Limits on the Accuracy of Pore Pressure Estimates by Analysis of Random Measurement Error and Means for Improvement

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Overview

- Accuracy Limits of Logging Tool Measurements
- How Uncertainty Propagates through Calculations
- Uncertainty Estimates in Pore Pressure and Fracture Gradient Calculations
- Combining Measurements can be used to Reduce Uncertainty

Summary of Rules for Error Propagation

For quantities a and b with uncertainties δa and δb (errors which are uncorrelated and random), seeking quantity Q with uncertainty δQ :

- Addition and Subtraction (add **absolute** uncertainties, expressed in UOM)

If $Q = a + b$ or $a - b$,

then

$$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2}$$

$$a = 2.00 \pm 0.03m, b = 0.88 \pm 0.04m, Q = a - b$$
$$Q^* = 2.00 - 0.88 = 1.12m$$
$$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2}$$
$$\delta Q = \sqrt{(0.03m)^2 + (0.04m)^2} = 0.05m$$
$$Q = 1.12 \pm 0.05m$$

http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf

Summary of Rules for Error Propagation

For quantities a and b with uncertainties δa and δb (errors which are uncorrelated and random), seeking quantity Q with uncertainty δQ :

- Multiplication and Division (add **relative** uncertainties, expressed in percent)

If $Q = a \times b$ or a / b,

then

$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2}$$

$$a = 120 \pm 3m, b = 20.0 \pm 1.2s, Q = a / b$$
$$Q^* = 120 / 20.0 = 6.0m / s$$
$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2}$$
$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{3m}{120m}\right)^2 + \left(\frac{1.2s}{20.0s}\right)^2} = \sqrt{(2.5\%)^2 + (6\%)^2} = 6.5\%$$
$$\delta Q = (6\,m/s)(6.5\%) = 0.39\,m/s$$
$$Q = 6.0 \pm 0.4\,m/s$$

http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf

Summary of Rules for Error Propagation

For quantity a with uncertainty δa (errors which are uncorrelated and random), seeking quantity Q with uncertainty δQ :

- Exponentiation (multiply **relative** uncertainty by exponent, expressed in percent)

If $Q = a^n$,

then

$$\frac{\delta Q}{|Q|} = |n| \frac{\delta a}{|a|}$$

$$a = 10.0 \pm 0.2m, Q = a^3$$
$$Q^* = 10.0^3 = 1{,}000m^3$$
$$\frac{\delta Q}{|Q|} = 3\frac{\delta a}{a} = 3 \times \frac{0.2m}{10m} = 6\%$$
$$\delta Q = (1{,}000m^3)(6\%) = 60m^3$$
$$Q = 1{,}000 \pm 60m^3$$

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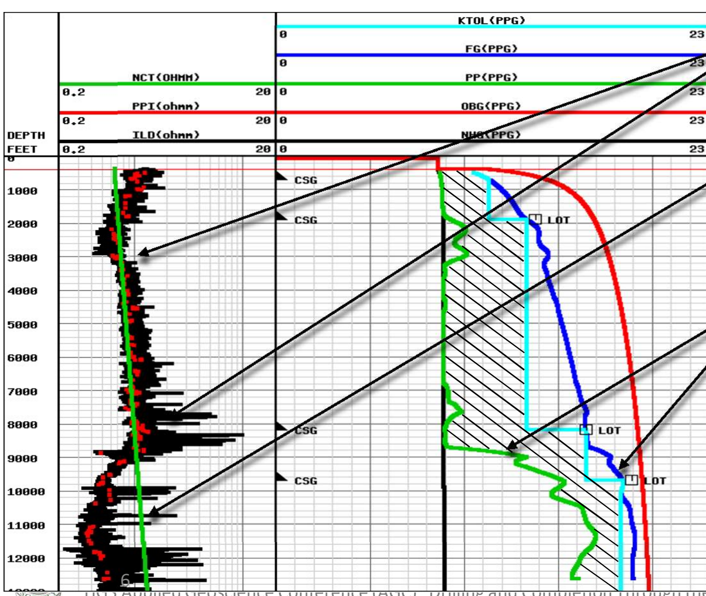
Pore Pressure Detection - Normal Compaction Trends



- Sediments undergo relatively uniform compaction as they are more deeply buried – the normal compaction trend.
- Processes that inhibit compaction will show up as a porosity increase on logs and seismic velocity functions, as data inversions (reversing the trend).
- Pore pressure studies define the onset of abnormal pressure, its magnitude, and the range of mud weights that can be used to maintain safe drilling conditions.

Porosity to Pore Pressure Equation: Eaton

Eaton Equation – To estimate the pore pressure from porosity sensitive data using the Eaton equation, each data point is entered into the following equations:

$$PPG = OBG - (OBG - NHG)\left(\frac{X_{obs}}{X_{nct}}\right)^{n}$$

n = effective stress (Eaton) exponent

X_{obs} = observed porosity sensitive data value

X_{nct} = normal porosity sensitive data value

OBG = Overburden pressure

NHG = Normal Hydrostatic Gradient

PPG = Pore Pressure Gradient

PPFG Processing Steps

- Import TVD, GR, RHOB, and DT
- Normal Hydrostatic Gradient
- Overburden Gradient
- Normal Compaction Trend
- Pore Pressure Gradient
- Fracture Gradient

TVD, RHOB, RHOF and DT ~ Uncertainties

LOG CURVE	MNEMONIC	UNCERTAINTY TYPE	UNCERTAINTY VALUE	SOURCE
DEPTH	TVD	RELATIVE	0.05%	Cable stretch & temperature tables
BULK DENSITY	RHOB	ABSOLUTE	0.025 G/CC	Instrumentation*
SONIC RESISTIVITY	DT R	RELATIVE	2.0%	Instrumentation*

* Product Data sheets provided by Schlumberger, Halliburton, and Weatherford

OTHER CURVE	MNEMONIC	UNCERTAINTY TYPE	UNCERTAINTY VALUE	CAUSE
FLUID DENSITY	RHOF	RELATIVE	1.0%	Estimated from formation fluids

Basic Equations

- True Vertical Depth Below Mud Line (TVD_{bml})
  - $\underline{TVD}_{bml} = \underline{TVD} - (AG + WD)$
- Normal Hydrostatic Gradient (NHG) – Integrated Fluid Density
  - $\underline{NHG} = (0.4335 \times \underline{RHOF} \times \underline{TVD}_{bml} + WD \times 0.448 \text{ psi/ft}) / \underline{TVD}$
- Overburden Gradient (OBG) – Integrated Bulk Density
  - $\underline{OBG} = \Sigma\, ((\underline{TVD}_i - \underline{TVD}_{i-1}) \times (\underline{RHOB}_i + \underline{RHOB}_{i-1}) \times 0.4335 / 2\,) / \underline{TVD}$

Constants
AG (air gap): 100’
WD (water depth): 100’

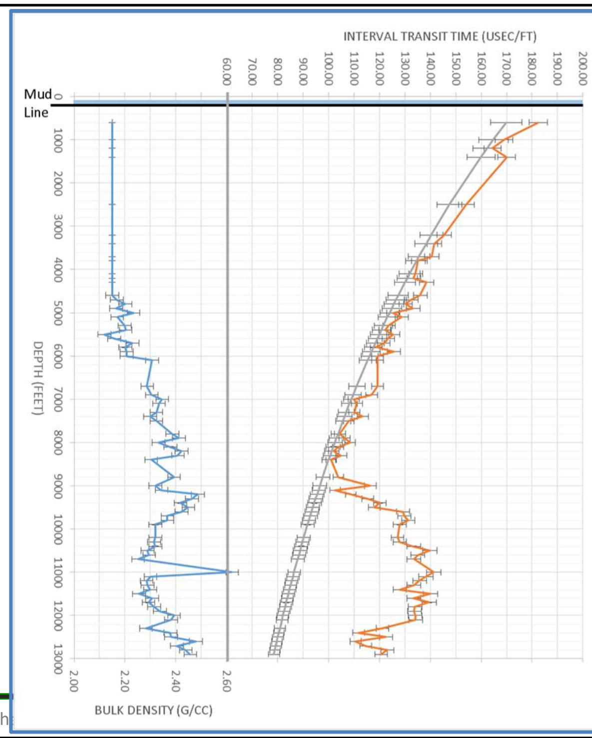
Basic Equations

- Normal Compaction Trend (NCT) – Exponential Porosity Decay
  - $\underline{\mathbf{NCT}} = 40 + 135 / 10^{0.000042858 \times \underline{\mathbf{TVDbml}}}$
- Pore Pressure Gradient (PPG) – Eaton Equation for Sonic
  - $\underline{\mathbf{PPG}} = \underline{\mathbf{OBG}} - (\underline{\mathbf{OBG}} - \underline{\mathbf{NHG}}) \times (\underline{\mathbf{NCT}} / \underline{\mathbf{DT}})^3$
- Fracture Gradient (FG) – Matrix Stress Equation
  - $\underline{\mathbf{FG}} = \underline{\mathbf{PPG}} + (\underline{\mathbf{OBG}} - \underline{\mathbf{PPG}}) \times K$

Constants
K (matrix stress coefficient): 0.5
Poisson's Ratio: 0.333

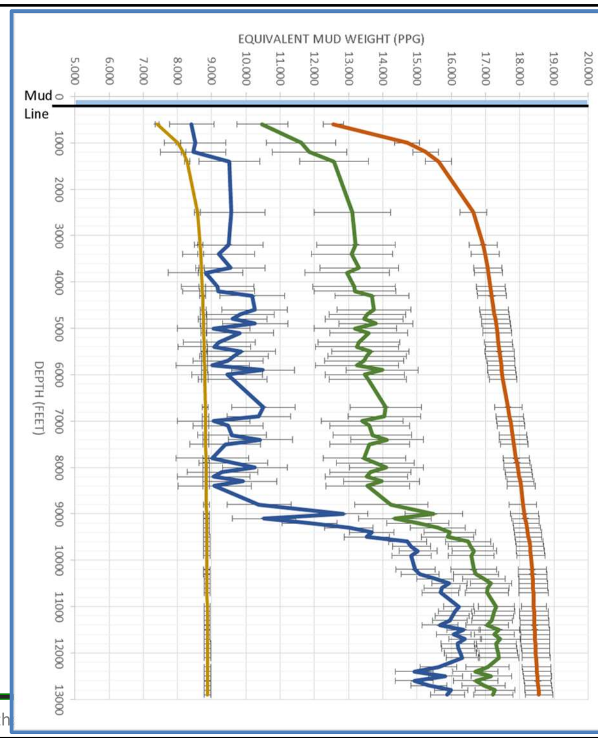
Analysis

- Bulk Density (RHOB) has measurement uncertainty of ±0.025 G/CC
- Constant RHOB value of 2.15 G/CC taken above 4,600' with "no" uncertainty
- Sonic (DT) has relative measurement uncertainty of ±2.0%, so absolute error is greater where the measured values are larger
- Normal Compaction Trend (NCT) has measurement uncertainty combined from the DT and the TVD



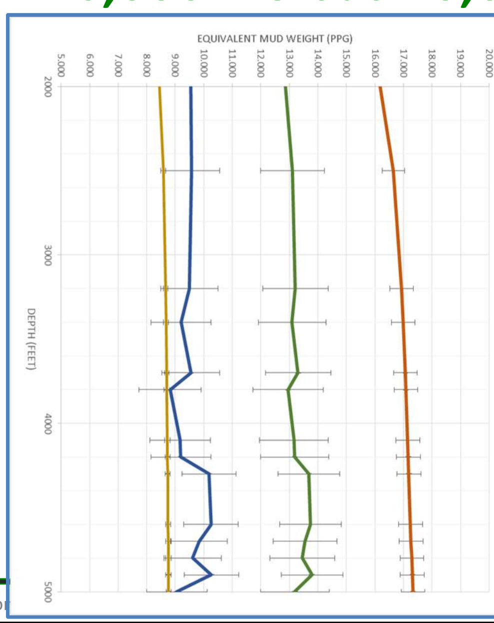
Inherent Error - DT

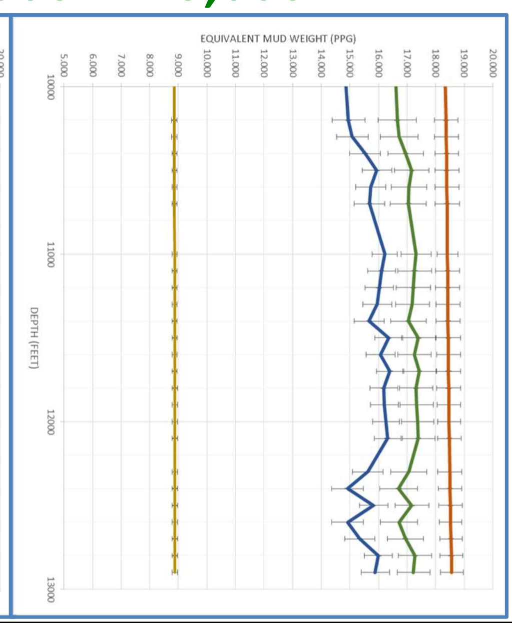
- Pore Pressure Gradient
  - Minimum < NHG
  - Maximum > FG
  - Mean Error ±0.7 ppg
- Fracture Gradient
  - Minimum < PPG
  - Maximum < OBG
  - Mean Error ±0.6 ppg



DT: 3,000’ – 6,000’ versus 10,000’ – 13,000’

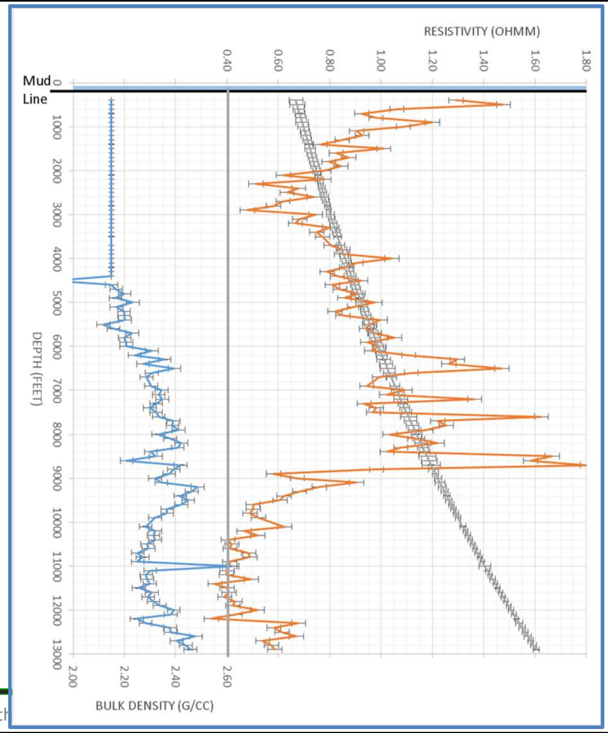
- Decrease in estimated uncertainty with increasing depth for Sonic – DT data





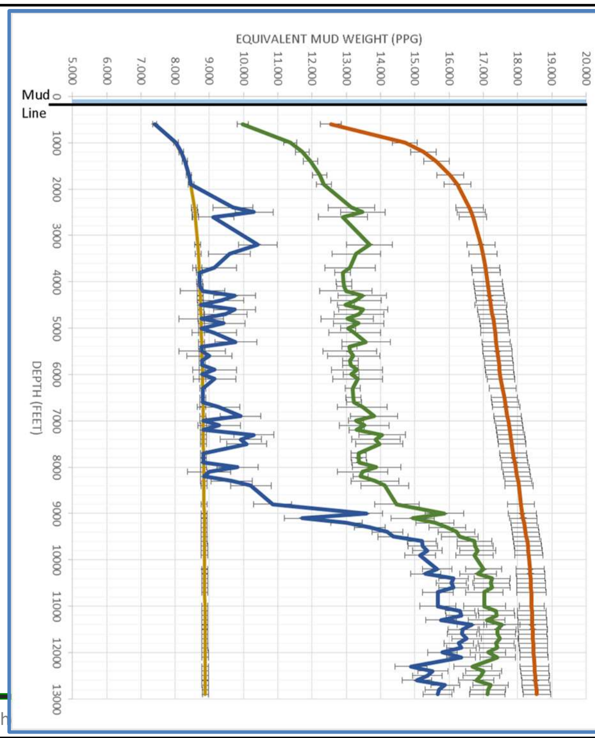
Analysis

- Bulk Density (RHOB) has measurement uncertainty of ±0.025 G/CC
- Constant RHOB value of 2.15 G/CC taken above 4,600' with "no" uncertainty
- Resistivity (ILD) has relative measurement uncertainty of ±2.0%, so absolute error is greater where the measured values are larger
- Normal Compaction Trend (NCT) has measurement uncertainty combined from the ILD and the TVD



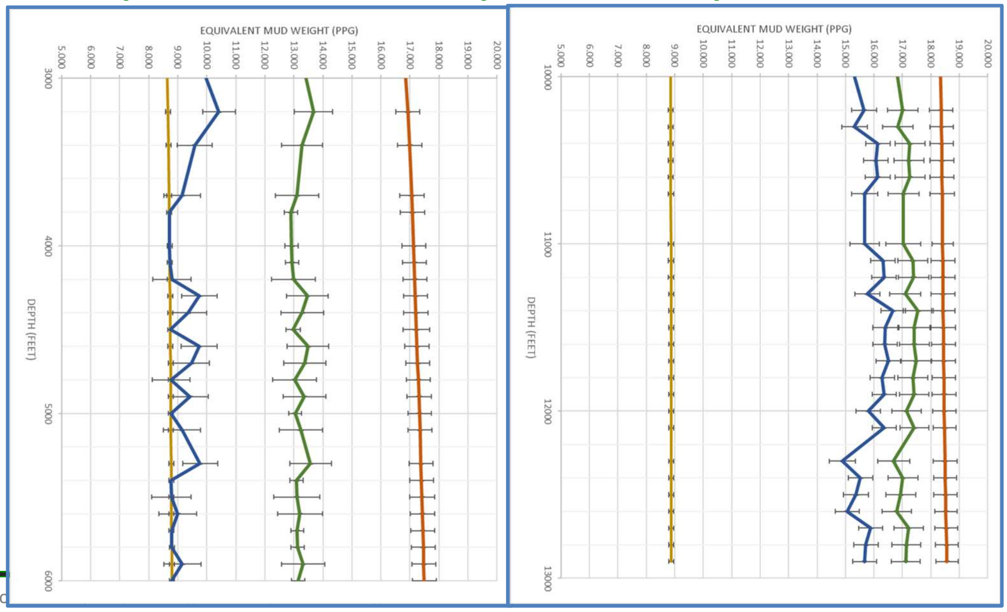
Results – ILD

- Pore Pressure Gradient
  - Minimum < NHG
  - Maximum ≈ FG
  - Mean Error ±0.6 ppg
- Fracture Gradient
  - Minimum ≈ PPG
  - Maximum < OBG
  - Mean Error ±0.6 ppg



ILD: 3,000' – 6,000' versus 10,000' – 13,000'

- Increase in estimated uncertainty with increasing depth for Resistivity – ILD data



Means for Reducing Uncertainty

- Mud Weight
  - Actual mud density measurements constraining the pore pressure gradient
- Gas Chromatography
  - Pump-Off gas events constraining pore pressure gradient
- XRD
  - Density measurements refining the overburden gradient

Comparing Two Quantities with Uncertainty

For quantities a and b with uncertainties δa and δb (errors which are uncorrelated and random), a and b agree (are equal) if:

- Comparison (subtract measurements and add **absolute** uncertainties)

$$If\ |a-b| \leq \sqrt{\delta a^2 + \delta b^2},$$
$$then$$
$$a = b$$
$$else$$
$$a \neq b$$

$a = 3.6 \pm 0.2 m/s, b = 3.3 \pm 0.3 m/s$, is $a = b$?

Let $Q = |a-b|$

$Q^* = 3.6 - 3.3 = 0.3 m/s$

$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2}$

$\delta Q = \sqrt{(0.2 m/s)^2 + (0.3 m/s)^2} = 0.36 m/s = 0.4 m/s$

Because $0.3 m/s \leq 0.4 m/s$, $\therefore a = b$ is true.

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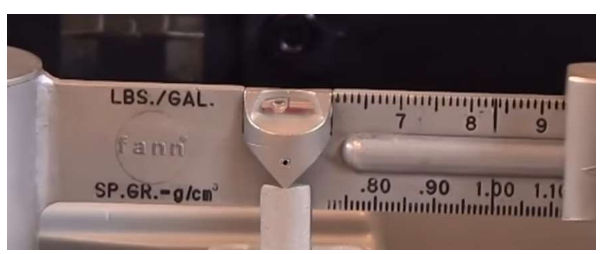
Mud Balance Density Measurement

- Density Measurement Ranges:
  - 0.79 - 2.72 g/cm³, 0.01 g/cm³, ±0.005 g/cm³
  - 6.5 - 23.0 lbs/gal, 0.1 lbs/gal, ±0.05 lbs/gal
- Approximately ±0.333% in the mid-range

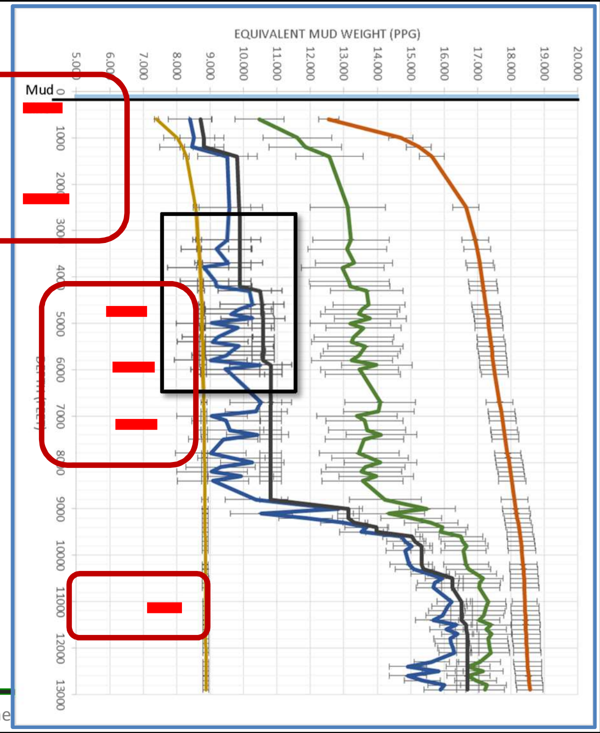

Fann Model 140 Mud Balance



http://www.fann.com/public1/pubsdata/Manuals/Model%20140%20Mud%20Balance.pdf

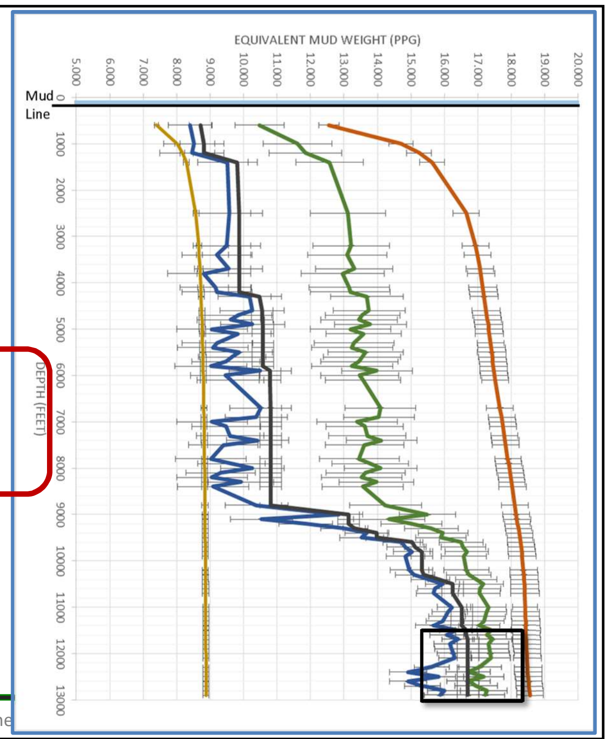
MW Constraining PP

- If the calculated PP is less than the measured MW:
  - If there is a kick, it must fall where the error bars overlap otherwise the PP must be recalculated
- If the calculated PP is greater than the measured MW:
  - If there is no kick, then the error bars must overlap otherwise the PP must be recalculated

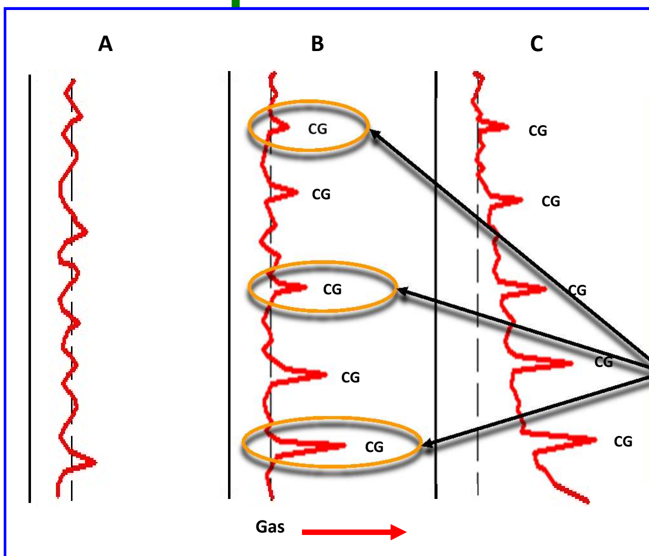


MW Constraining FG

- If the calculated FG is greater than the measured MW:
  - If there is a loss, it must fall where the error bars overlap otherwise the FG must be recalculated
- If the calculated FG is less than the measured MW:
  - If there is no loss, then the error bars must overlap otherwise the FG must be recalculated



Gas Response to Differential Pressure



Effect of Differential Pressure (DP) on Connection Gas (CG):

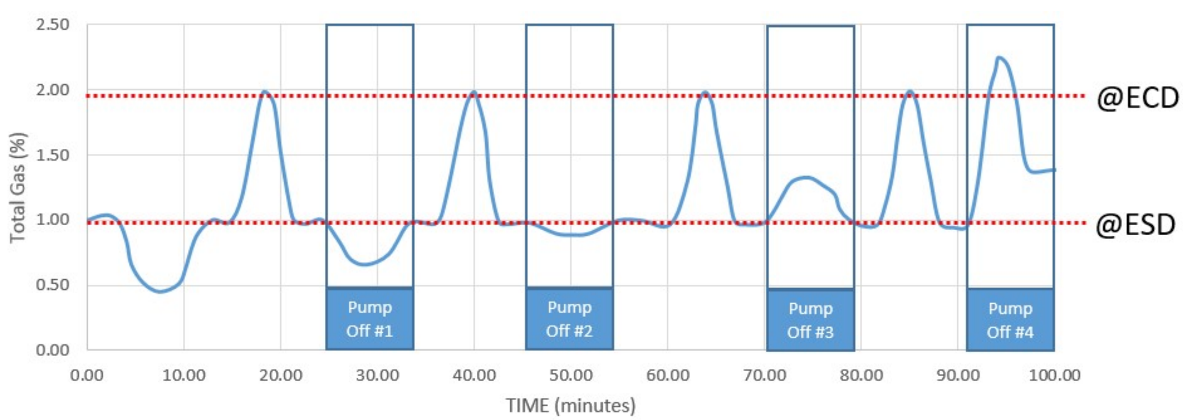
A. Positive, stable DP
B. Positive, decreasing DP
C. Negative DP

Increasing CG when differential pressure (DP) decreases…

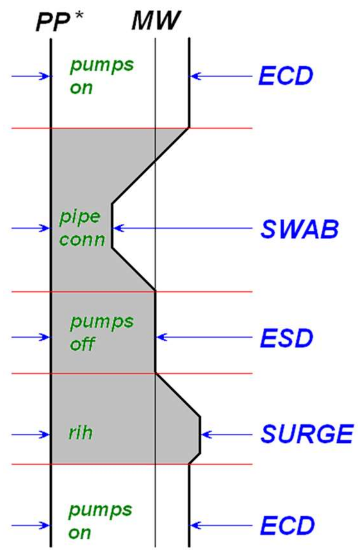
When does it start and what is the magnitude of gas vs DP?

Gas Response to Differential Pressure

- Pump Off #1: PP < ESD by 0.25 to 0.40 ±0.04 ppg (0.03 to 0.05 ±0.005 g/cm³)
- Pump Off #2: PP < ESD by 0.08 to 0.25 ± 0.04 ppg (0.01 to 0.03 ±0.005 g/cm³)
- Pump Off #3: PP > ESD and PP < ECD ═► PP* ± 0.04 ppg (PP* ±0.005 g/cm³) (see next slide)
- Pump Off #4: PP > ECD (exact value of PP unknown)



Calculating PP from Connection Gas



$$PP^* = ESD + (ECD - ESD) \times \frac{(TGAS_{ECD} - TGAS_{ESD})}{(TGAS_{SWAB} - TGAS_{ESD})}$$

where:

PP^* = Pore Pressure (estimated)

ESD = Equivalent Static Density (pumps off)

ECD = Equivalent Circulating Density (pumps on)

$TGAS_{ECD}$ = Total GAS with pumps on

$TGAS_{ESD}$ = Total GAS with pumps off

$TGAS_{SWAB}$ = Total GAS during swab pressure drop

Pore Pressure Gradient Estimated by a Total Gas Peak

TIME (min)	DEPTH (ft)	TGAS (%)		PP (ppg)
68.16	9000	0.97	pump off	12.48
69.89		0.97		12.49
70.89		1.06		12.53
71.89		1.19		12.59
72.90		1.30		12.65
74.63		1.33	po peak #3	12.66
76.09		1.27		12.63
77.31		1.20		12.60
77.79		1.08		12.54
78.76		1.00		12.50
80.23		0.95		12.48
81.71	9000	0.96	pump on	12.48

Cuttings Mineralogy by X-Ray Diffraction

XRD analyzer

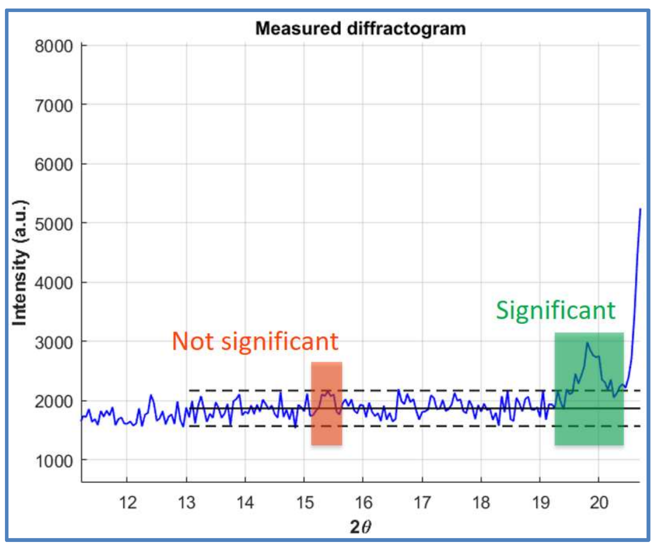
Compact benchtop for on-site near-real time analysis

How much of each mineral is in the sample?

QUARTZ/PYRITE	CARBONATES	NON-SWELLING CLAYS
quartz	calcite	clinochlore
pyrite	dolomite	kaolinite
FELDSPARS	ankerite	illite
albite	siderite	**SWELLING CLAYS**
microcline	**SULFATES**	illite-smectite
	anhydrite	montmorillonite
	gypsum	

Using XRD to Constrain RHOB

- Different levels of accuracy based on the lithology being detected:
- Can range between: ±1.0% and ±10.0%
- Calcite is a “noisy” mineral, generating lower signal to noise ratios



Combining Mineral Constituents For RHOB

- XRD: Once the quantity of the minerals present have been determined, they are combined to produce an estimate of the matrix density:

$$RHOM = \sum \%MINERAL_i \times RHOM_i$$

- Pyconometry: Determines envelope density (RHOE), which can be combined with RHOM gives decimal porosity (PHI):

$$PHI = 1 - \frac{RHOE}{RHOM}$$

- Bulk Density: By combining RHOF, RHOB, and PHI, RHOB is found:

$$RHOB = PHI \times RHOF + (1 - PHI) \times RHOM$$

Conclusions

- All measurements have associated uncertainty.
- Using *only* tool uncertainty and by propagating error, minimum attainable uncertainty for PPFG calculations is approximately ±0.6 ppg.
- Combining independent measurements and using the rules for comparing uncertainties provides a means to lower uncertainty without advances in instrumentation technology.

Questions?

Thank you for your time and attention

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