Abstract

Basin thermal history is one of the key uncertainties for the evaluation of prospective petroleum systems. Vitrinite reflectance ($R_o$) is one of the most common measurements used to evaluate thermal maturity. Thermal calibration of basin and petroleum system models (BPSM) should allow replication of dogleg structures in vitrinite reflectance versus depth that are commonly observed at depths corresponding to ~0.7 to 1.0% $R_o$.

In this study, we compared different vitrinite reflectance models (Easy$\%R_o$, its update Easy$\%R_o$DL, and Basin$\%R_o$). We assigned the kinetic models to 1D BPSM at wells from the Alaska North Slope, a geologically complex petroleum province that evolved through the tectonic stages of passive margin, rift, foreland basin, and foreland fold-and-thrust belt. Rift-related structures and a regional break-up unconformity facilitated trapping and migration of the largest oil and gas accumulations. Thermal maturation was mainly controlled by the Brookian Sequence deposited from WSW to ENE during Late Cretaceous to Cenozoic time in a prograding foreland basin. We calibrated the various model scenarios against well data with $R_o$ and Horner-corrected temperatures to assess the impact on timing of maturity and hydrocarbon generation. Here, Basin$\%R_o$ and Easy$\%R_o$DL show significant improvements for calibration against vitrinite reflectance profiles that show the characteristic dogleg structure with different rates of increasing maturity. The calibrated thermal models required different thermal boundary
conditions, which influenced timing of source rock maturation, hydrocarbon generation, and migration in relation to trap formation.

Based on the results in this study area, we recommend consideration of several vitrinite reflectance models for thermal calibration. It is currently uncertain whether a universal algorithm for vitrinite reflectance exists. In addition, the maturation of vitrinite and oil-prone kerogen are not universally correlated, and may require correction for the individual kerogen types. Basin and petroleum system models that were calibrated only against a selected depth interval above or below a dogleg should be reevaluated.

References Cited


Sensitivity Analysis of Thermal Maturation of Alaska North Slope Source Rocks Based on Various Vitrinite Reflectance Models

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Thermal History is Key to Understand Petroleum Systems

- Critical to evaluate prospectivity (e.g., timing of generation/migration relative to trap formation)
- Depends on burial/erosion, thermo-tectonic events, lithologic properties, paleo-heat flow
- Parameters that help constrain thermal history
  - Vitrinite reflectance (\(\%R_o\))
  - Apatite fission track analysis (AFTA)
  - Bottom-hole temperatures (BHT)
  - Rock-Eval \(T_{max}\)
  - Thermal alteration index (TAI)
  - Fluorescence color
Vitrinite Originates from Higher Plants

Low Maturity Vitrinite
Vitrinite Reflectance ($R_o$) Increases with Thermal Maturity

From Peters et al., 2005
Vitrinite Maturation Can be Described Using the Arrhenius Equation

Arrhenius Equation

\[ k = \frac{Ae^{-E_a/RT}} { \text{k} = \text{reaction rate constant} \ (1/\text{my}); \text{kerogen to oil} \& \text{gas} } \]
\[ A = \text{frequency factor} \ (1/\text{my}); \text{vibrational frequency of bonds broken} \]
\[ E_a = \text{activation energy} \ (\text{kcal/mol}) \]
\[ R = \text{universal gas constant} \]
\[ T = \text{temperature} \ (\text{K}) \]
Various Vitrinite Reflectance Kinetic Models Have Been Proposed

Genetic relationships

- Lopatin TTI Waples
- Isoconversional Kinetics
- Arrhenius TTI Wood
- Vitrimat Burnham & Sweeney
- IFP TR Model Ungerer
- Max T → VR Barker
- Simple-R₀ Suzuki et al.
- Easy%R₀ Sweeney & Burnham
- Easy%R₀ M Easy%R₀₂ Burnham
- Vitrimat2 Burnham
- Power-law Arrhenius R₀ Huang
- High Press Power-law Arrhenius R₀ Le Bayon et al.
- IKU%R₀ Ritter et al.
- Basin%R₀ Nielsen et al.
- PresR₀ Carr
- T-P-R₀ Zou & Peng

Driving forces:
- Computational speed
- Pressure suppression
- Better calibration sets

Burnham et al., 2016
Many Reflectance Models Are Modified Versions of Vitrimat

Genetic relationships

- Lopatin TTI
- Waples
- Isoconversional kinetics
- Arrhenius TTI
- Wood
- Vitrimat
- Burnham & Sweeney
- Easy \( R_0 \)
- Sweeney & Burnham
- Easy \( R_0 \) M
- Easy \( R_0 \) 2
- Burnham
- VitrImat 2
- Burnham
- Power-law
- Arrhenius \( R_0 \)
- Huang
- High press
- Power-law
- Arrhenius \( R_0 \)
- Le Bayon et al.
- IkU \( R_0 \)
- Ritter et al.
- Basin \( R_0 \)
- Nielsen et al.
- Pres \( R_0 \)
- Carr
- T-P- \( R_0 \)
- Zou & Peng

Driving forces:
- Computational speed
- Pressure suppression
- Better calibration sets

Burnham et al., 2016
This Presentation Introduces Easy%\(R_o\)DL (Dogleg)

Genetic relationships

Driving forces:
- Computational speed
- Pressure suppression
- Better calibration sets

Burnham et al., 2016
We Will Compare Easy\(R_o\), Basin\(R_o\), and Easy\(R_o\)DL

Genetic relationships

- **Lopatin TTI Waples**
- **Isoconversional kinetics**
- **Arrhenius TTI Wood**
- **Vitrimat Burnham & Sweeney**
- **IFP TR Model Ungerer**
- **Max T → VR Barker**
- **Simple-\(R_o\) Suzuki et al.**
- **Easy-\(R_o\) Sweeney & Burnham**
- **IKU-\(R_o\) Ritter et al.**
- **Basin-\(R_o\) Nielsen et al.**
- **Power-law Arrhenius \(R_o\) Huang**
- **High Press Power-law Arrhenius \(R_o\) Le Bayon et al.**
- **Easy-\(R_o\) DL Burnham**
- **PresR\(R_o\) Carr**
- **T-P-\(R_o\) Zou & Peng**

Driving forces:
- Computational speed
- Pressure suppression
- Better calibration sets

Burnham et al., 2016
“Dogleg” Structures in Reflectance-Depth Profiles are Common

Middle Upper Rhine Graben, Germany

- Simple geologic conditions: linear geotherms, equilibration of $R_o$ with maximum temperature
- Suggate (1998) defined two segments with a dogleg at $\sim 0.7$ to $1.0\% R_o$

![Graph showing dogleg structures in reflectance-depth profiles.](image)
Example of Easy%R₀ vs. Temperature Focuses on Highlighted Box

Easy%R₀ (Sweeney and Burnham, 1990) may overestimate maturity in the range of 0.7-1.0% R₀.
Basin%R₀ Better Identifies Dogleg in the Range 0.7-1.0% R₀

Comparison

Easy%R₀ (Sweeney and Burnham, 1990) may overestimate maturity in the range of 0.7-1.0% R₀.

Basin%R₀ (Nielsen et al., 2015)

- Agrees better with dogleg structure in wells
- But performs less well for pyrolysis data than Easy%R₀
Easy$\%R_o$DL Matches Basin$\%R_o$, Fits Both Geology and Lab Rates

Comparison

**Easy$\%R_o$** (Sweeney and Burnham, 1990) may overestimate maturity in the range of 0.7-1.0% $R_o$

**Basin$\%R_o$** (Nielsen et al., 2015)
- Agrees better with dogleg structure in wells
- But performs less well for pyrolysis data than Easy$\%R_o$

**Simultaneous match at geologic and laboratory timescales requires adjustment of the frequency factor (A)**

Burnham (2016) recalibrated the $E_a$ distribution of Easy$\%R_o \rightarrow$ Easy$\%R_o$DL by changing $A$ to $2 \times 10^{14}$ s$^{-1}$
- Similar to Basin$\%R_o$ at geologic heating rates
- Agrees better with $R_o$ from lab experiments
Case Study: Alaska North Slope

Dogleg structure at Inigok-1

Vitrinite reflectance [%Ro]

- Linear
  - Prince Creek
  - Tuluvak
  - Seabee
  - Nanushuk
  - Torok
  - Kuparuk/LCU
  - Kingak
  - Shublik
  - Ledge
  - Echoooka
  - Lisburne
  - Kayak
  - Kekiktuk
  - Basement

- Semi-log
  - Prince Creek
  - Tuluvak
  - Seabee
  - Nanushuk
  - Torok
  - Kuparuk/LCU
  - Kingak
  - Shublik
  - Ledge
  - Echoooka
  - Lisburne
  - Kayak
  - Kekiktuk
  - Basement
Regional Geology of the Alaska North Slope

Schenk et al., 2012
Comparison of Vitrinite Reflectance Models: Aurora-1 and Inigok-1

Significant Late Brookian burial
Minor Tertiary erosion

Schenk et al., 2012
Comparison of Aurora-1 Reflectance Models

Vitrinite reflectance [%Ro]

Temperature [°C]

Basal heat flow trend

Transformation Ratio [%]
Comparison of Inigok-1 Reflectance Models

Significant Brookian burial
Significant erosion

Schenk et al., 2012
Comparison of Inigok-1 Reflectance Models
Conclusions

Comparison of different vitrinite reflectance kinetic models

• Basin%R$_o$ and Easy%R$_o$DL match R$_o$ doglegs better than Easy%R$_o$.
• Basin%R$_o$ matches geologic data better than laboratory pyrolysis data.
• Easy%R$_o$DL yields a better match of R$_o$ for both geologic and laboratory heating rates.

Impact on petroleum systems

• Alaskan wells show slight differences in petroleum generation timing due to the different vitrinite kinetic models. Rapid Brookian burial is the main control on hydrocarbon generation.
• Differences in the compositions of generated products are likely because of the boundary conditions needed to calibrate R$_o$ data for each vitrinite kinetic model.

General

• Maturation of vitrinite and kerogen are not universally correlated and may have to be corrected for individual kerogens.
• We recommend consideration of several vitrinite reflectance models for each thermal calibration.
Pressure Effects on $R_o$: Small or Inconsistent at Geologic Pressure

- Huang (1996): large differences for open vs. closed pyrolysis, but little difference from 0.5-2.0 kbar
- Landais et al. (1994): little effect between 0.5 and 4 kbar
- Uguna et al. (2012): pressure slightly inhibited $R_o$ between 0.2 and 0.9 kbar
- Della Torre et al. (1997) & Le Bayon et al. (2011): inhibition/acceleration depending on pressure and $R_o$ range

Relevant geological pressures are <2 kbar!