Shell Exploration & Production Europe

Pseudo Relative Permeabilities
A means of more accurate reservoir simulations

1. History of pseudo relative permeability methods

2. Example of pseudos technology developed and applied in Brent field simulations 1986 – 89

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My Resume

2006 - Present	Regional Value Assurance Advisor – Shell EP Europe Reviews of Shell's projects in Europe
2003 - 2006	Regional Resource Volume Manager – Shell EP Europe Management of Shell's reserves in Europe during reserves dispute with SEC
2001 - 2003	Capability Manager, Norske Shell Strengthening technical skills of PE staff
1999 - 2001	Managing Shell's interests in a group of fields and looking after staff skills
1998 - 1999	Responsible for all Shell's PE work and PE staff (25) in Norway
1991 - 1998	Responsible for all Shell's RE work in Norway, including Troll and Draugen developments
1989 – 1991	Managing Shell's interests in all partner operated oil fields in Norway
1986 - 1989	Major simulation study (20 man years) leading to Brent field depressurisation
1980 - 1986	Reservoir engineer for Troll gas development/leading multi company task force
1976 - 1980	Development of Statfjord field (Mobil)
1971 -1975	Student NTH

Pseudo relative permeabilities

A means of incorporating more accurate physics into each grid block

- Effects of detailed geology and saturation distribution represented in (pseudo) relative permeabilities for large grid blocks

Advantages

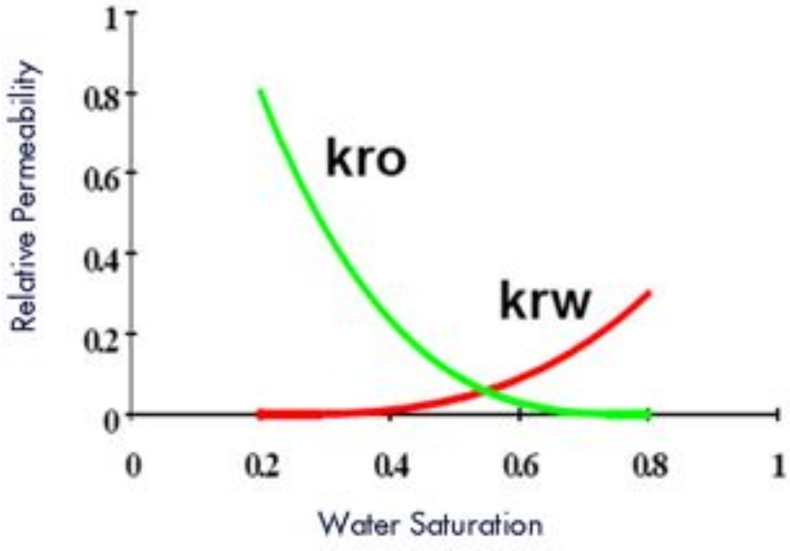
- Allows accurate simulation with fewer grid blocks
- Suppresses numerical dispersion
  (non-physical flow of displacing fluid into neighbouring grid blocks)
- Reduced turn-around times for simulation runs

Disadvantages

- Not well understood by simulation engineers
- Generation of pseudos is seen as cumbersome
- Belief that more grid blocks are a simpler option
- Pseudos cannot fully solve all grid resolution issues
  (e.g. local balance between gravity and viscous forces in well coning/cusping situations)

Relative Permeability as measured in laboratory
Basic input to all reservoir simulation work

- Measured on small core plugs
- Often applied in field scale reservoir simulation
  - Assumed valid for entire grid block volume
  - Does not account for saturation gradients within the grid block
  - Leads to non-physical numeric dispersion and inaccurate simulation results
- Pseudo relative permeabilities represent a method for more accurate field scale simulation



Brief history of pseudo rel. perm. technology

- Early concepts (late 1960's – 1970's) focussed on representing 3D problems in 2D areal simulators (Coates et. al., Hearn, Jacks et. al., Kyte & Berry)
  - Available computers allowed very limited number of grid blocks
- During the 1980's a number of papers aimed at refining the generation of psuedos
  - Many papers focus on upscaling of models of heterogeneous reservoirs (Killough et. al., Davies & Haldorsen, Kossack et. al.)
- In 1991 Stone presented a rigorous method which allows reproduction of fine grid model results for varying rates and including non-communicating layers
- In later years the interest in pseudo relative permeabilities has faded
  - Apparently the belief is that more powerful computers, allowing many more grid blocks, has removed the need for pseudos
  - Another factor is that preparation of pseudos is seen as combersome and is not well understood by simulation engineers

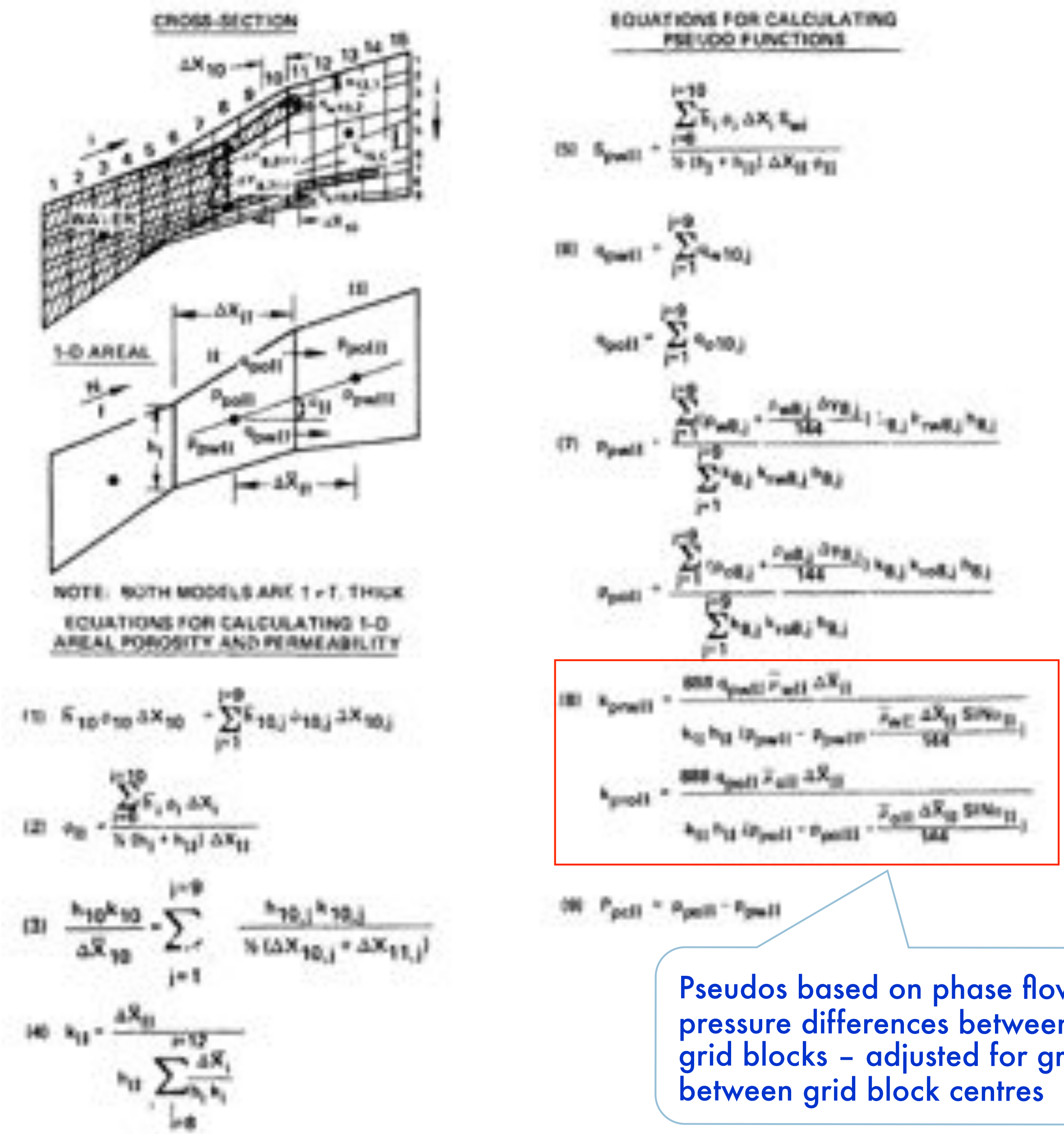
SPE Advanced Technology Workshop on History Matching in Nov. 2009 concluded:

Session 1: Up-Scaling Issues

- Pseudo-Kr is still needed in today's models
  - Heterolithic, laminated zones cannot be captured in full-field coarse cells without some type of p-Kr
  - Viscous flow effects cannot be ignored either
  - Level of scale-up affects p-Kr curves
  - Well locations and rates can affect p-Kr curves
- P-Kr accounts for scale-up errors introduced by using rock-Kr in coarse cells
  - Accounts for detail that has been washed out
  - Water breakthrough can be too late
  - Sw hold-up still needed for numerical dispersion
- Effective Sor may be increased due to heterogeneity

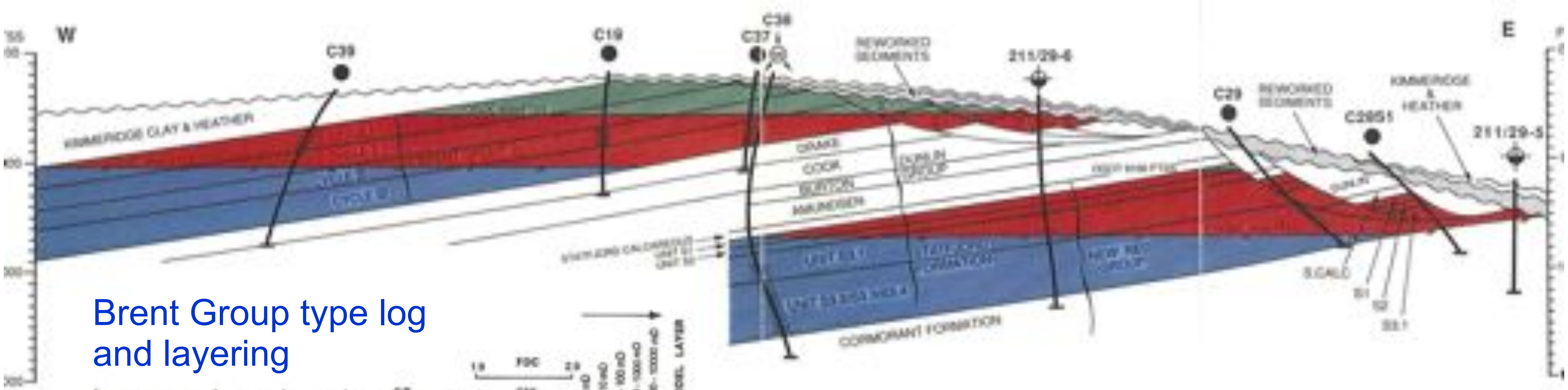
Kyte & Berry procedure for calculating pseudos

SPE5105

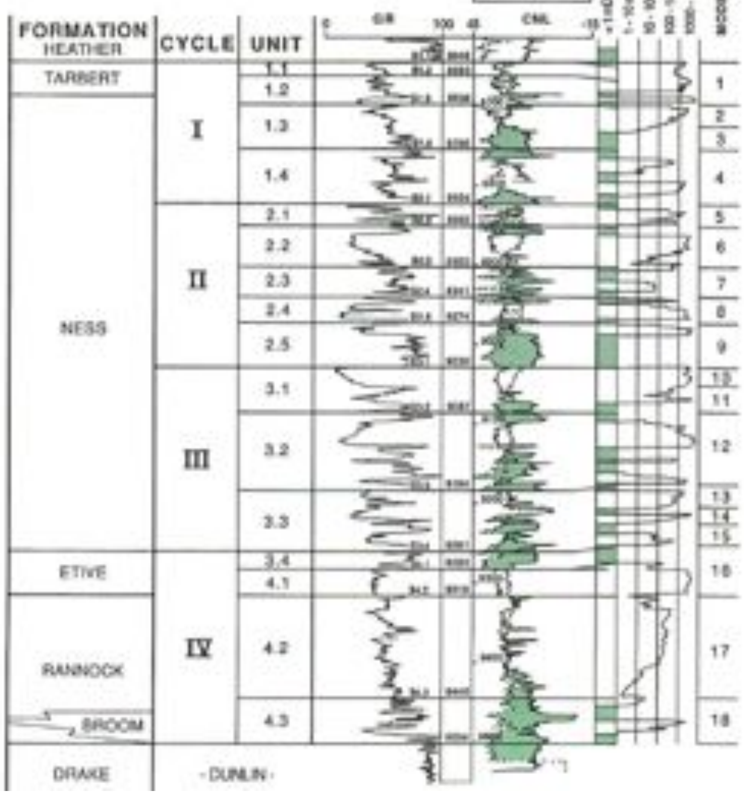


Pseudos based on phase flow and phase pressure differences between upscaled grid blocks – adjusted for gravity head between grid block centres

Brent Field - Structural Cross-section



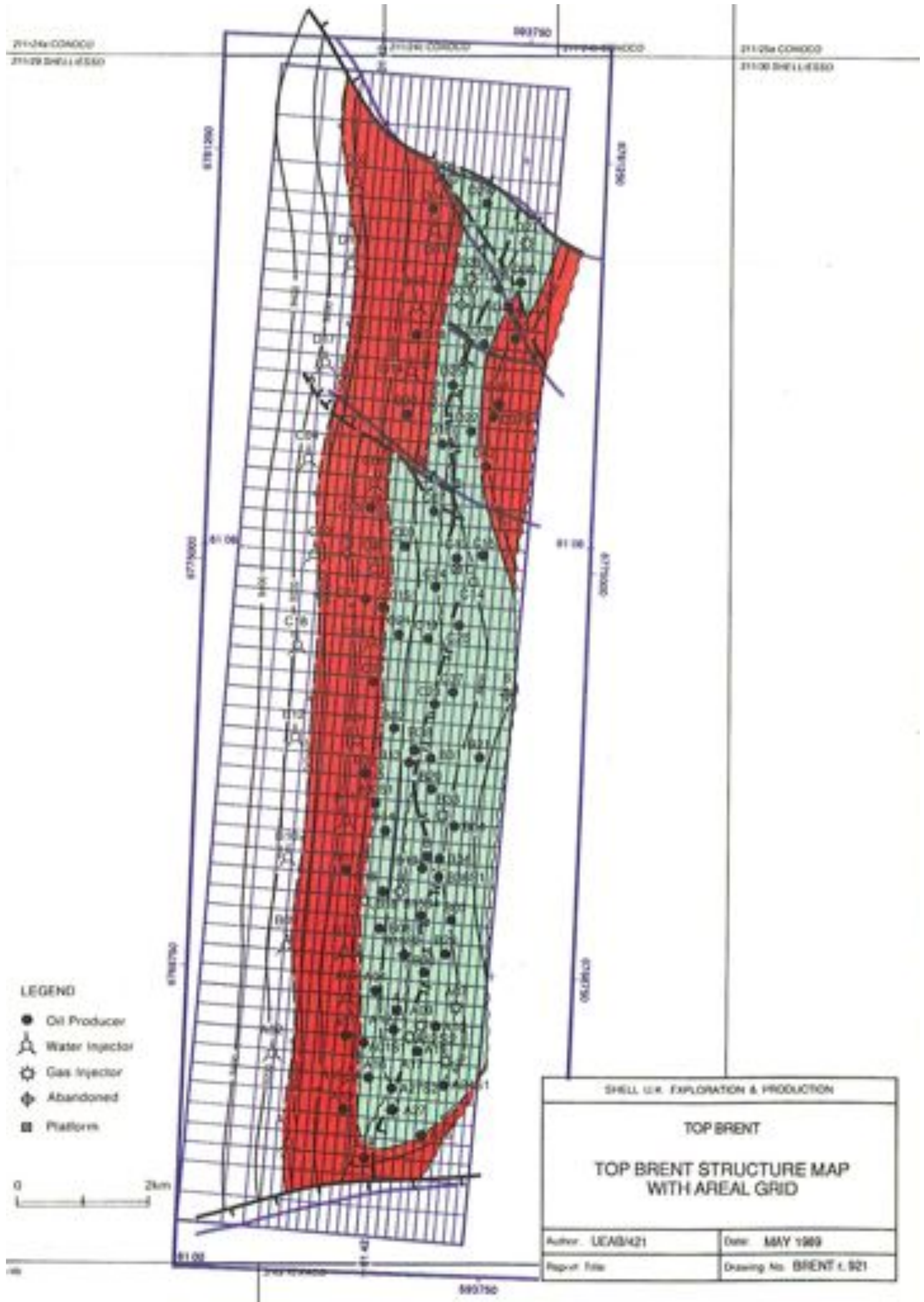
Brent Group type log and layering



- Model layering is based on the presence of extensive shales covering most of field area
- Holes in these shales are mapped based on well observations

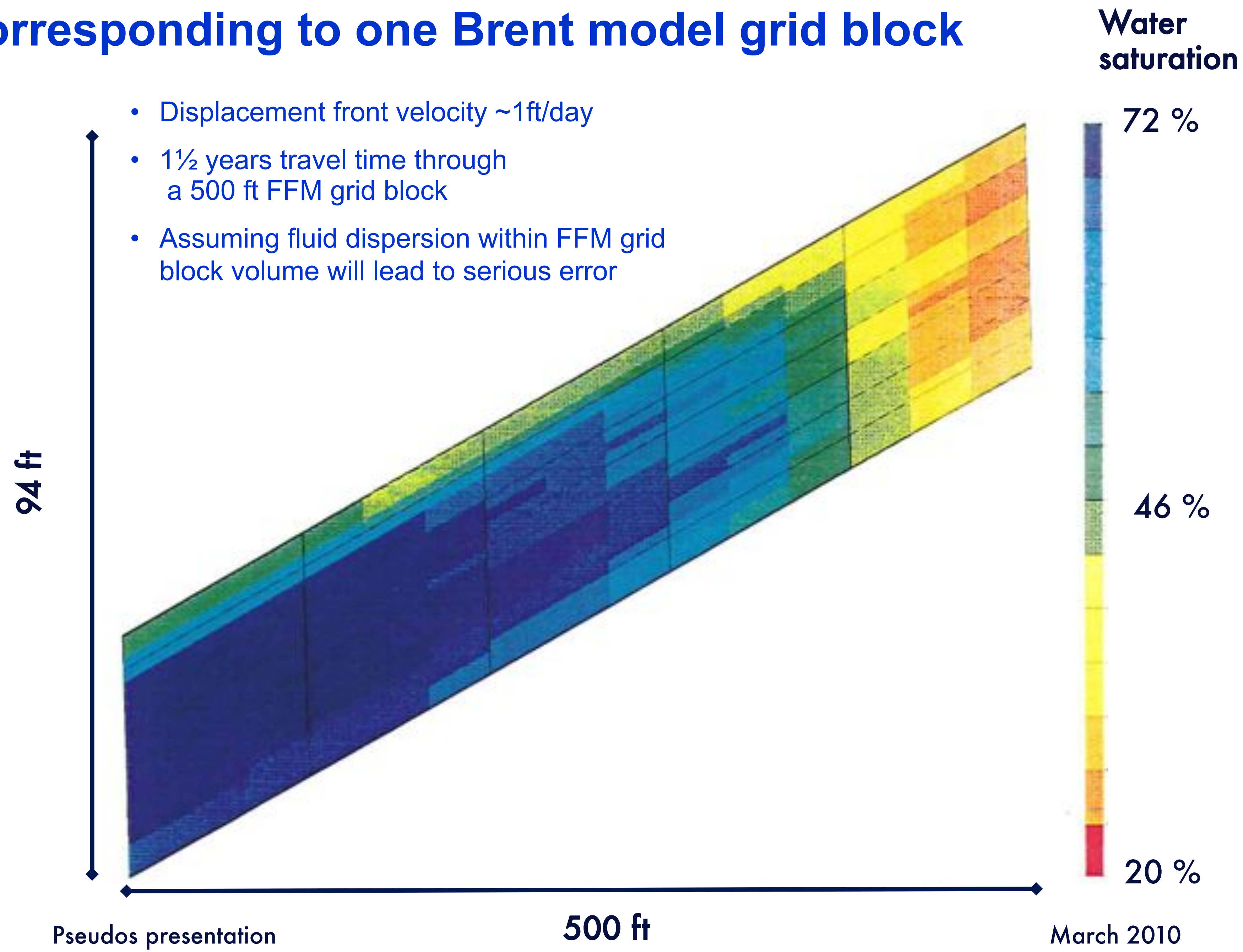
Areal simulation grid
Brent reservoir

- Grid block size 1000ft x 500ft
- Basis for grid block size:
  - Overnight turnaround of history match runs
- About 100 wells during field history



Water saturation distribution in area corresponding to one Brent model grid block

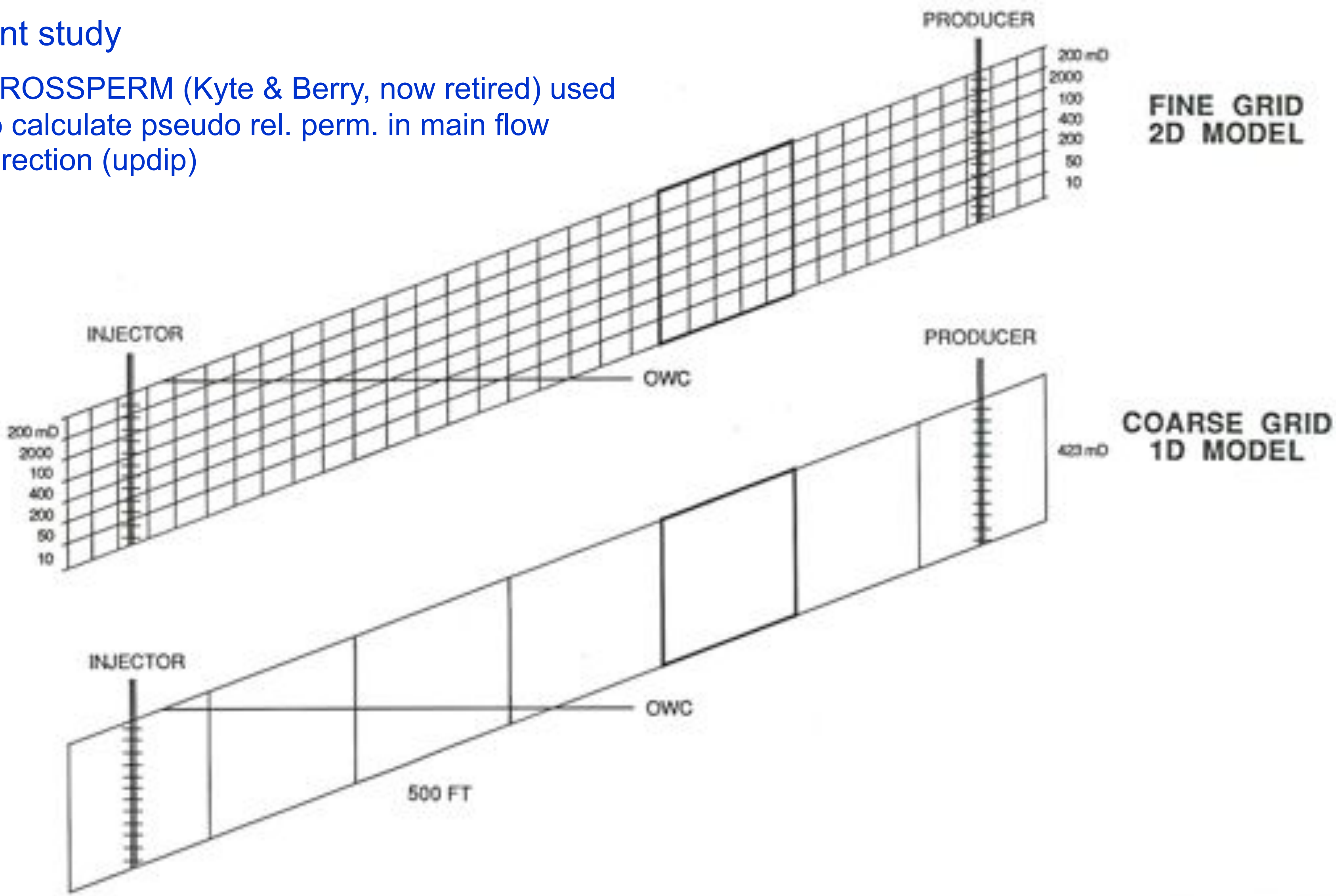
- Displacement front velocity ~1ft/day
- 1½ years travel time through a 500 ft FFM grid block
- Assuming fluid dispersion within FFM grid block volume will lead to serious error



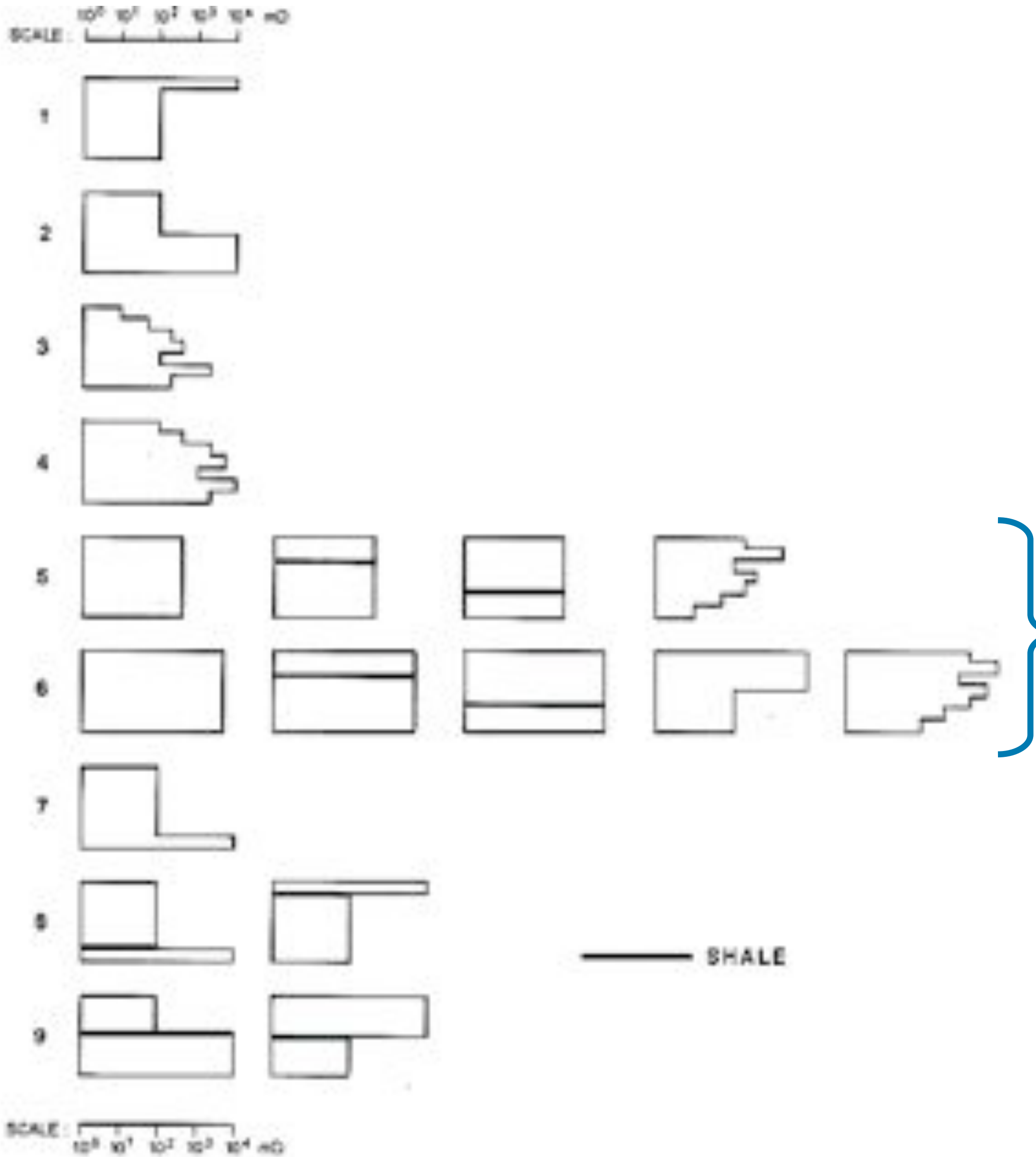
2-D and 1-D simulation models for generation and checking of pseudo curves

Brent study

- CROSSPERM (Kyte & Berry, now retired) used to calculate pseudo rel. perm. in main flow direction (updip)



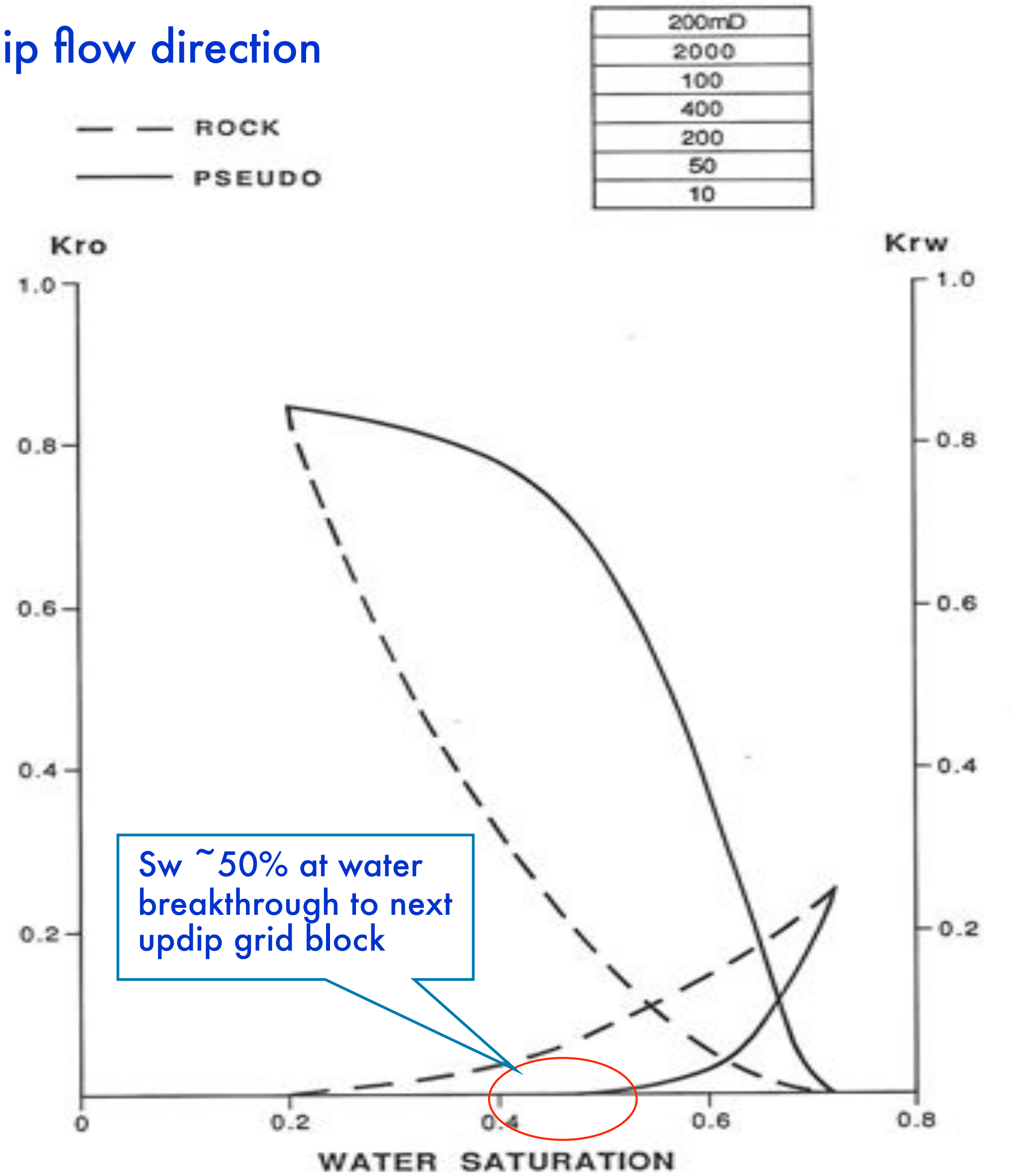
Brent reservoir intra-layer permeability profiles



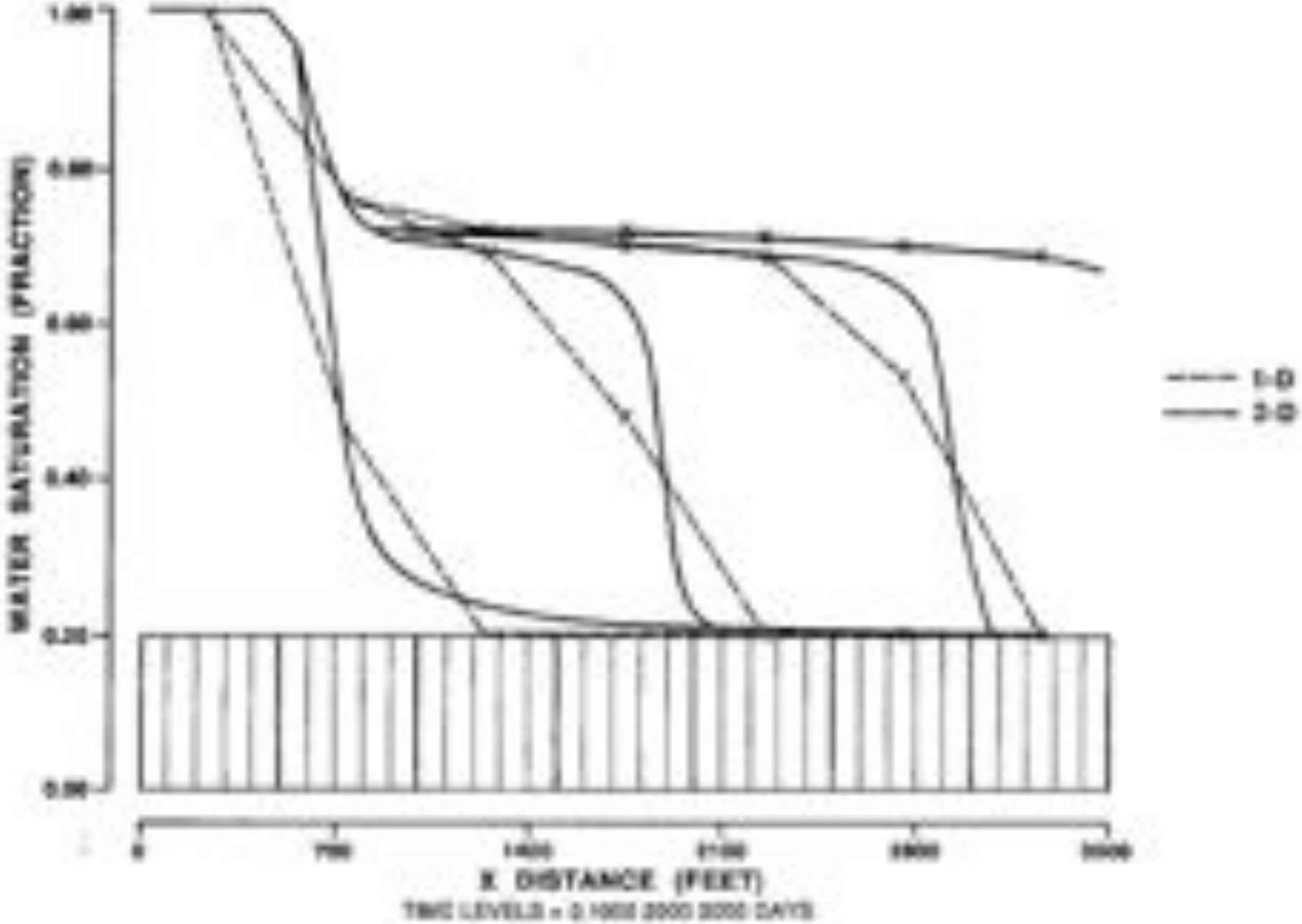
Several profiles gave the "same" pseudo rel. perm

Pseudo relative permeability for coarsening upwards sequence

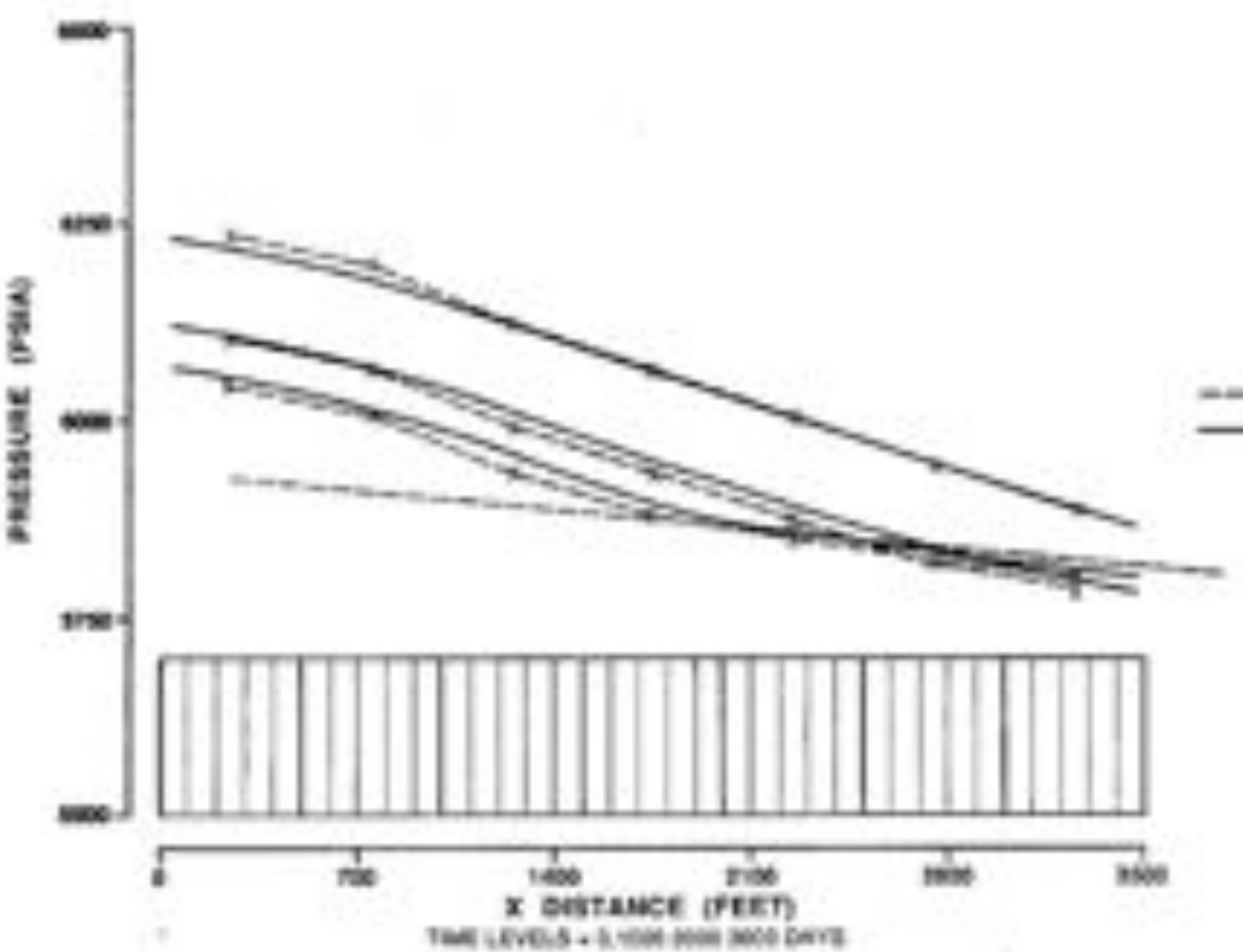
Updip flow direction



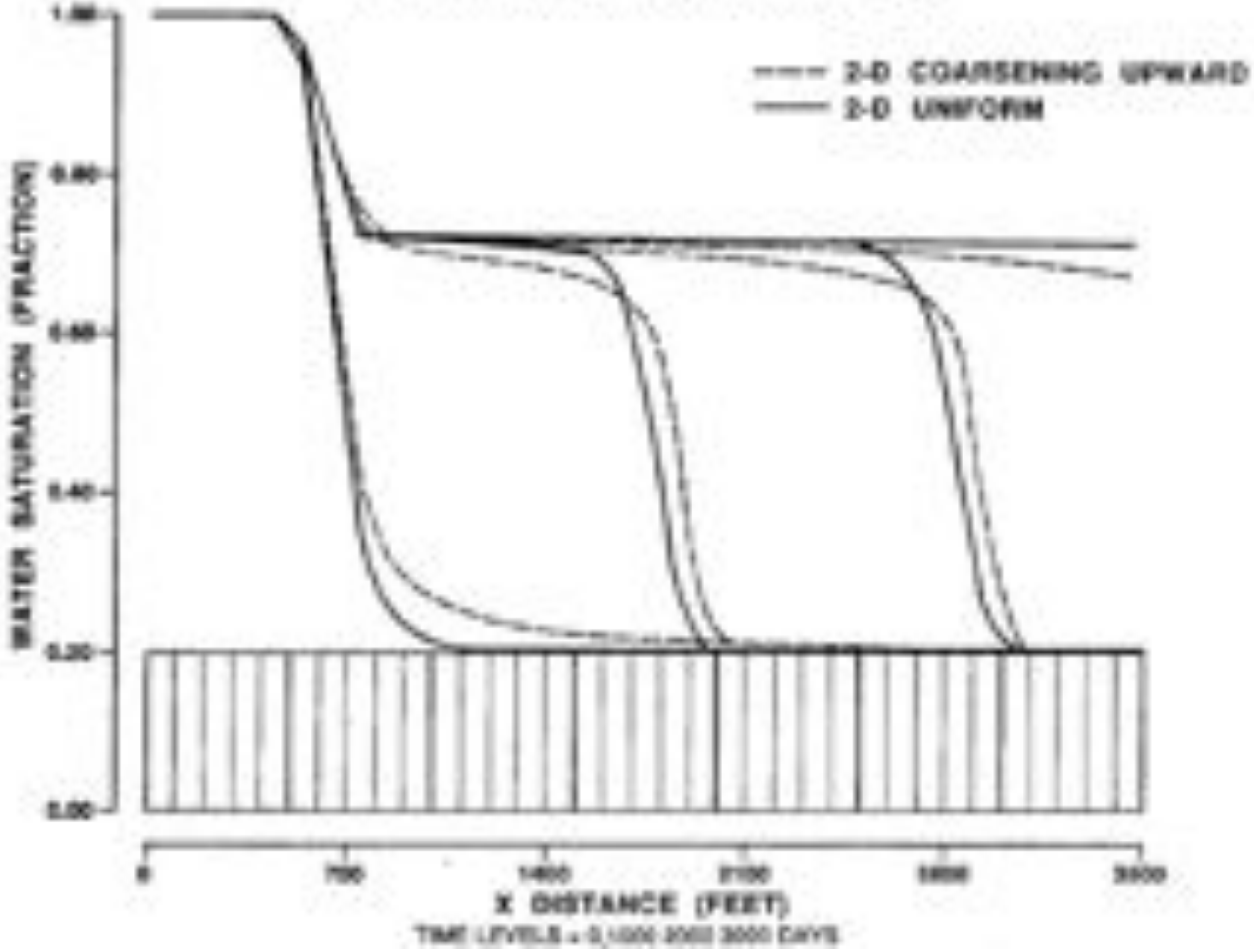
Comparison of 2-D and 1-D model saturation profiles
Low permeability coarsening upwards profile



Comparison of 2-D and 1-D model pressure profiles
Low permeability coarsening upwards profile

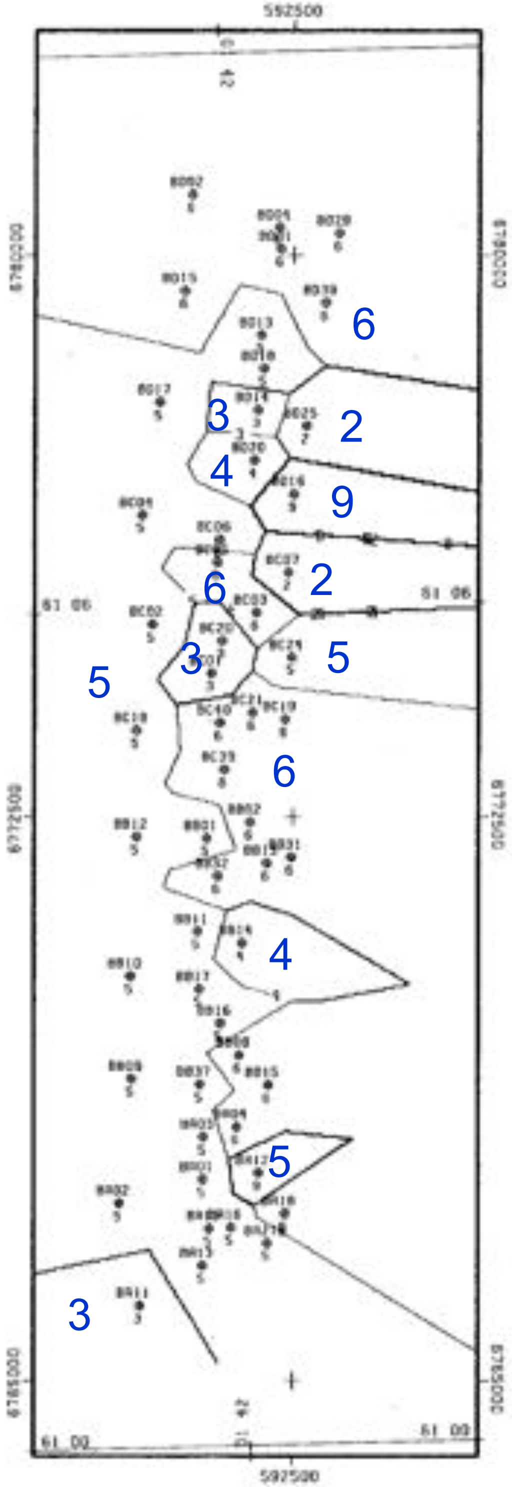


Comparison of 2-D model saturation profiles for uniform and coarsening upwards permeability profiles

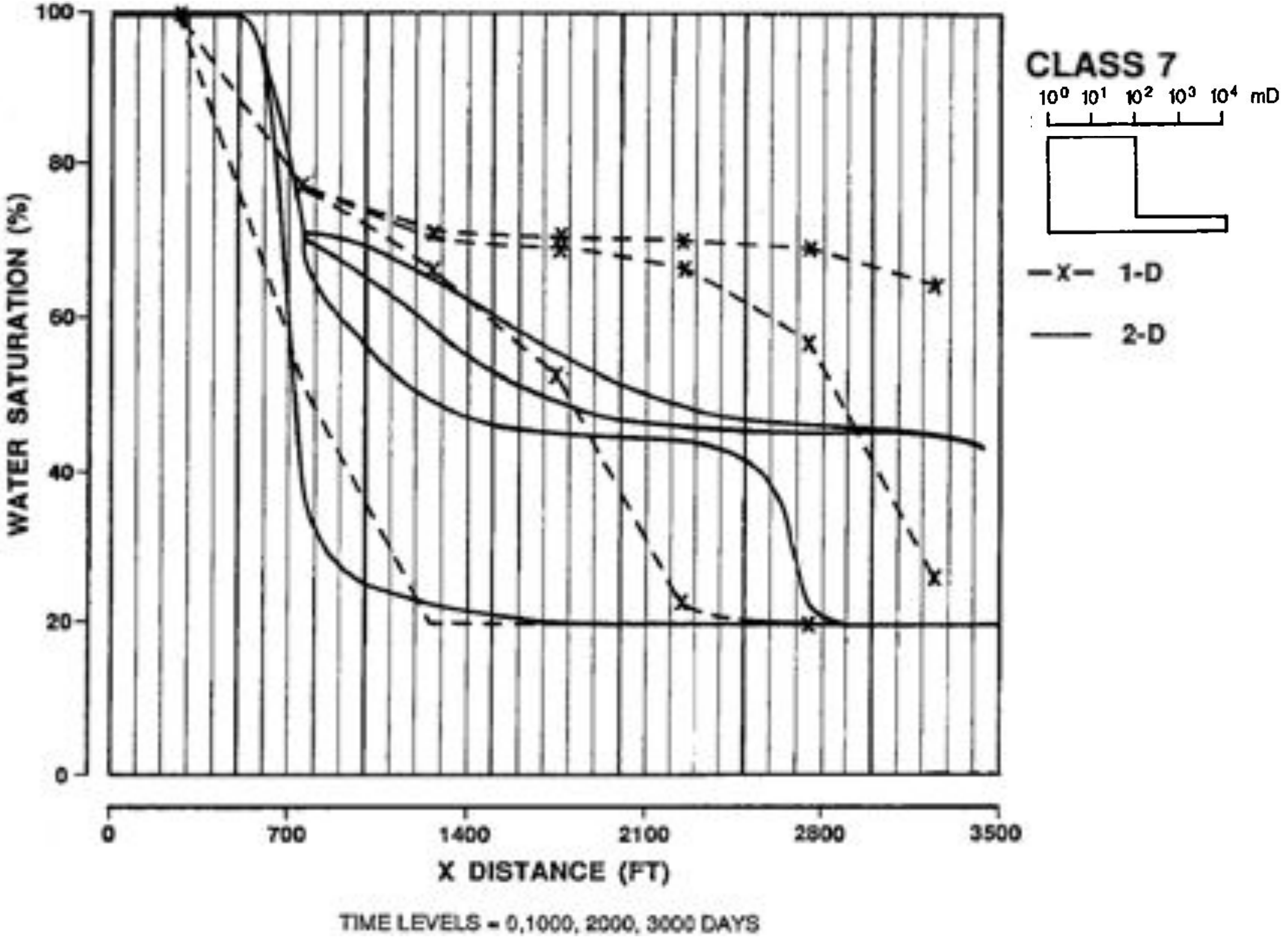


Pseudo rel. perm. type allocation

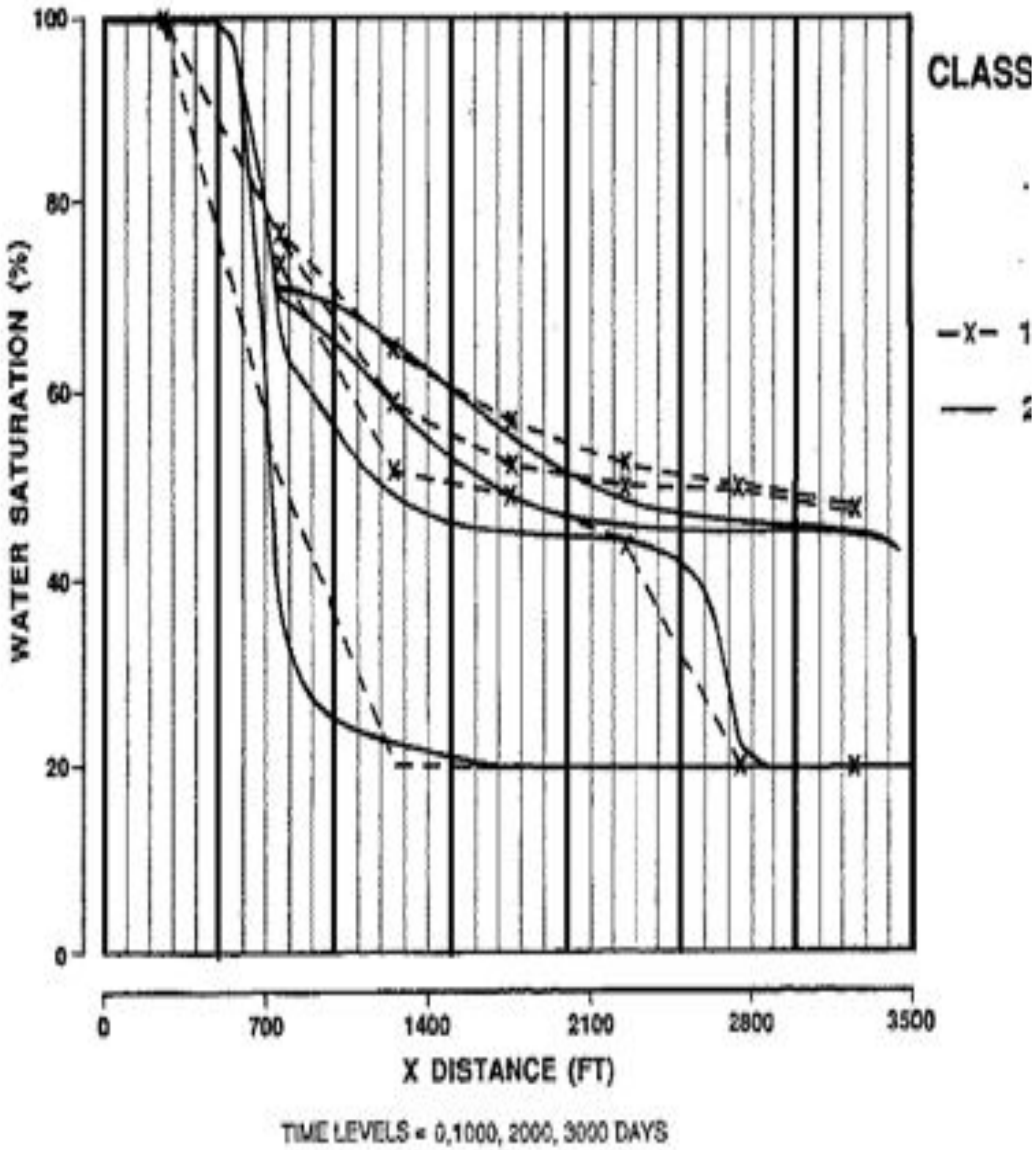
Brent reservoir layer 1



Water saturation profiles in 2-D and 1-D simulations – both with rock curves



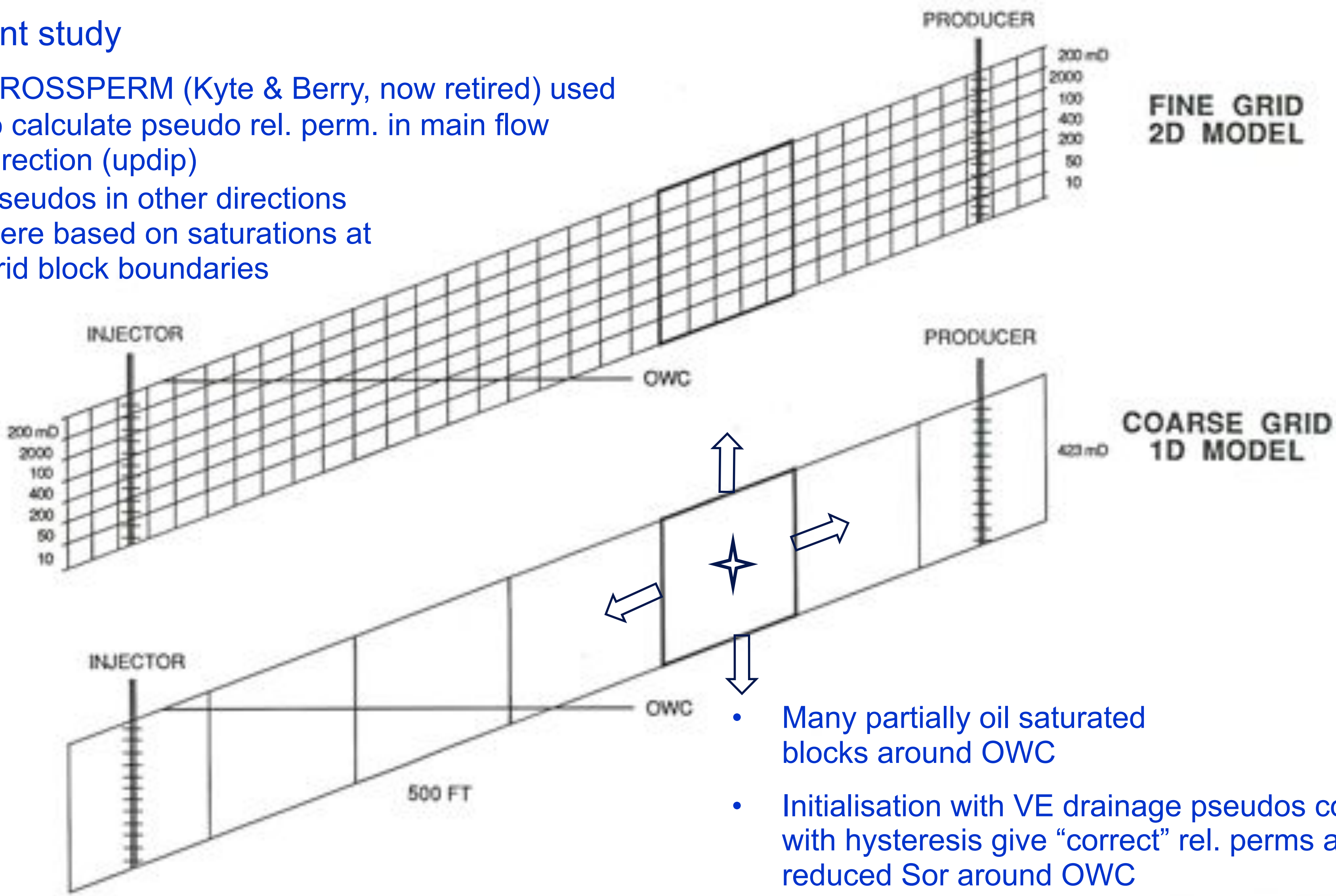
Water saturation profiles in 2-D with rock curves and 1-D simulations with pseudo curves



Pseudos in other directions

Brent study

- CROSSPERM (Kyte & Berry, now retired) used to calculate pseudo rel. perm. in main flow direction (updip)
- Pseudos in other directions were based on saturations at grid block boundaries

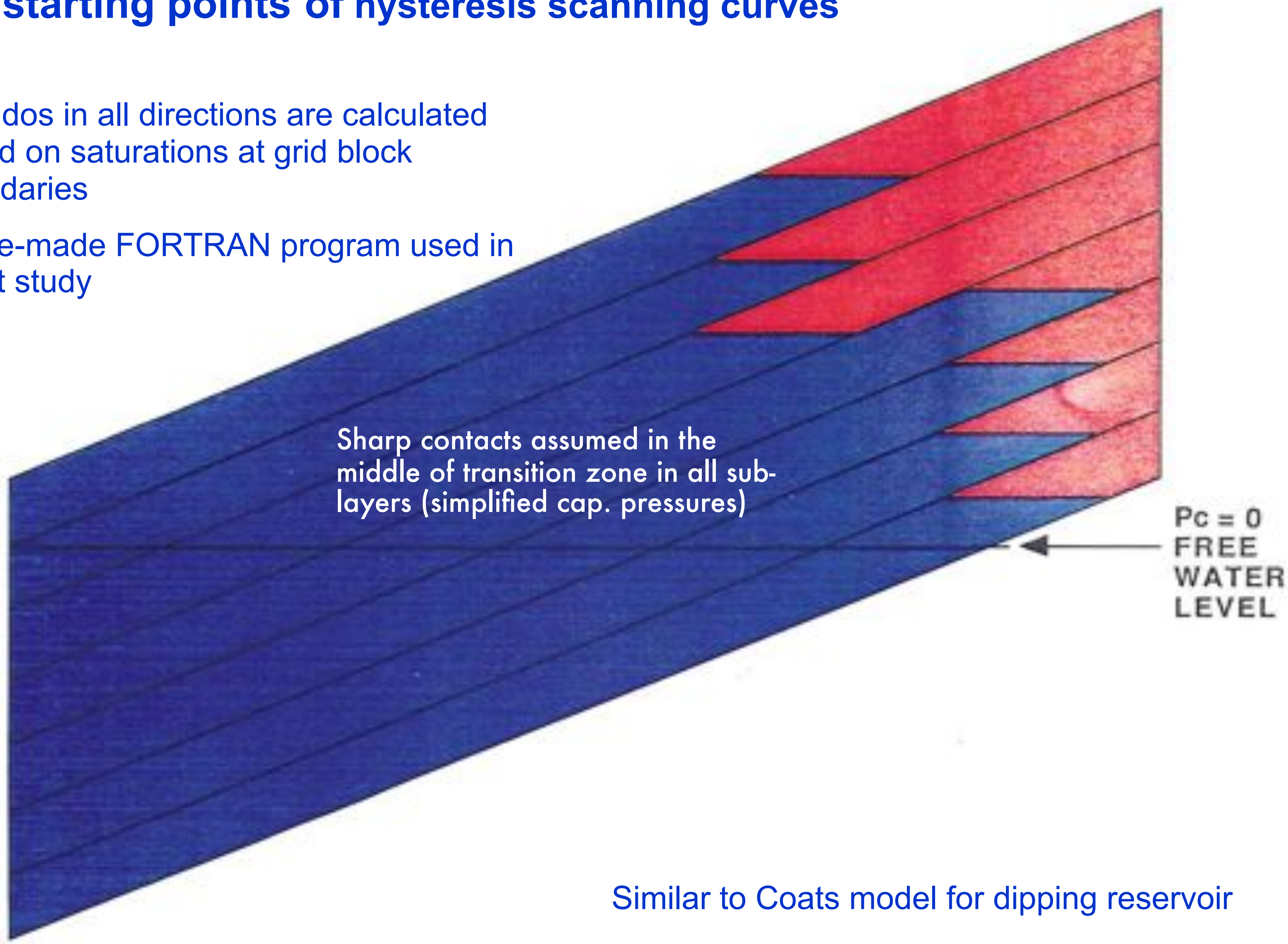


- Many partially oil saturated blocks around OWC
- Initialisation with VE drainage pseudos combined with hysteresis give “correct” rel. perms and reduced Sor around OWC

Simplified vertical equilibrium model for drainage

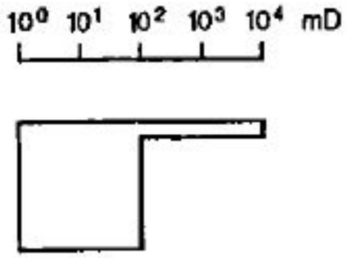
1) for initialising model and
2) for starting points of hysteresis scanning curves

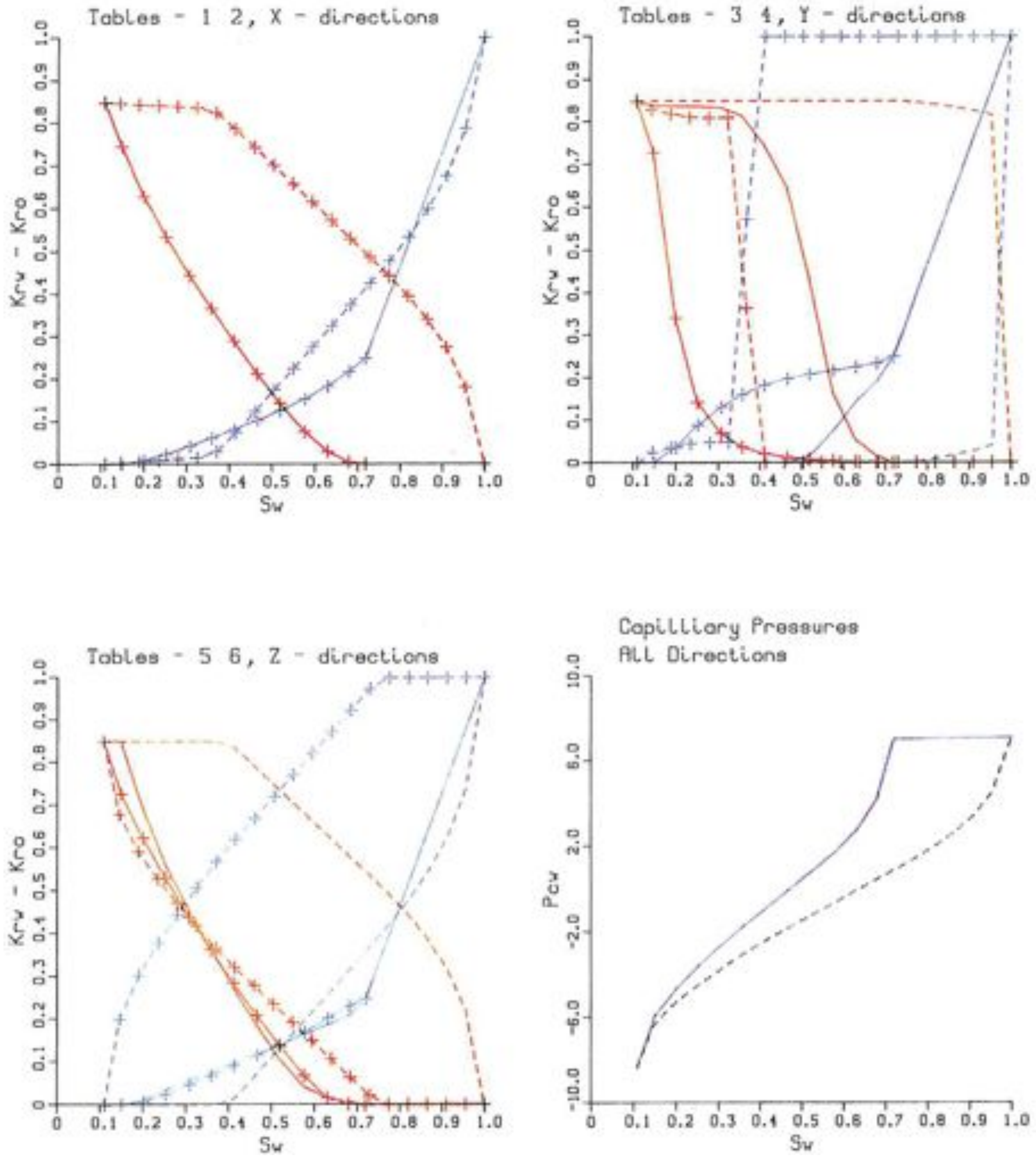
- Pseudos in all directions are calculated based on saturations at grid block boundaries
- Home-made FORTRAN program used in Brent study



Similar to Coats model for dipping reservoir

Total set of oil/water pseudos
Brent permeability profile prototype 1





Solid lines- imbibition

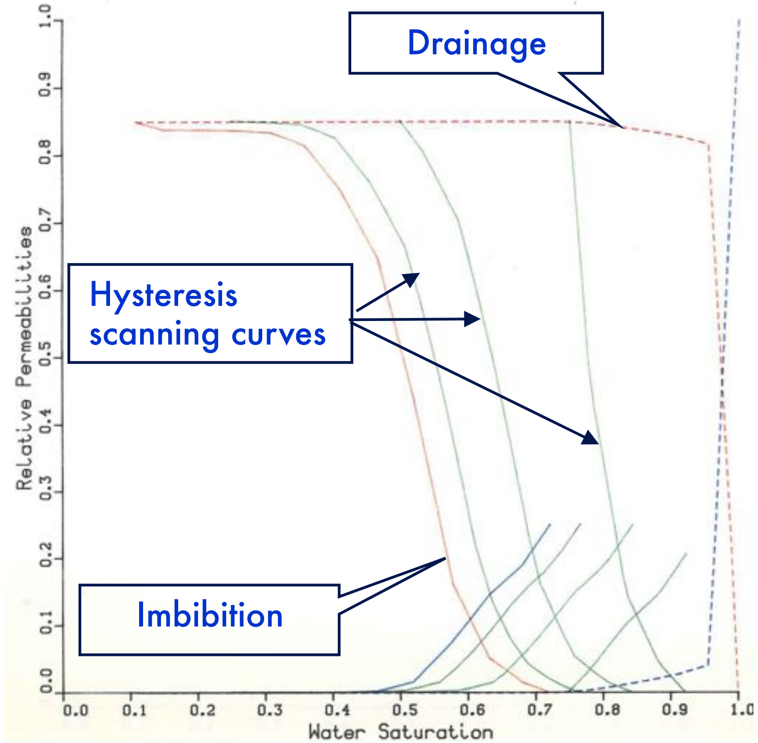
Dashed lines – drainage

+ signs shows positive direction

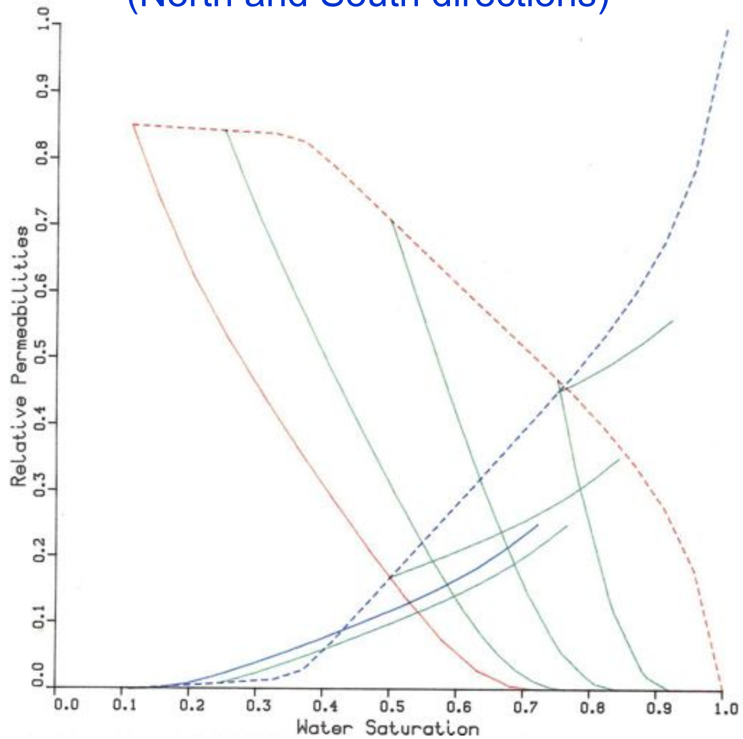
Hysteresis on pseudo relative permeabilities

New hysteresis model developed for Brent implemented in Shell's BOSIM simulator

Upddip direction(East)



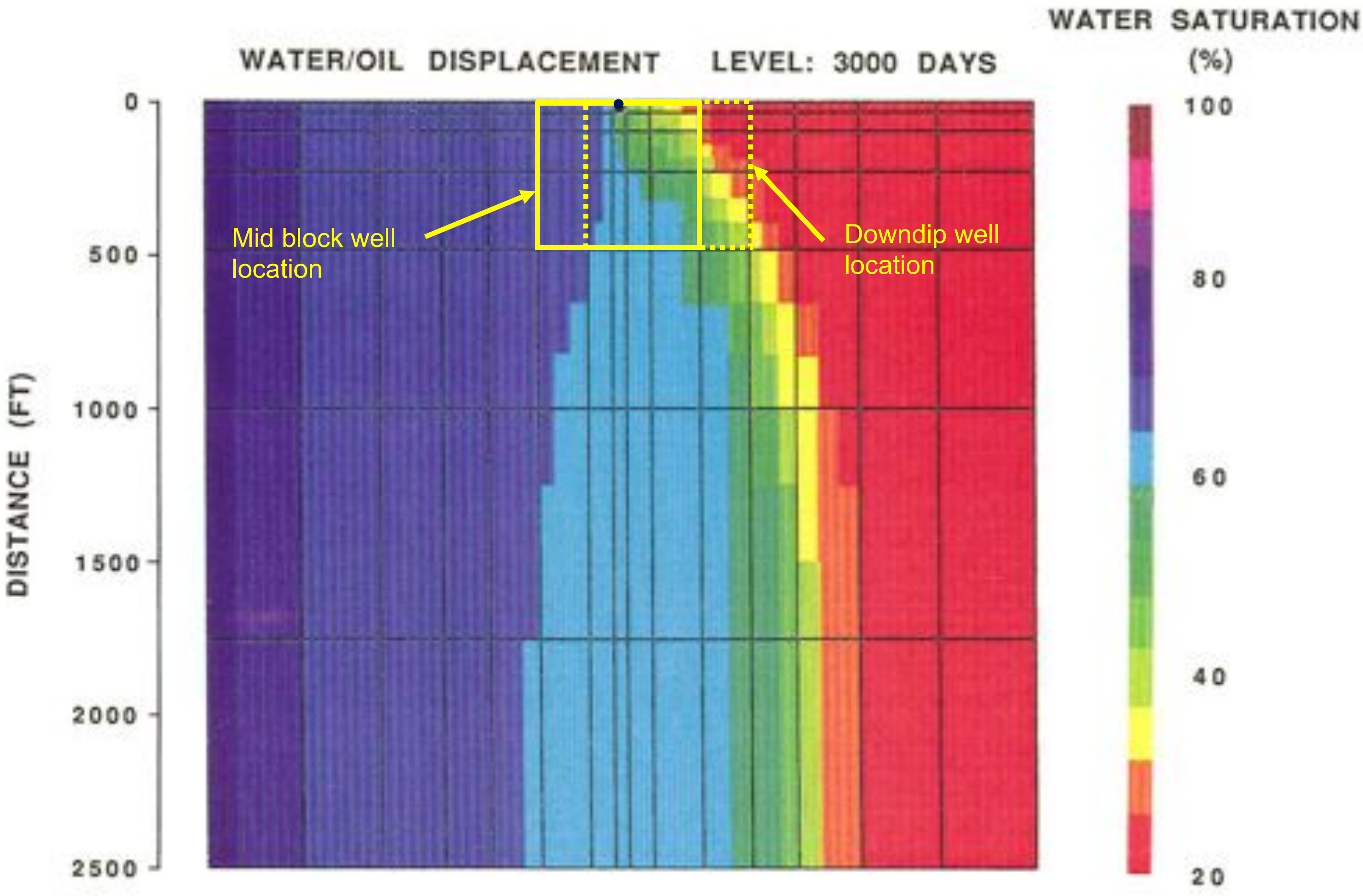
Perpendicular to displacement
(North and South directions)



Observations

- Hysteresis options in most simulators are in principle based on dispersed flow
- However, in some cases functions are flexible and may allow valid hysteresis representation also for pseudo rel. perms

Reverse (down) cusping of oil in areal layer 2 of detailed 3-D model



Calculation method for oil/water well pseudos

- The following information was extracted from the simulator at selected time steps:
  - q_o - Oil rate for the producing half well
  - q_w - Water rate for the producing half well
  - *BHFP* - Bottom hold flowing pressure at the mid point of top completed grid block (datum level)
  - p_w - Pore volume weighted datum water phase pressure within the 20 grid block areal window
  - p_o - Pore volume weighted datum oil phase pressure within the 20 grid block areal window
  - S_w - Pore volume weighted water saturation within the 20 grid block areal window

- For convenience a constant is calculated during the period of single phase flow before water reaches the well area (drawdown per unit oil rate for k_{ro}=1)

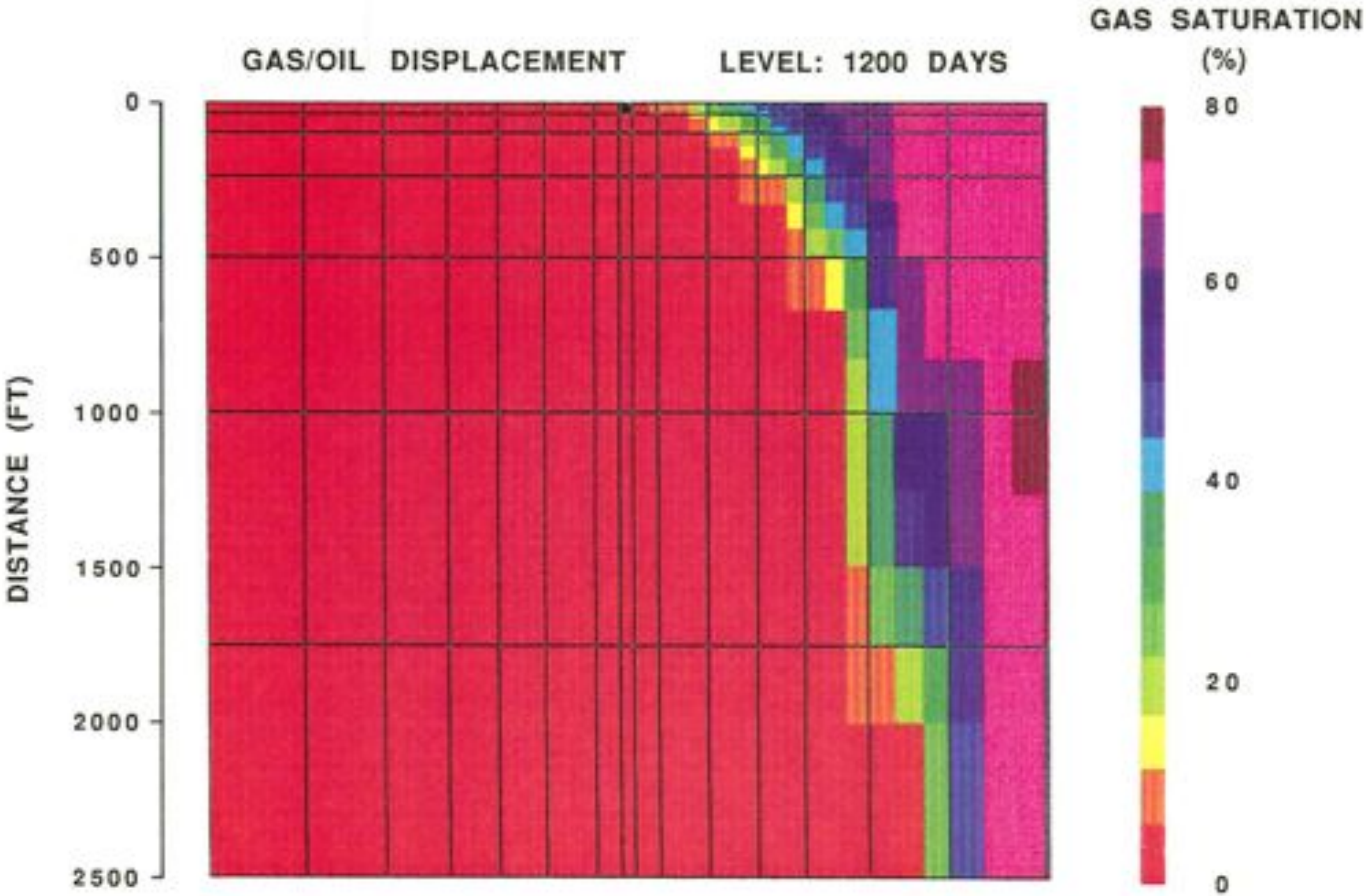
$$C = (p_o - BHFP) \cdot k_{ro}(S_{wc}) / q_o$$

- Well pseudo oil and water relative permeabilities at later times are calculated as follows:

$$k_{ro} = \frac{q_o \cdot C}{p_o - BHFP}$$

$$k_{rw} = \frac{q_w \cdot \mu_w B_w \cdot C}{\mu_o B_o (p_o - BHFP)}$$

Cusping of gas in areal layer 2 of detailed 3-D model



Calculation method for gas/oil well pseudos

- The following information was extracted from the simulator at selected time steps:
  - q_o - Oil rate for the producing half well
  - q_g - Water rate for the producing half well
  - *BHFP* (datum level) - Bottom hold flowing pressure at the mid point of top completed grid block
  - p_g - Pore volume weighted datum gas phase pressure within the 20 grid block areal window
  - p_o - Pore volume weighted datum oil phase pressure within the 20 grid block areal window
  - S_l - Pore volume weighted liquid saturation within the 20 grid block areal window

- For convenience a constant is calculated (drawdown per unit oil rate for k_{ro}=1)

$$C = (p_o - BHFP) \cdot k_{ro}(1 - S_{gc}) / qo$$

- Well pseudo oil and water relative permeabilities are calculated as follows:

$$k_{ro} = \frac{q_o \cdot C}{p_o - BHFP}$$

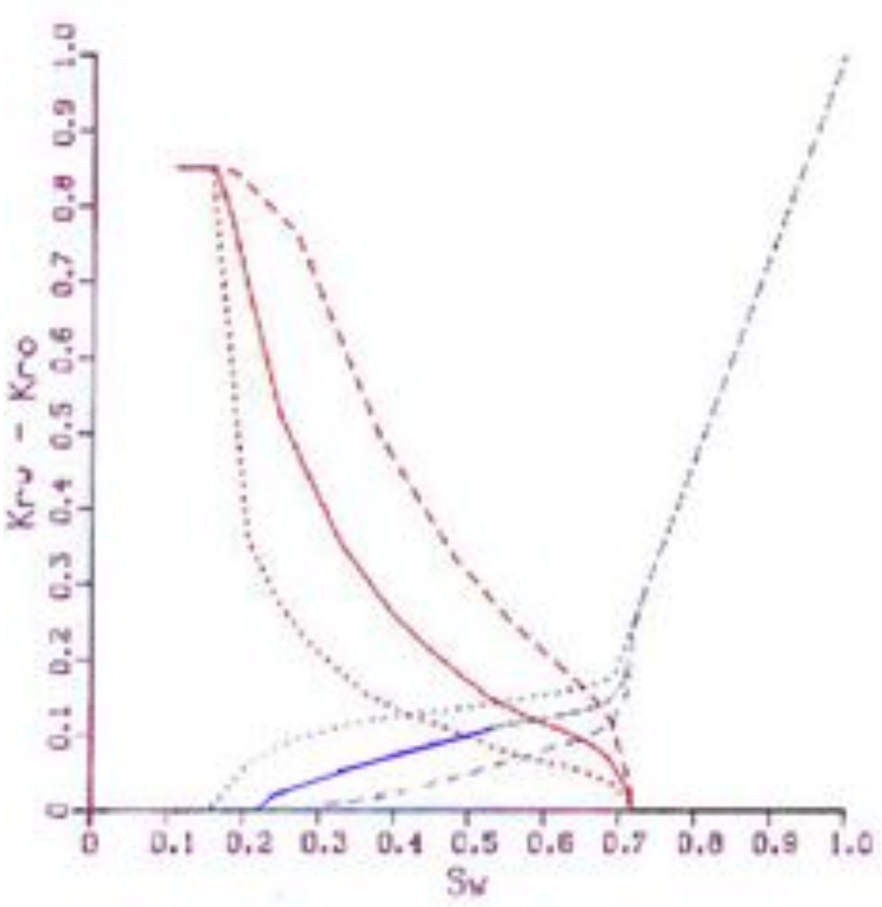
$$k_{rg} = \frac{(q_g - q_o \cdot R_s) \cdot \mu_g B_g \cdot C}{\mu_o B_o (p_o - BHFP)}$$

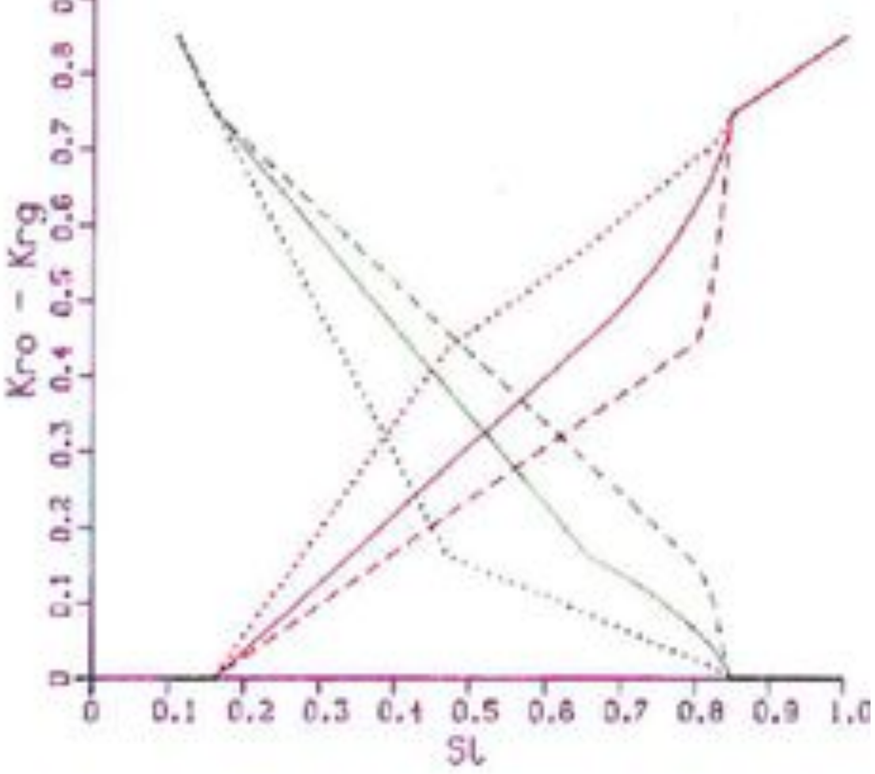
Well pseudos – Brent prototype 1

Solid lines - midblock well location

Dashed lines – updip well location

Dotted lines – downdip well location

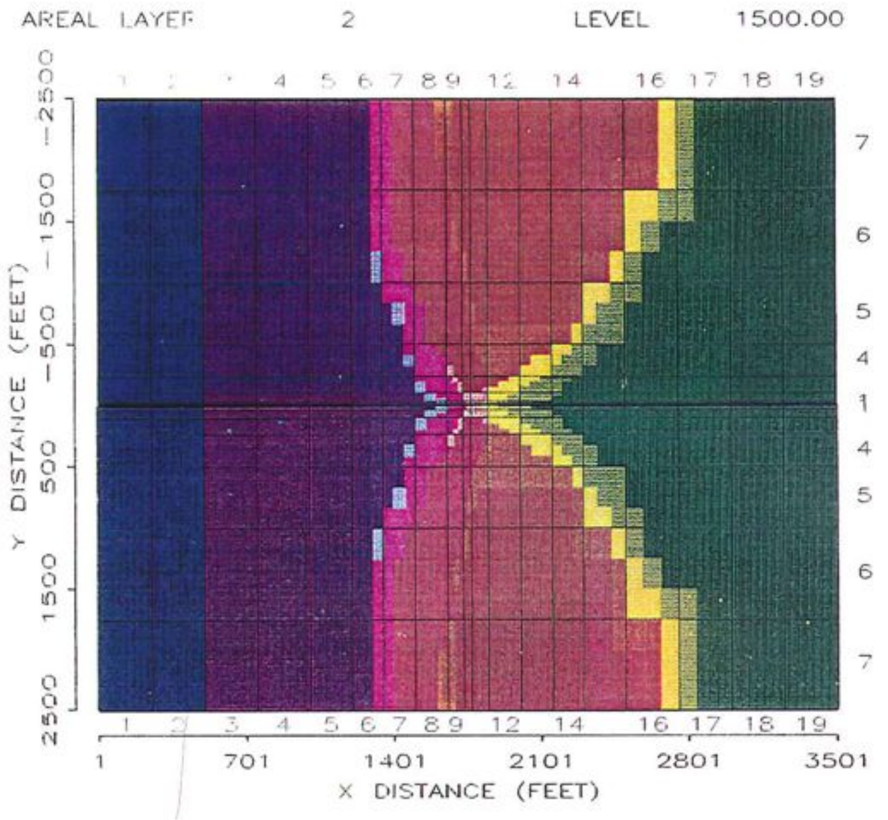




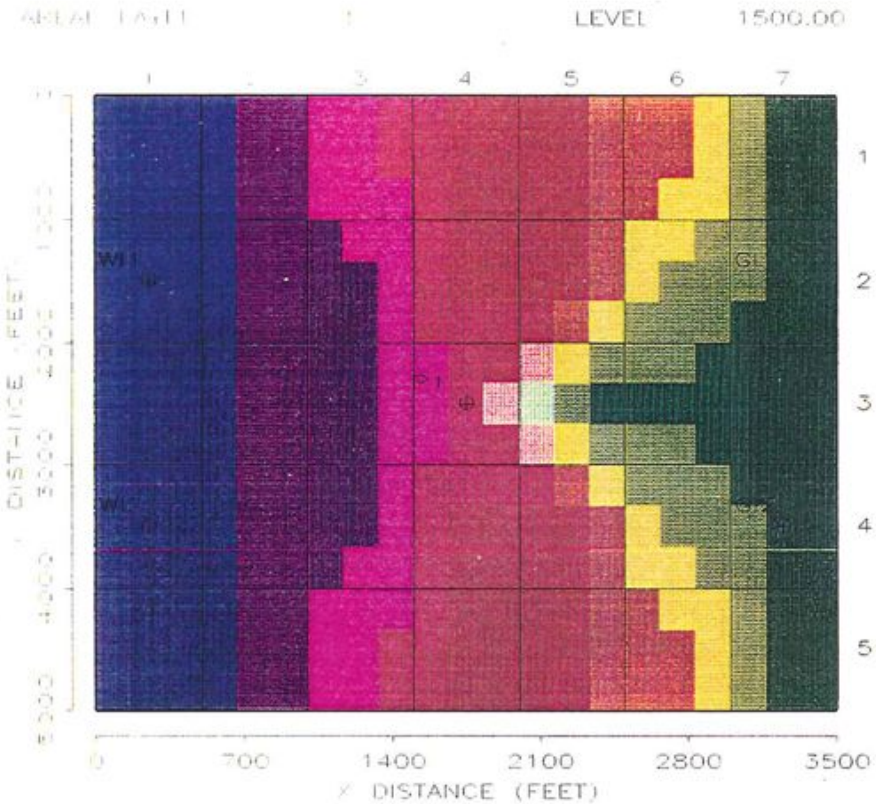
- Facility for generating well pseudos is not readily available in MoReS
- However, same approach as used in Brent study can be adopted

Saturation distribution in oil rim models subsequent to water and gas breakthrough

3-D fine grid model with rock rel. perms - layer 2

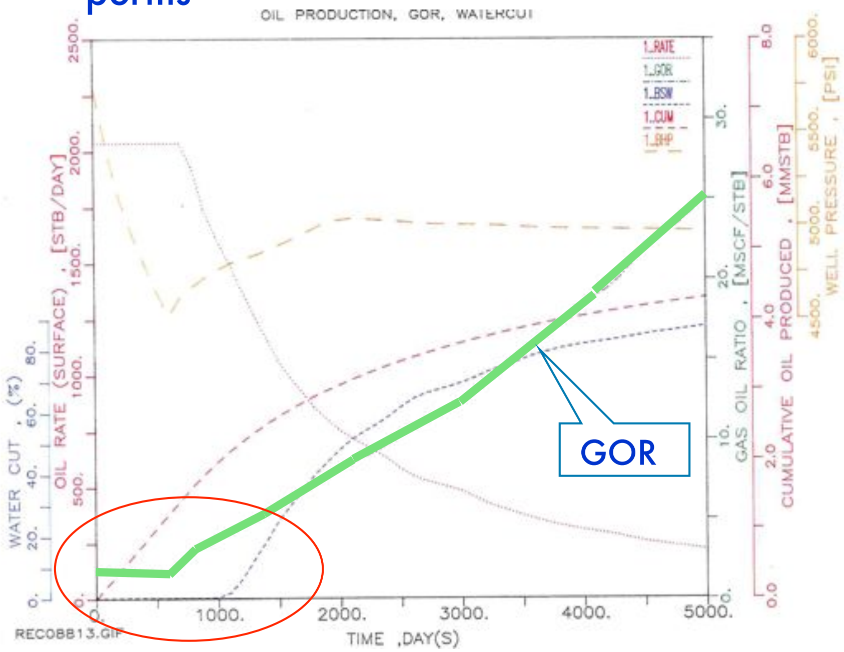


2-D coarse grid model with inter grid block pseudos and well pseudos

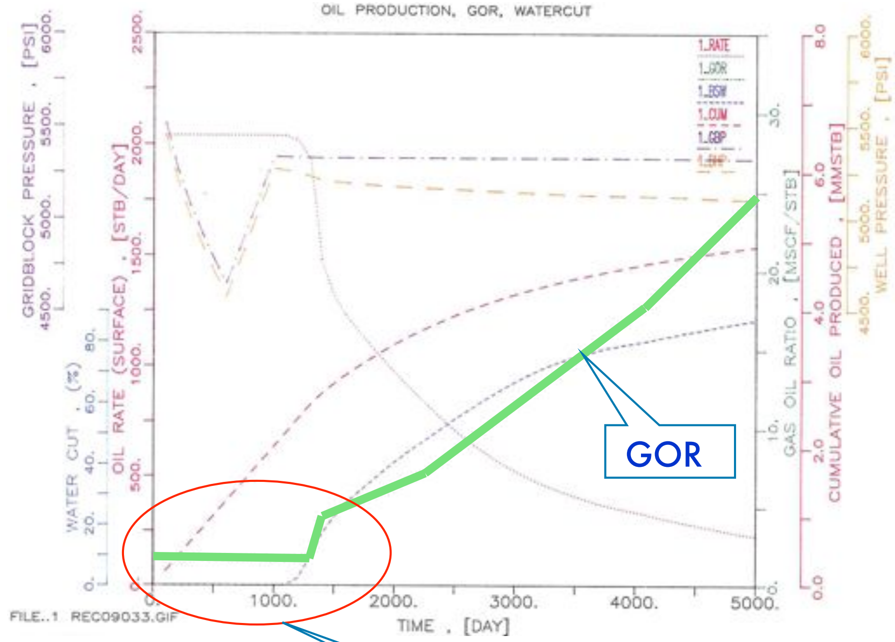


Performance comparison
Fine and coarse grid oil rim models

3-D fine grid model with rock rel. perms



2-D coarse grid model with inter grid block pseudos and well pseudos



Delayed gas breakthrough

Observations

- Production performances of the two models are similar
- However, gas breakthrough is delayed by about 2 years in the coarse grid model (GOR development thereafter is accurate)
- Demonstrates limitation of pseudos
  - Focussed pressure sink around well not properly represented in coarse grid

Conclusions

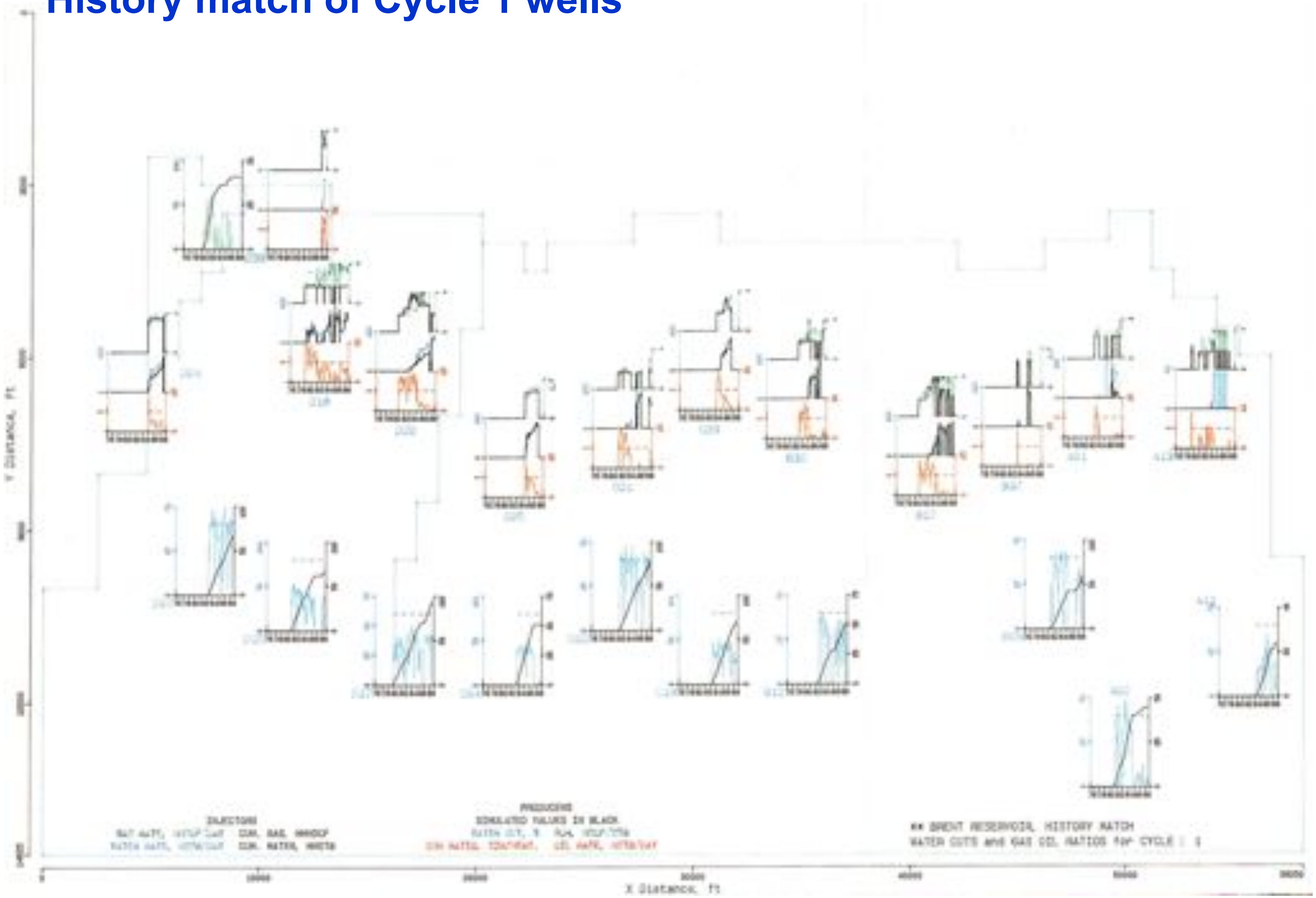
- Pseudo relative permeabilities can substantially reduce the number of grid blocks
  - Accurate simulation can be achieved with number of grid blocks reduced by a factor of 10 or more
  - The Brent study demonstrates the potential of this technology

- Pseudos can be introduced in any commercial simulator, but may require separate software and manipulation of data from fine grid simulations

- Simulation of large fields with many wells are the most obvious candidates for the use of pseudo relative permeabilities

END

Brent reservoir model
History match of Cycle 1 wells



Brent reservoir model
History match of RFT pressures