Modified Athy-Law Compaction to Account for Porosity Generation and Preservation from Kerogen Conversion in Terzaghi-Like Models of Petroleum Source Rocks*

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Abstract

A new algorithm is proposed and calibrated for assessing the effect of organic matter on compaction, porosity generation, and porosity preservation in organic-rich fine-grained sediments at various maturities. The algorithm involves the addition of simple terms to the Athy-Law exponent relating porosity to effective stress in Terzaghi-like compaction models, which are often used in basin and petroleum systems models to calculate expulsion of water and petroleum from source rocks. The central concept in these models is that porosity is related to the difference between vertical lithostatic pressure and pore pressure, and pore pressure is calculated from a simple permeability model, either 0D or 1D. The new model presented here is empirical and requires calibration for the source rock of interest. It considers that because kerogen is softer than most inorganic grains, when in high concentration, it can lead to lower rock porosity prior to catagenesis. This part of the model was calibrated for the Green River Formation using log data at 600-700 m that shows porosity decreasing from 15-25% to about 7% as the kerogen volume fraction increases from negligible to 50 vol%. In addition, the new model was designed to consider that preservation of porosity created from kerogen conversion can be related to its geometric shape and the ductility of the surrounding mineral grains. Model results are shown for the ranges of residual kerogen porosities observed in source rocks. The model has been incorporated into TRESORS, a 0D simulator of source rock maturation and expulsion at both laboratory and geological conditions.

References Cited


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Presented by M. Cremon, A. K. Burnham, Y. Liu, and A. Lapene

Stanford University, Stanford CA, and Total E&P R&D, Pau France
Common compaction modeling laws

Athy (1930):
Exponential decline of porosity with depth

Terzaghi (1923):
Exponential decline of porosity with effective stress ($P_L - P$)

Key questions for modeling porosity evolution

How does porosity evolve in mixtures of brittle and ductile materials?
- Clay and kerogen are more ductile than quartz, silicates, and carbonates
- Related to the classical discussion of whether kerogen is load bearing or pore filling

How does the porosity evolve with kerogen conversion?
- Conversion of kerogen to oil and gas creates void space amounting to 20-80 % of the kerogen volume depending on Hydrogen Index
- How much of this generated porosity is lost immediately and during subsequent burial?

Note: The initial discussion uses Athy’s law as an example with the understanding that compaction in the absence of organic matter is more complicated than a single exponential
Green River Formation porosity depends strongly on organic content
Adjusting Athy’s Law for organic content

\[ \varphi = \varphi_0 e^{-ad/(1-k^n)} \]

\( \varphi \) is porosity
\( d \) is depth
\( a \) is a compaction coefficient
\( k \) is kerogen volume fraction
\( n \) is an organic grain compaction correction

<table>
<thead>
<tr>
<th>Interval</th>
<th>Depth, ft</th>
<th>( \varphi_0 )</th>
<th>( a )</th>
<th>( n )</th>
</tr>
</thead>
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<tr>
<td>R1</td>
<td>2014-2135</td>
<td>0.6</td>
<td>0.0011</td>
<td>0.5</td>
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<tr>
<td>R0-L0</td>
<td>2135-2250</td>
<td>0.5</td>
<td>0.0016</td>
<td>0.7</td>
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</table>
Kerogen reduces porosity because it is softer

\[ \text{Young's modulus, GPa} = 0.8 + 1.3 \times \exp\left(-\frac{\text{gpt}}{12}\right) + 0.076 \left(\frac{304.8}{\text{DTCO}}\right)^3 \]

\[ \text{Uniaxial compressive strength, MPa} = 6.5 + 9.5 \times \exp\left(-\frac{\text{gpt}}{12}\right) + 0.77 \left(\frac{304.8}{\text{DTCO}}\right)^2 \]

TOC, wt% is 50 vol%

DTCO is the sonic log compressional wave arrival time; gpt = gal/ton \approx 2 \times \text{TOC}

Asymptotic limit of Young’s modulus is the same as for high-density polyethylene
Clay-quartz mixtures have analogous enhanced compaction

Ductility of clay enables more deformation and compaction under lithostatic load corresponding to ~6600 ft of burial

From Linked-In PSA Webinar #5 by Rob Lander of UT Austin
Clay has a smaller effect on porosity than kerogen for the Green River Formation

Clay mineral content determined by Schlumberger ELAN

Clay is uncorrelated to anti-correlated with kerogen content depending on depth interval

Porosity correlates weaker with clay than kerogen content

Parameter fits including both kerogen and clay content are negligibly better than for kerogen alone

\[ \text{porosity} = (a + b \cdot \text{clay}) \cdot \exp(-c \cdot \text{kerogen}) + d \]
Kerogen conversion modifies Athy’s Law

Kerogen conversion creates porosity
   20-80% of kerogen volume, depending on HI
   A large fraction has pore diameters less than 100 nm

Does this porosity cause a positive deviation from Athy’s law?
   It will not if the porosity is easily filled by rearrangement of surrounding mineral grains
   It will if the porosity is stable due to mineral bridges
   Compaction likely depends on ductility of mineral matrix (Fishman et al., 2012)
   Compaction efficiency likely depends on kerogen geometry (globular versus lenticular)

Why do we care? Compaction likely affects expulsion efficiency
   Generation of oil and gas increases organic volume by only ~20% at generation T & P
   Sorption capacity of kerogen may depend on applied lithostatic load
   Expulsion may depend on hydrocarbon saturation level of pore fluids (relative permeability)
Porosity generated is calculated simply from mass and volume balance

Generated porosity

\[ \varphi_k = \rho_R \times (K_i/\rho_i - K_r/\rho_r) = \rho_R \times K_i(1/\rho_i - f_r/\rho_r) \]

- \( \rho_R = \) density of rock
- \( \rho_i = \) density of immature kerogen
- \( \rho_r = \) density of residual kerogen
- \( K_i = \) mass fraction of immature kerogen
- \( K_r = \) mass fraction of residual kerogen = \( f_r \times K_i \)
- \( f_r = \) mass fractional conversion of immature to mature kerogen
Measured and calculated porosities agree well for low applied stress

From Burnham (2017)
Mature source rock porosity is largely within residual organic matter

From Sone and Zoback (2013)

From Chen and Jiang (2016)
Athy’s Law corrected for additional porosity from kerogen conversion

\[ \varphi = \varphi_0 e^{-ad/(1-k_i^n)} + \varphi_k e^{-bd} \]

\( \varphi \) is porosity
\( \varphi_0 \) is initial porosity at burial
\( \varphi_k \) is porosity from kerogen decomposition
\( d \) is depth
\( a \) is a mineral porosity compaction coefficient
\( k_i \) is initial kerogen volume fraction
  (perhaps labile kerogen only)
\( n \) is an organic grain compaction correction
\( b \) is a kerogen porosity compaction coefficient

6 wt% Type I kerogen \( \Rightarrow \) 12.6 vol%
35% converted to residual kerogen \( \Rightarrow \) 3.3 vol%
Single first-order reaction
\( \varphi_0 = 0.6; a=0.0008; n=0.5; b=0.0002 \)
Alternate and additional approaches provide better agreement for complex systems

Use effective stress instead of depth
Include a fracture pressure relief valve
Include a residual irreducible baseline porosity

Example:
\[ \varphi = \varphi_0 e^{-K \varepsilon (P_L - P) / (1 - k_i^n)} + \varphi_k e^{-K_k (P_L - P)} + \varphi_{ir} \]

- \( \varphi_k \) is porosity from kerogen conversion
- \( K_\varepsilon \) is a mineral compaction coefficient
- \( K_k \) is a kerogen compaction coefficient
- \( \varphi_{ir} \) is the irreducible porosity
- \( P \) is the pore pressure
- \( P_L \) is the lithostatic pressure
- \( P_H \) is the normal hydrostatic pressure

From Braun and Burnham (1992)
Summary and Conclusions

Ductility of kerogen causes greater compaction for richer source rocks
  Similar to observations by others for clay in quartz matrices
  CMR and other logging tools can be used to gather much more data than laboratory measurements to better discern trends and calibrate appropriate models
  Unambiguous trends were observed for the Green River Formation in the Piceance Basin and used to calibrate a simple enhanced-compaction model

Generation of porosity from kerogen decomposition is well known but preservation is not well quantified
  Data in the literature is relatively sparse with large scatter
  Others have suggested that ductility of mineral matrix dominates porosity preservation
  Several empirical functional forms were suggested for modeling preservation and compaction but await better data for calibration

These effects have been incorporated into the in-house single-cell compositional kinetics-fluid flow-geomechanics computer code TRESORS currently under development through TOTAL E&P R&D
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