Understanding Porosity and Permeability using High-Pressure MICP Data: Insights into Hydrocarbon Recovery*

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Abstract

A study using over 400 samples with porosity, permeability and mercury injection capillary pressure (MICP) data identified several key parameters calculated from MICP data that characterize reservoir quality and quantify the likelihood of hydrocarbon recovery. The sum of pore-throat diameter x the porosity accessed by a pore-throat of a given diameter (SumDB) accurately predicts permeability using the equation $k_{air} = 10(C_1 \cdot \log(SumDB) - C_2)$ over a range of permeability from $<0.001$ md to over $1000$ md, where $C_1 = 1.6337$ and $C_2 = 2.2081$. The "Pseudo Pore Throat Aperture" (PPTA) is equal to $\frac{SumDB}{\text{Total Porosity}}$ and is the effective hydraulic radius of the rock.

The PPTA can be used to divide the reservoir into flow units. A cross plot of porosity versus permeability contoured by PPTA indicates that the size of the connecting pore-throats controls the effectiveness of porosity toward permeability. At higher porosity values, pore-throat size is the dominant control on permeability. Porosity has a greater impact on permeability as the hydraulic radius and the porosity of the rock decrease. Although the research is preliminary, the ability of hydrocarbons to be produced seems to be linked to a combination of pore-throat size and fluid properties. When comparing rocks with the same air permeability but different porosities, rocks with lower porosity are better reservoirs because the pore-throats are larger, and therefore will have higher relative permeability to hydrocarbons. The more viscous the fluid, the larger the pore-throats must be to recover the hydrocarbons.

Using this logic, effective porosity values are determined by fluid type using different pore-throat size cut-offs. Pay in a field can be ranked based on pore-throat size cutoffs and fluid properties.
Understanding Porosity and Permeability using High-Pressure MICP Data

“Insights into Hydrocarbon Recovery”

John S. Sneider
George W. Bolger
What is the lower limit of pay?
Outline

• Introduction
• Review
  • Rock Relationships
    • Porosity vs. Permeability
• Studying the Rocks Via Pc
  • Rock Properties vs. MICP
  • Capillary Tube Model
  • Simplifying Pore Structure
• Defining Pay using Pc
• Summary & Conclusions
Main Goal of Research

Find simple relationships to help determine if hydrocarbons can be recovered from potential reservoir rocks.
Project

• Studied >400 samples with
  – Porosity, permeability and mercury injection capillary pressure (MICP) data

• Characterized reservoir quality
  – Simple calculations using MICP data

• Compared to production
  – Difficult to do in practice
  – Quantify the likelihood of hydrocarbon recovery
In a nutshell!

The SIZE of...

...PORE THROATS...

...determines if a rock PRODUCES hydrocarbons
IT’S THE PORE THROAT SIZE THAT MATTERS!
IT’S THE PORE THROAT SIZE THAT MATTERS!

The pore-throat connects larger pores together
Other Important Factors

- Fluid properties
  - Heavy Oil
  - Light Oil
  - Gas

- Other Factors
  - Wettability
  - Well spacing
  - Completion
  - Drive mechanism
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Clastics

The Effect of Texture
(grain size & sorting)
Effect of Grain-Size & Sorting

After Beard & Weyl (1973)
Increased Sorting = Increased Porosity

**Graph Description:**

The graph illustrates the relationship between median grain size and permeability, with sorting on the y-axis and grain size on the x-axis. The chart is color-coded to show permeability ranges:

- **Extremely Well:** Extremely high permeability, indicated by a yellow shade.
- **Very Well:** High permeability, indicated by a yellow shade.
- **Well:** Moderate permeability, indicated by a yellow shade.
- **Moderate:** Lower permeability, indicated by a yellow shade.
- **Poor:** Even lower permeability, indicated by a yellow shade.
- **Very Poor:** Lowest permeability, indicated by a yellow shade.

The sorting scale ranges from coarse to very fine, with each sorting level marked with a plus sign (+). The permeability scale ranges from coarse to very fine grain sizes, with specific permeability values indicated for each grain size category.

**Mathematical Representation:**

- The relationship between median grain size and permeability is defined by the chart.
- The formula or equation for this relationship is not explicitly stated in the image.
Increased Grain Size = \uparrow\text{ Pore-Throat Size}
Permeability Increases

MEDIAN GRAIN SIZE - mm

PERMEABILITY - DARCIES

- Coarse
- Medium
- Fine
- Very Fine
- Silt

SORTING

- Extremely Well
- Very Well
- Well
- Moderate
- Poor
- Very Poor

Φ

Size

After Beard & Weyl
Carbonates

The Effect of Crystal Size
Porosity vs. Permeability
Particle - Crystals Size

FOR INTERPARTICLE INTERCRYSTAL POROSITY

Modified after Lucia (e.g., 1995, 2002)
At a constant $\Phi$

![Graph showing permeability vs. porosity for different particle size categories. The graph is modified after Lucia (e.g., 1995, 2002).]
Bigger Crystals = Higher k

Modified after Lucia, 1982
DOLOMITE RESERVOIR ROCKS

DECREASING CRYSTAL SIZE
DOLOMITE RESERVOIR ROCKS

DECREASING PERMEABILITY
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Pore Aperture Size Distribution

- Create from Pc data

The amount of porosity accessed
2 Rocks with Similar Porosity

Ø=24.35%,

Ø=22.5%,
At \( \sim \)constant \( \Phi \)

![Graphs showing pore aperture diameter vs. pore volume for two different porosities: PHI= 24.35% and PHI= 22.5%.](image)
At ~constant $\Phi$

Larger pore-throat means higher $k$.
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Capillary Tube
Flow Velocity

Velocity = \( \frac{1}{\mu} \cdot R^2 \cdot \frac{\Delta P}{8L'} \)

Hagen-Poiseuille law
Bundle of Capillary Tubes

- \( \uparrow \# \text{ Capillaries} \) (\( \uparrow \Phi \))
- \( \uparrow \) fluid flow
- \( \uparrow \) Size Capillaries
- \( \uparrow \) fluid flow
Characterization of Flow Potential
Characterization
Flow Potential

SumDia = \sum (\Delta \Phi \cdot D)

\Delta \Phi = \text{Porosity accessed through pore-throat}

D = \text{Threshold Diameter}
   \text{i.e. size of pore-throat}
Pore Aperture Size Distribution

SumDia = + (1% • 19µ) +
Pore Aperture Size Distribution

SumDia =

= + (7.3% • 12 \mu) +
Pore Aperture Size Distribution

\[ \text{SumDia} = + (1.8\% \cdot 5 \mu) + \]
Pore Aperture Size Distribution

\[
\text{SumDia} = + (1\% \cdot 1 \mu) +
\]
Pore Aperture Size Distribution

\[ \text{SumDia} = + (0.8\% \cdot 0.5\mu) + \]
Pore Aperture Size Distribution

SumDia =

200 Tubes Across
Stacked 100 High

= + (0.4\% \cdot 0.1\mu) +
SumDia = Σ(ΔΦ • D)
Characterization
Flow Potential

SumDia = $\sum (\Delta \Phi \cdot D)$

Proxy for
Permeability
$K_{air}$ vs SumDia
\[ k_{\text{air}} = 10^{(C1 \times \text{LOG}(\text{SumDia}) - C2)} \]

C1 = 1.6337  
C2 = 2.2081
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Characterization
Flow Potential

Pseudo Pore-Throat Size =

= \text{SumDia} \Phi_{\text{Total}}

• Equivalent capillary tube size
  • Characterize pore-throats with single value
  • \text{"Dominant"} pore-throat size

• Larger Pseudo Pore-Throat Size
  • Higher permeability – same \Phi
Pseudo Pore Throat

12.23 microns
Pseudo Pore Throat

22.91 microns
POROSITY vs. PERMEABILITY (Pseudo Pore Throat)

- >400 Samples
- Z-axis Pseudo Pore-Throat Diameter

Porosity vs. Permeability plot showing the relationship between porosity and permeability for different pseudo pore-throat diameters ranging from 0.2 to 60.0 microns.
The graph illustrates the relationship between porosity, permeability, and pseudo pore throat size. The x-axis represents porosity ranging from 0 to 50, while the y-axis represents permeability ranging from 0.0001 to 10000. Different lines on the graph correspond to various pseudo pore throat sizes, including 60.0 microns, 40.0 microns, 20.0 microns, 10.0 microns, 5.0 microns, 2.0 microns, 1.0 micron, 0.2 micron, and 0.1 micron. The relationship between these variables is shown, highlighting how changes in porosity affect permeability through the pseudo pore throat size.
POROSITY vs. PERMEABILITY (Pseudo Pore Throat)

- Not only factor
  - Size dominant
  - Shape pores/pore-throats
    - impacts
Porosity vs. Permeability (Pseudo Pore Throat)

- Higher Φ
- Permeability linked to pore-throat size
Porosity vs. Permeability (Pseudo Pore Throat)

- Lower Φ more effect on permeability
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Pay

- Rock capable of flowing hydrocarbons economically
- Two parts
  - Does rock contain hydrocarbons?
  - Can they be produced?

Pore-throat size can be used to identify pay potential
Criteria for Pay

• Why not just use permeability as the criteria for pay?
POROSITY vs. PERMEABILITY (Pseudo Pore Throat)

- At a constant k
- As Φ decreases
- Pore-throat must ↑

<table>
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<th>Porosity</th>
<th>Permeability</th>
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<td>0</td>
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<td>100000</td>
</tr>
<tr>
<td>50</td>
<td>1000000</td>
</tr>
</tbody>
</table>

- 60.0 microns
- 40.0 microns
- 20.0 microns
- 10.0 microns
- 5.0 microns
- 2.0 microns
- 1.0 micron
- 0.2 micron
- 0.1 micron
Porosity vs. Permeability ($S_{w_{irr}}$)

- Larger pore-throats
- Less bound water
Criteria for Pay

- Why not just use permeability as the criteria for pay?
  - Larger pore-throats $\rightarrow$ higher $k_o$ or $g$
  - For rocks with the same $k_{air}$
    - Lower $\Phi$ $\rightarrow$ Larger Diameter
    - Larger Diameter $\rightarrow$ Lower $S_{w_{irr}}$
    - Lower $S_{w_{irr}}$ $\rightarrow$ Higher $k_o$ or $g$

**Rocks with same $K_{air}$ & lower $\Phi$**
**BETTER RESERVOIRS!**
Empirical Data
Likelihood of Production

- **Oil**
  - $\Phi$ accessed $>1$ micron dia.

- **Gas**
  - $\Phi$ accessed $>0.1$ micron dia.
Detailed Review

Oil

$\Phi_{e1.0} = \Phi > 1.0 \mu$

14.4% 1.57 md

10.96% 0.061 md

9.37% 0.028 md
Detailed Review

Gas

\[ \Phi_{e0.1} = \Phi > 0.1\mu \]

14.4% 1.57 md

10.96% 0.061 md

9.37% 0.028 md
PHIE to Gas
(Φ > 0.1 µ)

PHIE to Oil
(Φ > 1 µ)
Jacketed (vert.) vs. non-Jacketed (horz.) Plug

YOU CANNOT COMPARE NON-JACKETED PLUGS TO STRESSED JACKETED PLUGS

Pc is Directional.
If The Vertical Plugs Were Not Jacketed They Would Look Like The Horizontal Plugs
Summary & Conclusions

• Reservoir Quality
  – Larger grain size & crystal size
    • Bigger pore-throats
  – Bigger pore-throats
    • Higher k
    • Lower Sw_{irr}
    • Lower Sw_{irr} → higher kr_{o or g}

• Determining Pay
  – Throat-size better than k
    • 2 phase flow
  – Smaller pore-throats need more mobile fluid
    • >1 micron dia. oil
    • >0.1 micron dia. for gas
References

