Lecture Presentation

PGE385(K,M)

Advanced Multi-Well Formation Evaluation

Lecture Presentation

Estimation of Volumetric Concentrations of Mineral Constituents from Logs

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Mineralogy Determination, Why?

- Determines grain density → Porosity
- Mechanical properties and borehole stability
- Propensity to fracture
- Clay type - formation damage (effect of fresh water, acid, …)
- Limestone vs. Dolomite - Dolomite is generally more porous in low ϕ carbonates.
- Used to infer other petrophysical properties (e.g. velocity, …)

Minerals for Petroleum Geoscientists

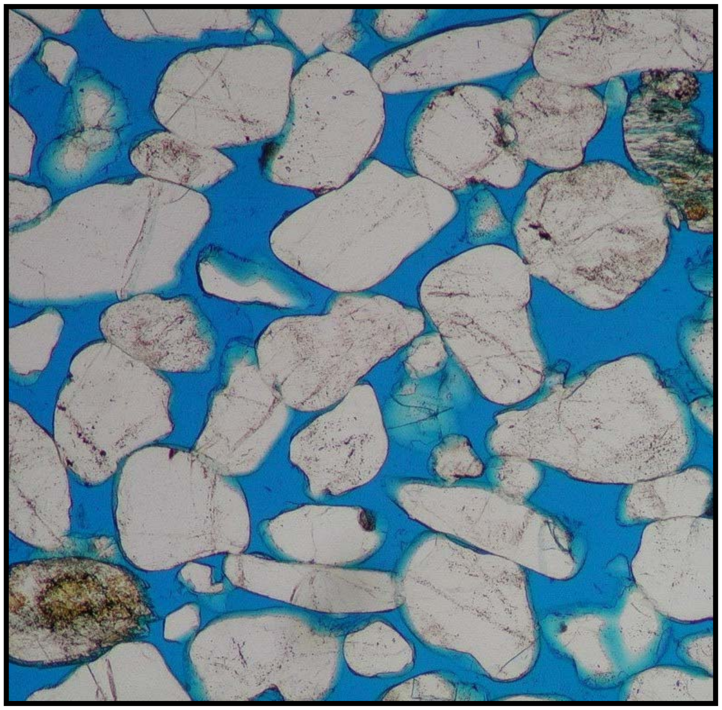
- Limestone, Dolomite
- Quartz, Chert, Opal (hydrous silica)
- Syderite, Ankerite
- Anhydrite, Gypsum (hydrous anhydrite)
- Halite
- Clay minerals (illite, smectite, kaolinite, chlorite)
- Feldspars
- Coals
- Glauconite

Important in the determination of depositional environment and reservoir quality

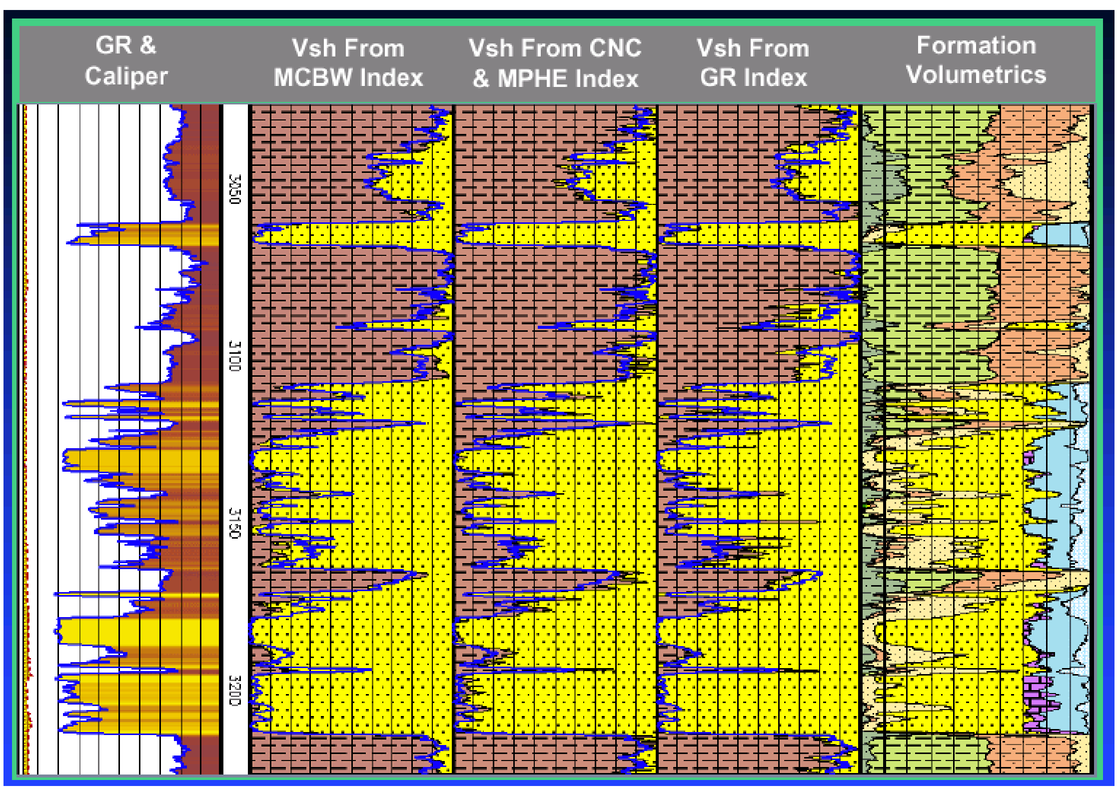
Objectives:

1. To introduce the methodology used to estimate apparent matrix density in a rock whose solid composition is a mixture of elemental constituents,
2. To introduce basic procedure to identify the elemental constituents included in the solid component of a rock,
3. To assess porosity, fluid saturation, and permeability in a rock with mixed solid composition, and
4. To exercise the estimation of volumetric concentrations using basic linear algebra and linear minimization with constraints.

Mineral Composition of Grains: Pure or Mixed Constituents?



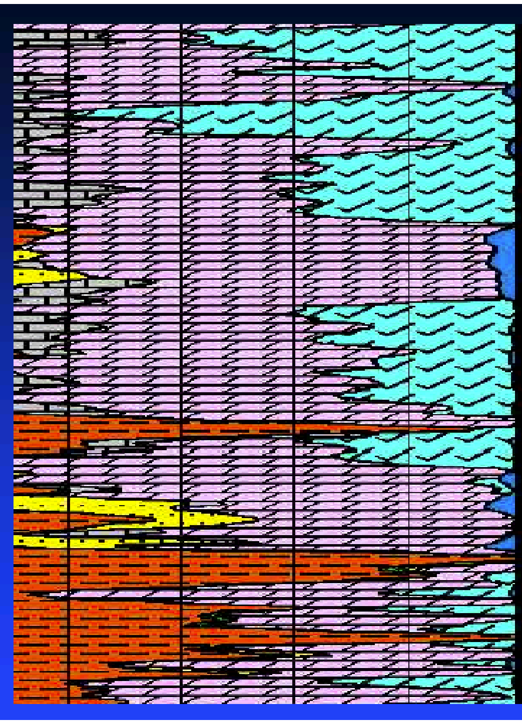
FORMATION VOLUMETRICS: Example



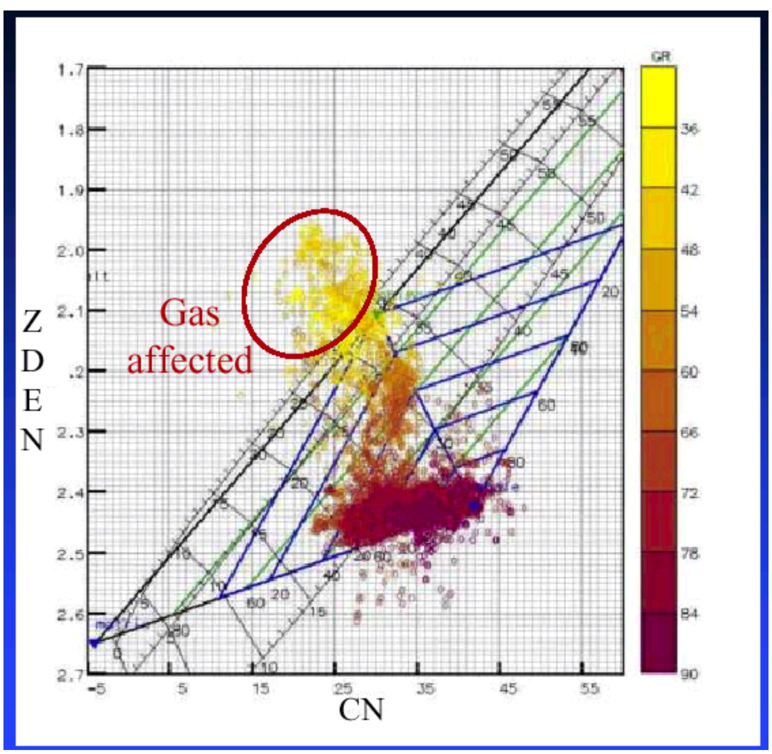
Mineralogy Determination

- **Input**
  - Pe
  - ϕ_N-ϕ_D
  - $\phi_{t\text{-}NMR}$
  - Δt

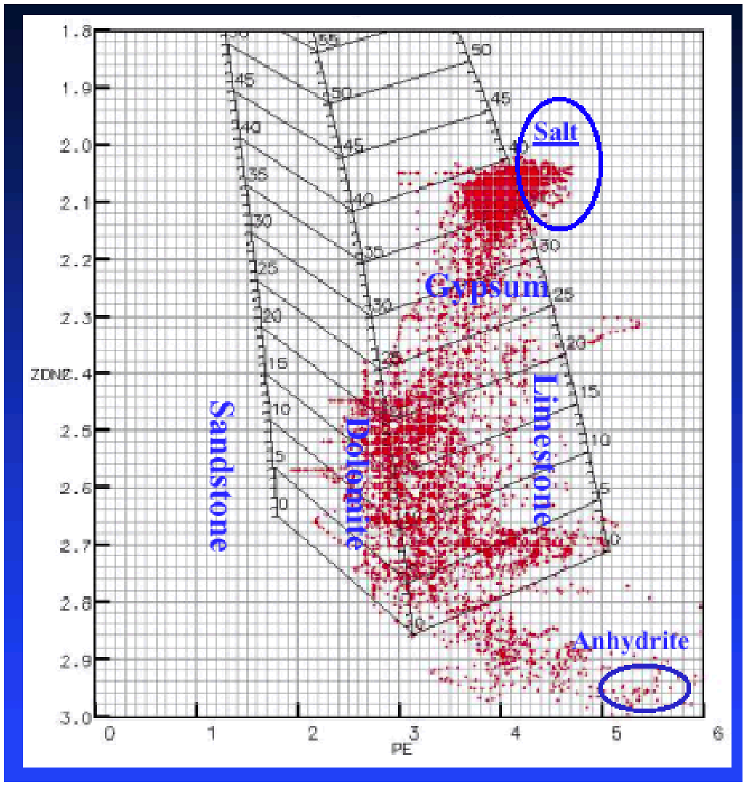
  Optima
- **Other data**
  - Cuttings
  - Whole core
  - Rotary Sidewall
  - Percussion Sidewall
  - Geologic knowledge



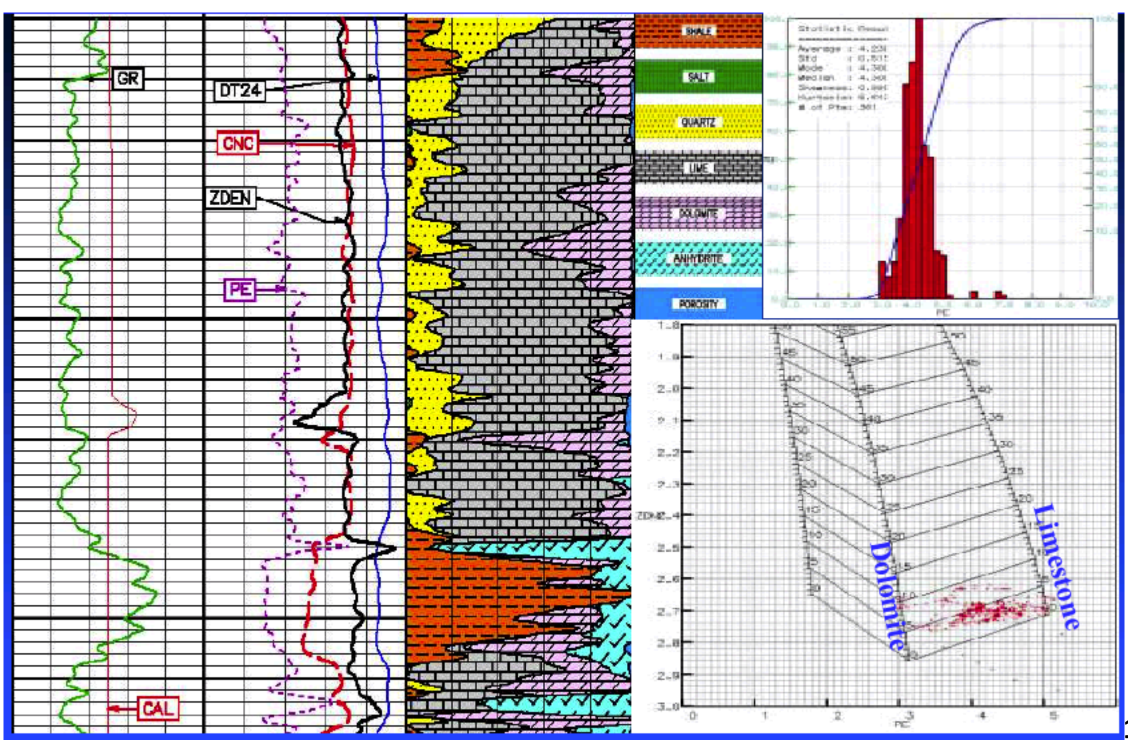
Cross-Plot Analysis: Example



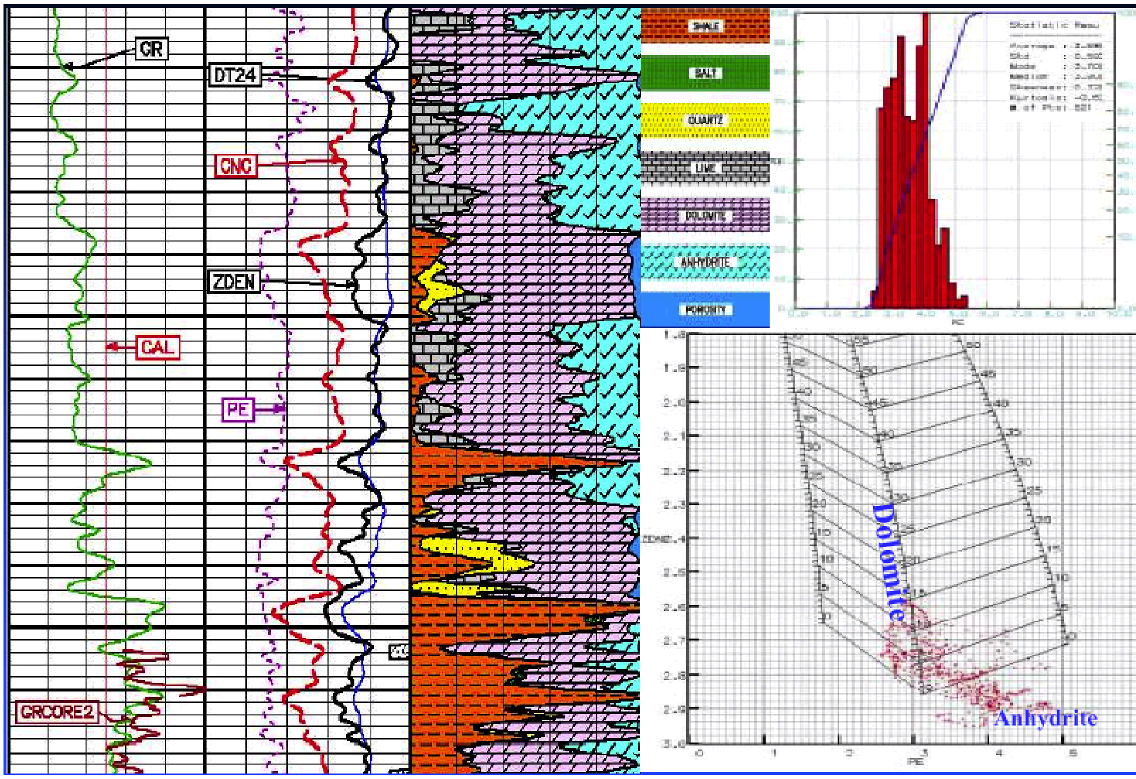
PEF-Density Cross-Plot Analysis: Example



Porosity and Lithology From PEF and Density: Example



Porosity and Lithology From PEF and Density: Example



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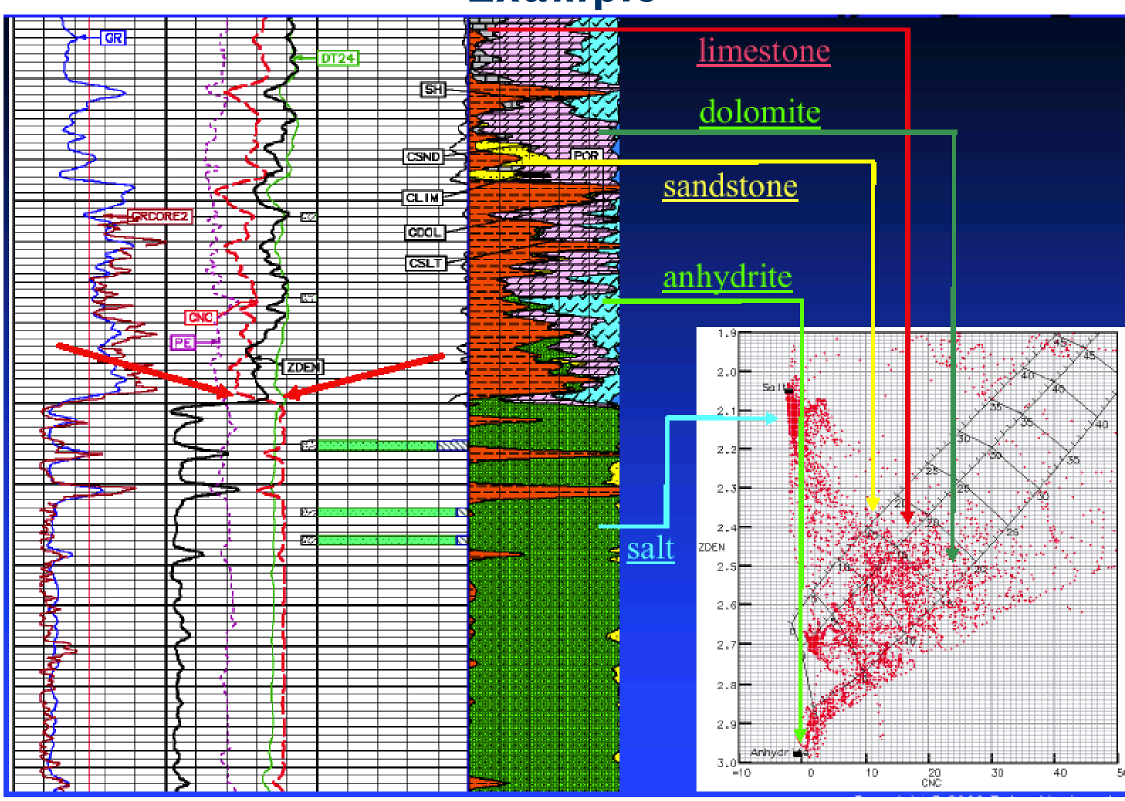
Mineral Identification From Neutron and Density: Example



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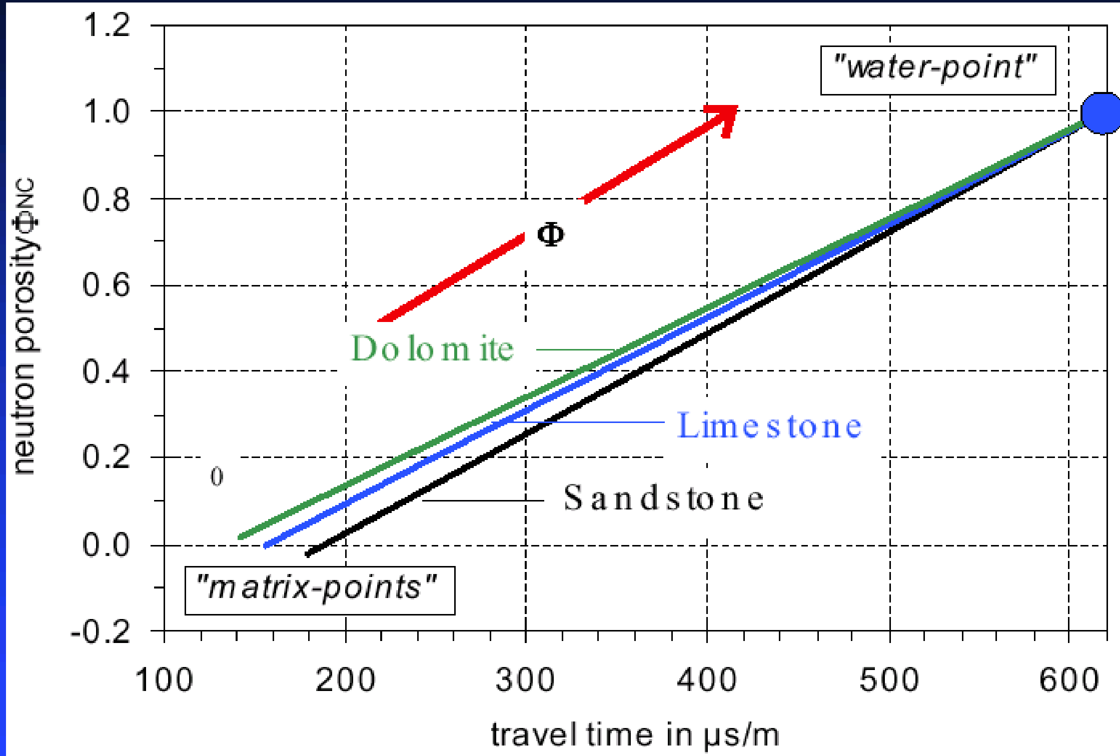
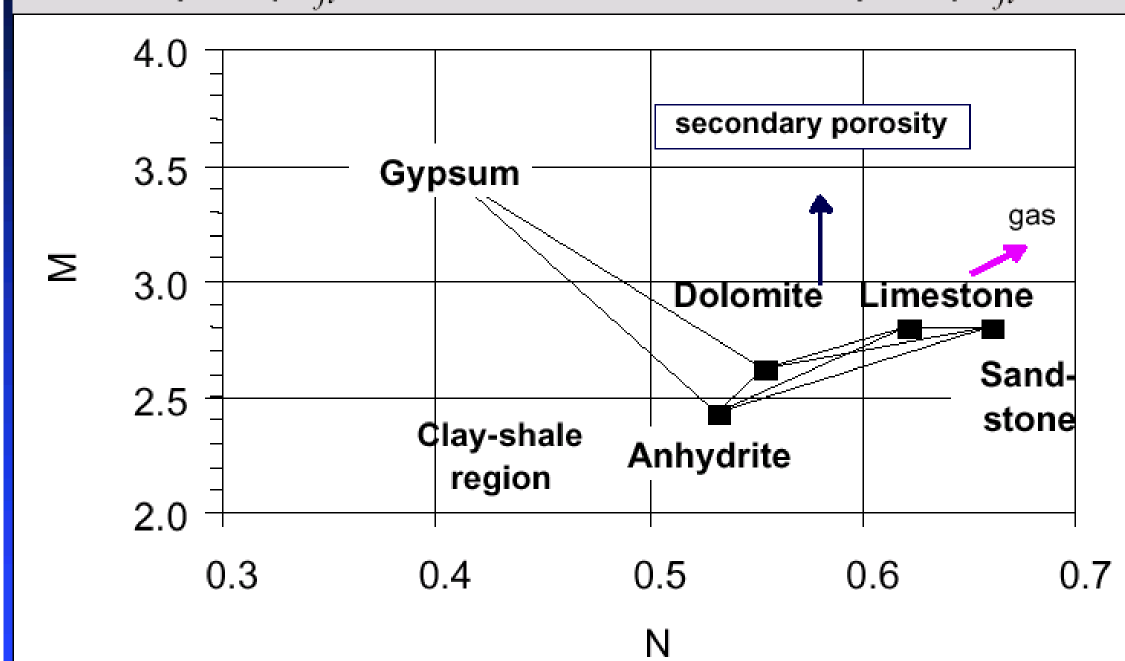
EXAMPLE: Sonic-Neutron Cross-Plot



EXAMPLE: M-N Cross-Plots

$$M = \frac{\Delta t_{fl} - \Delta t}{\rho - \rho_{fl}} \cdot 100 \qquad N = \frac{\Phi_{CN,fl} - \Phi_{CN}}{\rho - \rho_{fl}}$$



Linear Equations and Volumetric Models

resulting rock property is sum of contributions of components

examples are density, Pe & neutron-porosity.

Density of a porous rock

$$\rho = (1-\Phi)\cdot\rho_m + \Phi\cdot\rho_{fl}$$

Density of n-component rock

$$\rho = \sum_{i=1}^{n} \rho_i \cdot V_i \qquad \sum_{i=1}^{n} V_i = 1$$

V_i volume fraction component i

Model is exactly valid for scalar rock properties, that don't depend on structure or distribution of components.

Linear Equations and Volumetric Models

n components

$$g = \sum_{i=1}^{n} g_i \cdot V_i$$

$$\sum_{i=1}^{n} V_i = 1$$

Measured property ***g***

Volume fraction V_i

Component ***i***

system of linear equations:

→ ***m*** independent equations (logs)

n = m +1 unknown components

Applications

Foundation for various techniques for determining:

- rock composition
- porosity

Example:

- sonic-neutron crossplot, sonic-density crossplot
- mineral-identification (MID) plots
- M-N-plots

Applications

a. Determination of

rock composition (lithology) and porosity

crossplot, M-N-plot etc.

Matrix-inversion techniques

b. Shaly sand analysis based on nuclear measurements

Thomas-Stieber and Juhasz Model

Linear Equations: Four Components

Substance	ρ (g/cm^3)	Φ_{CN}	Δt (μs/m)
quartz	2.65	-0.02	180
calcite	2.71	0	156
dolomite	2.87	0.02	143
water	1.00	1.00	620

$\rho = 2.71\,V_{calcite} + 2.87\,V_{dolomite} + 2.65\,V_{quartz} + 1.00\,\Phi$

$\Phi_{CN} = 0.02\,V_{dolomite} - 0.02\,V_{quartz} + 1.00\,\Phi$

$\Delta t = 156\,V_{calcite} + 143\,V_{dolomite} + 180\,V_{quartz} + 620\,\Phi$

$1 = V_{calcite} + V_{dolomite} + V_{quartz} + \Phi$

Linear Equations: Four Components

Example:

Measured values ρ = 2.485 g/cm^3 Φ_{CN} = 0.158 Δt = 225 μs/m

1. Choose the model: C + D +Q +W

2. Insert

$2.485 = 2.71\,V_{calcite} + 2.87\,V_{dolomite} + 2.65\,V_{quartz} + 1.00\,\Phi$

$0.158 = 0.02\,V_{dolomite} - 0.02\,V_{quartz} + 1.00\,\Phi$

$225 = 156\,V_{calcite} + 143\,V_{dolomite} + 180\,V_{quartz} + 620\,\Phi$

$1 = V_{calcite} + V_{dolomite} + V_{quartz} + \Phi$

3. Solve for volume fractions:

$V_{calcite} = 0.52$ $V_{dolomite} = 0.23$ $V_{quartz} = 0.10$ $\Phi = 0.15$

Matrix Representation: Four Components

$\rho = 2.71\ V_{calcite} + 2.87\ V_{dolomite} + 2.65\ V_{quartz} + 1.00\ \Phi$

$\Phi_{CN} = 0.02\ V_{dolomite} - 0.02\ V_{quartz} + 1.00\ \Phi$

$\Delta t = 156\ V_{calcite} + 143\ V_{dolomite} + 180\ V_{quartz} + 620\ \Phi$

$1 = V_{calcite} + V_{dolomite} + V_{quartz} + \Phi$

$$\begin{bmatrix} \rho \\ \phi_{NC} \\ \Delta t \\ 1 \end{bmatrix} = \begin{bmatrix} 2.71 & 2.87 & 2.65 & 1.00 \\ 0.00 & 0.02 & -0.02 & 1.00 \\ 156 & 143 & 180 & 620 \\ 1.00 & 1.00 & 1.00 & 1.00 \end{bmatrix} \cdot \begin{bmatrix} V_{\text{calcite}} \\ V_{\text{dolomite}} \\ V_{\text{quartz}} \\ \phi \end{bmatrix}$$

Matrix Inversion: Four Components

$$\mathbf{M} = \mathbf{R}\mathbf{V}$$

M matrix - measured properties

R matrix - response

V matrix - volume fractions

$$\mathbf{V} = \mathbf{R}^{-1}\mathbf{M}$$

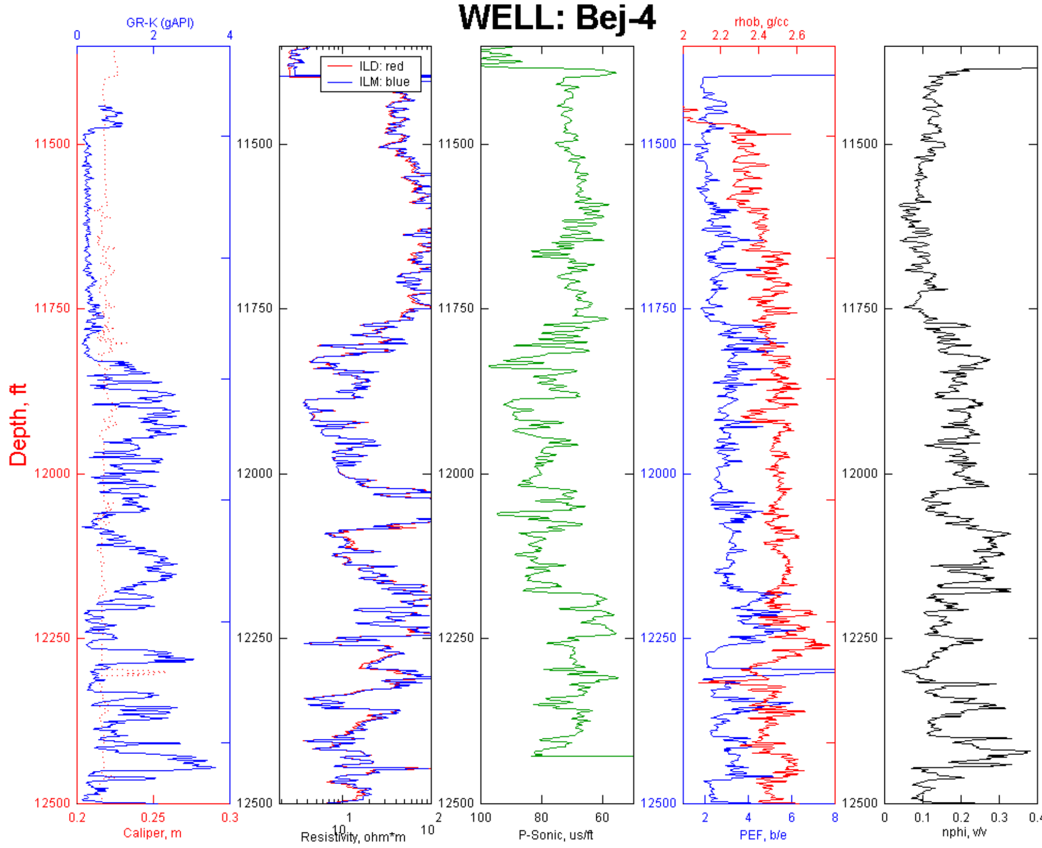
$\mathbf{R}^{-1}$ inverse matrix

Matrix Inversion: Four Components

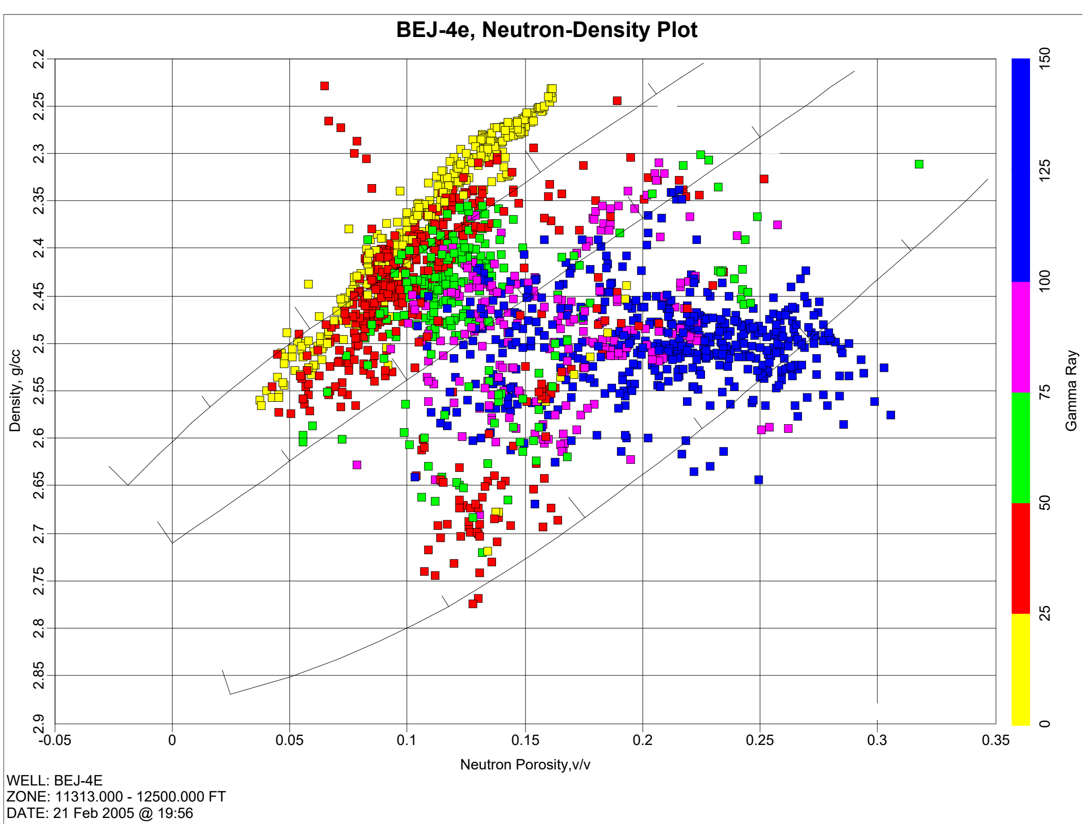
$$\begin{bmatrix} \rho \\ \phi_{NC} \\ \Delta t \\ 1 \end{bmatrix} = \begin{bmatrix} 2.71 & 2.87 & 2.65 & 1.00 \\ 0.00 & 0.02 & -0.02 & 1.00 \\ 156 & 143 & 180 & 620 \\ 1.00 & 1.00 & 1.00 & 1.00 \end{bmatrix} \cdot \begin{bmatrix} V_{\text{calcite}} \\ V_{\text{dolomite}} \\ V_{\text{quartz}} \\ \phi \end{bmatrix}$$

$$\begin{bmatrix} V_{\text{calcite}} \\ V_{\text{dolomite}} \\ V_{\text{quartz}} \\ \phi \end{bmatrix} = \begin{bmatrix} -12.68 & 8.19 & -0.0665 & 45.74 \\ 7.63 & 3.02 & 0.0216 & -24.03 \\ 5.11 & -11.91 & 0.0445 & -20.78 \\ -0.05 & 0.70 & 0.0004 & 0.0651 \end{bmatrix} \cdot \begin{bmatrix} \rho \\ \phi_{NC} \\ \Delta t \\ 1 \end{bmatrix}$$

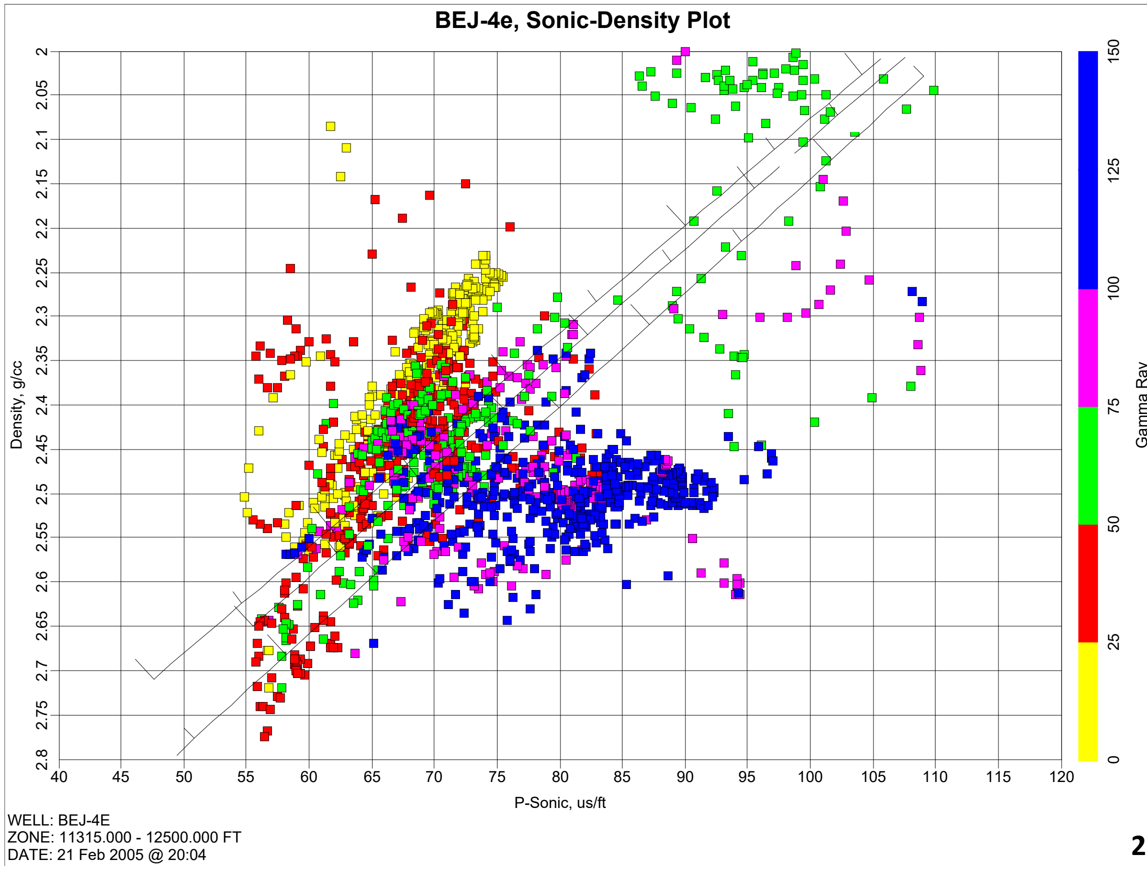
EXAMPLE OF IMPLEMENTATION



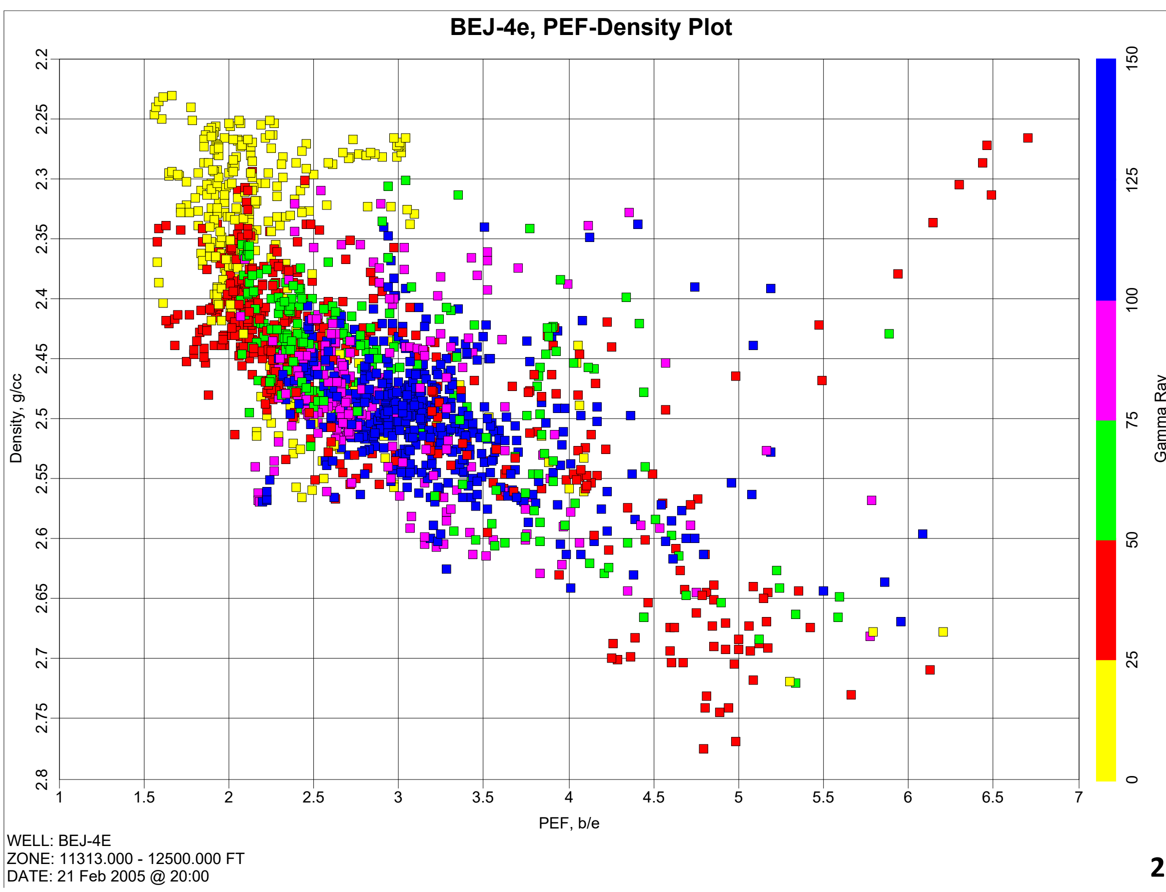
WELL: Bej-4
GR-K (gAPI)
rhob, g/cc
ILD: red
ILM: blue
Depth, ft
Caliper, m
Resistivity, ohm*m
P-Sonic, us/ft
PEF, b/e
nphi, v/v



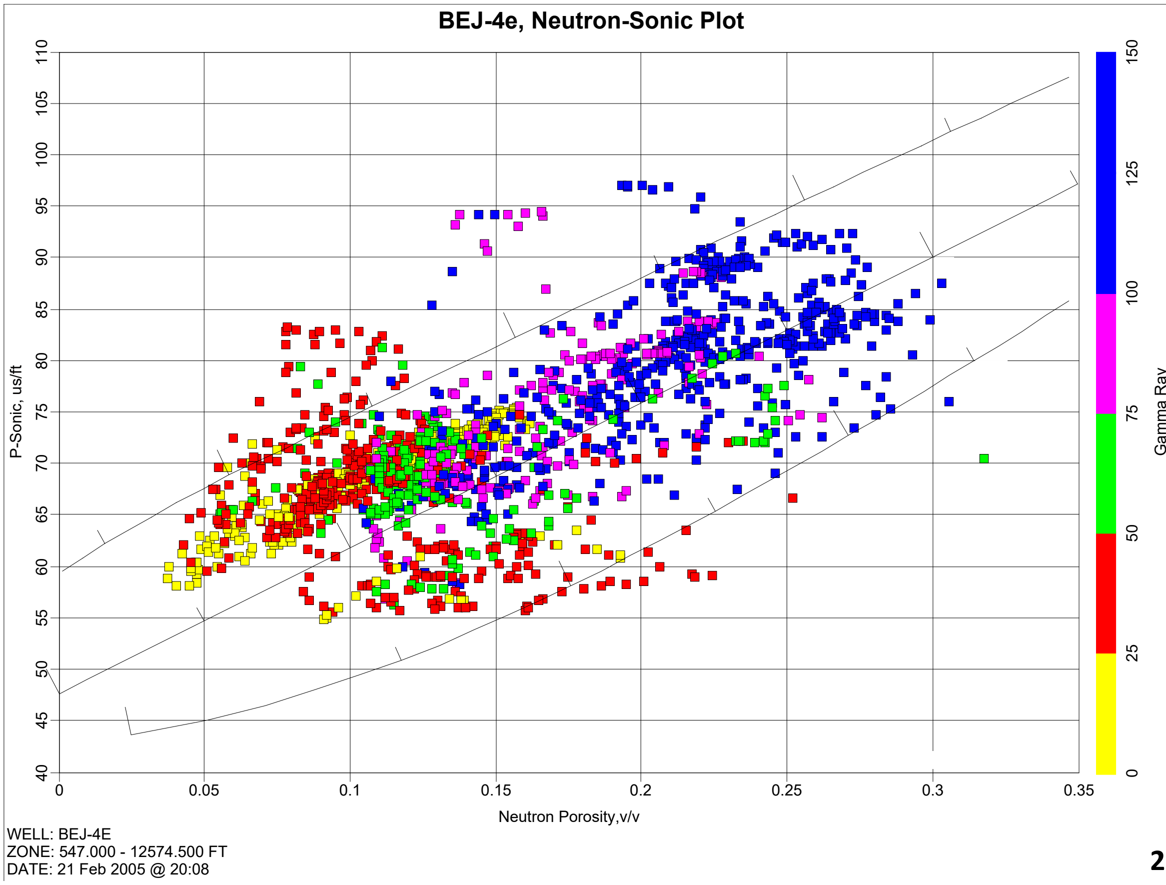
BEJ-4e, Neutron-Density Plot
Density, g/cc
Neutron Porosity,v/v
Gamma Ray
WELL: BEJ-4E
ZONE: 11313.000 - 12500.000 FT
DATE: 21 Feb 2005 @ 19:56

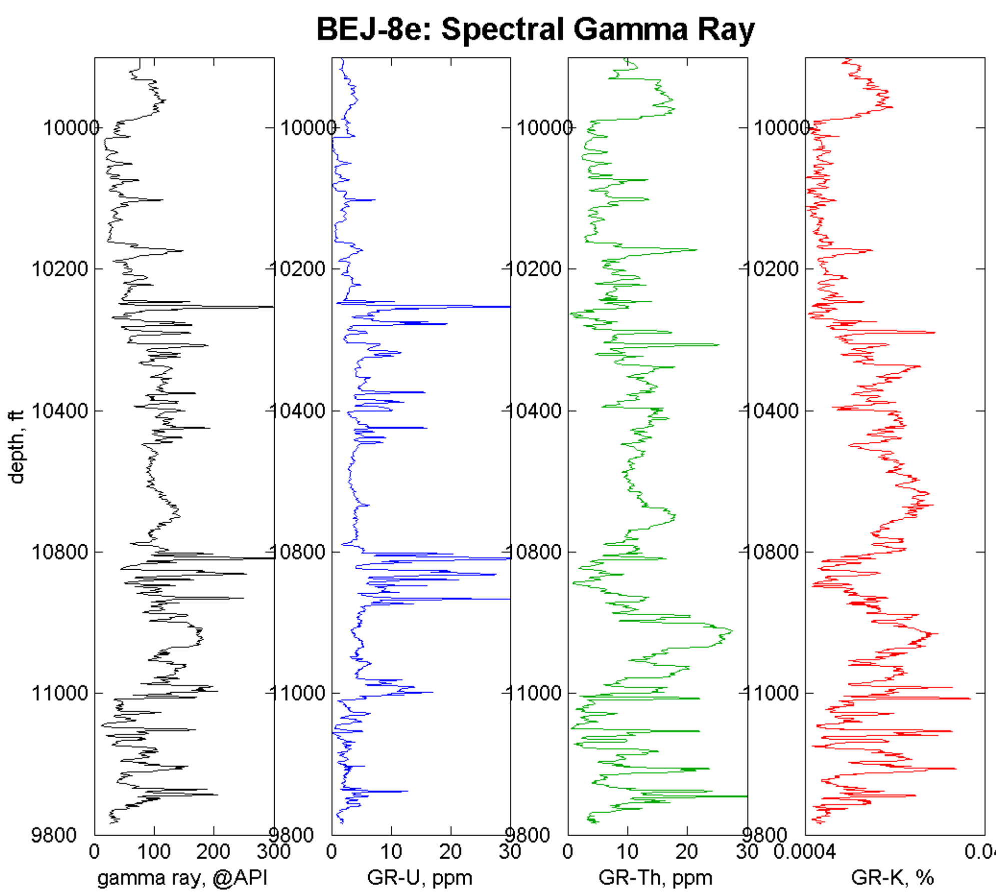


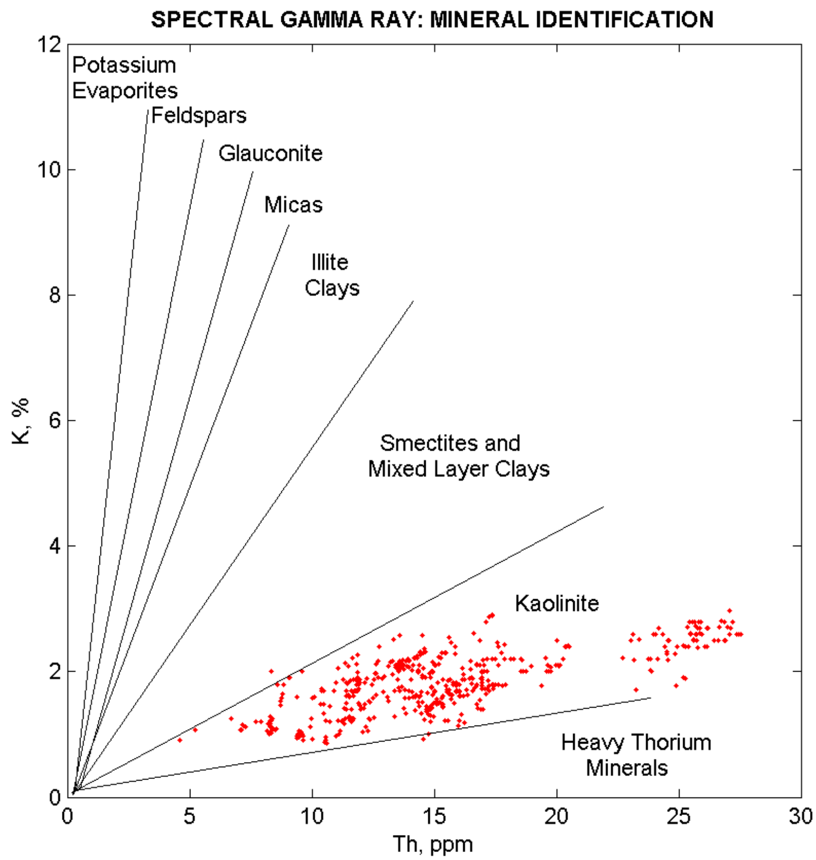
BEJ-4e, Sonic-Density Plot
Density, g/cc
P-Sonic, us/ft
Gamma Ray
WELL: BEJ-4E
ZONE: 11315.000 - 12500.000 FT
DATE: 21 Feb 2005 @ 20:04



BEJ-4e, PEF-Density Plot
Density, g/cc
PEF, b/e
Gamma Ray
WELL: BEJ-4E
ZONE: 11313.000 - 12500.000 FT
DATE: 21 Feb 2005 @ 20:00


BEJ-4e, Neutron-Sonic Plot
P-Sonic, us/ft
Neutron Porosity,v/v
Gamma Ray
WELL: BEJ-4E
ZONE: 547.000 - 12574.500 FT
DATE: 21 Feb 2005 @ 20:08


BEJ-8e: Spectral Gamma Ray
depth, ft
gamma ray, @API
GR-U, ppm
GR-Th, ppm
GR-K, %



ASSESSMENT OF VOLUMETRIC FRACTIONS
(4 input logs and estimating porosity/shale concentration)

$\delta \; = C_q \,.\, \delta_q + C_c \,.\, \delta_c + \phi \,.\, \delta_f + C_{sh} \,.\, \delta_{sh}$

$\phi_n = C_q \,.\, (\phi_n)_q + C_c \,.\, (\phi_n)_c + \phi \,.\, (\phi_n)_f + C_{sh} \,.\, (\phi_n)_{sh}$

$\Delta t = C_q \,.\, \Delta t_q + C_c \,.\, \Delta t_c + \phi \,.\, \Delta t_f + C_{sh} \,.\, \Delta t_{sh}$

$\upsilon \; = C_q \,.\, \upsilon_q + C_c \,.\, \upsilon_c + \phi \,.\, \upsilon_f + C_{sh} \,.\, \upsilon_{sh}$

$1 \; = C_q + C_c + \phi + C_{sh}$

$$\underbrace{\begin{pmatrix} \delta_{quartz} & \delta_{carbonate} & \delta_{fluid} & \delta_{shale} \\ (\phi_n)_{quartz} & (\phi_n)_{carbonate} & (\phi_n)_{fluid} & (\phi_n)_{shale} \\ \Delta t_{quartz} & \Delta t_{carbonate} & \Delta t_{fluid} & \Delta t_{shale} \\ \upsilon_{quartz} & \upsilon_{carbonate} & \upsilon_{fluid} & \upsilon_{shale} \\ 1 & 1 & 1 & 1 \end{pmatrix}}_{C} * \underbrace{\begin{pmatrix} C_q \\ C_c \\ phi \\ C_{sh} \end{pmatrix}}_{x} = \underbrace{\begin{pmatrix} \delta_b \\ \phi_n \\ \Delta t \\ \upsilon \\ 1 \end{pmatrix}}_{d}$$

A= [1 1 1 1]

b= 1

Aeq= [ ]

Beq= [ ]

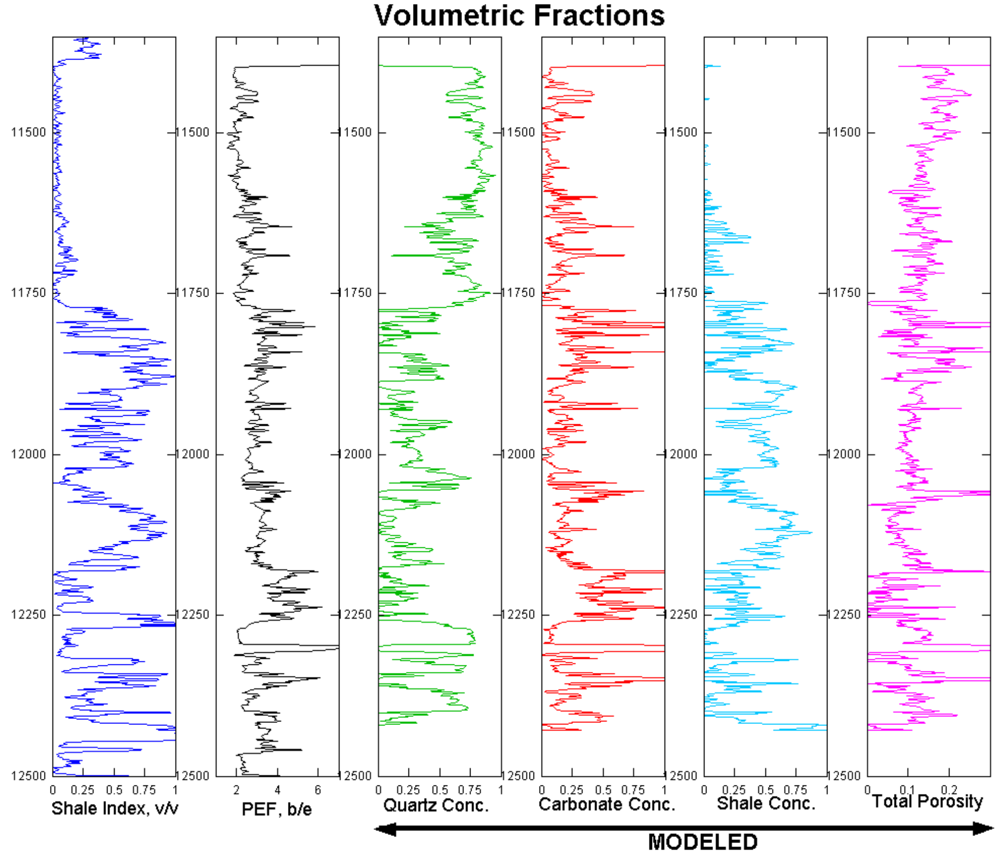
$\boxed{\textbf{x= lsqlin (C, d, A, b, Aeq, Beq, 0, 1)}}$

$\boxed{\textbf{x= lsqlin (C, d, A, b, Aeq, Beq, zeros(4,1), ones(4,1))}}$

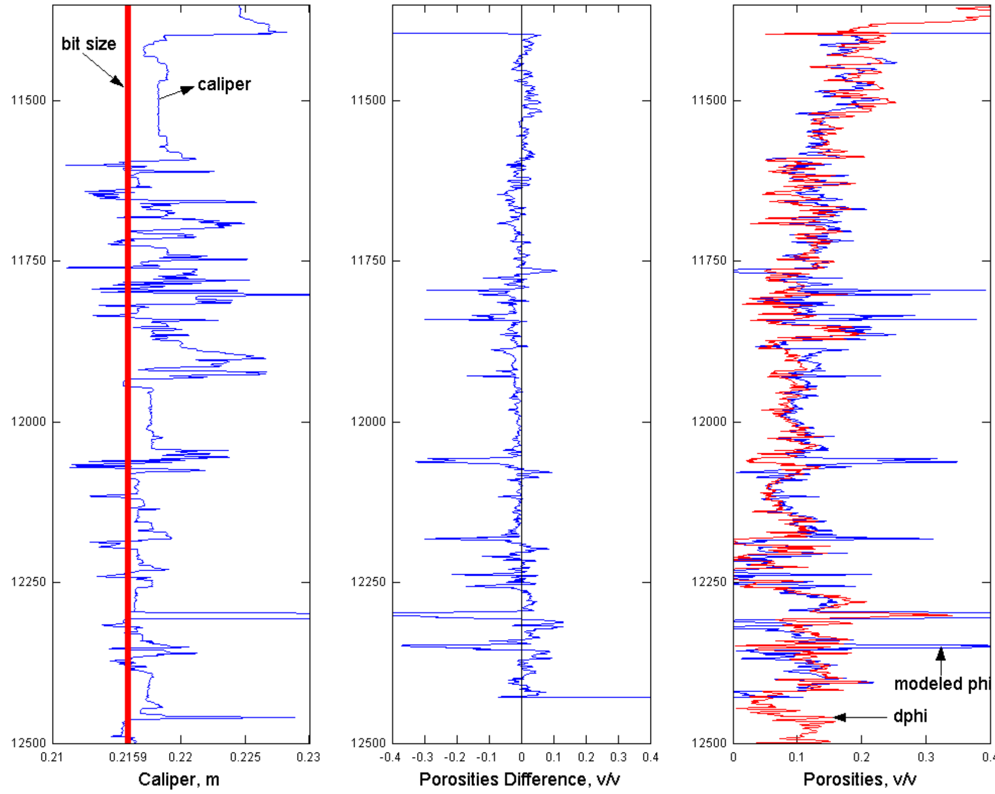
TABLE 5-1 – Logging Parameters for Some Common Rocks and Minerals

		Pe	ρ_b (g/cc)	Σ (c.u.)	Δt (μs/ft)	ϕ_{CN} (lime)	K (%)	U (ppm)	Th (ppm)
Common Sediment	Quartz	1.8	2.65	8.0 – 13.0	51.3 – 55.5	– 0.04	< 0.15	< 0.4	< 0.2
	Calcite	5.1	2.71	8.0 – 10.0	47.6	0.00	< 0.40	1.5 – 15.0	< 2.0
	Dolomite	3.1	2.87	8.0 – 12.0	43.5	0.02	0.1 – 0.3	1.5 – 10.0	< 2.0
	Shales		1.80 – 2.70	25.0 – 45.0	63.0 – 170.0	0.09 – 0.45			
Common Evaporites	Halite	4.7	2.04	748.0	67.0	– 0.02 – 0.03		< 0.3	< 0.2
	Anhydrite	5.0	2.98	12.3	50.0	0.00		0.25 – 0.43	< 0.2
	Gypsum	4.0	2.35	18.8	52.5	0.50 – 0.60			
	Trona	0.7	2.10	18.5	65.0	0.42			
Coals	Lignite	0.16	1.05	12.8	140.0	0.60			
	Bituminous	0.17	1.33	16.4	120.0	0.60			
	Anthracite	0.20	1.57	10.5	105.0	0.40			
Iron Minerals	Limonite	13.0	3.59		57.0				
	Pyrite	17.0	4.99	90.0	39.0				
	Siderite	14.7	3.94	52.3	48.0				
	Hematite	21.5	5.18		44.0				
Micas	Glauconite	5.5 – 7.1	2.54	23.4		0.19	5.08 – 5.30		
	Biotite	6.2 – 6.4	2.99	30.0	51.0	0.06	6.7 – 8.3		< 0.01
	Muscovite	2.4	2.82	16.9	49.0	0.13	7.9 – 9.8		< 0.01
Clays	Kaolinite		2.61	12.8		0.37	0.42	1.5 – 3.0	6.0 – 19.0
	Chlorite		2.88	25.3		0.32			
	Illite		2.63	15.5		0.09	4.50	1.0 – 5.0	< 2.0
	Smectite		2.02	14.5		0.17	0.16	2.0 – 5.0	6.0 – 19.0

Volumetric Fractions



Quality Control of Modeled Porosity



CASE No. 2

ASSESSMENT OF VOLUMETRIC FRACTIONS

(3 input logs and estimating quartz, shale and carbonate concentration)

$$
\begin{aligned}
\delta &= C_q \cdot \delta_q + C_c \cdot \delta_c + C_{sh} \cdot \delta_{sh} \\
\Delta t &= C_q \cdot \Delta t_q + C_c \cdot \Delta t_c + C_{sh} \cdot \Delta t_{sh} \\
\upsilon &= C_q \cdot \upsilon_q + C_c \cdot \upsilon_c + C_{sh} \cdot \upsilon_{sh} \\
1 &= C_q + C_c + C_{sh}
\end{aligned}
$$

$$
\underbrace{\begin{pmatrix} \delta_{quartz} & \delta_{carbonate} & \delta_{shale} \\ \Delta t_{quartz} & \Delta t_{carbonate} & \Delta t_{shale} \\ \upsilon_{quartz} & \upsilon_{carbonate} & \upsilon_{shale} \\ 1 & 1 & 1 \end{pmatrix}}_{\mathbf{C}} * \underbrace{\begin{pmatrix} C_q \\ C_c \\ C_{sh} \end{pmatrix}}_{\mathbf{x}} = \underbrace{\begin{pmatrix} \delta_b \\ \Delta t \\ \upsilon \\ 1 \end{pmatrix}}_{\mathbf{d}}
$$

A= [1 1 1]

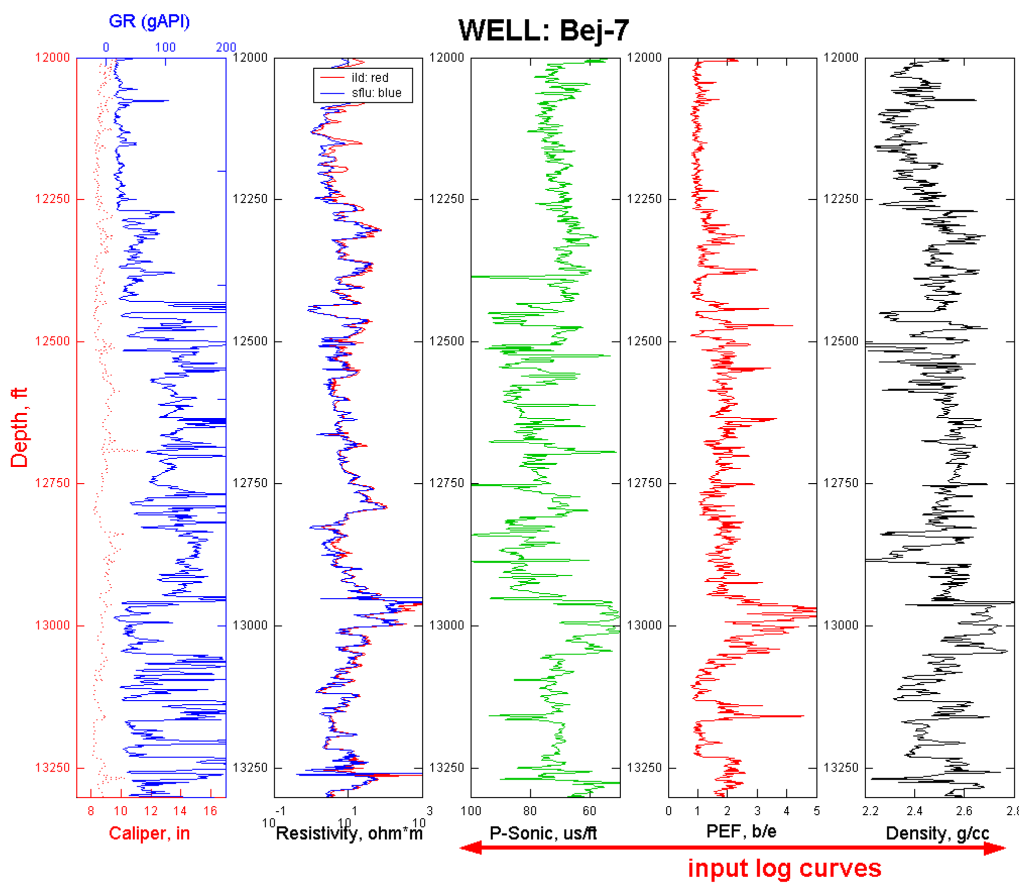
b= 1

Aeq= [ ]

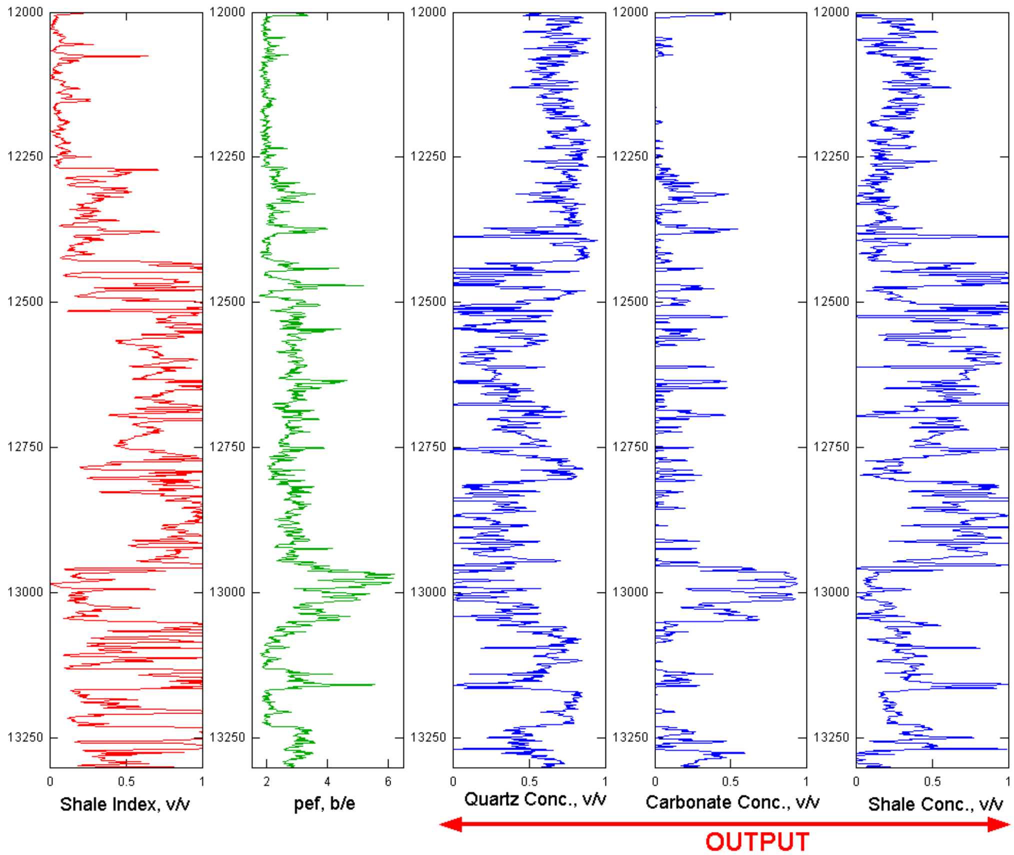
Beq= [ ]

$\boxed{\textbf{x= lsqlin (C, d, A, b, Aeq, Beq, 0, 1)}}$

$\boxed{\textbf{x= lsqlin (C, d, A, b, Aeq, Beq, zeros(3,1), ones(3,1))}}$



Bej-7: Volumetric Fractions



CASE No. 3

ASSESSMENT OF VOLUMETRIC FRACTIONS

(considering Csh as an input log)

$$\delta - (C_{sh} \,.\, \delta_{sh}) = C_q \,.\, \delta_q + C_l \,.\, \delta_l + \phi \,.\, \delta_f + C_d \,.\, \delta_d$$

$$\phi_n - (C_{sh} \,.\, (\phi_n)_{sh}) = C_q \,.\, (\phi_n)_q + C_l \,.\, (\phi_n)_l + \phi \,.\, (\phi_n)_f + C_d \,.\, (\phi_n)_d$$

$$\Delta t - (C_{sh} \,.\, \Delta t_{sh}) = C_q \,.\, \Delta t_q + C_l \,.\, \Delta t_l + \phi \,.\, \Delta t_f + C_d \,.\, \Delta t_d$$

$$\upsilon - (C_{sh} \,.\, \upsilon_{sh}) = C_q \,.\, \upsilon_q + C_l \,.\, \upsilon_l + \phi \,.\, \upsilon_f + C_d \,.\, \upsilon_d$$

$$1 - C_{sh} = C_q + C_l + \phi + C_d$$

$$\underbrace{\begin{pmatrix} \delta_{quartz} & \delta_{limestone} & \delta_{fluid} & \delta_{dolomite} \\ (\phi_n)_{quartz} & (\phi_n)_{limestone} & (\phi_n)_{fluid} & (\phi_n)_{dolomite} \\ \Delta t_{quartz} & \Delta t_{limestone} & \Delta t_{fluid} & \Delta t_{dolomite} \\ \upsilon_{quartz} & \upsilon_{limestone} & \upsilon_{fluid} & \upsilon_{dolomite} \\ 1 & 1 & 1 & 1 \end{pmatrix}}_{\mathbf{C}} * \underbrace{\begin{pmatrix} C_q \\ C_l \\ \phi \\ C_d \end{pmatrix}}_{\mathbf{x}} = \underbrace{\begin{pmatrix} \delta - (C_{sh} \,.\, \delta_{sh}) \\ \phi_n - (C_{sh} \,.\, (\phi_n)_{sh}) \\ \Delta t - (C_{sh} \,.\, \Delta t_{sh}) \\ \upsilon - (C_{sh} \,.\, \upsilon_{sh}) \\ 1 - C_{sh} \end{pmatrix}}_{\mathbf{d}}$$

A= [1 1 1 1]

b= 1

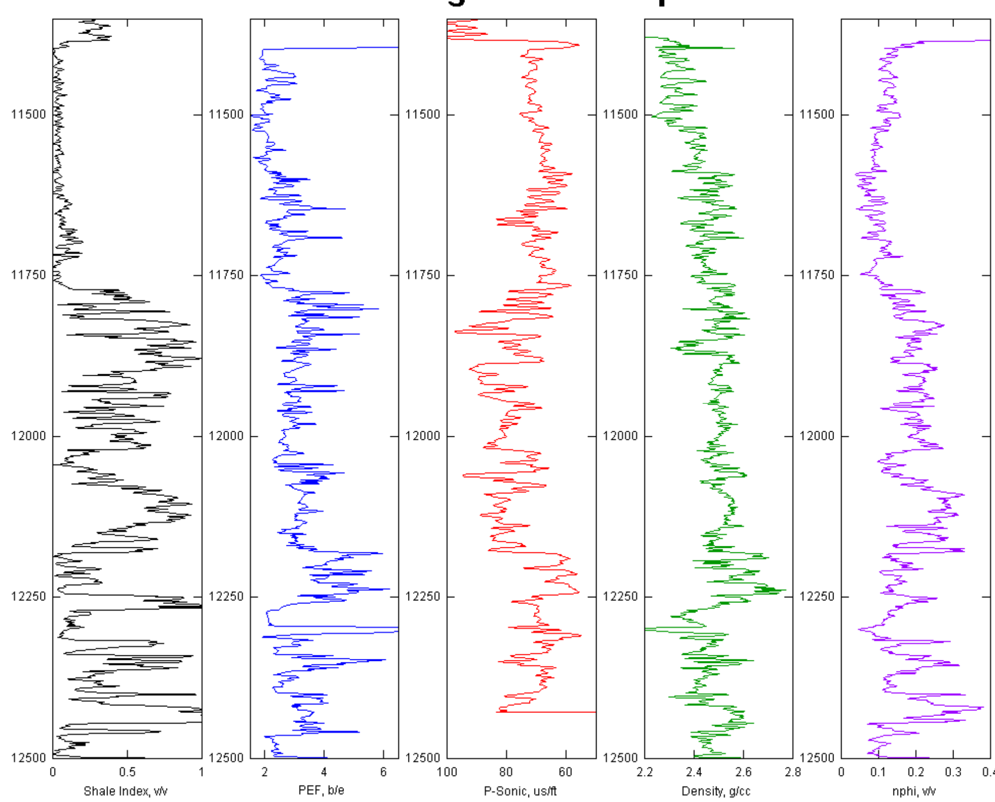
Aeq= [ ]

Beq= [ ]

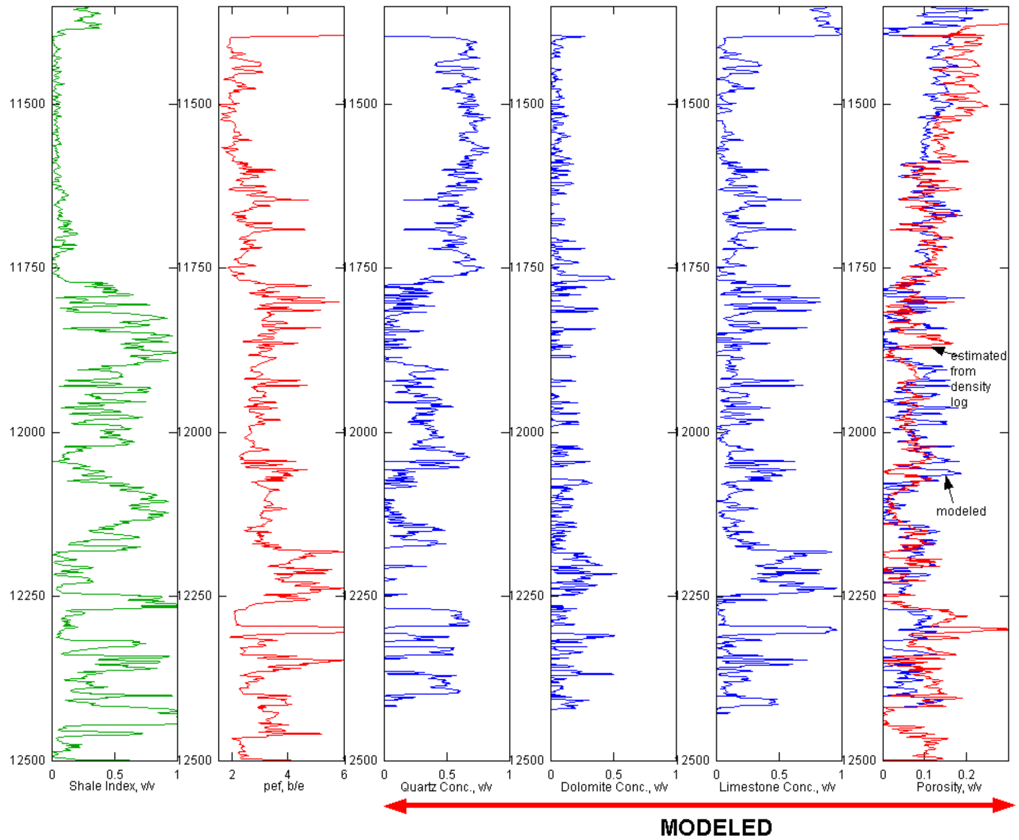
x= lsqlin (C, d, A, b, Aeq, Beq, 0, 1)

x= lsqlin (C, d, A, b, Aeq, Beq, zeros(4,1), ones(4,1))

Well Logs Used as Input



Volumetric Fractions



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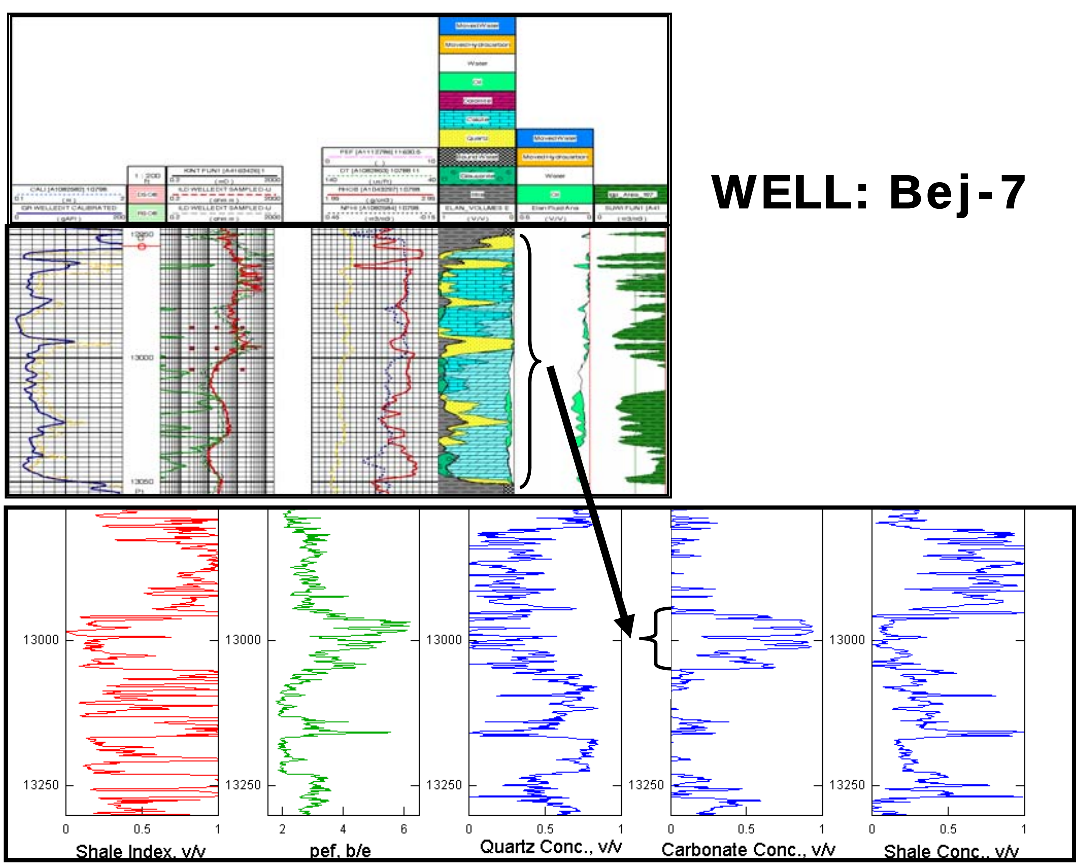

WELL: Bej-7

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Conventional Depth-by-Depth Estimation Method

- **Linear system of equations:**
  - **Nonlinear gas correction**
  - **Saturation correction**

$$\boldsymbol{A} = \begin{bmatrix} \rho_{b,1} & \rho_{b,2} & \dots & \rho_{b,p} & \rho_{b,sh} & \rho_{fluid} \\ \boxed{\phi_{N,1} & \phi_{N,2} & \dots & \phi_{N,p} & \phi_{N,sh} & \phi_{N,fluid}} \\ \Delta t_1 & \Delta t_2 & \dots & \Delta t_p & \Delta t_{sh} & \Delta t_{fluid} \\ U_1 & U_2 & \dots & U_p & U_{sh} & U_{fluid} \end{bmatrix}$$

$$\min \| \boldsymbol{A} \cdot \boldsymbol{x} - \boldsymbol{b} \|_2^2$$

$$\boldsymbol{x} = [C_1 \;\; C_2 \;\; \dots \;\; C_p \;\; C_{sh} \;\; \phi_s]^T$$

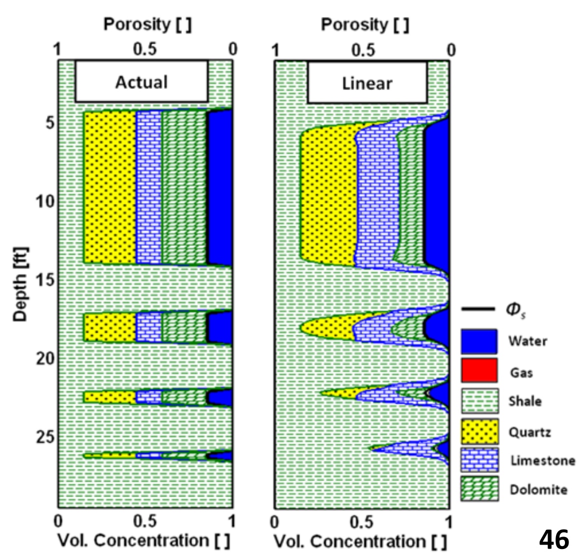
$$\boldsymbol{b} = [\rho_b \;\; \phi_N \;\; \Delta t \;\; U]^T$$

Is it a correct assumption?

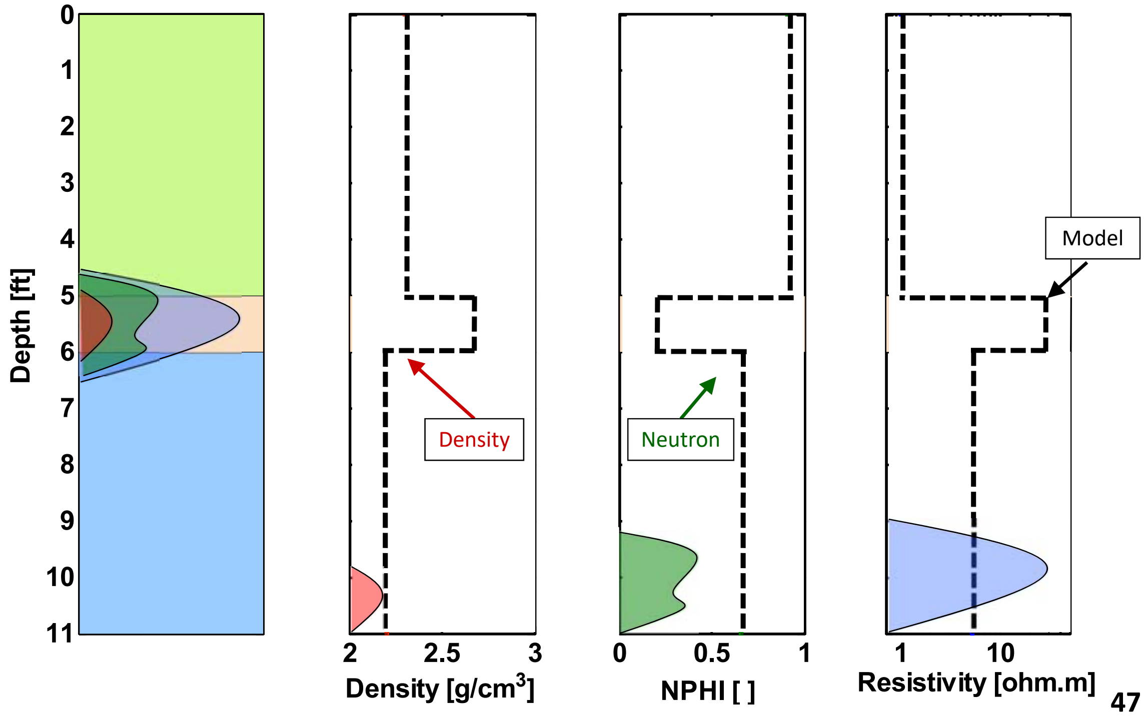
$$\sum_{i=1}^{n_c} C_i + C_{sh} + \phi_s = 1 \qquad 0 \le \boldsymbol{x}_i \le 1$$

Limitations of the Conventional Estimation Method

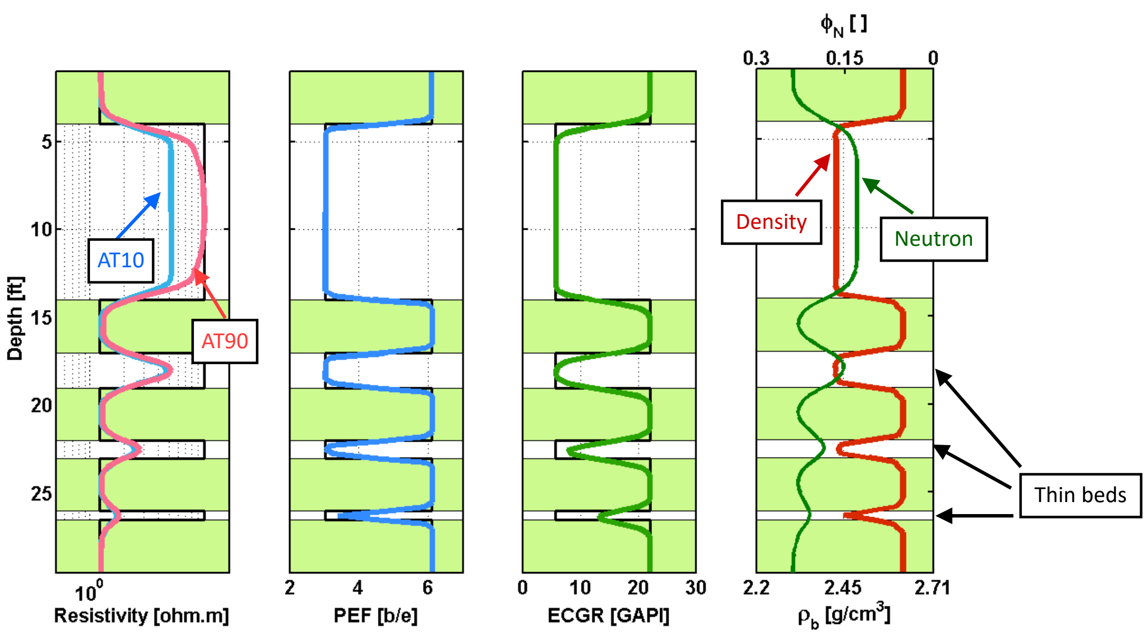
- Nonlinearity between well logs and concentrations, especially in gas-bearing zones and presence of salt
  - Fresh water-bearing zone
  - Gas-bearing zone
- Shoulder-bed effects
  - Thin beds



Uneven Vertical Resolution and Depth of Investigation



Thin-Bed Effects on Resistivity and Nuclear Logs



New Estimation Method

- **Limitations of conventional methods:**
  - **Unlike resistivity logs, nuclear logs were not easy to simulate**
    - **High CPU processing time** → **Hours/Days**

⇩

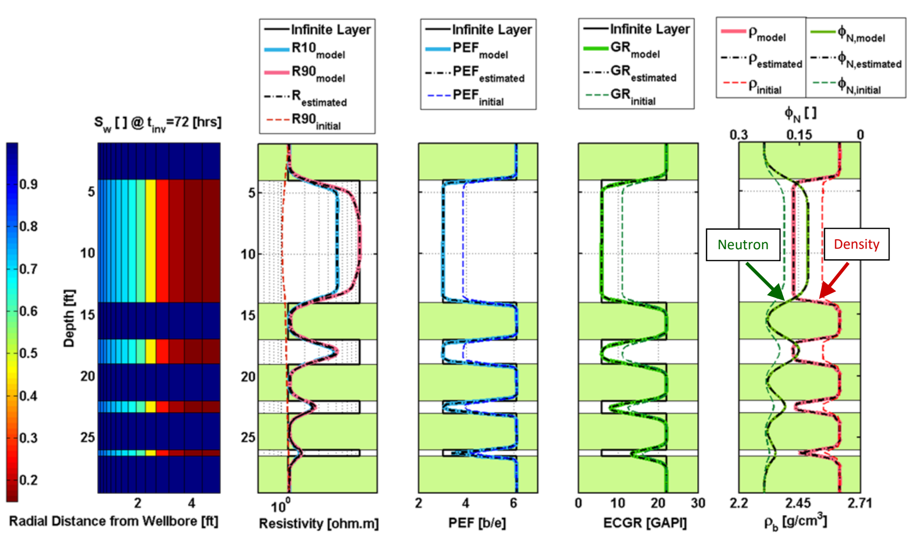
Numerically simulate nuclear logs using fast linear iterative refinement method → **Sec./Min.**

⇩

Nonlinear joint inversion of resistivity and nuclear logs

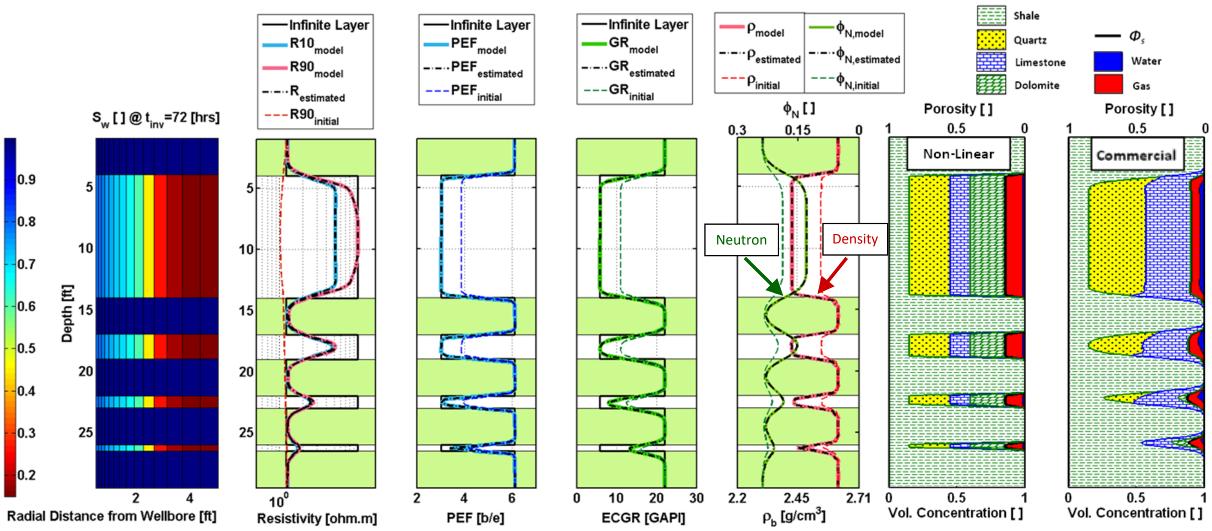
Synthetic Case No. 1

- **Gas-Bearing, Single-Layer Formation**



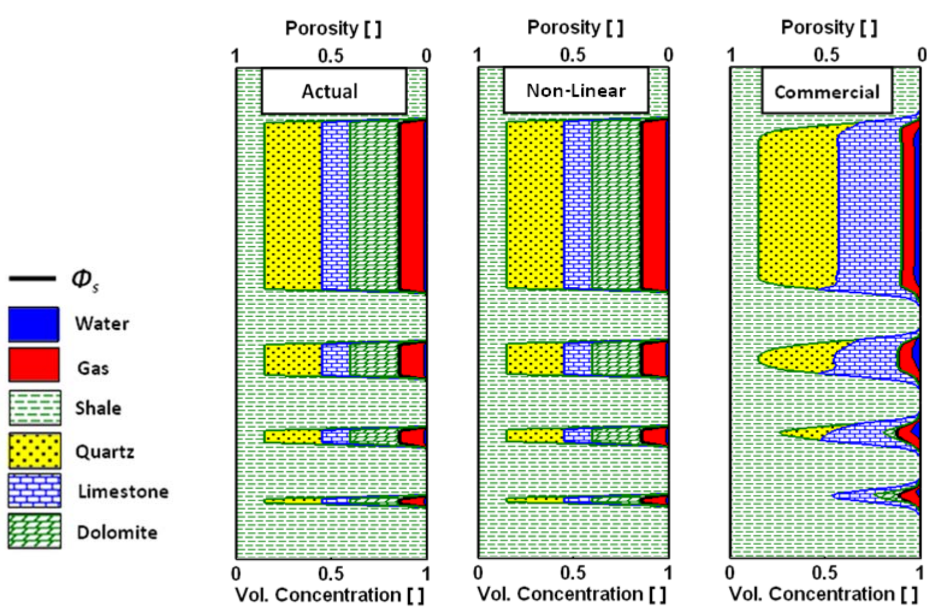
Synthetic Case No. 1

- **Gas-Bearing, Single-Layer Formation**



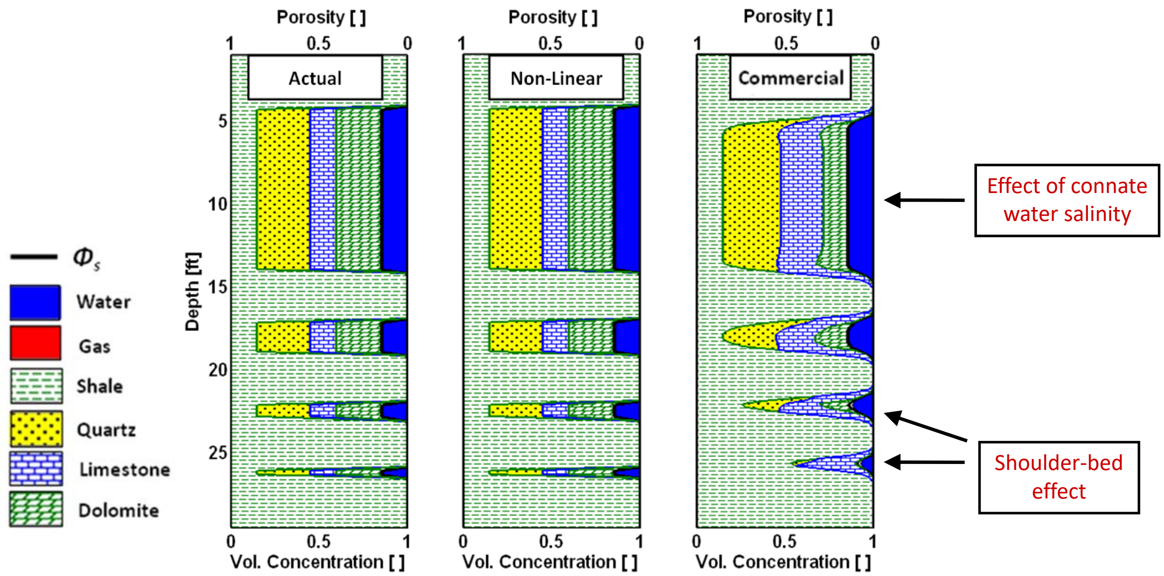
Synthetic Case No. 1

- **Synthetic Case No. 1: Gas-Bearing, Single-Layer Formation**



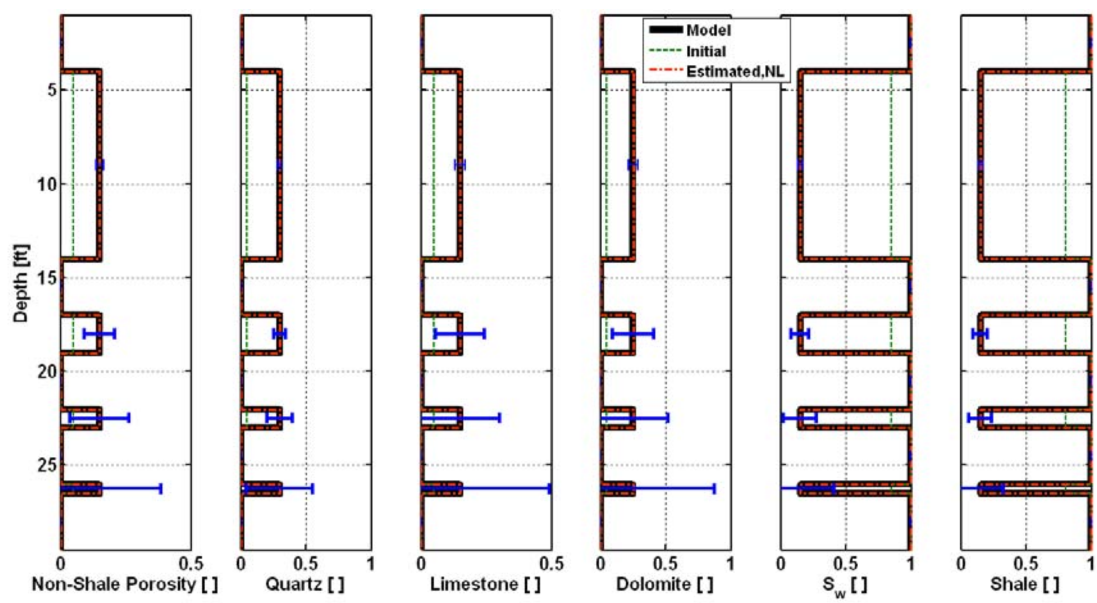
Synthetic Case No. 1

- **Synthetic Case No. 1: Water-Bearing, Single-Layer Formation**



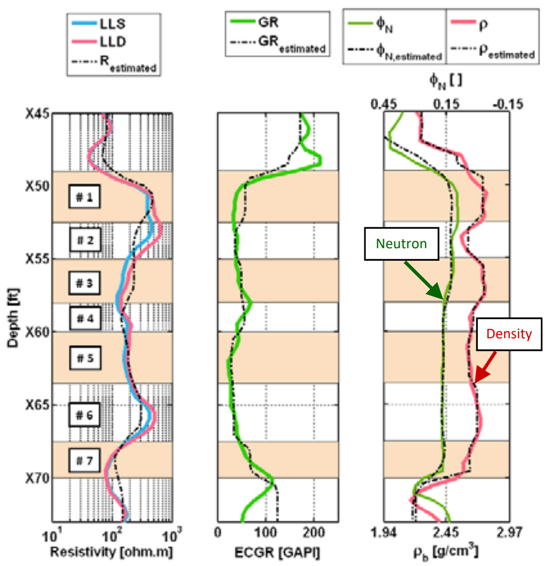
Effect of Layer Thickness

- **Synthetic Case No. 1:** 5% zero-mean Gaussian random perturbations on the original synthetic well logs



Field Example No. 1

- **Hydrocarbon-Bearing Carbonate Formation**

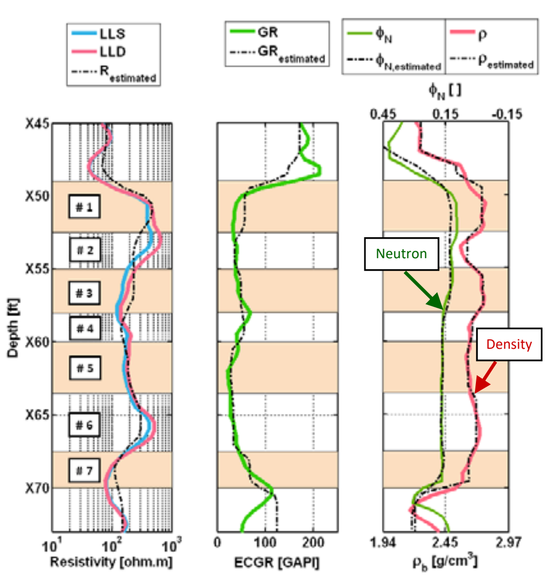


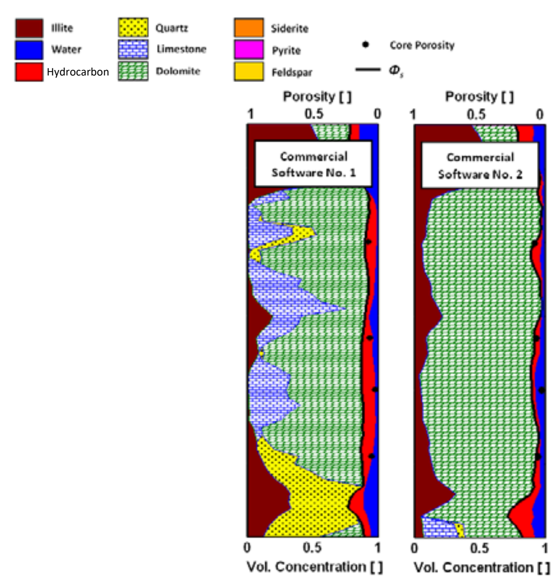
- Permeability = 0.1 [md]
- Non-shale porosity = 0.06 [ ]
- WBM invasion
- Negligible separation between resistivity logs
- No cross-over between neutron and density logs

Very deep mud-filtrate invasion

Field Example No. 1

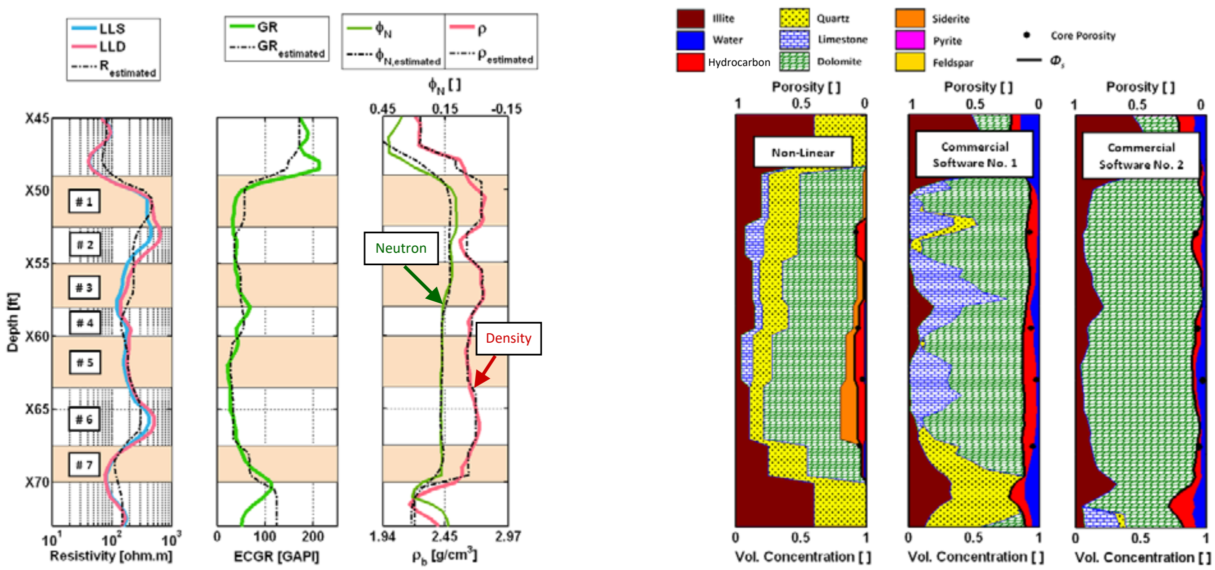
- **Hydrocarbon-Bearing Carbonate Formation**





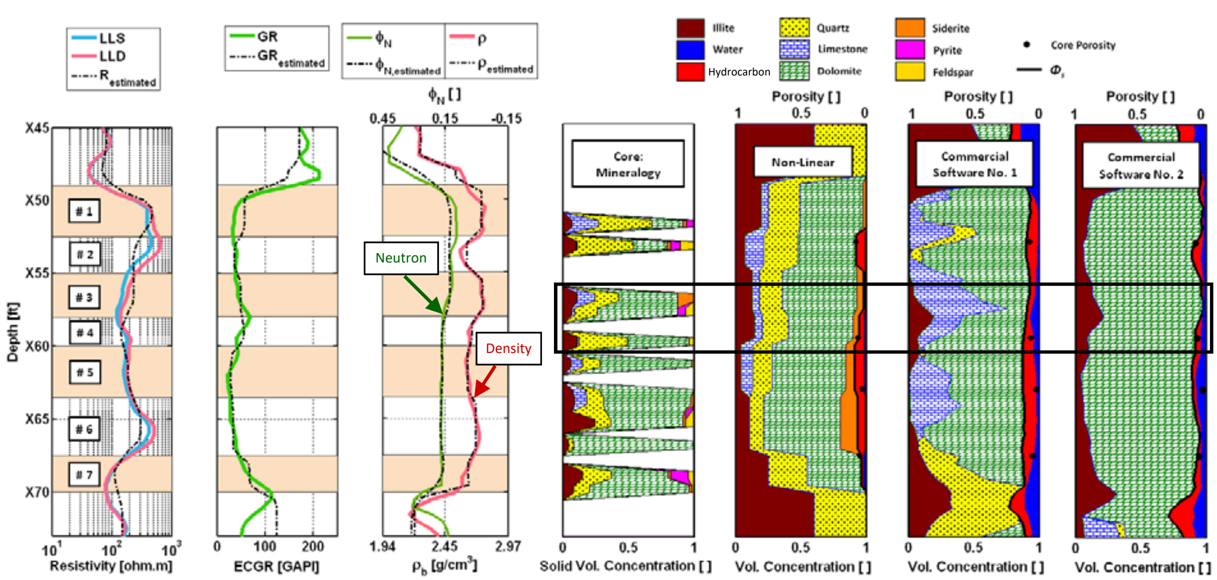
Field Example No. 1

- **Hydrocarbon-Bearing Carbonate Formation**



Field Example No. 1

- **Hydrocarbon-Bearing Carbonate Formation**



Acknowledgements:

- **Baker Atlas**