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From Monte Carlo to Bayes Theory: The Role of Uncertainty in Petrophysics

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Subsurface Characterisation

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The main goal of the oil-industry geoscience professional is to characterise the complete range of possible configurations of the subsurface for a given set of data and related analogues.

This characterisation of the subsurface should lead to a comprehensive description of uncertainty that leads to the complete disclosure of the financial risk of further exploration, appraisal or development of a potential hydrocarbon resource.

Subsurface Realisation Tables

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		Parameters						
		Comm. with Tor	Productivity	Variation North-South (N-S)	In place Volume	Fault sealing capacity	Water injectivity	Flank Potential
Realisations	1	Hardground Seals	Good Matrix High Fracture	N Good S Med Gradual change	High case	Sealing	Possible	Loads
	2	Hardground does not seal	Good Matrix Low Fracture	N Bad S Good Gradual change	Low case	Not Sealing	Not possible	Some
	3	Variable seal	Poor Matrix High Fracture	N Good S Bad Sudden change	Mid case	Partially sealing		None
	4		Poor Matrix No Fracture	N Good S Good				
	5		Med Matrix Med Fracture	Only have what is producing today				

Petrophysical workflows

$$VclGr = \frac{Gr - GrClean}{GrClay - GRClean}$$

Calculate Volume of Clay

Volume of Clay

$$\phi = \frac{(\rho_{ma} - \rho_b - Vcl \times (\rho_{ma} - \rho_{cl}))}{(\rho_{ma} - \rho_{fl} \times Sxo - \rho_{HyAp} \times (1 - Sxo))}$$

Calculate Clay Corrected Porosity

Effective and Total Porosity

$$SwT = \sqrt[n]{\frac{a \times Rw}{Rt \times PhiT^{m}}}$$

Calculate Clay Corrected Saturation

Effective and Total Water Saturation

$$S_{av} = 1 - \frac{\sum_{i=1}^{i=n} \phi_i \times h_i \times (1 - Sw)}{\sum_{i=1}^{i=n} \phi_i \times h_i}$$

Apply cut-offs for net sand, reservoir and pay and averages

Average Vcl, Por, Phi And HPVOL

Petrophysical Base Case Interpretation

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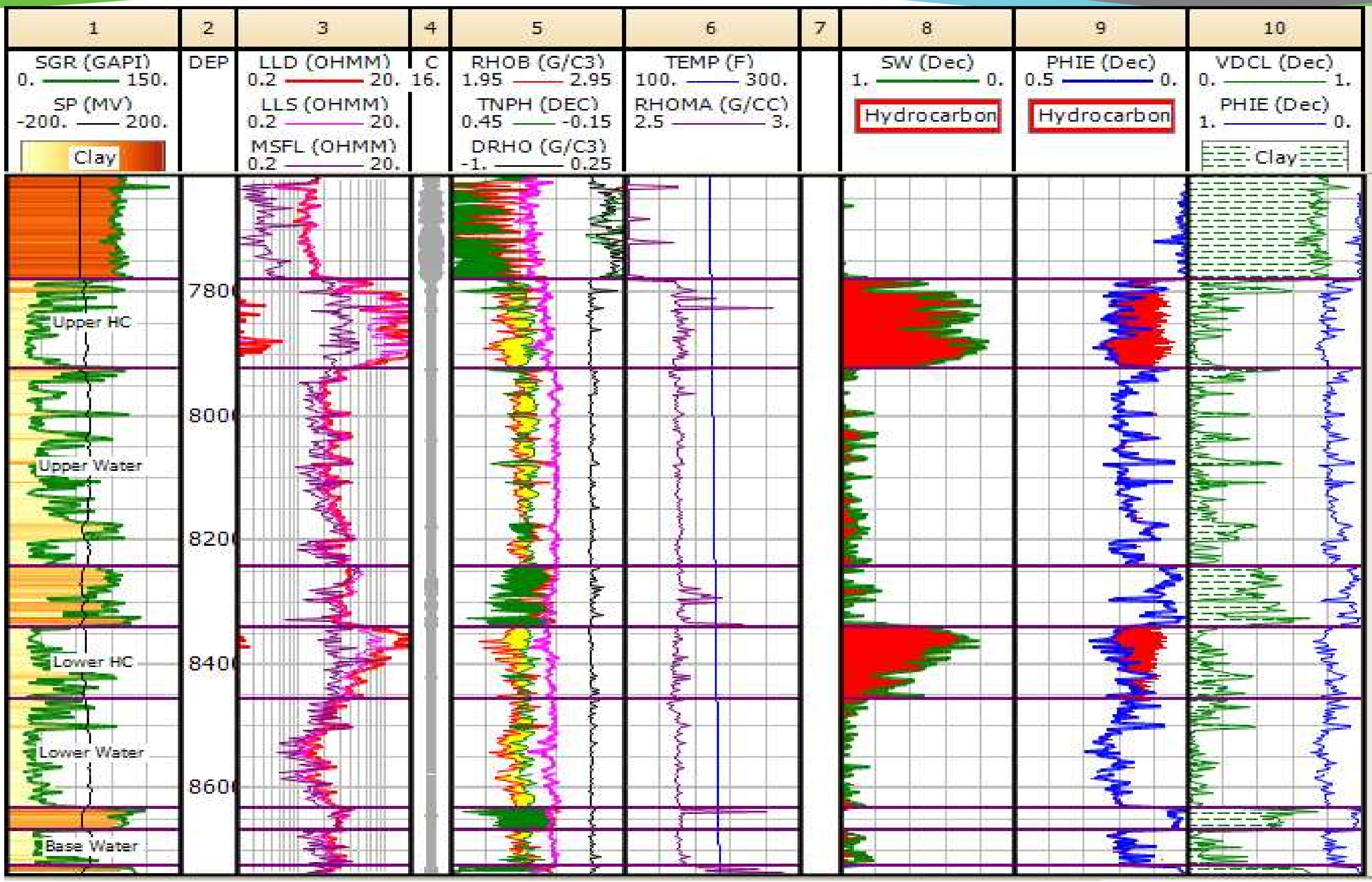

Petrophysical Base Case Interpretation

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Zone Depths | Reservoir Cutoffs | Pay Cutoffs | Reservoir Results | Pay Results

Zone #	Gross interval	Net Pay	Net/Gross Pay	Av Phi Pay	Av Sw Pay	Av Vcl Pay	PhiH Pay	PhiSoH Pay	VclH Pay
1	142.50	122.50	0.860	0.205	0.343	0.105	25.11	16.50	12.83
2	318.00	0.00	0.000	---	---	---	---	---	---
3	117.00	92.50	0.791	0.199	0.453	0.121	18.38	10.05	11.18
4	175.50	$$0.00	0.000	---	---	---	---	---	---
5	59.00	0.00	0.000	---	---	---	---	---	---
6	460.50	122.50	0.266	0.205	0.343	0.105	25.11	16.50	12.83
7	292.50	92.50	0.316	0.199	0.453	0.121	18.38	10.05	11.18

Methods of Uncertainty Analysis

- Parameter sensitivity analysis
- Partial derivative analysis
- Monte Carlo Simulation
- Bayesian Analysis for Diagnostic Reliability

Sensitivity Analysis of Input Parameters – Single Parameter

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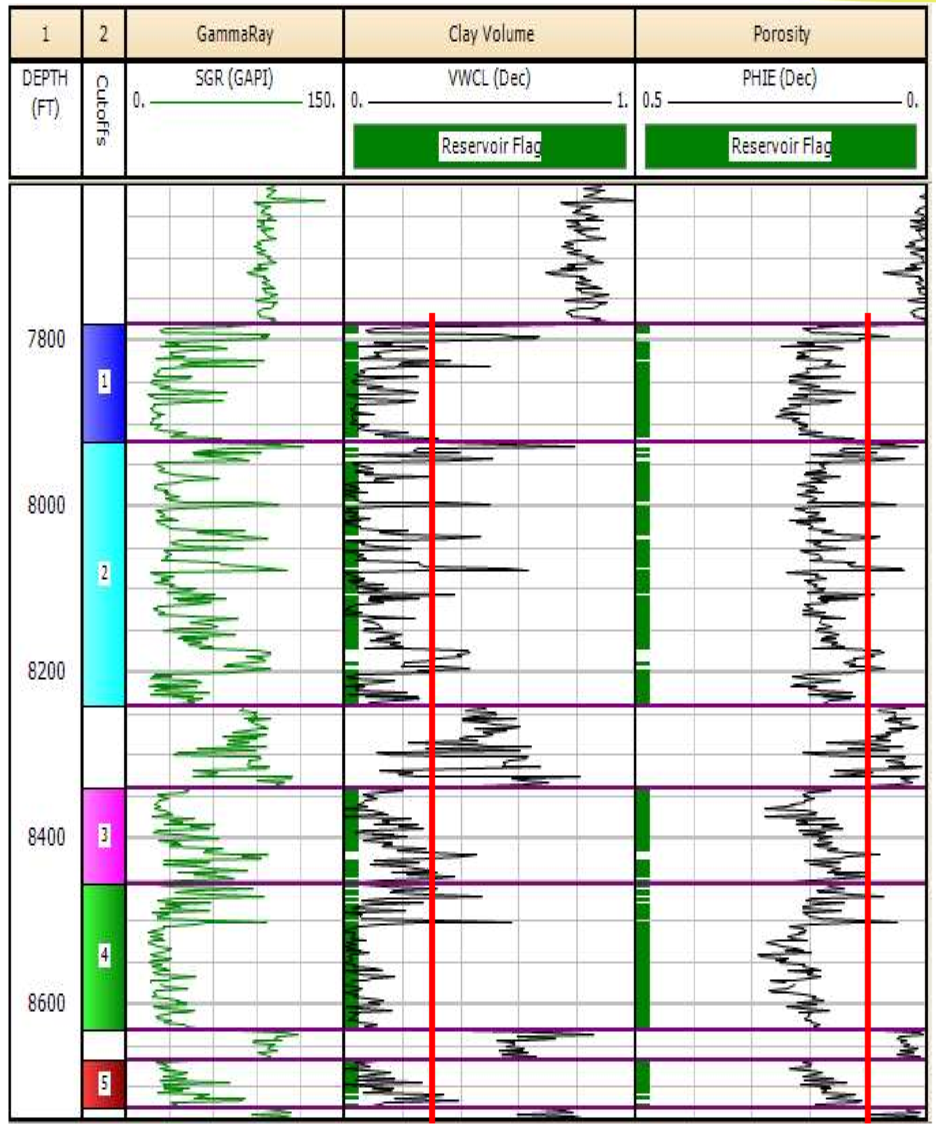
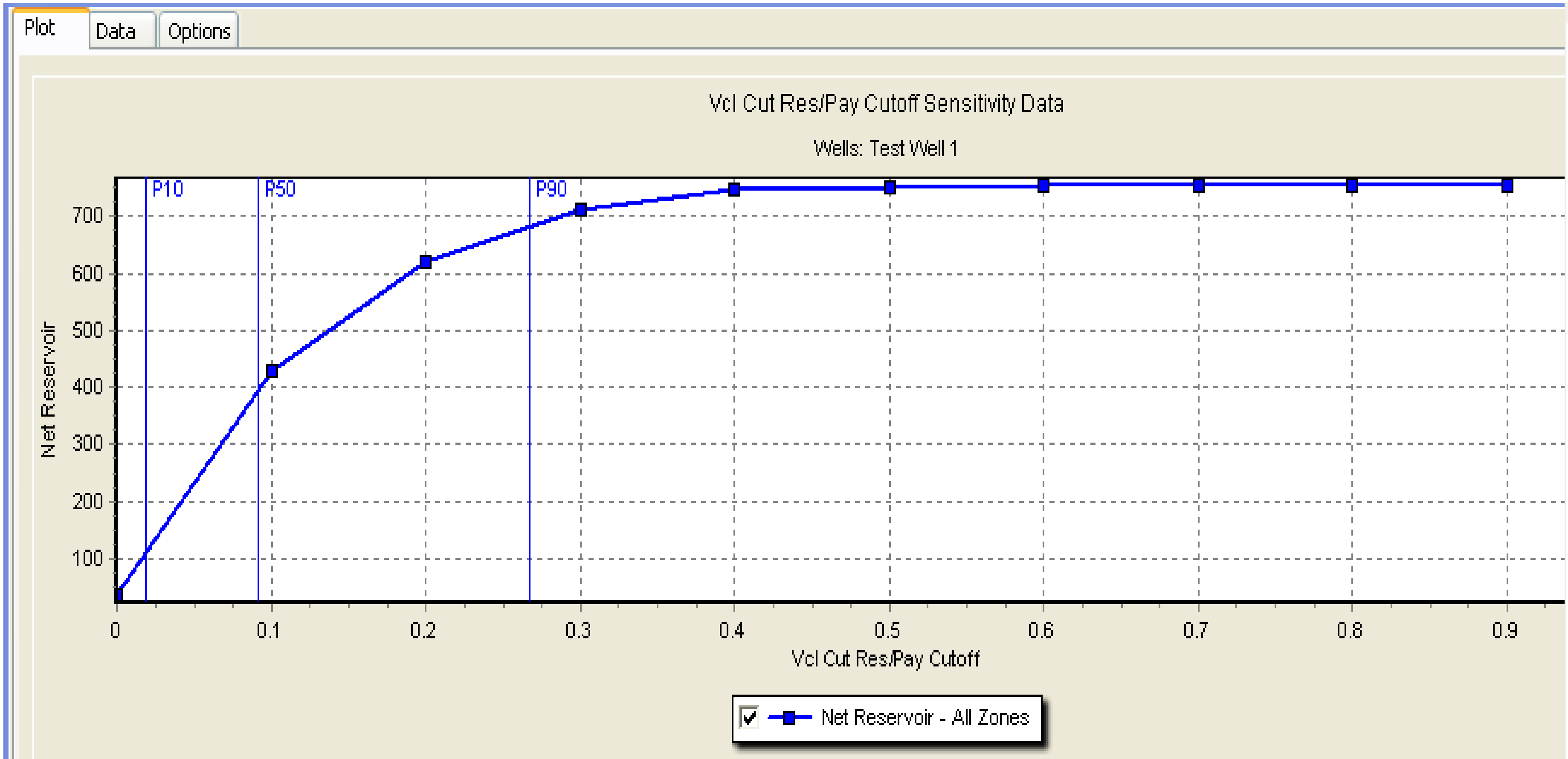
- For example:
  - Volume of clay cut-off for net reservoir
  - If VCL <= 0.3 and
  - If PHIE >= 0.1 then
  - The interval is flagged as net reservoir



Sensitivity Analysis of Input Parameters – Single Parameter



Y axis	Zone	Percentile	Cutoff	Value	Show		Percentile	Cutoff	Value	Show		Percentile	Cutoff	Value
Net Reservoir	All Zones	10	0.018	107.425	✓		50	0.092	395.125	✓		90	0.268	682.825

Sensitivity Analysis of Input Parameters – Single Parameters

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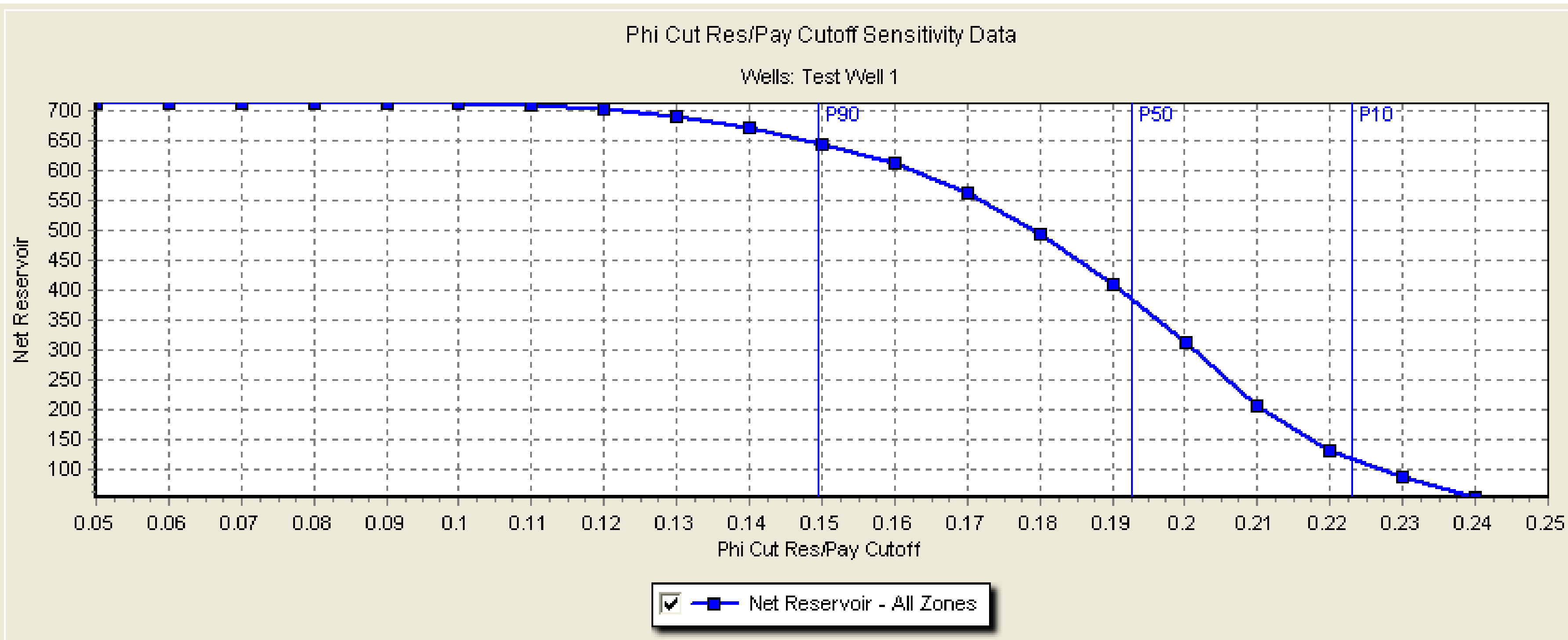

Y axis	Zone	Percentile	Cutoff	Value	Show		Percentile	Cutoff	Value	Show		Percentile	Cutoff
Net Reservoir	All Zones	10	0.223	118.65	✓		50	0.193	383.25	✓		90	0.15

Partial Derivative Analysis

- In mathematics, a partial derivative of a function of several variables is its derivative with respect to one of those variables, with the others held constant (as opposed to the total derivative, in which all variables are allowed to vary). Partial derivatives are used in vector calculus and differential geometry.

- The partial derivative of a function f with respect to the variable x is variously denoted by

$$f'_x,\ f_x,\ \partial_x f,\ \text{or}\ \frac{\partial f}{\partial x}.$$

- The partial-derivative symbol is ∂. The notation was introduced by Adrien-Marie Legendre and gained general acceptance after its reintroduction by Carl Gustav Jacob Jacobi.

Partial Derivative Analysis – Example

- Volume of a cone is:

$$V(r,h) = \frac{\pi r^2 h}{3}.$$

- The partial derivative of the volume with respect to the radius is

$$\frac{\partial V}{\partial r} = \frac{2\pi r h}{3},$$

- Which describes the rate at which the volume changes with change in radius if the height is kept constant.

Partial Derivative Analysis for Waxman-Smits Equation for Saturation

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$$Sw = \left(\frac{Rt \cdot \left(1 + \frac{Rw \cdot B \cdot Qv}{Sw}\right) \cdot \phi^m}{A \cdot Rw} \right)^{-1/n}$$

$$\delta Sw = \sqrt{\left(\frac{\partial Sw}{\partial Rt} \cdot \delta Rt\right)^2 + \left(\frac{\partial Sw}{\partial Rw} \cdot \delta Rw\right)^2 + \left(\frac{\partial Sw}{\partial \phi} \cdot \delta \phi\right)^2 + \left(\frac{\partial Sw}{\partial A} \cdot \delta A\right)^2 + \left(\frac{\partial Sw}{\partial m} \cdot \delta m\right)^2 + \left(\frac{\partial Sw}{\partial n} \cdot \delta n\right)^2}$$

$$\frac{\partial Sw}{\partial Rt} = -\frac{Rw}{E \cdot Rt}; \qquad \frac{\partial Sw}{\partial Rw} = \frac{Sw^2}{E \cdot Rw}; \qquad \frac{\partial Sw}{\partial \phi} = -\frac{m \cdot Rw \cdot F}{E \cdot \phi}$$

$$\frac{\partial Sw}{\partial A} = \frac{Rw \cdot F}{E \cdot A}; \qquad \frac{\partial Sw}{\partial m} = -\frac{Rw \cdot F \cdot \ln(\phi)}{E}; \qquad \frac{\partial Sw}{\partial n} = -\frac{Rw \cdot F \cdot \ln(Sw)}{E}$$

$$E = Sw + (n-1) \cdot (Sw + Rw \cdot B \cdot Qv); \qquad F = \frac{A \cdot \phi^{-m}}{Rt \cdot Sw^{(n-2)}}$$

Partial Derivative Analysis for A Complete Deterministic Petrophysical Analysis

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$$\delta total = \sqrt{\delta stat^2 + \delta sys^2 + \delta geol^2}$$

$$\delta stat = \frac{\sigma}{\sqrt{n}}; \quad \sigma = 1\,std\,dev; \quad n = number\ of\ samples$$

$$\phi = \frac{\rho ma - \rho b}{\rho ma - \rho fl}$$

$$\delta\phi = \sqrt{\left(\frac{\partial\phi}{\partial\rho ma}\cdot\delta\rho ma\right)^2 + \left(\frac{\partial\phi}{\partial\rho fl}\cdot\delta\rho fl\right)^2 + \left(\frac{\partial\phi}{\partial\rho b}\cdot\delta\rho b\right)^2}$$

$$\frac{\partial\phi}{\partial\rho ma} = \frac{\rho b - \rho fl}{(\rho ma - \rho fl)^2}; \quad \frac{\partial\phi}{\partial\rho fl} = \frac{\rho ma - \rho b}{(\rho ma - \rho fl)^2}; \quad \frac{\partial\phi}{\partial\rho b} = \frac{-1}{(\rho ma - \rho fl)};$$

$$Foil = \frac{n}{g}\cdot\phi\cdot(1 - Sw)$$

$$\delta Foil = \sqrt{\left(\frac{\partial Foil}{\partial n/g}\cdot\delta n/g\right)^2 + \left(\frac{\partial Foil}{\partial\phi}\cdot\delta\phi\right)^2 + \left(\frac{\partial Foil}{\partial Sw}\cdot\delta Sw\right)^2}$$

$$\frac{\partial Foil}{\partial n/g} = \phi\cdot(1 - Sw)$$

$$\frac{\partial Foil}{\partial\phi} = \frac{n}{g}\cdot\left(1 - Sw + \frac{m\cdot Rw\cdot F}{E}\right)$$

$$\frac{\partial Foil}{\partial Sw} = -\frac{n}{g}\cdot\phi$$

$$Sw = \left(\frac{Rt\cdot\left(1 + \frac{Rw\cdot B\cdot Qv}{Sw}\right)\cdot\phi^m}{A\cdot Rw}\right)^{-1/n}$$

$$\delta Sw = \sqrt{\left(\frac{\partial Sw}{\partial Rt}\cdot\delta Rt\right)^2 + \left(\frac{\partial Sw}{\partial Rw}\cdot\delta Rw\right)^2 + \left(\frac{\partial Sw}{\partial\phi}\cdot\delta\phi\right)^2 + \left(\frac{\partial Sw}{\partial A}\cdot\delta A\right)^2 + \left(\frac{\partial Sw}{\partial m}\cdot\delta m\right)^2 + \left(\frac{\partial Sw}{\partial n}\cdot\delta n\right)^2}$$

$$\frac{\partial Sw}{\partial Rt} = -\frac{Rw}{E\cdot Rt}; \quad \frac{\partial Sw}{\partial Rw} = \frac{Sw^2}{E\cdot Rw}; \quad \frac{\partial Sw}{\partial\phi} = -\frac{m\cdot Rw\cdot F}{E\cdot\phi}$$

$$\frac{\partial Sw}{\partial A} = \frac{Rw\cdot F}{E\cdot A}; \quad \frac{\partial Sw}{\partial m} = -\frac{Rw\cdot F\cdot\ln(\phi)}{E}; \quad \frac{\partial Sw}{\partial n} = -\frac{Rw\cdot F\cdot\ln(Sw)}{E}$$

$$E = Sw + (n-1)\cdot(Sw + Rw\cdot B\cdot Qv); \quad F = \frac{A\cdot\phi^{-m}}{Rt\cdot Sw^{(n-2)}}$$

Partial Derivative – Input Data

Zonal Averages

Sumavs						
well	zone	gross	net	n2g	por	Sw
1	HSGHL	45.6	30.8	0.676	0.264	0.364
2	HSGHL	19.9	11.9	0.595	0.243	0.478
4	HSGHL	44.8	22.2	0.497	0.256	0.347
5	HSGHL	31.3	11.7	0.376	0.266	0.319
6	HSGHL	5.7	0.0	0.000	0.000	1.000
7	HSGHL	40.0	12.2	0.305	0.239	0.292
8	HSGHL	46.8	16.2	0.345	0.270	0.393

Partial Derivative – Input Uncertainty

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Field:

Zone:

Porosity				
parameter	value	1 std dev	part error	% error
count	6			
w average	0.258	0.013		
δstat			0.005	2.0%
rhob	2.224	0.010	-0.006	-2.3%
rhoma	2.650	0.010	0.004	1.7%
rhofl	1.000	0.020	0.003	1.2%
δsys			0.008	3.2%
δgeol			0.000	0.0%
average	**0.258**	**δtotal**	**0.010**	**3.8%**

Hydrocarbon Saturation				
parameter	value	1 std dev	part error	% error
count	6			
w average	0.636	0.065		
δstat			0.027	4.2%
Rt	10.723	1.072	-0.026	-4.1%
Rw	0.300	0.060	0.021	3.4%
por	0.258	0.010	-0.017	-2.7%
A	1.000	0.001	0.000	0.0%
m	1.800	0.150	0.052	8.2%
n	2.000	0.200	0.052	8.2%
B	7.000	1.400	-0.030	-4.7%
Qv	0.245	0.025	-0.015	-2.4%
δsys			0.089	14.1%
δgeol			0.000	0.0%
average	**0.636**	**δtotal**	**0.093**	**14.7%**

net/gross				
count	7			
w average	0.449	0.222		
δstat			0.084	18.7%
δgeol			0.100	22.3%
average	**0.449**	**δtotal**	**0.131**	**29.1%**

Foil=n/g*por*Sh				
count	6			
w average	0.074	0.022		
n/g	0.449	0.131	0.021	29.1%
por	0.258	0.010	0.005	6.5%
Sh	0.636	0.093	-0.011	-14.7%
δsys			0.024	33.2%
average	**0.074**	**δtotal**	**0.024**	**33.2%**

Partial Derivative Analysis Results

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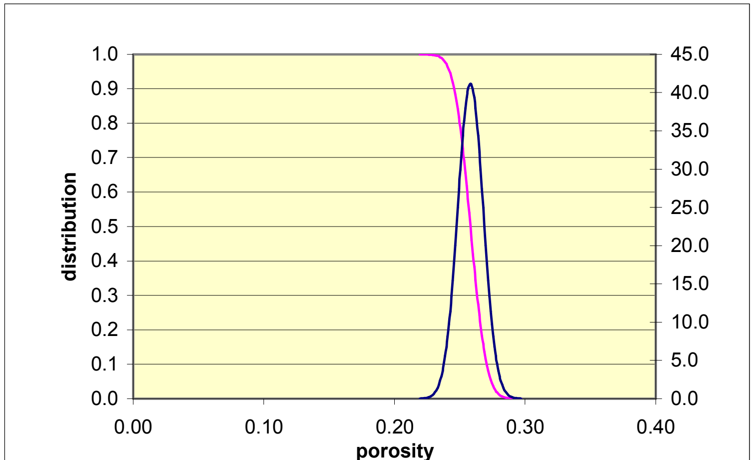
Uncertainty (Normal) Distribution Curves

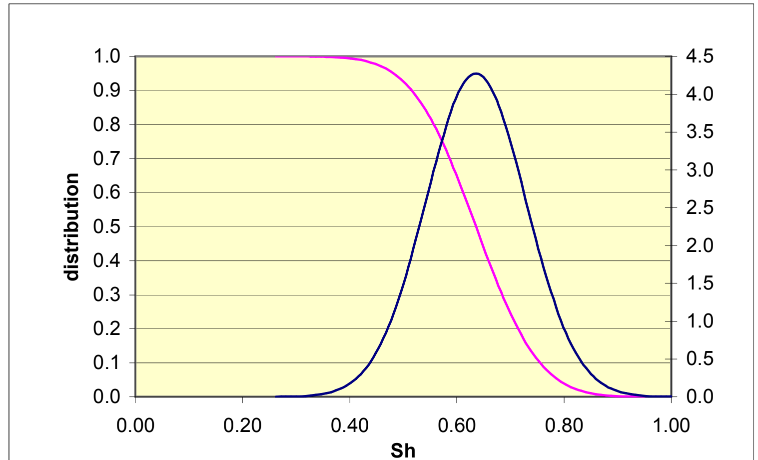
porosity



avg=0.258, std=0.010, std=3.8%

μ−3σ=0.229, μ+3σ=0.287

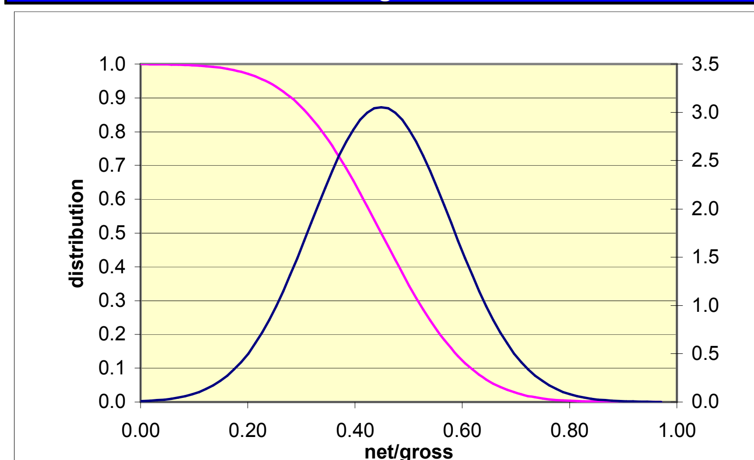
Hydrocarbon Saturation



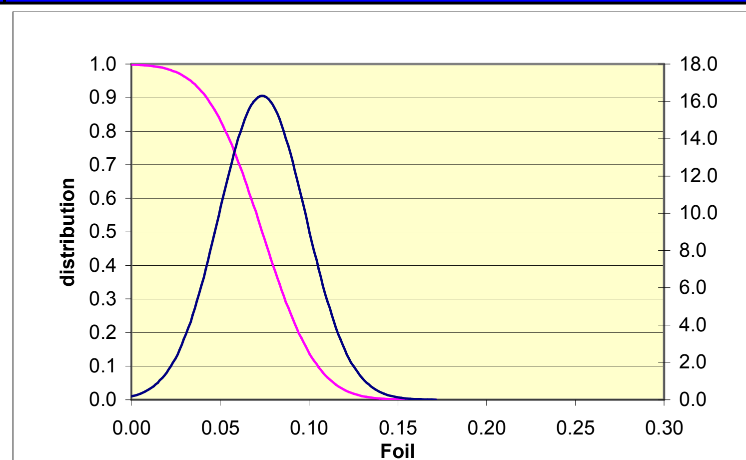
avg=0.636, std=0.093, std=14.7%

μ−3σ=0.356, μ+3σ=0.916

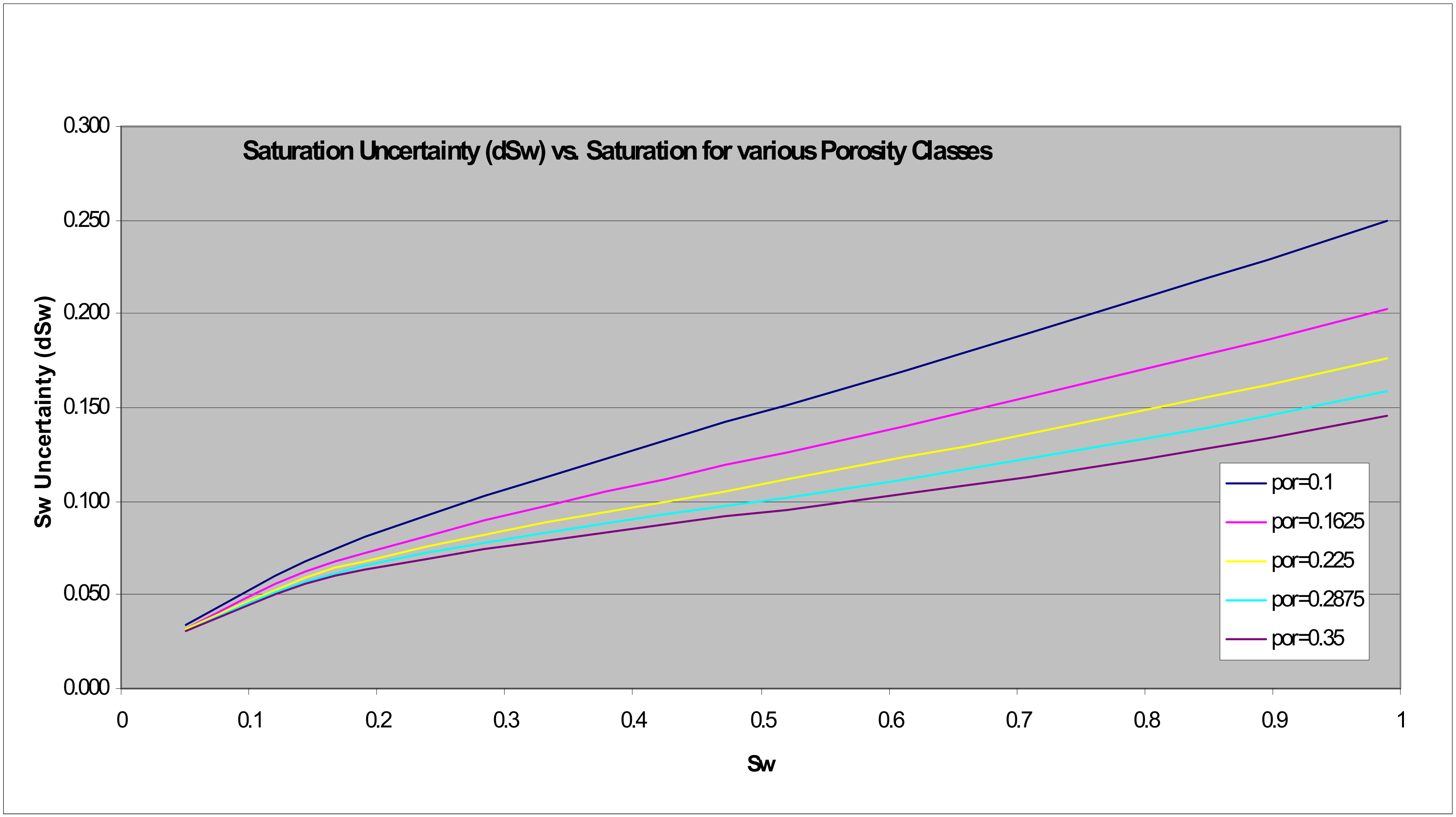
net/gross



Foil



Partial derivative Analysis - Saturation

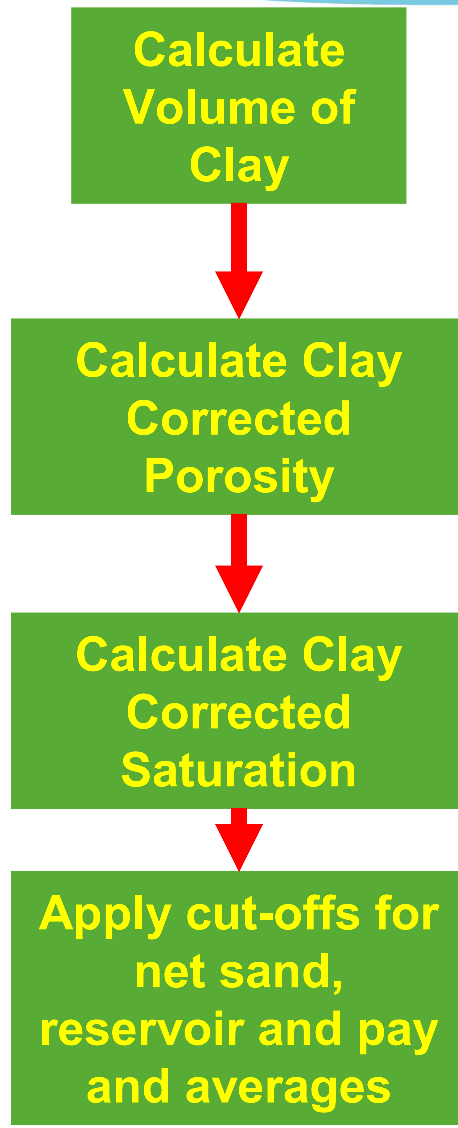


Monte-Carlo Simulation

- Multiple repeated calculation of all deterministic equations
- All input parameters can be sampled from a ‘distribution’ of expected range in parameters
- Co-dependency can be honoured
- All output can be analysed
- Relative contribution to error can

Be analysed

Requires a computer



Monte-Carlo Simulation

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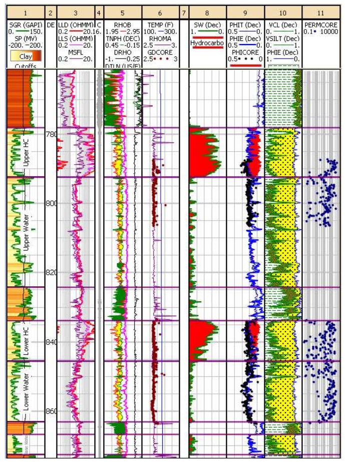
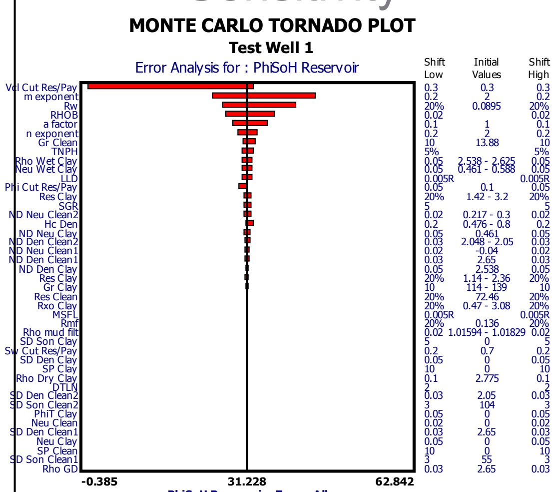
Reference Case



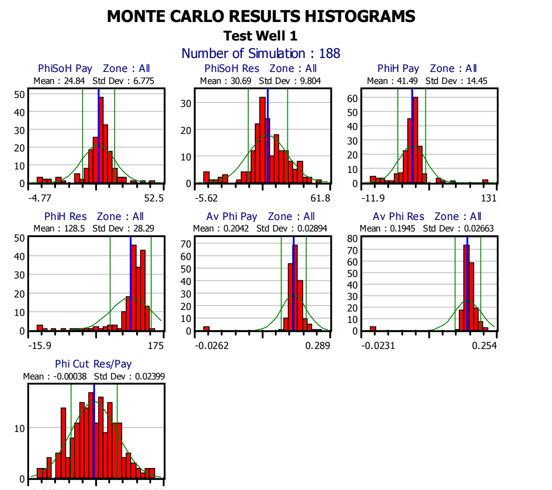
Uncertainty Definition

Use	Parameter Name	Type Shift	Shift Distribution	Initial Value	Low Value Shift	High Value Shift
✓	Gr Clean	Linear	Gaussian	13.88	10	10
✓	Gr Clay	Linear	Gaussian	114 - 139	10	10
✓	Neu Clean	Linear	Gaussian	0	0.02	0.02
✓	Neu Clay	Linear	Gaussian	0	0.05	0.05
✓	SP Clean	Linear	Gaussian	0	10	10
✓	SP Clay	Linear	Gaussian	0	10	10
✓	Res Clean	Percent	Gaussian	72.46	20	20
✓	Res Clay	Percent	Gaussian	1.14 - 2.36	20	20
✓	ND Neu Clay	Linear	Gaussian	0.461	0.05	0.05
✓	ND Den Clay	Linear	Gaussian	2.538	0.05	0.05
✓	ND Den Clean1	Linear	Gaussian	2.65	0.03	0.03
✓	ND Den Clean2	Linear	Gaussian	2.048 - 2.05	0.03	0.03
✓	ND Neu Clean1	Linear	Gaussian	-0.04	0.02	0.02
✓	ND Neu Clean2	Linear	Gaussian	0.217 - 0.3	0.02	0.02
✓	SD Son Clay	Linear	Gaussian	0	5	5
✓	SD Den Clay	Linear	Gaussian	0	0.05	0.05
✓	SD Den Clean1	Linear	Gaussian	2.65	0.03	0.03
✓	SD Den Clean2	Linear	Gaussian	2.05	0.03	0.03
✓	SD Son Clean1	Linear	Gaussian	55	3	3
✓	SD Son Clean2	Linear	Gaussian	104	3	3

Sensitivity



Results

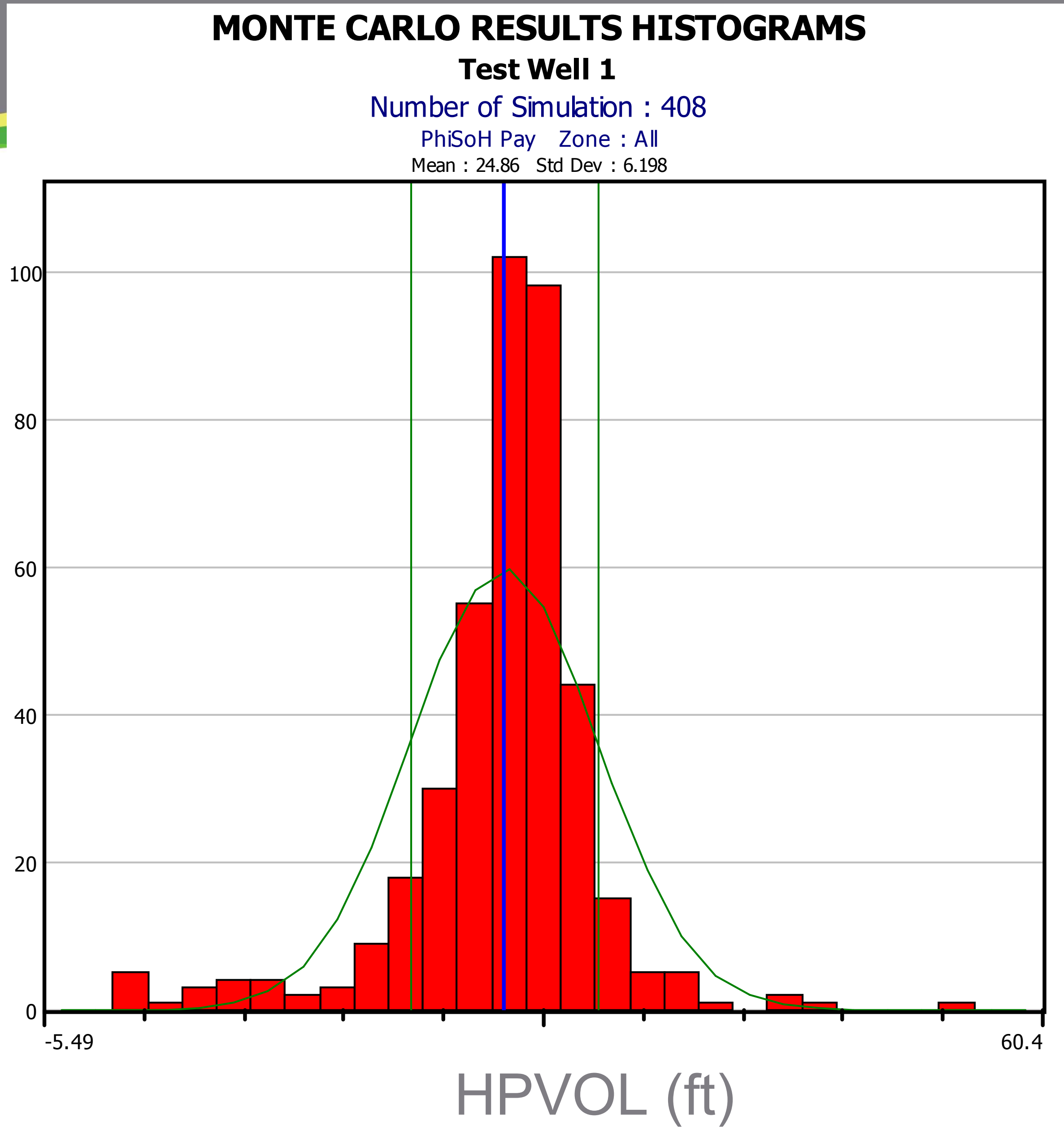


Models and Equations

Use	Module	Set Name	
✓	Clay Volume	ClayVol.set	Browse
✓	Porosity Sw	PhiSw.set	Browse
✓	Cutoff	Cutoff.set	Browse
	Formula		Browse

Use	Parameter Name	Type Shift	Shift Distribution	Initial Value	Low Value Shift	High Value Shift
✓	Rw	Percent	Gaussian	0.0895	20	20
✓	Rmf	Percent	Gaussian	0.136	20	20
✓	Rho mud_filt	Linear	Gaussian	1.01594 - 1.0	0.02	0.02
✓	Hc Den	Linear	Gaussian	0.476 - 0.8	0.2	0.2
✓	a factor	Linear	Gaussian	1	0.1	0.1
✓	m exponent	Linear	Gaussian	2	0.2	0.2
✓	n exponent	Linear	Gaussian	2	0.2	0.2
✓	Rho Wet Clay	Linear	Gaussian	2.538 - 2.625	0.05	0.05
✓	Neu Wet Clay	Linear	Gaussian	0.461 - 0.588	0.05	0.05
✓	Rho Dry Clay	Linear	Gaussian	2.775	0.1	0.1
✓	Res Clay	Percent	Gaussian	1.42 - 3.2	20	20
✓	Rxo Clay	Percent	Gaussian	0.47 - 3.08	20	20
✓	PhiT Clay	Linear	Gaussian	0	0.05	0.05
✓	Rho GD	Linear	Gaussian	2.65	0.03	0.03

Results

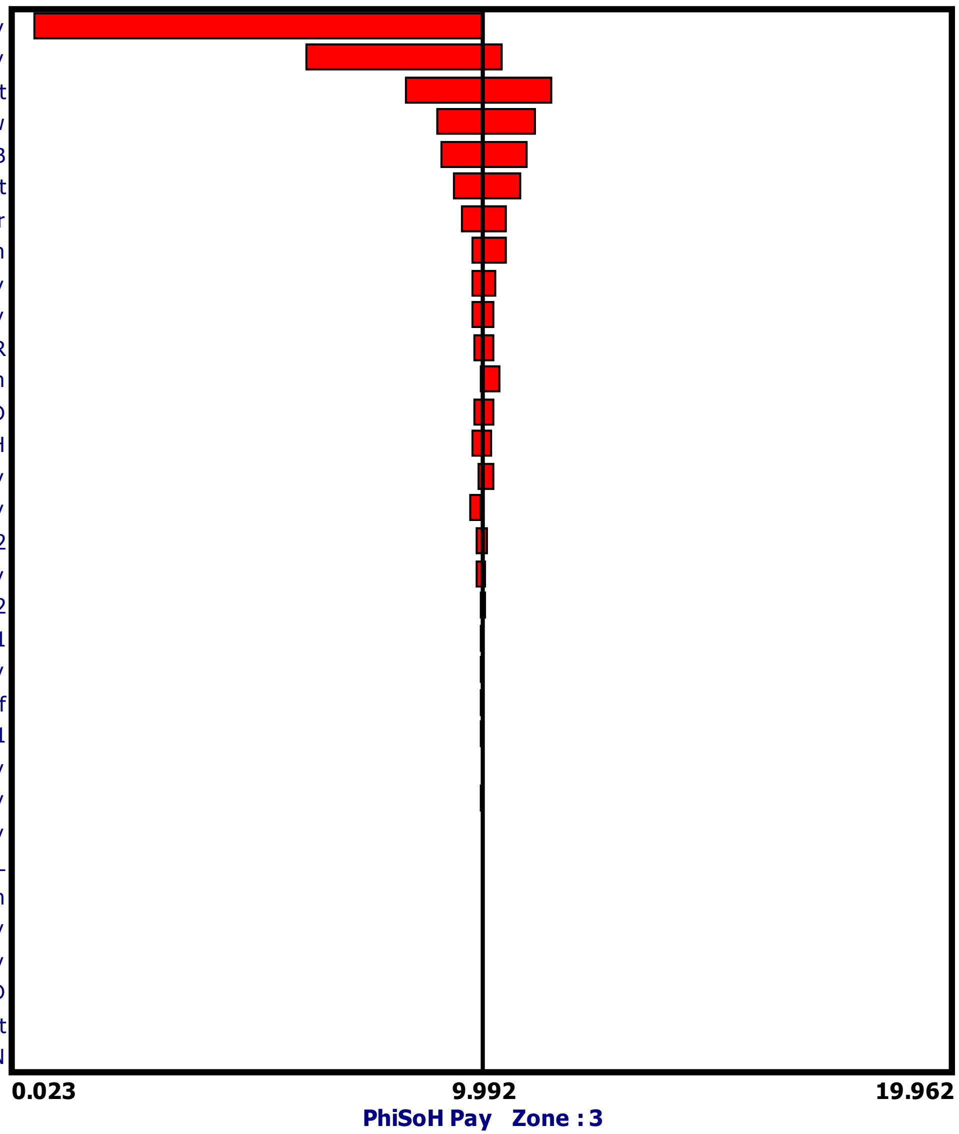

MONTE CARLO RESULTS HISTOGRAMS
Test Well 1
Number of Simulation : 408
PhiSoH Pay Zone : All
Mean : 24.86 Std Dev : 6.198
100
80
60
40
20
0
-5.49
60.4
HPVOL (ft)

Sensitivity

MONTE CARLO TORNADO PLOT

Test Well 1

Error Analysis for : PhiSoH Pay



	Shift Low	Initial Values	Shift High
Vcl Cut Res/Pay	0.3	0.3	0.3
Sw Cut Res/Pay	0.2	0.7	0.2
m exponent	0.2	2	0.2
Rw	20%	0.0895	20%
RHOB	0.02		0.02
n exponent	0.2	2	0.2
a factor	0.1	1	0.1
Gr Clean	10	13.88	10
Rho Wet Clay	0.05	2.538 - 2.625	0.05
Neu Wet Clay	0.05	0.461 - 0.588	0.05
SGR	5		5
Hc Den	0.2	0.476 - 0.8	0.2
LLD	0.005R		0.005R
TNPH	5%		5%
Res Clay	20%	1.42 - 3.2	20%
Phi Cut Res/Pay	0.05	0.1	0.05
ND Neu Clean2	0.02	0.217 - 0.3	0.02
ND Neu Clay	0.05	0.461	0.05
ND Den Clean2	0.03	2.048 - 2.05	0.03
ND Neu Clean1	0.02	-0.04	0.02
Gr Clay	10	114 - 139	10
Rmf	20%	0.136	20%
ND Den Clean1	0.03	2.65	0.03
Res Clay	20%	1.14 - 2.36	20%
ND Den Clay	0.05	2.538	0.05
Rxo Clay	20%	0.47 - 3.08	20%
MSFL	0.005R		0.005R
Res Clean	20%	72.46	20%
PhiT Clay	0.05	0	0.05
Rho Dry Clay	0.1	2.775	0.1
Rho GD	0.03	2.65	0.03
Rho mud filt	0.02	1.01594 - 1.01829	0.02
DTLN	2		2

Bayesian Analysis For Reliability

Bayes allows modified probabilities to be calculated based on

1. The expected rate of occurrence in nature
2. A diagnostic test that is less than 100% reliable

For example

- There is a 1:10,000 (0.0001%) occurrence of a rare disease in the population
- There is a **single test** of the disease that is 99.99% accurate
- A patient is tested positive for that disease
- What is the likelihood that the patient tested positive actually has the disease?

Bayesian Theory

- Bayes' theory is the statistical method to revise probability based on a assessment from new information. This is Bayesian analysis.

- To set up the problem:
  - Consider mutually collective and collectively exhaustive outcome (E1, E2…….En)
  - A is the outcome of an information event, or a symptom related to E.
  - If A is perfect information, Bayes theorem is NOT needed.

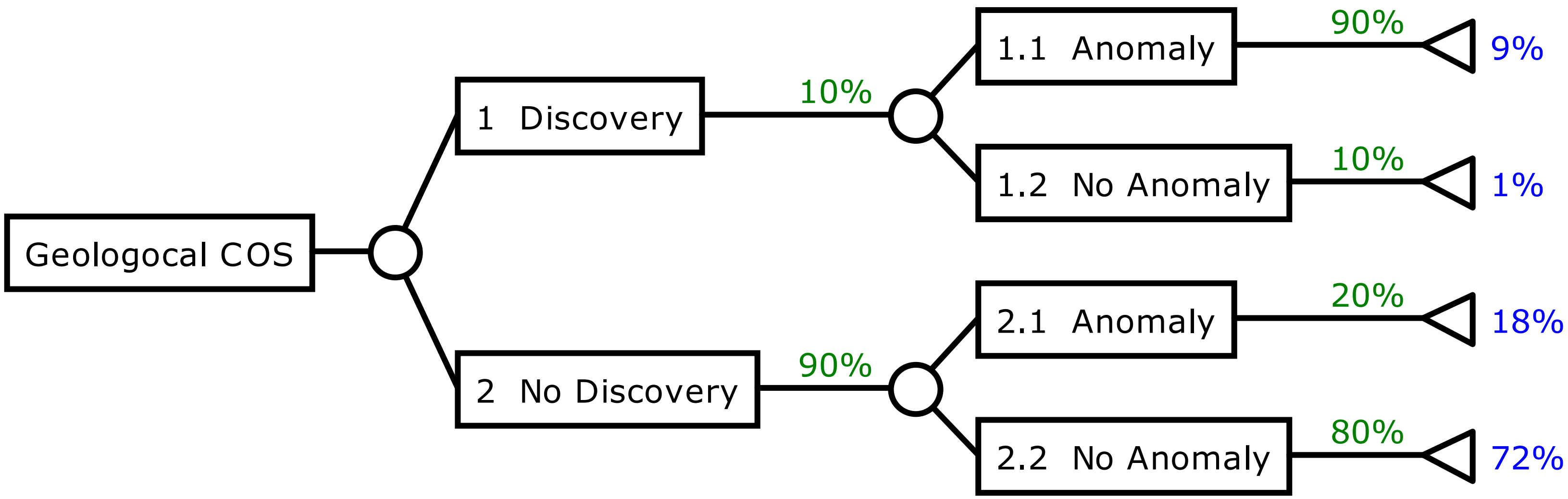
$$P(E_i|A) = \frac{P(A|E_i)P(E_i)}{\sum_{j=1}^{N} P(A|E_j)P(E_j)} = \frac{P(A \bullet E_i)}{P(A)}$$

Bayes Theory

	Input Number Calculation				
INPUTS	Probability of (state of nature) occurring	P(A)	Input		0.10
	Probablity of state of nature not occuring	P(nA)	1-P(A)		0.90
	Probability of True Positive Test (that B will be detected if A exists)	P(B|A)	Input		0.90
	Probability of False Positive Test (That B will be detected if A does not exist)	P(B|nA)	Input		0.20
	False Negative Test	P(nB|A)	1-P(B|A)		0.10
	Probability of a true negative test.	P(nB|nA)	1-P(B|nA)		0.80
OUTPUTS	Total probability of detecting A (whether it present or not)	P(B)	P(B|nA)*P(nA)+(P(B|A)*P(A)		0.27
	Total probability of not detecting A (whether it present or not)	P(nB)	1-P(B)		0.73
	Probability that A is present given that it was detected	P(A|B)	P(B|A)*P(A)/P(B)		0.33
	Probability that A is present given that it was not detected (probability of a a false negative)	P(A|nB)	P(nB|A)*P(A)/P(nB)		0.01
	Probability that A is NOT present given it was detected	P(nA|B)	1-P(A|B)		0.67
	Probability that A is NOT present given it was NOT detected	P(nA|nB)	1-P(A|nB)		0.99

- **AVO Anomaly**
- Information
  - Our geophysicist has evaluated AVO anomalies and has assessed that:
    - There is a 10% chance of geological success
    - There is a 90% chance of seeing an AVO if there is a discovery
    - There is a 20% chance of seeing a false anomaly if there is no discovery
  - Question
    - If we have a 10% COS based on the geological interpretation and an anomaly is observed, what is the revised COS if an AVO is observed
    - What is the added value of AVO

AVO


Geologocal COS
1 Discovery
10%
1.1 Anomaly
90%
9%
1.2 No Anomaly
10%
1%
2 No Discovery
90%
2.1 Anomaly
20%
18%
2.2 No Anomaly
80%
72%

AVO-Bayes Theory

AFES

	Input Number				
	Calculation				
INPUTS	Probability of (state of nature) occurring	P(A)	Input		0.10
	Probablity of state of nature not occuring	P(nA)	1-P(A)		0.90
	Probability of True Positive Test (that B will be detected if A exists)	P(B|A)	Input		0.90
	Probability of False Positive Test (That B will be detected if A does not exist)	P(B|nA)	Input		0.20
	False Negative Test	P(nB|A)	1-P(B|A)		0.10
	Probability of a true negative test.	P(nB|nA)	1-P(B|nA)		0.80
OUTPUTS	Total probability of detecting A (whether it present or not)	P(B)	P(B|nA)*P(nA)+(P(B|A)*P(A)		0.27
	Total probability of not detecting A (whether it present or not)	P(nB)	1-P(B)		0.73
	Probability that A is present given that it was detected	P(A|B)	P(B|A)*P(A)/P(B)		0.33
	Probability that A is present given that it was not detected (probability of a a false negative)	P(A|nB)	P(nB|A)*P(A)/P(nB)		0.01
	Probability that A is NOT present given it was detected	P(nA|B)	1-P(A|B)		0.67
	Probability that A is NOT present given it was NOT detected	P(nA|nB)	1-P(A|nB)		0.99

AVO

- **AVO Anomaly**

  - Question
    - If we have a 10% COS based on the geological interpretation and an anomaly is observed, what is the revised COS if an AVO is observed
    - What is the added value of AVO

  - Answer based on Bayes is that if there is an AVO anomaly there is a 33% chance it is a discovery.

  - Also we can calculate, if there in NO AVO anomaly then the chance it is a discovery is 1%/

Assessing Critical Porosity in Shallow Hole Sections

AFES

- Synopsis of SPE paper in press
  - New technique for deriving porosity from sonic logs in oversize boreholes
  - Sonic porosity used to determine of porosity is at critical porosity
    - Critical porosity 42 to 45 p.u.
  - If lower than critical porosity rock is load bearing
  - Near or at critical porosity the rocks may have insufficient strength to contain the forces of shutting in the well
  - Sonic porosity (using the new technique) is used to determine if rock is below critical porosity and used as part of the justification for NOT running a conductor

Case Study: Assessing Critical Porosity in Shallow Hole Sections

AFES

- LWD acoustic compression slowness below the drive pipe
- LWD sonic device optimised for large bore holes
  - **Data showed conclusive evidence of absence of hazards and were immediately accepted as waiver for running the diverter and conductor string of casing**
- DTCO used to asses if rock consolidated (below critical porosity)
  - Gives the resultant DTCO and porosity interpretation
    - Raymer Hunt Gardner model with shale correction
- No mention of the reliability of the interpretation
    - Processed DTCO accuracy
    - Interpretation model uncertainty

Assessing Critical Porosity in Shallow Hole Sections

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- Question
  - What is the potential impact of tool accuracy and model uncertainty on the interpretation
  - Should this be considered as part of the risk management for making the decision on running the conductor

  - ***What is the reliability of the method and measurement for preventing the unnecessary running of diverter and conductor string of casing***

Baseline Interpretation

Raymer equation:

$$\phi_{clay} = \frac{(2 \times Vma - Vf) - \sqrt{(2 \times Vma - Vf)^2 - 4 \times Vma \times (Vma - Vclay)}}{2 \times Vma}$$

$$Vfc = \frac{1}{Dtfl \times Sxo + Dthy \times (1 - Sxo)}$$

$$\phi_{son} = \frac{(2 \times Vma - Vfc) - \sqrt{(2 \times Vma - Vfc)^2 - 4 \times Vma \times (Vma - V\log)}}{2 \times Vma}$$

$$\phi = \phi_{son} - \phi_{clay} \times Vcl$$

Where

Vma = 1/Dtma

Vf = 1/Dtfl

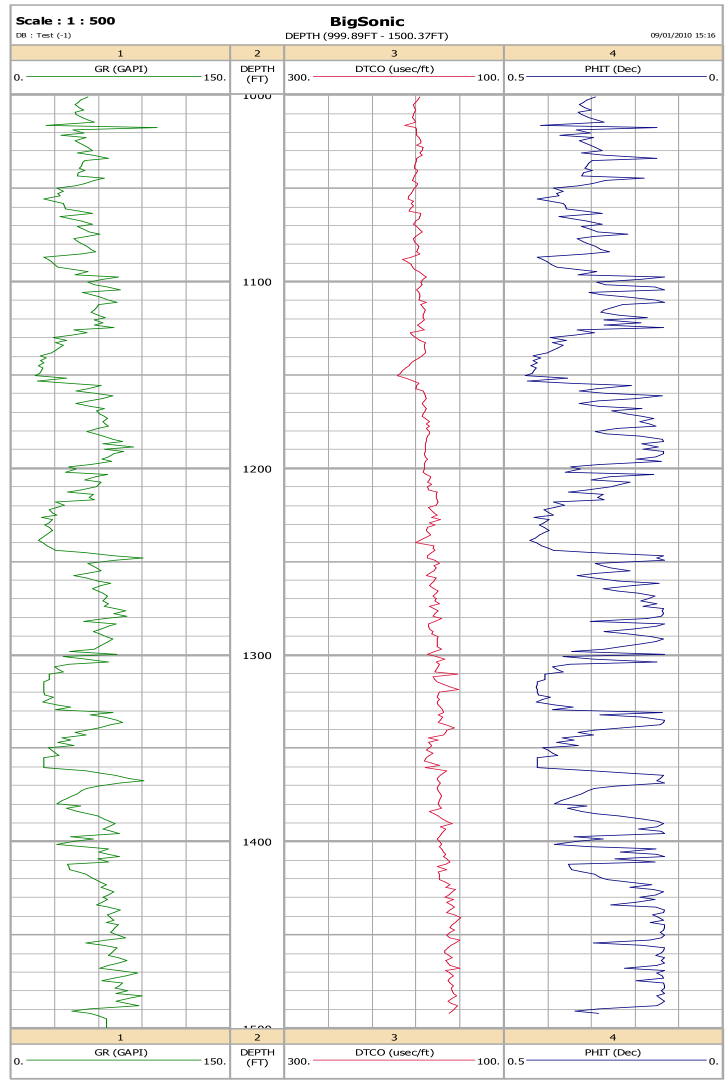
Vclay = 1/Dtclay

Vlog = 1/Dt

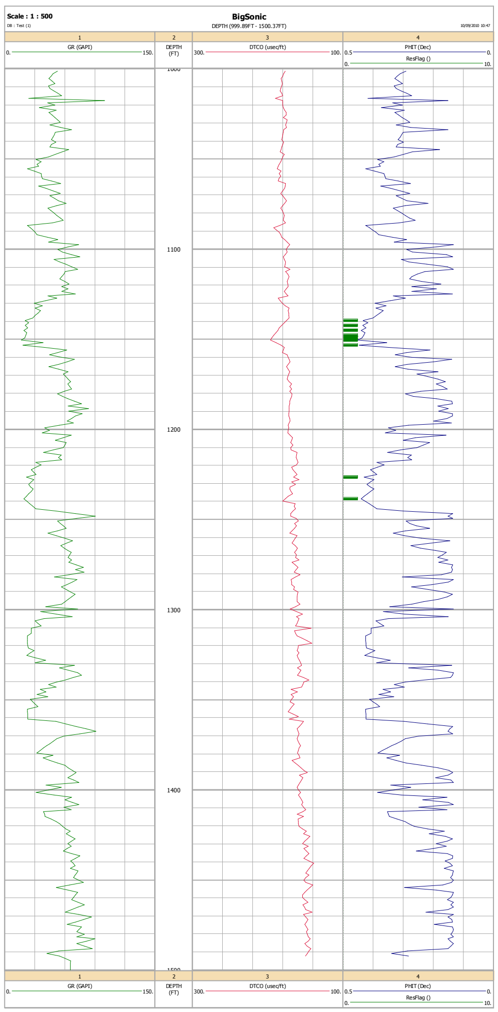
Baseline Interpretation

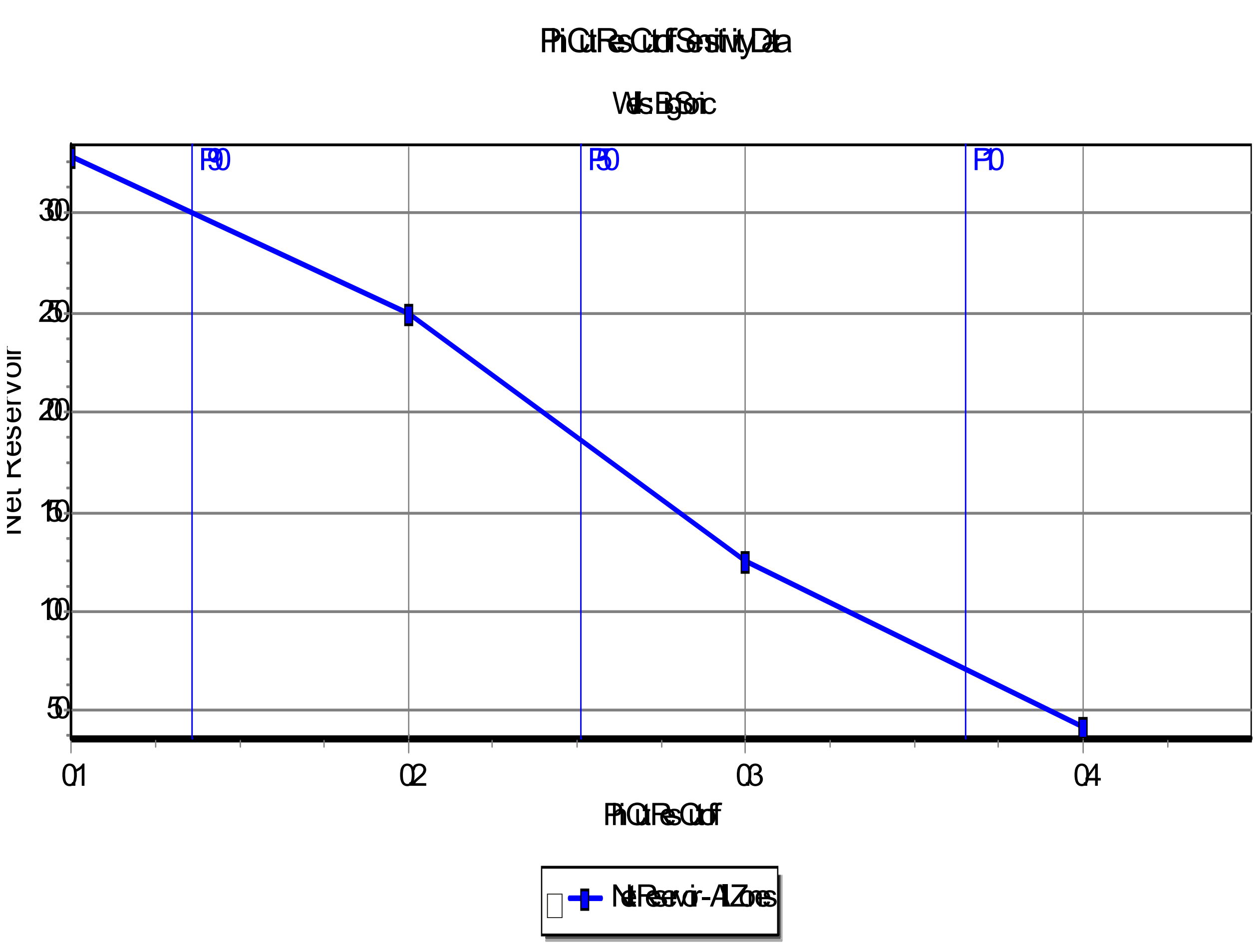
AFES

- DT matrix = 55.5 usec/ft
- DT Fluid = 189 usec/ft
- DT wet clay = 160 usec/ft
  - (uncompacted sediment)
- VCL from GR using linear method



Rock above CP



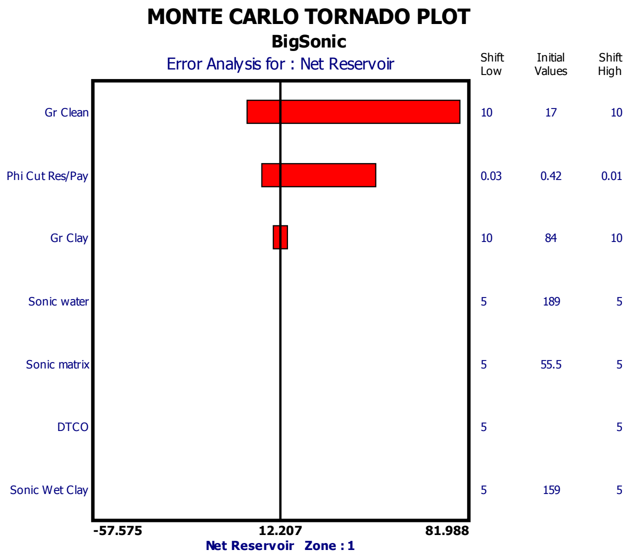


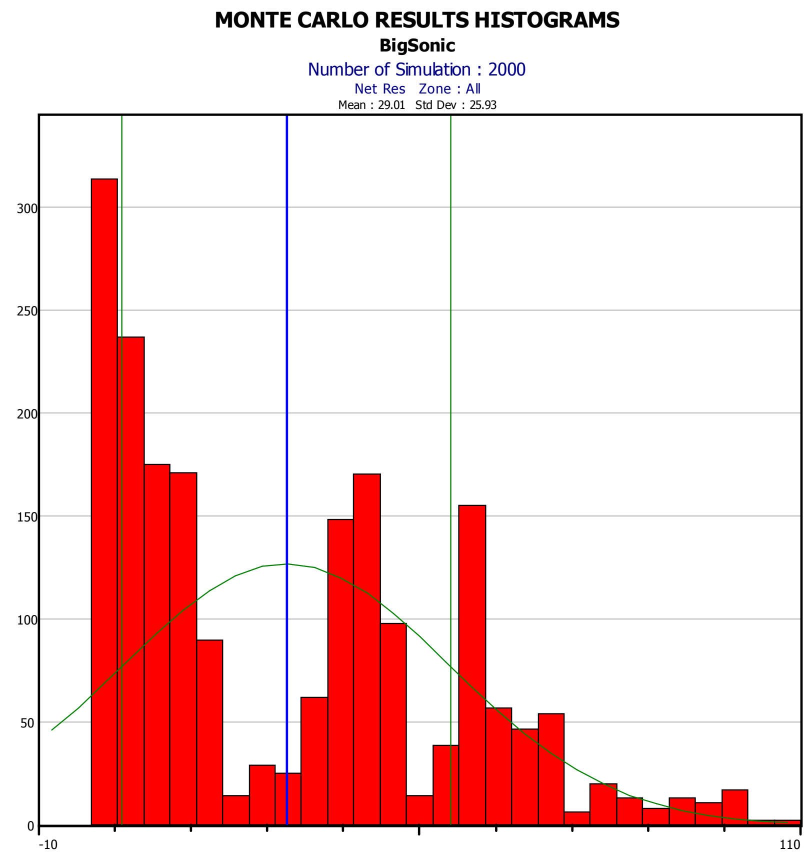
Uncertainty Analysis (Monte Carlo)

	Distribution	Default	+	-
DTCO (usec/ft)	Gaussian	log	5	5
GR clean	Gaussian	17	10	10
GR Clay	Gaussian	84	10	10
DT wet clay (usec/ft)	Gaussian	159	5	5
DT Matrix (usec/ft)	Gaussian	55.5	5	5
DT Water (usec/ft)	Gaussian	189	5	5
Cutoff for critical Porosity (v/v)	Square	0.42	0.03	0.01

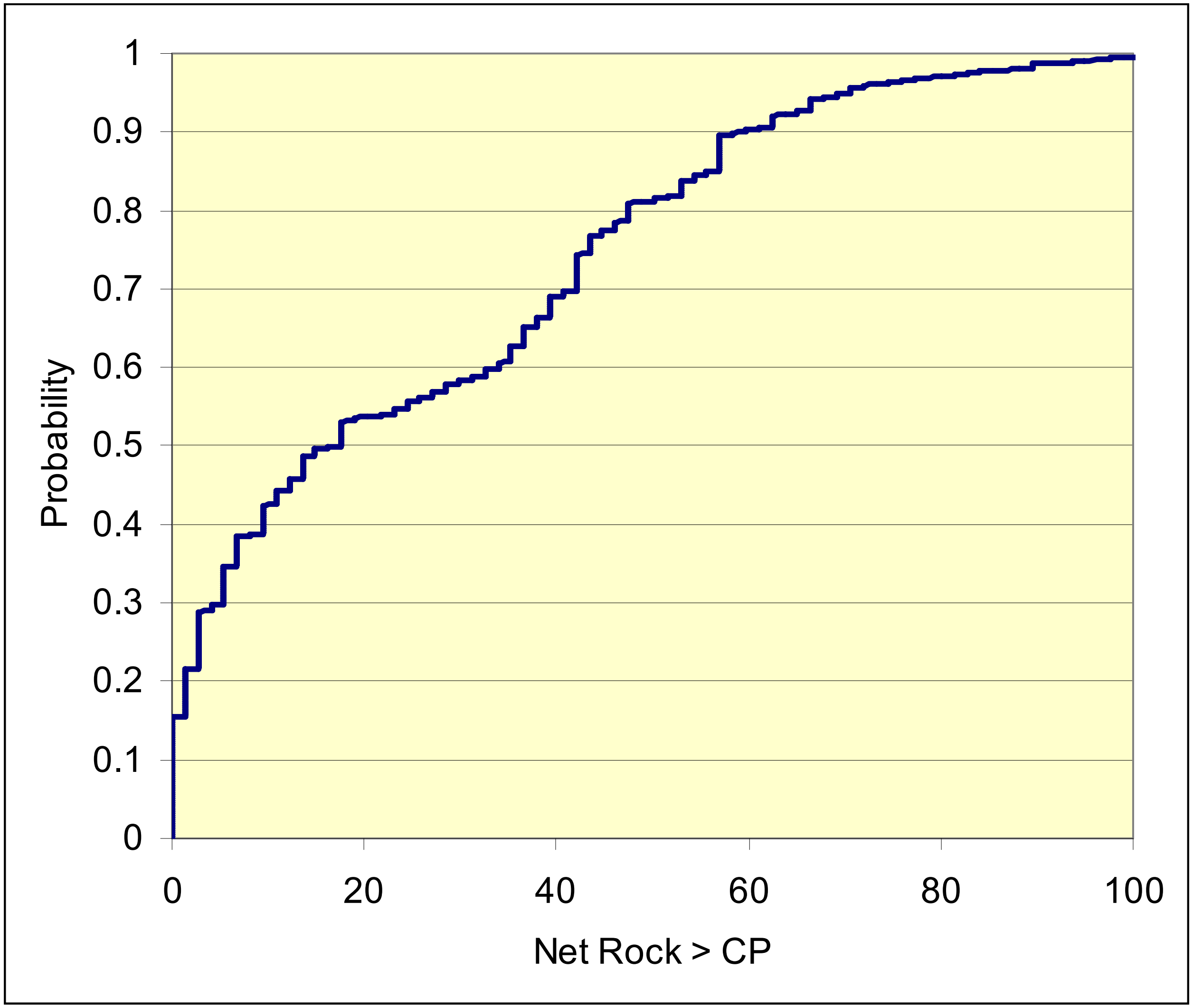
Uncertainty Analysis (Monte Carlo)

- Footage where porosity exceeds critical porosity
- Gross Section =
- P10 = 0ft
- P50 = 23 ft
- P90 = 62.5 ft





Results of Monte-Carlo



Tornado Plot

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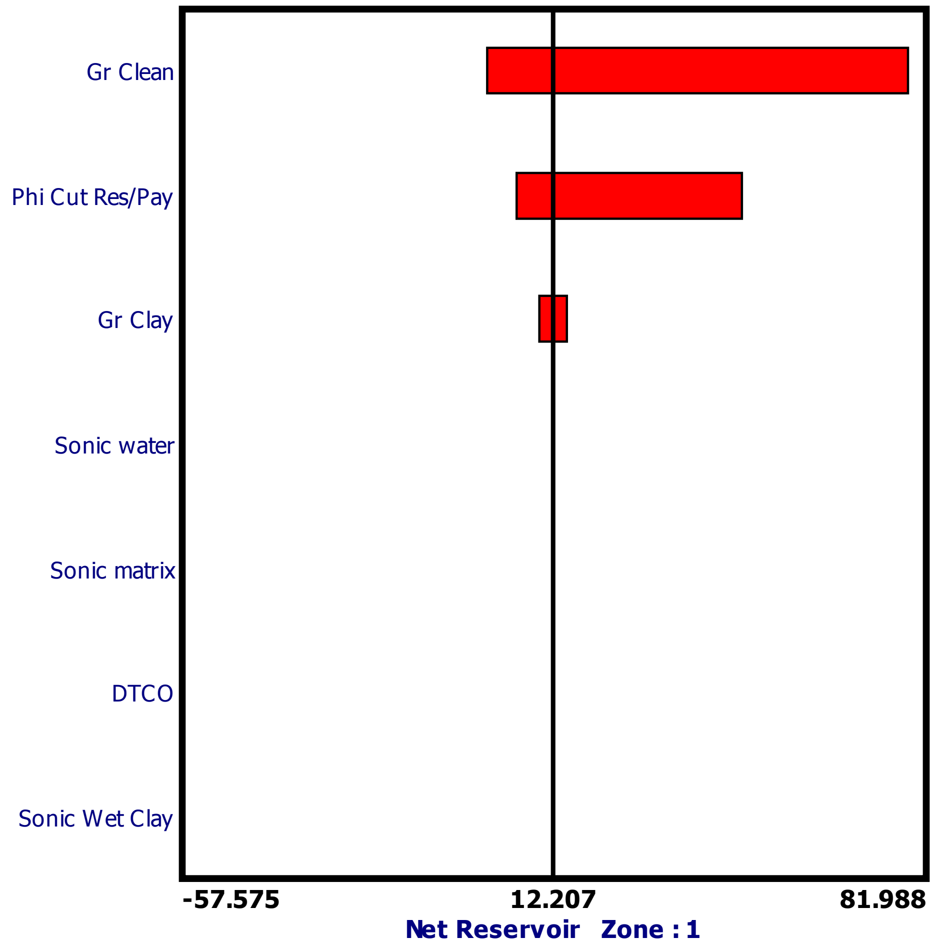
MONTE CARLO TORNADO PLOT

BigSonic

Error Analysis for : Net Reservoir



Shift Low	Initial Values	Shift High
10	17	10
0.03	0.42	0.01
10	84	10
5	189	5
5	55.5	5
5		5
5	159	5

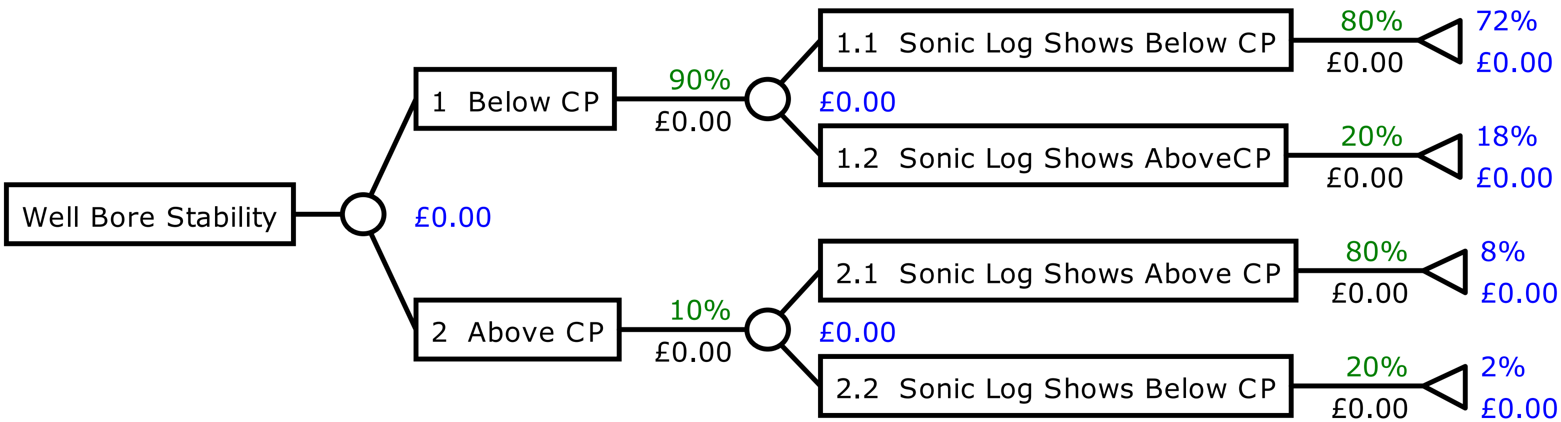
Conclusions from Monte Carlo

- The model processed DTCO and model uncertainty leads to significant doubt that the rock is below critical porosity
- The most important considerations are:
  - The clay volume and clay correction
  - The actual porosity value for critical porosity (0.41 to 0.45)
  - Tool Accuracy is not a concern (+/- 5 usec/ft)

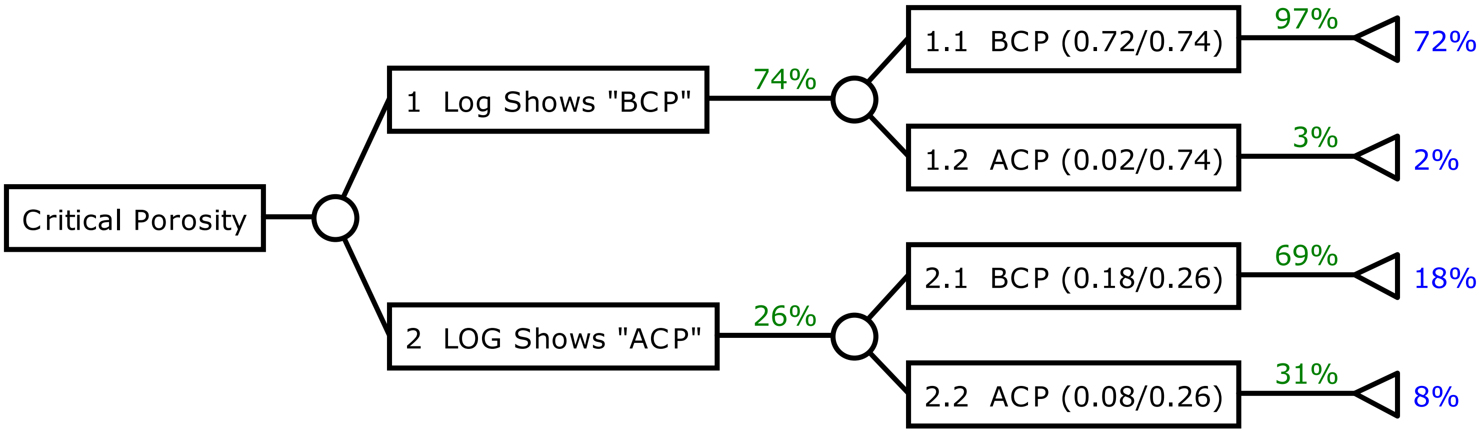
  - A good question to ask is what is the tool accuracy given the new processing technique and challenges of running sonic in big bore-holes?

Bayesian Analysis of Reliability

- Lets assume that the regional data shows that the 90% of all top hole sections will be below CP and stable
- Based on Monte-Carlo it is judged that the interpretation will be 80% reliable



Bayesian Inversion of Tree



% Wells below CP regionally	0.9
Reliability of the log	0.8

	"BCP"	"ACP"
BCP	0.72	0.18
ACP	0.02	0.08
	0.74	**0.26**

If Log shows BCP	**0.97**
If Log Shows ACP	**0.31**

Bayesian Analysis of Reliability
Joint Probability Table

AFES

- If the log shows that the section is below critical porosity then we can be **97% certain** that it is below critical porosity

% Wells below CP regionally	0.9
Reliability of the log	0.8

	"BCP"	"ACP"
BCP	0.72	0.18
ACP	0.02	0.08
	0.74	**0.26**

If Log shows BCP	**0.97**
If Log Shows ACP	**0.31**

Bayesian Analysis 2

AFES

- What if only 60% of the wells in the area are below critical porosity. What is the value of the sonic?

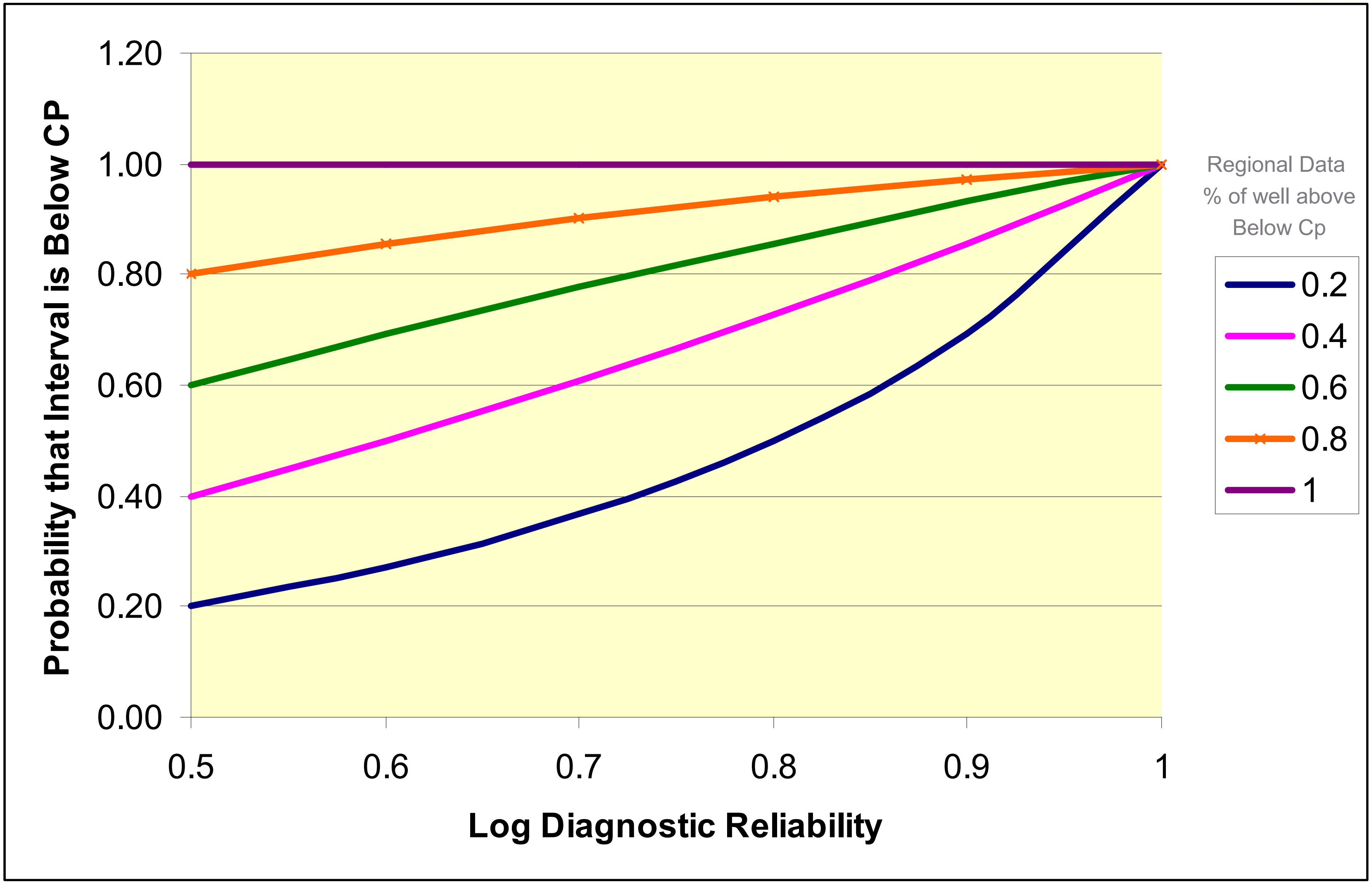
% Wells below CP regionally	0.6
Reliability of the log	0.8

	"BCP"	"ACP"
BCP	0.48	0.12
ACP	0.08	0.32
	0.56	**0.44**

If Log shows BCP	**0.86**
If Log Shows ACP	**0.73**

- If the sonic log shows below CP there is an 86% chance it is really below CP

Reliability of Diagnosis Chart



Conclusions From Reliability Analysis

AFES

- If the Sonic is 100% reliable as a diagnosis of the well being above or below CP then the log data then we can be sure the interval is above/below CP
- If the Sonic log is not 100% reliable then we need to take into account
  - Regional data trends
  - Reliability of the Sonic log
- If we believe that the sonic log is less than 100% diagnostic then there is always a risk that the well will be above CP, even if the log data shows otherwise.

Conclusions

AFES

- The most important task of the geoscientist is to make statements about
  - Range of possible subsurface outcomes based on:
    - Uncertainty
    - Diagnostic reliability of data

- There are several ways to analyse the range of outcomes based on uncertain input parameters
  - Single parameter sensitivity
  - Partial derivative analysis
  - Monte-Carlo simulation
  - Bayes’ analysis for diagnostic reliability

- The results of uncertainty and reliability analysis can be counter intuitive