Petroleum Resource Evaluation

Numerical Modeling
Reservoir Simulation Theory

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Reservoir Simulation Theory

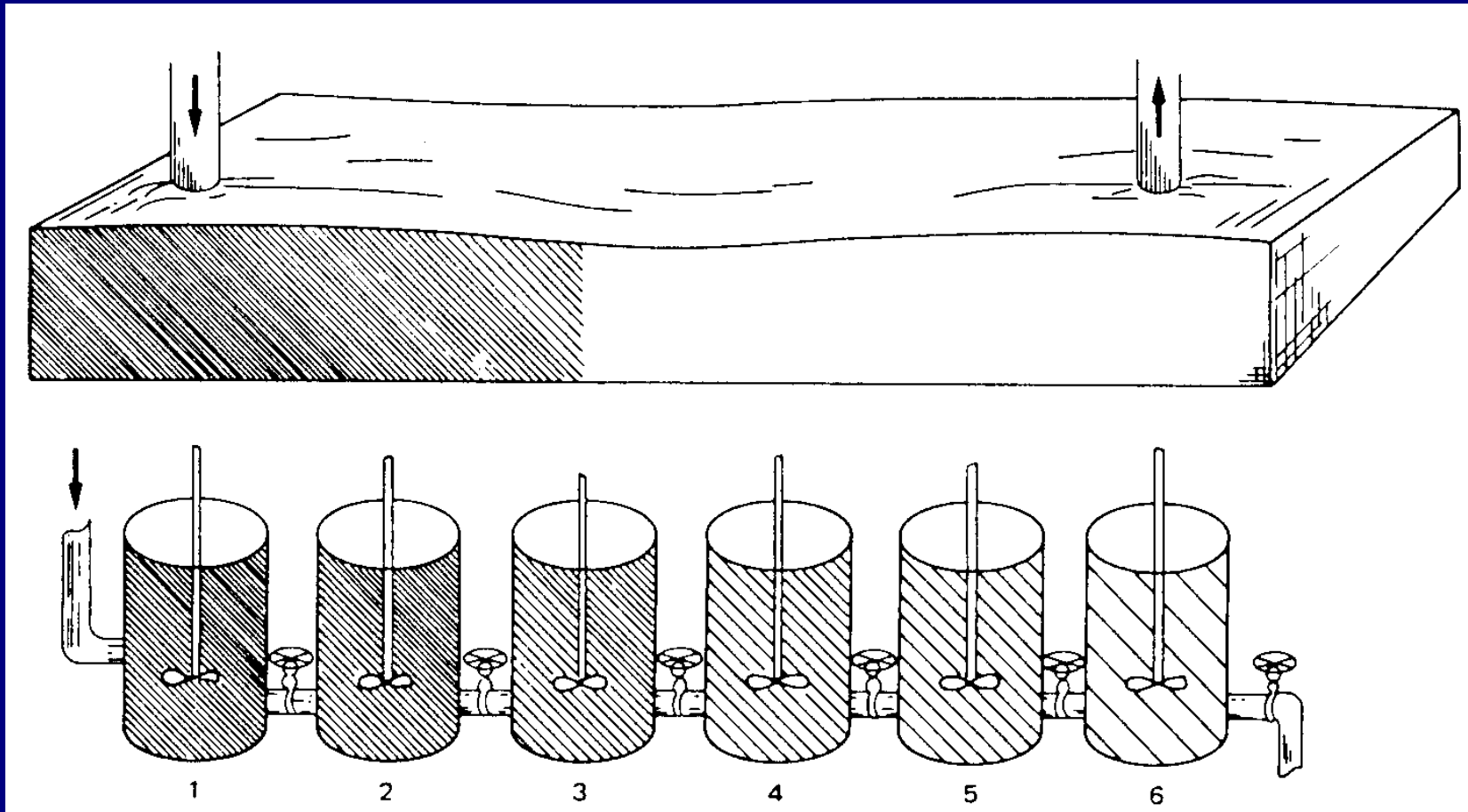
Introduction

- The purpose of this section is to provide an orientation to the fundamentals of reservoir simulation so that one can recognize both the strong points and the potential trouble spots in the usage of reservoir simulation techniques.

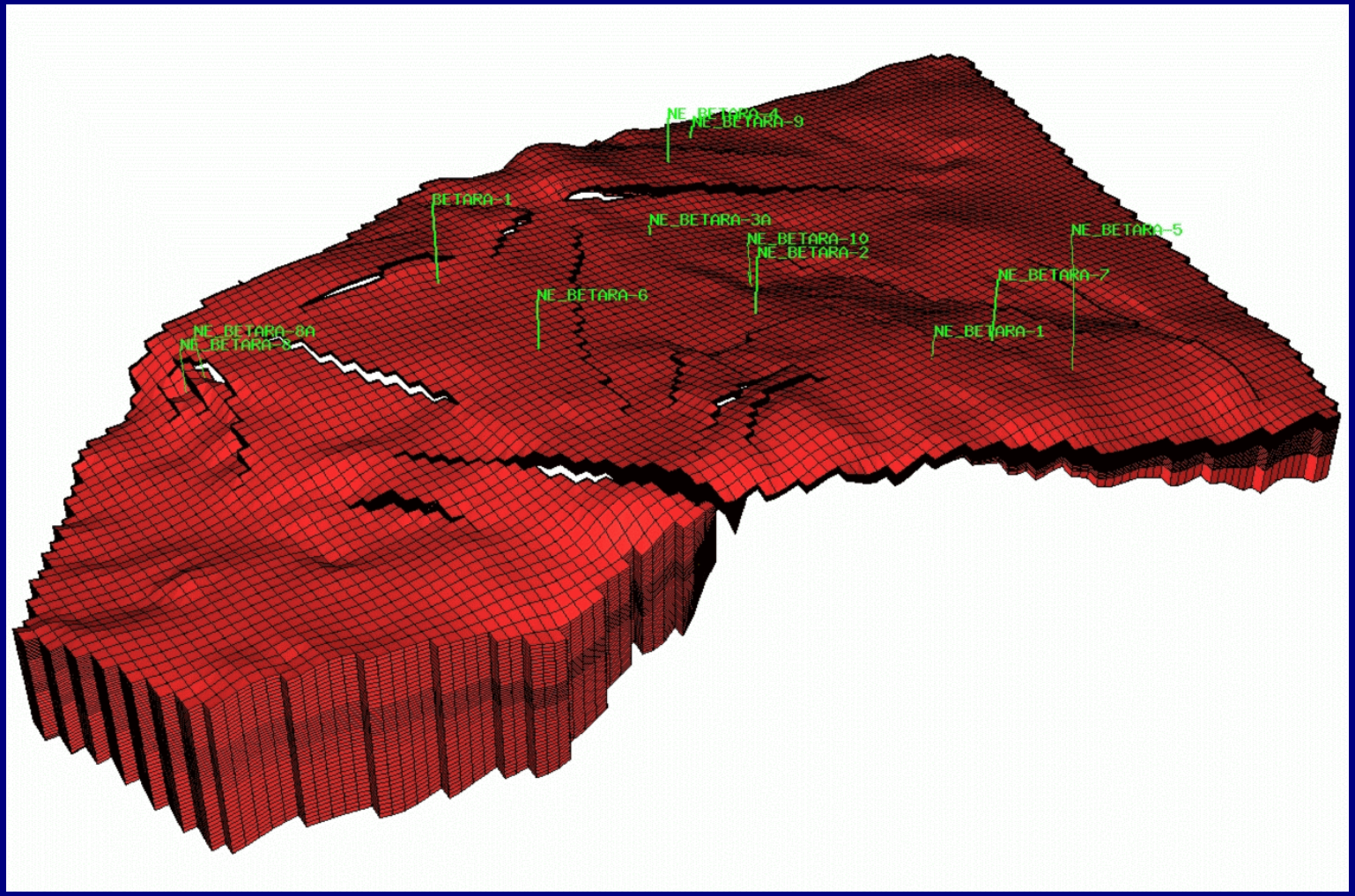
- The use of a reservoir simulation model in an engineering study requires that the user have a fundamental understanding of the principles upon which the model is based. Specifically, the user should appreciate the types of errors that are inherent in a reservoir model and how these errors might effect the results.

Reservoir Simulation Theory

Introduction



Reservoir Simulation Theory



Reservoir Simulation Theory

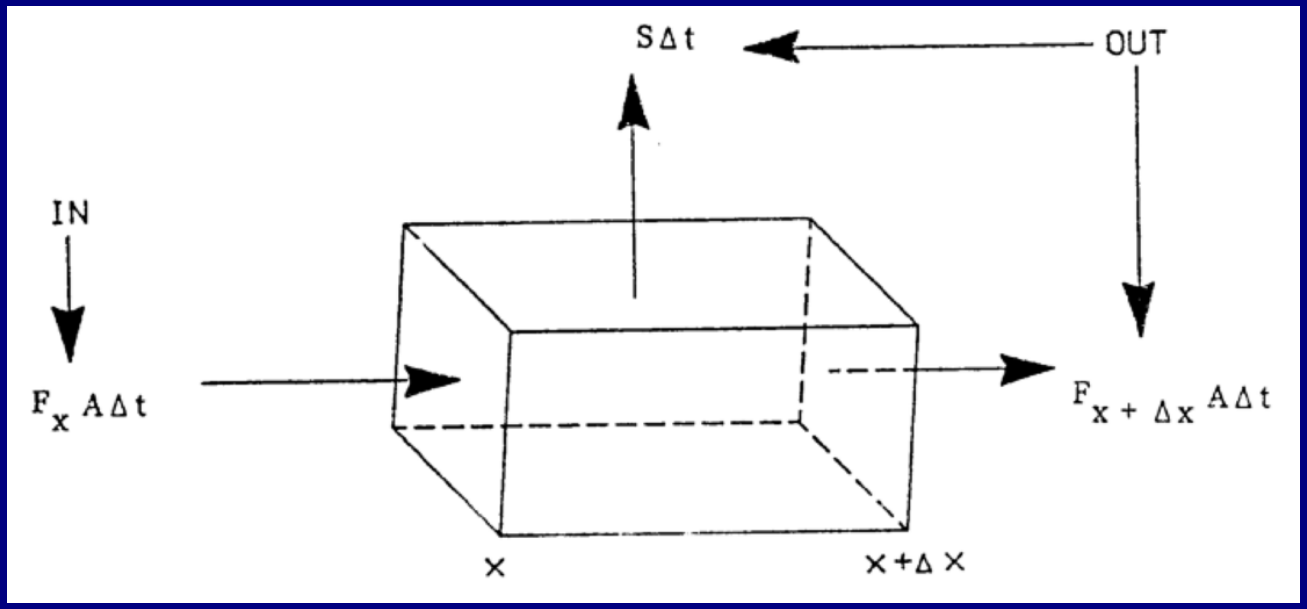
General Conservation Equation

- Almost all reservoir simulation applications are based upon the conservation of mass or heat.

- A conventional black oil model conserves the mass of oil (as stb), the mass of gas (as Mscf) both rather complex mixtures, and the mass of water (as stb). For example, a material balance around a representative volume, a cube in this case can be expressed simply as:

Reservoir Simulation Theory

General Conservation Equation



The conserved quantity entering the cube is given as the flux, F_x times the cross-sectional area to flow, A, multiplied by the time period, Δt, over which the flow occurs. The amount leaving the cube from the opposite face is expressed in a similar manner. The sink term represents production from a well.

Reservoir Simulation Theory

General Conservation Equation

$$In - Out = Gain$$

$$[(F_x) A \Delta t] - [(F_{x+\Delta x}) A \Delta t + S \Delta t] = [(C_{t+\Delta t} - C_t) A \Delta x]$$

$$-\left[\frac{F_{x+\Delta x} - F_x}{\Delta x}\right] - \frac{S}{V} = \left[\frac{C_{t+\Delta t} - C_t}{\Delta t}\right]$$

$$-\frac{\partial F_x}{\partial x} - q_V = \frac{\partial C_t}{\partial t}$$

where:

x = length
t = time
F_x = flux (quantity conserved/unit time - unit cross-sectional area)
C = concentration (quantity conserved/unit volume)
q_v = specific sink (quantity conserved/unit time -unit volume)

Reservoir Simulation Theory

Constitutive and Transport Equations

To use the equation derived above, it is necessary to define the quantity we wish to conserve. It is in this step that a simulation model is first tailored to solve specific problems.

For example, let us conserve the mass (lbs-mass) of a slightly compressible fluid in a horizontal reservoir. In this case we express the flux as:

$$F_x = \rho u_x$$

where : ρ = fluid density (lbs-mass/ft^2)
u_x = volumetric (ft^3/ft^2-day)

Reservoir Simulation Theory

Constitutive and Transport Equations

- The concentration is a function of both the fluid density and the porosity of the reservoir, i.e. :

$$C = \phi\rho$$

  - *where:* ρ = *fluid density (lbs mass/ft^3)*
    ϕ = *reservoir porosity (fraction) - note fluid saturation is 1.0*

- The density and porosity may be expressed in terms of pressure through *constitutive* relationships.

$$c_f = \frac{1}{\rho}\frac{d\rho}{dp} \qquad c_r = \frac{1}{\phi}\frac{d\phi}{dp}$$

  - *where:* c_f = *fluid compressibility (psi^{-1})*
    c_r = *rock compressibility (psi^{-1})*
    ρ = *fluid density (lbs-mass/ft^2)*
    ϕ = *formation porosity (fraction)*
    p = *pressure (psi)*

Reservoir Simulation Theory

Constitutive and Transport Equations

- The volumetric velocity may, in turn, be related to the pressure distribution in the reservoir by Darcy's law or a transport equation as :

$$u_x = -\frac{k_x}{\mu}\frac{dp}{dx}$$

  - *where:* μ *= fluid viscosity (cp)*
    x *= distance (feet)*
    k *= permeability (.00633 md)*
    p *= pressure (psia)*
    u_x *= superficial velocity (*ft^3/ft^2*-day)*

- If we were considering a thermal problem the transport equation would be Fourier's law. Fick's law would be used if we were simulating a diffusion process. These transport laws are quite analogous. Also, these laws are often combined (e.g., a process where both convection and diffusion occur).

Reservoir Simulation Theory

Diffusivity Equation

- Combining the constitutive and transport equations with the general conservation equation leads to the familiar single phase diffusivity equation i.e. :

$$\frac{\partial}{\partial x}\left(\frac{k_x}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k_y}{\mu}\frac{\partial p}{\partial y}\right) + \frac{q_v}{\rho} = (c_r + c_f)\,\phi\,\frac{\partial p}{\partial t}$$

- If the permeabilities and viscosity of the fluid do not vary across the reservoir, the standard form of the diffusivity equation as a linear differential equation in pressure is as follows :

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} - \frac{\mu}{k\rho}\,q_v = \frac{c_T\,\phi\,\mu}{k}\,\frac{\partial p}{\partial t}$$

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Finite Difference Approximations

- The purpose of finite difference approximations is to express a differential equation as a algebraic equation approximating the original equation at a specific point.

- For instance, if the value of pressure, p, is represented graphically as a function of distance, x then the derivative of p with respect to x at x_i may be approximated in several ways using the values of the pressure p at known points in the immediate vicinity of i, that is

Reservoir Simulation Theory

Finite Difference Approximations

Forward difference

$$\frac{\partial p}{\partial x} = \frac{P_{i+1} - P_i}{\Delta x}$$

Backward difference

$$\frac{\partial p}{\partial x} = \frac{P_i - P_{i-1}}{\Delta x}$$

Central difference

$$\frac{\partial p}{\partial x} = \frac{P_{i+1} - P_{i-1}}{2\Delta x}$$

Each of the above three approximations to the first derivative are equally valid.

Reservoir Simulation Theory

Finite Difference Approximations

The second derivative of pressure with respect to distance can be determined in a similar manner but in this instance adjacent values of the first derivative are used as the function of distance.

$$\frac{\partial^2 p}{\partial x^2} = \frac{\left(\frac{\partial p}{\partial x}\right)_{i+\frac{1}{2}} - \left(\frac{\partial p}{\partial x}\right)_{i-\frac{1}{2}}}{\Delta x}$$

If the approximation to the first derivatives are used rather than the exact values of these derivatives, we obtain an approximation to the second derivative of pressure with respect to distance in terms of three pressure values i.e.

$$\frac{\partial^2 p}{\partial x^2} = \frac{\left(\frac{p_{i+1} - p_i}{\Delta x}\right) - \left(\frac{p_i - p_{i-1}}{\Delta x}\right)}{\Delta x}$$

$$= \frac{\left(p_{i+1} - 2p_i - p_{i-1}\right)}{(\Delta x)^2}$$

Reservoir Simulation Theory

Finite Difference Approximations

The errors associated with these derivative approximations are referred to as truncation errors and can be quantified through the use of Taylor's series. For example the Taylor's Series Approximation of p_{i+1} is:

$$p_{i+1} = p_i + \Delta x\left(\frac{\partial p}{\partial x}\right)_i + \frac{(\Delta x)^2}{2!}\left(\frac{\partial^2 p}{\partial x^2}\right)_i + \frac{(\Delta x)^3}{3!}\left(\frac{\partial^3 p}{\partial x^3}\right)_i + \text{.....}$$

Difference Approximation to First Derivative

$$\left(\frac{\partial p}{\partial x}\right)_i = \frac{p_i - p_{i+1}}{\Delta x} + \Delta x\left(\frac{\partial p}{\partial x}\right)_i + \frac{(\Delta x)^2}{2!}\left(\frac{\partial^2 p}{\partial x^2}\right)_i + \frac{(\Delta x)^3}{3!}\left(\frac{\partial^3 p}{\partial x^3}\right)_i + \text{.....}$$

Reservoir Simulation Theory

Finite Difference Approximations

The terms containing derivatives that remain in the series are referred to as the truncation error as they are dropped or truncated from the approximation. The truncation error is referred to as of order Δx or order $(\Delta x)^2$ depending on the form of the first term in truncated portion of the series.

By combining the Taylor's series approximations to the i + 1 and i - 1 points, we obtain an approximation to the second derivative and determine that the truncation error is of order $(\Delta x)^2$.

Reservoir Simulation Theory

Finite Difference Approximations

Taylor's Series Approximation of p_{i-1}

$$\left(\frac{\partial^2 p}{\partial x^2}\right)_i = \frac{p_{i+1} - 2p_i + p_{i-1}}{(\Delta x)^2} - \frac{(\Delta x)^2}{12}\left(\frac{\partial^4 p}{\partial x^4}\right)_i + \text{.....}$$

Combining the p_{i+1} and p_{i-1} formulations we obtain

$$p_{i-1} = p_i - \Delta x\left(\frac{\partial p}{\partial x}\right)_i + \frac{(\Delta x)^2}{2!}\left(\frac{\partial^2 p}{\partial x^2}\right)_i - \frac{(\Delta x)^3}{3!}\left(\frac{\partial^3 p}{\partial x^3}\right)_i + \text{.....}$$

Reservoir Simulation Theory

Finite Difference Approximations

By successive use of Taylor's series we are able to develop higher order approximations, for example:

$$\left(\frac{\partial^2 p}{\partial x^2}\right)_i = \frac{-p_{i+2} + 16p_{i+1} - 30p_i + 16p_{i-1} - p_{i-2}}{12\Delta x^2} + (O(\Delta x)^4 .....$$

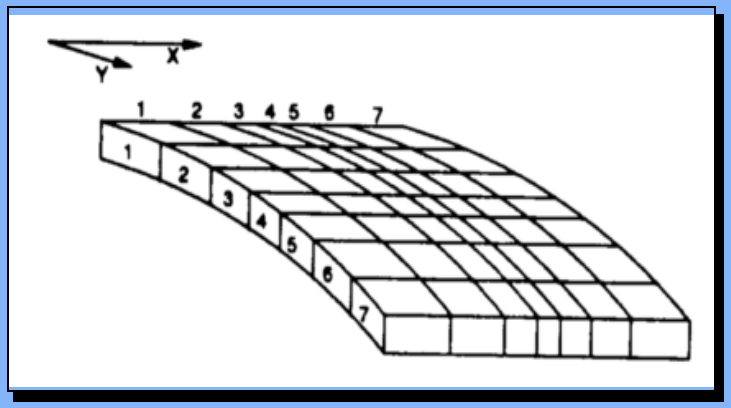
Reservoir Simulation Theory

Finite Difference Approximations

Using the finite difference approximations just discussed, we may rewrite the single phase diffusivity equation in approximate form as :

$$\left[\frac{p_{i+1,j} - 2p_{i,j} + p_{i-1,j}}{(\Delta x)^2} + \frac{p_{i,j+1} - 2p_{i,j} + p_{i,j-1}}{(\Delta y)^2} - \left(\frac{\mu}{kh} q_v\right)_{i,j}\right]_{n \text{ or } n+1} = \frac{c_t \phi \mu}{kh}\left(\frac{p_{n+1} - p_n}{\Delta t}\right)_{i,j}$$

The figure shows an example of a calculation mesh, or grid, which is used to locate those discrete points in the reservoir, for which the difference equation can be written.



Reservoir Simulation Theory

Finite Difference Approximations

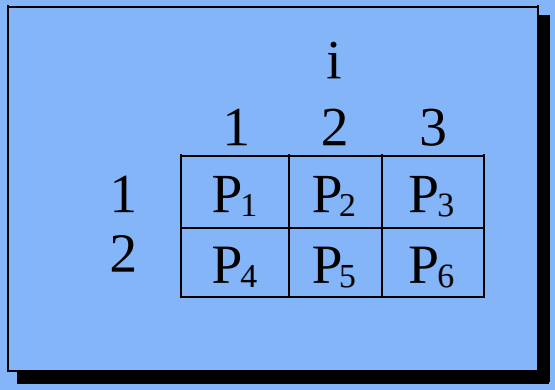
Note that we have an option when writing the spatial derivatives of expressing the time level at the 'current' time level, n, or at the next time level n + 1. If we chose the n time level, we have an explicit expression while a choice of time level n + 1 is called implicit. For this equation, time level n + 1 is virtually always chosen to assure that the resulting computations are stable.

Writing the algebraic difference equations for each grid block results in an interdependent set of equations that can be expressed in the form of a matrix :

Reservoir Simulation Theory

Finite Difference Formulation

Calculation Grid



Linear Systems of Equations

$$
\begin{array}{ccccccccccccc}
c_1p_1 & + & d_1p_2 & & & + & e_1p_4 & & & & & = & f_1 \\
b_2p_1 & + & c_2p_2 & + & d_2p_3 & & & + & e_2p_5 & & & = & f_2 \\
 & + & b_3p_2 & + & c_3p_3 & + & d_3p_4 & & & + & e_3p_6 & = & f_3 \\
a_4p_1 & & & + & b_4p_3 & + & c_4p_4 & + & d_4p_5 & & & = & f_4 \\
 & & a_5p_2 & & & + & b_5p_4 & + & c_5p_5 & + & d_5p_6 & = & f_5 \\
 & & & & a_6p_3 & & & + & b_6p_5 & + & c_6p_6 & = & f_6
\end{array}
$$

Reservoir Simulation Theory

Finite Difference Formulation

Matrix Formulation

$$\begin{bmatrix} c_1 & d_1 & o & e_1 & o & o \\ b_2 & c_2 & d_2 & o & e_2 & o \\ o & b_3 & c_3 & d_3 & o & e_3 \\ a_4 & o & b_4 & c_4 & d_4 & o \\ o & a_5 & o & b_5 & c_5 & d_5 \\ o & o & d_6 & o & b_6 & c_6 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix}$$

Reservoir Simulation Theory

Diffusivity Equation in Finite Difference Form

Usually, the more general form of the diffusivity equation would be used in a simulation model as shown below.

$$\frac{\partial}{\partial x}\left(\frac{k_x h}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k_y h}{\mu}\frac{\partial p}{\partial y}\right) + \frac{q_v h}{\rho} = (c_r + c_f)\,\phi\, h \frac{\partial p}{\partial t}$$

Reservoir Simulation Theory

Diffusivity Equation in Finite Difference Form

Using the difference representation at discrete points across the reservoir, allows us to vary the permeability and porosity across the grid.

$$\frac{1}{(\Delta x)^2}\left[\left(\frac{k_x h}{\mu}\right)_{i+\frac{1}{2},j}(p_{i+1,j} - p_{i,j}) - \left(\frac{k_x h}{\mu}\right)_{i-\frac{1}{2},j}(p_{i,j} - p_{i-1,j})\right]_{n+1}$$

$$+\frac{1}{(\Delta y)^2}\left[\left(\frac{k_y h}{\mu}\right)_{i,j+\frac{1}{2}}(p_{i,j+1} - p_{i,j}) - \left(\frac{k_y h}{\mu}\right)_{i,j-\frac{1}{2}}(p_{i,j} - p_{i,j-1})\right]_{n+1}$$

$$-\left(\frac{q_v h}{\rho}\right)_{i,j} = (c_r + c_f)\,\phi\, h\left(\frac{p_{n+1} - p_n}{\Delta t}\right)_{i,j}$$

Reservoir Simulation Theory

Diffusivity Equation in Finite Difference Form

or,

$$\left[\left(\frac{k_x h\,(\Delta y)}{\mu\,(\Delta x)}\right)_{i+\frac{1}{2},j}(p_{i+1,j} - p_{i,j}) - \left(\frac{k_x h\,(\Delta y)}{\mu\,(\Delta x)}\right)_{i-\frac{1}{2},j}(p_{i,j} - p_{i-1,j})\right]_{n+1}$$

$$+\left[\left(\frac{k_y h\,(\Delta x)}{\mu\,(\Delta y)}\right)_{i,j+\frac{1}{2}}(p_{i,j+1} - p_{i,j}) - \left(\frac{k_y h\,(\Delta x)}{\mu\,(\Delta y)}\right)_{i,j-\frac{1}{2}}(p_{i,j} - p_{i,j-1})\right]_{n+1}$$

$$-\left(\frac{q_v h\,\Delta x\,\Delta y}{\rho}\right)_{i,j} = (c_r + c_f)\,\phi\,h\,\Delta x\,\Delta y\left(\frac{p_{n+1} - p_n}{\Delta t}\right)_{i,j}$$

This flexibility is one of the main advantages to using numerical techniques in the analysis of reservoir engineering problems.

Reservoir Simulation Theory

Diffusivity Equation in Finite Difference Form

Transmissibility and pore volume which are common terms in the reservoir simulation vernacular. Pore volume is self-explanatory i.e.:

$$V_p = (\phi \Delta x \Delta y h)_{i,j}$$

The transmissibility definition is nothing more than the Darcy's law coefficient for flow between two adjacent grid blocks.

$$T_{x_{i+\frac{1}{2},j}} = \left[\frac{k_x h(\Delta y)}{\mu(\Delta x)}\right]_{i+\frac{1}{2},j}$$

The production term now is expressed as a volumetric flow rate, that is

$$Q = \left(\frac{q_v \Delta x \Delta y h}{\rho}\right)_{i,j)}$$

Reservoir Simulation Theory

Diffusivity Equation in Finite Difference Form

And the resulting form of the diffusivity equation is :

$$\left[T_{i+\frac{1}{2},j}\left(p_{i+1,j} - p_{i,j}\right) - T_{i-\frac{1}{2},j}\left(p_{i,j} - p_{i-1,j}\right)\right]_{n+1}$$

$$+ \left[T_{i,j+\frac{1}{2}}\left(p_{i,j+1} - p_{i,j}\right) - T_{i,j-\frac{1}{2}}\left(p_{i,j} - p_{i,j-1}\right)\right]_{n+1}$$

$$- Q = \left(c_r + c_f\right) V_p \left(\frac{p_{n+1} - p_n}{\Delta t}\right)_{i,j}$$

Reservoir Simulation Theory

Black Oil Model

The Black Oil Model assumes that three components exist in the system; oil, gas, and water. Gas may dissolve in oil, but oil does not vaporize into the gas phase. The other basic assumption of the model is that Darcy's law as modified by relative permeability to account for multiphase flow adequately describes the mass-transport phenomena, i.e.

$$u_{xo} = \frac{k_x K_{ro}}{\mu_o}\left(\frac{\partial p_o}{\partial x} - \gamma_o \frac{\partial D}{\partial x}\right)$$

Reservoir Simulation Theory

Black Oil Model

The quantities being conserved are stock tank measures of oil, gas and water. The fluxes are as follows :

$$Oil \quad F_{xo} = \frac{u_{xo}}{B_o} \qquad (stb/ft^2 - day)$$

$$Water \quad F_{xw} = \frac{u_{xw}}{B_w} \qquad (stb/ft^2 - day)$$

$$Gas \quad F_{xg} = \frac{u_{xg}}{B_g} + \frac{R_s u_{xo}}{B_o} \qquad (Msc/ft^2 - day)$$

Reservoir Simulation Theory

Black Oil Model

Concentrations :

$$Oil \quad C_o = \frac{\phi S_o}{B_o} \qquad (stb/ft^3)$$

$$Water \quad C_w = \frac{\phi S_w}{B_w} \qquad (stb/ft^3 - day)$$

$$Gas \quad C_g = \phi\left(\frac{S_g}{B_g} + \frac{R_s S_o}{B_o}\right) \qquad (Mscf/ft^3)$$

Reservoir Simulation Theory

Black Oil Model

- Combining the conservation equations and the Darcy's law expressions result in:

$$\nabla\cdot\left[\frac{kk_{ro}}{B_o\mu_o}(\nabla p_o - \gamma_o\nabla D)\right] - q_{vo} = \frac{\partial}{\partial t}\left(\phi\frac{S_o}{B_o}\right)$$

$$\nabla\cdot\left[\frac{kk_{rw}}{B_w\mu_w}(\nabla p_w - \gamma_w\nabla D)\right] - q_{vw} = \frac{\partial}{\partial t}\left(\phi\frac{S_w}{B_w}\right)$$

$$\nabla\cdot\left[\frac{kk_{rg}}{B_g\mu_g}(\nabla p_g - \gamma_g\nabla D) + \frac{R_s kk_{ro}}{B_o\mu_0}(\nabla p_o - \gamma_o\nabla D)\right] - q_{vg} = \frac{\partial}{\partial t}\left[\phi\left(\frac{S_g}{B_g} + R_s\frac{S_o}{B_o}\right)\right]$$

Reservoir Simulation Theory

Black Oil Model

- These are supplemented by the two capillary pressure equations that relate phase pressures, and the saturation identity.

$$p_o = p_w + p_{cwo}$$

$$p_g = p_o + p_{cgo}$$

$$S_o + S_w + S_g = 1.0$$

- The dependent variables to be solved for in this system of six equations are the three phase pressures and the three phase saturations.

Reservoir Simulation Theory

Black Oil Model

These equations are expressed in finite difference form, and then solved by techniques of linear algebra.

There are several different approaches to solving this set of equations. The technique selected depends to a large part on the conditions of the problem. A very straight forward iteration procedure called IMPES (implicit pressure -explicit saturation) will solve many problems in a cost effective manner.

However, there are situations (for instance, single well coning problems) in which it is necessary to use the more powerful Full Implicit procedure to achieve an answer.

Many simulators incorporate several of these procedures.

Reservoir Simulation Theory

Black Oil Model

Examination of the Black Oil Equations also reveals that there are several parameters (relative permeabilities, fluid densities, etc.) that are themselves functions of the pressure and saturation variables.

These non-linearities and how they are treated in the simulator have a profound influence on the computed results and model efficiency. If these non-linearities are treated as implicit, that is, at the next time step, n + 1, larger time steps can be used. However, the computational cost is higher.

Again, many simulators allow the user to select the degree of implicitness that is used in the computations during each portion of a simulation run.

Petroleum Resource Evaluation

Numerical Modeling Reservoir Simulation Application - BOAST

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Reservoir Simulation Application

Boast - Black Oil Applied Simulation Tool

BOAST is a Black Oil Applied Simulation Tool used routinely for performing evaluation and design work in modern petroleum reservoir engineering. In 1982 the U.S. Department of Energy released the original black oil model called BOAST. BOAST II was released in 1987, and BOAST III in 1995. The current version BOAST 98 (BOAST IV Beta) was first released in 1998. It is basically BOAST III in terms of functionality, updated with a graphical user interface and an Editor called EdBoast designed to provide more flexibility and to overcome some of the limitations of the original BOAST. Many features were added to improve the versatility of the model.

BOAST simulates isothermal, darcy flow in three dimensions. It assumes that reservoir fluids can be described by three fluid phases (oil, gas, and water) of constant composition with physical properties that depend on pressure only. It can simulate both oil and/or gas recovery by fluid expansion, displacement, gravity drainage, and capillary imbibition mechanisms. Some of the typical field production problems that can be handled by BOAST include but are not limited to:

- Primary depletion studies;
- Pressure maintenance by water and/or gas injection; and
- Evaluation of water flooding, operations.

Reservoir Simulation Application

Boast - Black Oil Applied Simulation Tool

- User-Friendly Enhancements:
  - Free format data entry on most data cards
  - Restructured recurrent data input to allow separate specification of time step size and output frequency
  - Restart capability
  - One-line time step summary
  - Summary table of program output
  - Output pressure map corrected to user-specified datum
  - Gas PVT default option

- Reservoir Engineering Features:
  - Optional three-phase relative permeability algorithm
  - Multiple rock regions allowed
  - Multiple PVT regions allowed
  - Bubble point pressure can vary with depth and PVT region
  - Several different analytic aquifer models
  - Direct input of noncontiguous layers
  - Net and gross thicknesses allowed

Reservoir Simulation Application

Boast - Black Oil Applied Simulation Tool

- Well Model Features:
  - Individual well gas/oil ratio (GOR) and water/oil ratio (WOR) constraints
  - Minimum oil production and maximum liquid withdrawal well constraints
  - Multiple wells per grid block
  - Gas well model using a laminar-inertial-turbulent analysis
  - Maximum water/gas injection rates

- Numerical Features:
  - Two new iterative matrix solution methods: y and z direction line successive over-relaxation (LSOR) methods
  - Zero pore volume (inactive) grid blocks allowed
  - Optional two-point upstream weighting for reducing numerical dispersion

Reservoir Simulation Application

Boast - Black Oil Applied Simulation Tool

Requirements

The data editing application, *EDBOAST.EXE* limits the grid size of the reservoir being edited to the physical memory and/or the virtual memory size. The simulator application *BOAST98.EXE* also allows unlimited reservoir grid size. All the applications require Window 95, Windows NT, or Windows XP. Recommended physical memory size is 32 MB or higher for *BOAST98*, and also 32 MB or higher for *EDBOAST*. Recommended disk space varies according to print options selected for output files and also on the size of the reservoir grid. A range of from 40 MB to 100 MB of disk space use could be anticipated.

Limitations

The major limitations exist mainly in the application, Boast98.exe. The Boast98 limitations are:

- A large grid size of x-direction blocks, y-direction blocks, and z-direction blocks or layers will force the use of virtual memory and drastically slow down the array iteration processes.
- Maximum well blocks of 200.
- Maximum time steps of 8000.
- Maximum data sets of 200.
- Maximum wells of 150.
- Maximum nodes per well of 10.
- Maximum modifications to permeability, porosity, and transmissibility of 55 each (EdBoast only).
- Maximum rock regions and PVT regions of 5.
- Maximum table entries for relative permeability curves and for capillary pressure curves of 25 .

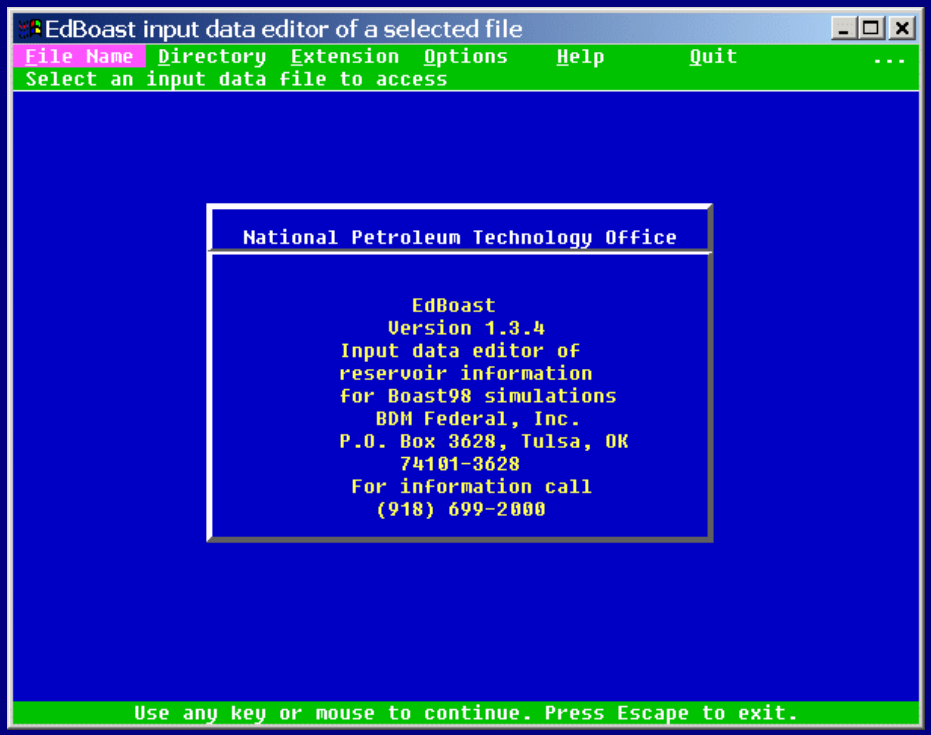
The grid size for *BOAST98.EXE* and *EDBOAST* is unlimited since memory is allocated to fit grid demand.

Reservoir Simulation Application

Boast - EdBoast

Menu Items

A simulation run can be started from either the EDBOAST or the BOAST98 application. However, beginning with the EDBOAST program, the user will be able to review the input data file first and locate any mistakes that apply to the BOAST98 application. To begin EDBOAST, double-click the icon representing the application with the mouse. At the top of the opened window, from left to right, are 7 horizontal menu items. These items are "File Name", " Directory", " Extension", " Options", " Help", " Quit", and "About". A brief description of each horizontal item is shown in the second line below the menu. The horizontal and vertical arrow keys permit moving from item to item. This method of describing the highlighted item generally applies to the vertical sub-items as well. If the arrow keys should fail to respond, re-entering the program will correct the problem.



Reservoir Simulation Application

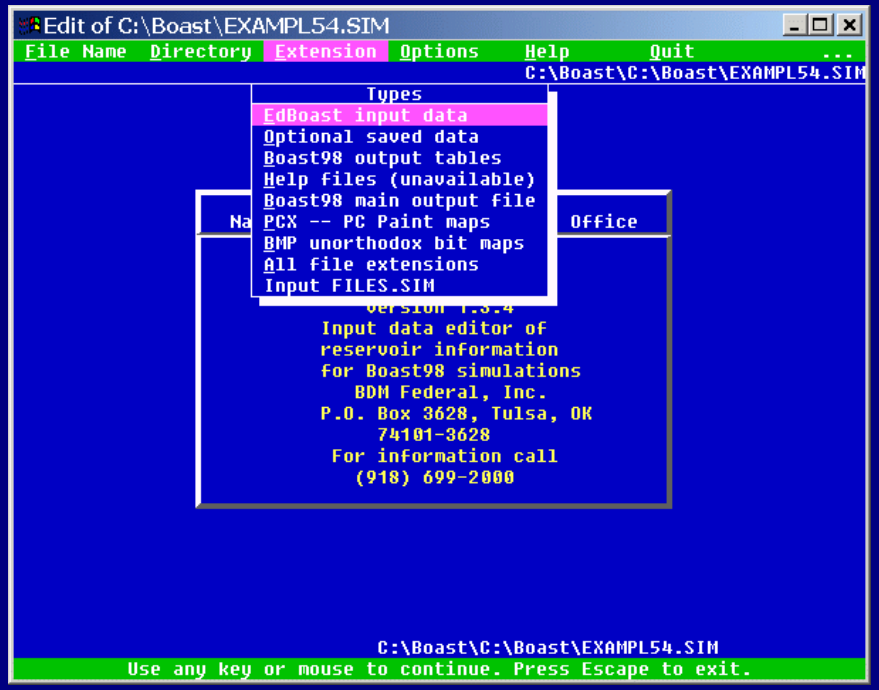
Boast - EdBoast

File Name
The first item, "File Name", allows the selection of a pre-existing data input file. Select File Name by clicking once on the item. Then select the input file from the scrollable list of names. To scroll, use the up and down arrows on your keyboard. If the file is in another directory follow the next step.

Directory
A list of scrollable of subdirectories is found under the second item, "Directory", with the current directory shown in the top title. To find the parent directory, click on the double dots ".". Repeat the process of clicking the double dots to back farther up the directory hierarchy.

Extension
The "Extension" item allows the user to filter out the different types of files. The bottom line on the list shows which are input and which are output files and what their extensions are.

The file extensions included in the list are (1) input data files with the extension of .SIM for Boast98 simulations, (2) Boast98 input data files with an alternate extension of .NEW, (3) output results of Boast98 simulations in a table form with extensions of .TAB, (4) input help files with the extension of .HLP, (5) the main output results of Boast98 simulations with extensions of .OUT, (6) picture files with the extension of .PCX, (7) bit map files with extensions of .BMP resulting from captures of the screen during graphic displays using the F5 key or the "Capture" command, and (8) all files extensions are available (these files must be text file in an ASCII format).

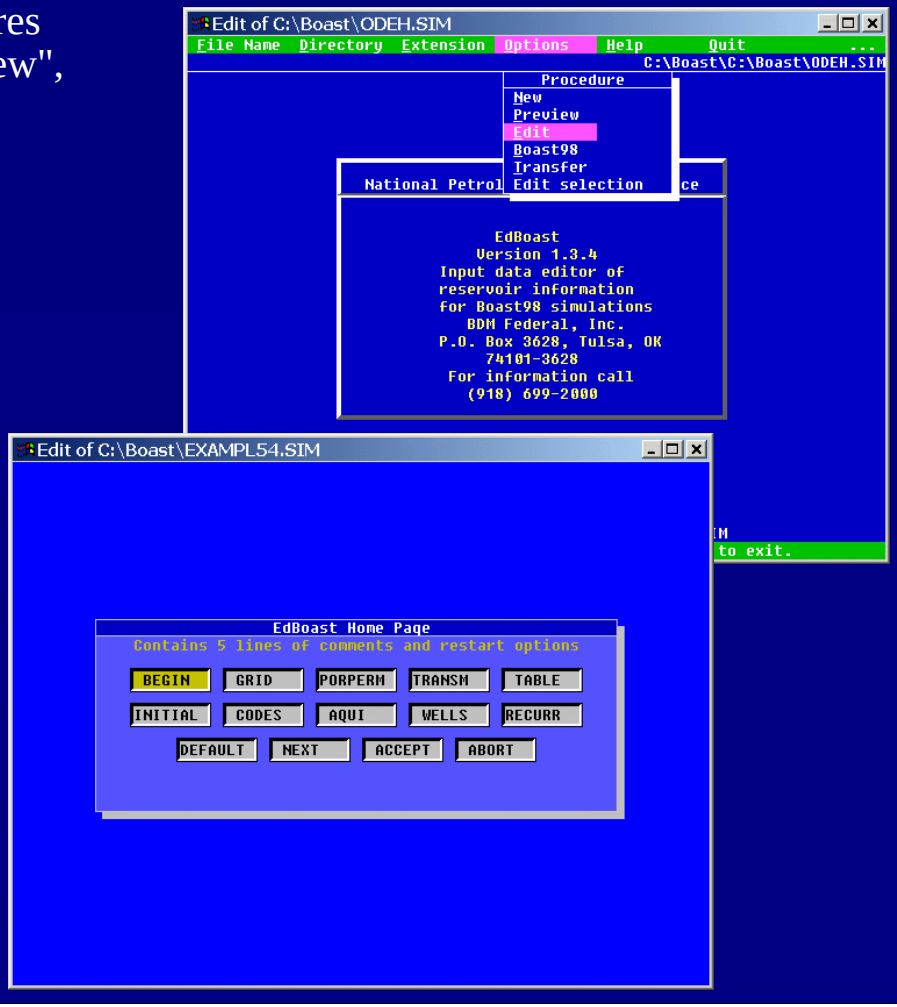


Reservoir Simulation Application

Boast - EdBoast

The fourth item, "Options", has a variety of procedures on its vertical sub-item list. These sub-items are "New", "Preview", "Edit", "Boast98", and "Transfer".

- **New:** Permits the user to create a new input data file for future simulation.
- **Preview:** will allow a read-only look at the contents of the file selected under File Name.
- **Edit:** brings the contents of the file into a series of dialogs for inputting or modifying reservoir data., and will bring up the "EdBoast Home Page" which has a series of 14 buttons for selecting which dialog group to access. A description of each highlighted button is shown on the second line below the title. The vertical arrow keys or the tab key are used to move to different highlighted buttons. Use the Abort button to leave the "EdBoast Home Page" buttons and before calling Boast98 under Options.
- **Boast98**: sub-item immediately begins simulation action on the current file selected. Calling "Boast98" under "Options" will place two running applications into memory, Boast98 and EdBoast. Each will still run independently, however, a file can no longer be edited while still engaged in simulation under Boast98.
- **Transfer:** will allow the user to run any application existing in the currently selected directory. Nothing will show in the list if there are no program applications available. Change directory to browse, then reselect "Transfer".



Reservoir Simulation Application

Boast - EdBoast

EdBoast Home Page

Selecting "Edit" under the "Options" item of the main menu brings up this EdBoast Home Page dialog window. The EdBoast Home Page consists of 14 home page buttons. These 14 buttons are "BEGIN", "GRID", "PORPERM", "TRANSM", "TABLE", "INITIAL", "CODES", "AQUI", "WELLS", "RECURR", "DEFAULT", "NEXT", "ACCEPT", and "ABORT".

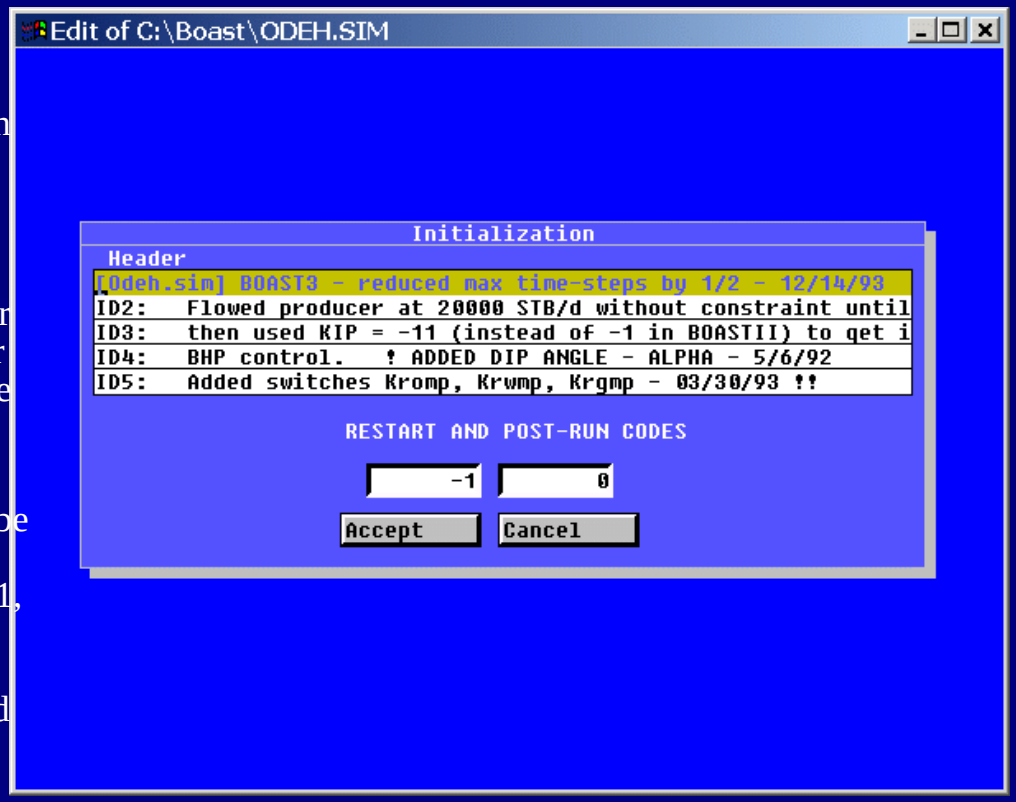
Many of the button selections bring up dialog boxes with an integer of 0 or 1 and sometimes a minus 1. Where only a 0 or a 1 is used, the 0 means, NO or turn off, and the 1 means, YES or turn on. Please consult the Boast3 manual for the meanings of each integer as a switch.

Reservoir Simulation Application

Boast - EdBoast

BEGIN:

- **BEGIN**: This introduces the dialog frame, which contains 5 lines of reservoir description called "Header". The first line of the "Header" will be the title card. The other 4 lines are run identification records. The next 2 boxes in the frame contain 2 integers representing switches for restart initialization or restart run, and another for writing a post-run table. This information may be found at the beginning of page 11 of the Boast3 manual.
- Although the restart run parameters are stated to be "still underconstruction", the switches and input data appear to work at this time. For IREOPT = 1, full restart editing of the saved restart file is not available. When IREOPT = - 1, the no restart option is invoked. The restart option is initialized with IREOPT = 0.
-
- Button 2.GRID
- The GRID button brings up 5 or more dialogs or spreadsheets for entering reservoir model grid dimensions (II, JJ, & KK) and geometry data



Reservoir Simulation Application

Boast - EdBoast

GRID

The GRID button brings up 5 or more dialogs or spreadsheets for entering reservoir model grid dimensions (II, JJ, & KK) and geometry data (KDX, KDY, KDZ, & KDZNET) as found in pages 14-15 of the Boast3 manual. The values of the codes for KDX, etc. determine the type of dialog window that follows. Entering a minus 1 (-1), indicates a constant values for all grid blocks. Special spread sheets for rows, columns, or 2-dimensional array results from a value of 0 or identification.

Before each spreadsheet of values is presented, a page of instructions is shown which describes the invisible commands or various key shortcuts which can be used on all the spreadsheets. Check out this page in the Boast3 manual.

Also, a special dialog box is presented for each region modified for grid dimensions (NUMDX, NUMDY, NUMDZ, NUMDZN, & IDCODE). This dialog contains a listing of the selected region's location value followed by a left-most (I1) and right-most (I2) column number, and an upper-most (J1) and a lower-most (J2) row number, along with a layer range (K1 - K2) for the grid region affected by the grid dimension value in the box. This same style of setting region values applies to several other modifications of reservoir parameters, such as porosity, permeability, and transmissibility.

The next dialogs box requests the KEL code for inputting depth values and dip angle (see page 15 of Boast3 manual). A correct KEL code of -2 and 2 (non-contiguous layers) is not supported.

- **BEGIN**: This introduces the dialog frame, which contains 5 lines of reservoir description called "Header". The first line of the "Header" will be the title card. The other 4 lines are run identification records. The next 2 boxes in the frame contain 2 integers representing switches for restart initialization or restart run, and another for writing a post run table. This information may be found at the beginning of Chapter 4 of the Boast3 manual.
- Although the restart run parameters are stated to be "still under construction", the switches and input data appear to work at this time. For IREOPT = 1, full restart capability of the saved restart file is available. When IREOPT = 1, the no restart option is invoked. The restart option is initialized with IREOPT = 0.
- Button 2.GRID
- The GRID button brings up 5 or more dialogs or spreadsheets for entering reservoir model grid dimensions (II, JJ, & KK) and geometry data

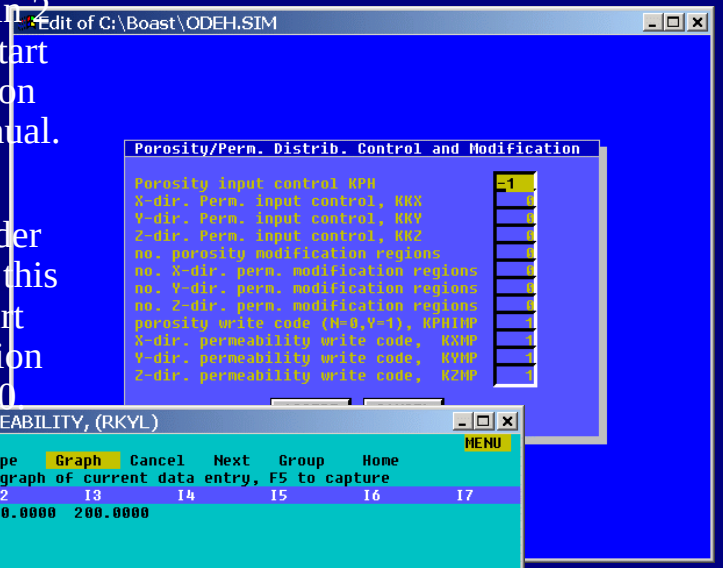
Reservoir Simulation Application

Boast - EdBoast

- BEGIN
  - This first button introduces the dialog frame, which contains 5 lines of reservoir description called "Header". The first line of the "Header" will be the title card. The other 4 lines are run identification records. The next 2 boxes in the frame contain 2 integers representing switches for restart initialization or restart run, and another for writing a post-run table. This information may be found at the beginning of page 11 of the Boast3 manual.
  - The same type of dialog is used as described under GRID button 2. A dialog window is presented with the switches that contain a 1 or 0, or a 1. This also brings up dialog boxes for a constant value or spreadsheet of values, as in GRID
- Button 2 GRID
- The GRID button brings up 5 or more dialogs or spreadsheets for entering reservoir model grid dimensions (II, JJ, & KK) and geometry data as found beginning at the top of page 20 of the Boast3 manual. Also a special dialog box is presented for each region modified for porosity or permeability.

PORPERM

- The PERM button brings up 1 or more dialogs or spreadsheets containing reservoir porosity and permeability data as found beginning at the top of page 20 of the Boast3 manual. Also a special dialog box is presented for each region modified for porosity or permeability.

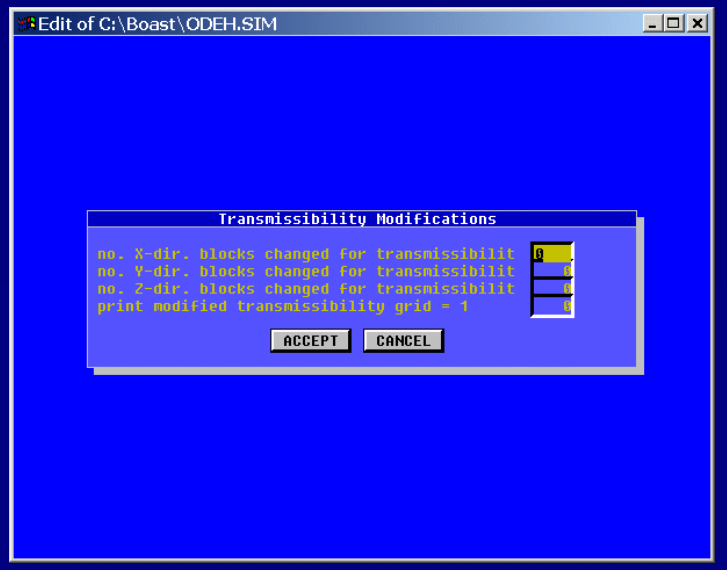


Reservoir Simulation Application

Boast - EdBoast

TRANSM

The TRANSM button presents transmissibility modifications shown near the bottom of page 22 in the Boast3 manual. The dialog format is similar to the other modification dialogs.



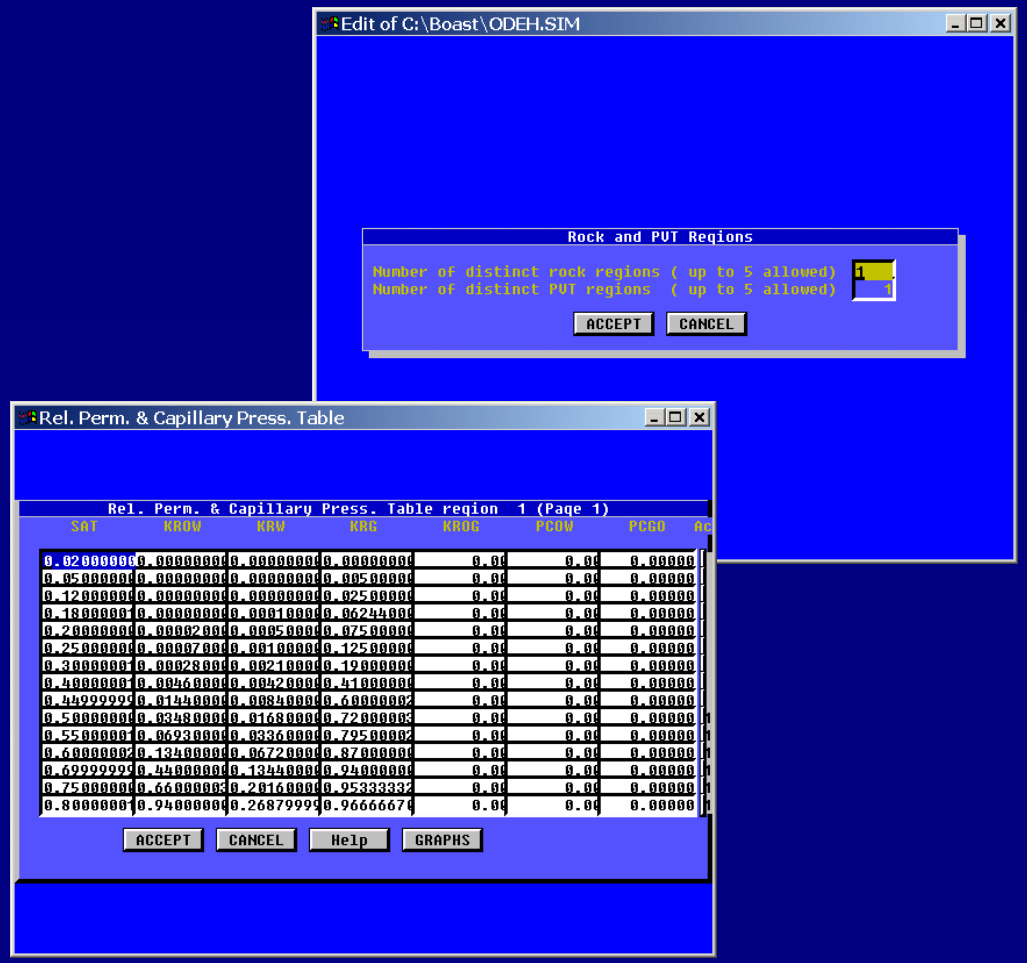
Reservoir Simulation Application

Boast - EdBoast

TABLE

A description of the sequence of requested information for Rock and PVT regions and their respective relative permeability and capillary pressure tables is given beginning on page 24 of the Boast3 manual.

The first dialog from this button, allows entry for the number of distinct rock regions is to be changed and the number of regions where the PVT default region value of 1 is to be changed. The rock region is a saturation dependent data set for relative permeability. The PVT region is a pressure dependent data set, including oil, water, and gas PVT tables. At least one rock region and one saturation region is required.

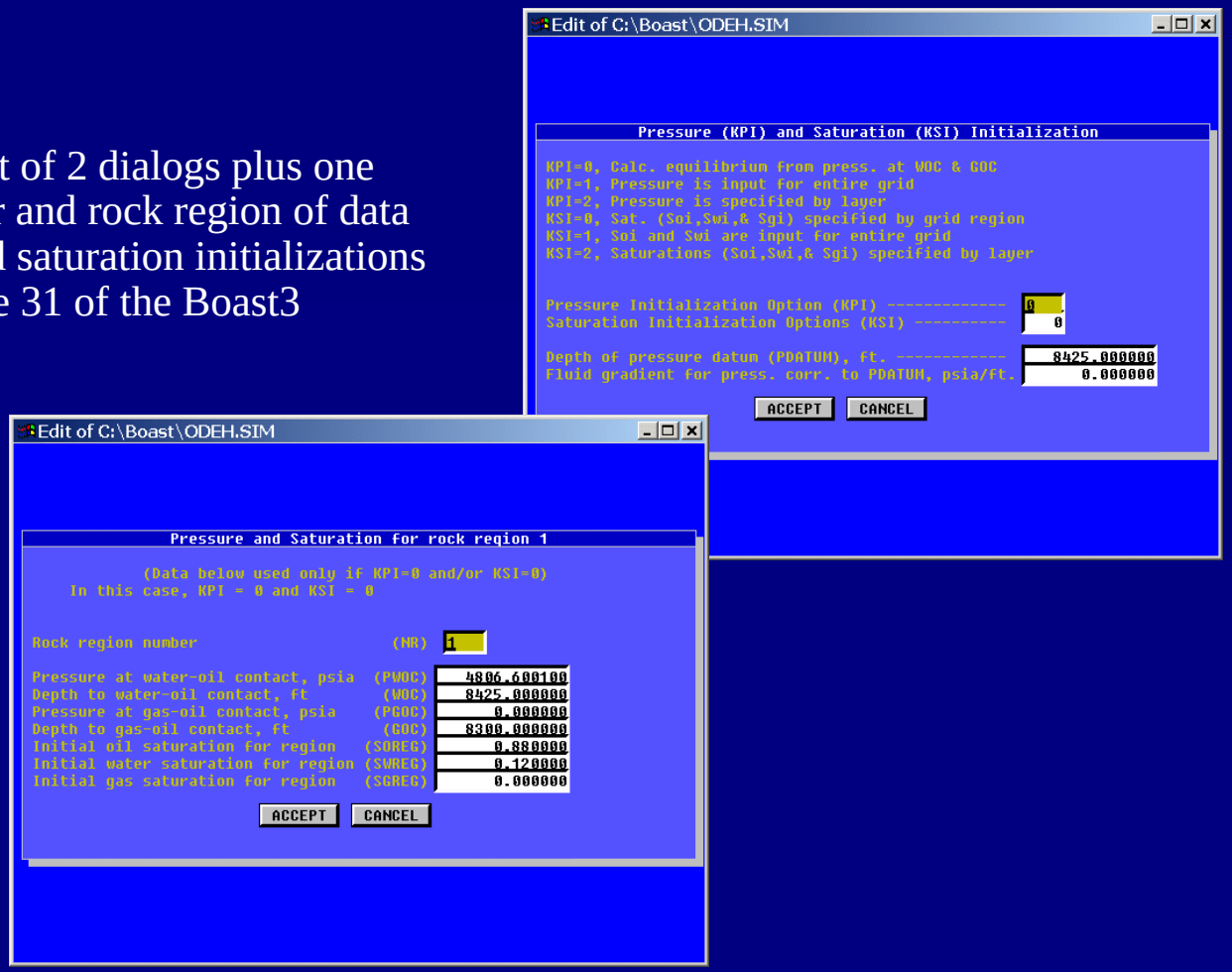


Reservoir Simulation Application

Boast - EdBoast

INITIAL

This button introduces a set of 2 dialogs plus one more dialogs for each layer and rock region of data containing the pressure and saturation initializations as found beginning on page 31 of the Boast3 manual.

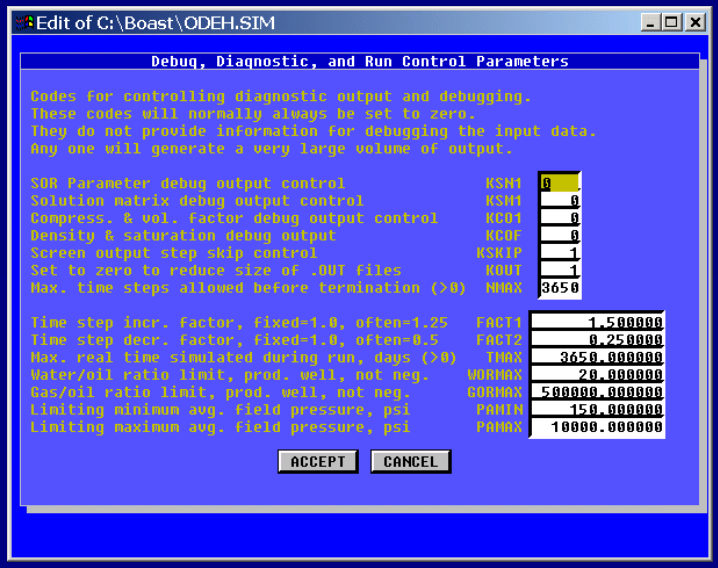


Reservoir Simulation Application

Boast - EdBoast

CODES

This button introduces debug and diagnostic controls options and solution method specifications as found beginning on page 32 of the Boast3 manual. The data can be entered in a series of 2 dialogs.



Reservoir Simulation Application

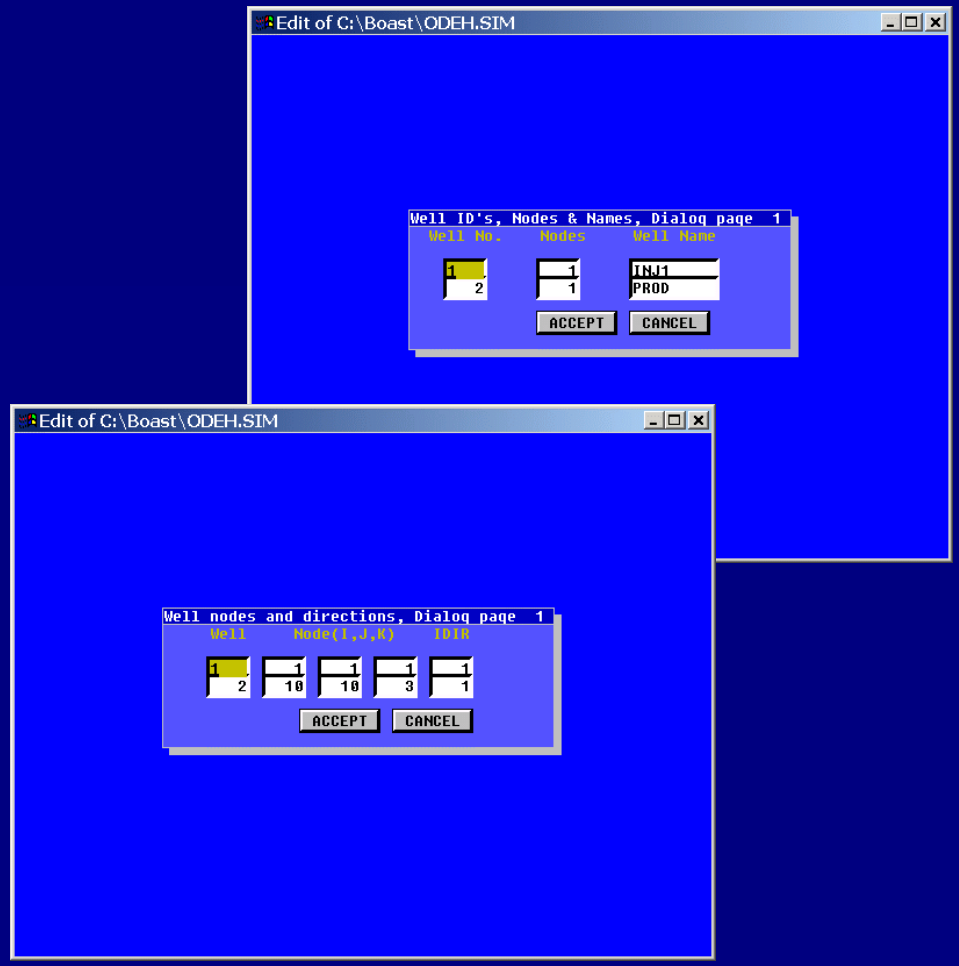
Boast - EdBoast

AQUI

This button introduces the installation of the aquifer data as found beginning on page 35 of the Boast3 manual.

WELLS

This button introduces well data as found beginning on page 37 of the Boast3 manual. The total number of wells that will be used in the entire simulations must be entered first. Then each well ID, the number of well nodes, and the well name for each well are entered. This is followed by X, Y, Z locations of each well node being entered. The well direction, IDIR, is entered to conform to the Boast3 format.

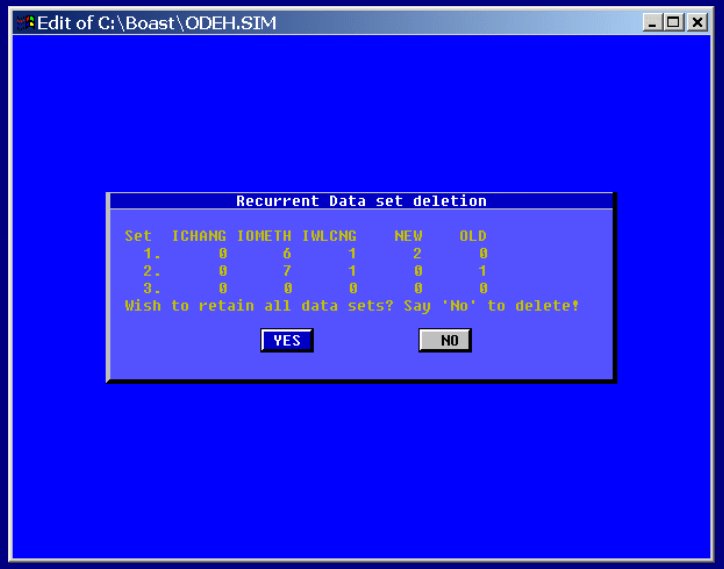


Reservoir Simulation Application

Boast - EdBoast

RECURR

This button introduces a set of 6 dialogs for each data set for entering recurrent data as found beginning on page 38 of the Boast3 manual. The total number of data sets entered (up to 200) is displayed in the first window(s) presented. Up to 21 data sets with associated information are allowed in the first page and 22 data sets on each succeeding page. This allows a preview of the number (IOMETH) of elapsed times (FTIO) in days and also a break down on the number of NEW and OLD (modified) wells are in each data set. This preview is repeated twice. Once for "Data set deletion" . The second for "Data set selection". The second preview is followed by 6 separate dialogs, if only YES is selected.



Data set deletion. By saying YES, the entire group of data sets is retained and data set selection is next. By saying NO, the last data set number is presented for deletion. To delete any other data set, enter a different number. This decision may be canceled immediately or later by the ABORT command in the Home Page. It is always wise to look over the data set to be deleted before a deletion is made. After a deletion has been made and accepted, the data set numbers following the deleted set are moved back by one. (Note: If the YES and NO button should every disappear use the Enter key to bring them back. This happens when another program window overlaps the preview or a resize event occurs.) Data set selection will be offered next.

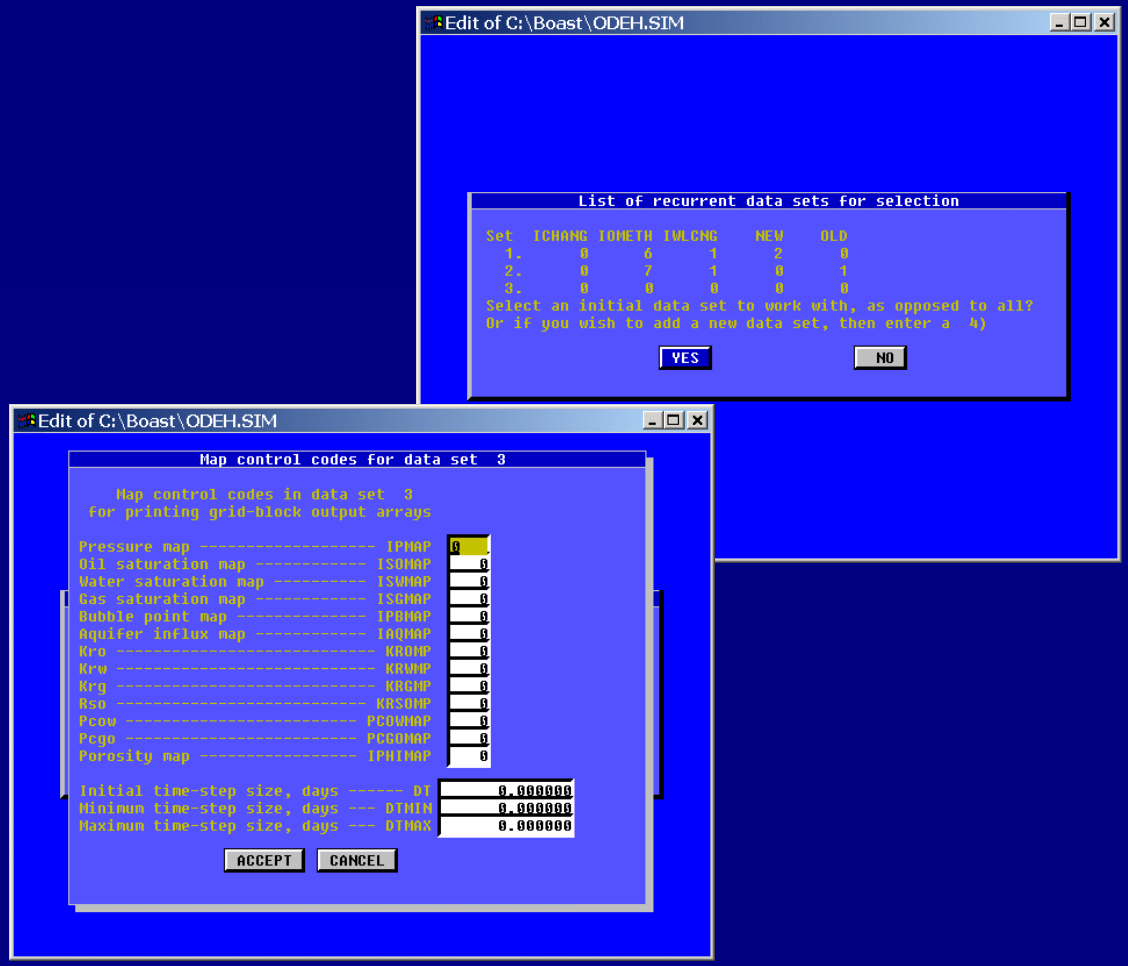
Reservoir Simulation Application

Boast - EdBoast

RECURR

Every data set and associated dialog procedure can be identified in the title found at the top of each window.

Old and New well selection. Each data set will include the number of old and new wells. A new well is one that if fully defined with a PID and PWF value for each layer. An old well then is one that has been previously defined. The same IDWELL number is kept for the old WELLID as was used when it was a new well. For the old wells, the program remembers the PID and PWF values placed there as new wells. The PID and PWF values can be changed for a well by redefining the same IDWELL number as a new well. This is also true for the values of ALIT and BLIT for a dry gas reservoir. These values of ALIT and BLIT can be produced with the program GASDEL, mentioned in the Boast 3 manual.



Reservoir Simulation Application

Boast - EdBoast

DEFAULT
This button will initiate a set of pre-selected input data, which will allow the beginner a quick step forward. The selection of this button will warn a person that their data will be overwritten by the default-input data. Even if a YES is chosen for this warning, using the ABORT button will reject saving this overwritten file. One more chance is give to reject modified or defaulted information when the ACCEPT button is chosen by next choosing NO to the question "Open output file?".

NEXT
This button will advance to the next button in the line up. This is the same as the Tab plus the Enter key being hit. The Up and Down arrow keys will advance or reverse the highlighted button selections.

ACCEPT
This button will allow the saving of the edited input data under the same or a different file name. This button selection can be canceled by choosing NO instead of YES.

ABORT
Returns to the original main menu. The same file name is in the buffer and another command such as Preview or Boast98 can apply to file name previously selected.

Reservoir Simulation Application

Boast - EdBoast

Alternatively Use an Editor

Rather that use EdBoast one can always use and Editor like WinEdit or WordPad to change the *.sim file, which is the Boast input file that will be run.

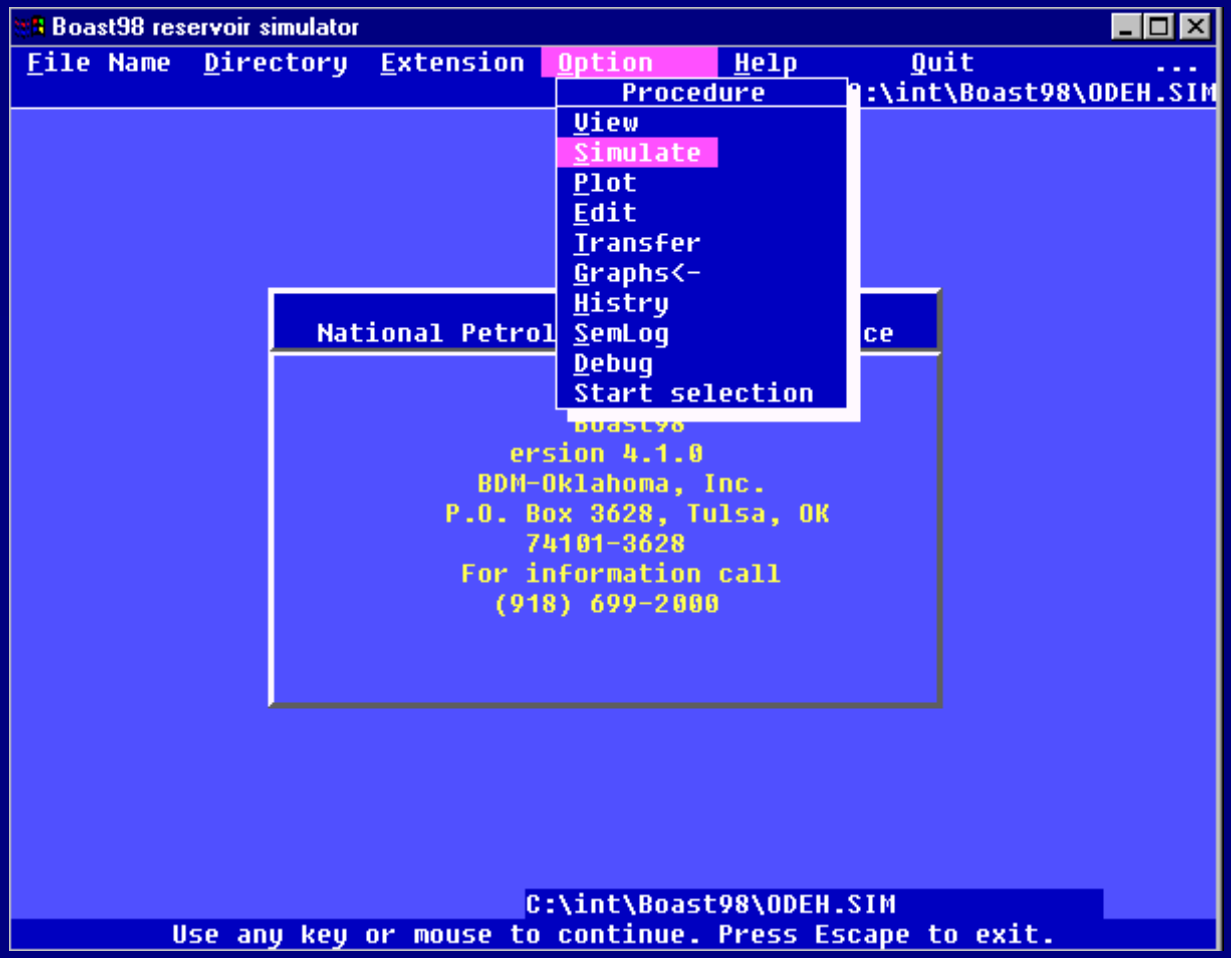
This is the most efficient way to edit the simulation deck for knowledge users.

```
[ODEH553.SIM]  TESTING RESTART OPTION IN BOAST3 6/05/95
ID2:   INITIALIZATION RUN WITH IREOPT = 0
ID3:   ONE RESTART RECORD WRITTEN AT 1825 DAYS
ID4:   NO INPUT RESTART FILE IS NEEDED; HENCE USING "DUMMY.RIN"
ID5:   OUTPUT RESTART FILE IS NAMED "ODEH553.ROT"
RESTART AND POST-RUN CODES
     0    0          <--- IREOPT, IPOSTP
     1    0    0 0000.<--- IRNUM,IRSTRT, NN,TMAX (NN & TMAX used only for
                                                  IREOPT=l)
DUMMY.RIN  <--- Input Restart File Name  - used only for IREOPT=l
ODEH553.ROT <-- Output Restart File Name-TO BE USED AS INPUT FOR RESTART RUN!
1825.  <--- Times @ which Restart Records are written
GRID DATA
5 5 3
GRID BLOCK LENGTHS
-1 -1 0  0
2000.
2000.
20. 30. 50.
20. 30. 50.
GRID BLOCK LENGTH MODIFICATIONS
5*0
CONSTANT DEPTH TO TOP OF LAYER ONE
0 0.0   <---KEL, ALPHA
8325.
POROSITY AND PERMEABILITY DISTRIBUTIONS
-1     0 0 0
.30
500.   50.    200.
500.   50.    200.
100    37.5   20.83
POROSITY &  PERMEABILITY MODS:  (IPCODE replaced by KPHIMP,KXMP,KYMP,KZMP)
0 0 0 0 1 1 1 1
TRANSMISSIBILITY MODIFICATIONS
```

Reservoir Simulation Application

BOAST98

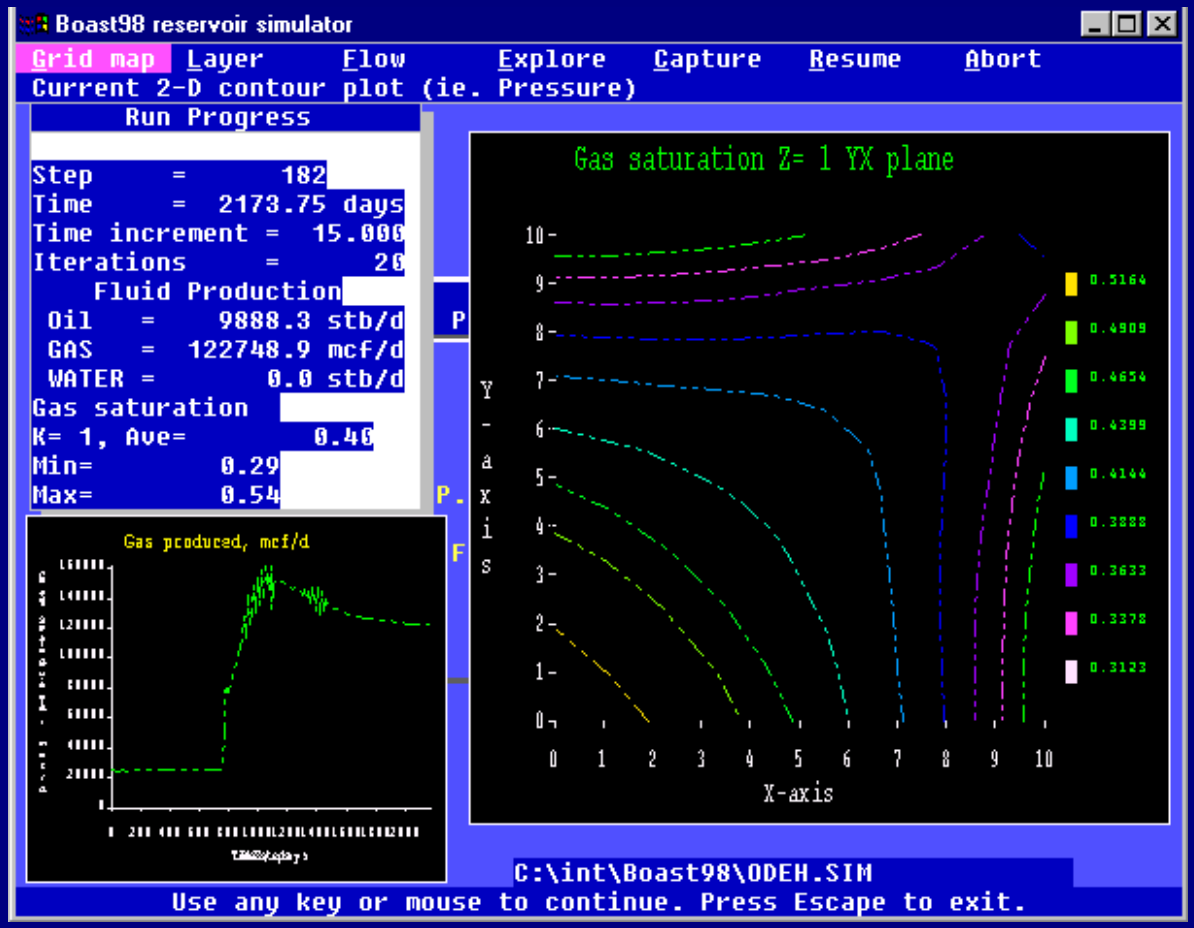
In this primary menu display, the "Option" menu item has been selected. The opened menu item "Option" shows a list of sub-items with "Simulate" highlighted. The last line in the list, "Start selection" is a description of the highlighted sub-item. Use the up and down arrows to highlight different sub selections. A mouse click on a sub-item will invoke the described procedure. In this case, an Enter key, or a mouse click on Simulate will begin the reservoir simulation of the selected file name, "ODEH.SIM", as seen in the second to the bottom line. This file name is often seen also seen on the right side of the second line from the top.



Reservoir Simulation Application

BOAST98

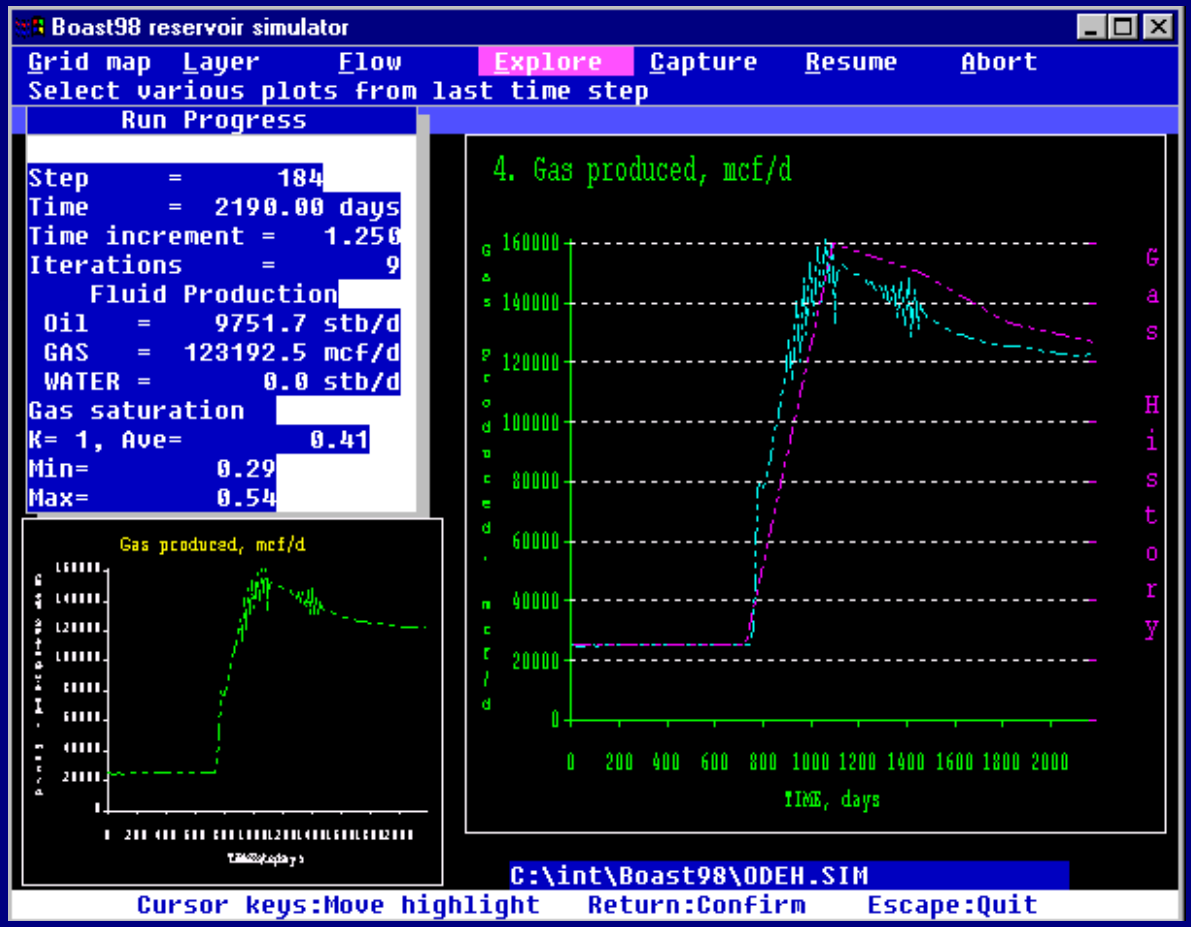
The right mouse click during a simulation run will cause an immediate suspension of simulation after finishing one more time step. A secondary menu is displayed as shown in the figure above. The highlighted menu item "Explore" has its description shown on the second line. In this case, "Explore" would select from a large number variables and plot as 1, 2, and 3 dimensional graphic constructions. The run simulation is resumed when the menu item "Resume" is selected.



Reservoir Simulation Application

BOAST98

The use of history matching is selected before simulation begins. The charts of the history matching are only viewed under the Explore menu selection during simulation suspension.

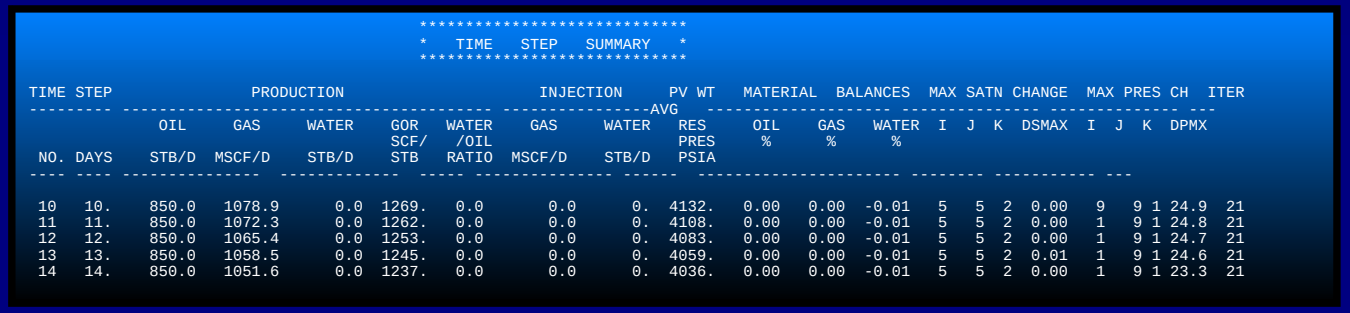


Reservoir Simulation Application

BOAST98

When the simulator is run and the following generic output files are created:

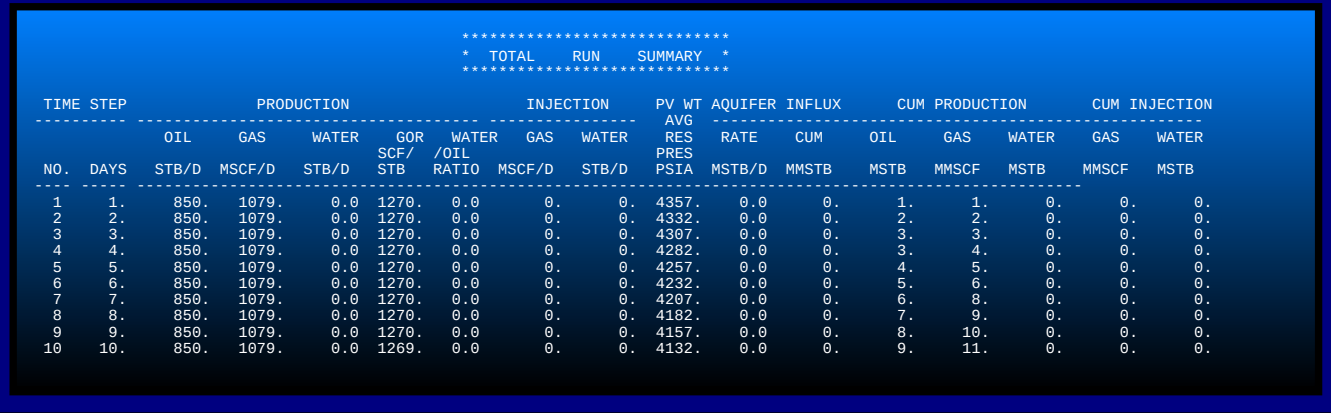
1. B.OUT Output listing
2. B.SCR Screen output
3. B.WEL Well production summary
4. B.TAB Field production summary
S. B.GWN Grid & wellblock data for B3PLOT2
6. B.BPD Binary production data for B3PLOT2
7. B.CGD Grid & well data for COLORGRID
8. B.MAP Binary file of 3D arrays for COLORGRID



```
                                ****************************
                                *   TIME   STEP   SUMMARY   *
                                ****************************

TIME STEP              PRODUCTION                      INJECTION     PV WT   MATERIAL  BALANCES  MAX SATN CHANGE  MAX PRES CH  ITER
--------- ---------------------------------------- ---------------AVG   ------------------ -------------- -------------- ---
              OIL     GAS     WATER    GOR   WATER    GAS     WATER   RES     OIL    GAS   WATER  I  J  K  DSMAX  I  J  K  DPMX
                                        SCF/   /OIL                    PRES     %      %     %
 NO. DAYS    STB/D  MSCF/D    STB/D     STB   RATIO  MSCF/D    STB/D   PSIA
---- ---- -------------  -------------  -----  ----- ------ ------  -------- -------- -------- --- --- --- ------ --- --- --- ----- ---

 10   10.    850.0   1078.9      0.0  1269.   0.0      0.0      0.  4132.   0.00     0.00  -0.01   5   5  2  0.00   9   9 1 24.9  21
 11   11.    850.0   1072.3      0.0  1262.   0.0      0.0      0.  4108.   0.00     0.00  -0.01   5   5  2  0.00   1   9 1 24.8  21
 12   12.    850.0   1065.4      0.0  1253.   0.0      0.0      0.  4083.   0.00     0.00  -0.01   5   5  2  0.00   1   9 1 24.7  21
 13   13.    850.0   1058.5      0.0  1245.   0.0      0.0      0.  4059.   0.00     0.00  -0.01   5   5  2  0.01   1   9 1 24.6  21
 14   14.    850.0   1051.6      0.0  1237.   0.0      0.0      0.  4036.   0.00     0.00  -0.01   5   5  2  0.00   1   9 1 23.3  21
```



```
                                ****************************
                                *  TOTAL    RUN    SUMMARY  *
                                ****************************

 TIME STEP              PRODUCTION                      INJECTION     PV WT AQUIFER INFLUX      CUM PRODUCTION       CUM INJECTION
---------- ---------------------------------------- ---------------  AVG  ---------------------------------------------------------
              OIL     GAS     WATER    GOR   WATER    GAS     WATER   RES    RATE    CUM      OIL     GAS     WATER    GAS     WATER
                                        SCF/   /OIL                    PRES
 NO.  DAYS   STB/D  MSCF/D    STB/D     STB   RATIO  MSCF/D    STB/D   PSIA  MSTB/D  MMSTB     MSTB    MMSCF    MSTB    MMSCF    MSTB
---- ----- ------------------------------------------------------------------------------------------------------------------------
  1     1.     850.    1079.      0.0  1270.   0.0      0.      0.  4357.    0.0      0.       1.      1.      0.      0.      0.
  2     2.     850.    1079.      0.0  1270.   0.0      0.      0.  4332.    0.0      0.       2.      2.      0.      0.      0.
  3     3.     850.    1079.      0.0  1270.   0.0      0.      0.  4307.    0.0      0.       3.      3.      0.      0.      0.
  4     4.     850.    1079.      0.0  1270.   0.0      0.      0.  4282.    0.0      0.       3.      4.      0.      0.      0.
  5     5.     850.    1079.      0.0  1270.   0.0      0.      0.  4257.    0.0      0.       4.      5.      0.      0.      0.
  6     6.     850.    1079.      0.0  1270.   0.0      0.      0.  4232.    0.0      0.       5.      6.      0.      0.      0.
  7     7.     850.    1079.      0.0  1270.   0.0      0.      0.  4207.    0.0      0.       6.      8.      0.      0.      0.
  8     8.     850.    1079.      0.0  1270.   0.0      0.      0.  4182.    0.0      0.       7.      9.      0.      0.      0.
  9     9.     850.    1079.      0.0  1270.   0.0      0.      0.  4157.    0.0      0.       8.     10.      0.      0.      0.
 10    10.     850.    1079.      0.0  1269.   0.0      0.      0.  4132.    0.0      0.       9.     11.      0.      0.      0.
```

Reservoir Simulation Application

BOAST98

```
*****************************
*   TOTAL    RUN    SUMMARY  *
*****************************
```

TIME STEP		PRODUCTION					INJECTION		PV WT	AQUIFER INFLUX		CUM PRODUCTION			CUM INJECTION	
		OIL	GAS	WATER	GOR	WATER	GAS	WATER	AVG RES PRES	RATE	CUM	OIL	GAS	WATER	GAS	WATER
NO.	DAYS	STB/D	MSCF/D	STB/D	SCF/ STB	/OIL RATIO	MSCF/D	STB/D	PSIA	MSTB/D	MMSTB	MSTB	MMSCF	MSTB	MMSCF	MSTB
1	1.	850.	1079.	0.0	1270.	0.0	0.	0.	4357.	0.0	0.	1.	1.	0.	0.	0.
2	2.	850.	1079.	0.0	1270.	0.0	0.	0.	4332.	0.0	0.	2.	2.	0.	0.	0.
3	3.	850.	1079.	0.0	1270.	0.0	0.	0.	4307.	0.0	0.	3.	3.	0.	0.	0.
4	4.	850.	1079.	0.0	1270.	0.0	0.	0.	4282.	0.0	0.	3.	4.	0.	0.	0.
5	5.	850.	1079.	0.0	1270.	0.0	0.	0.	4257.	0.0	0.	4.	5.	0.	0.	0.
6	6.	850.	1079.	0.0	1270.	0.0	0.	0.	4232.	0.0	0.	5.	6.	0.	0.	0.
7	7.	850.	1079.	0.0	1270.	0.0	0.	0.	4207.	0.0	0.	6.	8.	0.	0.	0.
8	8.	850.	1079.	0.0	1270.	0.0	0.	0.	4182.	0.0	0.	7.	9.	0.	0.	0.
9	9.	850.	1079.	0.0	1270.	0.0	0.	0.	4157.	0.0	0.	8.	10.	0.	0.	0.
10	10.	850.	1079.	0.0	1269.	0.0	0.	0.	4132.	0.0	0.	9.	11.	0.	0.	0.
11	11.	850.	1072.	0.0	1262.	0.0	0.	0.	4108.	0.0	0.	9.	12.	0.	0.	0.
12	12.	850.	1065.	0.0	1253.	0.0	0.	0.	4083.	0.0	0.	10.	13.	0.	0.	0.
13	13.	850.	1059.	0.0	1245.	0.0	0.	0.	4059.	0.0	0.	11.	14.	0.	0.	0.
14	14.	850.	1052.	0.0	1237.	0.0	0.	0.	4036.	0.0	0.	12.	15.	0.	0.	0.
15	15.	850.	1063.	0.0	1251.	0.0	0.	0.	4017.	0.0	0.	13.	16.	0.	0.	0.
16	16.	850.	1092.	0.0	1285.	0.0	0.	0.	4004.	0.0	0.	14.	17.	0.	0.	0.
17	17.	850.	1094.	0.0	1287.	0.0	0.	0.	3999.	0.0	0.	14.	18.	0.	0.	0.
18	18.	850.	1086.	0.0	1278.	0.0	0.	0.	3994.	0.0	0.	15.	19.	0.	0.	0.
19	19.	850.	1079.	0.0	1270.	0.0	0.	0.	3989.	0.0	0.	16.	20.	0.	0.	0.
20	20.	850.	1074.	0.0	1264.	0.0	0.	0.	3985.	0.0	0.	17.	22.	0.	0.	0.
21	21.	850.	1071.	0.0	1260.	0.0	0.	0.	3980.	0.0	0.	18.	23.	0.	0.	0.
22	22.	850.	1069.	0.0	1257.	0.0	0.	0.	3975.	0.0	0.	19.	24.	0.	0.	0.
23	23.	850.	1067.	0.0	1255.	0.0	0.	0.	3970.	0.0	0.	20.	25.	0.	0.	0.
24	24.	850.	1065.	0.0	1253.	0.0	0.	0.	3966.	0.0	0.	20.	26.	0.	0.	0.
25	25.	850.	1063.	0.0	1251.	0.0	0.	0.	3961.	0.0	0.	21.	27.	0.	0.	0.
26	26.	850.	1062.	0.0	1249.	0.0	0.	0.	3956.	0.0	0.	22.	28.	0.	0.	0.
27	27.	850.	1060.	0.0	1247.	0.0	0.	0.	3952.	0.0	0.	23.	29.	0.	0.	0.
28	28.	850.	1059.	0.0	1245.	0.0	0.	0.	3947.	0.0	0.	24.	30.	0.	0.	0.
29	29.	850.	1057.	0.0	1244.	0.0	0.	0.	3943.	0.0	0.	25.	31.	0.	0.	0.
30	30.	850.	1056.	0.0	1242.	0.0	0.	0.	3938.	0.0	0.	26.	32.	0.	0.	0.
31	31.	850.	1054.	0.0	1240.	0.0	0.	0.	3934.	0.0	0.	26.	33.	0.	0.	0.
32	32.	850.	1053.	0.0	1239.	0.0	0.	0.	3929.	0.0	0.	27.	34.	0.	0.	0.
33	33.	850.	1054.	0.0	1240.	0.0	0.	0.	3925.	0.0	0.	28.	35.	0.	0.	0.
34	34.	850.	1059.	0.0	1246.	0.0	0.	0.	3920.	0.0	0.	29.	36.	0.	0.	0.
35	35.	850.	1064.	0.0	1252.	0.0	0.	0.	3916.	0.0	0.	30.	37.	0.	0.	0.

Reservoir Simulation Application

BOAST98

```
                                ****************************
                                *   TIME   STEP   SUMMARY   *
                                ****************************

TIME STEP              PRODUCTION                          INJECTION      PV WT   MATERIAL  BALANCES  MAX SATN CHANGE  MAX PRES CH  ITER
--------- ---------------------------------------- ----------------  AVG  -------------------- -------------- -------------- ---
                OIL      GAS      WATER    GOR   WATER     GAS      WATER   RES      OIL      GAS     WATER  I  J  K  DSMAX  I  J  K  DPMX
 NO.  DAYS     STB/D   MSCF/D    STB/D    SCF/  /OIL    MSCF/D    STB/D   PRES      %        %       %
                                          STB   RATIO                       PSIA
---- ---- -------- ------- ------- ------ ----- -------- ------- ------ ------ ------ ------ -- -- -- ------ -- -- -- ----- ---

325  821.    380.0   3191.6     0.0  8399.   0.0      0.0      0.   299.   0.00   0.04   0.00   4   5  2  0.00   5   5 2 23.5  22
326  823.    380.0   3284.7     0.0  8644.   0.0      0.0      0.   293.   0.00   0.08   0.00   5   4  2  0.00   5   5 2 29.8  21
327  825.    380.0   3367.4     0.0  8862.   0.0      0.0      0.   286.   0.00   0.14   0.00   5   4  2  0.00   5   5 2 39.6  21
328  827.    380.0   3431.8     0.0  9031.   0.0      0.0      0.   275.   0.00   0.04  -0.01   4   4  2  0.01   5   5 1 55.8  20
329  831.    380.0   3442.1     0.0  9058.   0.0      0.0      0.   263.   0.00  -0.68  -0.01   6   6  2  0.01   5   5 1 72.5  20
330  835.    380.0   3326.1     0.0  8753.   0.0      0.0      0.   250.   0.00  -1.14  -0.01   5   3  2  0.01   5   5 1 74.2  20
331  840.    380.0   3024.5     0.0  7959.   0.0      0.0      0.   239.   0.00  -3.30  -0.01   5   5  2  0.01   5   5 1 44.4  20
332  847.    380.0   2626.4     0.0  6911.   0.0      0.0      0.   232.   0.00   1.14   0.00   5   5  2  0.01   5   6 1 26.4  19
333  855.    380.0   2238.0     0.0  5889.   0.0      0.0      0.   224.   0.00   1.33   0.00   5   5  2  0.01   5   5 2 57.4  22
334  865.    380.0   1962.6     0.0  5165.   0.0      0.0      0.   213.   0.00   1.74  -0.01   5   5  2  0.01   5   5 2 58.9  21
===>Repeating time-step 335   Reduced DELT=   6.330
PPM,SOM,SWM,SGM:   -87.9283       0.555787E-01   0.000000      -0.555787E-01
335  871.    380.0   2129.4     0.0  5604.   0.0      0.0      0.   198.   0.61  -0.84  -0.01   5   5  2  0.03   5   5 2 87.1  22
===>Repeating time-step 336   Reduced DELT=   3.956
PPM,SOM,SWM,SGM:    167.034      -0.616223E-01   0.000000       0.616223E-01
===>Repeating time-step 336   Reduced DELT=   1.978
PPM,SOM,SWM,SGM:    154.289      -0.284457E-01   0.000000       0.284457E-01
===>Repeating time-step 336   Reduced DELT=   0.989
PPM,SOM,SWM,SGM:    134.160      -0.117181E-01   0.000000       0.117181E-01
===>Repeating time-step 336   Reduced DELT=   0.500
PPM,SOM,SWM,SGM:    107.135      -0.410962E-02   0.000000       0.410962E-02
336  872.    380.0   1544.3     0.0  4064.   0.0      0.0      0.   198.   0.05  -0.12  -0.01   5   5  2  0.00   5   5 2 77.5  20
337  872.    380.0   1566.2     0.0  4122.   0.0      0.0      0.   197.   0.00  -0.11   0.00   5   5  2  0.00   5   5 2 44.3  18
338  873.    380.0   1634.8     0.0  4302.   0.0      0.0      0.   196.   0.00  -0.05   0.00   5   5  2  0.00   5   5 2 12.8  14
339  874.    380.0   1737.2     0.0  4572.   0.0      0.0      0.   194.   0.00   0.02   0.00   5   5  2  0.00   5   5 2 13.7  15
340  875.    380.0   1827.6     0.0  4810.   0.0      0.0      0.   192.   0.00   0.09   0.00   5   5  2  0.00   5   5 2 26.6  16
341  877.    380.0   1884.4     0.0  4959.   0.0      0.0      0.   189.   0.00   0.14   0.00   5   2  2  0.00   5   5 2 26.3  18
342  879.    380.0   1898.3     0.0  4996.   0.0      0.0      0.   185.   0.00   0.16   0.00   7   4  2  0.00   5   5 2 17.0  17
343  881.    380.0   1880.8     0.0  4950.   0.0      0.0      0.   180.   0.00   0.18   0.00   3   4  2  0.00   5   4 1  8.2  18
344  884.    380.0   1861.2     0.0  4898.   0.0      0.0      0.   174.   0.00   0.23   0.00   7   4  2  0.00   5   4 1  9.1  20
345  888.    380.0   1852.3     0.0  4874.   0.0      0.0      0.   166.   0.00   0.32   0.00   5   2  2  0.00   5   4 1 11.5  23
346  892.    380.0   1844.4     0.0  4854.   0.0      0.0      0.   156.   0.00   0.65  -0.01   5   2  2  0.00   5   4 1 15.0  23

          MINIMUM AVERAGE RESERVOIR PRESSURE WAS NOT ACHIEVED ---SIMULATION IS BEING TERMINATED
```

Reservoir Simulation Application

BOAST98

Exercise 1

Run EdBoast and load the Boast input file ***Depletion.sim***. View the input file and notice that the water injection wells have been switched off for this run. this was done by commenting out the desired lines with "*C*". Run this case and plot the results from the ***Depletion.out*** file.

(1) What are the oil and gas recovery factors?
(2) When does the reservoir drop below bubble point pressure?
(3) What is wrong with this run?

Exercise 2

Copy Depletion.sim and name the copy Waterflood.sim. Edit Waterflood.sim and delete the comment character (the lines with *"C"*), to switch the water injection wells back on. Run this case and plot the reulsts frome the *Waterflood.out* file.

(1) What are the oil and gas recovery factors?
(2) When does the reservoir drop below bubble point pressure?
(3) When does water breakthrough?
(3) What is wrong with this run?

Petroleum Resource Evaluation

Numerical Modeling
Reservoir Simulation
Applied Modeling

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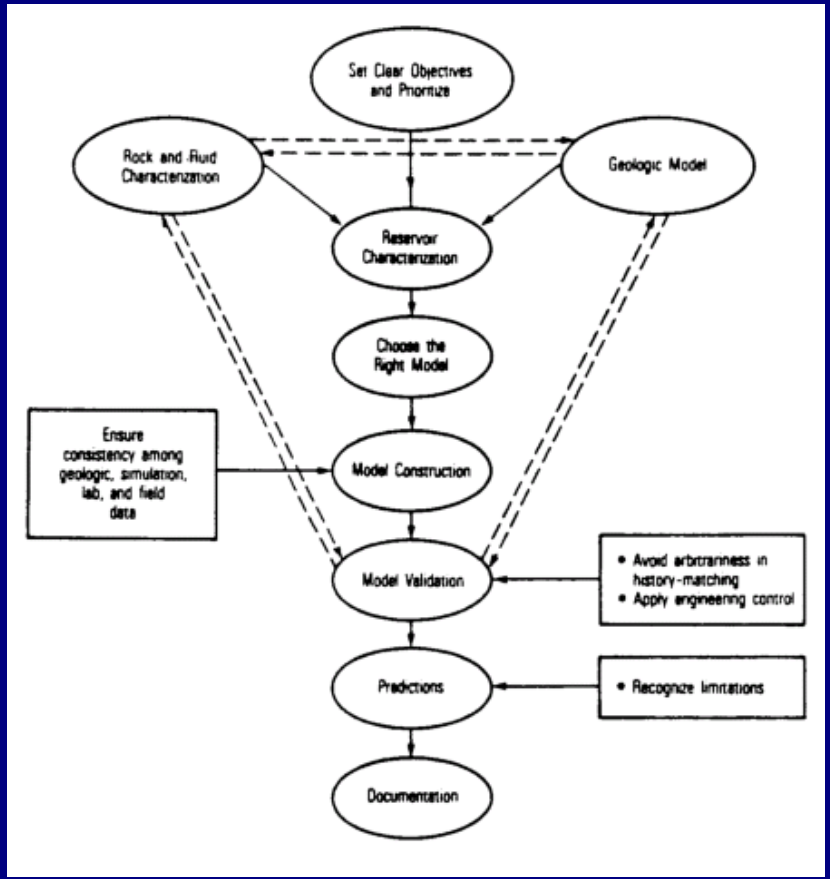
Reservoir Simulation Applied Modeling

Introduction

- In general, the key steps of a reservoir study can be summarized as follows :
  - Statement and Prioritization of Objectives
  - Reservoir Characterization
  - Model Selection
  - Model Construction
  - Validation
  - Predictions
  - Documentation
- Emphasis will be placed on the basic principles involved and the engineering and geologic control needed within each of the above steps.

Reservoir Simulation Applied Modeling

Introduction



Reservoir Simulation Applied Modeling

Statement and Prioritization of Objectives

- A clear statement of objectives is the most important step in a study. When several goals are involved, a prioritization process is needed.
  - Pressure and production forecasts
  - Critical gas and water coning rates
  - Timing and sizing of facilities (e.g., platforms)
  - In-fill drilling requirements
  - Comparative benefits of gas vs. water injection
  - Workover potential evaluation
  - Lease-line migration

Reservoir Simulation Applied Modeling

Statement and Prioritization of Objectives

- The modeling requirements of each objective are usually incompatible with one another, and thus the need for prioritizing objectives arises because of cost time constraints.
- For example, the griding and layering of a model to study workover potential can be very different from that of a model directed at estimating lease-line migration

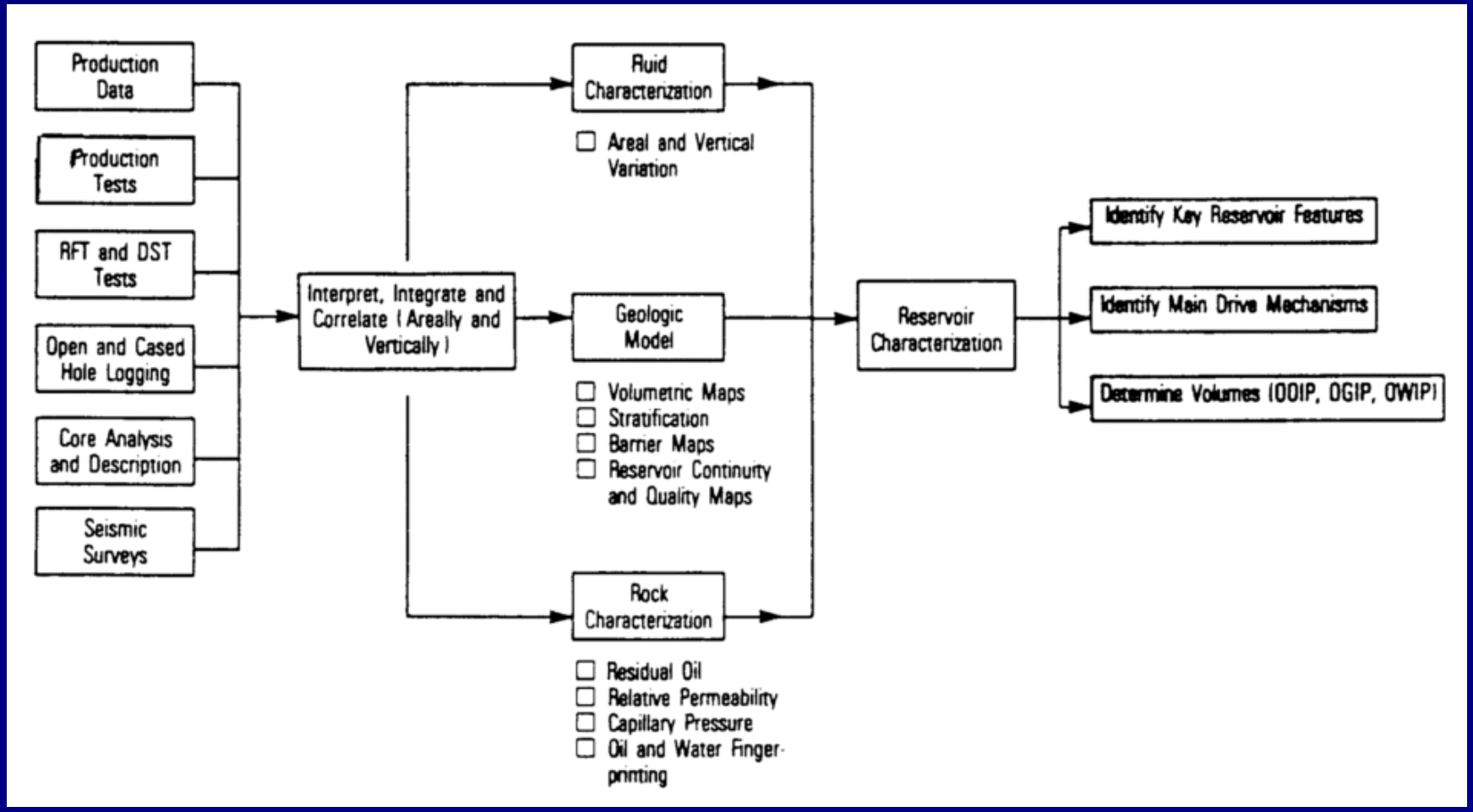
Reservoir Simulation Applied Modeling

Reservoir Characterization

- Reservoir characterization (RC) can be described as three interdependent components :
  - fluid characterization,
  - rock characterization, and
  - geologic modeling.
- The purpose of RC is to capture geologic and petrophysical features which affect reservoir flow mechanisms. The role engineering control and judgment plays in developing the reservoir model will be emphasized.

Reservoir Simulation Applied Modeling

Reservoir Characterization



Reservoir Simulation Applied Modeling

Reservoir Characterization

- In essence this process has three objectives :
  - To identify the key reservoir features
  - To identify the main drive mechanisms
  - To determine the reservoir volumetrics (STOIIP, GIIP, WIIP)
- RC forms the foundation for the other simulation steps; hence, any error in RC can be costly in terms of engineering results.
- Of the three components of RC, the geologic model is the most important and perhaps the most complex. This is where engineering control is especially needed. Since the primary issues in reservoir simulation involve in-situ flow, a geologic model must be able to capture features that directly affect in-situ flow.

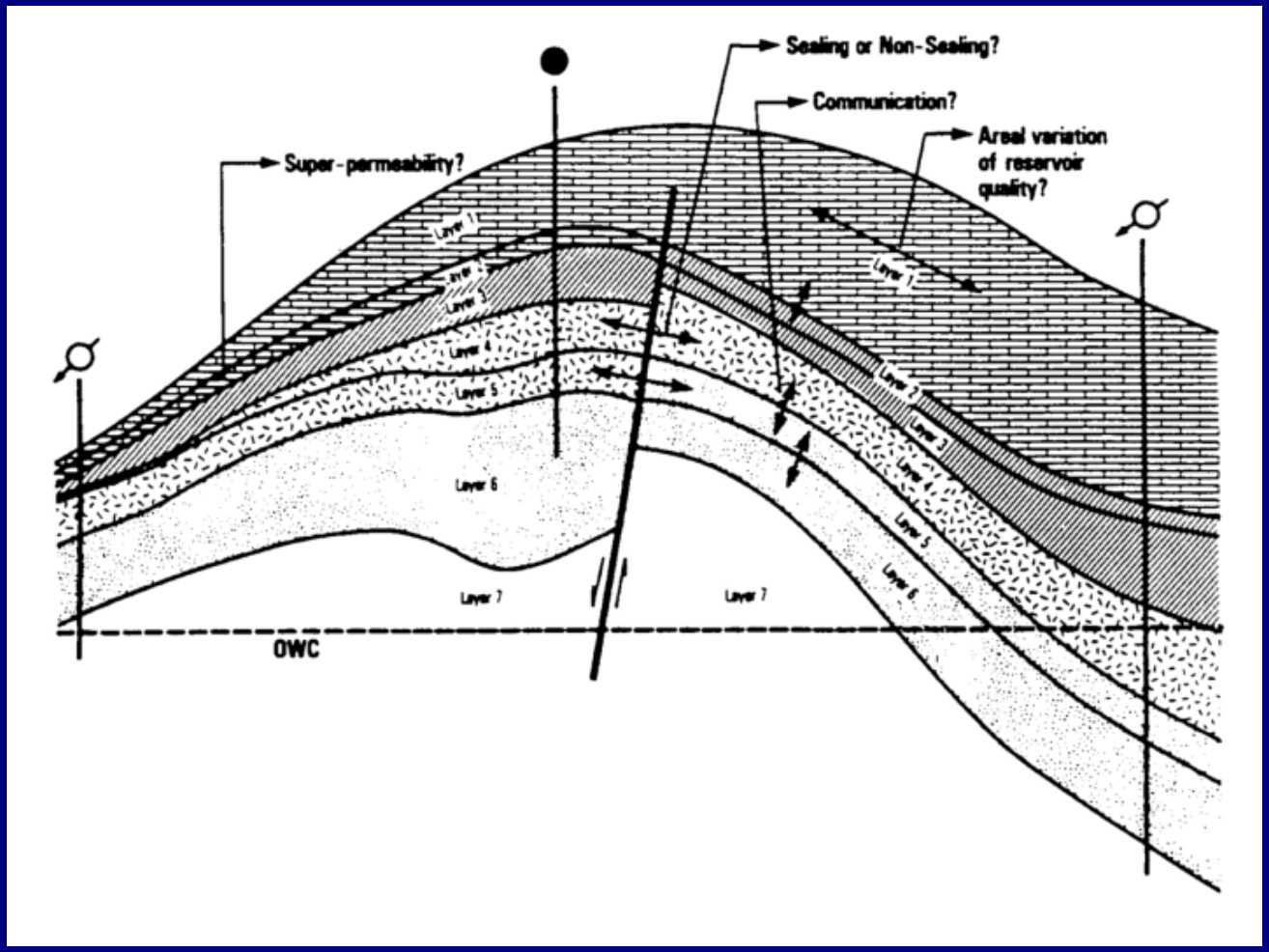
Reservoir Simulation Applied Modeling

Reservoir Characterization

- Specifically it must :
  - Identify stratification and degree of vertical communication of the zones.
  - Define what constitutes pay and reservoir.
  - Establish areal connectivity and the variation in reservoir quality.
  - Identify contrasting lithologic zones (high versus low permeability streaks).
  - Identify reservoir boundary conditions (e.g., sealing versus non-sealing faults, sand continuity toward neighboring areas, aquifer extent).
  - Distinguish between localized versus regional geologic features.

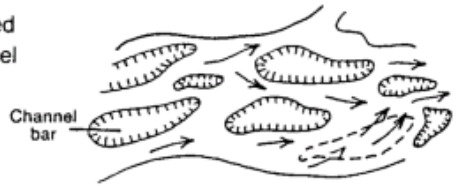
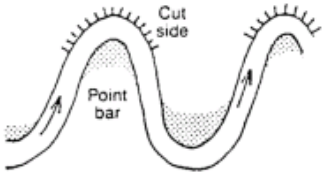
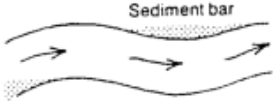
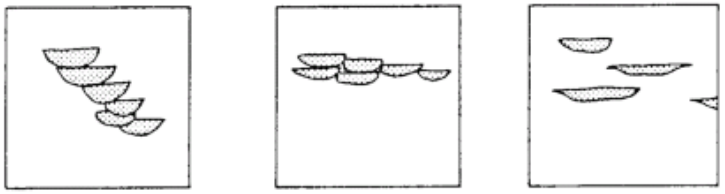
Reservoir Simulation Applied Modeling

Reservoir Characterization

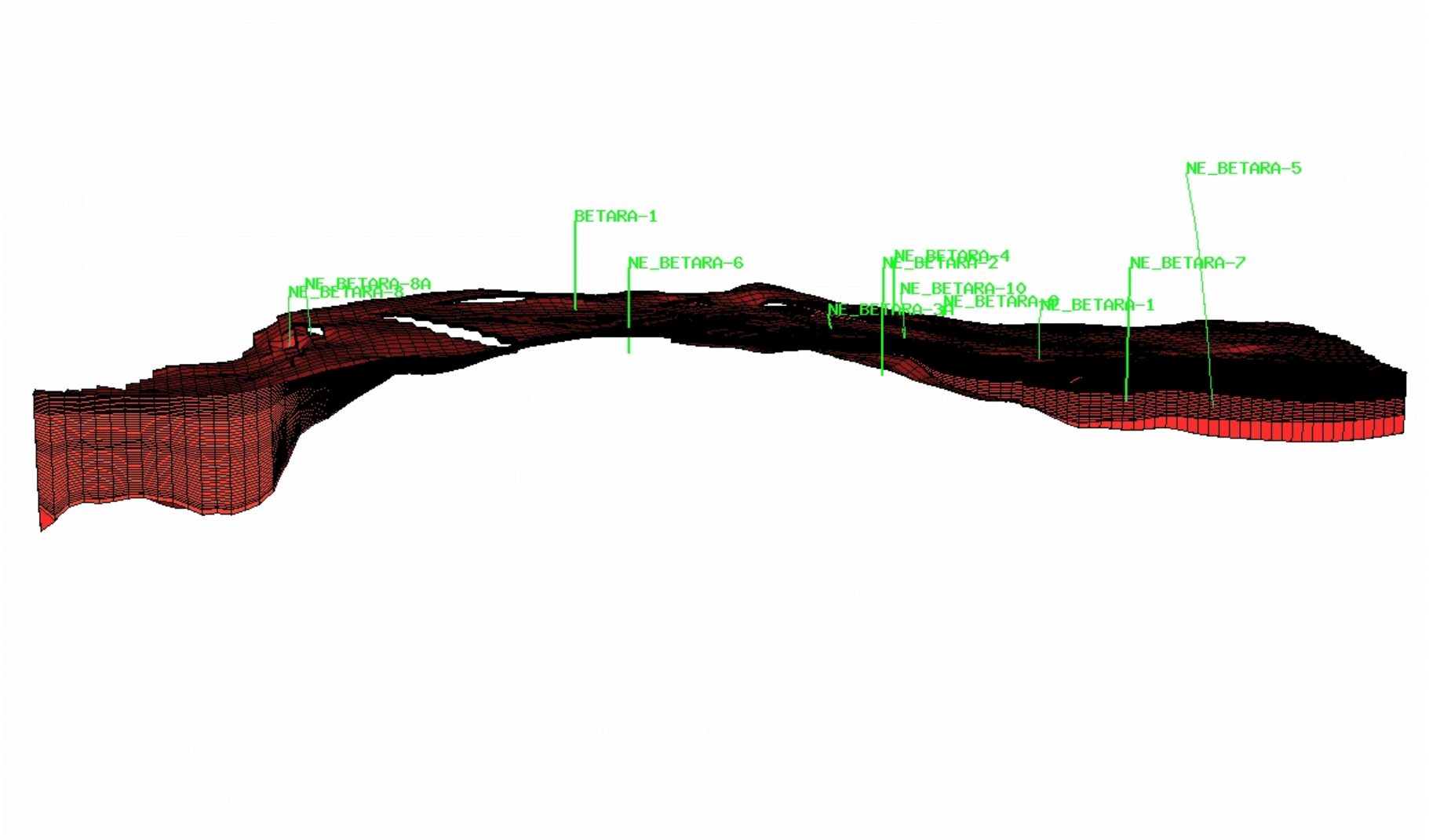


Reservoir Simulation Applied Modeling

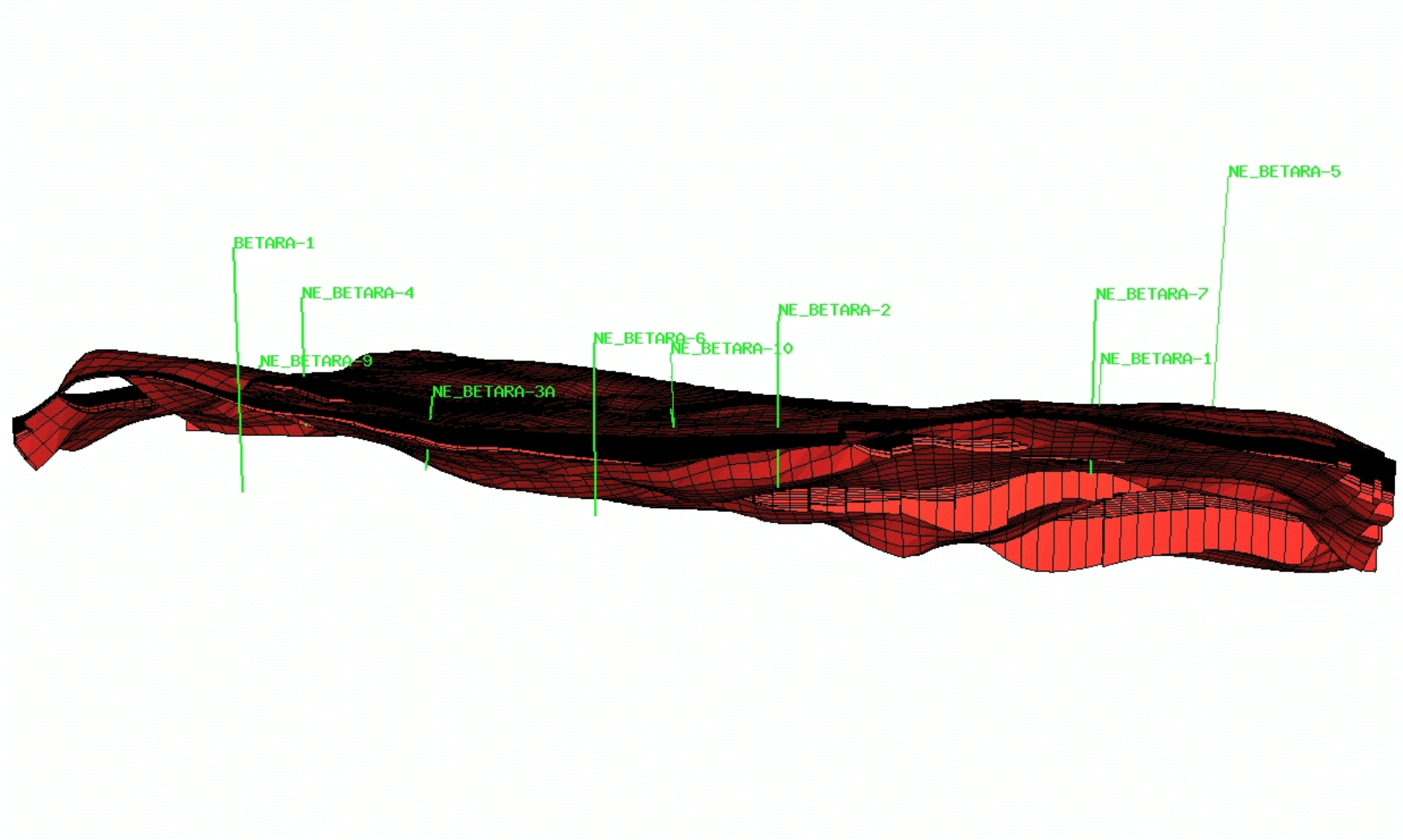
Reservoir Characterization

Single channels	*Appearance*	*Dimensions*	*Reservoir potential*
Braided channel		Typically upstream part of flood plain; thickness up to 50', width ½ mile to 8 miles, length may be hundreds of miles.	Excellent
Meandering channel		Typically downstream part of flood plain, 3–100' thick, multiple sands of meander belt may extend for many miles.	Excellent
Straight channel		Typically deltaic distributaries; 10–60' thick, 100–2000' wide, up to 10 miles long.	Fair to excellent depending on size
Coalesced channels	 *Vertical stacking (Map: belt)* *(Map: continuous sheet)* *Isolated stacking (Map: discontinuous sheet)*		Reservoir quality depends on size and stacking pattern.

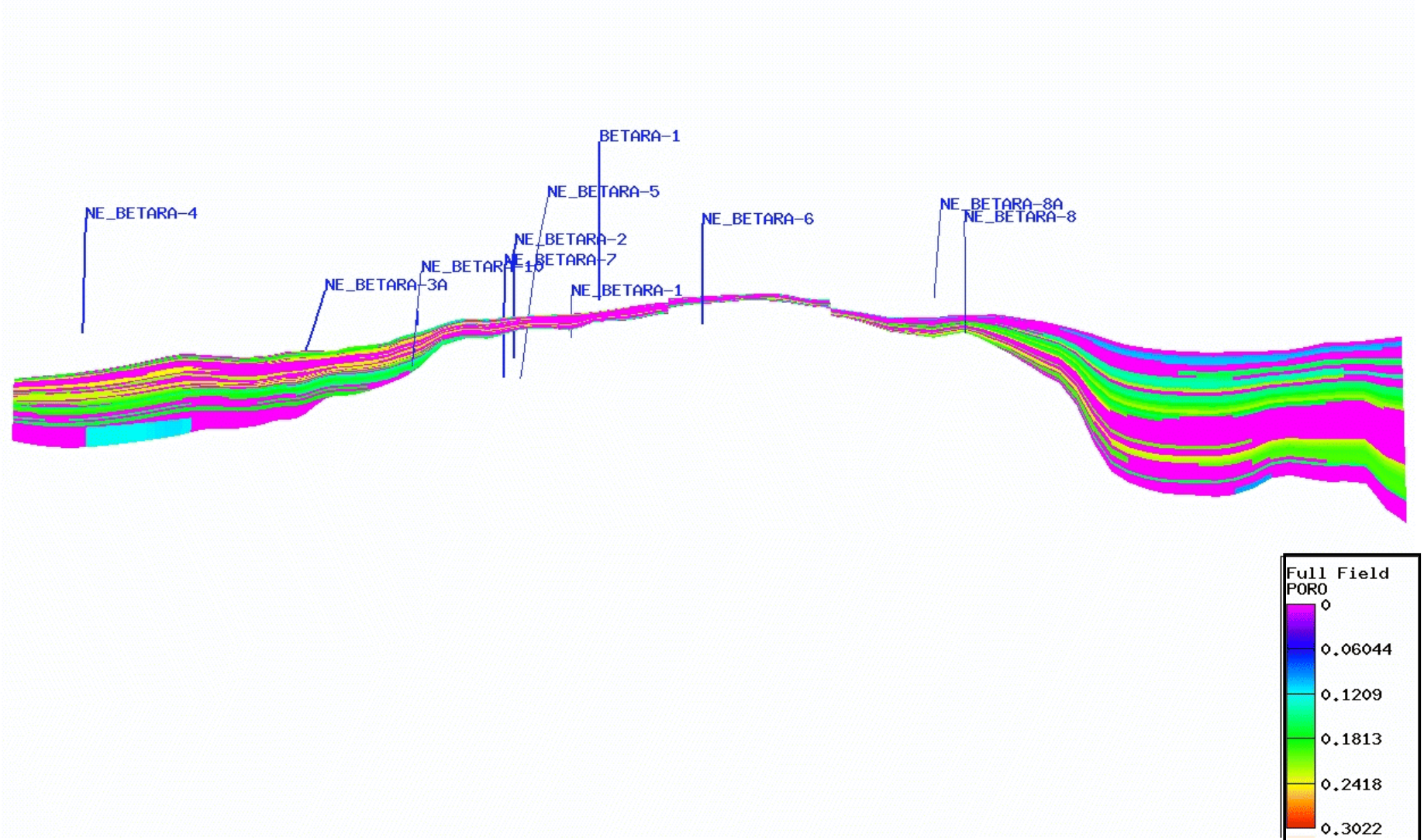
Reservoir Simulation Applied Modeling
Phase II Simulation Grid YZ Cross Section



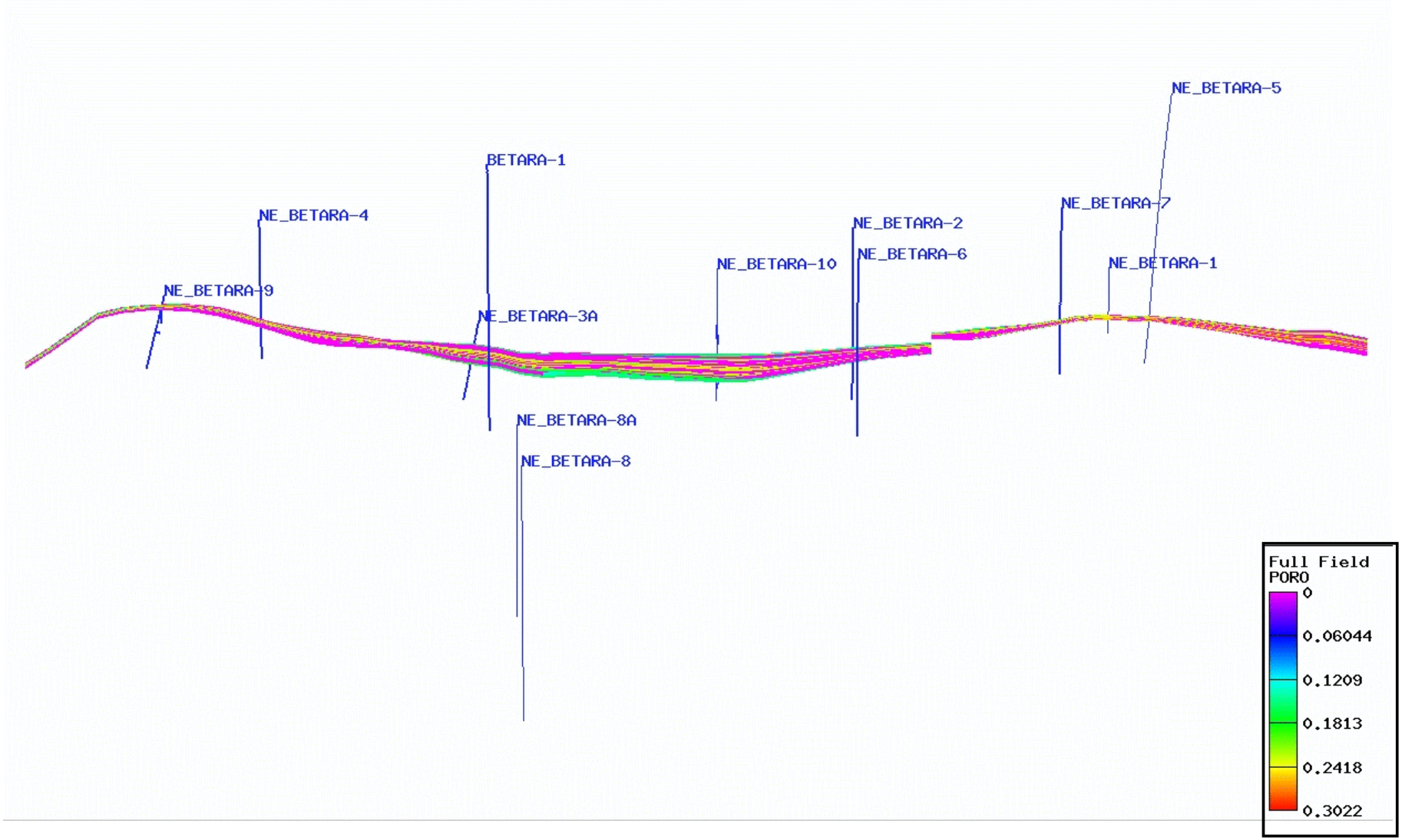
Reservoir Simulation Applied Modeling
Phase II Simulation Grid XZ Cross Section



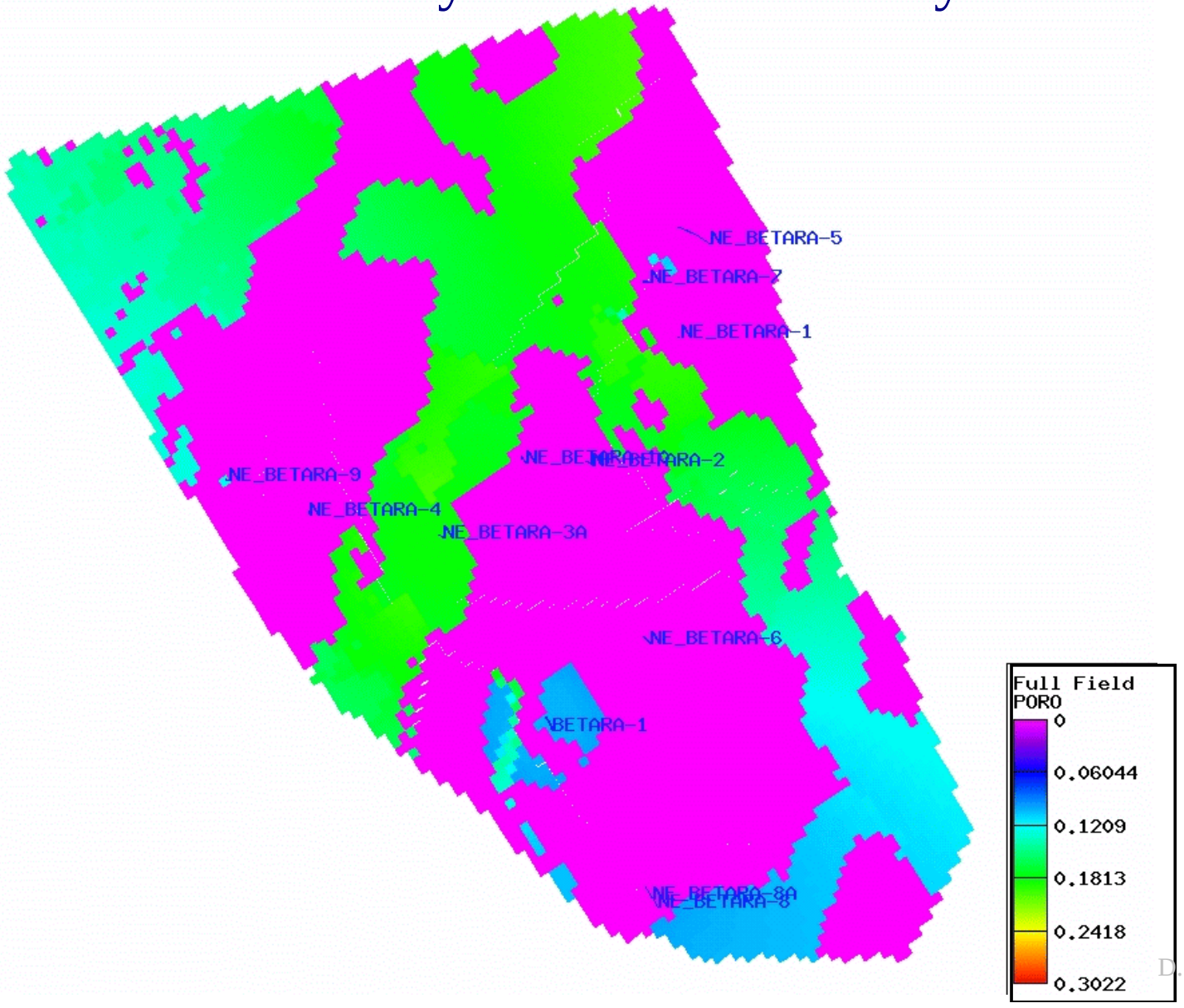
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution - YZ Cross Section



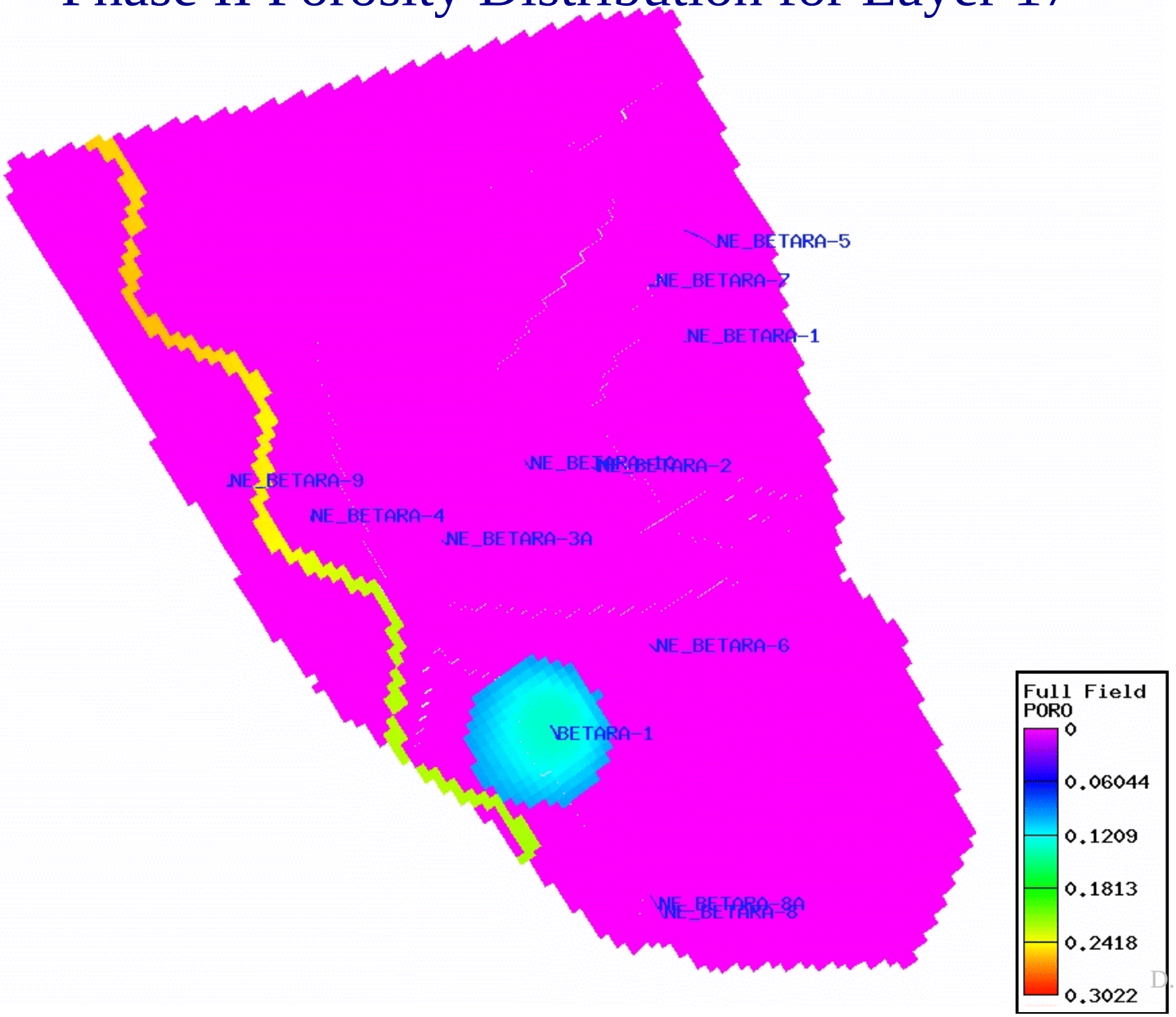
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution - XZ Cross Section



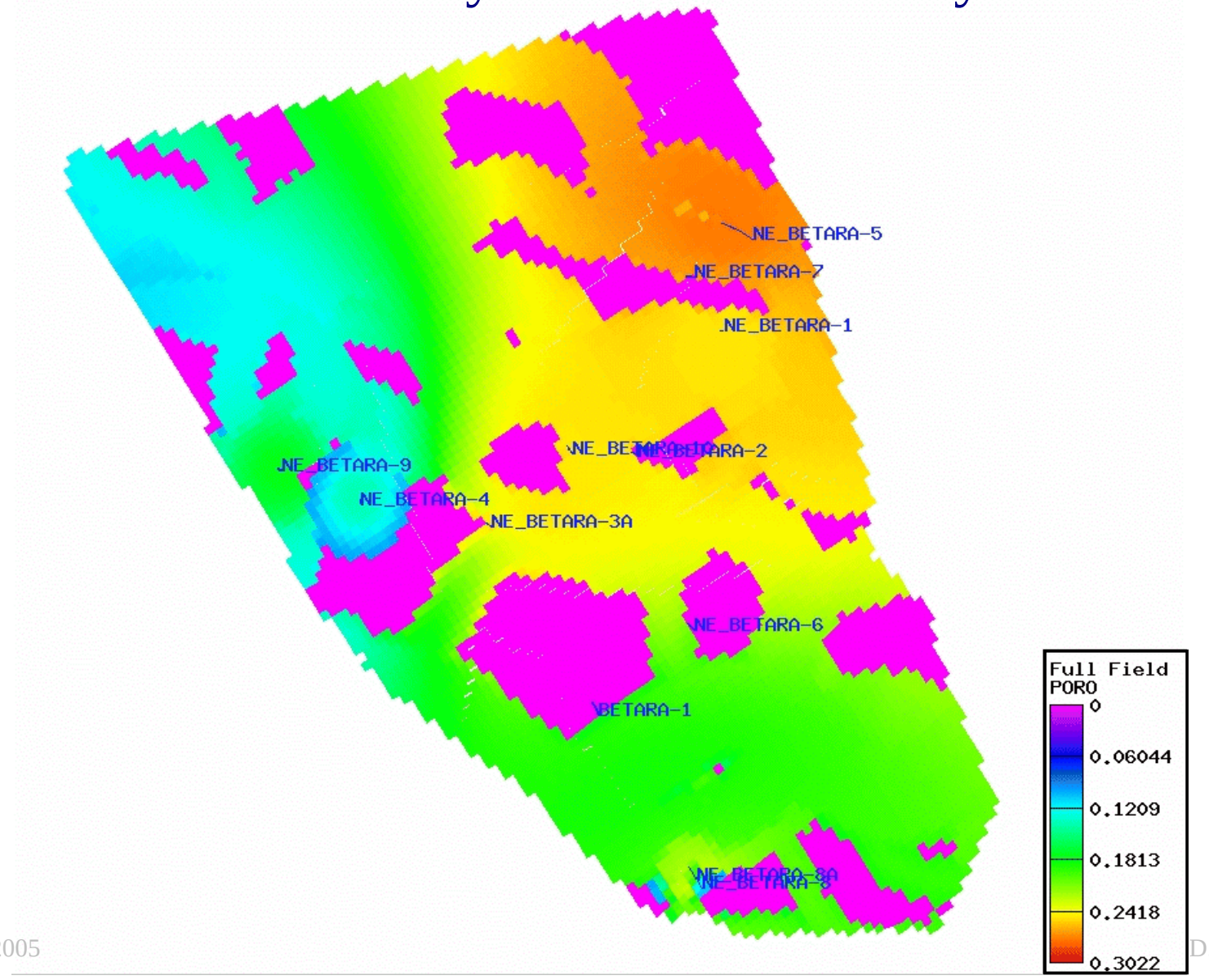
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 6



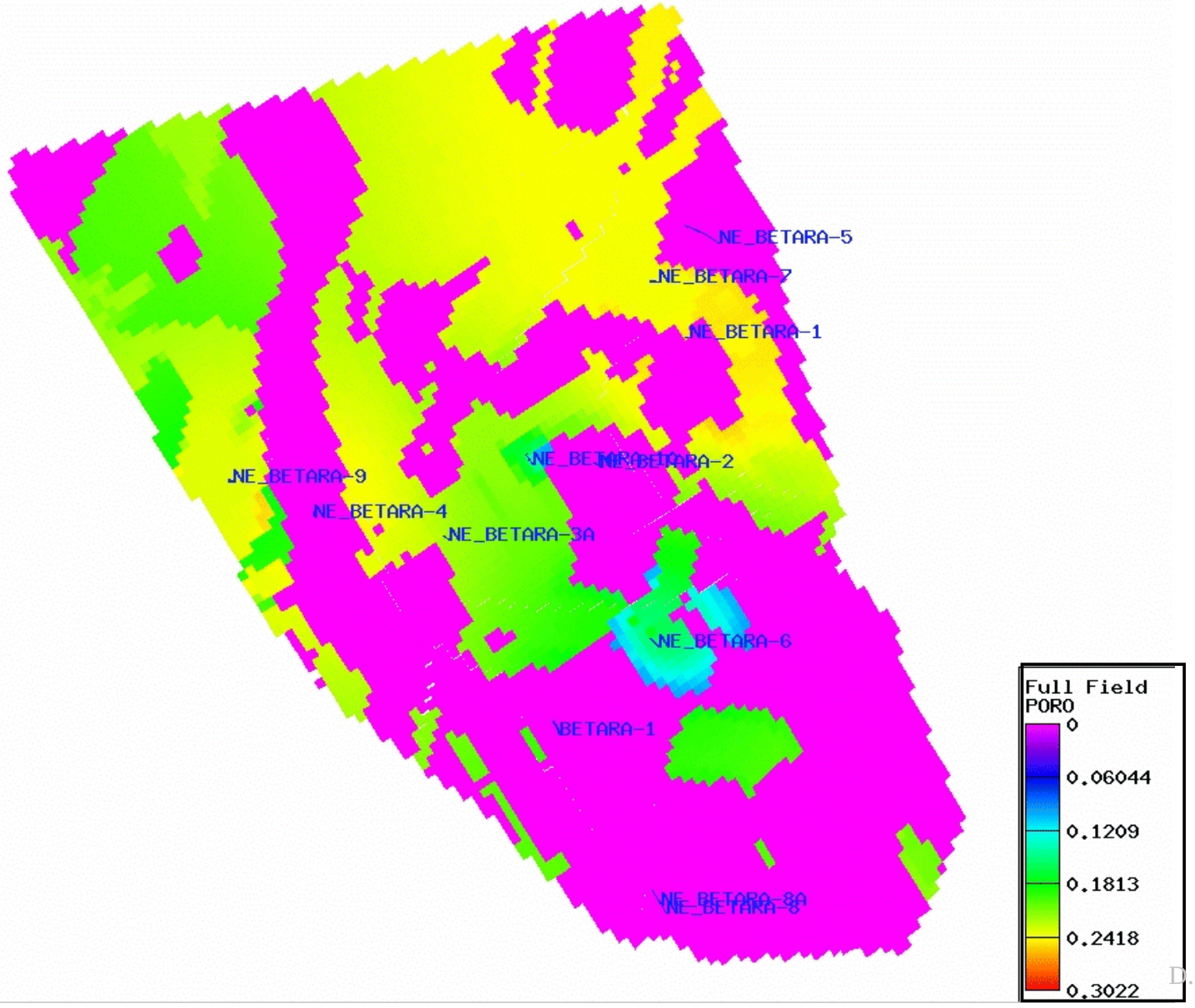
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 17



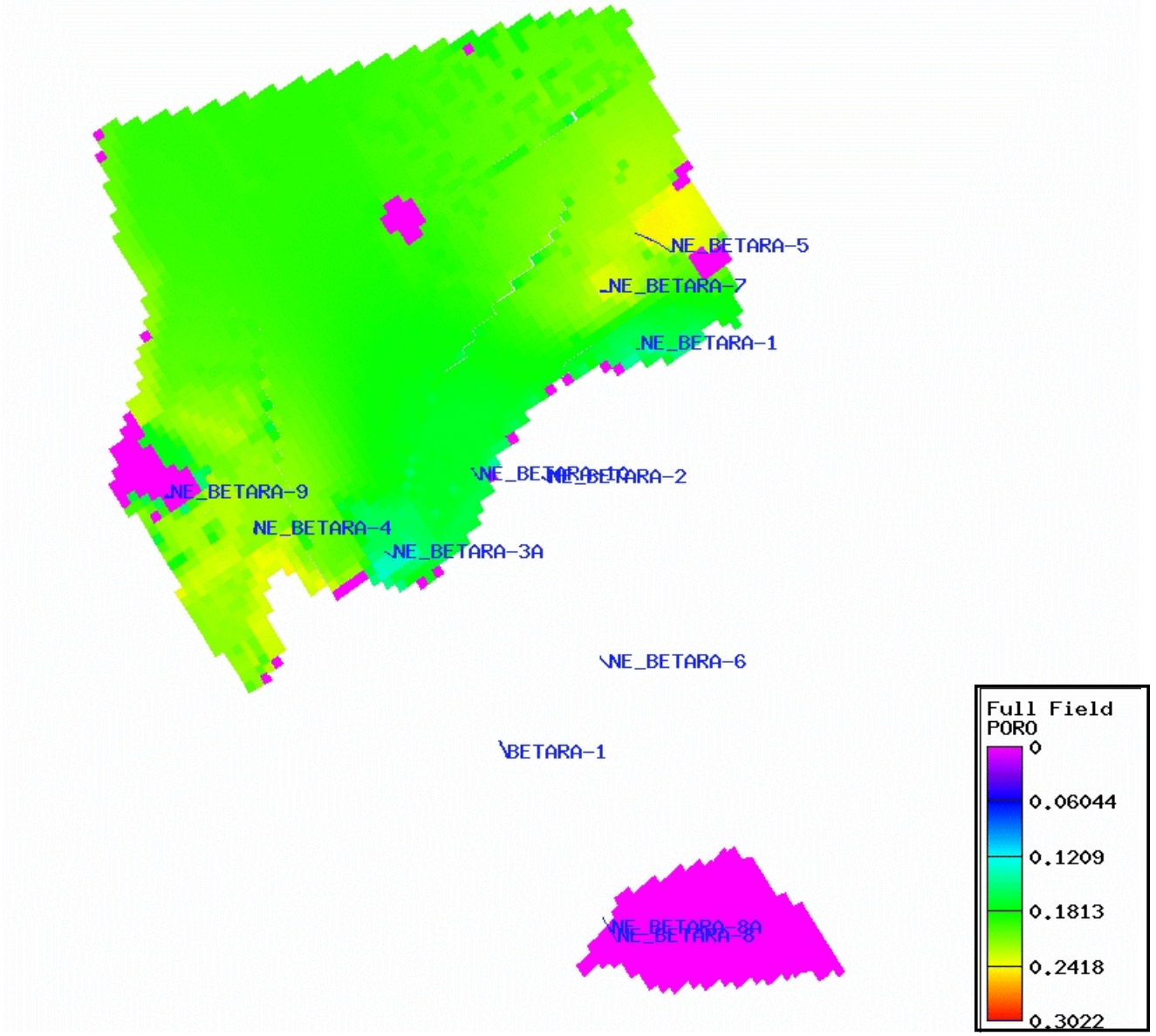
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 25



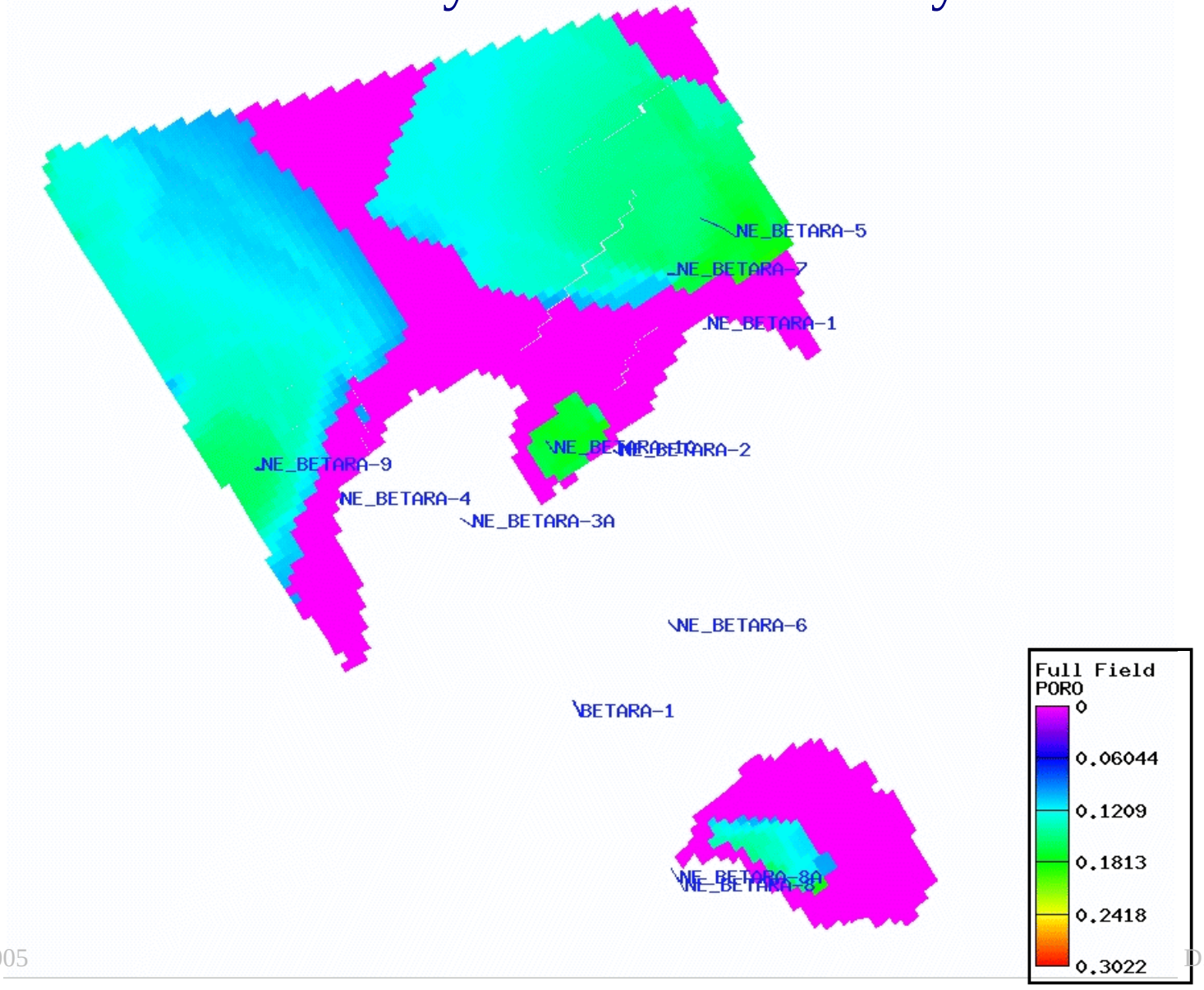
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 34



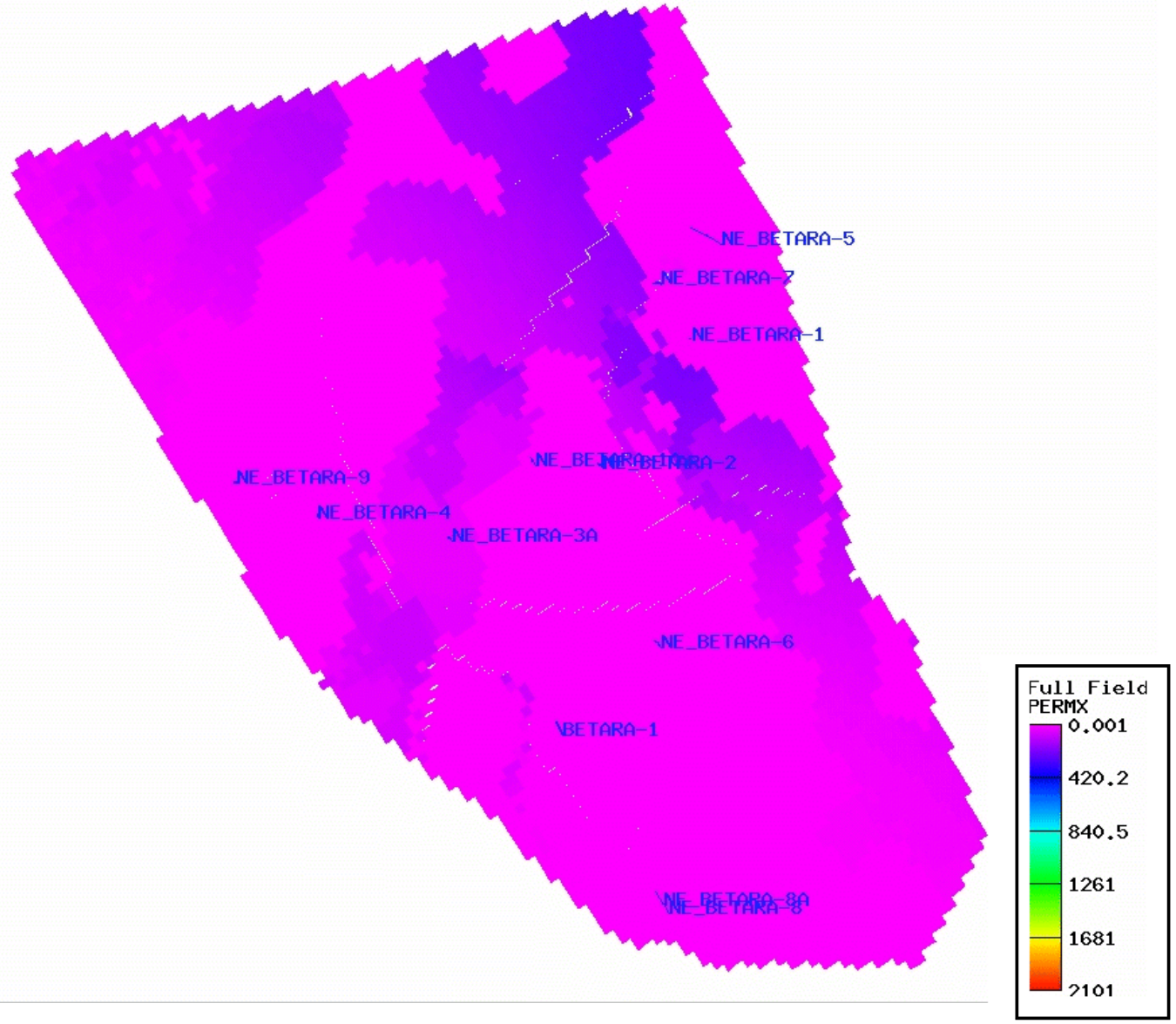
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 45



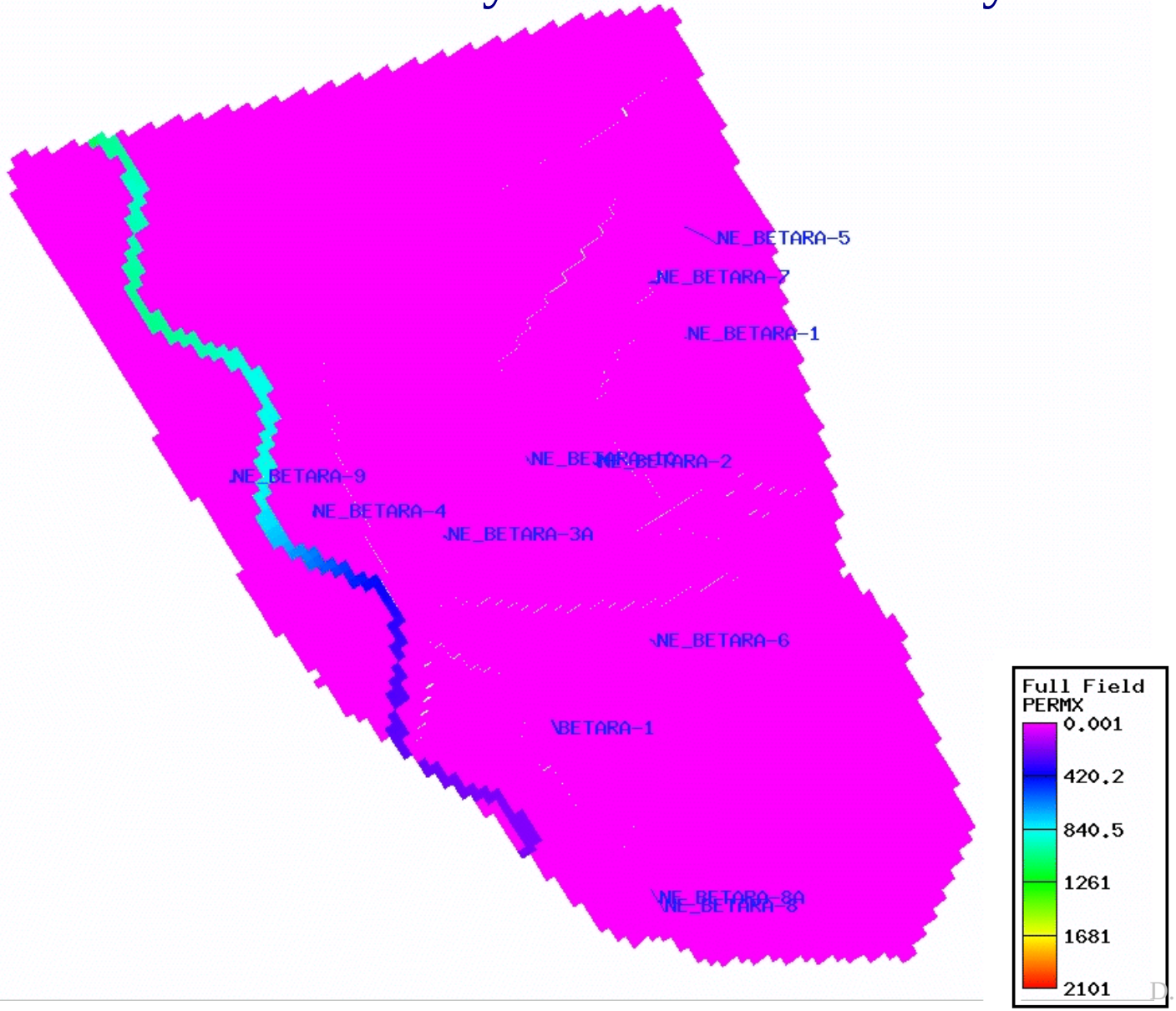
Reservoir Simulation Applied Modeling
Phase II Porosity Distribution for Layer 66



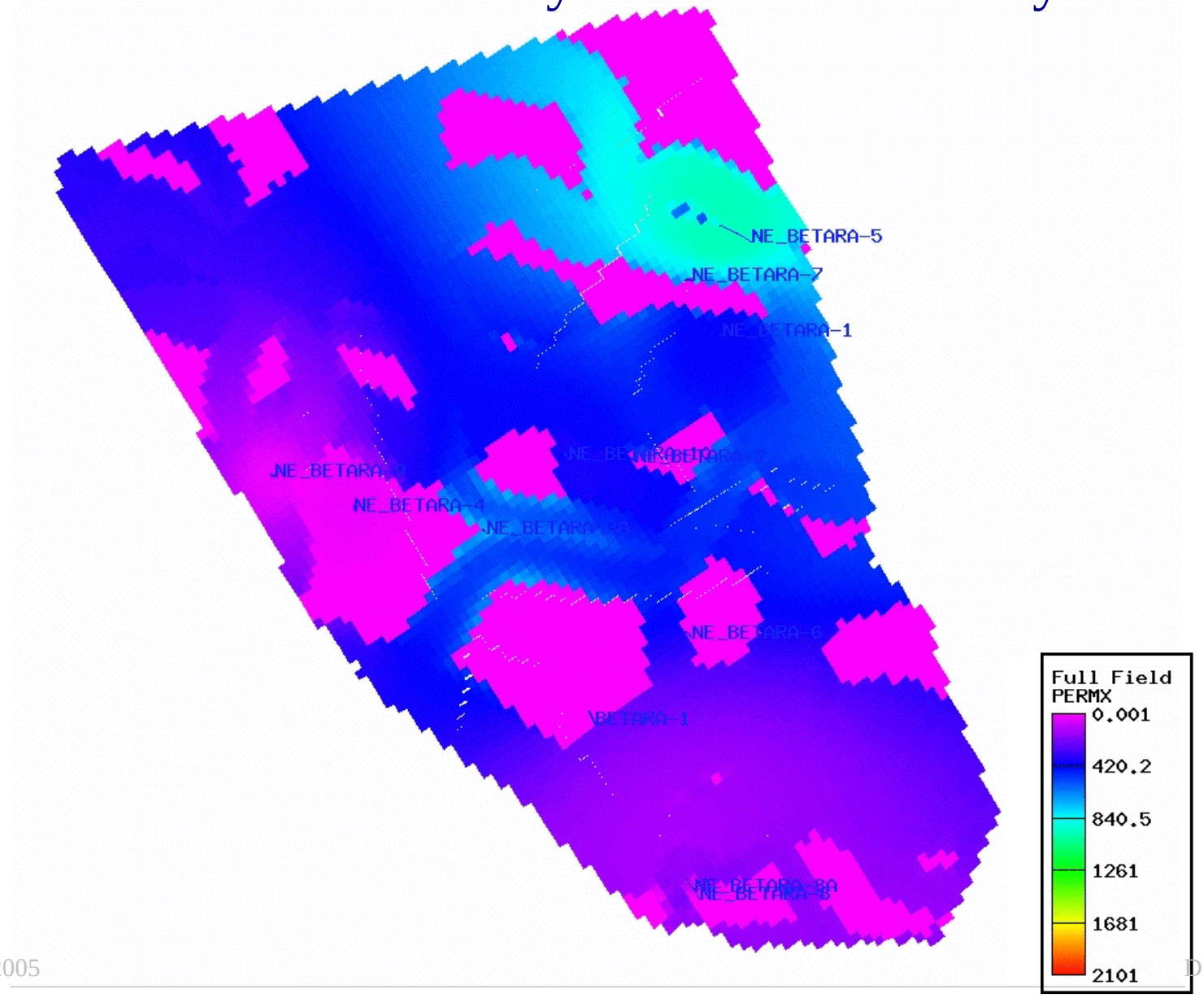
Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 6



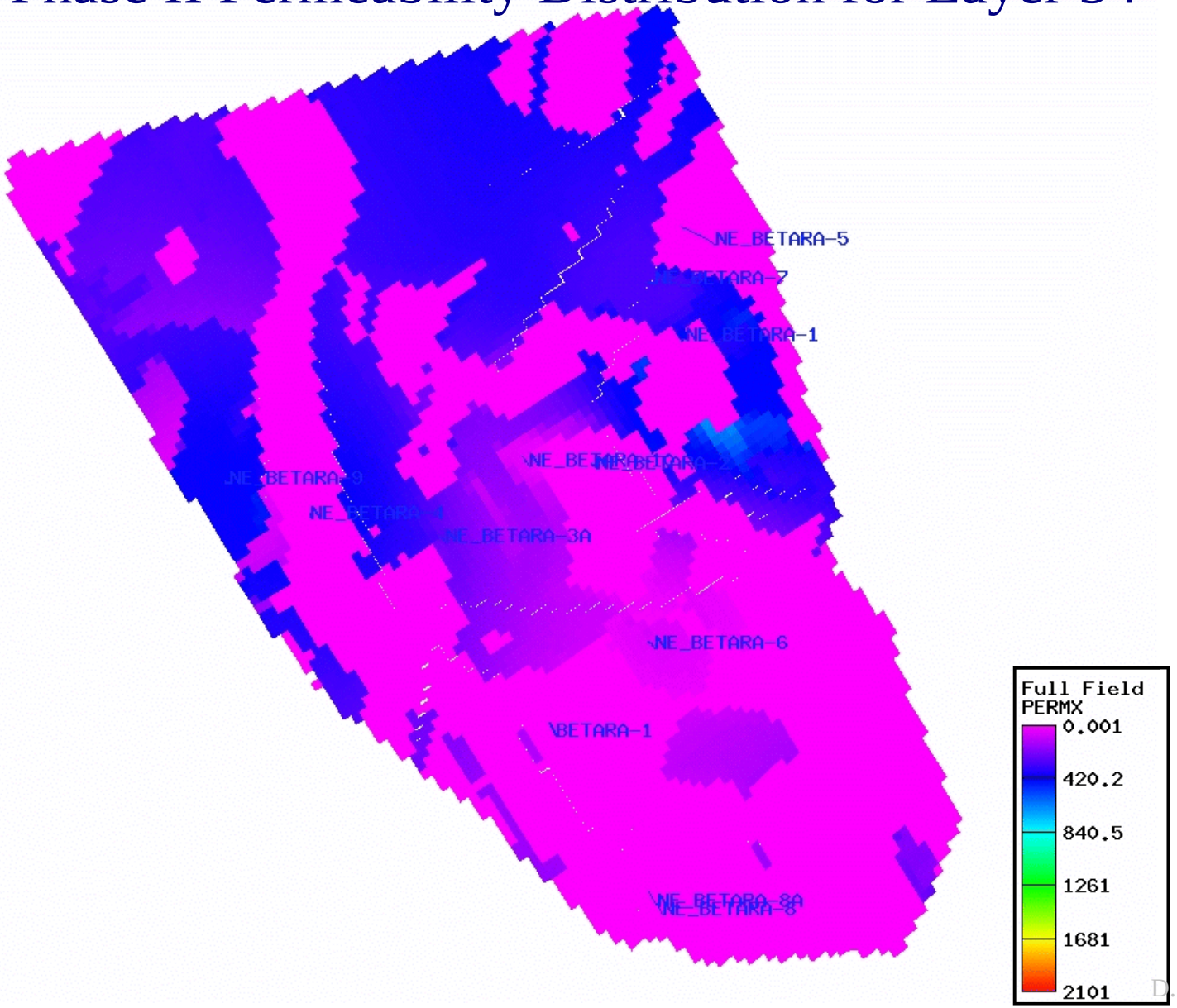
Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 17



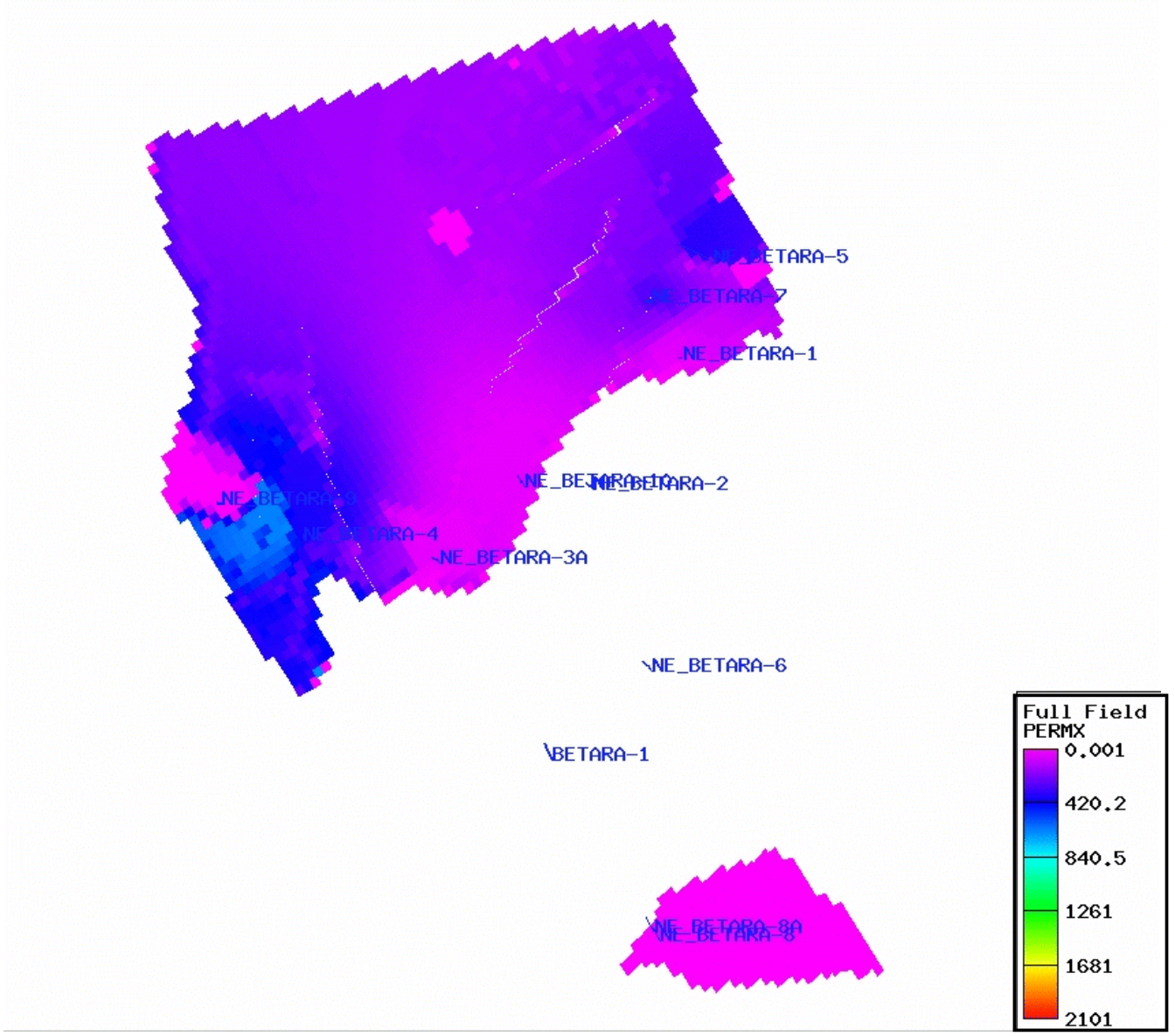
Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 25



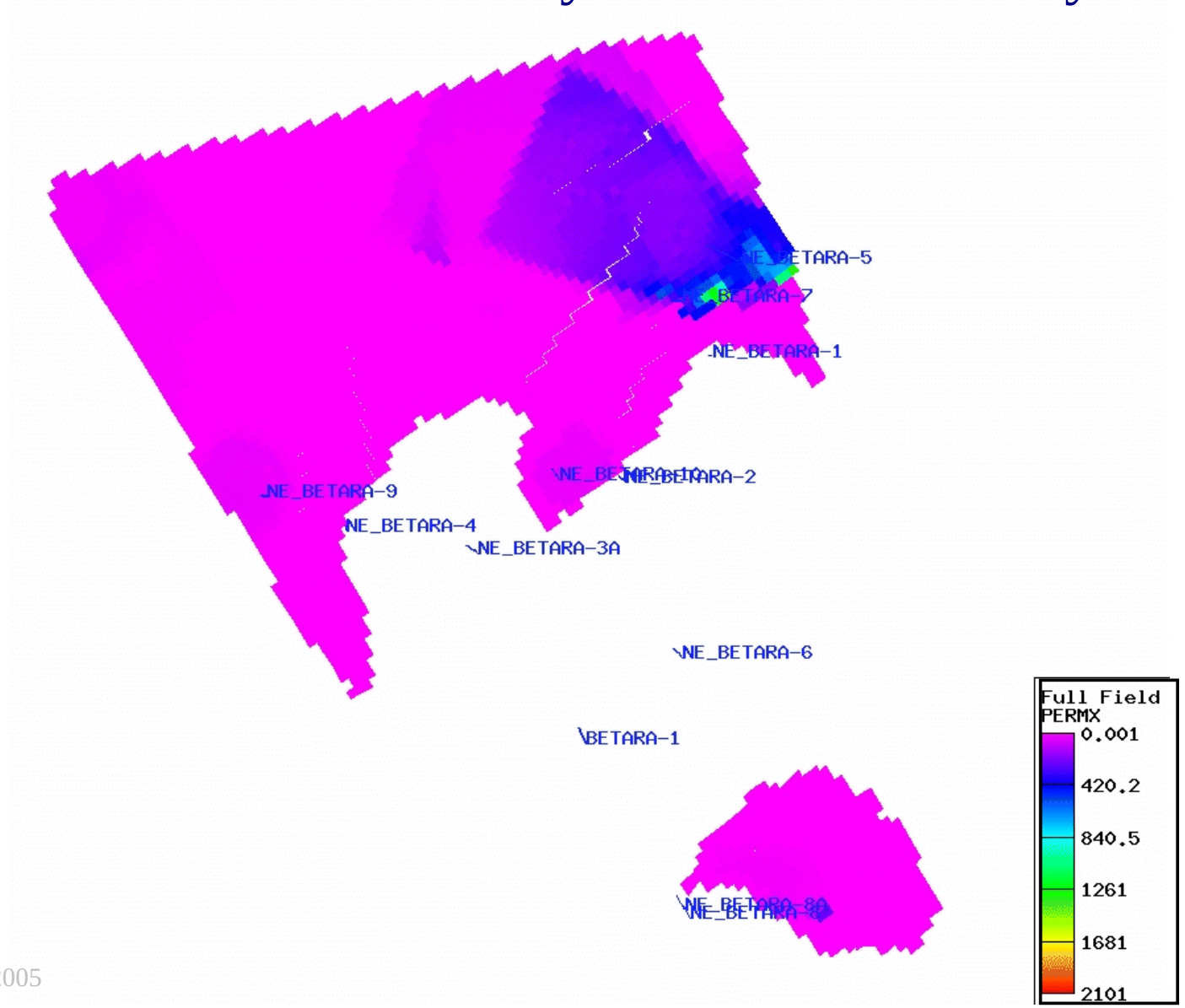
Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 34



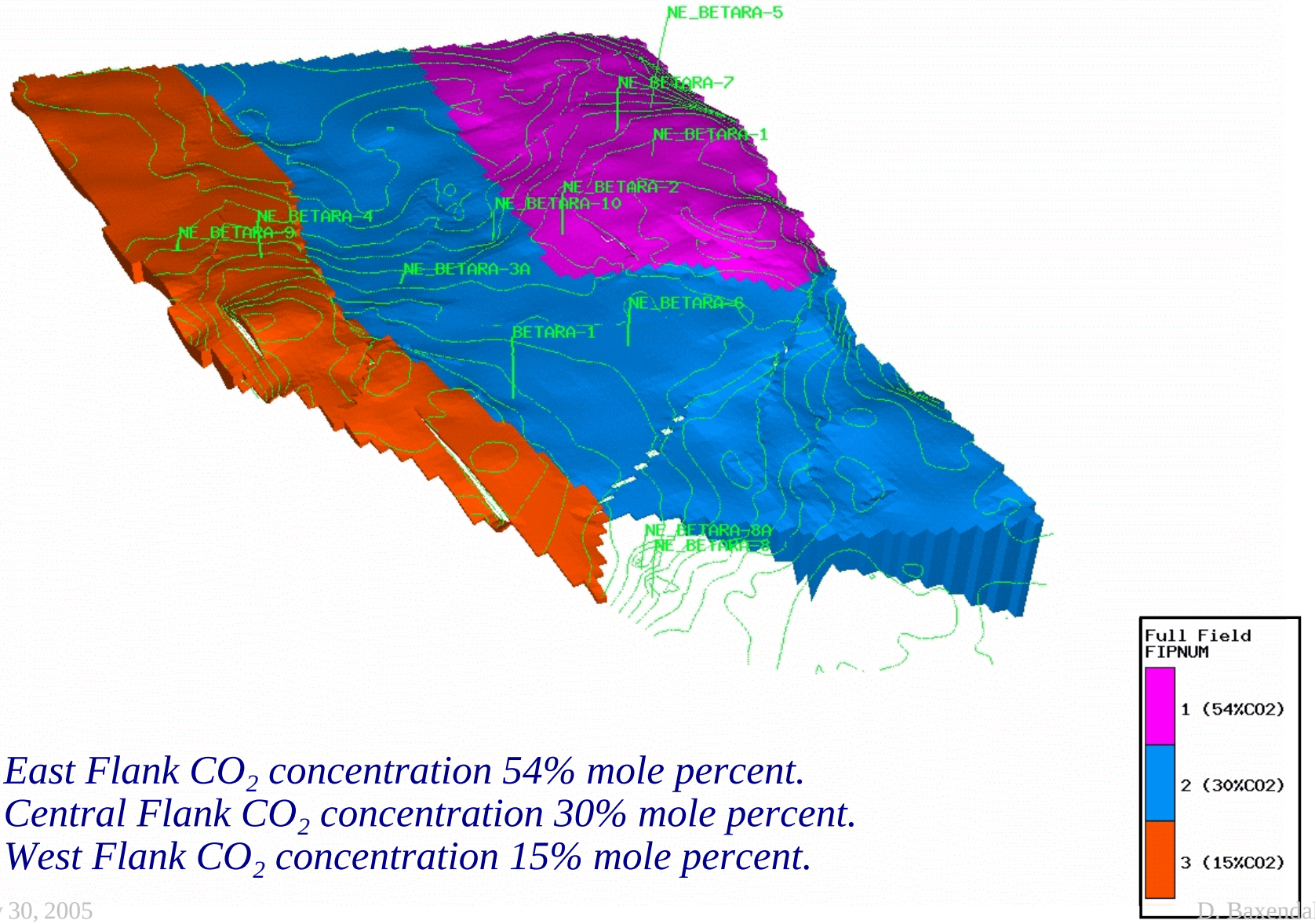
Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 45



Reservoir Simulation Applied Modeling
Phase II Permeability Distribution for Layer 66

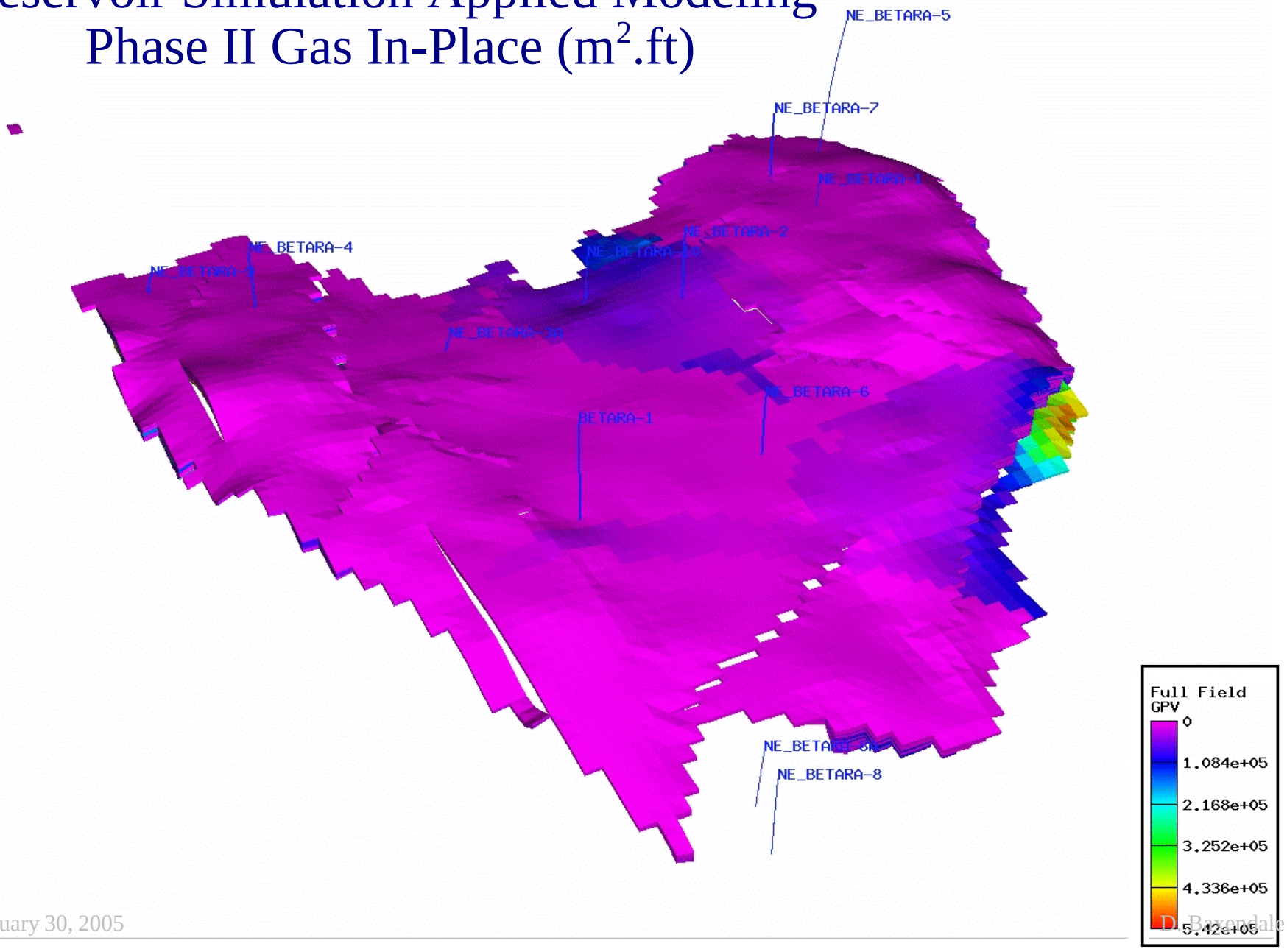


Reservoir Simulation Applied Modeling
Phase II CO_2 Areal Distribution

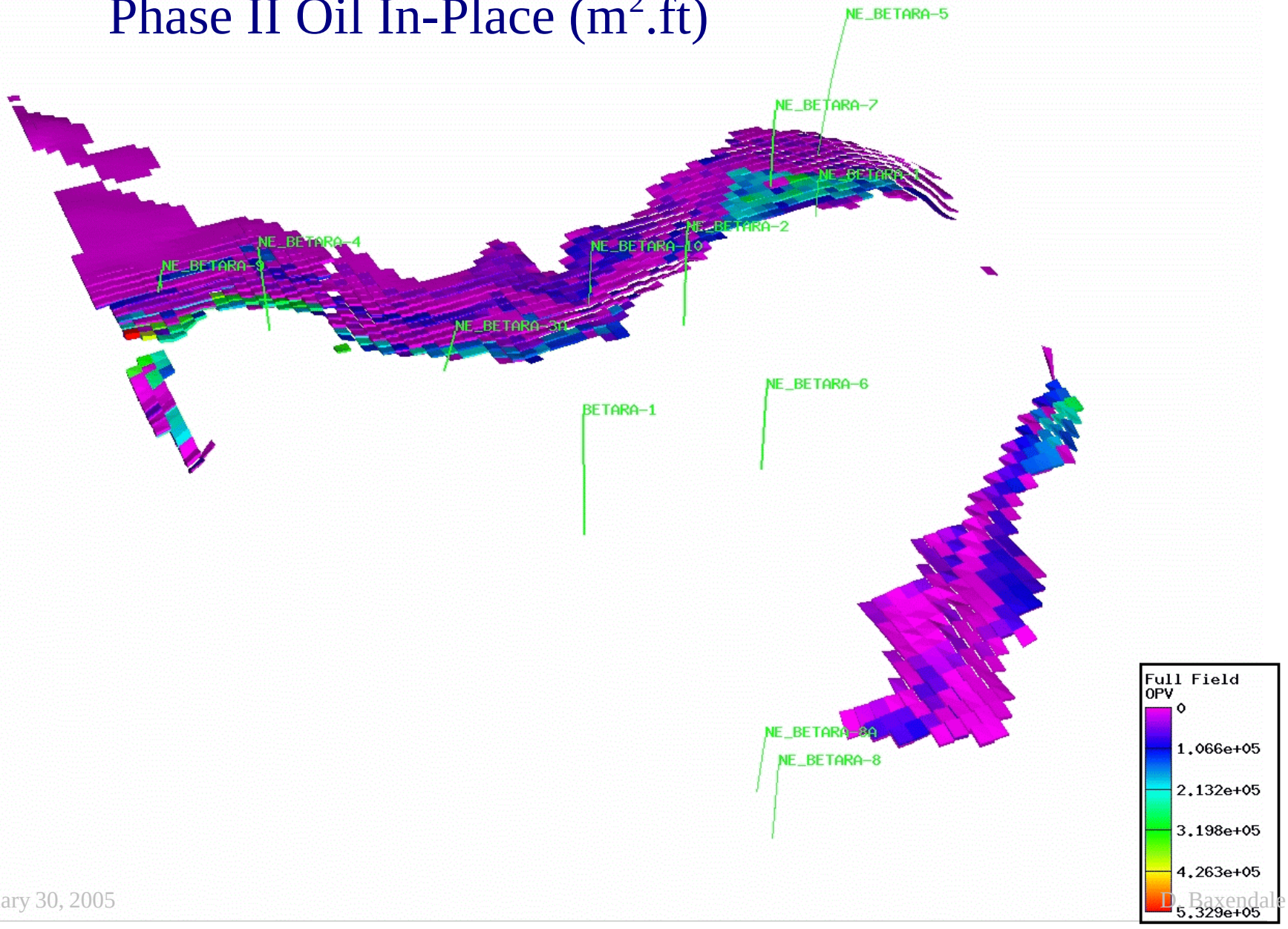


East Flank CO_2 concentration 54% mole percent.
Central Flank CO_2 concentration 30% mole percent.
West Flank CO_2 concentration 15% mole percent.

Reservoir Simulation Applied Modeling
Phase II Gas In-Place (m^2.ft)



Reservoir Simulation Applied Modeling
Phase II Oil In-Place (m^2.ft)



Reservoir Simulation Applied Modeling

Reservoir Characterization

- What is expected from a geologic model for reservoir simulation is a 3-D version of the same schematics.

- The six features noted above directly affect reservoir performance. To the degree that they are known, one may speak of a complete geologic model. Very often available data do not permit full resolution of items "1" through "6". If so, the task is to identify the areas where uncertainties exist and explore their impact on the study results through sensitivity analyses.

- History-matching offers limited possibilities in enhancing RC. The non-unique aspect of the process excludes its use as a definitive criteria, although qualitative assessments can certainly be made.

Reservoir Simulation Applied Modeling

Reservoir Characterization

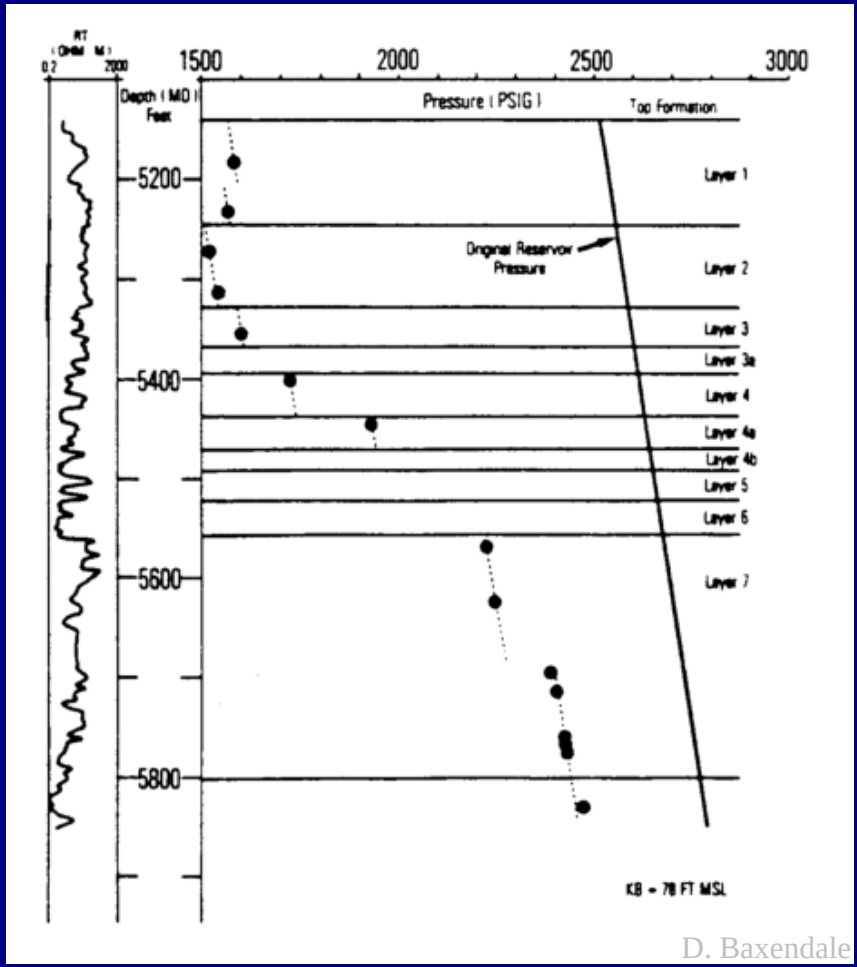
- Often reservoirs are layered based on time stratigraphic markers. Geological properties (i.e., S_w, k) are then mapped within each stratigraphic layer. However, the non-reservoir portion of the rock is also important in determining the in-situ flow performance of reservoirs.

- The areal and vertical communication (within and between layers) can be deduced from these maps when used as adjuncts to other tools such as Repeat Formation Tests (RFT).

Reservoir Simulation Applied Modeling

Reservoir Characterization

- Example
  - The lithology in the reservoir is quite varied and consists of limestone, dolomite, sandy dolomite, sandstone and shale. The presence of large pressure differentials indicates a very stratified reservoir system.



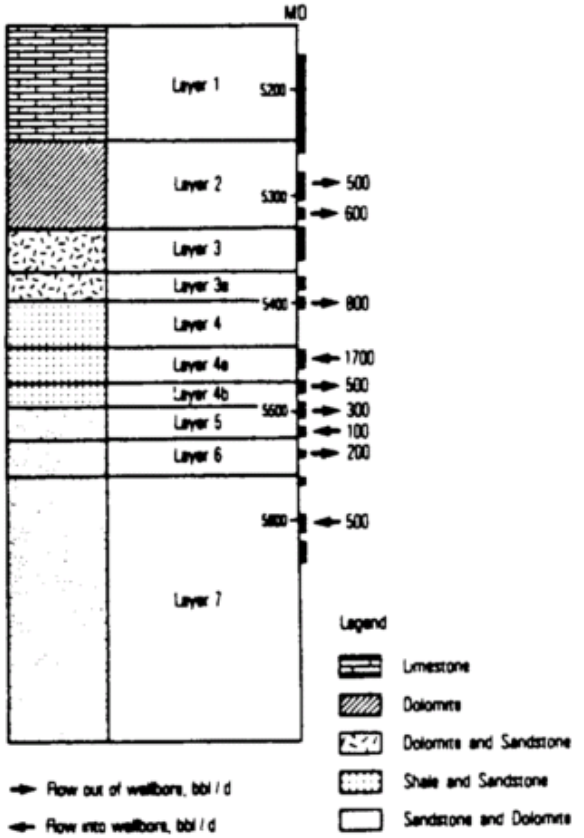
D. Baxendale

Reservoir Simulation Applied Modeling

Reservoir Characterization

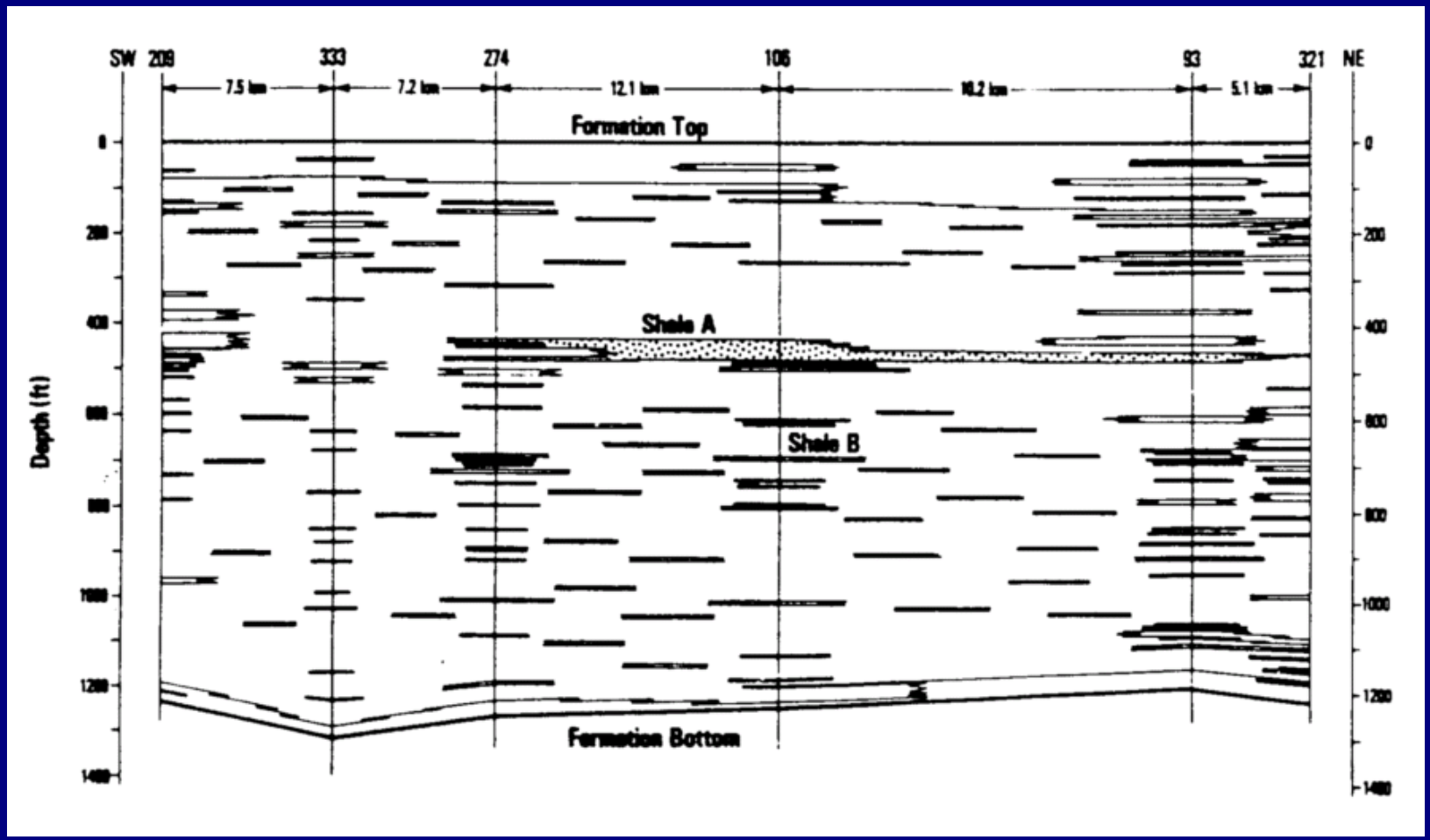
A spinner survey on the same well also indicates significant amounts of cross-flow, further supporting the vertical non-communication among geologic layers (in effect, zero vertical permeability).

This example shows the useful role engineering data, such as provided through RFTs and spinner surveys, can play in RC.



Reservoir Simulation Applied Modeling

Reservoir Characterization

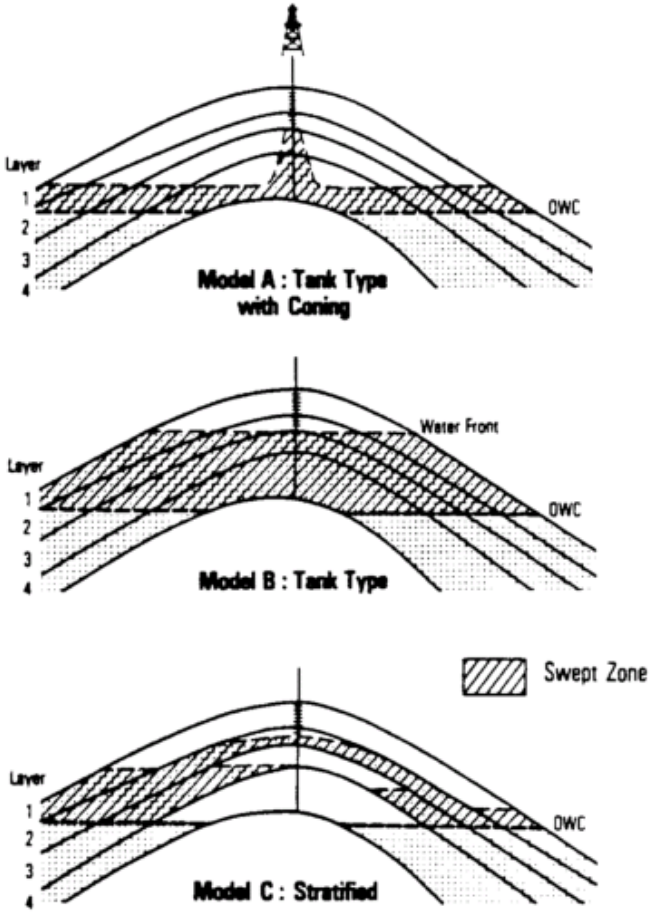


Reservoir Simulation Applied Modeling

Reservoir Characterization

The second objective of RC is to identify the main encroachment mechanisms of the reservoir. This is important since it will affect the model selection process.

Three alternative encroachment mechanisms are shown for a four-layer reservoir. A complete RC for this system should point to the right alternative which in turn will simplify the model selection. The point is that an understanding of the basic reservoir mechanisms must precede the numerical phase of the study.



D. Baxendale

Reservoir Simulation Applied Modeling

Reservoir Characterization

The third objective of RC is reservoir volumetric determination. Two emerging techniques in RC appear promising.

- Geostatistics

  Kriging which provides a minimum error-variance estimate of any unsampled data; however, has the tendency to smooth out details and extreme values of the original data set. Has several general forms: Simple Kriging, Ordinary Kriging, Kriging with a Trend Model, Kriging with an External Drift, Factorial Kriging, etc.

  Stochastic Simulation which builds alternative, equally probable, high resolution models of spatial data. The simulation is considered conditional if the resulting realizations honor the data values at their locations. Again numerous forms are available: Gaussian Simulation, Sequential Indicator, Boolean Simulation, Simulated Annealing etc.

- Seismic methods

  These diverse approaches hold the potential to significantly improve the quality and completeness of RC for reservoir simulation, particularly when used as adjuncts to (as opposed to substitutes for) other geologic and engineering data.

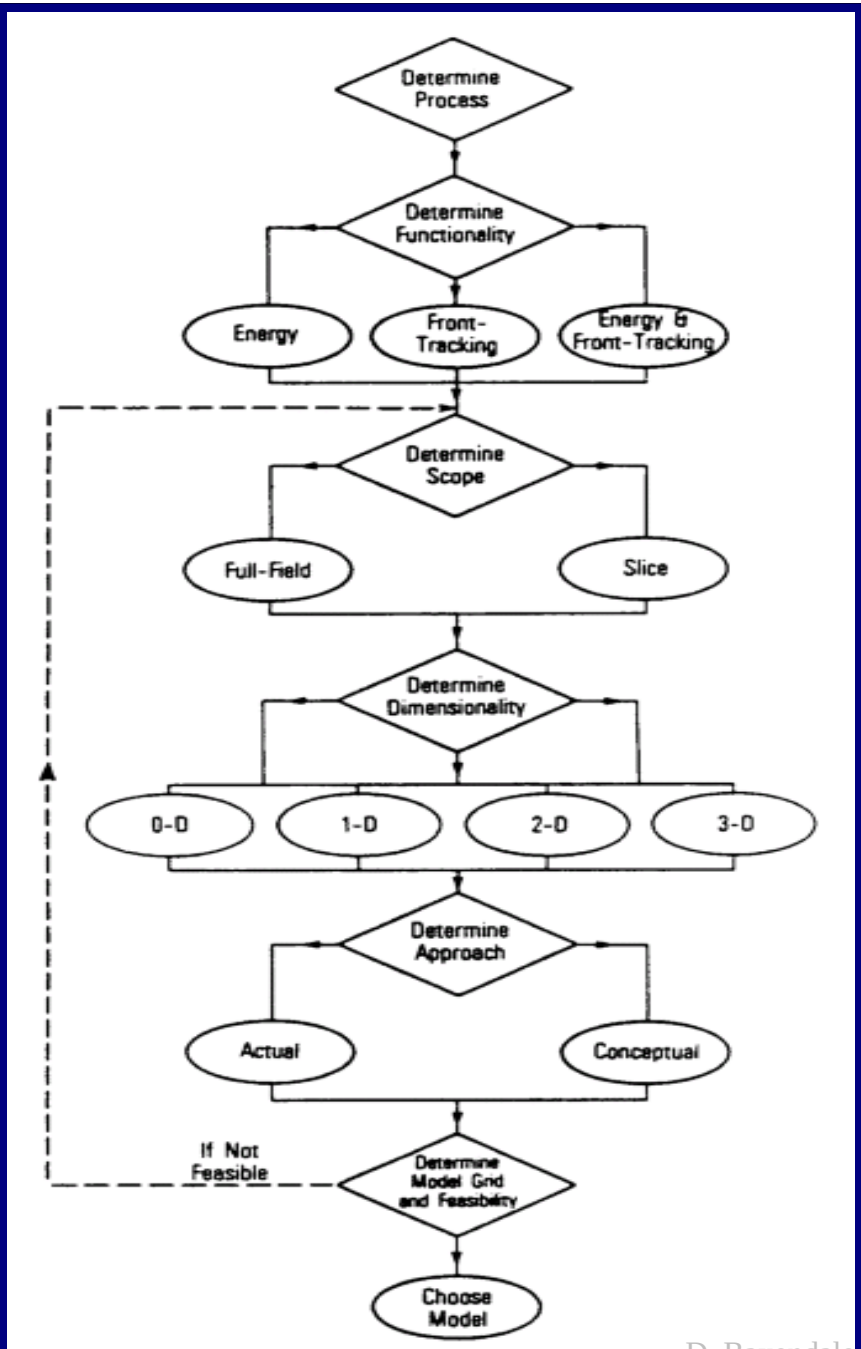
Reservoir Simulation Applied Modeling

Model Selection

- "What simulation model is best suited to meet our objectives?"
- The answer lies in a systematic model selection process, which can be grouped under six main headings, each describing a facet of modeling:
  - Process
  - Functionality
  - Scope
  - Dimensionality
  - Approach
  - Grid Selection

Reservoir Simulation Applied Modeling

Model Selection



Reservoir Simulation Applied Modeling

Model Selection - Process

- As shown a total in the next few slides there are 48 modeling possibilities available once the process (e.g., immiscible, miscible, thermal) is identified. Each choice has certain advantages and disadvantages.

	Advantages	Disadvantages	Suitable for Reservoirs/Models Where:	Unsuitable for Reservoirs/Models Where:
Energy	Simplicity of approach	Lacks accurate computation of phase saturation distribution	Material balance and pressure calculations in time are important	Saturation distributions in time are important (e.g., in-fill drilling, workover planning individual well performance)
Front-Tracking	Simplicity of approach	Requires very fine griding	Phase saturation tracking in reservoir is important	Large scale field studies
Energy / Front-Tracking	Allows accurate computation of reservoir pressures and phase saturations	Complexity of approach relative to energy and front-tracking models	Energy and phase saturation distributions in time are important	

- Most Reservoir Engineering problems fall into the third category, since engineering decisions require a knowledge of both energy and saturation with respect to time

Reservoir Simulation Applied Modeling

Model Selection - Functionality

- The next and most important step after the process selection is to define the overall function of the model based on the objectives under consideration.
  - Energy Models
    - *Primarily aimed at computation of reservoir pressures.*
  - Front-Tracking
    - *Used to track the phase distribution of reservoir fluids.*
  - Energy & Front-Tracking
    - *Are used to compute both reservoir pressures and fluid saturation distributions in time.*
- Most reservoir engineering problems fall in the third category, since engineering decisions require a knowledge of both energy and saturation with respect to time.

Reservoir Simulation Applied Modeling

Model Selection - Functionality

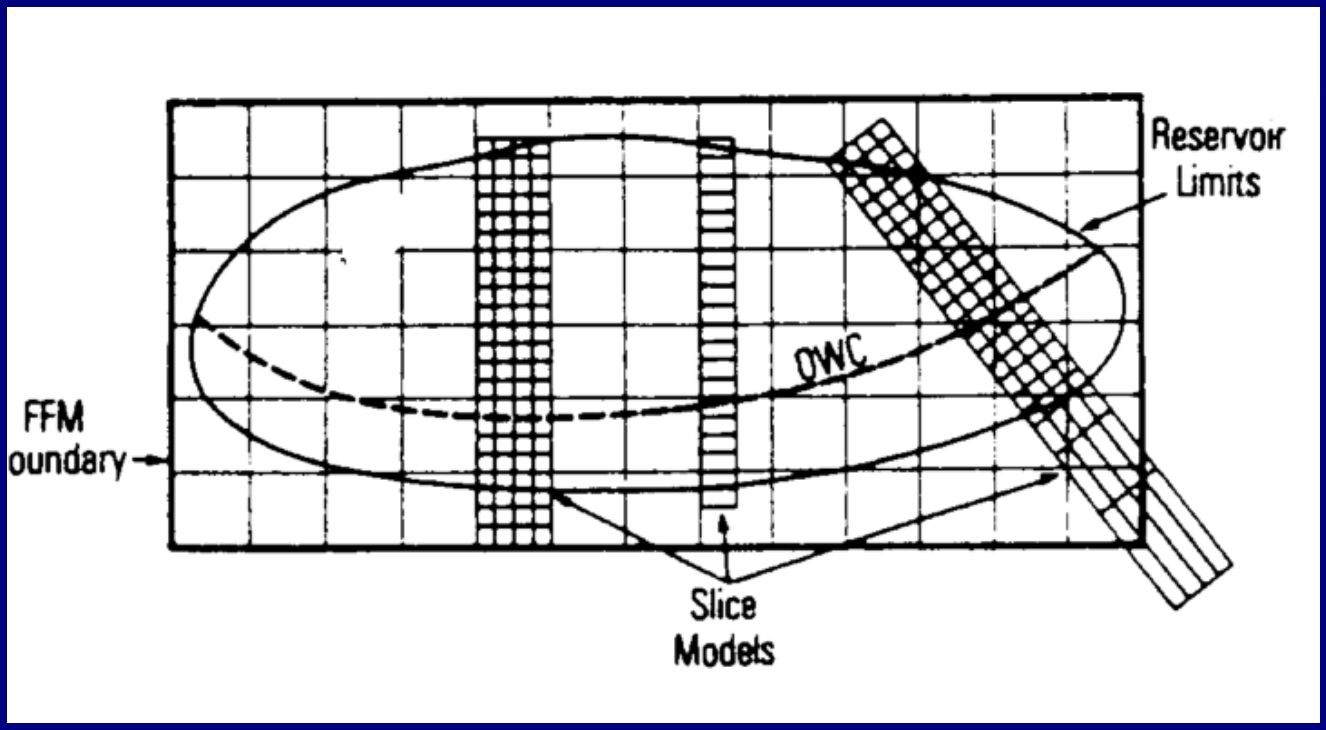
However, there is a sizeable class of problems where only one of the two aspects is important. Some typical applications under each category are given below.

Type of Model	Example
Energy	Estimation of STOIIP/GIIP. Material balance computations.
Front-Tracking	Determination of critical well coning rates. Pattern-flood studies. Workover and re-completion evaluation studies. Development of inter-block relative-permeability curves for coarse-grid models.
Energy & Front-Tracking	Estimation of pressure and production forecasts. Determination of drilling, workover and artificial-lift requirements. Evaluation of primary and secondary recovery programs and field development plans.

Reservoir Simulation Applied Modeling

Model Selection - Scope

The next decision involves determining the model boundaries. Generally, there are two choices : Sector or Slice Models and Full-Field Models (FFM) .



Reservoir Simulation Applied Modeling

Model Selection - Scope

- Slice Models (SM)
  - SMs represent only a segment of the full reservoir and, therefore, require two very important assumptions :
    - *Fluxes across the SM boundaries are known or can be estimated.*
    - *Results from the SM can be accurately scaled up to the full field.*
- Full-Field Models (FFM) .
  - FFMs allow representation of the reservoir in its entirety, including neighboring fields. No assumptions need to be made regarding model-boundary fluxes.

In general, for Energy models where the main question concerns material balance, FFMs are the more appropriate model while SMs are more suited for Front-Tracking models because of the finer grid necessary to define the frontal movement.

Reservoir Simulation Applied Modeling

Model Selection - Dimensionality

Dimensionality can be 0-D, 1-D, 2-D, or 3-D depending on the objectives, and the reservoir mechanisms (e.g., coning, cusping) and flow attributes (e.g., stratification). Important questions to be answered are:

- How many dimensions does the reservoir exhibit in regard to in-situ flow performance (i.e., Are there areal as well as vertical effects?)
- Which dimensions are important to the objectives?

Functionality, dimensionality and model-grid size are so intricately related they cannot be determined independently, and hence the process is iterative.

Reservoir Simulation Applied Modeling

Model Selection - Approach

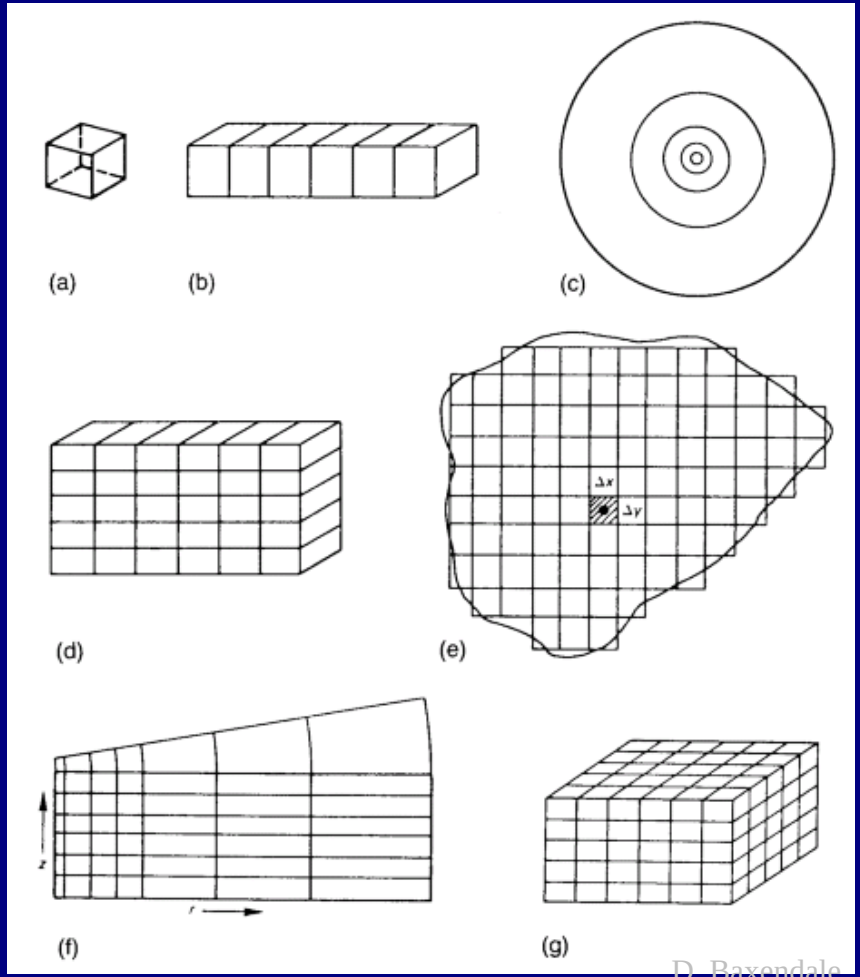
- Actual
  - Actual models represent the reservoir characteristics based on real data, and offer the possibility of validation of this data. Commensurate with increased data availability, the accuracy of simulation results can be improved. Most reservoir engineering problems are best suited for Actual models.
- Conceptual
  - Conceptual models use a more idealized version of real data to achieve a simpler representation of the reservoir, and thus offer limited validation, and the accuracy of model results is often untested. Their main utility lies in simple process evaluations and/or reservoir parameter sensitivity studies where validation is not critical to the integrity of the results.

Reservoir Simulation Applied Modeling

Model Selection - Grid

Functionality and dimensionality of the model and the well-spacing of the reservoir jointly define the resolution required (vertically or areally) for pressure and saturation computations.

The resolution dictates the number and coarseness of the cells. Because computer resources are limited, the grid determination is an iterative process balancing available computing capabilities and modelling needs.



Model Selection - Grid

A general classification of models based on grid size is given below :

Model Type	Areal Grid * Side Length (ft)	Vertical Cell Height (ft)
Very fine	1 to 50	0 to 10
Fine	50 to 300	10 to 30
Moderate	300 to 1000	30 to 50
Coarse	> 1000	> 50

* Square-shaped

Reservoir Simulation Applied Modeling

Model Selection - Grid

Note that consideration of Very-fine type models is possible only for moderately-sized fields (1000 acres or less). For instance, the grid requirements for a 10,000-acre, 100-ft-thick reservoir will be as follows :

Model Area (Acres)	Grid Size (ft x ft)	No. of Layers	Total No. of Cells
10,000	50 x 50	1	174,000
	50 x 50	10	1,740,000
	500 x 500	1	1,740
	500 x 500	10	17,400

Current PC computing capabilities limit black-oil models to roughly 1,000,000 active cells, with practical considerations reducing it further to 500,000 to 750,000 cells.

Reservoir Simulation Applied Modeling

Model Selection - Grid

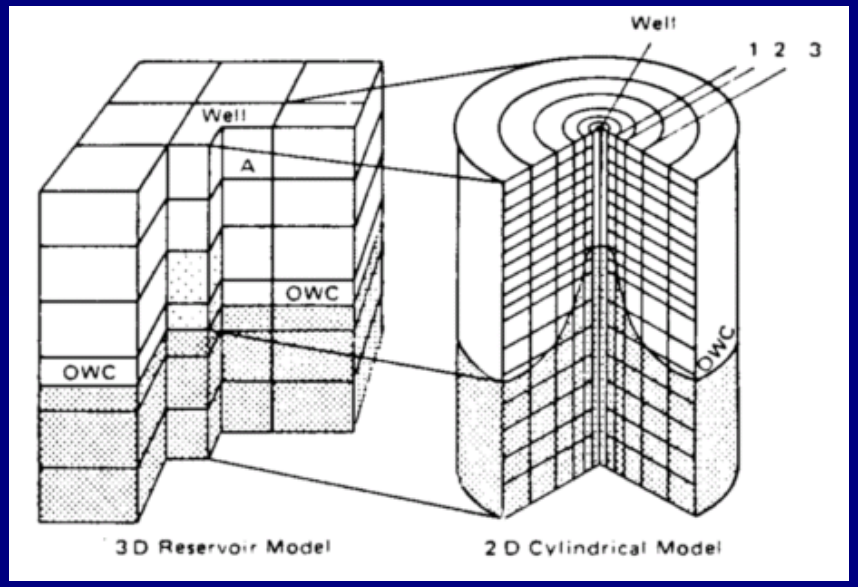
- We are thus faced with compromises in modeling options for large fields:
  - Changing the scope of the model from FFM to SM, thus reducing the modeled area.
  - Reducing the dimensionality from 3-D to 2-D or 1-D.
  - Reducing the number of layers under consideration.
- These compromises are perfectly reasonable so long as they are not contrary to the study objectives and the RC. This further emphasizes the need for completing the RC step before selecting the model.

Reservoir Simulation Applied Modeling

Model Selection - Grid

Radial flow exists near the wellbore and linear or Cartesian flow exists within the reservoir away from the wellbore.

For field-wide studies the growth or decay of reservoir volumes activated by unsteady-state flow is small and hence linear flow is modeled i.e., via linear grid



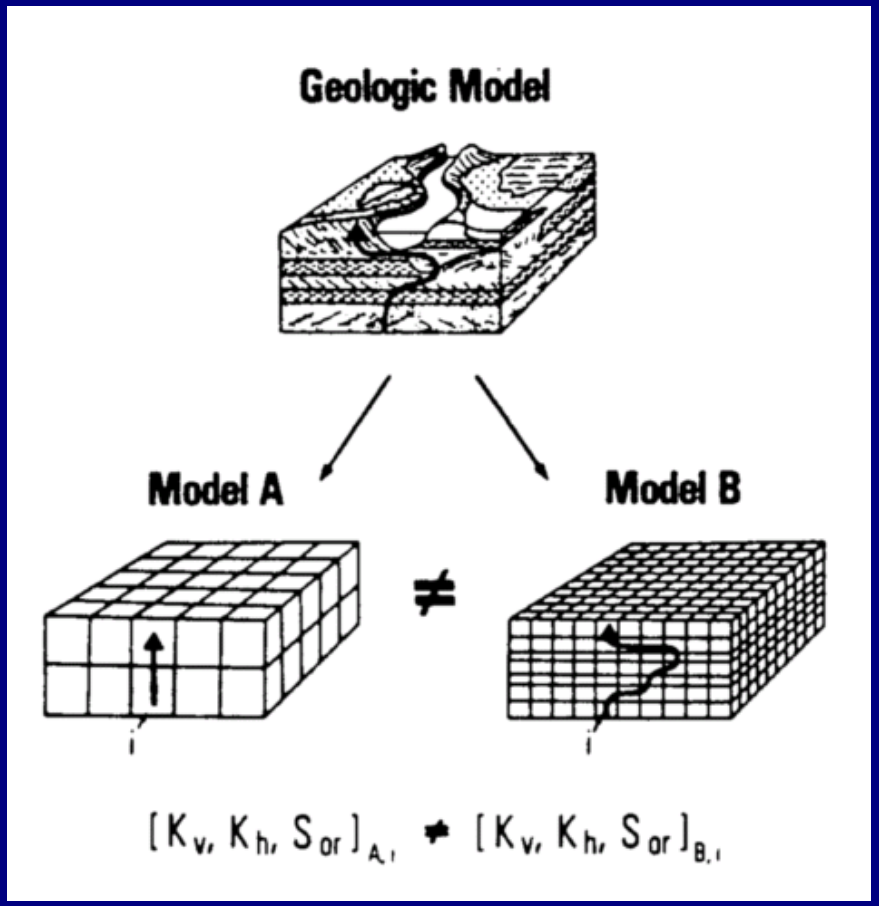
On the other hand, for converging flow near wells the growth or decay of reservoir volumes activated by unsteady-state flow is large and radial flow is modeled via radial grid. Therefore, radial flow is important in only very localised areas of the reservoir and linear flow is modeled in most reservoir studies.

Reservoir Simulation Applied Modeling

Model Construction

The transformation of geologic and petrophysical data into a simulation model constitutes a potential source of errors, due to scale-dependencies.

Key reservoir parameters such as vertical and horizontal permeabilities, relative permeability, porosity, capillarity and residual oil saturation depend on model cell dimensions. This scale dependency must be recognized in the model construction step.



Reservoir Simulation Applied Modeling

Model Construction

- An equality between laboratory-measured, well test derived, and correct model values of permeabilities will be coincidental for most reservoirs. This is a consequence of several factors:
  - Inherent in modeling is the presumption of direct connectivity (along a straight path) between two adjoining blocks. Yet in-situ flow occurs along a path of least resistance which is anything but a straight path, particularly in heterogeneous environments.
  - The flow path can be through micro-fractures, super-permeability streaks, or in the case of near-wellbore flow via any other channel (e.g., behind pipe leaks). Because laboratory, well test and model flow occur in different scales, their corresponding flow capacities can only be the same when the dominant flow features noted above are scale-independent.

Reservoir Simulation Applied Modeling

Model Construction

- Vertical Permeability
  - Lake and others have noted the problem associated with scale dependency in permeability assignments, i.e., that core-plug based k_v data bear little resemblance to model-cell scale values. Experience indicates that:
    - *k_v is not a measurable quantity in the scale of the model grids.*
    - *For most reservoirs, the available reservoir control (e.g., wells, logs, correlations) is and probably will always be insufficient to provide the reservoir description to compute k_v at the model cell scale.*
  - Because of the above there is an level of uncertainty in k_v assignments.

Reservoir Simulation Applied Modeling

Model Construction

- Vertical Permeability
  - Thus the problem is reduced to arriving at a best guess for initializing the model, and then relying on history-matching to refine the initial value. Haldorsen and others have published excellent methodologies for guesstimating initial vertical permeability distributions in reservoir models based on geostatistical and/or geologic interpretations.
  - For reservoirs where adequate data exist (e.g., RFTs, production profiles), history-matching offers the most practical and effective way of determining model cell scale k_v (via the process of refinement couple with the noted techniques).
  - For reservoirs where adequate data exist (e.g., RFTs, production profiles), history-matching offers the most practical and effective way of determining model cell scale k_v (via the process of refinement couple with the noted techniques).

Reservoir Simulation Applied Modeling

Model Construction

- Horizontal Permeability
  - Scale-dependency is also present for k_h; however, this is not as severe since we are mainly dealing with arithmetic averages (harmonic averages used for k_v).
  - When data with different scales (such as cores and well tests) are compared the values are different. The best approach in k_h assignments appears to be:
    - *Initializing with a best-guess based on permeability transforms calibrated with in-situ data (i.e., well tests).*
    - *Refining through history-matching.*
  - Implementation of best guess does not guarantee correct scale-up to model cell conditions.

Reservoir Simulation Applied Modeling

Validation

There are four ideas that are central to the discussion on validation:

- History-matching is only a component of validation.
- There are degrees of validation and history-matching, often when the term "history-matched" is used, the reference is to a partially-validated model.
- History-matching must not be achieved at the expense of parameter modifications that are physically and/or geologically wrong.
- Even when a model is full validated, simulation results are bound to be probabilistic and not definitive.

Reservoir Simulation Applied Modeling

Validation

- Validation can be broken into a sequence of steps :
  - Initialization
    - *Process of reviewing the model to be sure that all data have been properly input.*
  - Equilibration
    - *Bringing the model to equilibrium with respect to internal and external boundary conditions.*
  - History-Matching
    - *Process of modifying the model parameters to achieve a match between model and measured field performance over a period of time at known rates.*
  - Calibration
    - *Adjusting parameters to match field performance with known back pressures.*

Reservoir Simulation Applied Modeling

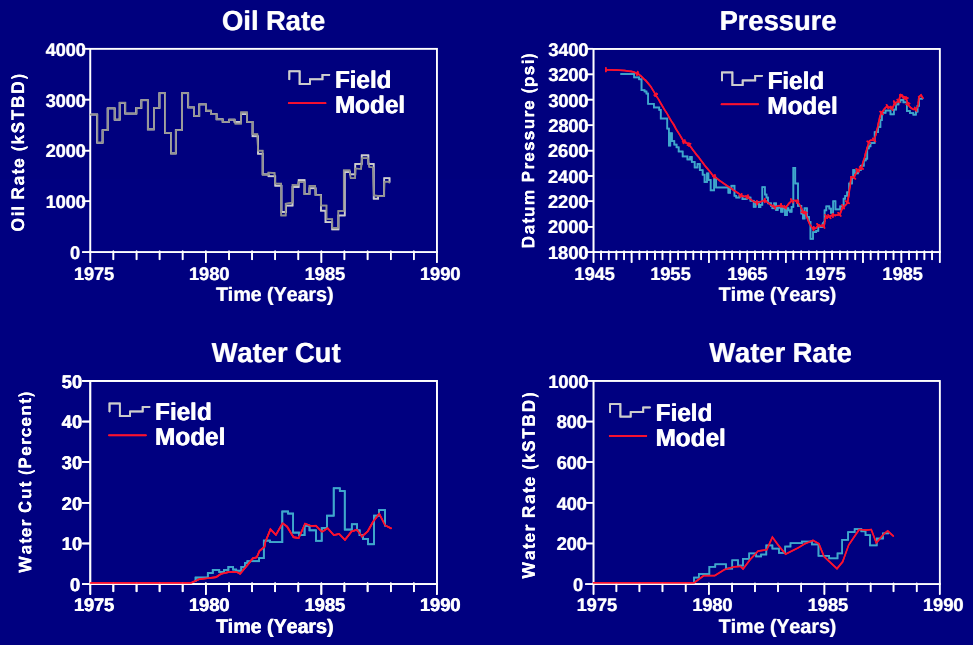
Validation - History Matching

- The general format of the manual history-matching process:
  - Formulate a Plan
    - Review the reservoir-production data to determine which data should be fixed (e.g., rates, pore volumes), what parameters should be adjusted, and what level of control criteria should be used to obtain a match.
  - Adjust the Data
    - This step is needed mainly to a) allocate production data areally and vertically to the pertinent areas and zones, b) correct field production data to separator conditions consistent with model conditions and c) correct reported pressures for simulation use.

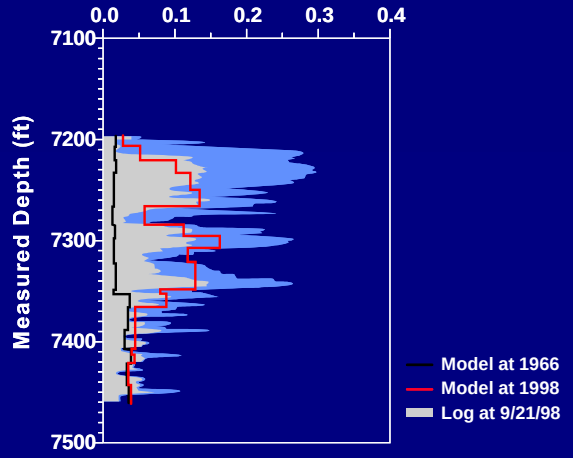
Reservoir Simulation Applied Modeling

Validation - History Matching

Full Field Matching of Rates, Pressures, and Flood Fronts



Well Matching of Rates, Pressures, and Flood Fronts



One hydrocarbon phase is a target, and the simulator predicts the other phase. In the above example oil is the target phase, and hence the perfect match for oil, the quality of the match is from the other phases and pressures.

Reservoir Simulation Applied Modeling

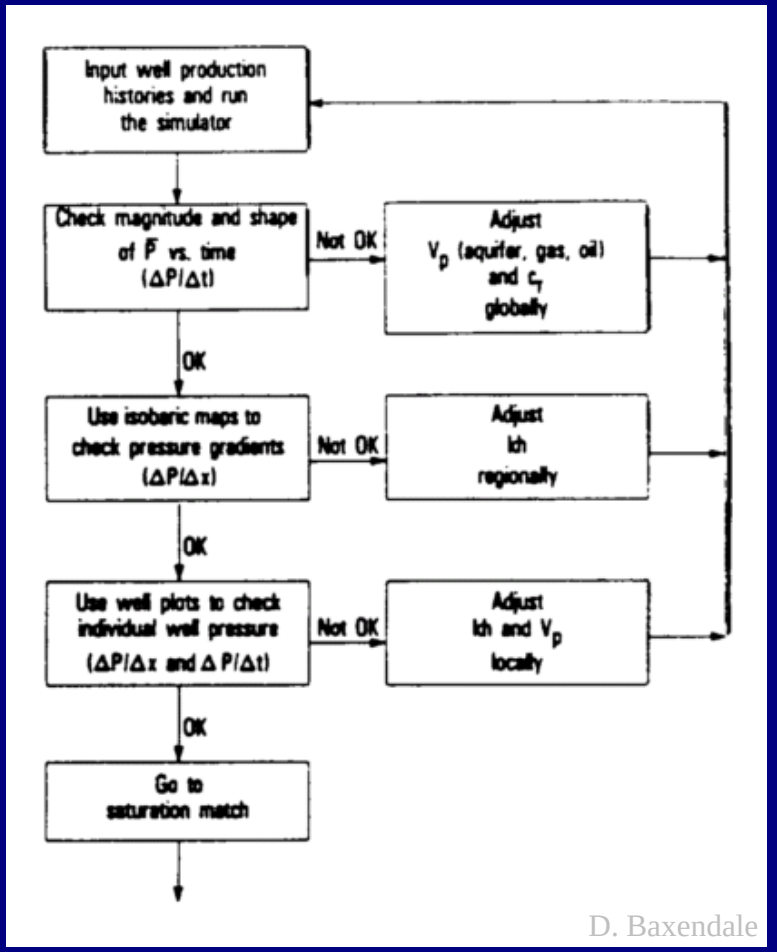
Validation - History Matching

- Match Pressures

- The process is iterative and involves global changes (affecting all cells in the model) before making local changes (affecting only some cells).

- Spatial pressure gradients can be more rapidly matched by changing conductance and/or total mobility than by changing total compressibility and/or pore volume.

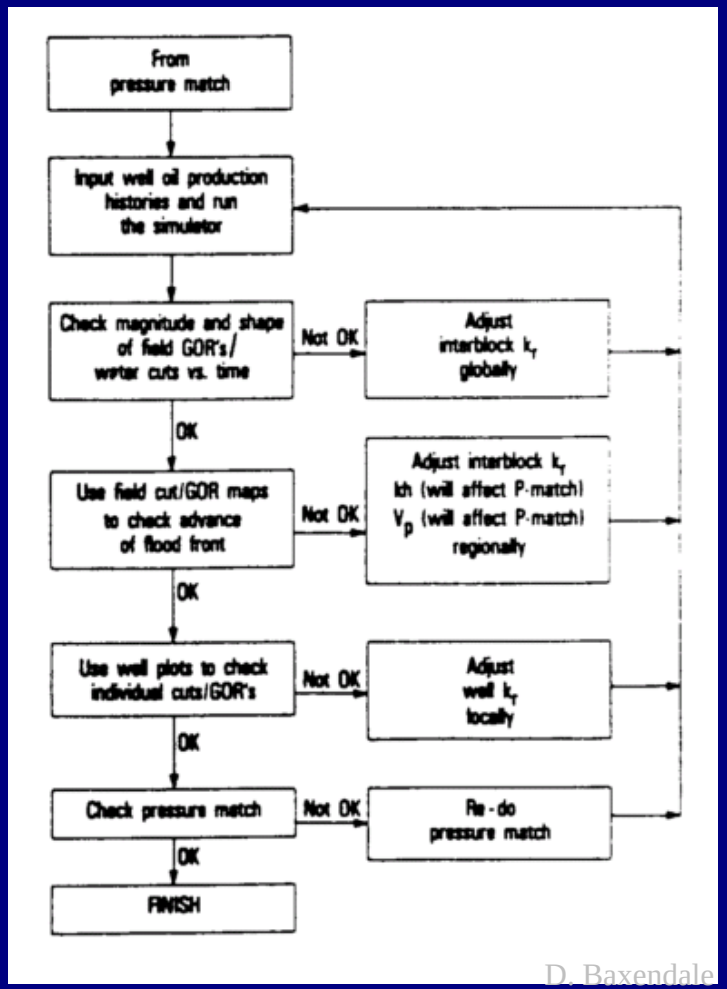
- Temporal pressure gradients can be more rapidly matched by changing compressibility and/or pore volume than by changing conductance and/or total mobility.



Reservoir Simulation Applied Modeling

Validation - History Matching

- **Match Saturations**
- Changes in a well's producing GOR and/or water-cut performance can be caused by near-wellbore (coning, cusping) or field wide (gas-cap shrinkage) effects.
- Near wellbore behavior can be matched by modifying well relative permeability curves, while field-wide behavior can be matched by changes to inter-block curves.
- Changes to inter-block curves should be a last resort. The most effective approach is to initialize models with correctly scaled-up relative permeability curves. Any changes to permeability curves must be explained in terms of geologic and reservoir flow features.



Reservoir Simulation Applied Modeling

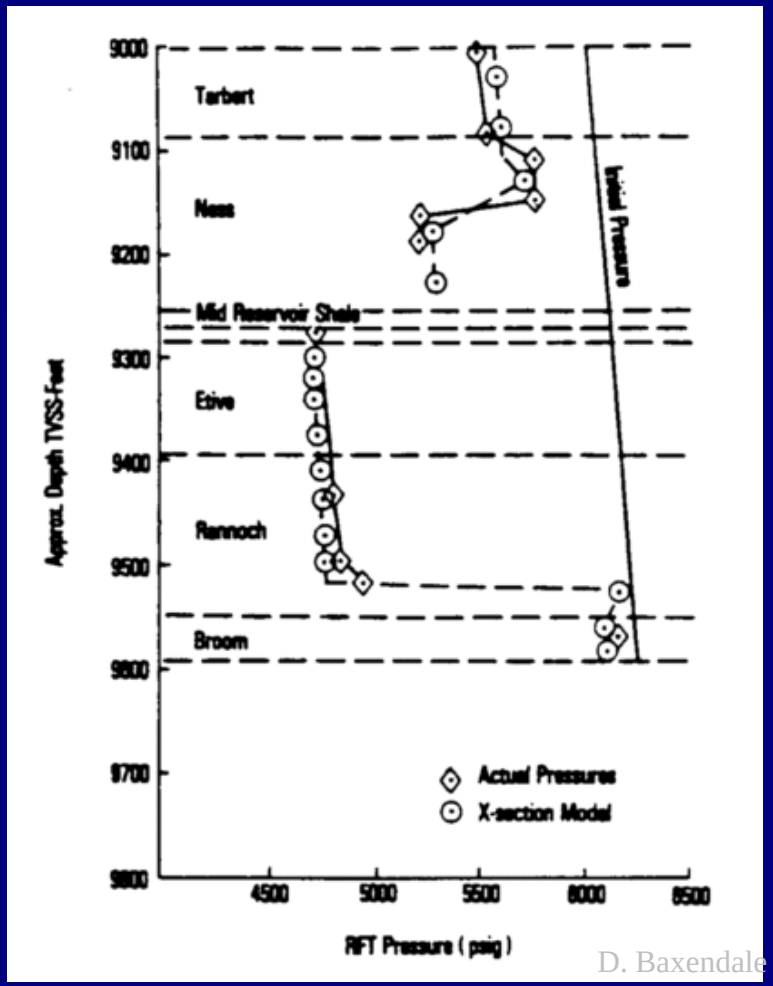
Validation - History Matching

- Levels and Criteria of Control
  - The history-matching process can range from being superficial to thorough depending on data availability. The purpose of a history-matched model is to duplicate:
    - Pressure and saturation distributions existing in the field both areally and vertically and
    - Observed water cuts and GORs both on a field and well basis.
  - Often, achievement of the latter is accepted as a sufficient condition for history-matching, when in reality both purposes have to be fulfilled for a full match.

Reservoir Simulation Applied Modeling

Validation - History Matching

- Levels and Criteria of Control
- The following figure shows the model pressures versus the observed vertical pressures from the Dunlin field RFT data, as reported by Barbe.



Reservoir Simulation Applied Modeling

Validation - History Matching

- Levels and Criteria of Control
  - There are two levels of control : field level and well level. At the field level, the intent is to ensure that a given model represents the main drive mechanisms of the reservoir.
  - While at the well level, matching of well production rates and RFTs is the objective.
  - No quantitative measures of history-matching are given due to the diversity of reservoir problems. For instance for a reservoir which has declined by 1000 psi over a given period, a pressure match with a mean error of 50 psi could be considered acceptable. Yet for a reservoir which has declined only 200 psi over a comparable period, a 50 psi error would be unacceptable.

Reservoir Simulation Applied Modeling

Validation - History Matching

Field Level and Criteria of Control		
	Model vs. Observed Data	**Source of Observed Data**
PRESSURE	1. Average reservoir pressure vs. time	Isobaric maps through time
	2. Areal pressure differentials at selected times*	Isobaric maps through time
	3. Vertical pressure differentials at selected times	RFT's, DST's and production data from wells with single zone completions
	4. Offset** field/aquifer pressure vs. time	Pressure data from offset fields/aquifers
PRODUCTION	5. Field watercut vs. time	Field production data
	6. Field GOR vs. time	Field production data
	7. Field oil-rate *** at the end of history period	Field production data
	8. Cumulative water production vs. time	Field production data
	9. Cumulative gas production vs. time	Field production data

Reservoir Simulation Applied Modeling

Validation - History Matching

Field Level and Criteria of Control		
	Model vs. Observed Data	**Source of Observed Data**
FLUID	10. Average GOC/OWC vs. time	Open hole/production logs (e.g., TDT's, fluid-density surveys, DIL, carbon-oxygen logs)

* Selected times would preferably be at early, mid-history and late history.
** To establish possible interference with neighbouring fields and verify assumed reservoir boundaries.
*** To ensure that the model is calibrated adequately prior to beginning predictions.

Reservoir Simulation Applied Modeling

Validation - History Matching

Well Level and Criteria of Control		
	Model vs. Observed Data	**Source of Observed Data**
PRESSURE	1. SIBHP vs. time	Pressure surveys
	2. Vertical pressure differentials at selected times	RFT's and DST's on infill wells, spinner surveys
PRODUCTION	3. Watercut vs. time	Production data
	4. GOR vs. time	Production data, FWHP data
	5. Oil rate at the end of the history period	Production data
	6. Breakthrough times (gas or water)	Production data
	7. Fluid* entry profile at selected times	Production logs (e.g., spinner surveys, temperature logs, fluid-density surveys, TDT's)
	8. Cumulative gas production vs. time	Production data
	9. Cumulative water production vs. time	Production data
*To ensure that flow stratification (if any) is correctly modeled.		

Reservoir Simulation Applied Modeling

Validation - History Matching

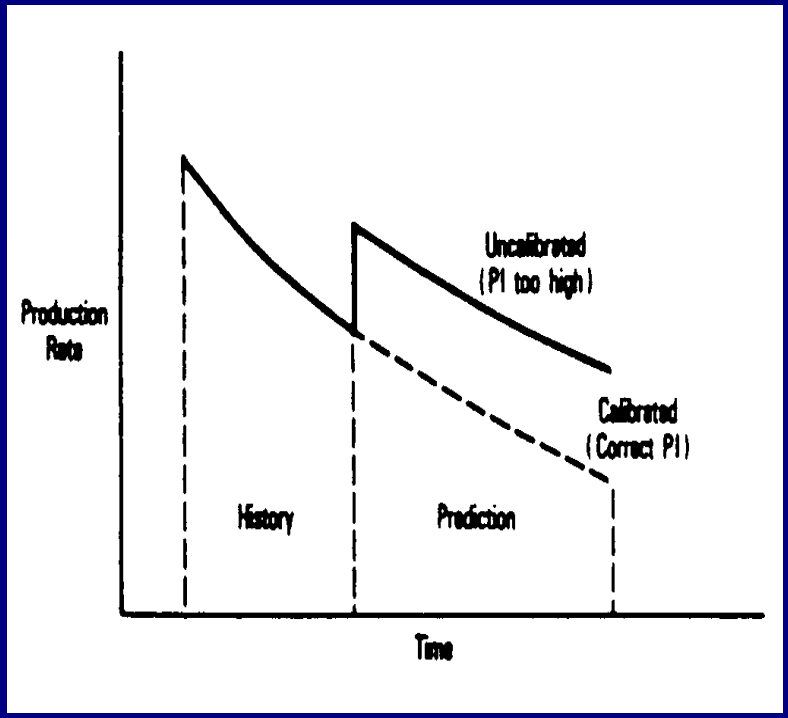
Well Level and Criteria of Control		
	Model vs. Observed Data	**Source of Observed Data**
FLUIDS	10. GOC/OWC vs. time	Open-hole/production logs (e.g., fluid-density surveys, DIL, carbon-oxygen, flowmeters, temperature surveys, TDT's)
	11. Fluid saturations at selected times	Open-hole/production logs (e.g., fluid-density surveys, DIL, carbon-oxygen, flowmeters, temperature surveys, TDT's)

Reservoir Simulation Applied Modeling

Validation - Calibration

History-matching uses specified production rates and is directed toward matching pressures and phase distributions. Predictions runs require that production rates be computed.

An uncalibrated model can result in a mismatch between historical and predictive well performance. Hence the purpose of this step is to eliminate this mismatch and allow a smooth transition between the historical and predictive model phases.



Reservoir Simulation Applied Modeling

Validation - Calibration

- Calibration is achieved by running the model at the back pressures held against the wells. This could be at one or several time-steps. The well PIs and/or wellbore flow parameters are adjusted to duplicate field-observed rates. Although the calibration step is usually done after the history-matching step, there are times when it must be done beforehand (e.g., when modeling multi-layer flow into a well). This is because in stratified reservoirs the correct allocation of rates among layers is dependent on the absolute value of the well's PI (and not solely on the ratios of PIs of various layers).

Reservoir Simulation Applied Modeling

History Matching - Arun Field Example

Development History

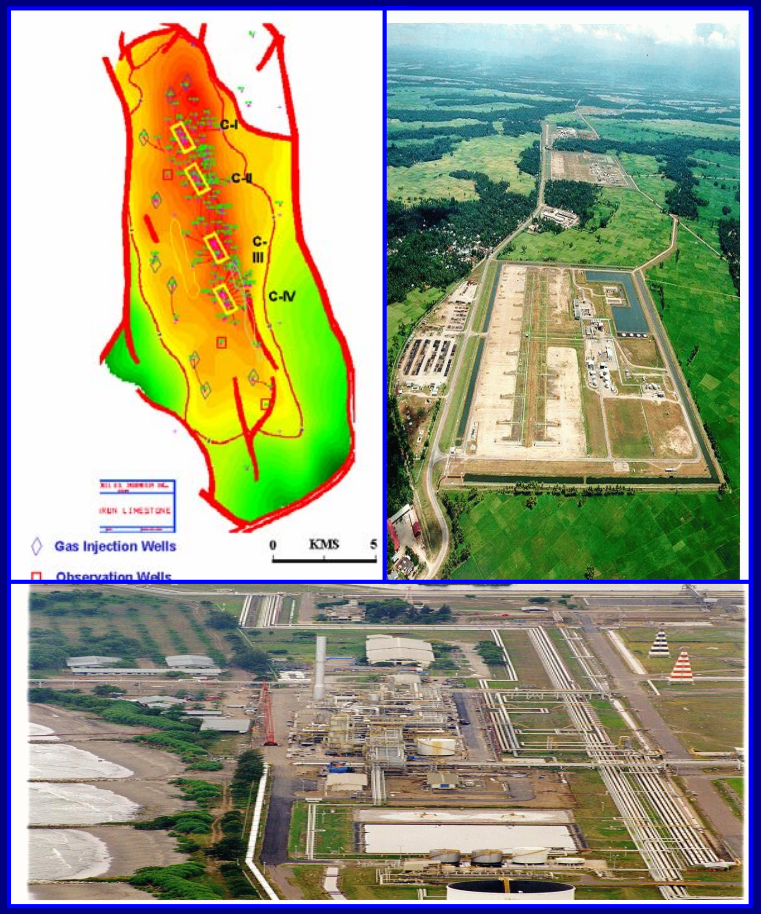
The field was discovered in 1971 by Arun A1.

The initial field development begun in 1975 with the cluster concept (clusters III and II), followed in 1977 with the first liquid production with gas re-cycling, and in 1978 with the first LNG shipment.

In 1982 two additional clusters (I and IV) were developed, for a total of four, and the LNG Plant was expanded in 1984, with NGL Plant & LPG Sales starting 1988.

Eleven bigbore wells (9 5/8 tubing) were drilled from 1992 through to 1995. As of January, 2001 a total of 111 wells have been drilled in the field, including 29 sidetracks.

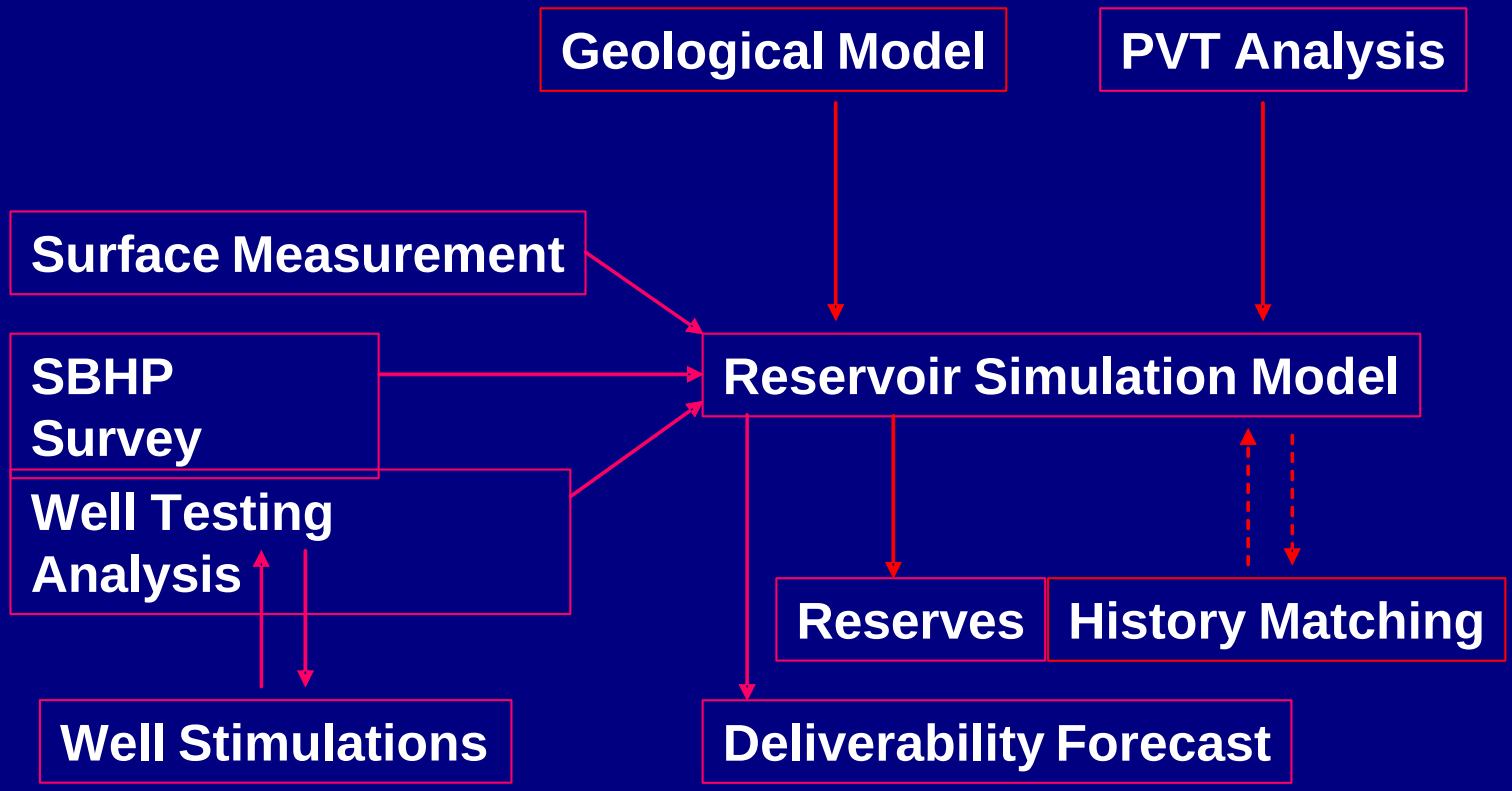
The Dehydration project was initiated in 1992, followed in 1995 by the Booster Compressors project. In 1999 gas injection was halted, and the gas injectors were converted to producers. Finally, in 2000 the Arun-I contract expired, and the LPG sales were terminated.



Reservoir Simulation Applied Modeling

History Matching - Arun Field Example

Field Surveillance: Numerical Simulation Model



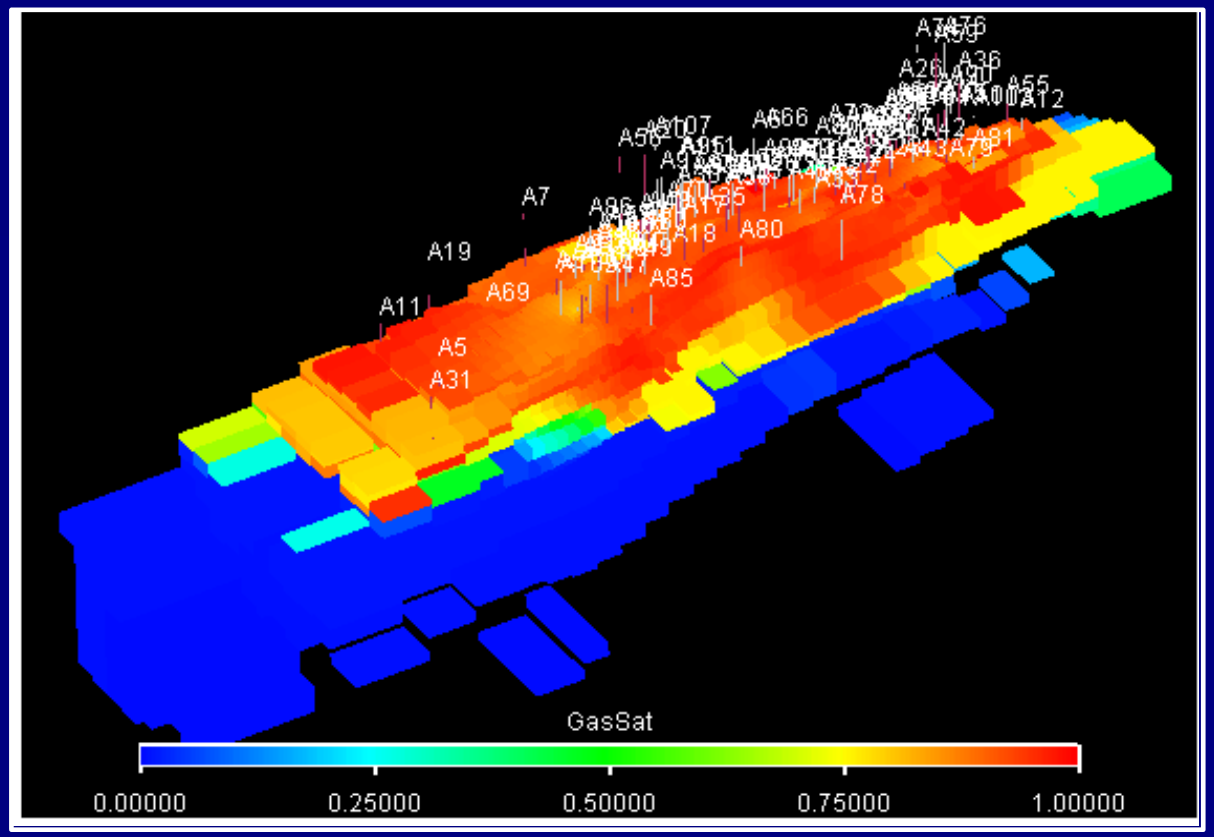
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example

Global grid is 14 x 30 x 9 (x,y,z) for a total of 3,780 of which 1,901 are active.

Local Grid Refinement 1 (LGR1) is 14 x 42 x 9 resulting in a total of 5,292 grid blocks.

LGR2 is 16 x 70 x 9 for a total of 10,080 grid blocks.



Reservoir Simulation Applied Modeling

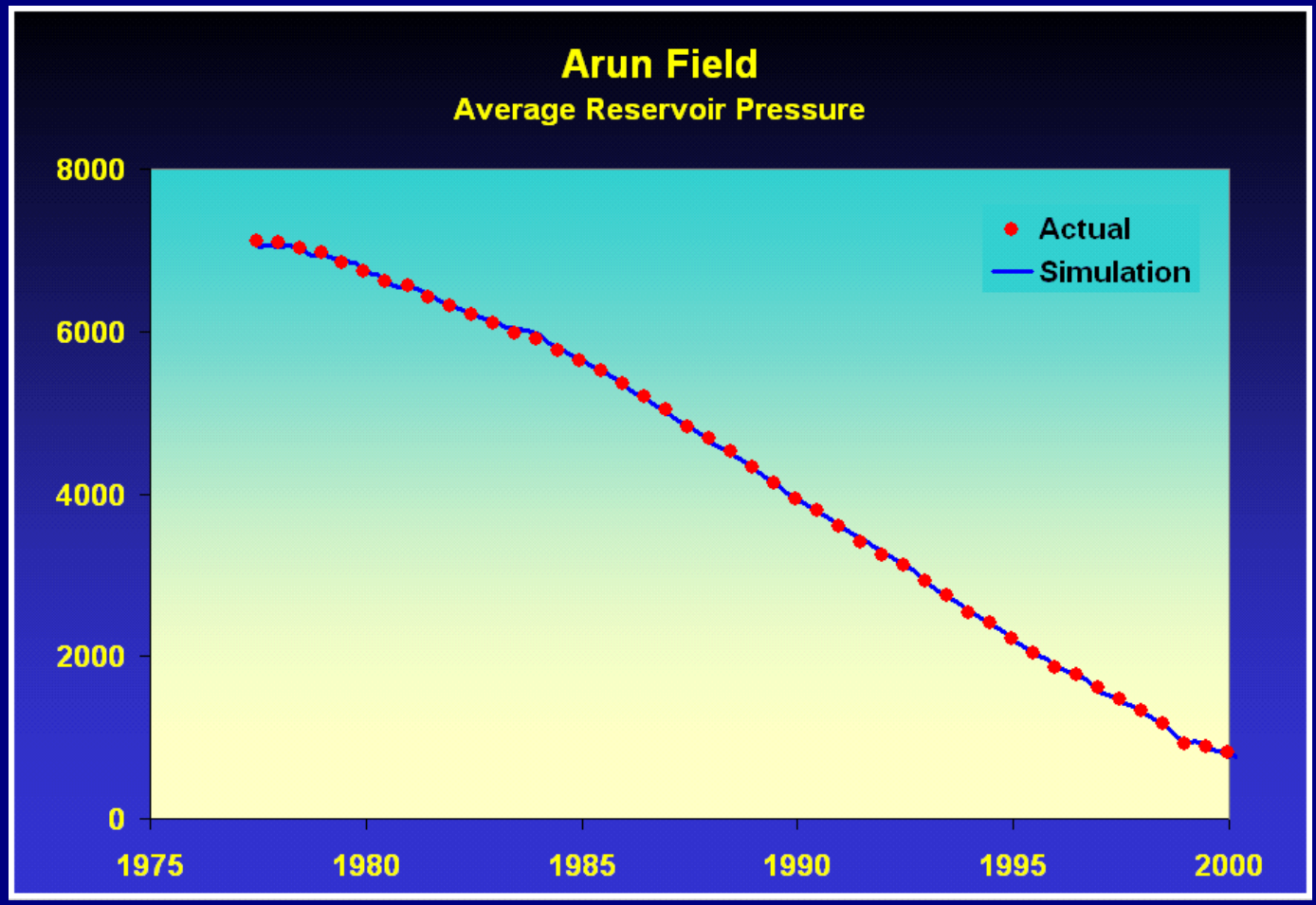
History Matching - Arun Field Example

History Matching Variables

Variable	by
Average Reservoir Pressure	Cluster and Field
Static Bottomhole Pressure	Individual Well
Wet Gas Production	Individual Well
Separator Gas Production	Cluster and Field
CO2 Content in Separator Gas	Cluster
Unstabilized Condensate Production	Cluster and field
Condensate to Gas Ratio	Cluster and field
Separator Water Production	Cluster and field
Water Yield in TWS	Cluster
Water Vapor vs Reservoir Pressure	Cluster
Downstream Products (LNG, LPG, NP, Condensate)	Field

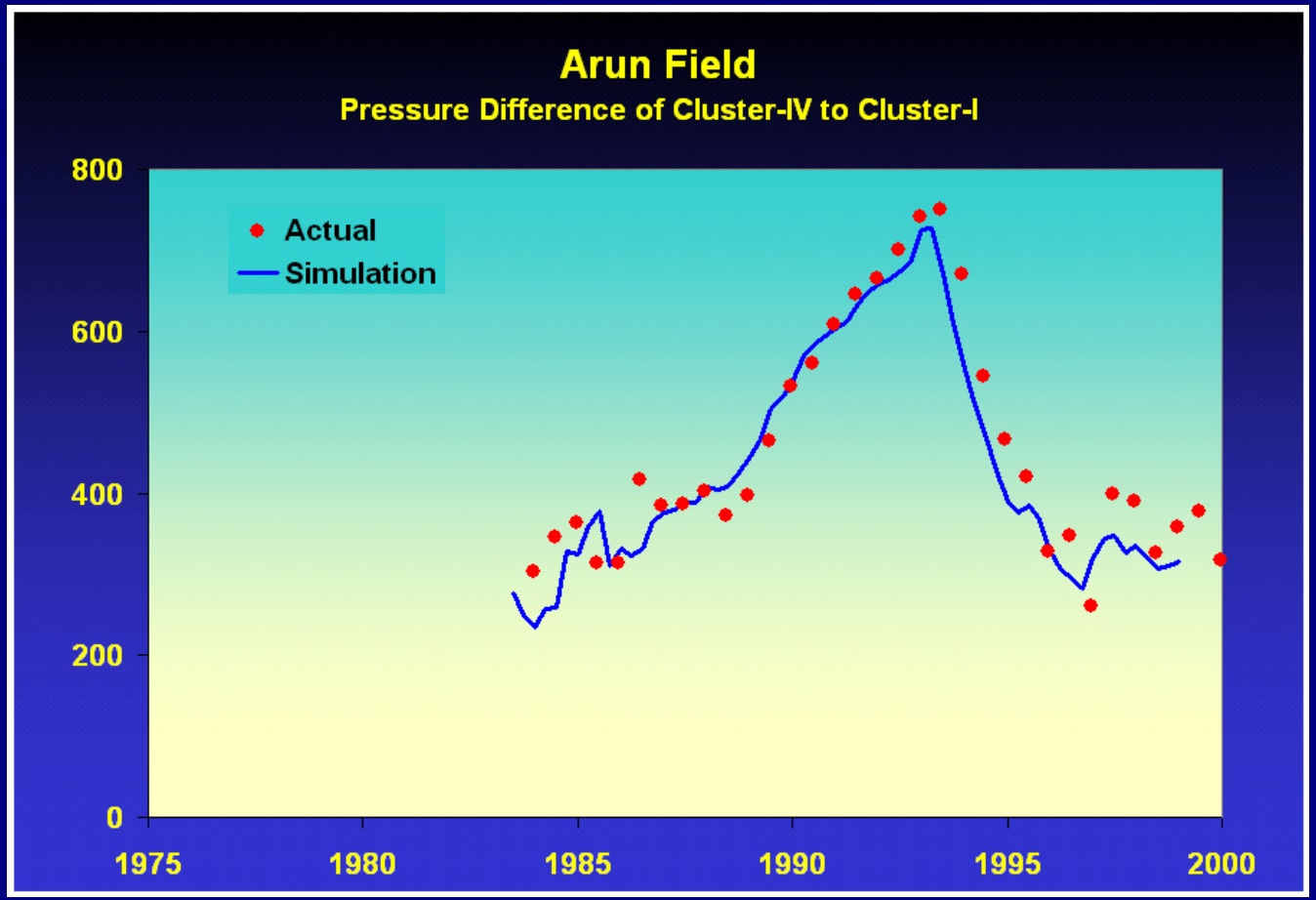
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



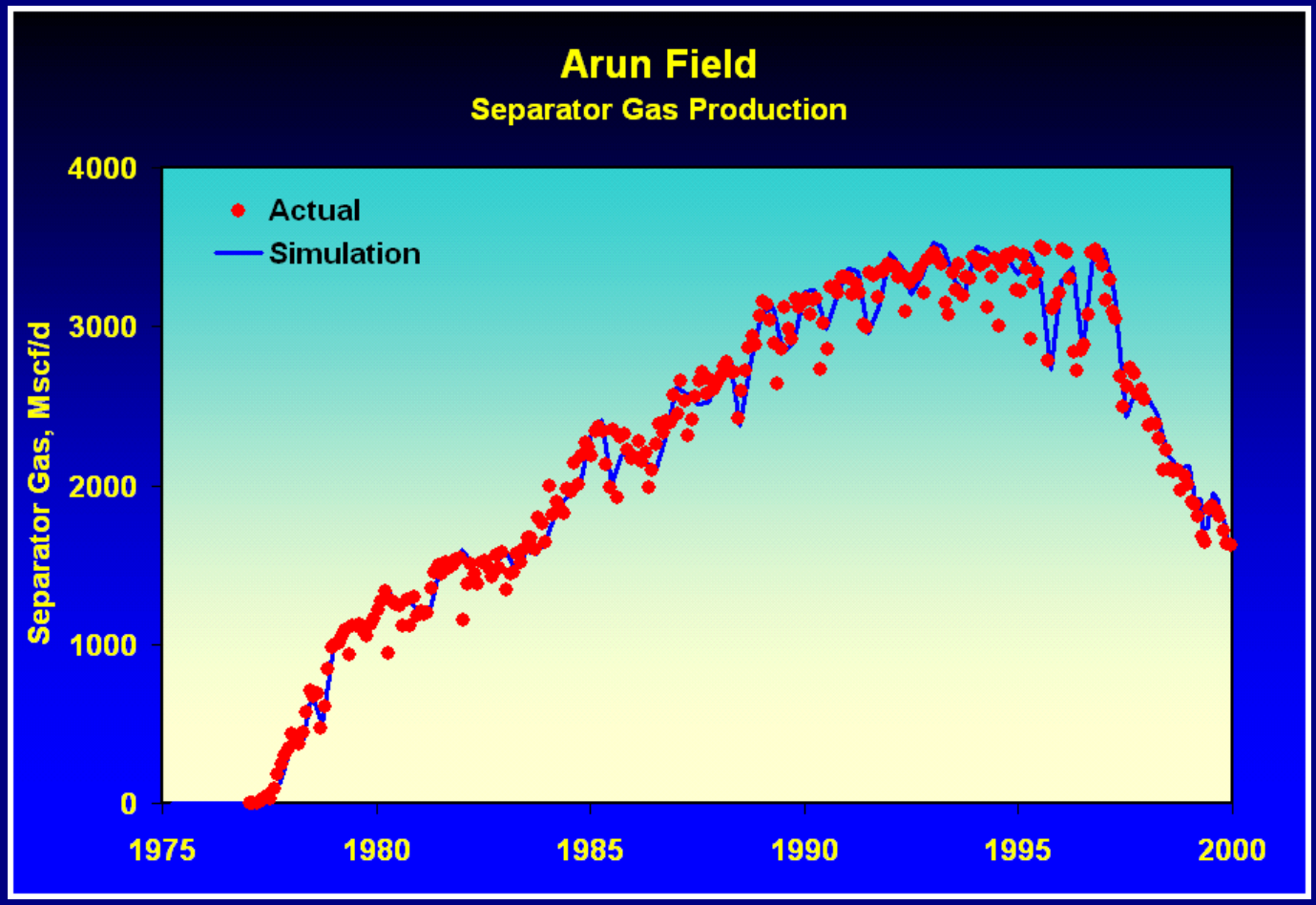
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



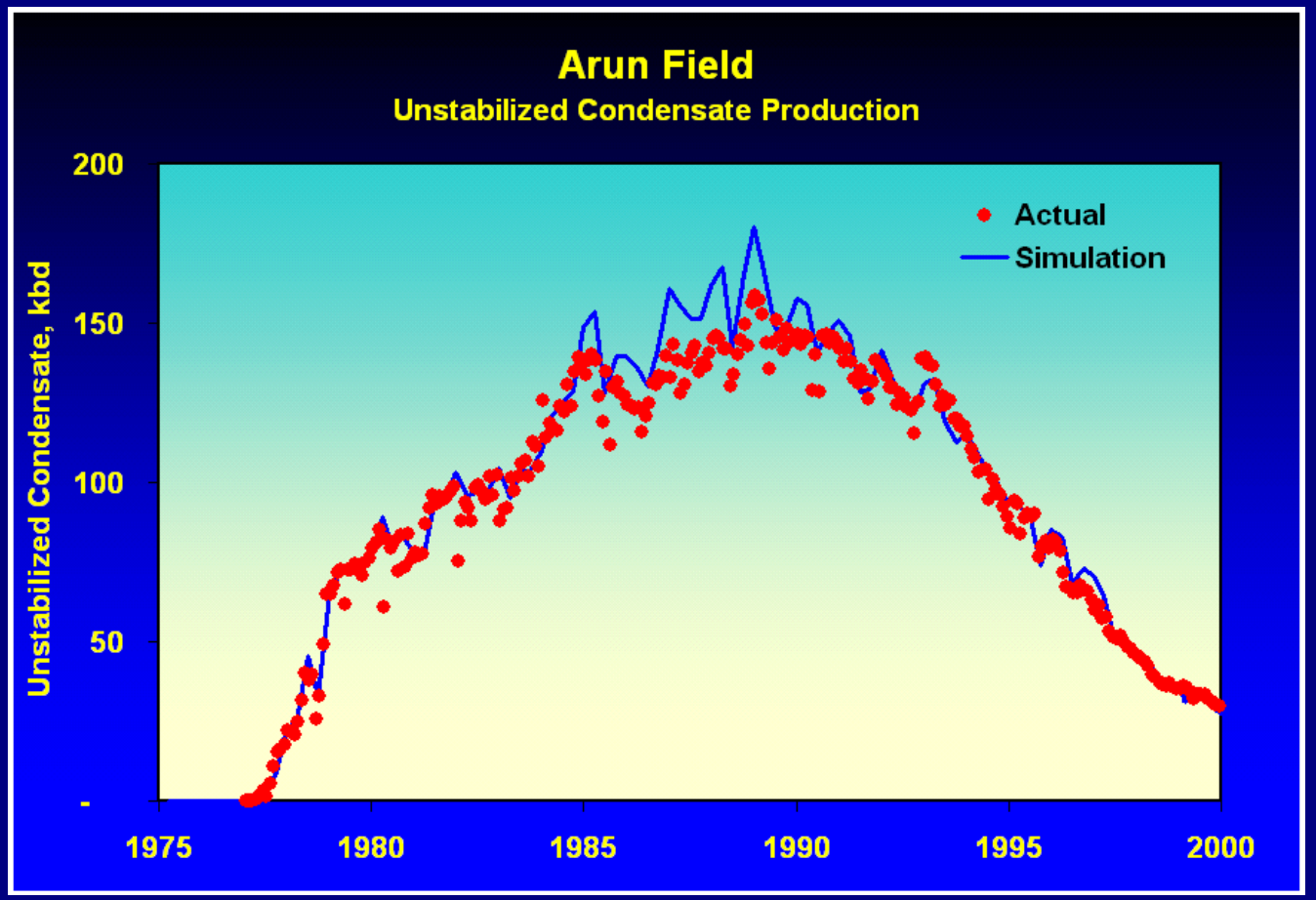
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



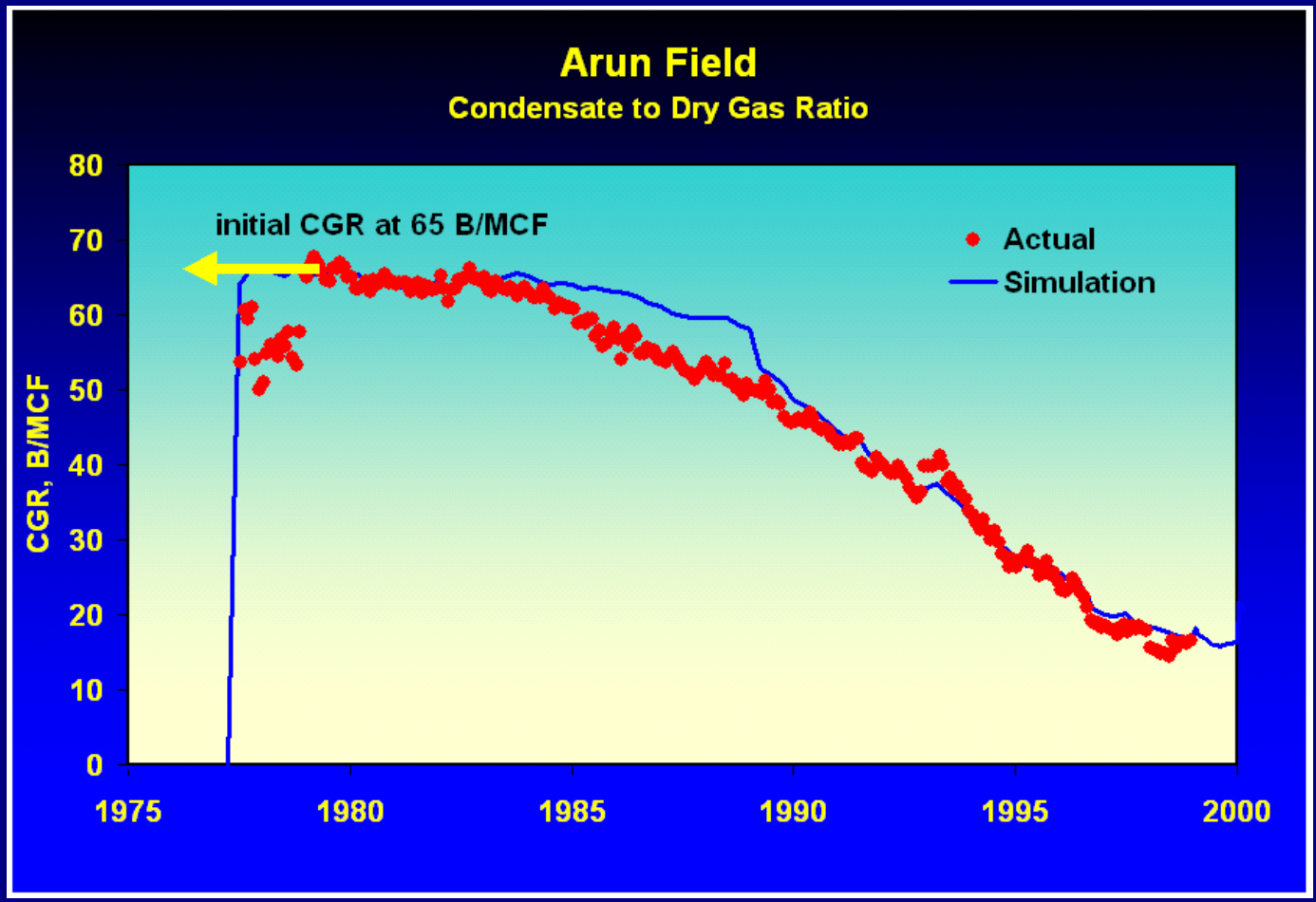
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



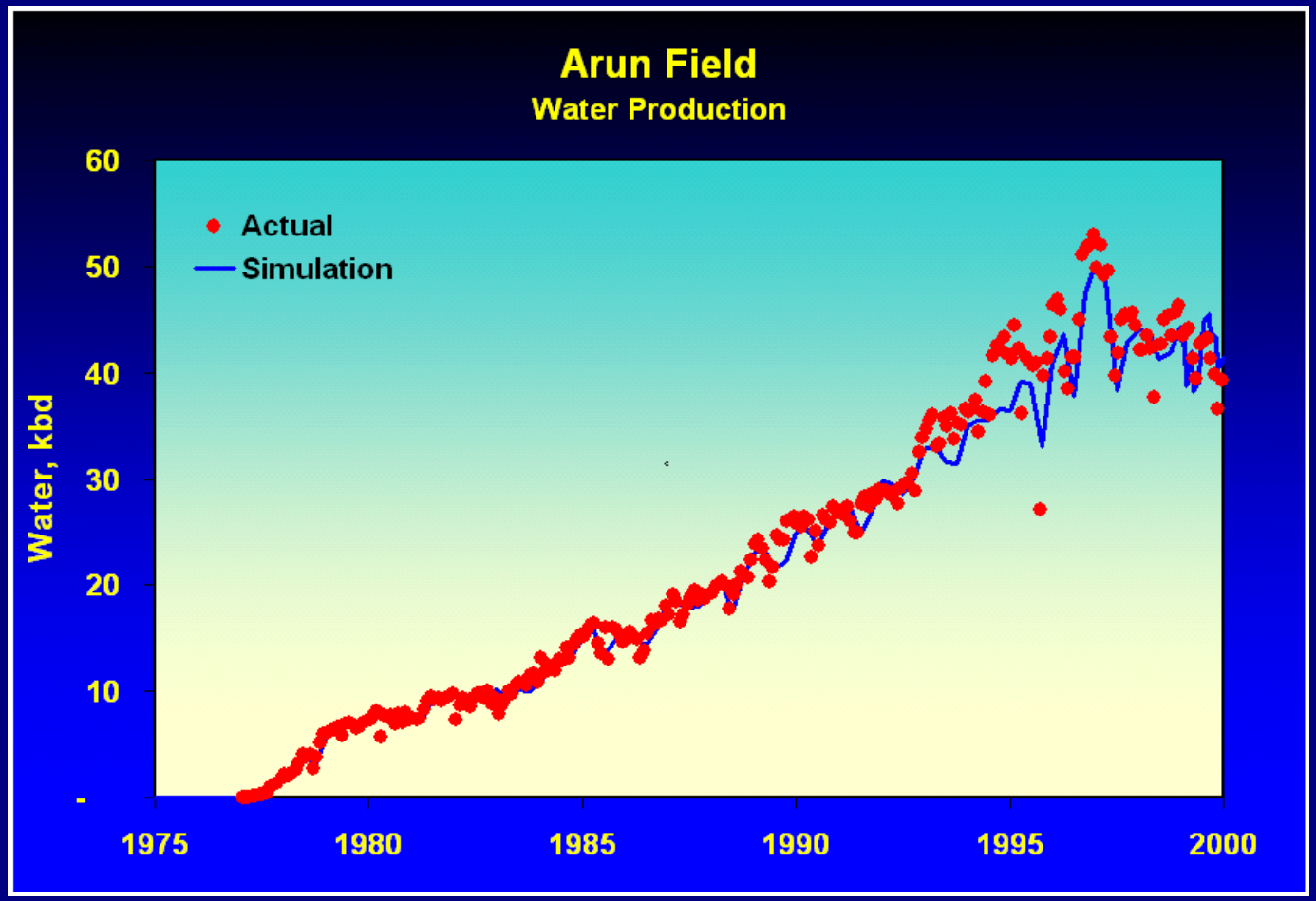
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



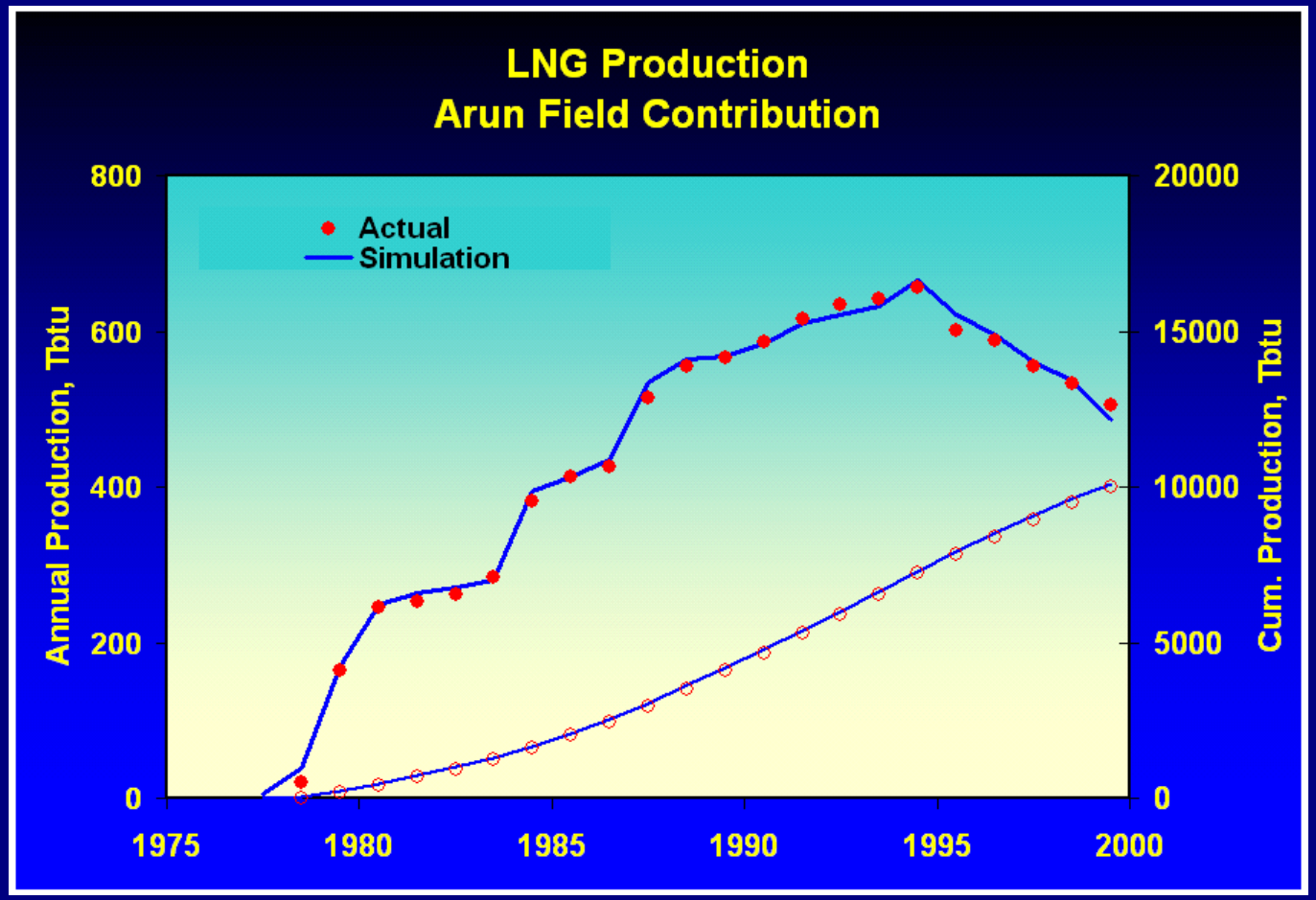
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



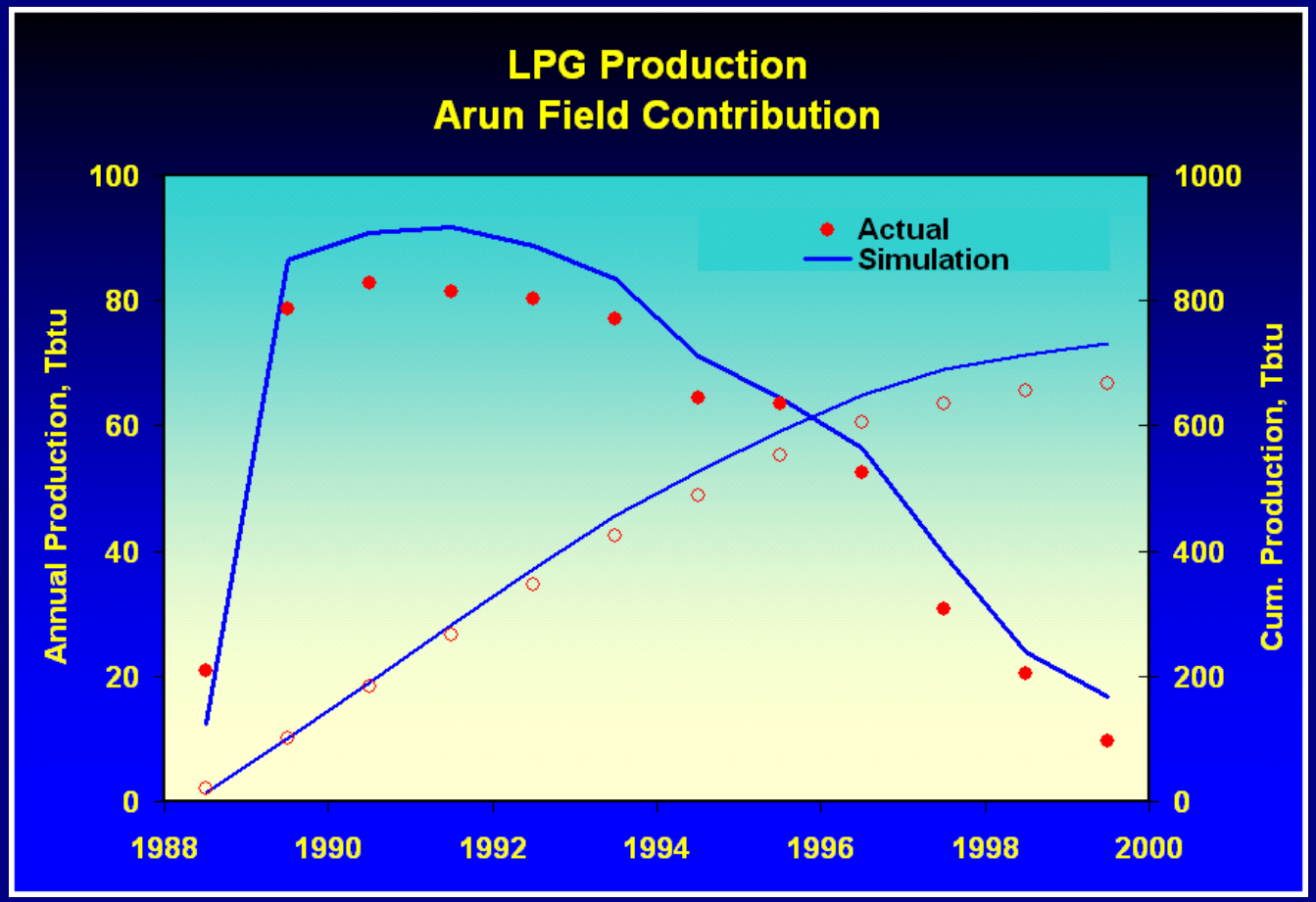
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



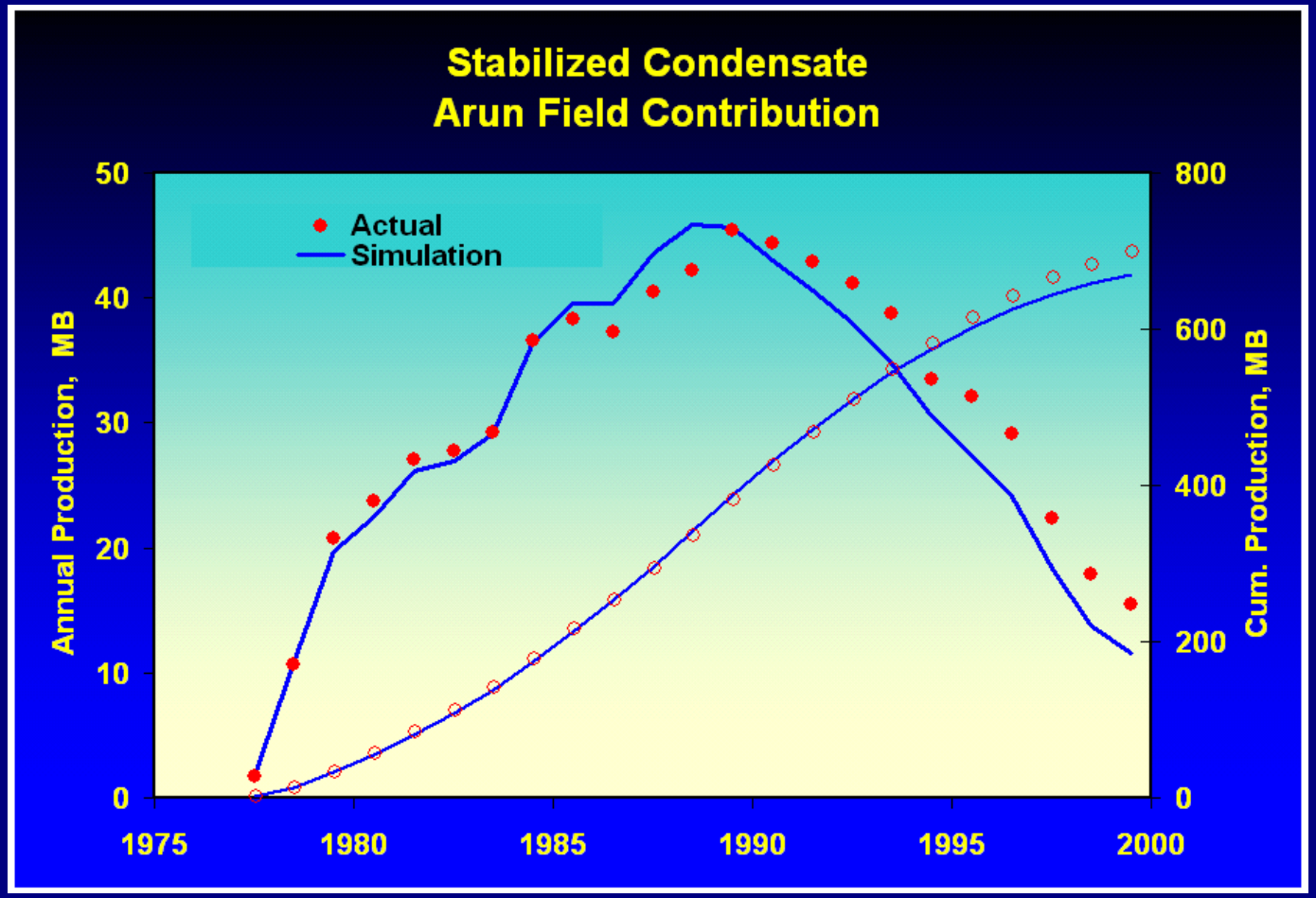
Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



Reservoir Simulation Applied Modeling

History Matching - Arun Field Example



Reservoir Simulation Applied Modeling

Predictions

- This is the phase where most study objectives are met. To avoid the common errors noted earlier, prediction cases must be carried out while recognizing the limitations of the particular model being used:
  - Lack of validation (e.g., reservoirs with sparse geologic or engineering data).
  - Modeling/mathematical constraints due to compromises in model selection.
  - Inherent uncertainties in RC and/or scale-up of RC to model dimensions.
- The recognition of these factors and in turn, the realization of the probabilistic nature of simulation is critical to its use in a rational manner.

Reservoir Simulation Applied Modeling

Predictions

- The key point here is that despite the limitations noted above, most study objectives can still be met by conducting sensitivity runs using "bracketing."
  - Identify the main limitations of the model.
  - Identify the key parameters (reservoir, model, etc.) causing the limitations.
  - Conduct parameter sensitivity cases to evaluate the effects on model results.
- These parameters may include geologic attributes such as sand continuity or aquifer size

Reservoir Simulation Applied Modeling

Documentation

- The last step requires little elaboration, but no project can be considered complete without it. The main function of the documentation is to outline the :
  - Objectives, data, and methodology.
  - Results and conclusions.
  - Limitations of results and the methodology.
- In particular, the last point is important for any engineering decision that will be based on the study.