Everything you always wanted to know about Pickett Plots*

* BUT WERE AFRAID TO ASK

Roberto Aguilera
Schulich School of Engineering
University of Calgary
April 24, 2011
© Roberto Aguilera (2012)
OUTLINE

- Pickett plots, basic equations
- Clean formations, shaly formations
- $m$, $n$ and $Sw$
- $k$, $rp35$, $Pc$, $h$

In the case of shale formations:
- $Sw$, TOC, LOM, viscous vs. diffusion-like flow
- Conclusions
Archie’s Equation for Clean Formations

\[ S_w = I^{-1/n}, \]

\[ I = \frac{R_t}{(F \cdot R_w)} = \frac{R_t}{R_o} \]

\[ F = a \phi^{-m} = \frac{R_o}{R_w} \]

Sw = water saturation, fraction, I = resistivity index, n = water saturation exponent, Rt = true resistivity (ohm-m), F = formation factor, Rw = water resistivity at formation temperature, Ro = resistivity of reservoir system when it is 100% saturated with water, a = constant, phi = total porosity, m = porosity (cementation) exponent of the composite system of matrix and fractures.
PICKETT PLOT (CLEAN FORMATIONS)
PICKETT PLOT (CLEAN FORMATIONS)
PICKETT PLOT (CLEAN FORMATIONS)
CARBONATE EXAMPLE
Integrate in a Pickett Plot:

- Porosity and water saturation
- Permeability and process speed
  - Capillary pressure
  - Height above free water table
- Pore throat aperture and particle size
  - Kozeni’s constant
- Rock fabric number (grainstones, packstones, wackstones…)
  - Range of initial flow rates
PROCESS (or DELIVERY) SPEED

IS THE RATIO OF PERMEABILITY AND POROSITY \((k / \varnothing)\) AND IS RELATED DIRECTLY TO PORE THROAT APERTURE. IT PROVIDES A RELATIVE INDICATION OF HOW QUICKLY FLUIDS CAN MOVE THROUGH POROUS MEDIA (Chopra et al., 1987; Gunter et al., 1997)
PERMEABILITY

\[ K^{1/2} = 250 \, \varnothing^3 / Sw_i^1 \]

AT IRREDUCIBLE CONDITIONS (MEDIUM GRAVITY OIL)

(Source: Morris and Biggs)
CAPILLARY PRESSURE
(Based on Kwon and Pickett Data; over 2,500 samples from 30 formations in North America)

\[ P_{c_{Hg-Air}} = (19.5 \ Sw^{-1.7}) (\frac{K}{\varnothing})^{-0.45} \]

\[ Pc = \text{Mercury injection capillary pressure, psi} \]

(Aguilera, AAPG, 2004)
PORE THROAT RADIUS (µm)

\[ r = \frac{108.1}{P_{c_{Hg-Air}}} \]

ASSUMING:
INTERFACIAL TENSION:
\[ \sigma_{Hg-Air} = 480 \text{ Dyne/cm} \]

AIR/MERCURY CONTACT ANGLE:
\[ \theta_{Hg-Air} = 140 \text{ Degrees} \]

(Aguilera, AAPG, 2004)
HEIGHT ABOVE FREE WATER TABLE \((h)\)

\[ h (\text{ft}) \approx 0.705 \, P_{\text{Hg-Air}} \]

ASSUMING A MEDIUM GRAVITY OIL RESERVOIR

(Aguilera, AAPG, 2004)
HEIGHT ABOVE FREE WATER TABLE ($h$)

$$h \text{ (ft)} \approx 0.405 \ P_{c_{\text{Hg-Air}}}$$

ASSUMING A DRY GAS OIL RESERVOIR

(Aguilera, AAPG, 2004)
HEIGHT ABOVE FREE WATER TABLE (h)

\[ h \text{ (ft)} \approx 0.205 \, P_{c_{\text{Hg-Air}}} \]

ASSUMING A GEOTHERMAL RESERVOIR

(Aguilera, AAPG, 2004)
CARMAN-KOZENY EQUATION

\[
\frac{k}{\phi} = 1014 \ \left[ \frac{\phi^2}{(1-\phi)^2} \right] \cdot \left[ \frac{1}{(F_s \tau^2 S_{gv}^2)} \right]
\]

\[
r_{mh} = \phi / [S_{gv} \ (1-\phi)]
\]

\[
\frac{k}{\phi} = 1014 \ r_{mh}^2 / F_s \tau^2
\]

\[
r_{mh} \approx r_{p35}
\]

\[
r_{p35} = 2.665 \ (0.01k/\phi)^{0.45}
\]

\[
F_s \tau^2 = 114.14 \ (k/\phi)^{-0.1}
\]

\[
F_s \tau^2 = 89.543 \ r_{p35}^{-0.2222}
\]

\[F_s \tau^2 = \text{Kozeny’s constant}\]

\[S_{gv}^2 = \text{surface area per unit grain volume, microns}\]

\[r_{mh} = \text{mean hydraulic radius, microns}\]

\[r_{p35} = \text{pore throat aperture at 35% cumulative pore volume}\]
ROCK FABRIC ($\lambda$)

Rock fabric ($\lambda$) refers to the geologic description of particle size ($d_p$ in microns) and sorting (Lucia, 1983, 1995). Pore size distribution is related to rock fabric and controls permeability and saturation.

(Aguilera, AAPG, 2004)
Porosity and permeability relationship for various particle size groups in uniform cemented non-vuggy rocks (After Lucia, 1983)
Lucia’s straight lines (1983) intersect at porosity of 3.5% and permeability of 0.0015 md.

(Aguilera, AAPG, 2004)
ROCK FABRIC ($\lambda$)

$$\lambda = -0.6213 \ln (d_p) + 4.3614$$

$$k = e^{a(\lambda)} \phi^{b(\lambda)}$$

$$a(\lambda) = 22.56 - 12.08 \ln (\lambda)$$

$$b(\lambda) = 8.671 - 3.603 \ln (\lambda)$$

(Jennings and Lucia, 2002)
Rock fabric ($\lambda$)
Process speed ($k/\phi$)
Cap pressure ($p_c$)
Height above free water table ($h$)
Pore throat radius ($r_p$)
Porosity exponent ($m$)
Water saturation ($S_w$)

$P_c$ and $r_p$ are valid between $S_w=30\%$ and $90\%$

Source: Aguilera, AAPG, 2004
PICKETT PLOT (MISSION CANYON CARBONATES)
Little Knife field, North Dakota. Flow units after Martin et al. (1997)

GFREE RESEARCH PROJECT
(Aguilera, AAPG, 2004)
SHALY FORMATIONS

GFREE RESEARCH PROJECT
PICKETT PLOT (SHALY FORMATIONS)

\[ S_w = 100\% \]

\[ a R_w \]

\[ S_w = I_{sh}^{-1/n} \]

or, \[ S_w = (\phi_w / \phi_h)^{m/n} \]

\[ \frac{R_t}{A_{sh}} \]

\[ (R_t / A_{sh})_{hyd} \]

\[ (R_t / A_{sh})_{water} \]

\[ I_{sh} = \frac{(R_t / A_{sh})_{hyd}}{(R_t / A_{sh})_{water}} \]

\[ m = y / x \]

\[ \phi_h \]

\[ \phi_w \]
SHALE GAS: Δ log R Technique

Clast with a mean grain size of less than 0.0625 mm including siltstone, mudstone, claystone and carbonates

Fine-grained, non-source rock
PASSEY ET AL CURVES FOR Sw = 100% from Δ log R Technique

Log(R_t) vs Δt

- Shale
- Sandstone
- Limestone
- Dolomite

GFREE RESEARCH PROJECT
PICKETT PLOT USING PASSEY ET AL DATA FOR Sw = 100%

\[(\Delta t - \Delta t_m) \text{ vs } R_t\]

- Dolomite
- Sandstone
- Limestone
- Shale

\[\Delta t - \Delta t_m (\mu s/ft)\]

\[R_t (\Omega m)\]
PICKETT PLOT (HAYNESVILLE SHALE)
Sw data from Ramirez et al. (2011)

$\phi$ vs $R_t$

Sw from detailed log analysis

$m < 2.0$

25%<Sw<50%

Power (Sw=100%)

Power (Sw=50%)

Power (Sw=25%)
TOC on Pickett Plot

TOC = total organic carbon
LOM = level or organic metamorphism
(Yu and Aguilera, 2011)

\[
\log R_t = -0.02 BB_c \Phi - 0.02 \Delta t_m + 0.02 \Delta t_{\text{baseline}} + \log R_{t,\text{baseline}} + TOC 10^{(0.1688 LOM - 2.297)}
\]

\[
LOM = 8.18 \left( \frac{\text{Rov}}{0.59 + 0.41 \left[ \exp \left(1 - \frac{\text{Rov}}{0.36} \right) \right]^{28.45}} \right)^{1/m}
\]

\( B_c \) = correction between density porosity and core crushed sample
\( Rov \) = vitrinite reflectance, \( m \) = porosity exponent

Baseline: The transit time and resistivity logs are scaled in such a way that their relative scaling is -50μs/ft per logarithmic resistivity cycle. These two logs need to be overlain and baselined in a fine-grained, non-source rock.
Prediction of TOC and LOM with the Use of Pickett Plot
(TOC and LOM Data from Passey et al., 1990)

\[ \phi \text{ vs } R_t \]

- 0%<TOC<5%
- 5%<TOC<10%
- Log. (LOM=6.5,TOC=0%)
- Log. (LOM=6.5,TOC=5%)
- Log. (LOM=6.5,TOC=10%)
- Log. (LOM=7,TOC=0%)
- Log. (LOM=7,TOC=5%)
- Log. (LOM=7,TOC=10%)
- Log. (LOM=7.5,TOC=0%)
- Log. (LOM=7.5,TOC=5%)
- Log. (LOM=7.5,TOC=10%)

GFREE RESEARCH PROJECT
Prediction of Flow Types with the Use of Knudsen Number (Kn) (TOC Data from Passey et al., 1990)

\[ \phi \text{ vs } R_t \]

\[ \text{Continuous flow} \]

\[ \text{Diffusion-like flow} \]

Kn = 0.001

5%<TOC<10%

Kn = 0.01

0%<TOC<5%

Kn = 0.1
Integrated Pickett Plot
(TOC Data from Passey et al., 1990)

\[ \phi \text{ vs } R_t \]

- Log Data
- Log. (TOC=0%)
- Log. (TOC=5%)
- Log. (TOC=10%)
- Log. (TOC=15%)
- Power (Sw=100%)
- Power (Sw=50%)
- Power (Sw=25%)
- Power (Kn=0.1)
- Power (Kn=0.01)
- Power (Kn=0.001)

GFREE RESEARCH PROJECT
Conclusion (1)

- Pickett plots are not a panacea but are useful for estimating:

  - Porosity and water saturation
  - Permeability and process speed
  - Capillary pressure
  - Height above free water table
  - Pore throat aperture and particle size
  - Kozeni’s constant
  - Rock fabric number (grainstones, packstones, wackstones…)
  - Range of initial flow rates
Conclusion (2)

- Pickett plots are not a panacea but are useful for estimating:
  
  Porosity and water saturation
  Permeability and process speed
  Capillary pressure
  Height above free water table
  Pore throat aperture and particle size
  Kozeni’s constant

  **In carbonates**: Rock fabric number (grainstones, packstones, wackstones…)

  **In shales**: TOC, LOM, viscous vs. diffusion-like flow
Acknowledgement

Parts of this work were funded by ConocoPhillips, the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Alberta Innovates – Energy and Environmental Solutions (formerly AERI). Their contributions are gratefully acknowledged.
Thank you