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

Oliver Schenk[1], Ken Bird[2], Ken Peters[3,4], and Alan Burnham[4]

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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_oDL, 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_oDL 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.

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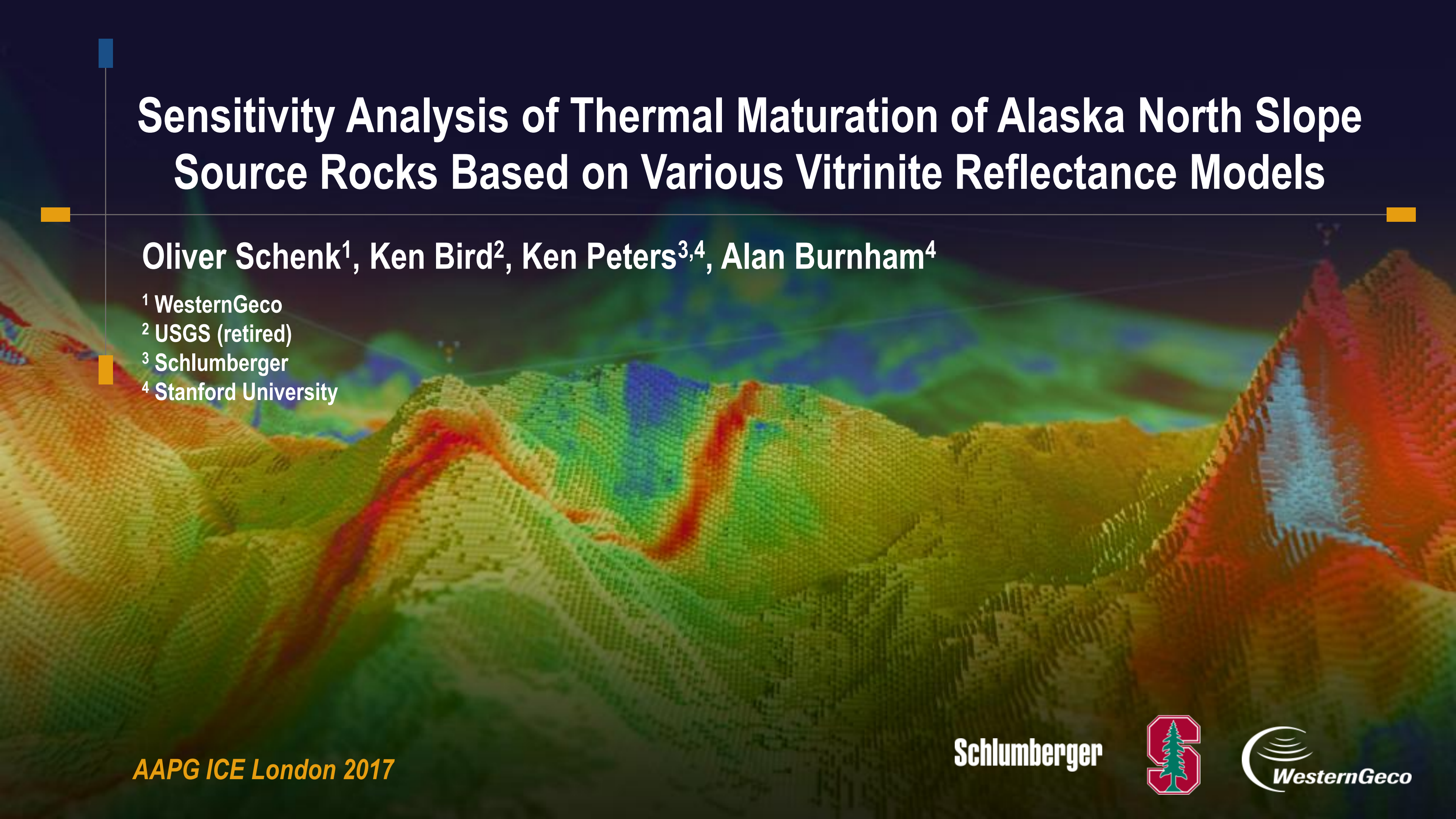

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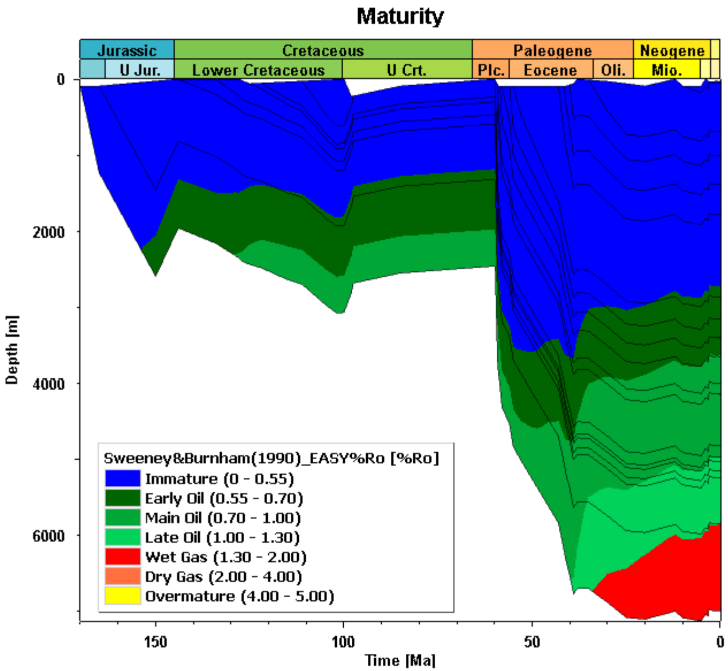
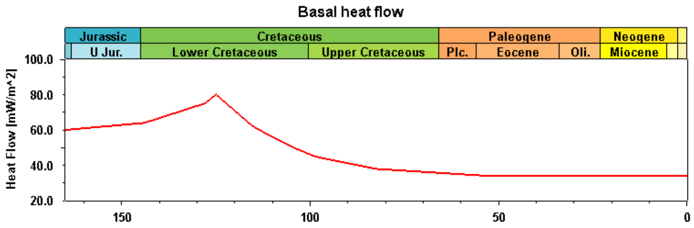
AAPG ICE London 2017

Thermal History is Key to Understand Petroleum Systems

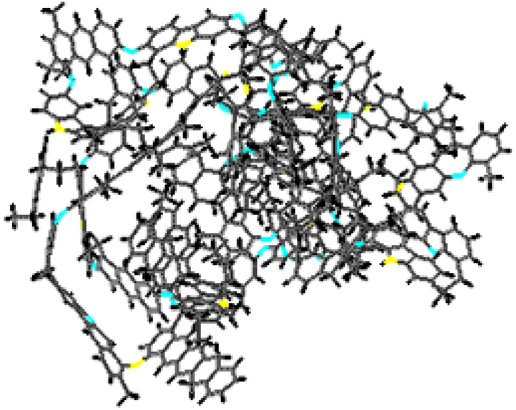
- Critical to evaluate prospectivity (e.g., timing of generation/migration relative to trap formation)
- Depends on burial/erosion, thermo-tectonic events, lithologic properties, paleo-heat flow
- Parameters that help constrain thermal history
  - Vitrinite reflectance (%R_o)
  - Apatite fission track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





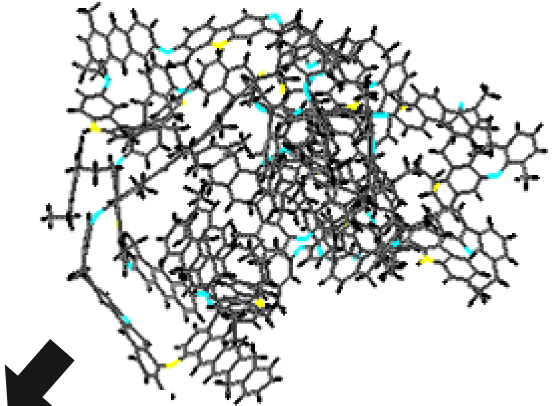
Vitrinite Originates from Higher Plants

Low Maturity Vitrinite

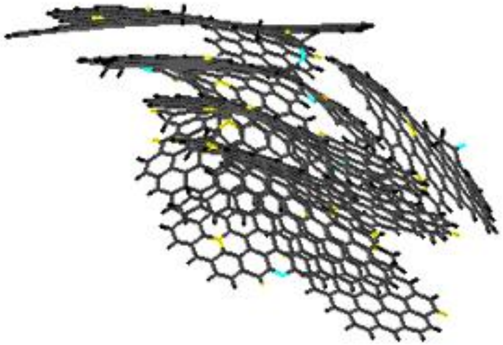


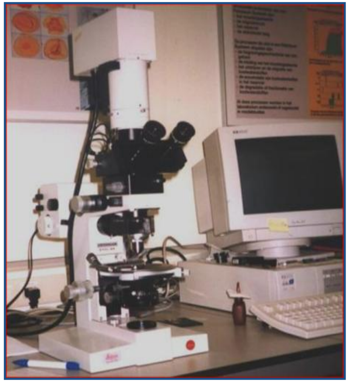
Vitrinite Reflectance (R_o) Increases with Thermal Maturity

Low Maturity Vitrinite



Anthracite





From Peters et al., 2005

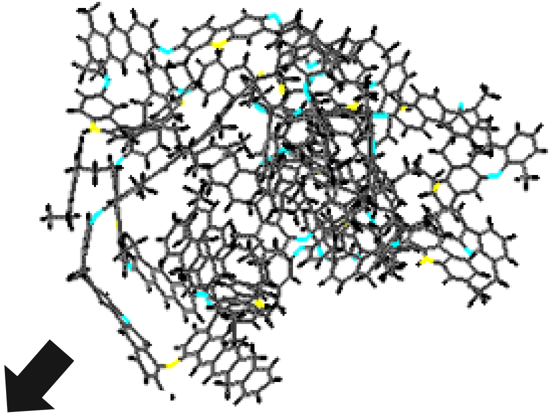
Vitrinite Maturation Can be Described Using the Arrhenius Equation

Arrhenius Equation

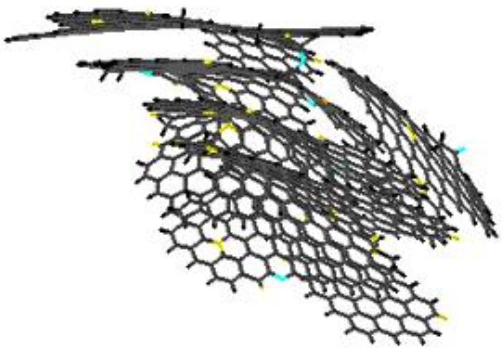
$$k = Ae^{-E_a/RT}$$

k = reaction rate constant (1/my); kerogen to oil & gas
A = frequency factor (1/my); vibrational frequency of bonds broken
E_a = activation energy (kcal/mol)
R = universal gas constant
T = temperature (K)

Low Maturity Vitrinite

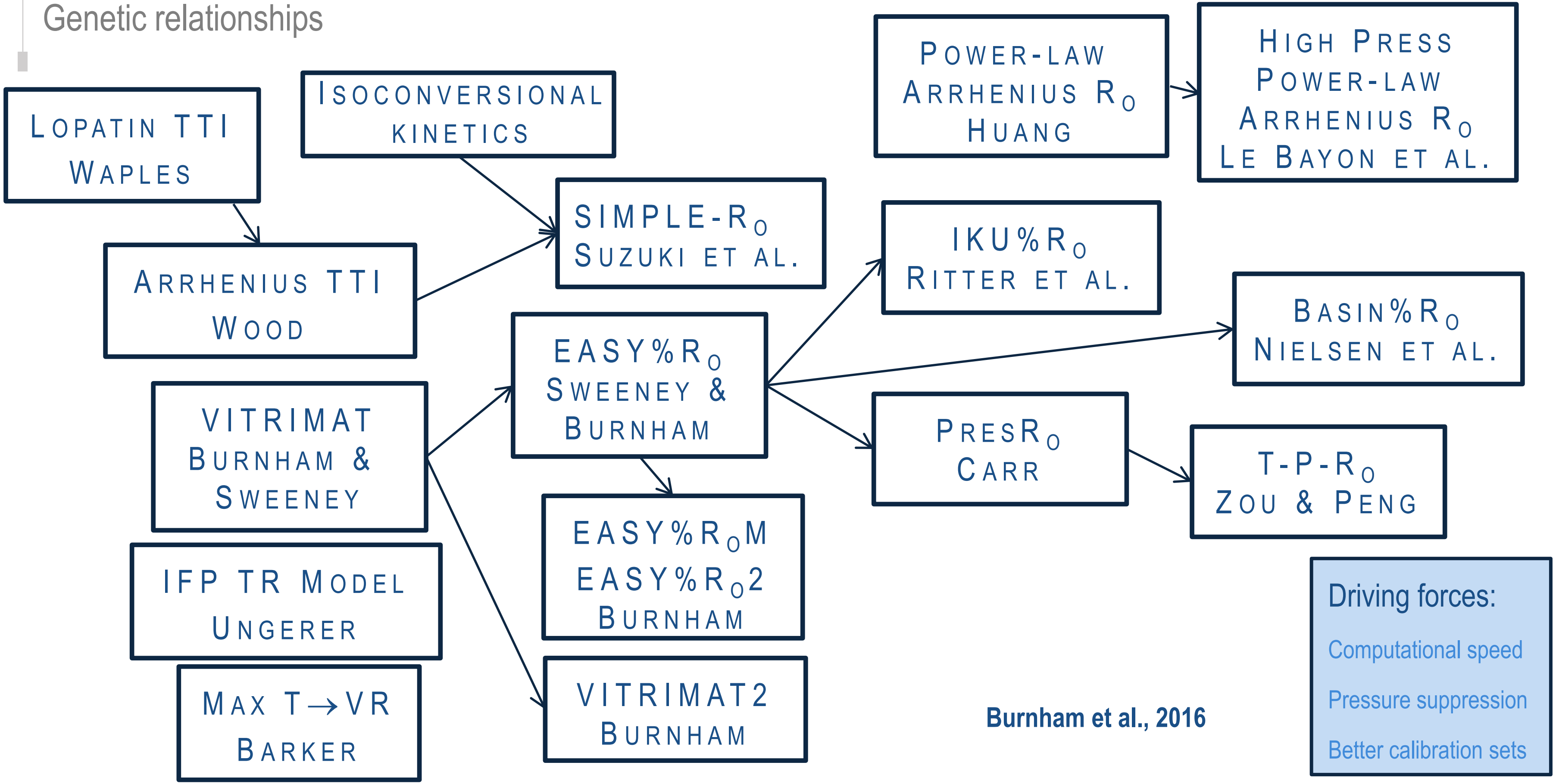


Anthracite



Various Vitrinite Reflectance Kinetic Models Have Been Proposed

Genetic relationships



Lopatin TTI
Waples

Isoconversional
kinetics

Arrhenius TTI
Wood

Simple-R_o
Suzuki et al.

Power-law
Arrhenius R_o
Huang

High Press
Power-law
Arrhenius R_o
Le Bayon et al.

IKU%R_o
Ritter et al.

Basin%R_o
Nielsen et al.

Easy%R_o
Sweeney & Burnham

VITRIMAT
Burnham & Sweeney

PresR$_o$
Carr

T-P-R_o
Zou & Peng

Easy%R_oM
Easy%R_o2
Burnham

IFP TR Model
Ungerer

Max T→VR
Barker

VITRIMAT2
Burnham

Burnham et al., 2016

Driving forces:

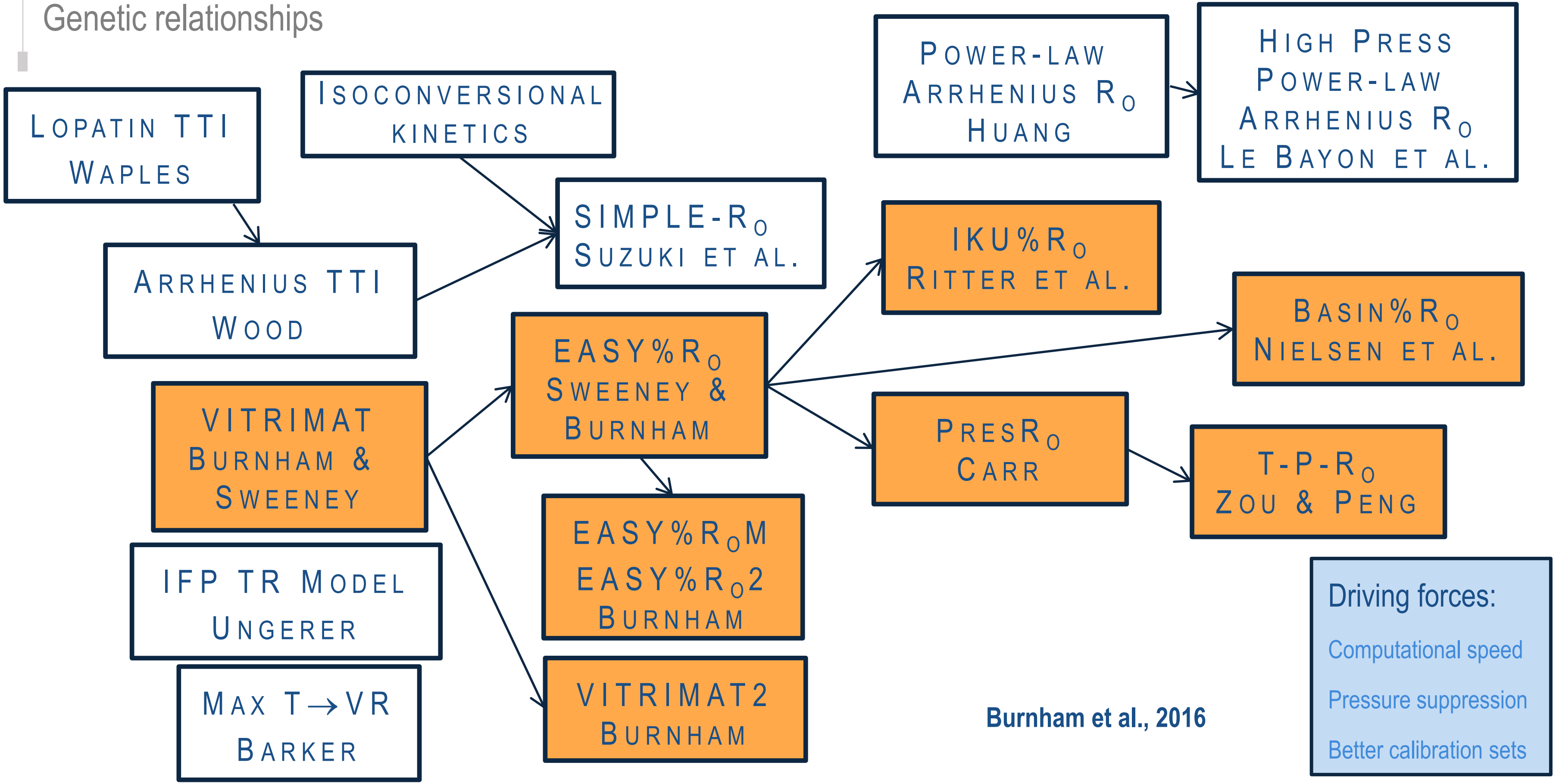
Computational speed

Pressure suppression

Better calibration sets

Many Reflectance Models Are Modified Versions of Vitrimat

Genetic relationships



Lopatin TTI
Waples

Isoconversional kinetics

Arrhenius TTI
Wood

SIMPLE-R_o
Suzuki et al.

Vitrimat
Burnham & Sweeney

EASY%R_o
Sweeney & Burnham

EASY%R_oM
EASY%R_o2
Burnham

Vitrimat2
Burnham

IFP TR Model
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Max T→VR
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Power-law Arrhenius R_o
Huang

High Press Power-law Arrhenius R_o
Le Bayon et al.

IKU%R_o
Ritter et al.

Basin%R_o
Nielsen et al.

PresR$_o$
Carr

T-P-R_o
Zou & Peng

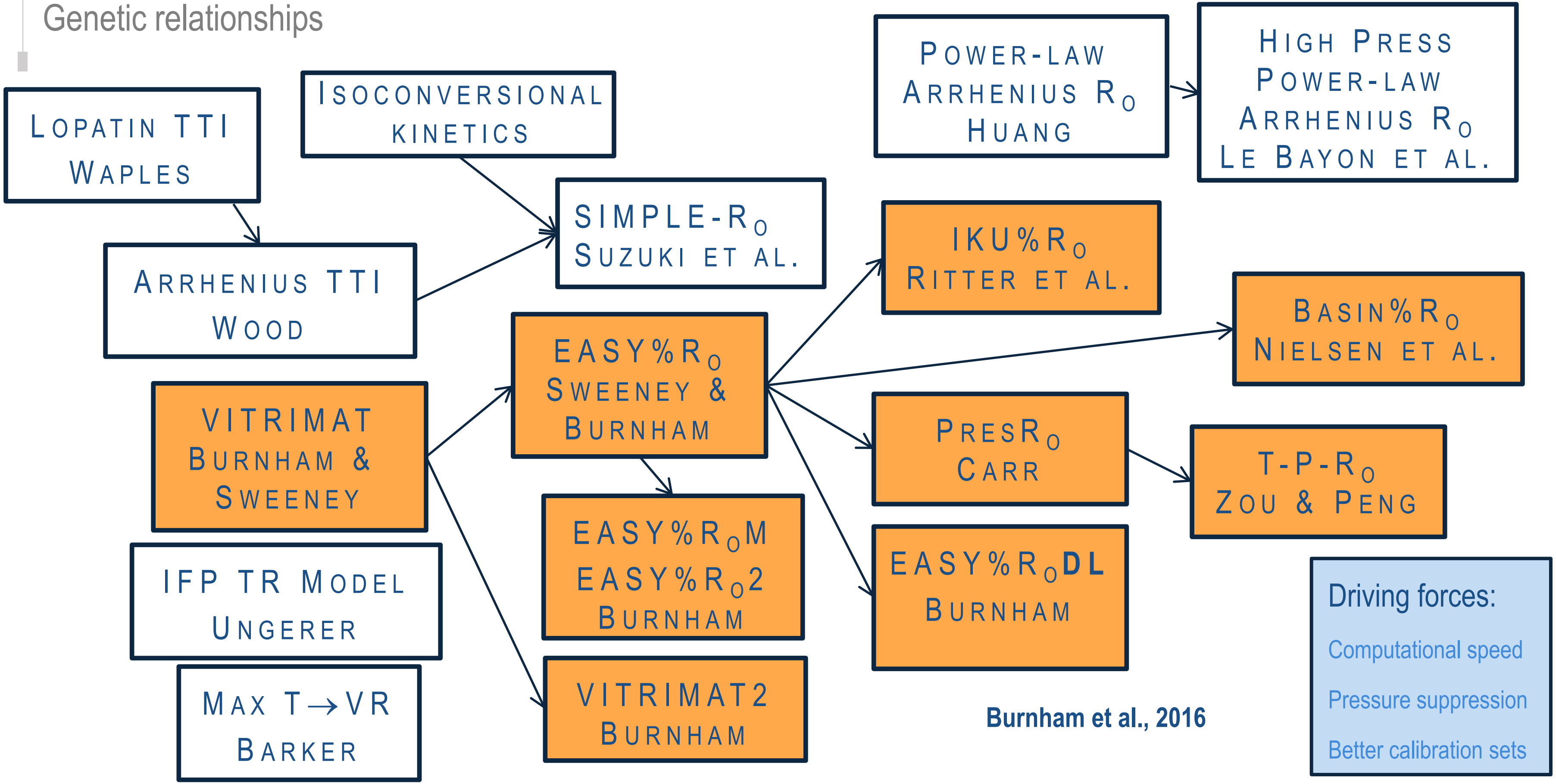
Burnham et al., 2016

Driving forces:

- Computational speed
- Pressure suppression
- Better calibration sets

This Presentation Introduces Easy%R$_o$DL (Dogleg)

Genetic relationships



Lopatin TTI
Waples

Isoconversional
kinetics

Arrhenius TTI
Wood

Simple-R$_o$
Suzuki et al.

Power-law
Arrhenius R$_o$
Huang

High Press
Power-law
Arrhenius R$_o$
Le Bayon et al.

IKU%R$_o$
Ritter et al.

Basin%R$_o$
Nielsen et al.

Vitrimat
Burnham &
Sweeney

Easy%R$_o$
Sweeney &
Burnham

PresR$_o$
Carr

T-P-R$_o$
Zou & Peng

Easy%R$_o$M
Easy%R$_o$2
Burnham

Easy%R$_o$DL
Burnham

IFP TR Model
Ungerer

Max T→VR
Barker

Vitrimat2
Burnham

Burnham et al., 2016

Driving forces:

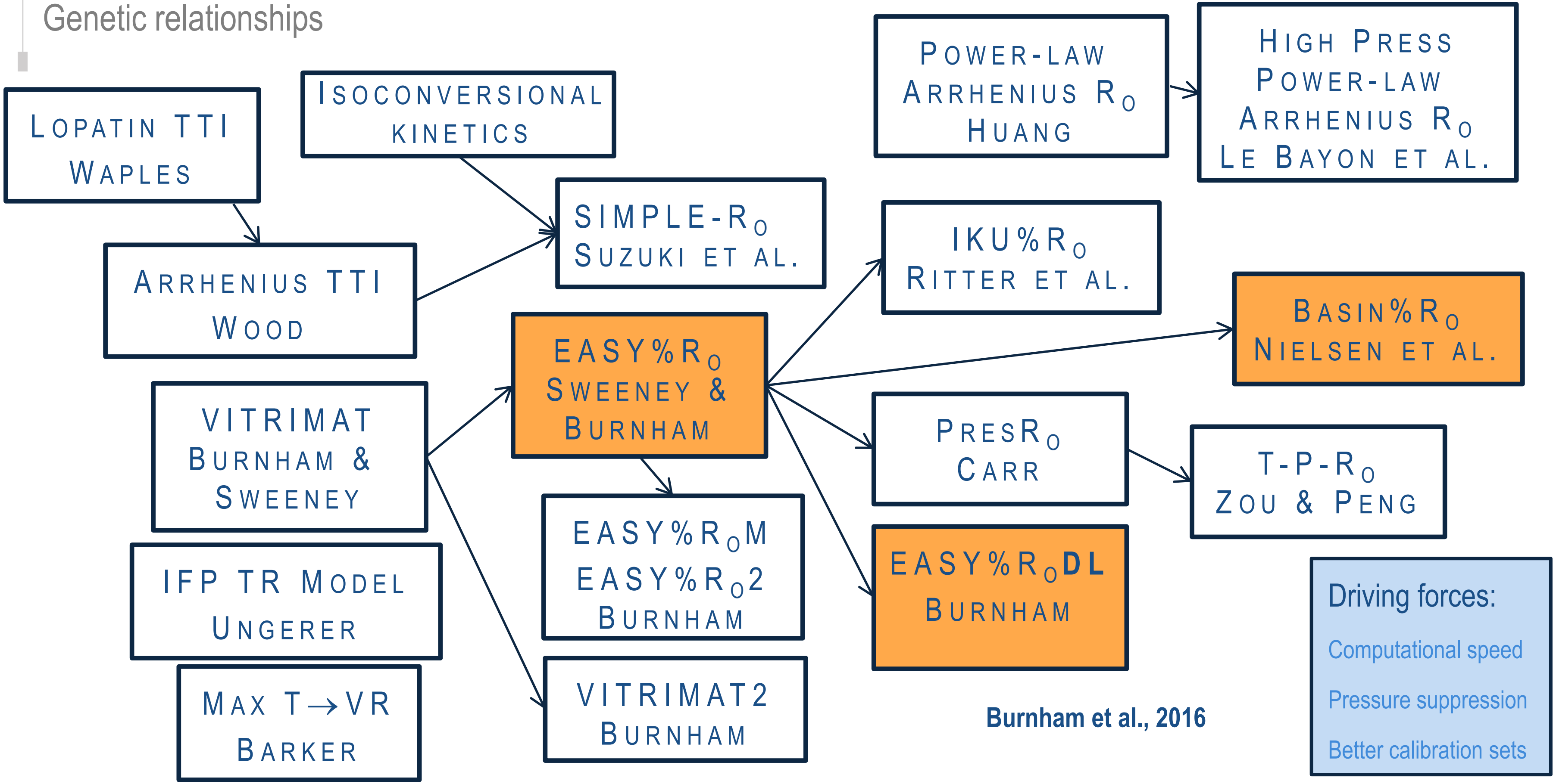
Computational speed

Pressure suppression

Better calibration sets

We Will Compare Easy%R$_o$, Basin%R$_o$, and Easy%R$_o$DL

Genetic relationships



Lopatin TTI
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Simple-R$_o$
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EASY%R$_o$
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Nielsen et al.

PresR$_o$
Carr

T-P-R$_o$
Zou & Peng

EASY%R$_o$**DL**
Burnham

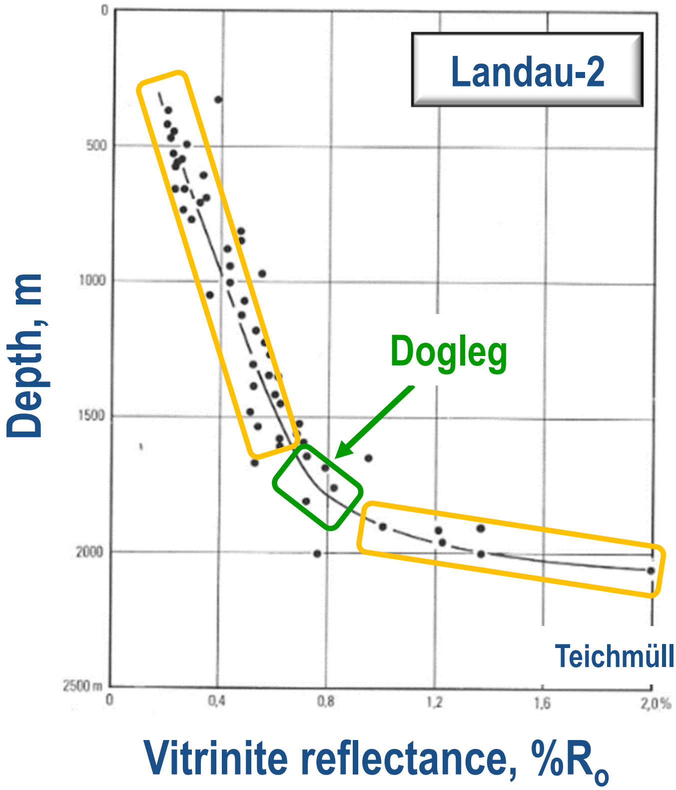
Burnham et al., 2016

Driving forces:

- Computational speed
- Pressure suppression
- Better calibration sets

“Dogleg” Structures in Reflectance-Depth Profiles are Common

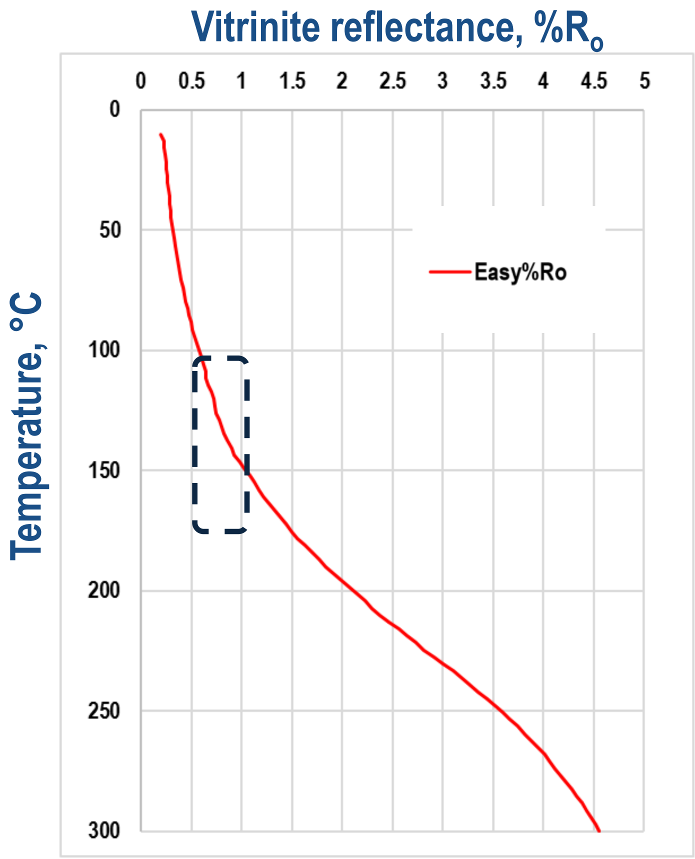
Middle Upper Rhine Graben, Germany



Teichmüller, 1979

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

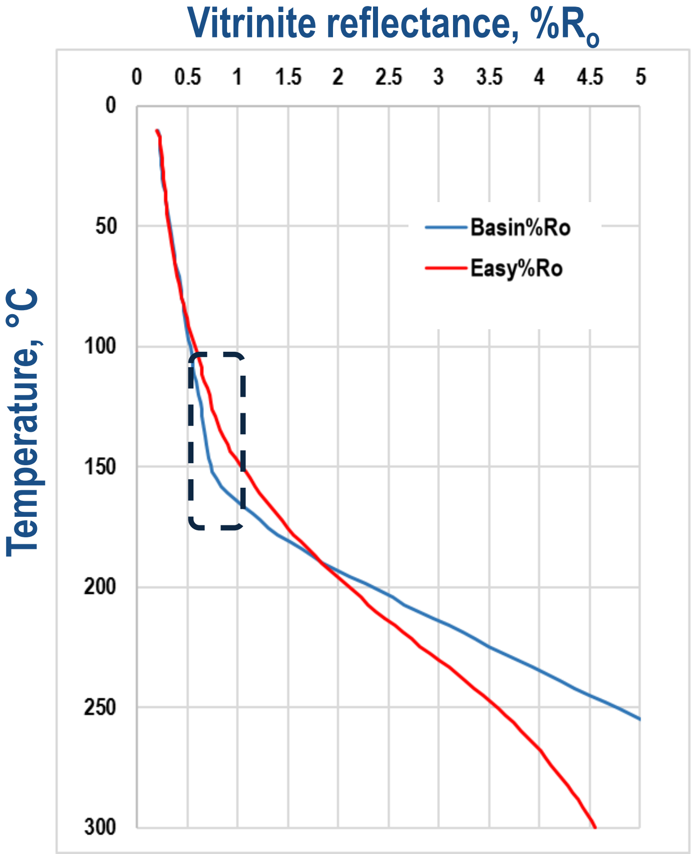
Example of Easy%R_o vs. Temperature Focuses on Highlighted Box



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

Basin%R_o Better Identifies Dogleg in the Range 0.7-1.0% R_o

Comparison



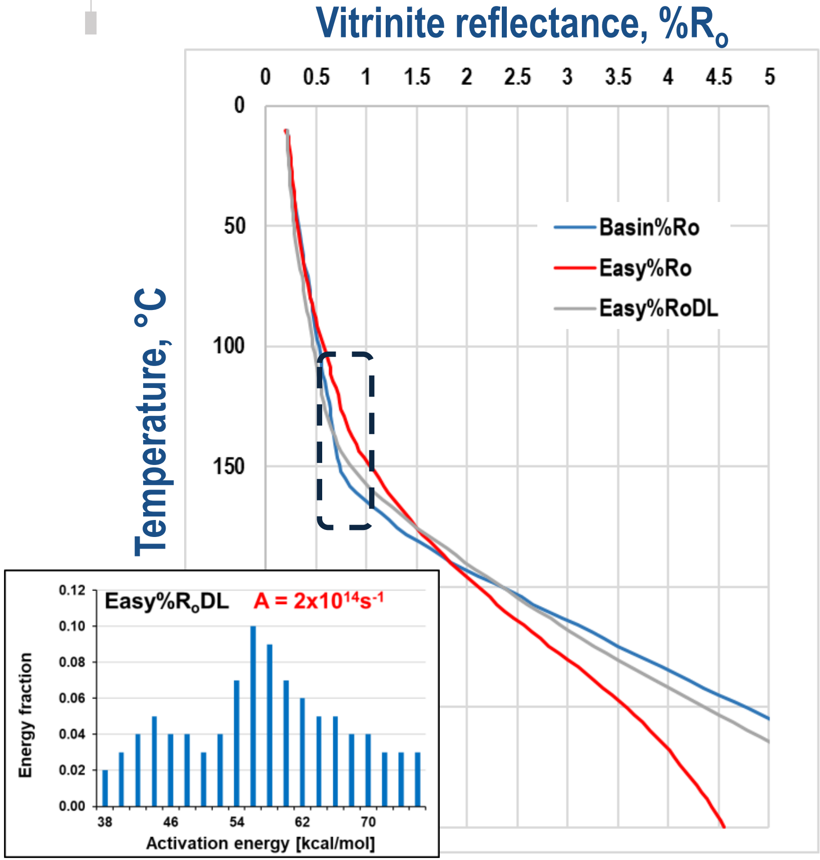
Easy%R_o (Sweeney and Burnham, 1990) may overestimate maturity in the range of 0.7-1.0% R_o

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

Easy%R_oDL Matches Basin%R_o, Fits *Both* Geology and Lab Rates

Comparison



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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

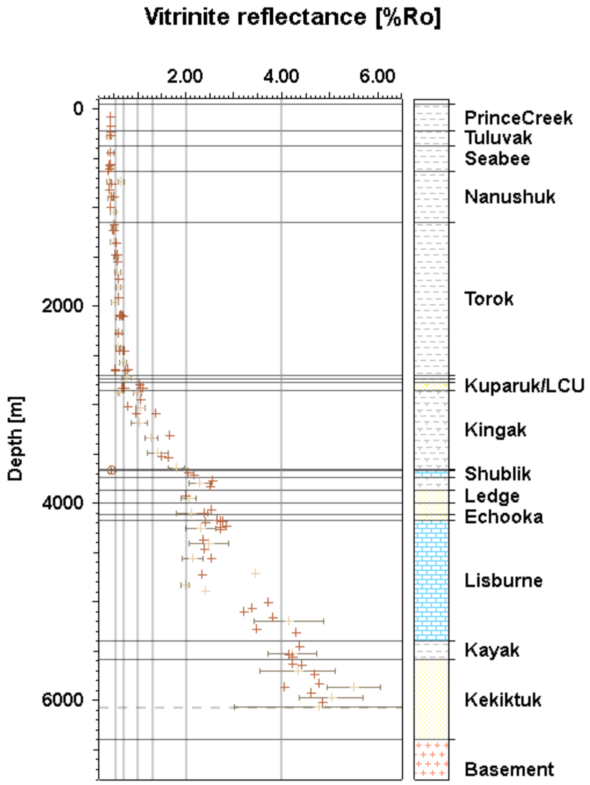
Simultaneous match at geologic and laboratory timescales requires adjustment of the frequency factor (A)

Burnham (2016) recalibrated the E_a distribution of Easy%R_o → Easy%R_oDL by changing A to 2 x 10^{14} s^{-1}

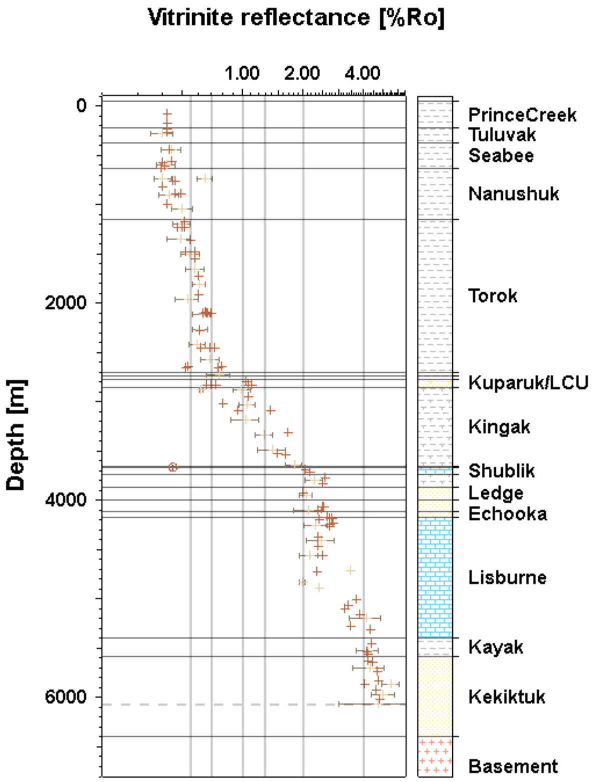
- Similar to Basin%R_o at geologic heating rates
- Agrees better with R_o from lab experiments

Case Study: Alaska North Slope

Dogleg structure at Inigok-1

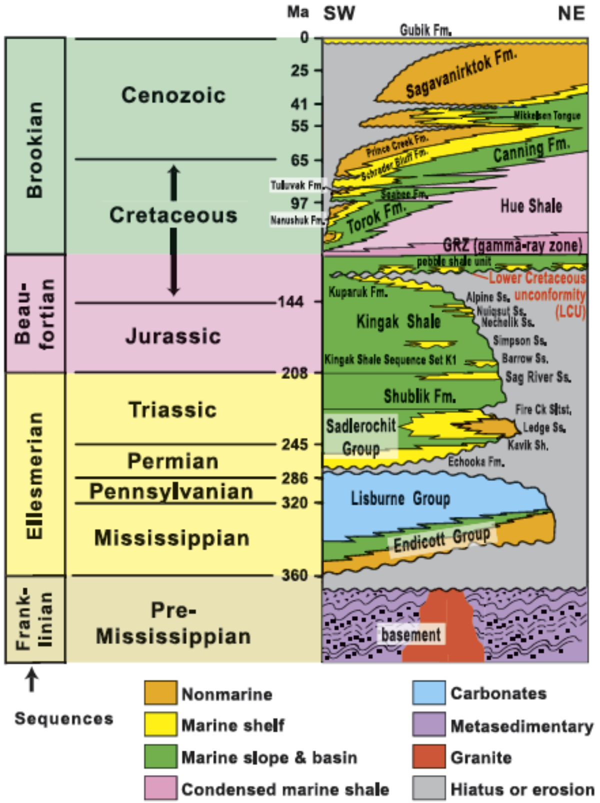


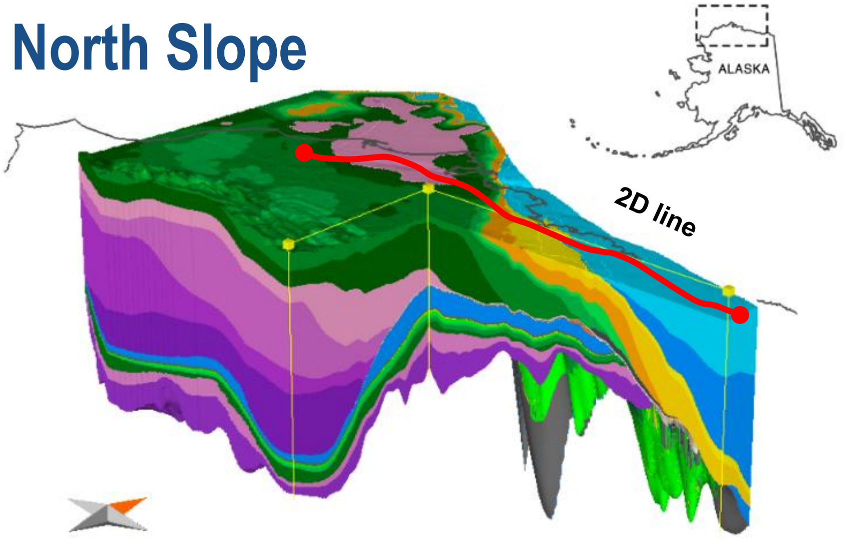
Linear

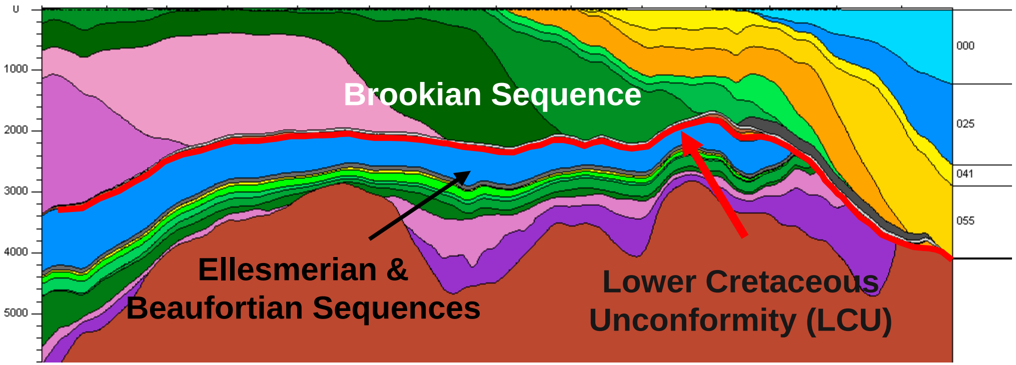


Semi-log

Regional Geology of the Alaska North Slope

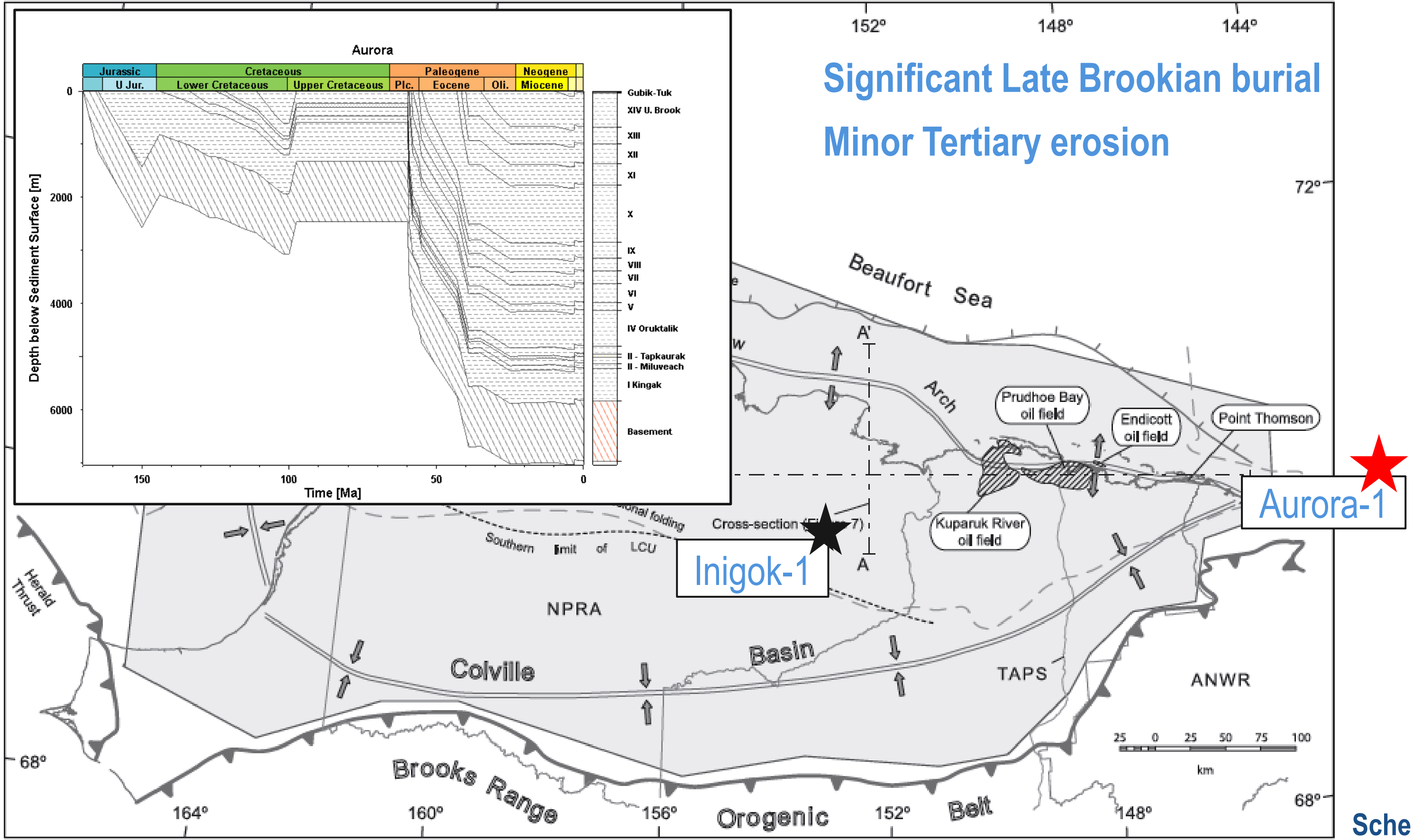






Schenk et al., 2012

Comparison of Vitrinite Reflectance Models: Aurora-1 and Inigok-1

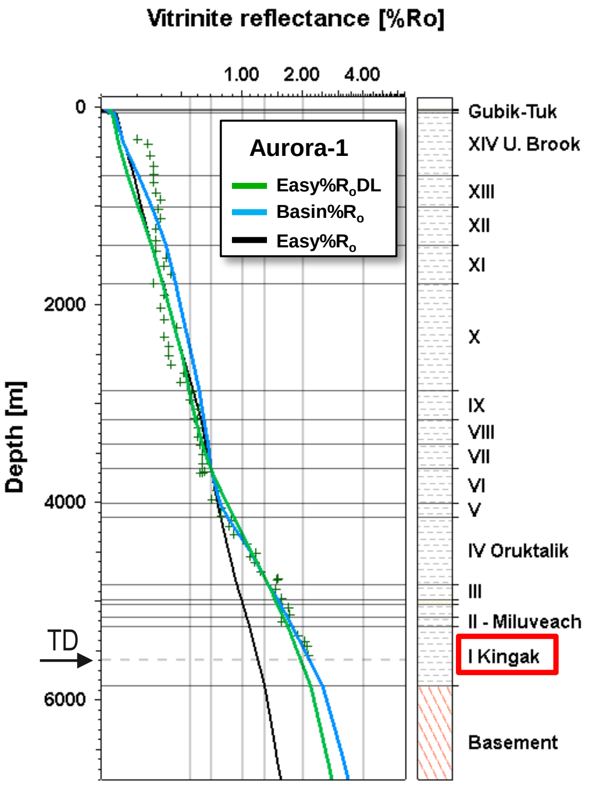


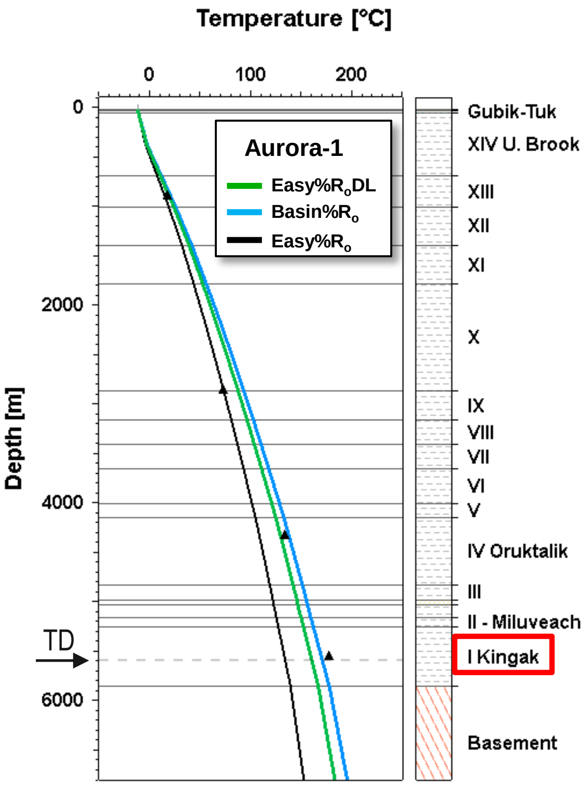
Significant Late Brookian burial

Minor Tertiary erosion

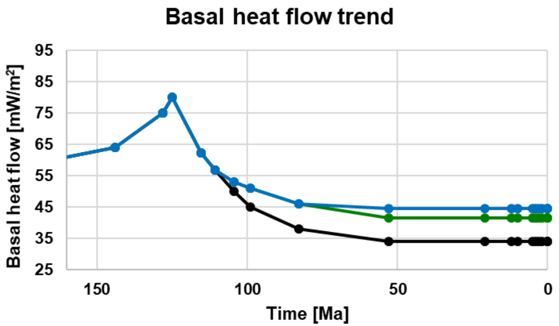
Schenk et al., 2012

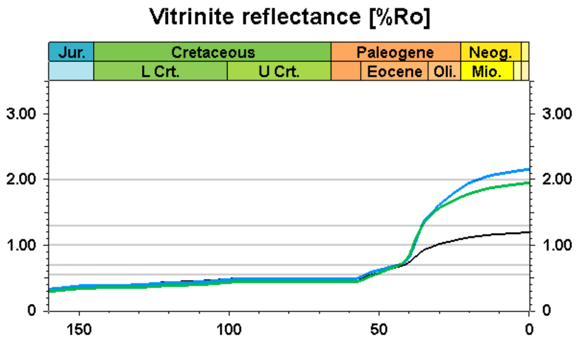
Comparison of Aurora-1 Reflectance Models

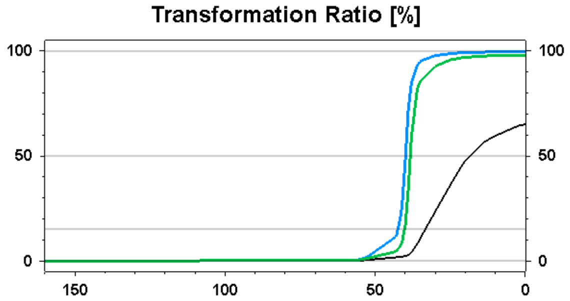




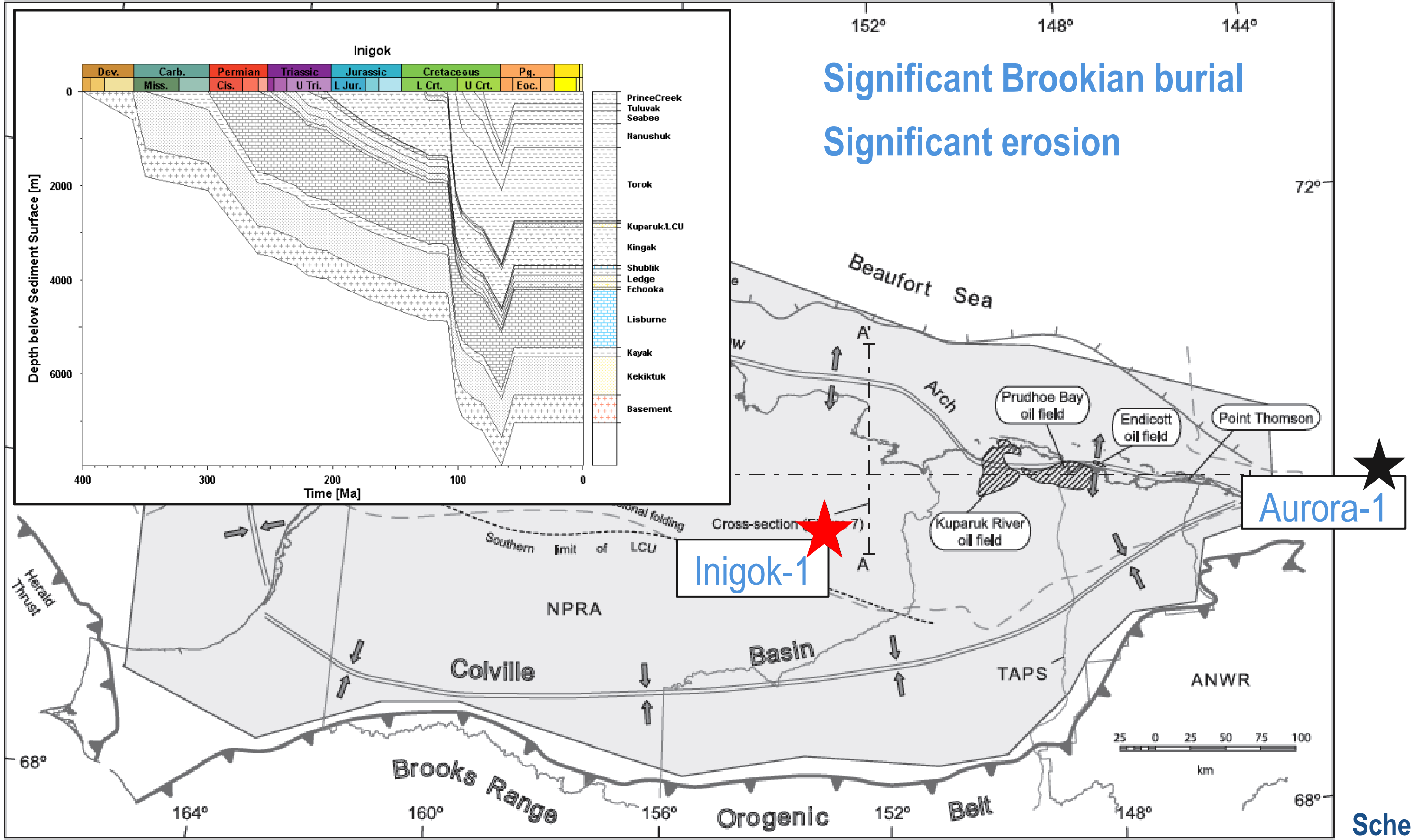
Horner-corrected BHT







Comparison of Inigok-1 Reflectance Models

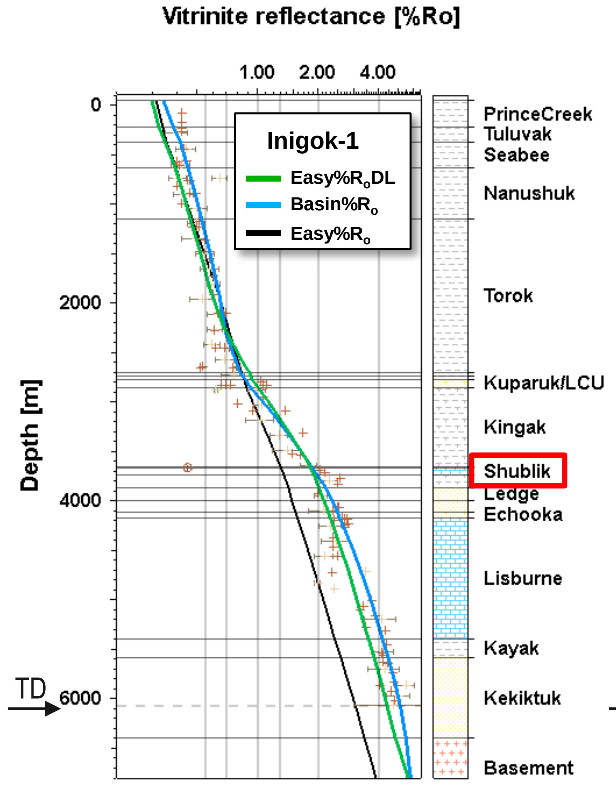


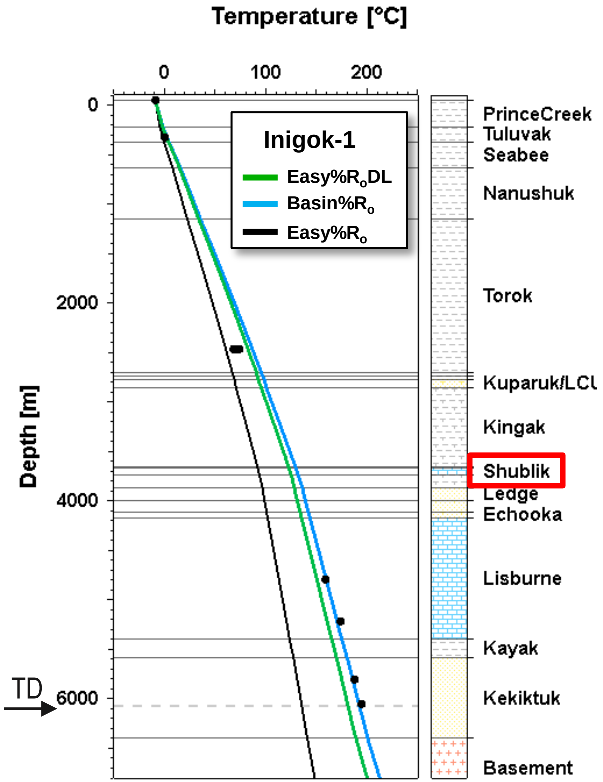
Significant Brookian burial

Significant erosion

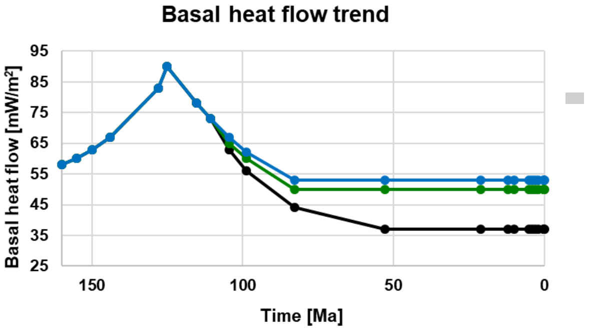
Schenk et al., 2012

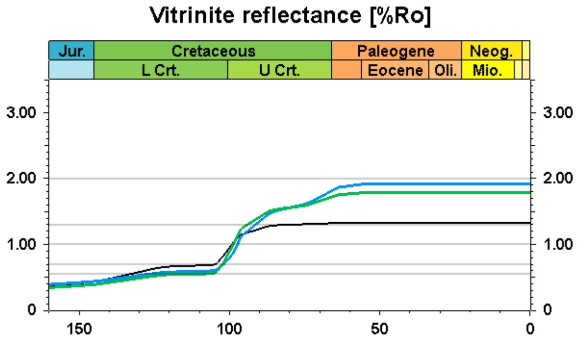
Comparison of Inigok-1 Reflectance Models

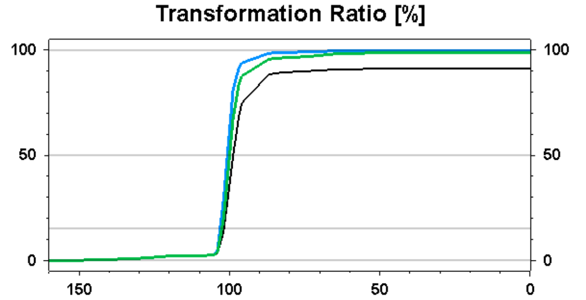

Vitrinite reflectance [%Ro]


Temperature [°C]

Horner-corrected BHT


Basal heat flow trend


Vitrinite reflectance [%Ro]


Transformation Ratio [%]

Conclusions

Comparison of different vitrinite reflectance kinetic models

- **Basin%R_o** and **Easy%R_oDL** match R_o doglegs better than **Easy%R_o**.
- **Basin%R_o** matches geologic data better than laboratory pyrolysis data.
- **Easy%R_oDL** yields a better match of R_o for *both* geologic and laboratory heating rates.

Impact on petroleum systems

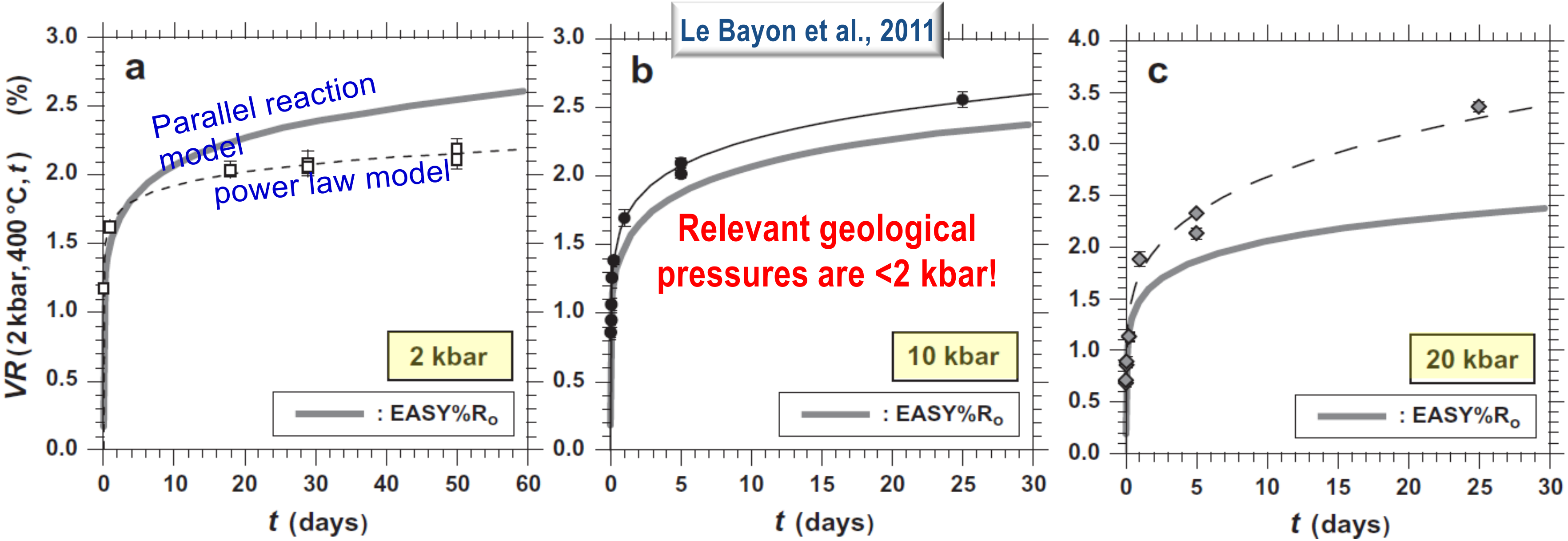
- Alaskan wells show slight differences in petroleum generation timing due to the different vitrinite kinetic models. Rapid Brookian burial is the main control on hydrocarbon generation.
- Differences in the compositions of generated products are likely because of the boundary conditions needed to calibrate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



Le Bayon et al., 2011

Parallel reaction model

power law model

Relevant geological pressures are <2 kbar!