Advanced Petrophysics PGE 381L,
Fall 2023

Unique Number: 20215

Homework Assignment No. 3

September 14, 2023

Due on September 28, 2023, before 11:00 PM

Name: **RENATO ESPIRITO BASSO POLI**

UT EID: **rep2656**

Objectives:

a) To practice assessment of porosity and fluid saturations in-situ condition
b) To practice calculation of hydrocarbon reserves
c) To practice assessment of fluid saturation in the presence of shale

Note: Please scan your homework assignment and upload it as one pdf file on the Canvas website before the deadline. Please name your homework document as follows:

PGE381L_2023_Fall _HW03_lastname_name.pdf

Example: PGE381L_2023_Fall_HW03_Heidari_Zoya.pdf

Question 1: Consider the well logs provided to you in Excel format, named "Question1_data." Answer the following questions:

Note: Please do not use any well-log interpretation software. You can assume a = 1, m =2, n = 2

a) Plot the well logs similar to the example distributed in the class (Example 1). Pay attention to the scale.

Question to think about (will not be graded): Do you know the reason behind the choice of scale for plotting bulk density, when plotted on top on neutron porosity in sandstone units versus the case it is plotted against neutron porosity in sandstone units?

Answer:

Please find the log tracks in the following pages.

b) Calculate the volumetric concentration of shale at each depth via

$$C_{sh} = \frac{GR - GR_s}{GR_{sh} - GR_s},$$

where GR_s and GR_{sh} are the gamma ray readings in clay-free sand and pure shale, respectively.

Answer:

Reading from the logs:

$$GR_{sh} = 120\ GAPI$$

$$GR_s = 15\ GAPI$$

The C_{sh} track was added to the log tracks (next pages).

c) Using the density log, calculate the porosity at each depth. Make appropriate assumptions for matrix and fluid densities. Plot the estimated depth-by-depth water saturation next to your well logs.
Consider 85% Illite and rest Chlorite clay type in shale. You can assume that 70% of the matrix in shale is composed of clay and the rest is silt.
What type of porosity are you calculating using the density log? Total or effective?

Answer:

We are calculating the total porosity.

First we identify the lithologies, then convert the $RHOZ$ logs to ϕ_D:

$$\phi_D = \frac{\rho_B - \rho_M}{\rho_f - \rho_M}$$

where ρ_B is the bulk density, ρ_M is the matrix density and ρ_f is the fluid density.

From tables:

$$\rho_{illite} = 2.75\ g/cm^3 \qquad \rho_{chlorite} = 2.95\ g/cm^3 \qquad \rho_{silt} = 2.65\ g/cm^3$$

$$\rho_M = 0.3\rho_{silt} + 0.7\ [0.85\ \rho_{illite} + 0.15\ \rho_{chlorite}] \rightarrow \rho_M = 2.68\ g/cm^3$$

The following properties were used:

	$\rho_M(g/cm^3)$
Sandstone	2.65
Shale	2.68
Limestone	2.71

Then we calculated the porosity using the formula:

$$\phi = \sqrt{\frac{\phi_D^2 + \phi_N^2}{2}}$$

We use Archie's formula to estimate the water saturation:

$$R_t = R_w \frac{a}{\phi^m S_w^n}$$

The porosity and water saturation tracks were added to the log tracks (next pages).

d) Identify the water-oil contact.

From the water saturation log, we can identify the water-oil contact:

$$WOC = 5903 \text{ ft}$$

e) Figure 1 shows deep resistivity measurements versus porosity for the water-saturated zone in this formation. This plot is called Pickett plot. Estimate the formation water resistivity using the data provided Figure 1.

Answer:

$$R_t = R_w \frac{a}{\phi^m S_w^n}$$

We read the graph

$$R_t = 0.003 \ \Omega\text{m} \ @ \ \phi = 1$$

Let $a = 1$, $S_w = 1$ (water saturated zone). Using Archie's formula, we get

$$R_w = 0.003 \ \Omega\text{m}$$

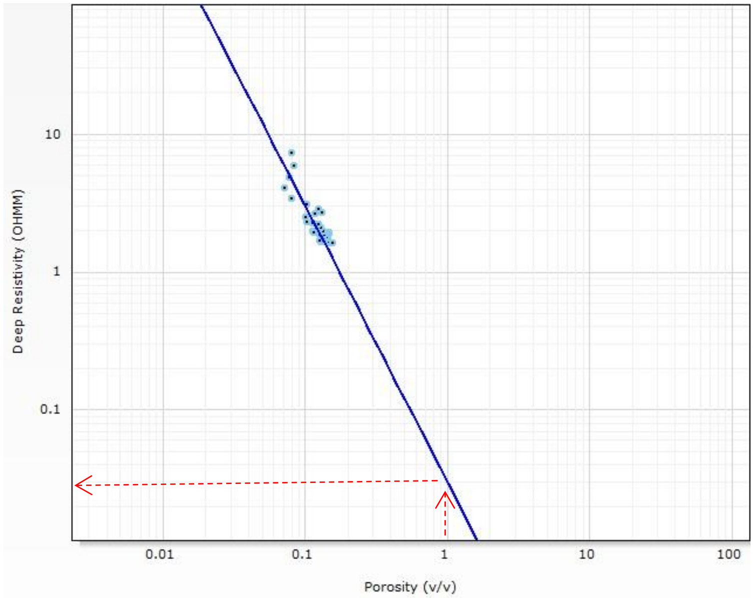


Figure 1: Pickett plot for Question 1-e

f) Estimate water/hydrocarbon saturation at each depth. Plot the estimated depth-by-depth water saturation next to your well logs. Plot the estimated depth-by-depth oil saturation next to your well logs. Note that shales are fully water saturated. You do not need to perform calculations for shale zones.

Answer:

$$S_o = 1 - S_w$$

The estimated fluid density and oil saturation were added to the log tracks.

g) Estimate total hydrocarbon reserves in place (in bbls/unit area).

Answer:

I used a Python routine to calculate the HC reserves, integrating depth by depth:

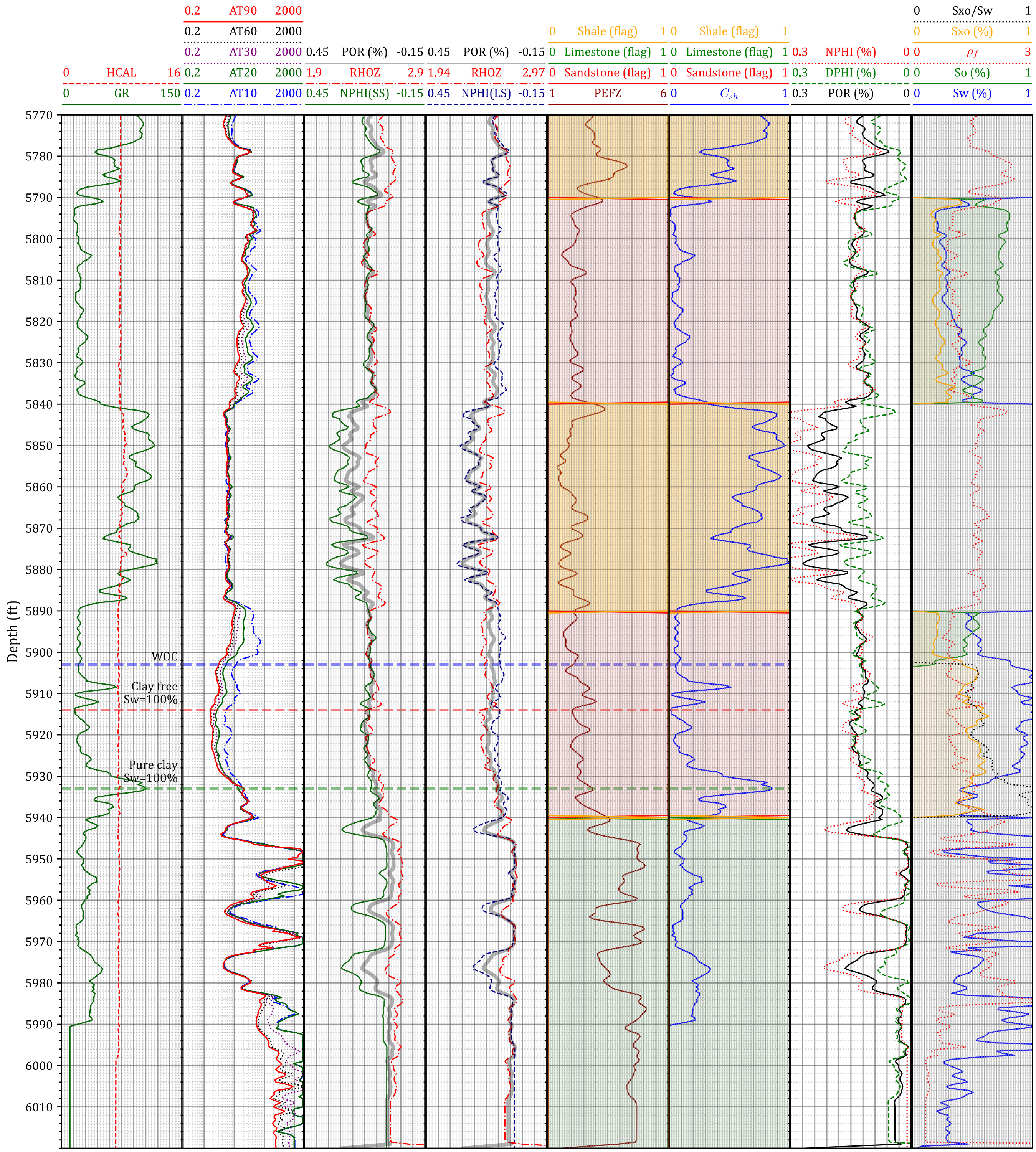
$$\frac{N}{A} = 7758 \sum_i \phi_i \, S_{o_i} \, h_i = 38.5 \text{ Mbbl}$$

h) **Bonus Question:** Estimate movable hydrocarbon saturation at each depth. Plot your results. What are the uncertainties associated with your interpretation?

Answer:

We must consider the properties of the drilling fluids to analyze the invaded zone and interpret data from the shallow resistivity log (AT10). Considering fresh water as the invading fluid (AT90<AT10), we can infer fluid mobility estimating the fluxed zone saturation S_{xo} using the AT10 log. The S_{xo} estimates are plot in the saturation track.

There are several uncertainties to be considered during interpretation. If we consider the properties of the fluid that was replaced, oil might have a very similar conductance as the injected fresh water. It would be a better idea to look at the log below the WOC, where electrically conductive brine is replaced by the less conductive fluid. However, as brine and fresh water interact, the electrical parameters may also be difficult to interpret and the analysis may be seen more reliably from qualitative perspective. Anyway, if we were to get a coarse estimation, in the zone of interest (5900 – 5930 ft) we can infer a fluid mobilization of around 40-50%.



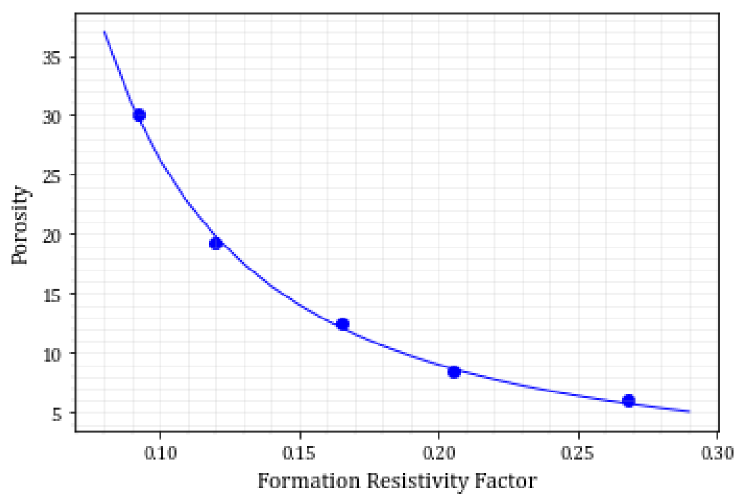
Question 2: A series of core measurements from a well provided the formation factor versus porosity data as listed in the following table:

Formation Resistivity Factor	Porosity
30	0.092
19.3	0.12
12.5	0.165
8.4	0.205
6	0.268

A thick salt water bearing layer of the reservoir is encountered in an offset well with a resistivity of 1.79 ohm-m. If the resistivity of the salt water is 0.076 ohm-m, estimate the porosity of the water bearing layer.

Answer:

I used a Python routine to fit Archie's parameters to the data.



Fit parameters:

$$F = 0.752/\phi^{1.5421}$$

$$a = 0.752 \qquad m = 1.542$$

We can now estimate porosity:

$$\phi = 10.7\%$$

Question 3: Figure 2 shows a synthetic porous medium which is made of insulator material and is shaped as a cube of length L. Three cylindrical shape tubes of radius *r* are drilled through the middle of this cube. You can assume:

$$r / L = 1 / \left(3\sqrt{\pi}\right)$$

Two of the cylindrical tubes are filled with brine of resistivity R_w, and the third one is filled with oil. Answer the following questions:

a) Calculate the formation resistivity factor (F), and the resistivity index (I) for the porous medium in the direction parallel to the length of the cylindrical tubes.

b) Determine the relationship between formation factor and porosity.

c) How does this compare with Archie's equation?

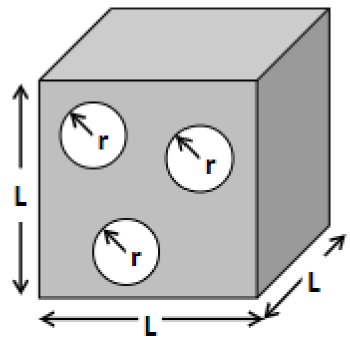
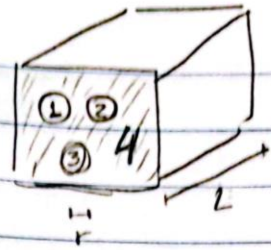


Figure 2: A synthetic porous medium. White and grey regions represent pores and insulator material, respectively.

Question 3

a)



$$r/L = \frac{1}{3\sqrt{\pi}} \Rightarrow \underline{L = 3r\sqrt{\pi}}$$

$$\frac{1}{R \cdot \cancel{L}/A} = \frac{1}{R_1 \cancel{L}/A_1} + \frac{1}{R_2 \cancel{L}/A_2} + \dots$$

$$\frac{L^2}{R} = \frac{\pi r^2}{R_1} + \frac{\pi r^2}{R_2} + \frac{\pi r^2}{R_3} + \frac{L^2 - 3\pi r^2}{R_4}$$

Set $L = 3r\sqrt{\pi} \rightarrow L^2 = 9r^2\pi$

$$\frac{9\cancel{r^2}\cancel{\pi}}{R} = \frac{\cancel{\pi}\cancel{r^2}}{R_1} + \frac{\cancel{\pi}\cancel{r^2}}{R_2} + \frac{\cancel{\pi}\cancel{r^2}}{R_3} + \frac{9\cancel{\pi}\cancel{r^2} - 3\cancel{\pi}\cancel{r^2}}{R_4}$$

$$\frac{1}{R} = \frac{1}{9}\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{6}{R_4}\right]$$

$\underline{R_0}$: $R_1 = R_2 = R_3 = R_w \quad R_4 >> R_w \Rightarrow \frac{1}{R_0} = \frac{1}{9}\frac{3}{R_w} \Rightarrow \frac{1}{R_0} = \frac{1}{3R_w}$;

$$\boxed{F = \frac{R_0}{R_w} = 3}$$

$\underline{R_t}$: $R_1 = R_2 = R_w \quad R_3 = R_4 >> R_w \Rightarrow \frac{1}{R_t} = \frac{1}{9} \cdot \frac{2}{R_w} \Rightarrow$

$$I = \frac{R_t}{R_0} = \frac{9}{2}\cancel{R_w} \cdot \frac{1}{\cancel{3}\cancel{R_w}} \Rightarrow \boxed{I = 3/2}$$

(b)

$$\phi = \frac{V_P}{V_B} = \frac{3 \cdot \pi r^2 \cancel{L}}{L^{3\,2}} = \frac{3\pi r^2}{9\pi r^2} = \frac{1}{3}.$$

Thus: $\boxed{F = \frac{1}{\phi}}$

(c) Archie: $R_t = R_w \frac{a}{\phi^m S_w^n} \to \frac{R_t}{R_w} = \frac{a}{\phi^m S_w^n} = I \times F$

$\boxed{\frac{R_t}{R_w} = I \times F}$ where $F = \frac{a}{\phi^m}$ and $I = \frac{1}{S_w^n}$

We can infer that, for an idealized media, as our example, $a = 1$, $m = 1$, $n = 1$.

As $S_w = 2/3$, $I = \frac{1}{S_w}$.

Question 4: We know that negative charge on the surface of clay minerals can cause variation (from surface of the clay mineral to the center of the pore) in electrical conductivity of water.

Figure 2 is a simplified illustration to model this variation in electrical conductivity of water in porous media by assuming two parallel layers of water. You can assume the electrical conductivity of clay-bound water layer is σ_{wb} and the electrical conductivity of formation water layer is σ_w. Saturation of clay-bound water is equal to S_{wb}.

Answer the following questions:

a) Estimate equivalent electrical conductivity of water, $\sigma_{w,avg}$, in the presence of clay minerals. You can assume the pore space is fully saturated with water.

b) Update Archie's equation by taking into account your updated electrical conductivity of water. You can assume the pore space is fully saturated with water.

c) How would you update your resistivity model in part (b), if there is hydrocarbon in the system? You can assume total saturation of water and hydrocarbon are S_{WT} and S_{HC}, respectively. Write your new model.

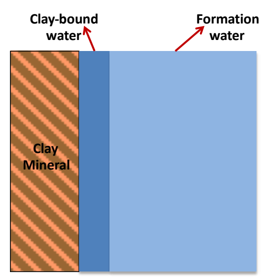
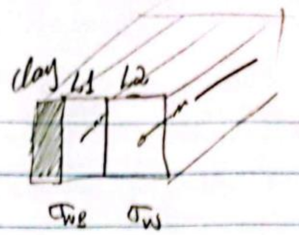


Figure 2

4



(a) S_{wB}.

$S_w = 1 - S_{wB}$

$\sigma = \frac{1}{R}$

$\Omega = R \cdot \frac{L}{A} \rightarrow \Omega = \frac{L}{\sigma A}$

$$\frac{1}{\Omega_{eq}} = \frac{1}{\Omega_1} + \frac{1}{\Omega_2} \Rightarrow \frac{\sigma_{eq} \cdot A_T}{\cancel{L}} = \frac{\sigma_{wb} A_{wB}}{\cancel{L}} + \frac{\sigma_w A_w}{\cancel{L}}$$

$$\sigma_{eq} = \frac{\sigma_{wb} A_{wb} + \sigma_w A_w}{A_{wb} + A_w}$$

$A_{wB} = A \cdot S_{wB}$

$A_w = A \cdot (1 - S_{wB})$

$A_{wB} + A_w = A$

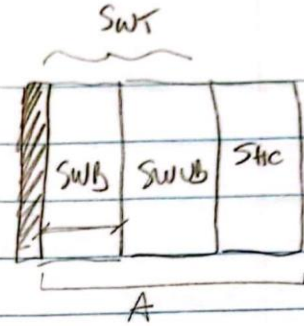
$$\boxed{\sigma_{eq} = \sigma_{wB} S_{wB} + (1 - S_{wB})\, \sigma_w}$$

(b) Let $S_w = 1$: $R_w = 1/\sigma_{w,eq}$

$R_o = R_w \frac{a}{\phi^m} \rightarrow$

$$R_o = \frac{1}{\sigma_{w,eq}} \frac{a}{\phi^m} \rightarrow \boxed{R_o = \frac{a}{\phi^m} \cdot \frac{1}{\sigma_{wB} S_{wB} + (1 - S_{wB})\, \sigma_w}}$$

(c)



Let $S_{WT} = 1 - S_{HC}$

$$\sigma_{weq} = S_{WB} \cdot \sigma_{WB} + S_{WUB}\,\sigma_{W}$$

$$S_{WB} + S_{WUB} = S_{WT} \Rightarrow S_{WUB} = S_{WT} - S_{WB} .$$

$$\boxed{\sigma_{weq} = S_{WB}\,\sigma_{WB} + (S_{WT} - S_{WB})\,\sigma_{W}}$$

Question 5: Consider the well logs in Example 2, of the well-log package which is distributed in the class. This is a laminated shaly-sand formation.

Answer the following questions for depth 5522 ft. You can consider the following readings for well-log measurements: Resistivity = 2.8 ohm-m (This is equivalent to horizontal resistivity).

a) Estimate hydrocarbon saturation at 5522 ft.

b) Estimate density of hydrocarbon at 5522 ft.

c) Estimate hydrocarbon pore volume per unit depth.

d) In the last three parts, it is expected that you take into account shale laminations in your calculations. Now assume that you use the measured resistivity without taking into account the impact of shale. What would be the relative error in estimate of hydrocarbon saturation, compared to what you obtained in part (a)?

⑤ $h = 5522\ ft$ $R_t = 2.8\ \Omega m$

a) $S_{HC} = ?$

Pure shale :
$GR_{sh} = 94\ GAPI$
$\phi_{D,sh} = 26.5\ \%$
$\phi_{N,sh} = 45\%$
$R_{SH} = 0.9\ \Omega \cdot m$

$$C_{sh} = \frac{G_R - G_s}{G_{sh} - G_s}$$

$$C_{sh} = \frac{50 - 25}{40 - 25} \doteq \frac{46 - 25}{94 - 25} = 30.4\%$$

$\phi_D = 39\%$, $\phi_N = 23.5\%$ @ 5522 ft

$$\phi_N^{(sh)} = \frac{\phi_N - C_{sh}(\phi_N)_{sh}}{1 - C_{sh}} = \frac{0.235 - 0.304\,(0.45)}{1 - 0.304} = 14.09\%$$

$$\phi_D^{(sh)} = \frac{\phi_D - C_{sh}(\phi_D)_{sh}}{1 - C_{sh}} = \frac{0.39 - 0.304\,(0.265)}{1 - 0.304} = 44.47\%$$

$$\phi_S = \sqrt{\frac{1}{2}\left(14.09^2 + 44.47^2\right)} \Rightarrow \boxed{\phi_S = 33\%}$$

$$\frac{1}{R_t} = \frac{C_{sh}}{R_{sh}} + \frac{1 - C_{sh}}{R_S} \Rightarrow \frac{1}{2.8} = \frac{0.304}{0.9} + \frac{1 - 0.304}{R_S}$$

$$\Rightarrow \boxed{R_S = 36.55\ \Omega \cdot m}$$

Water saturated sand : $R_t = R_w \cdot \frac{1}{\phi^2} \rightarrow R_w = (0.33)^2 \times 0.5$

$$\boxed{R_w = 0.0536\ \Omega\cdot m}$$

From Archie : Set $a = 1$, $m = 2$, $n = 2$

$$R_S = R_W \frac{a}{\phi_S^m \, S_W^n} \Rightarrow 36.55 = 0.0536 \frac{1}{0.33^2 \, S_W^2}$$

$$\Rightarrow \boxed{S_W = 11.6\ \%}$$

$$S_{HC} = 1 - S_W \Rightarrow \boxed{S_{HC} = 88.4\ \%}$$

(b) HC density?

$\rho_M = 2.65$

$$\phi_S = \frac{\rho_S - \rho_M}{\rho_F - \rho_M}$$

Water saturated zone, sandstone

$$\phi_{D,SS} = 0.39 = \frac{\rho_B - 2.65}{1 - 2.65} \Rightarrow \boxed{\rho_B \cong 2\ g/cm^3}$$

Water saturated, shale:

$$\phi_{D,sh} = 0.265 = \frac{\rho_{sh} - 2.65}{1 - 2.65} \Rightarrow \boxed{\rho_{sh} = 2.21\ g/cm^3}$$

Density of the sand layers:

$$\rho_B = \rho_S (1 - C_{sh}) + \rho_{sh} C_{sh}$$

$$2 = \rho_S (1 - 0.304) + 2.21 (0.304) \Rightarrow \boxed{\rho_S = 1.91\ g/cm^3}$$

$$\phi_S = \frac{\rho_S - \rho_M}{\rho_F - \rho_M} \rightarrow 0.33 = \frac{1.91 - 2.65}{\rho_F - 2.65}$$

$$\Rightarrow \boxed{\rho_F = 0.42\ g/cm^3}$$

$$\rho_F = S_W \rho_W + (1 - S_W)\rho_{HC}$$

$$0.42 = 0.116\,(1) + (1 - 0.116)\rho_{HC}$$

$$\boxed{\rho_{HC} = 0.35\ g/cm^3}$$

c) $$\frac{HCPV}{h} = \phi_S \cdot S_{HC,S} \cdot (1 - C_{sh})$$

$$= 0.33 \times 0.884 \times (1 - 0.304) = 0.20\ /ft$$

(d) From the logs:

$\phi_D = 39\%$ $\phi_N = 23.5\%$

$$\phi = \sqrt{\frac{0.39^2 + 0.235^2}{2}} = 32.2\%$$

$$R_t = R_w \frac{a}{\phi_s^m S_w^n} \Rightarrow 2.8 = 0.0536 \cdot \frac{1}{(0.322)^2 \cdot S_w^2}$$

$S_w = 43\% \rightarrow S_{HC} = 1 - S_w \Rightarrow \boxed{S_{HC} = 57\%}$

$$err = 1 - \frac{S_{HC}}{S_{HC}^{(SH)}} = 1 - \frac{57}{88.4} \Rightarrow \boxed{err = 35.5\%}$$

Appendix - Python Listing

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.lines import Line2D
```

QUESTION 1

```
df = pd.read_excel("q1data.xlsx").replace(-9999, np.nan)
plt.style.use('default')   ## reset!
plt.style.use('paper.mplstyle')

# Setup a track
def set_axis( ax, data, label, color, ls, xlim, idx, ticks=False, log=False, grid=False, alpha=1.0, lw=1.0 ) :
    global df

    if ticks :
        ax.tick_params(left = True)
        ax.set_ylabel("Depth (ft)")
    else :
        ax.tick_params(left = False)


    ax.set_xlim( xlim )
    if not log :
        ax.set_xticks( np.linspace( xlim[0], xlim[1], 11 ) )

    if grid :
        ax.grid(which='major', color='k', linewidth=.7, alpha=.4)
        ax.grid(which='minor', color='k', linestyle=':', linewidth=.5, alpha=.2)
        if log :
            import matplotlib as mpl
            locmin = mpl.ticker.LogLocator(base=10.0, subs=(0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9), numticks=5)
            resX.xaxis.set_minor_locator(locmin)
            resX.xaxis.set_minor_formatter(mpl.ticker.NullFormatter())

    ax.xaxis.set_ticks_position('bottom')
    ax.tick_params(axis='x', colors=color)
    ax.xaxis.label.set_color(color)

    yc = 1.01 + idx*0.02
    ycl = yc + .010

    l=Line2D([0.01,.99], [yc,yc], lw=1, linestyle=ls, color=color, transform=ax.transAxes, alpha=alpha)
    l.set_clip_on(False)
    ax.add_line( l )
    ax.text(0.01, ycl, xlim[0], horizontalalignment='left', verticalalignment='center', transform=ax.transAxes,
color=color)
    ax.text(0.5, ycl, label, horizontalalignment='center', verticalalignment='center', transform=ax.transAxes,
color=color)
    ax.text(.99, ycl, xlim[1], horizontalalignment='right', verticalalignment='center', transform=ax.transAxes,
color=color)

    ax.plot( df[data], df['depth'], linestyle=ls, c=color, alpha=alpha, lw=lw )
    ax.set_xticklabels([])
    ax.tick_params( axis='x', which='both', bottom = False, width=0 )

# Key GR measurements
GR_sh = 120
GR_s = 15

# Key depths
WOC = 5903
CLAY_FREE_SW100 = 5914
CLAY_PURE_SW100 = 5933

# Readings
PHI_SS_SW100 = np.interp( CLAY_FREE_SW100, df.depth, df["nphi-ss"] )
print(f"Clay free, Sw=100% porosity: phi={PHI_SS_SW100:.3f} @ {CLAY_FREE_SW100}ft")
RTW_SW100 = np.interp( CLAY_FREE_SW100, df.depth, df["at90"] )
PHI_SW100 = .14

RW = RTW_SW100 * PHI_SW100**2
```

```python
print(f"Clay free, Sw=100%: RTW={RTW_SW100:.3f} PHI={PHI_SW100} RW={RW:.4f} @ {CLAY_FREE_SW100}ft ")


# Calculate dphi in % for each lithology
rhom_ss = 2.65
rhom_sh = 2.68
rhom_ls = 2.71
# dphi assuming Sw=100%
df["dphi-ss"] = (df.rhoz - rhom_ss) / ( 1 - rhom_ss )
df["dphi-ls"] = (df.rhoz - rhom_ls) / ( 1 - rhom_ls )
df["dphi-sh"] = (df.rhoz - rhom_sh) / ( 1 - rhom_sh )

# Readings of key parameters
dphi_pure_shale = np.interp( CLAY_PURE_SW100, df.depth, df["dphi-sh"] )
nphi_pure_shale = np.interp( CLAY_PURE_SW100, df.depth, df["nphi-ss"] )
print(f"Pure shale, Sw=100% porosity: D_Phi={dphi_pure_shale:.3f} @ {CLAY_PURE_SW100}ft")
print(f"Pure shale, Sw=100% porosity: N_Phi={nphi_pure_shale:.3f} @ {CLAY_PURE_SW100}ft")

## Calculations ...
df["Csh"] = ( df.gr - GR_s ) / ( GR_sh - GR_s )

# Lithology
df["sandstone"] = 0
df["limestone"] = 0
df["shale"] = 0

ss1 = ( df.depth > 5790 ) & ( df.depth < 5840 )
ss2 = ( df.depth > 5890 ) & ( df.depth < 5940 )
ls1 = ( df.depth > 5940 )

df.loc[ ss1 | ss2 , "sandstone" ] = 1
df.loc[ ls1 , "limestone" ] = 1
df.loc[ (df.limestone + df.sandstone == 0) , "shale" ] = 1

# Correct dphi and nphi for lithology
df["dphi"] = 0.0
df.loc[ df.sandstone == 1, "dphi" ]  = df['dphi-ss']
df.loc[ df.limestone == 1 , "dphi" ] = df['dphi-ls']
df.loc[ df.shale == 1 , "dphi" ]     = df['dphi-sh']

df["nphi"] = 0.0
df.loc[ df.sandstone == 1, "nphi" ]  = df['nphi-ss']
df.loc[ df.limestone == 1 , "nphi" ] = df['nphi-ls']
df.loc[ df.shale == 1 , "nphi" ]     = df['nphi-ss']

df["rhom"] = 0.0
df.loc[ df.sandstone == 1, "rhom" ]  = rhom_ss
df.loc[ df.limestone == 1 , "rhom" ] = rhom_ls
df.loc[ df.shale == 1 , "rhom" ]     = rhom_sh

# Compute porosity and water saturation
df["porosity"] = df.apply( lambda x : np.sqrt( x['nphi']**2/2 + x['dphi']**2/2), axis=1 )
df["Sw"] = df.apply( lambda x : np.sqrt( RW/x['at90']/x['porosity']**2), axis=1 )
df.loc[ df.shale == 1 , "Sw" ] = 1
df["So"] = 1 - df.Sw
df.loc[ df.depth>WOC, "So" ] = 0

df["Sxo"] = df.apply( lambda x : np.sqrt( RW/x['at10']/x['porosity']**2), axis=1 )
df.loc[df.sandstone==0,"Sxo"] = 0

df["Sxo_div_Sw"] = df.Sxo / df.Sw
df.loc[ df.depth<WOC, "Sxo_div_Sw" ] = 0

df["rhof"] = df.rhom + ( df.rhoz - df.rhom ) / df.porosity

# Compute reserves
df["h"] = df.depth.diff().shift().fillna(0)
df["OIP_bbl"] = 7758 * (df.porosity * df.So * df.h).fillna(0)

OIP_Mbbl = df.OIP_bbl.cumsum().max()/1e3
print(f"Oil in place: {OIP_Mbbl:.1f} M bbl per unit area")
```

```
Clay free, Sw=100% porosity: phi=0.125 @ 5914ft
Clay free, Sw=100%: RTW=1.629 PHI=0.14 RW=0.0319 @ 5914ft
Pure shale, Sw=100% porosity: D_Phi=0.081 @ 5933ft
Pure shale, Sw=100% porosity: N_Phi=0.121 @ 5933ft
Oil in place: 38.5 M bbl per unit area
```

```
# Put all together
fig, [ grX, resX, ssX, lsX, pzX, cshX, porX, swX ] = plt.subplots( 1, 8, figsize=[14,15], sharey=True)
fig.subplots_adjust(wspace=0.01, hspace=0)

# GR
set_axis( grX, 'gr', 'GR', 'darkgreen', '-', [0,150], 0, ticks=True, grid=True )
set_axis( grX.twiny(), 'hcal', 'HCAL', 'red', '--', [0,16], 1, ticks=True )

# RESISTIVITY - Manual setup of limits for resX
resX.set_xscale('log')
resX.set_xticks( [ 1, 10, 100, 1000 ] )
lims = [.2, 2000 ]
set_axis( resX, 'at10', 'AT10', 'blue', '-.', lims, 0, log=True, grid=True )
set_axis( resX, 'at20', 'AT20', 'darkgreen', '-', lims, 1, log=True )
set_axis( resX, 'at30', 'AT30', 'purple', ':', lims, 2, log=True )
set_axis( resX, 'at60', 'AT60', 'k',   ':', lims, 3, log=True )
set_axis( resX, 'at90', 'AT90', 'red', '-',  lims, 4, log=True )

# POROSITY - SANDSTONE
set_axis( ssX, 'nphi-ss', 'NPHI(SS)', 'darkgreen', '-',  [0.45,-.15], 0, grid=True )
set_axis( ssX.twiny(), 'rhoz', 'RHOZ', 'red', '-.',  [1.9,2.9], 1 )
set_axis( ssX.twiny(), 'porosity','POR (%)', 'k', '-', [0.45,-.15], 2 , alpha=.3, lw=3  )

# POROSITY - LIMESTONE
set_axis( lsX, 'nphi-ls', 'NPHI(LS)', 'darkblue', '--',  [0.45,-.15], 0, grid=True )
set_axis( lsX.twiny(), 'rhoz', 'RHOZ', 'red', '-.',  [1.94,2.97], 1 )
set_axis( lsX.twiny(), 'porosity','POR (%)', 'k', '-', [0.45,-.15], 2, alpha=.3, lw=3 )

# PEFZ
set_axis( pzX, 'pefz', 'PEFZ', 'darkred', '-',  [1,6], 0, grid=True )
litX = pzX.twiny()
set_axis( litX, 'limestone', 'Limestone (flag)', 'green', '-',  [0,1], 2 )
set_axis( litX.twiny(), 'sandstone', 'Sandstone (flag)', 'red', '-',  [0,1], 1 )
set_axis( litX.twiny(), 'shale', 'Shale (flag)', 'orange', '-',  [0,1], 3 )

litX.fill_betweenx( df.depth, df.sandstone, color='r', alpha=0.1 )
litX.fill_betweenx( df.depth, df.limestone, color='green', alpha=0.1 )
litX.fill_betweenx( df.depth, df.shale, color='orange', alpha=0.3 )


# Csh
set_axis( cshX, 'Csh', '$C_{sh}$', 'blue', '-',  [0,1], 0, grid=True )
set_axis( cshX.twiny(), 'sandstone', 'Sandstone (flag)', 'red', '-',  [0,1], 1 )
cshX.fill_betweenx( df.depth, df.sandstone, color='r', alpha=0.1 )
set_axis( cshX.twiny(), 'limestone', 'Limestone (flag)', 'green', '-',  [0,1], 2 )
cshX.fill_betweenx( df.depth, df.limestone, color='green', alpha=0.1 )
set_axis( cshX.twiny(), 'shale', 'Shale (flag)', 'orange', '-',  [0,1], 3 )
cshX.fill_betweenx( df.depth, df.shale, color='orange', alpha=0.3 )

set_axis( porX, 'porosity','POR (%)', 'k', '-', [0.3,0], 0, alpha=1, grid=True )
set_axis( porX.twiny(), 'dphi','DPHI (%)', 'green', '--', [.3,0], 1, alpha=1 )
set_axis( porX.twiny(), 'nphi','NPHI (%)', 'r', ':', [.3,0], 2, alpha=1 )

set_axis( swX, 'Sw','Sw (%)', 'blue', '-', [0,1], 0, alpha=1, grid=True )
soX = swX.twiny()
set_axis( soX , 'So','So (%)', 'green', '-', [0,1], 1, alpha=1, lw=.5 )
soX.fill_betweenx( df.depth, df.So, color='green', alpha=0.1 )

set_axis( swX.twiny(), 'rhof',r'$\rho_f$', 'red', ':', [0,3], 2, alpha=1 )

sxoX = swX.twiny()
set_axis( sxoX , 'Sxo','Sxo (%)', 'orange', '-', [0,1], 3, alpha=1, lw=.5 )
sxoX.fill_betweenx( df.depth, df.Sxo, color='orange', alpha=0.1 )

set_axis( swX.twiny() , 'Sxo_div_Sw','Sxo/Sw', 'black', ':', [0,1], 4, alpha=1, lw=1 )

for ax in [ grX, resX, ssX, lsX, pzX, cshX ] :
    ax.axhline( y=WOC, lw=2, alpha=.5, ls='--', c='blue' )
    ax.axhline( y=CLAY_FREE_SW100, lw=2, ls='--', alpha=.5, c='r' )
```

```
    ax.axhline( y=CLAY_PURE_SW100, lw=2, ls='--', alpha=.5, c='GREEN' )
grX.text( 145, WOC-1, "WOC" , horizontalalignment='right')
grX.text( 145, CLAY_FREE_SW100-1, "Clay free\nSw=100%", horizontalalignment='right', verticalalignment='bottom' )
grX.text( 145, CLAY_PURE_SW100-1, "Pure clay\nSw=100%", horizontalalignment='right', verticalalignment='bottom' )
# Configure Y axis
grX.set_ylim( 5770, 6020 )
grX.set_yticks( np.arange(5770, 6020, 10) )
grX.invert_yaxis()
fig.savefig("tracks.svg")
```

QUESTION 2¶

```
import matplotlib.pyplot as plt
import numpy as np

df = pd.DataFrame({
 'frf' :      [ 30, 19.3, 12.5, 8.4, 6 ],
 'porosity' : [ 0.092, 0.12, 0.165, 0.205, 0.268 ]
})

fig, ax = plt.subplots()
ax.scatter( df.porosity, df.frf )
ax.set_xlabel( "Formation Resistivity Factor" )
ax.set_ylabel( "Porosity" )

# Fit curve
from scipy.optimize import curve_fit
def Rt_foo(phi, a, m):
    return a / np.power(phi, m)
popt, pcov = curve_fit(Rt_foo, df.porosity, df.frf)
a = popt[0]
m = popt[1]
print(f"Fit parameters: {popt[0]:.4e} / PHI ^ {popt[1]:.4e}")
print(f"               a={popt[0]} m={popt[1]}")

Rt = 1.79
Rw = 0.076


x = np.arange(.08,.3,0.01)
y = a / (x**m)
ax.plot(x,y)
x

phi = ( Rw / Rt * a )**(1/m)
print(f"Estimated porosity={phi:.3f}")
```

```
Fit parameters: 7.5237e-01 / PHI ^ 1.5421e+00
               a=0.7523733425623487 m=1.5420742791386597
Estimated porosity=0.107
```