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SPECIAL PGE358 HANDOUT

OBJECTIVE: Calculation of hydrocarbon saturation and hydrocarbon density in a sandstone-shale laminated sedimentary sequence.

WELL-LOG EXAMPLE: Page 1 of PGE358's Well-Log Compendium Part 2

PURE SHALE (5,780 ft MD, local maximum in GR log) PROPERTIES:
GR_{sh} = 94 gAPI
Density Porosity, sh = 26.5% ss
Neutron Porosity, sh =45% ss
R_{sh} = 0.9 ohm-m

WATER SANDSTONE (5,681 ft MD, local minimum in GR log) PROPERTIES:
Clean (shale free) because density porosity = neutron porosity
Density Porosity, w = 34.5% ss
Neutron Porosity, w = 34.5% ss
$R_{t,w}$ = 0.45 ohm-m

HYDROCARBON SANDSTONE I (5,522 ft MD) PROPERTIES:
GR = 46 gAPI
Density Porosity = 39% ss
Neutron Porosity = 23.5% ss
R_t = 2.8 ohm-m

HYDROCARBON SANDSTONE II (5,478 ft MD) PROPERTIES:
GR = 62 gAPI
Density Porosity = 26.5% ss
Neutron Porosity = 32% ss
R_t = 1.5 ohm-m

CLEAN SANDSTONE
Located at 5,550 ft MD
GR = 25 gAPI = GR_s

<u>Units: density is in g/cc, resistivity in ohm-m, GR in gAPI and Csh – phi – saturation in fraction or percentage.</u>

CALCULATIONS – WATER SANDSTONE
Clean sandstone

- $R_w = R_{t,w} * \dfrac{\phi^m}{a} = 0.45 * 0.345^2 = 0.0536 \ \text{ohm}-\text{m}$

CALCULATIONS – HYDROCARBON SANDSTONE I (5,522 ft MD)

- $C_{sh} = \dfrac{GR - GR_s}{GR_{sh} - GR_s} = \dfrac{46-25}{94-25} = 0.3043 = 30.43\%$

- $$\phi_D^c = \frac{\phi_D - C_{sh} * \phi_{D,sh}}{1 - C_{sh}} = \frac{0.39 - 0.3043 * 0.265}{1 - 0.3043} = 0.4447 = 44.47\%$$
  $$\phi_N^c = \frac{\phi_N - C_{sh} * \phi_{N,sh}}{1 - C_{sh}} = \frac{0.235 - 0.3043 * 0.45}{1 - 0.3043} = 0.1409 = 14.09\%$$
  $$\phi_N^c < \phi_D^c \Rightarrow HC$$
  $$\phi_S = \sqrt{\frac{\phi_D^{c\,2} + \phi_N^{c\,2}}{2}} = \sqrt{\frac{0.4447^2 + 0.1409^2}{2}} = 0.3298 = 32.98\%$$

Note that the difference between shale-corrected neutron and density porosity logs increases with respect to that of non-corrected neutron and density porosity logs.

- $$\frac{1}{R_t} = \frac{C_{sh}}{R_{sh}} + \frac{1 - C_{sh}}{R_s}$$
  $$\frac{1}{R_t} - \frac{C_{sh}}{R_{sh}} > 0 \Rightarrow R_{sh} - C_{sh} R_t > 0 \Rightarrow \boxed{C_{sh} < \frac{R_{sh}}{R_t}} \Rightarrow C_{sh} < \frac{0.9}{2.8} = 0.3214$$
  $$R_s = \frac{1 - C_{sh}}{\frac{1}{R_t} - \frac{C_{sh}}{R_{sh}}} = \frac{1 - 0.3043}{\frac{1}{2.8} - \frac{0.3043}{0.9}} = 36.55 \quad \text{ohm} - \text{m}$$
  $$S_w = \left(\frac{R_w}{R_s} \frac{a}{\phi_s^m} \right)^{1/n} = \left(\frac{0.0536}{36.55} \frac{1}{0.3298^2} \right)^{1/2} = 0.1161 = 11.61\%$$
  $$S_h = 1 - S_w = 0.8839 = 88.39\%$$

- Now calculate hydrocarbon pore volume per unit depth:

  $$\text{HPV} = \phi_s (1 - C_{sh})(1 - S_w) = 0.3298 \cdot (1 - 0.3043) \cdot 0.8839 = 0.2028$$
  (i.e. approx. 20% of every foot in this section of the reservoir is occupied by hydrocarbon!)

- $$\rho_b = \phi_D \rho_f + (1 - \phi_D)\rho_m = (0.39)(1) + (1 - 0.39)(2.65) = 2.0065 \quad g/cc$$
  $$\rho_{sh} = \phi_{D,sh} \rho_f + (1 - \phi_{D,sh})\rho_m = (0.265)(1) + (1 - 0.265)(2.65) = 2.2127 \quad g/cc$$

- $$\rho_b = \rho_{sh} C_{sh} + (1 - C_{sh})\rho_s$$
  $$\rho_s = \frac{1}{1 - C_{sh}}(\rho_b - \rho_{sh} C_{sh}) = \frac{1}{1 - 0.3043}(2.0065 - 2.2127 * 0.3043) = 1.916 \quad g/cc$$

- $$\rho_s = \phi_s \rho_f + (1-\phi_s)\rho_m$$
$$\rho_f = \frac{1}{\phi_s}\left(\rho_s - (1-\phi_s)\rho_m\right) = \frac{1}{0.3298}\left(1.916 - (1-0.3298)2.65\right) = 0.4244 \quad g/cc$$

- $$\rho_f = S_w \rho_w + (1-S_w)\rho_h$$
$$\rho_h = \frac{1}{1-S_w}\left(\rho_f - S_w \rho_w\right) = \frac{1}{1-0.1161}\left(0.4244 - 0.1161*1\right) = 0.35 \quad g/cc$$

Gas!!!

CALCULATIONS – HYDROCARBON SANDSTONE II (5,478 ft MD)

- $$C_{sh} = \frac{GR - GR_s}{GR_{sh} - GR_s} = \frac{62-25}{94-25} = 0.5362 = 53.62\%$$

- $$\phi_D^c = \frac{\phi_D - C_{sh} * \phi_{D,sh}}{1-C_{sh}} = \frac{0.265 - 0.5362 * 0.265}{1-0.5362} = 0.265 = 26.5\%$$
$$\phi_N^c = \frac{\phi_N - C_{sh} * \phi_{N,sh}}{1-C_{sh}} = \frac{0.32 - 0.5362 * 0.45}{1-0.5362} = 0.1697 = 16.97\%$$
$$\phi_N^c < \phi_D^c \Rightarrow HC$$
$$\phi_S = \sqrt{\frac{\phi_D^{c\,2} + \phi_N^{c\,2}}{2}} = \sqrt{\frac{0.265^2 + 0.1697^2}{2}} = 0.2225 = 22.25\%$$

Notice that a neutron-density crossover suddenly arises after implementing the shale correction! In other words, the hydrocarbon effects on neutron-density logs is unmasked by the shale corrections.

- $$\frac{1}{R_t} = \frac{C_{sh}}{R_{sh}} + \frac{1-C_{sh}}{R_s}$$
$$\frac{1}{R_t} - \frac{C_{sh}}{R_{sh}} > 0 \Rightarrow R_{sh} - C_{sh}R_t > 0 \Rightarrow \boxed{C_{sh} < \frac{R_{sh}}{R_t}} \Rightarrow C_{sh} < \frac{0.9}{1.5} = 0.6$$
$$R_s = \frac{1-C_{sh}}{\frac{1}{R_t} - \frac{C_{sh}}{R_{sh}}} = \frac{1-0.5362}{\frac{1}{1.5} - \frac{0.5362}{0.9}} = 6.54 \quad \text{ohm}-\text{m}$$
$$S_w = \left(\frac{R_w}{R_s}\frac{a}{\phi_s^m}\right)^{1/n} = \left(\frac{0.0536}{6.54}\frac{1}{0.2225^2}\right)^{1/2} = 0.4069 = 40.69\%$$
$$S_h = 1 - S_w = 0.5931 = 59.31\%$$

- Now calculate hydrocarbon pore volume per unit depth:

$$\text{HPV}=\phi_s(1-C_{sh})(1-S_w)=0.2225\cdot(1-0.4069)\cdot 0.5362=0.0708$$

(i.e. approx. 7% of every foot in this section of the reservoir is occupied by hydrocarbon!)

- $$\rho_b=\phi_D\rho_f+\left(1-\phi_D\right)\rho_m=\left(0.265\right)\left(1\right)+\left(1-0.265\right)\left(2.65\right)=2.2127\quad g/cc$$
  $$\rho_{sh}=\phi_{D,sh}\rho_f+\left(1-\phi_{D,sh}\right)\rho_m=\left(0.265\right)\left(1\right)+\left(1-0.265\right)\left(2.65\right)=2.2127\quad g/cc$$

- $$\rho_b=\rho_{sh}C_{sh}+\left(1-C_{sh}\right)\rho_s$$
  $$\rho_s=\frac{1}{1-C_{sh}}\left(\rho_b-\rho_{sh}C_{sh}\right)=\frac{1}{1-0.5362}\left(2.2127-2.2127*0.5362\right)=2.2127\quad g/cc$$

- $$\rho_s=\phi_s\rho_f+\left(1-\phi_s\right)\rho_m$$
  $$\rho_f=\frac{1}{\phi_s}\left(\rho_s-\left(1-\phi_s\right)\rho_m\right)=\frac{1}{0.2225}\left(2.2127-\left(1-0.2225\right)2.65\right)=0.6846\quad g/cc$$

- $$\rho_f=S_w\rho_w+\left(1-S_w\right)\rho_h$$
  $$\rho_h=\frac{1}{1-S_w}\left(\rho_f-S_w\rho_w\right)=\frac{1}{1-0.4069}\left(0.6846-0.4069*1\right)=0.468\quad g/cc$$