Modeling and Geo-Statistics

Getting a Grip on Stratigraphy and Compartmentalization – Most Importantly Flow Units

The Reservoir Management Process

Fig. 4—Iterative Reservoir Modeling Workflow

From SPE 87043
Flow Units

A flow unit is a continuous volume of the total reservoir rock within which geological and petrophysical properties that affect the fluid flow are more or less similar and different from those in other flow units.

Particular properties of interest:

- Permeability
- Capillarity
Permeability and Capillarity Characterize Flow Units

Flow Units in Clastic and Carbonate Rock
Flow Units – Rigorous

- Hydraulic quality of rock controlled by:
  - Pore geometry
  - Mineralogy (abundance, type, morphology, location relative to pore throats)
  - Texture (grain size, shape, sorting, packing)
- Mean hydraulic radius concept
- Calculate Reservoir Quality Index (RQI)
- Reference: SPE # 26436, Amaefule, et al.

Where the porosity ($\phi$, frac) and permeability ($k$, md) have been corrected to reservoir conditions, answer in micro-meters

$$RQI = 0.0314 \frac{k}{\sqrt[3]{\phi}}$$

Heterogeneity and Impact on Recovery
**Impediments to Flow**

- Barrier
- Baffle
- Permeability contrasts
- Permeability anisotropy

**GeoStatistical Modeling Techniques Summary**

Modeling techniques attempt to combine the “best of both worlds”

- Well logs have good vertical resolution
- Seismic has good areal resolution

May use geostatistics to combine

- **Geostatistics:**
  - Mathematical tools which employ the assumption that properties are correlated in space and are not randomly distributed
  - Provide formalized methods for integrating data of diverse type, quality, and quantity
Observations about Reservoirs

- Reservoir dimensions much larger in horizontal direction
- They are heterogeneous
- The more they are studied, the more heterogeneous they become

Geostatistical Model of a Large Middle East Field
Geostatistical Applications

- Data distributions
- Geometry of parameters
- Populating interwell space
- Multiple working models
- Testing hypotheses

Representing uncertainties

Geostatistical Methods

**Why use Geostatistical Methods?**

- Industry tends to under-predict variability, but over-predict continuity
- Large volumes of data
- Correlation of data sets
- Predict spatial variations in parameters
- Expand our understanding of data/models
Let's Look at When Stratigraphy Dictates

Recognizing Stratigraphic Complexities in Mature Fields

- Multiple fluid contacts
- Anomalous recovery factors; highly variable cumulative production
- Poor sweep efficiency
- Different water and/or HC chemical compositions
- Anomalous fluid relationships (gas under oil; oil down dip of water)
- Dry hole surrounded by producers

*Morton-Thompson and Galloway, AAPG Methods in Exploration Series, No. 10, 1992*

So… How do We Find These Stratigraphic Heterogeneities?

- Flow unit and impediments to flow
- Importance of understanding and utilizing sequence stratigraphy for correlation of reservoir units
- Definition of facies layers AND flow unit layers
- Understanding and constructing the reservoir “container”
Sequence Stratigraphy – Getting the Barriers and Flow Units Right is Critical to Identifying NOF

Correct Correlation of Reservoir Bodies Reveals True Heterogeneous Nature of the Reservoir

**Seq Strat Correlation**

**Sand Tops Correlation**

Parasequence boundary – abrupt and correlatable changes in sediment grain size either side of flooding surface.


Lithologic Units vs. Flow Units


A *flow unit zone* is different from a *lithofacies zone* in that geological, petrophysical, and production data are integrated to describe FLUID FLOW pathways, not distinctive lithologies.
What Are the Impediments to Flow?

Laminations  
Barrier  
Barrier

- Small scale
- Inter reservoir
- Intra reservoir

- Can Also Impact, Permeability (k):
- Contrasts within the same flow unit, variations in k occur at each chrono- and litho-stratigraphic boundary
- Anisotropy (directional k)
- Isolated Compartments

All of These Are Force Multipliers to Opportunities!

Stratigraphy Influences Macro $k_v/k_h$, and Micro $k_v/k_h$, Shown Here...

SPE 77825

OVERVIEW OF STIMULATION TECHNOLOGY FOR HORIZONTAL COMPLETIONS WITHOUT CEMENTED CASING IN THE LATERAL

$\frac{(K_v)_{plug}}{(K_v)_{core}} = 0.15 \text{ md}$  
$\frac{(K_h)_{plug}}{(K_h)_{core}} = 0.20 \text{ md}$

$\frac{(K_v)_{plug}}{(K_h)_{plug}} = 1.33$  
$\frac{(K_v)_{core}}{(K_h)_{core}} = 25$

Shale Layer ~0.05 in. (Field core samples often will separate here)

Fig. 1–In some formations, full-core vertical permeability may be drastically different than that indicated by test plugs drilled vertically.

McDaniel, East & Hazzard (SPE 77825)
Laminations May Result in Baffling When Not Continuous
(Sand-Shale Case)

**Baffling** impacts fluid flow due to gravity effects, i.e. water coming from below.

Figure 8 From SPE145070

When They are Continuous They Leave Isolated Opportunities
a Field Example

**Lower Delta Plain Depositional Model**

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Multiple diagrams and figures illustrating geological models and depositional processes.

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From *Depositional Environments*, Memoir 37 AAPG, Edited by
P.A. Scholle & D. Spearing

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See Original Pressures After Years of Production?

Upscaling
An Outcrop with One Permeability Over a Block

Dynamic Property k Scale Up

Depends on Flow Direction:

If flow occurs along layers of constant permeability, then

$$\bar{k}_{x,a} = \frac{1}{n} \sum_{i} k_{x,i}$$

If flow occurs across layers of constant permeability, then

$$\bar{k}_{x,h} = \frac{n}{\sum_{i} k_{x,i}}$$

If permeability values throughout a block are completely uncorrelated, then

$$\bar{k}_{x,o} = \left( \prod_{i} k_{x,i} \right)^{1/n}$$

In general, these methods are all part of a broader family of the Power average

$$\bar{k} = \left( \frac{1}{n} \sum_{i} k_{x,i}^{p} \right)^{1/p}$$.

If p = -1, this gives the harmonic average, p = 0 is the geometric, and p = 1 is the arithmetic.

Adapted from: Kelkar, M. G. and Perez G.; "Applied Geostatistics for Reservoir Characterization," Society of Petroleum Engineers (2002), 192
Dynamic Property k Scale Up

Incomplete Layer Method (Geometric Average):

Use this method when the permeabilities vary in more than one direction. Then, we have an upper bound $k_{\text{max}}$ computed by taking the harmonic average of the arithmetic average, and a lower bound $k_{\text{min}}$ given by an arithmetic average of the harmonic average. The best estimate of $\bar{k}$ is then $\sqrt{k_{\text{min}}k_{\text{max}}}$.

Or, the effective $k$ for this 5x5 illustrated coarse block (right) is derived by:

- $k_{\text{max}}$ from the arithmetic avg. of columns 1-5 (c1-5) and then assuming c1-5 are flowing with $k$ changing perpendicular to flow direction (harmonic avg)
- $k_{\text{min}}$ assumes $k$ is changing perpendicular to flow direction for rows 1-5 (r1-5) harmonic avg and then the arithmetic average of r1-5, i.e. $k$ changing parallel to flow direction

Adapted from: Kelkar, M. G. and Perez G.; “Applied Geostatistics for Reservoir Characterization,” Society of Petroleum Engineers (2002), 192, 193

Vertical Equilibrium (VE) and No-Crossflow

Vertical equilibrium is a condition where the sum of all the fluid flow driving forces in the direction perpendicular to the direction of bulk fluid flow is zero.

This means that there is communication between flow units.

Vertical equilibrium is contrasted with “No-Crossflow”, which is defined as no vertical flow between flow units. No-crossflow can also mean that within a single flow unit having a continuous vertical permeability barrier within it.

Adapted from: Kelkar, M. G. and Perez G.; “Applied Geostatistics for Reservoir Characterization,” Society of Petroleum Engineers (2002), 189-191
Upscaling Horizontal Permeability

- ϕ traces from well logs are loaded into modeling software
- Statistical relationships created by zone and well location → semi-variogram
- Each cell receives a single average k value
- Geostatistics or vertical equilibrium or no-crossflow understandings used to populate properties between wells
- k arrays are created from a porosity-k transform
- A script is written in modeling software to read the cell porosity data and use the transform to assign the cell a k value