Quantitative petrophysical uncertainties modeling and its impact on reserves estimates

Nicolas Poete, Paradigm
Topics of discussion

- Evaluation of reserves
- Source of uncertainties
- Type of uncertainties
- Accuracy and precision
- Modeling uncertainties
- Modular or single workflow?
- Horizontal or vertical processing?
- How many iterations?
- Petrophysical uncertainties with Paradigm
- Combining petrophysical uncertainty with other uncertainties
Evaluation of reserves

Source of uncertainties
Type of uncertainties
Accuracy and precision
Modeling uncertainties
Modular or single workflow?
Horizontal or vertical processing?
How many iterations?
Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
The challenge
To evaluate reserves, we need a reliable estimate of Hydrocarbon Pore Volume, Water Saturation and Recovery Factor

Reserves = GRV * NTG * Φ * (1 - Sw) * RF / FVF
Reserves evaluation challenge

The challenge
To evaluate reserves, we need a reliable estimate of Hydrocarbon Pore Volume, Water Saturation and Recovery Factor.

Reserves = GRV * NTG * Φ * (1 - Sw) * RF / FVF

Net to Gross  Porosity  Water Saturation

From the petrophysical interpretation!
**Booking reserves - Definitions**

- **Proved reserves**  
  *Proved reserves* are those quantities of petroleum which [...] can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under current economic conditions, operating methods, and government regulations. [...] If probabilistic methods are used, there should be at least a 90% probability that the quantities actually recovered will equal or exceed the estimate.

- **Probable reserves**  
  *Probable reserves* are those unproved reserves which [...] are more likely than not to be recoverable. If probabilistic methods are used, there should be at least a 50% probability that the quantities actually recovered will equal or exceed the sum of estimated proved plus probable reserves.

- **Possible reserves**  
  *Possible reserves* are those unproved reserves which [...] are less likely to be recoverable than probable reserves. If probabilistic methods are used, there should be at least a 10% probability that the quantities actually recovered will equal or exceed the sum of estimated proved plus probable plus possible reserves.

*Source: Guidelines for the Evaluation of Petroleum Reserves and Resources SPE/WPC*
The range of uncertainty reflects a reasonable range of estimated potentially recoverable volumes for an individual accumulation or a project.

In the case of reserves, and where appropriate, this range of uncertainty can be reflected in estimates for **proved reserves (1P)**, **proved plus probable reserves (2P)**, and **proved plus probable plus possible reserves (3P)** scenarios. For other resource categories, the equivalent terms Low Estimate, Best Estimate, and High Estimate are recommended.

![Resource Uncertainty Categories](image-url)

*Figure 2.3—Resource Uncertainty Categories*

Source: Guidelines for the Evaluation of Petroleum Reserves and Resources SPE/WPC
OIP estimates – Several scenarios

Facies
Porosity
Saturation
OIP
Reserves estimates – Several scenarios

- **P1 scenario**
- **P2 scenario**
- **P3 scenario**

- **P90 – Realization #67**
- **P50 – Realization #93**
- **P10 – Realization #50**
Reserve estimates - facts

- We need to provide 1P, 2P and 3P scenarios

- To provide such figures we need to integrate the notion of uncertainty from the various input of our reservoir model

- Petrophysical properties have a sensible contribution in the reserve estimation, so we should consider assessment of petrophysical uncertainties together with all other source of uncertainties

Reserves = GRV * NTG * Φ * (1 - Sw) * RF / FVF
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Combining petrophysical uncertainty with other uncertainties
Uncertainty is everywhere …

…and you cannot escape from it

Sources of uncertainties

**Structural:** horizon and fault position and extent, thickness, ...

**Fluid Contacts:** OWC, GOC, GWC

**Sedimentology:** Facies, rock type, reservoir distribution, ...

**Petrophysical:** Φ, NTG, Kx, Ky, Kz

**Fluids:** Sw, Bo/Bg, Rs,...
Structural uncertainties

Acquisition and processing

Velocity and time depth migration

Fault interpretation

Sparse data / poor resolution

Horizon picking
Geological uncertainties

- Facies / rocktype
- Isochore variation
- Reservoir distribution (channel, pinchout, …)
Fluid contact uncertainties

- Oil / Gas down to (ODT / GDT)
- Water up to (WUT)
- Unknown compartments
- Non flat contact
Petrophysical uncertainties

- Porosity
- Water saturation
- Net to gross
- Permeability ($K_x, K_y, K_z$)
Fluids uncertainties

- Formation volume factor (Bo / Bg)
- Gas Oil Ratio
- Uncertainty on well test interpretation
  - Gauge Reservoir pressure measurement
  - Flow behavior diagnostic & modeling
Uncertainties - facts

• Uncertainties are present everywhere:
  – Structural
  – Fluid contacts
  – Sedimentology
  – Petrophysics
  – Fluids

• We’ll look here at petrophysical uncertainties only
[...] Petrophysical uncertainty is fundamentally different from the gross rock volume and mapping related uncertainty, and causes the relative importance of petrophysical uncertainty to increase throughout a field's life cycle. At one point in maturing field's life, the petrophysical uncertainty will often become the most important source of HCPV uncertainty. [...]
An example

- Reservoir with following properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>300</td>
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<tr>
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<tr>
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<tr>
<td>Porosity</td>
<td>0.18</td>
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<tr>
<td>Water saturation</td>
<td>0.35</td>
</tr>
<tr>
<td>RF/FVF</td>
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</table>

Reserves = GRV * NTG * Φ * (1 - Sw) * RF / FVF = 95,472
Effect on reserves with error bars

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>±5%</td>
</tr>
<tr>
<td>Width</td>
<td>200</td>
<td>±5%</td>
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<tr>
<td>Height</td>
<td>20</td>
<td>±5%</td>
</tr>
<tr>
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</tr>
<tr>
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<td>±5%</td>
</tr>
<tr>
<td>RF/FVF</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: NTG, porosity and SW variation is absolute
Effect on reserves with error bars

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**Effect on reserves with error bars**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
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<td>Width</td>
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</tr>
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Note: NTG, porosity and SW variation is absolute.
Evaluation of reserves
Source of uncertainties

**Type of uncertainties**
Accuracy and precision
Modeling uncertainties
Modular or single workflow?
Horizontal or vertical processing?
How many iterations?
Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
Three types of uncertainty

- Random
- Systematic
- Model based
Random uncertainty

- Due to measurement noise

- Generally accounted for by zone averaging

- The effects must not be ignored, especially when picking parameters and cutoffs
Systematic uncertainty

- Where there is a bulk shift between a measurement and the true value

- In logs, due to calibration errors and environmental effects “Measurement uncertainty”

- In parameters, due to insufficient knowledge of the formation or lack of representative data “Geological uncertainty”
Model based uncertainty

- Where the interpretation model used might not be appropriate for the formation being evaluated

- Generally the biggest impact, the hardest to quantify and the least analyzed
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Accuracy and precision

• The **accuracy** of a measurement system is the degree of closeness of measurements of a quantity to that quantity's actual (true) value.

• The **precision** of a measurement system is the degree to which repeated measurements under unchanged conditions show the same results.

The target analogy

<table>
<thead>
<tr>
<th>High</th>
<th>Precision</th>
<th>Low</th>
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<tbody>
<tr>
<td>High</td>
<td><img src="image1.png" alt="High Precision" /></td>
<td><img src="image2.png" alt="High Low" /></td>
</tr>
<tr>
<td>Low</td>
<td><img src="image3.png" alt="Low Precision" /></td>
<td><img src="image4.png" alt="Low Low" /></td>
</tr>
</tbody>
</table>

Accuracy

- Low
- High
Accuracy and precision

- Low uncertainty does not always equate to accuracy – it might indicate the wrong model!

“It’s better to be vaguely accurate than precisely wrong” (Keynes)
Evaluation of reserves
Source of uncertainties
Type of uncertainties
Accuracy and precision

Modeling uncertainties

Modular or single workflow?
Horizontal or vertical processing?
How many iterations?
Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
• The objective of petrophysical uncertainty modeling is to take into account all of the potential errors and the appropriate methods of interpretation and to produce a range of results which are theoretically possible, given the data available at the time.

• Furthermore, a series of probabilities should be produced which indicate the likelihood of each of the possible answers being the true case.

• There are two ways in which petrophysical uncertainty can be quantified:
  – Analytical methods: Mathematical modeling of the possible ranges in results
  – Monte Carlo modeling: Iterative method varying each measurement and parameter within a given statistical distribution
Petrophysical Uncertainties

Uncertainty in the input parameters and well logs can have an overwhelming influence on the outcomes. A true probabilistic approach yields a statistically rigorous set of results.
Monte Carlo processing

- Monte Carlo processing involves running an interpretation many times with log and parameters values randomly selected from a user defined range.

- The output is a probability density function (PDF) for every value calculated at every depth.

![Diagram showing a bell curve indicating the number of calculations vs calculated value.](image-url)
PDF distributions

- Three type of distribution for input parameters and logs

Normal

Linear

Triangular
Triangular PDF

- Minimum Value
- Actual Log/Param Value
- Random value for iteration n
- Maximum Value

Number of occurrences
Evaluation of reserves
Source of uncertainties
Type of uncertainties
Accuracy and precision
Modeling uncertainties

Modular or single workflow?
Horizontal or vertical processing?
How many iterations?
Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
In a **Modular** MC system each part of the workflow is run separately, with three versions of each output curve passed to the later parts of the interpretation.

Strengths:  
- Little computer memory used, easy to code

Weaknesses:  
- Many steps, cumbersome, many opportunities for user error
  
- Actual distributions of data are lost in the process

- Parameter dependencies difficult to implement (some are ignored).
In a **Single Workflow** MC system a complete version of the interpretation is run for each iteration.

**EC** $\rightarrow$ **Vsh** $\rightarrow$ **Porosity** $\rightarrow$ **Permeability** $\rightarrow$ **Sw** $\rightarrow$ **BV_HC**

**Strengths:**
- Actual distributions are passed between interpretation steps
- Automatically accounts for most parameter dependencies
- Other dependencies can be accounted for using auto-adjust technique
- Easier to run, less opportunities for user error

**Weaknesses:**
- Uses more memory, complete workflow must be in one module.
Modular or Single Workflow Monte Carlo?

Output distributions are dependent on the functions used.

![Linear Function Diagram]
Output distributions are dependent on the functions used.
Modular or Single Workflow Monte Carlo?

When distributions of formation properties are used in modular systems dependencies are often overlooked.
Modular or Single Workflow Monte Carlo?

An example of the difference in a laminar interpretation model:

**Single Workflow**
- Variation only in \( V_{sh} \) and \( m \)
- Base case = 13.26', mean = 13.28'
- \( \text{min} = 11.66' \), \( \text{max} = 14.53' \), **St dev = 0.65'**

**Modular Workflow**
- Variation only in \( V_{sh} \) and \( m \)
- Base case = 13.26', mean = 13.24'
- \( \text{min} = 10.56' \), \( \text{max} = 16.06' \), **St dev = 1.27'**
Evaluation of reserves
Source of uncertainties
Type of uncertainties
Accuracy and precision
Modeling uncertainties
Modular or single workflow?

**Horizontal or vertical processing?**

How many iterations?
Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
**‘Horizontal’ or ‘Vertical’ processing?’**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Iteration 1</th>
<th>Iteration 2</th>
<th>Iteration 3</th>
<th>Iteration 4</th>
<th>Iteration 5</th>
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<tbody>
<tr>
<td>5000</td>
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<td>Vsh Ø Sw k bvhc</td>
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<tr>
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**“HORIZONTAL PROCESSING”**
### ‘Horizontal’ or ‘Vertical’ processing?

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<tbody>
<tr>
<td>5000</td>
<td>Vsh Ø Sw k bvhc</td>
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<td>5001.5</td>
<td>Vsh Ø Sw k bvhc</td>
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<tr>
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<td>Vsh Ø Sw k bvhc</td>
<td>Vsh Ø Sw k bvhc</td>
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<tr>
<td>5003</td>
<td>Vsh Ø Sw k bvhc</td>
<td>Vsh Ø Sw k bvhc</td>
<td>Vsh Ø Sw k bvhc</td>
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</tbody>
</table>
Horizontal vs. Vertical processing

- ‘Horizontal Processing’
  - A new parameter set is randomly selected for every depth
  - Allows for accurate modeling of *random* uncertainty
  - No vertical relation between data points

- ‘Vertical Processing’
  - Each set of randomly selected parameters is applied to all computations over the entire log section
  - Allows for accurate modeling of *systematic* uncertainty
  - Same parameters used at all depths give a vertical relationship of the output
Evaluation of reserves
Source of uncertainties
Type of uncertainties
Accuracy and precision
Modeling uncertainties
Modular or single workflow?
Horizontal or vertical processing?

How many iterations?

Petrophysical uncertainties with Paradigm
Combining petrophysical uncertainty with other uncertainties
How many iterations?
How many iterations?

Onshore well, Wyoming
How many iterations?

Offshore well, West Africa
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Petrophysical uncertainty in Geolog

- Determin Uncertainty module in Paradigm’s Geolog
- Coherent processing of entire interval produces full range of possible solutions for defined input PDFs
Deterministic uncertainty

Input logs

Input parameters

Petrophysical results

GR
Neutron Density
Rt Rxo

MA SH

VSH

FL

A M N Rw

Φ

Sw

Perm BV_HC
Input logs

Input parameters

Petrophysical results
### Input logs corrections

- Environmental corrections for various contractor
- Single module interface to correct all logs at once
- Input parameter error bar and log accuracy

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<td>DT_HI</td>
<td>RXD_HI</td>
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<tr>
<td>CR_COR</td>
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<td>NPHI_COR</td>
<td>DT_LO</td>
<td>RXD_LO</td>
<td>PT_LO</td>
</tr>
</tbody>
</table>

![Graph showing data on various parameters](image-url)
Input parameters

Input logs

Petrophysical results

GR
Neutron Density
Rt
Rxo
MA
SH
VSH
FL
A
M
N
Rw

Petrophysical results
- Intermediate results distributions need to be used for subsequent steps as input
- Only possible with a workflow/combined approach
Petrophysical uncertainty results

- 1P, 2P & 3P output curves for VSH, PHI, SW, etc.
- Plus a distribution of these (VSH_D, PHI_D, SW_D, etc. 100 Prob values)
Automatic parameter adjustment

\[ \phi \]

\[ Rt \]

\[ Rw \]

\[ m \]
Automatic parameter adjustment

Applying this $m$ value…

to this data point gives a huge error!

$m$ ???
Monte Carlo results

Equivalent Hydrocarbon Column for each zone, with distribution of possible answers, cumulative distribution function and P10, P50 and P90 figures

\[ \text{EHC} = \text{PHI} \times (1 - \text{SW}) \times \text{height} \]

Use of 1P, 2P and 3P terminology instead of P10/P50/P90

1P = possible
2P = possible + probable
3P = possible + probable + proven
Petrophysical uncertainty results

- Discrete probability results (P10, P50, P90) for each calculated parameter are easily output for use in reservoir modeling
Sensitivity Analysis

- Sensitivity analysis shows which inputs have greatest impact on results.
Which interpretation model?

- Many combination possible
- Need to be able to assess model based uncertainties
Multi model uncertainty evaluation
Multi model uncertainty evaluation

Combined EHC for different models

Blue bars represent the percentage of total calculations for each value

Red line is the Cumulative Distribution Function (CDF) with 10%, 50% and 90% probabilities shown
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Combining petrophysical uncertainty with other uncertainties
Petrophysical uncertainty results

- Discrete probability results (P10, P50, P90) for each calculated parameter are easily output for use in reservoir modeling
Uncertainty in facies and porosity logs

Sand A

Sand B
NTG uncertainty

• Cutoff values?
• TVD uncertainty
  – Sparse survey data
  – Uncertainty on survey tool position
  – TVD calculation method (interpolation)
• Big impact on net thickness and subsequently on NTG
Geologic Uncertainty - Reservoir Risk Assessment (JACTA)

Structural: Horizons, Thickness
Contacts: OWC, GOC, GWC
Sedimentology: Facies, Rocktypes,...
Petrophysical: $\Phi$, $N/G$, $K_x$, $K_y$, $K_z$
Fluids: Sw, Bo/Bg, Rs,...

Histogram

Realization Number

Volumes

CDF
Reserves estimates – Several scenarios

P1 scenario

P2 scenario

P3 scenario

P90 – Realization #67

P50 – Realization #93

P10 – Realization #50
Relative importance of petrophysical uncertainty

Including Structural and OWC uncertainty

No petrophysical uncertainty

With petrophysical uncertainty
Impact on production
Impact on production
Impact on production
• Petrophysical properties have a non negligible impact on reserves estimates and their uncertainties.

• Systematic and model uncertainties are the main source of inaccuracy in petrophysical interpretation.

• A holistic approach to petrophysical uncertainty is required to ensure that the true range of unknowns is considered for the hydrocarbon-in-place computation.

• Paradigm offers this type of petrophysical uncertainties assessment tools with a seamless integration with its reservoir risk assessment solution.
Thank you!

Questions?
References

“Quantification of Petrophysical Uncertainty and Its Effect on In-Place Volume Estimates: Numerous Challenges and Some Solutions”

“Accuracy - Essential Information for a Log Measurement”

“A serious look at repeat sections”

“Using quantified ‘model based' petrophysical uncertainty to aid in conflict resolution”
John Kennedy & Pujiyono, Hess Oil and Gas Malaysia, Andrew Cox & Rick Aldred, Paradigm - SPWLA 51th Annual Logging Symposium, June 19-23 2010, Perth, Australia

“Dependencies and ranking: two keys for an efficient petrophysical uncertainty evaluation”
Jacques Ventre& P. Terpolilli, Total, Wol Chaffe, Paradigm - SPWLA 45th Annual Logging Symposium, June 6-9 2014, Noordwijk, The Netherlands