps iteratively, converging on the “best answer”
- Multiple competing criteria means a trade-off in the optimal solution

Optimization Algorithm

- Particle Swarm Optimization (PSO)

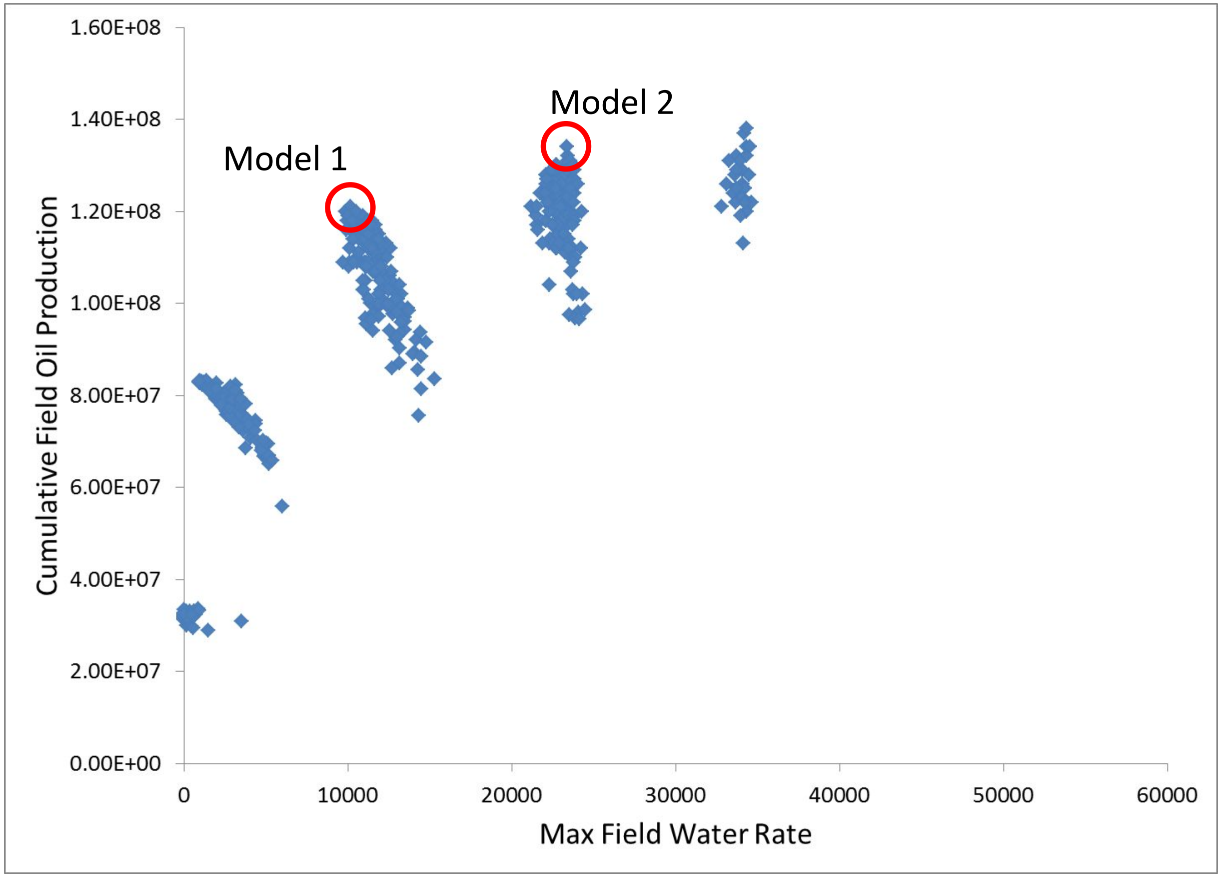


- Particles move based on their own experience and that of the swarm

L. Mohamed (2010)

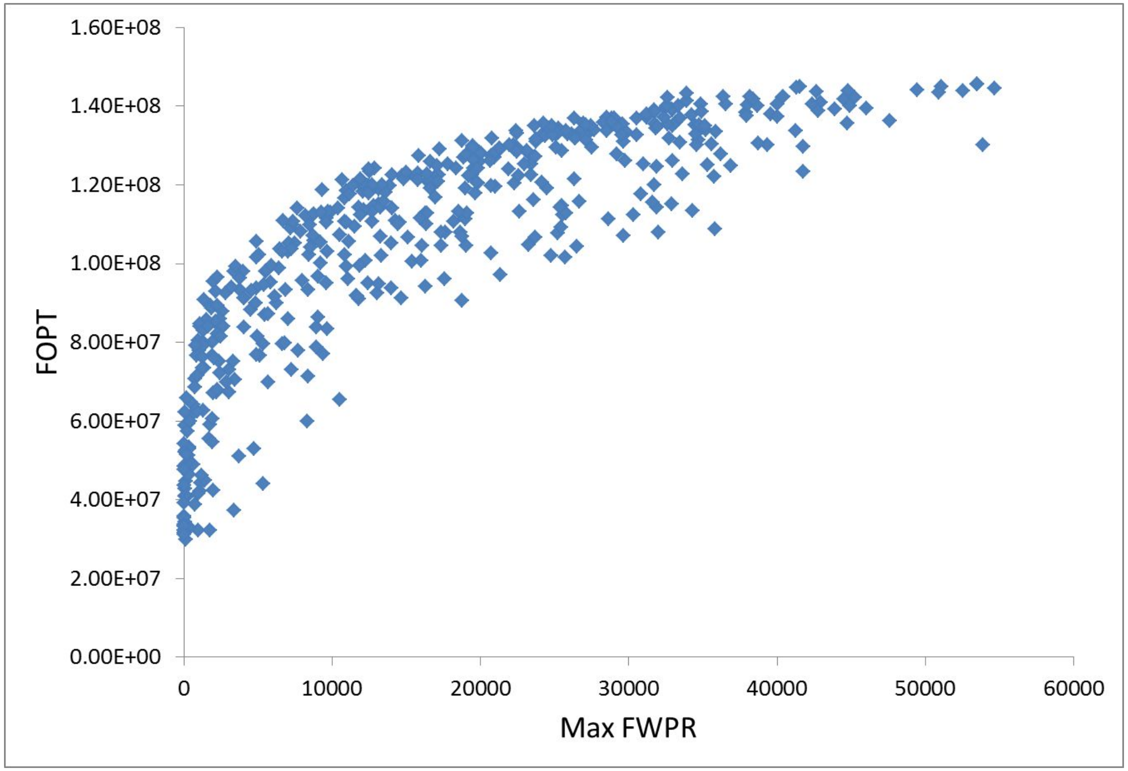
How many wells?

- Vary well status and well locations

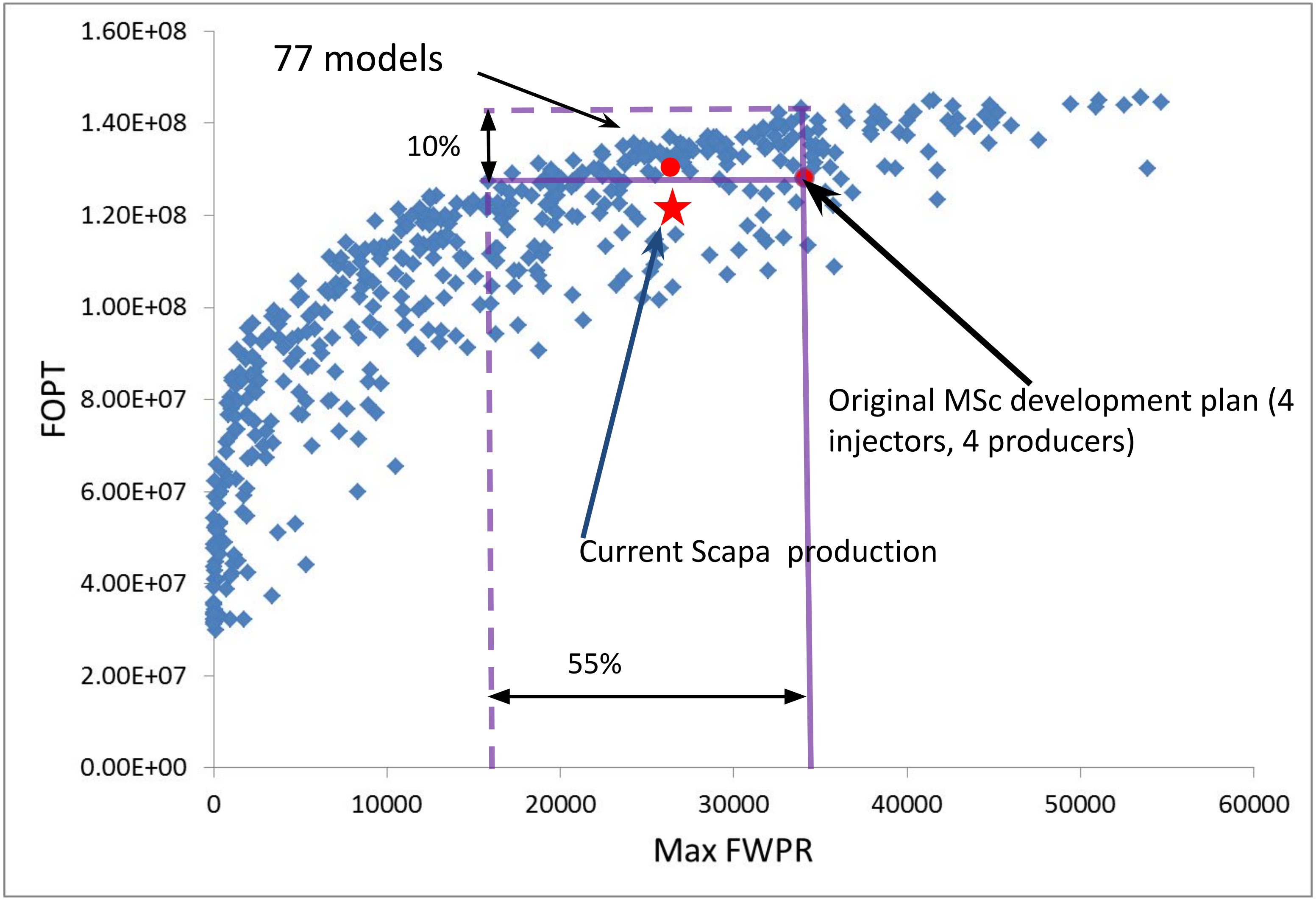


Real life trade-off in optimisation

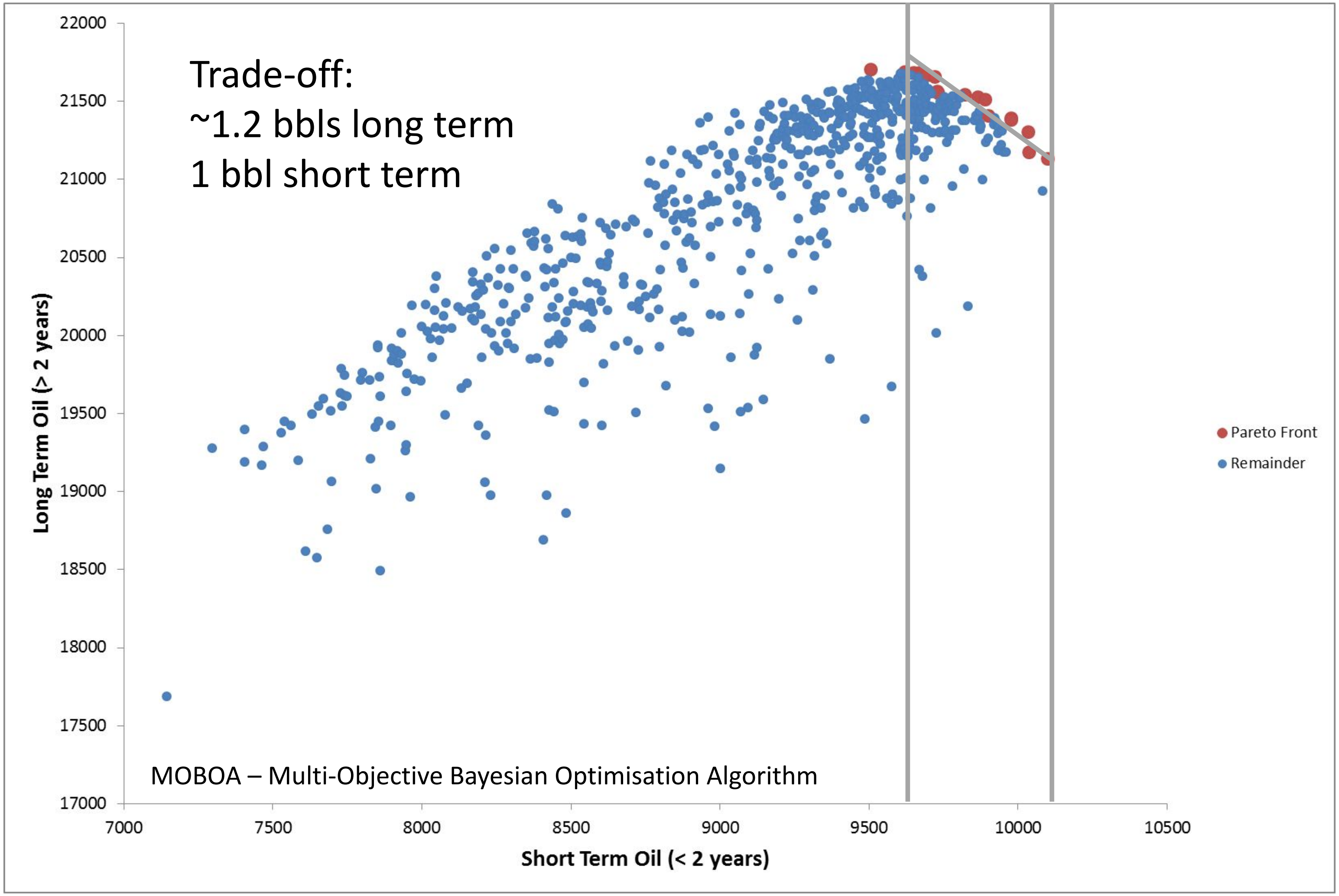
- Vary injection well rates and locations of wells
  - Well rates in [0,15] MBD



MSc students vs an algorithm?



Optimization of Infill Well Locations



In review

- **Creating value** from of our asset
- **Ongoing**, Life-of-field process
- **Risk** in decisions from uncertainty in the field
- We can **increase value** or **decrease costs**
- **Geology and engineering** are both important identifying the best development plan

Summary of strategies

- Developing plans
  - Maximise oil/gas prod. – field rehabilitation
- Implementing
  - SOA facilities and wells - redevelopment
- Monitoring
  - static and dynamic
- Evaluating
  - Geoengineering approach

RM Strategy

- Evaluating
- Developing
- Implmenting
- Monitoring

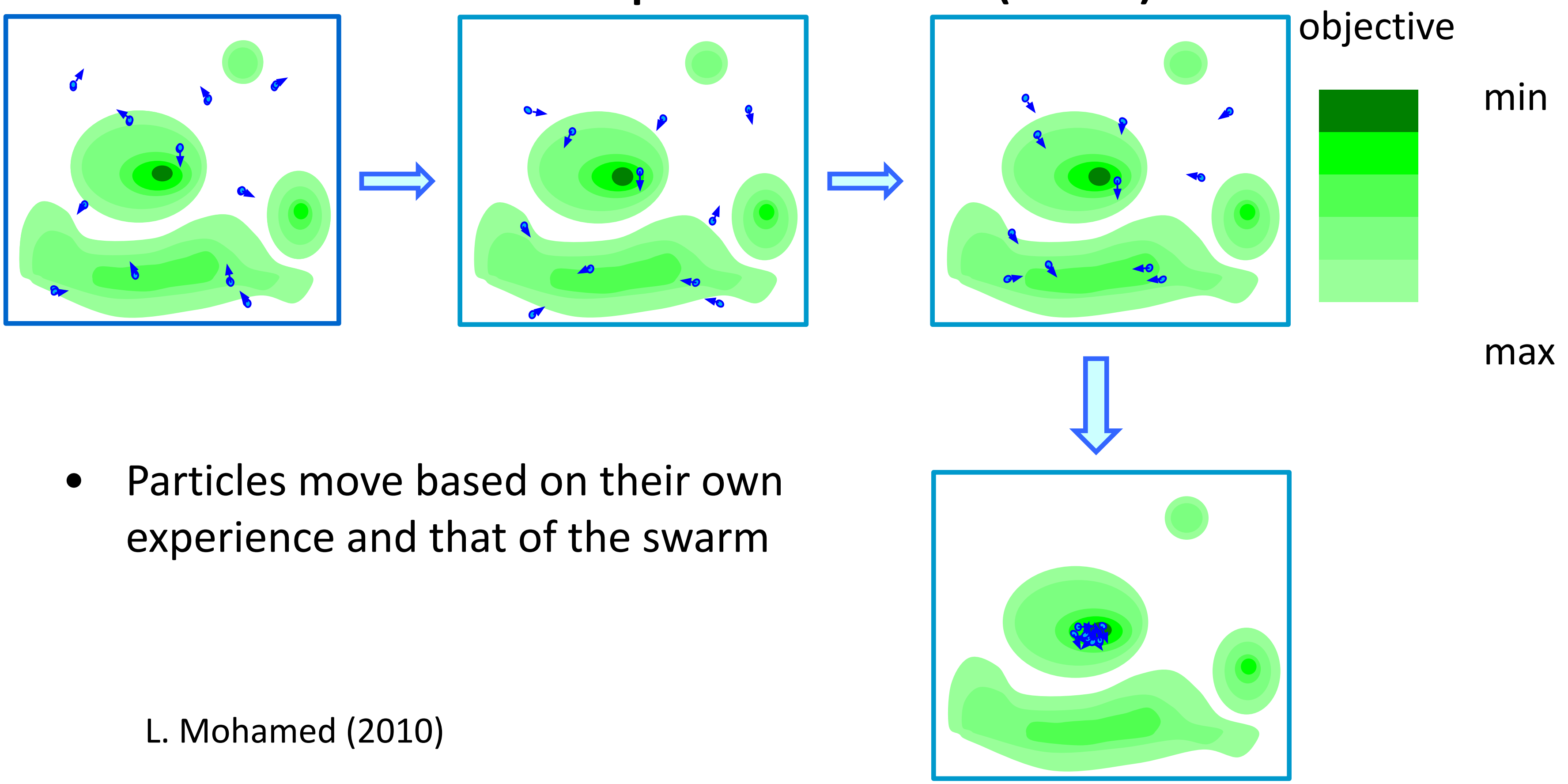
- EDIM - as in Edim-bourg……….

Reservoir Management - key points

- Integration
- Synergy
- Persistence
- Proactive

Optimization Algorithm

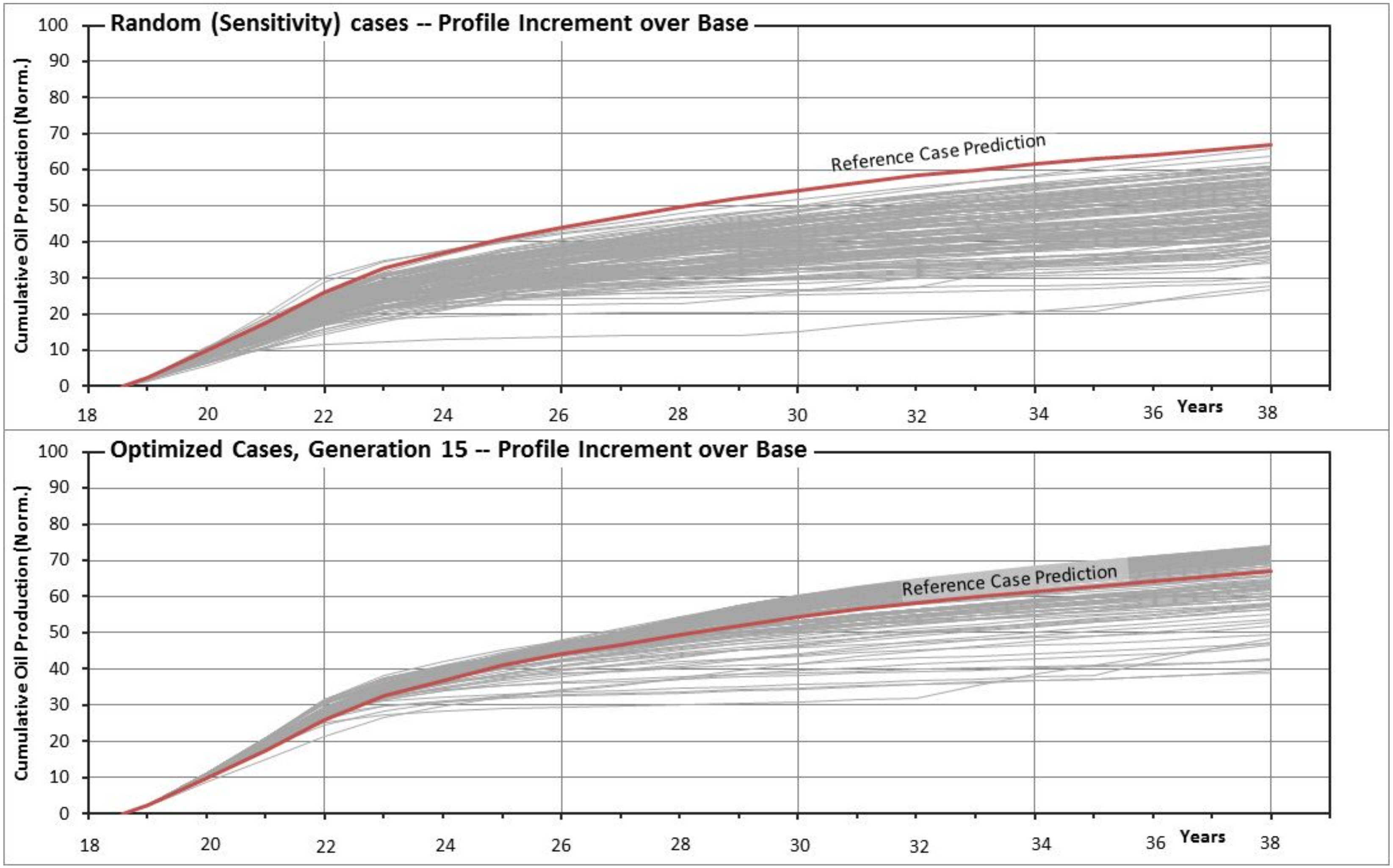
- Particle Swarm Optimization (PSO)



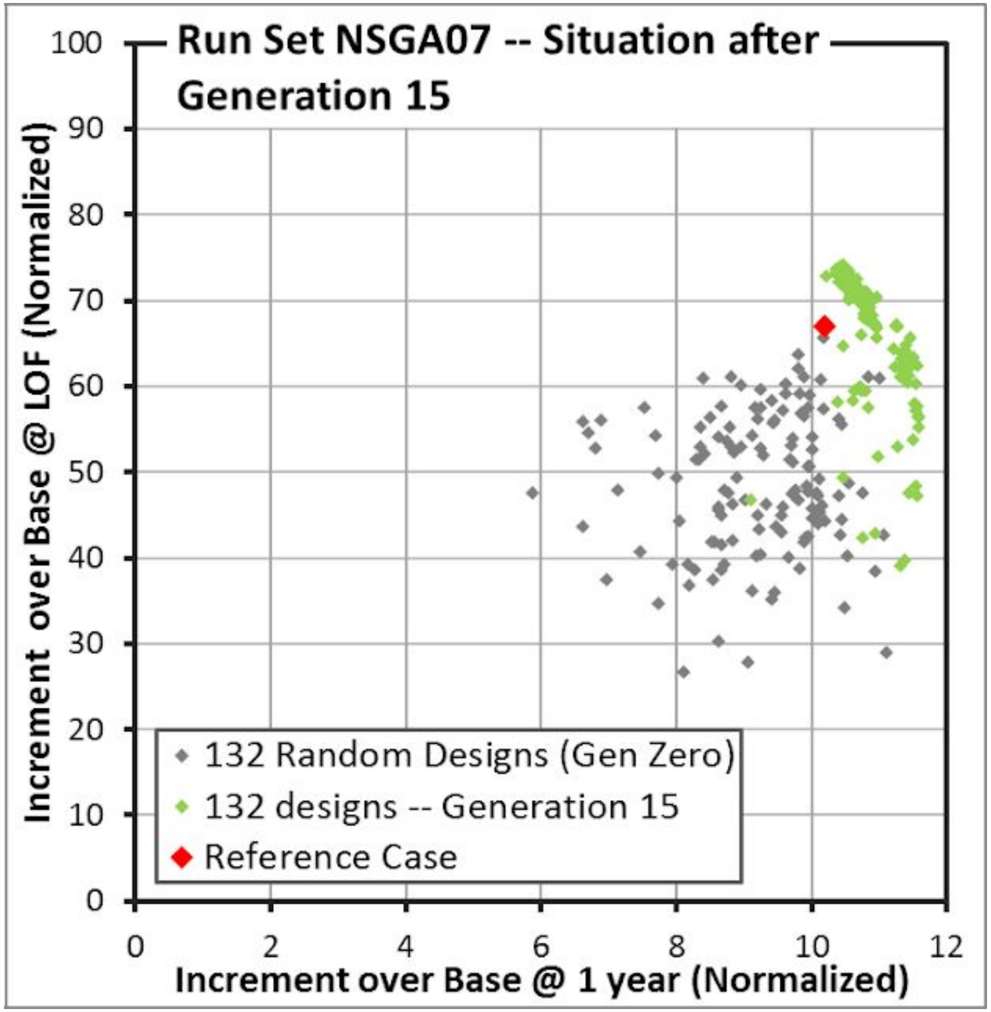
- Particles move based on their own experience and that of the swarm

L. Mohamed (2010)

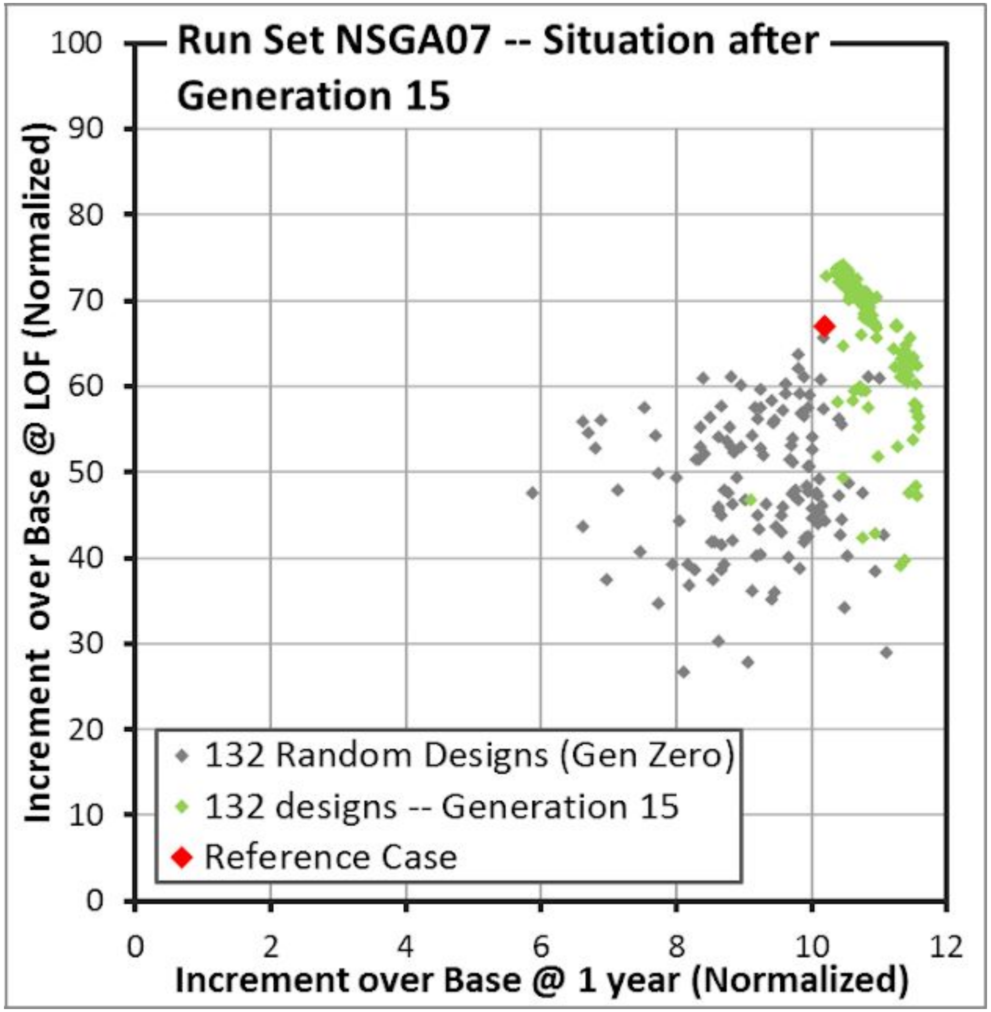
Application in North Sea



North Sea Application – Pareto Plot



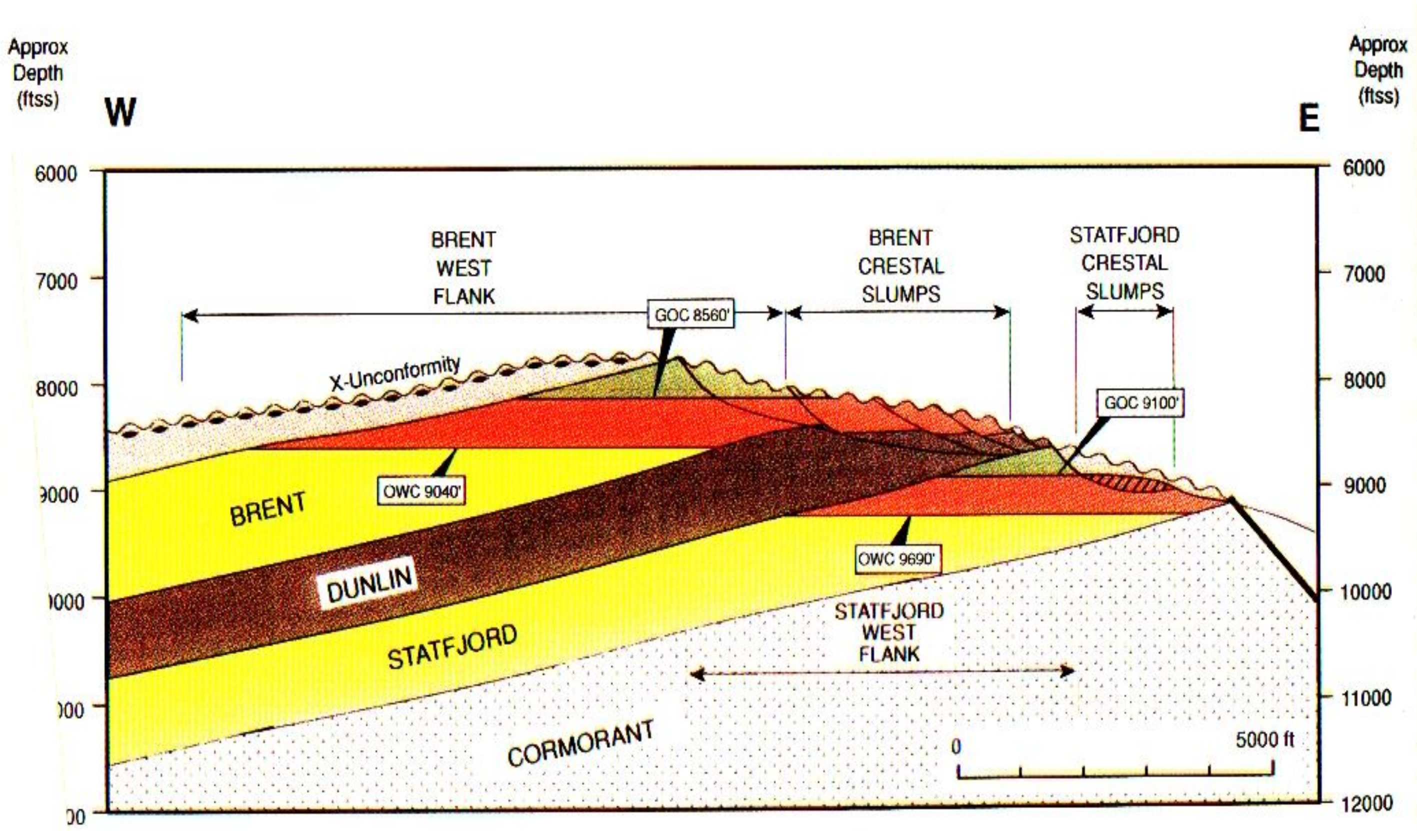
North Sea Application – Pareto Plot



Example: Brent Field

- Brent Field Depressurisation
  - Christiansen and Wilson, 1998, James et al., 1999
- Optimise oil recovery
  - Locate remaining oil (seismic inversion, AVO)
  - Slump developments
- Oil-rim management
- Critical gas saturation?
- Aquifer influx and BPW
- Full Field Simulation Model (FFSM)
- Scenario analysis

Brent Field



(from James et al., 1999)

OIIP 3800mmbbls GIIP 7.5TCF
Reserves(99) 200mmbbls & 2.6TCF
(biggest UK field)

Reservoir Management

- " Sound reservoir management practice relies on the use of available resources to maximise profits from a reservoir by optimising recovery and minimising capital investment and operating expenses" - Satter and Thakur, 1994

- maximise recovery?