Production of Oil Shale from The Green River Formation in Utah

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Outline

- *Geology background*
- Reservoir modeling
- Modeling results
- Summary

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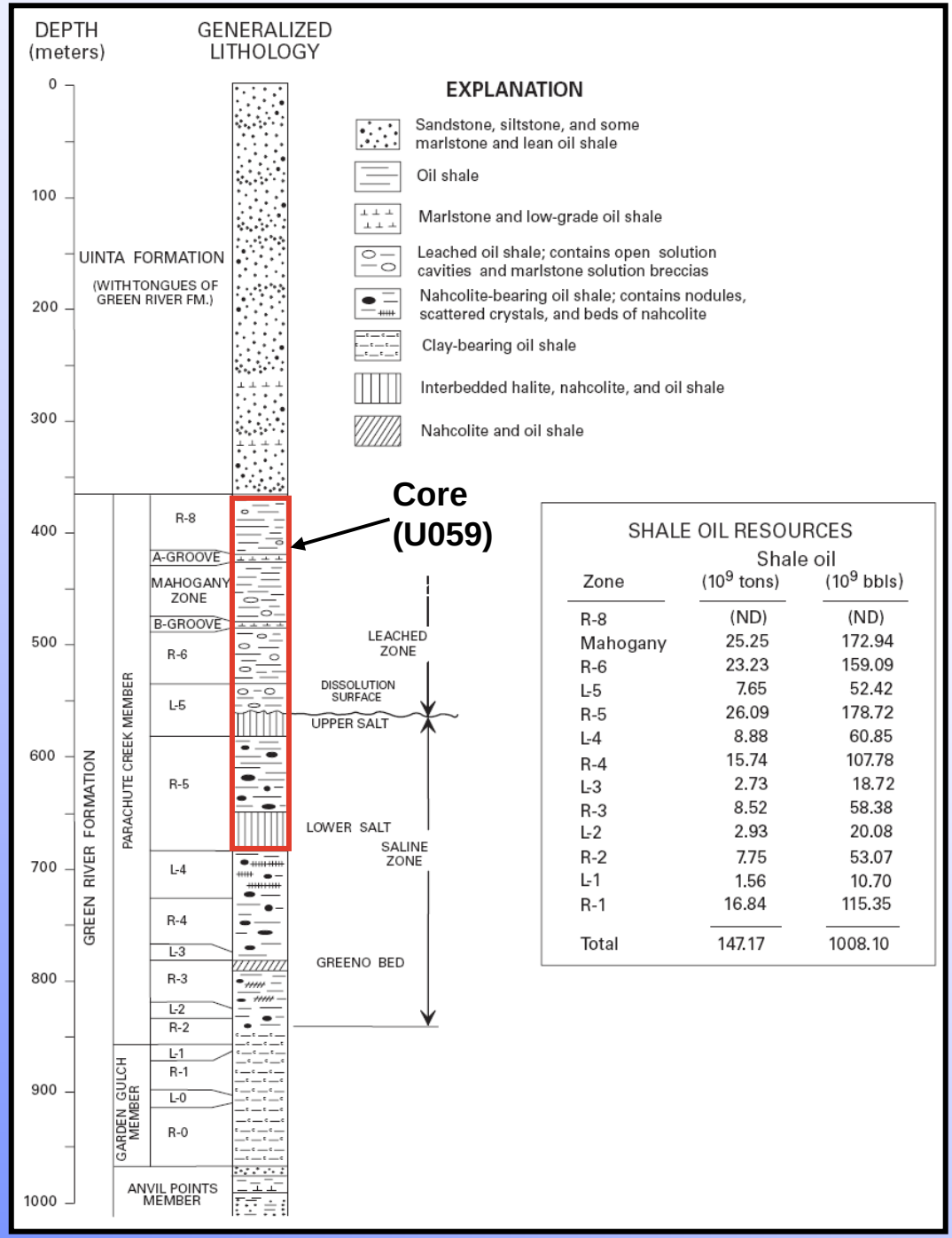
Introduction

- U.S. has the largest deposits of oil shale in the world
  - Conservative estimate: recoverable OOIP ca. 440~660 billion barrels
- One of the richest and thickest oil-shale bearing intervals of the Green River Formation is located in the eastern Uinta Basin, Utah
  - Sedimentology and sequence stratigraphy of this interval in the subsurface is so far poorly understood
- Aims of this study :
  - Depositional and sequence stratigraphic characterization of the upper Green River Fm based on core and well log correlation
  - Production modeling of the richest zone (Mahogany) based on available information

Generalized Stratigraphy of Green River Fm (from Dyni, 2006)

- Eocene Green River Fm was deposited in a lake environment.
- Information from core U059 is used to construct the kerogen content distribution in z-direction.

(Source: VandenBerg, UGS)

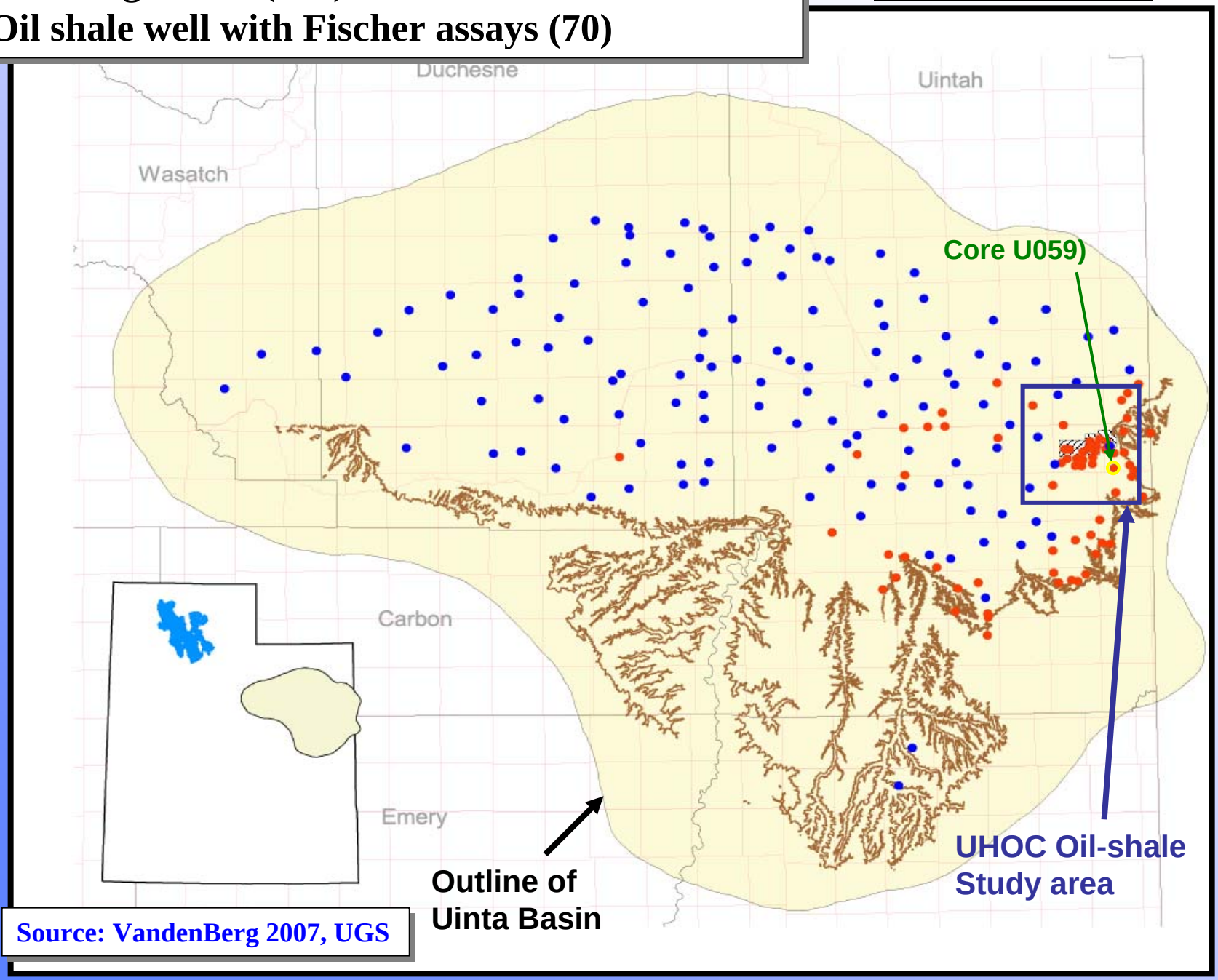


SHALE OIL RESOURCES

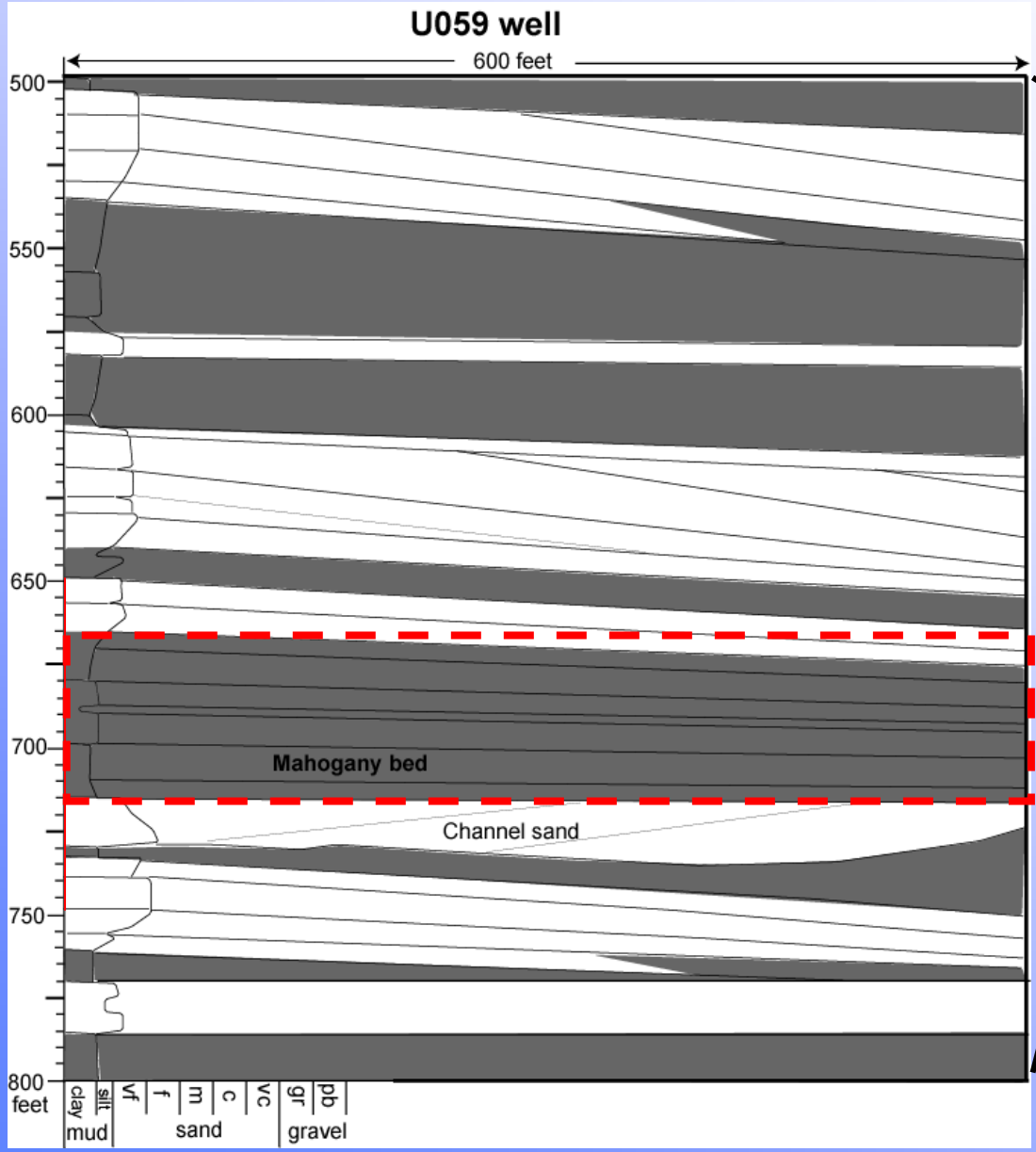
Zone	Shale oil (10^9 tons)	Shale oil (10^9 bbls)
R-8	(ND)	(ND)
Mahogany	25.25	172.94
R-6	23.23	159.09
L-5	7.65	52.42
R-5	26.09	178.72
L-4	8.88	60.85
R-4	15.74	107.78
L-3	2.73	18.72
R-3	8.52	58.38
L-2	2.93	20.08
R-2	7.75	53.07
L-1	1.56	10.70
R-1	16.84	115.35
Total	147.17	1008.10

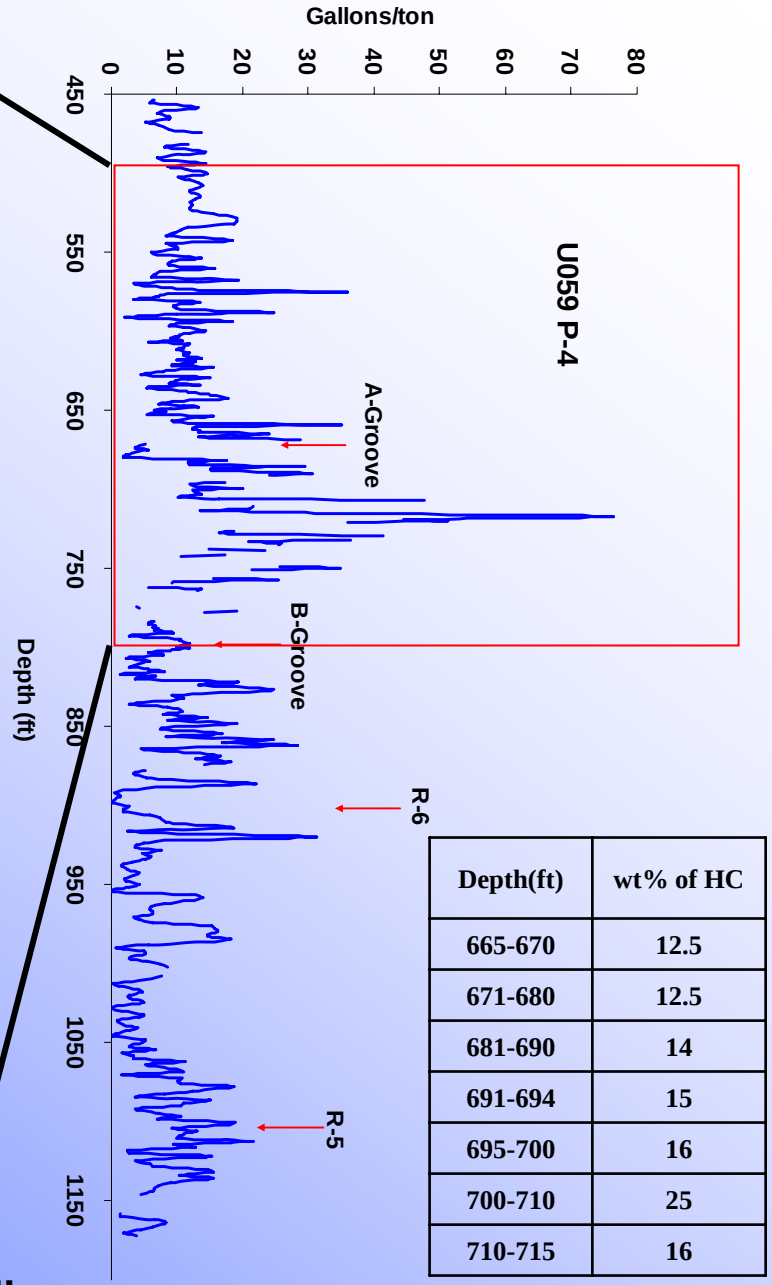
Study area

- - Oil and gas well (126)
- - Oil shale well with Fischer assays (70)



Source: VandenBerg 2007, UGS





Depth(ft)	wt% of HC
665-670	12.5
671-680	12.5
681-690	14
691-694	15
695-700	16
700-710	25
710-715	16

Sedimentology and bedding architecture of U059 well from gamma log (white: sandstone, gray: mudstone).

Oil-yield derived from density log

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Governing equations

Conservation of the fluid component i:

$$\frac{\partial \sum_{p}^{o,g,w} x_{p,i}\phi_f \rho_p S_p}{\partial t} + \sum_{p}^{o,g,w} \nabla \cdot (x_{p,i}\vec{f}_p) + \sum_{r}^{Nr} \Delta s_{r,i}\Upsilon_r = \sum_{p}^{o,g,w} x_{p,i} q_p$$

Constraint of the solid component i:

$$\frac{\partial \phi_v c_{s,i}}{\partial t} + \sum_{r}^{Nr} \Delta s_{r,i}\Upsilon_r = 0$$

Conservation of energy:

$$\frac{\partial \left(\phi_f \sum_{p}^{o,g,w} \overline{U}_p \rho_p S_p + \phi_v \sum_{i}^{Ns} c_{s,i}\overline{U}_{s,i} + (1-\phi_v)\overline{U}_r \right)}{\partial t} + \sum_{p}^{o,g,w} \nabla \cdot (\overline{H}_p \vec{f}_p) + \nabla \cdot \vec{q}_c + \sum_{r}^{Nr} \Delta \overline{H}_r \Upsilon_r = \sum_{p}^{o,g,w} \overline{H}_p q_p$$

where $\vec{f}_p = -\overline{\overline{K}} \frac{k_{rp}\rho_p}{\mu_p}(\nabla P_p + \gamma_p \nabla Z)$ **and** $\vec{q}_c = -\overline{\overline{\lambda}}_c \nabla T$

Computer Modeling Group simulator: STARS

Pore volume constraints

$$V = V_r + V_s + V_f = V_r + V_s + \sum_{p}^{o,g,w} V_p$$

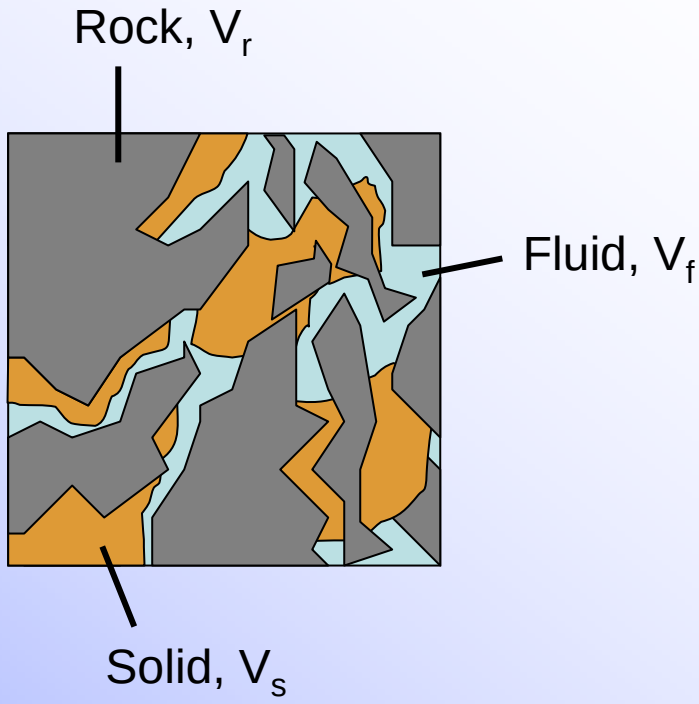
$$\phi_f = \phi_v \left(1 - \sum_{i}^{Ns} \frac{c_{s,i} Mw_i}{\rho_i}\right)$$

$$0 \le \sum_{i}^{Ns} \frac{c_{s,i} Mw_i}{\rho_i} \le 1$$

$$\text{wt\% } \textbf{of kerogen} = \frac{w_K}{w_R} = \frac{\text{Max}(c_{s,K}) Mw_K}{\rho_K} \phi_v$$

In V_f :

$$\sum_{p}^{o,g,w} \frac{V_p}{V_f} = \sum_{p}^{o,g,w} S_p = 1$$



Assumption:
Initially, rock contains $S_w < 0.01$ connate water.

Kinetics [modified from Robert L. B. et. al., 1975]

$$K \xrightarrow{k_1} B + G_1 + C_1 \qquad \frac{dK}{dt} = -k_1 K$$

$$B \xrightarrow{k_2} A + G_2 + C_2 \qquad \frac{dB}{dt} = k_1 f_1 K - k_2 B$$

$$K \xrightarrow{k_1} 2B \qquad \frac{dK}{dt} = -k_1 K$$

$$B \xrightarrow{k_2} s_{2,O} O + s_{2,C} C \qquad \frac{dB}{dt} = 2k_1 K - k_2 B$$

$$s_c = \frac{Mw_B}{Mw_C} \text{coking(wt\%)}$$

$$s_o = \frac{Mw_B}{Mw_O} \left(100(\text{wt\%}) - \text{coking(wt\%)}\right)$$

Components:

Kerogen = 1000 lb/lbmol
Bitumen* = 500 lb/lbmol
Oil* = 250 lb/lbmol (~FC17)
Coke = 13 lb/lbmol (CH)

*Bitumen is considered as dead oil component
*Oil is volatile, V-L behavior is determined by $K_V = K_V(T, P)$

Kinetics: product distribution

$$\frac{dm_K}{dt^*} = -k_1^* \phi c_{s,K}$$

$$\frac{dm_B}{dt^*} = 2k_1^* \phi c_{s,K} - k_2^* \phi S_o x_{o,B}$$

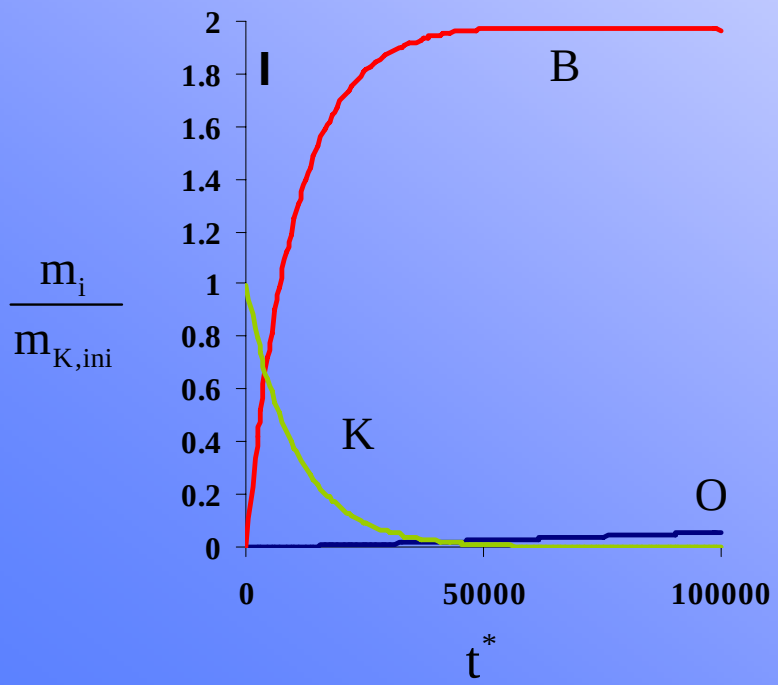
$$\frac{dm_O}{dt^*} = s_{2,O} k_2^* \phi S_o x_{o,B}$$

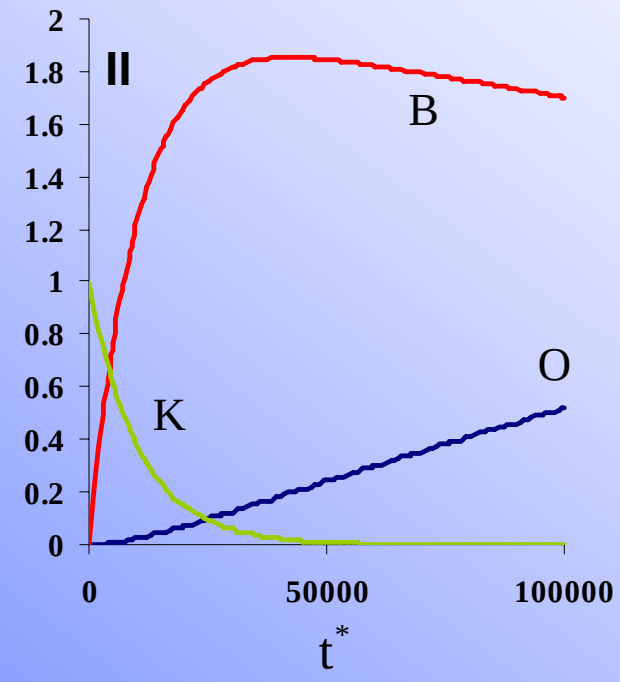
$$t^* = tk_1^0$$

$$k_1^* = \exp\left(\frac{-Ea_1}{RT}\right); k_2^* = \frac{k_2^0}{k_1^0}\exp\left(\frac{-Ea_2}{RT}\right)$$

at 600 ^{0}F

$$\frac{k_2^*}{k_1^*} = \begin{cases} \textbf{Ex I: } 10^9 \textbf{ (from Robert et. al.)} \\ \textbf{Ex II: } 10^{10} \end{cases}$$





Kinetics: effective reaction coefficient

1. Thermal equilibrium is established instantly, there is no temperature gradient inside the computational grid block
   Length scale: $L_{laboratory} << L_{simulation}$
2. “Apparent” reaction is slower due to diffusion, mass transfer effect.
3. A pre-factor ($\nu < 1$) is introduced to account this effect.
4. ‘ν’ can be obtained from experimental data or production history matching.

Modified Arrhenius equation:

$$k_{eff} = \nu k^{0} \exp\left(\frac{-Ea}{RT}\right)$$

Heat loss to cap/base rock model [Vinsome et. al.]

10~15% heat loss

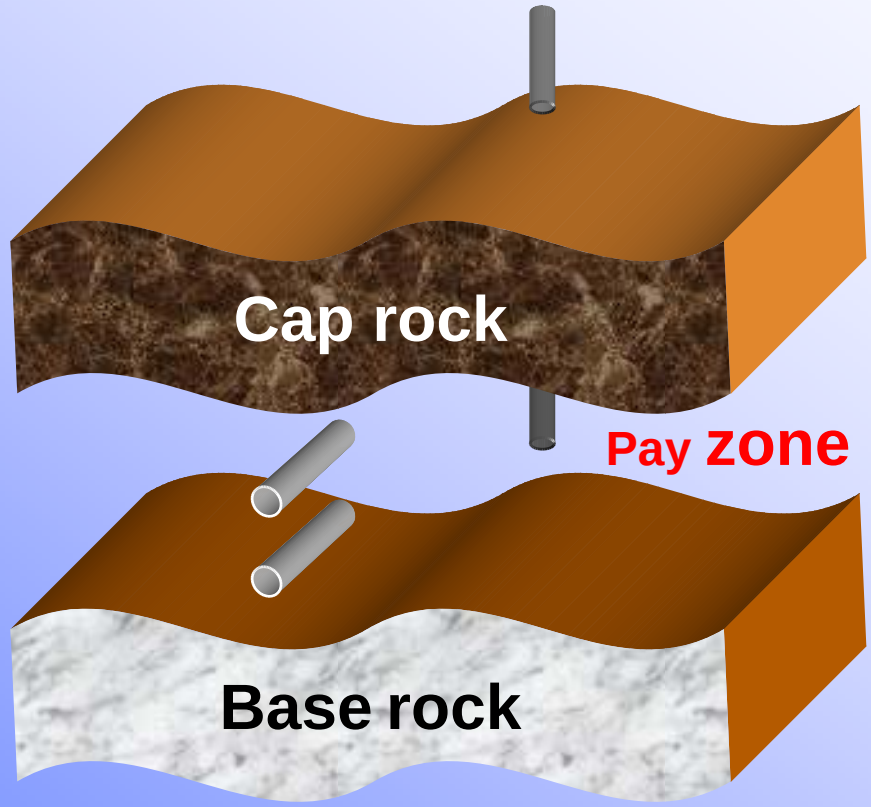
$$T(\bar{z}, t) - T_{ini} = (T_{res} - T_{ini} + p\bar{z} + q\bar{z}^{2})\exp(-\bar{z}/d)$$

$$d = \frac{\sqrt{\lambda_c / \overline{Cp} \times t}}{2}$$

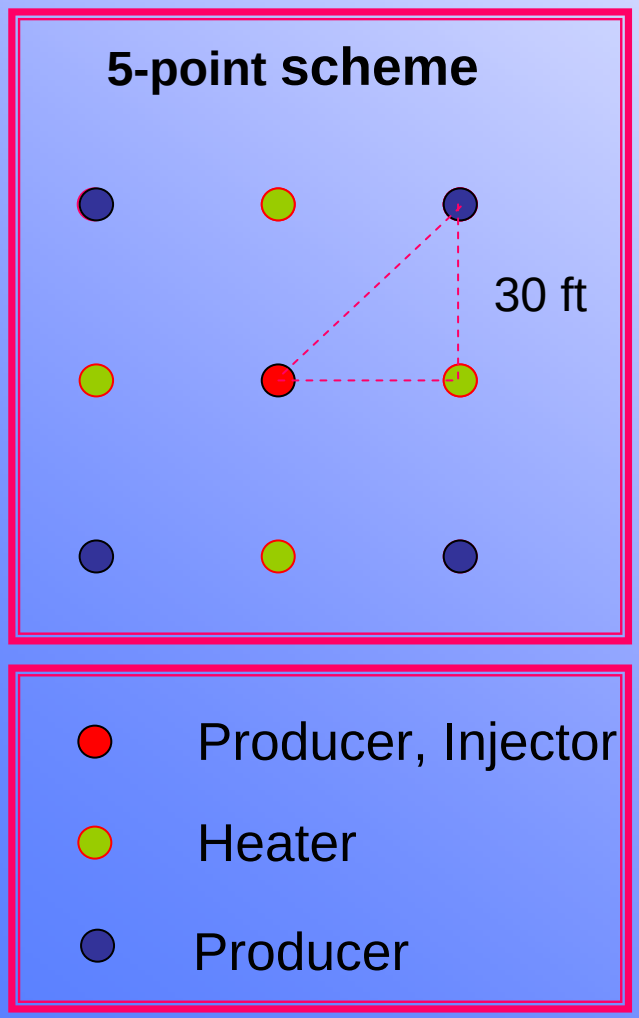
IC: $T(t = 0) = T_{ini}$

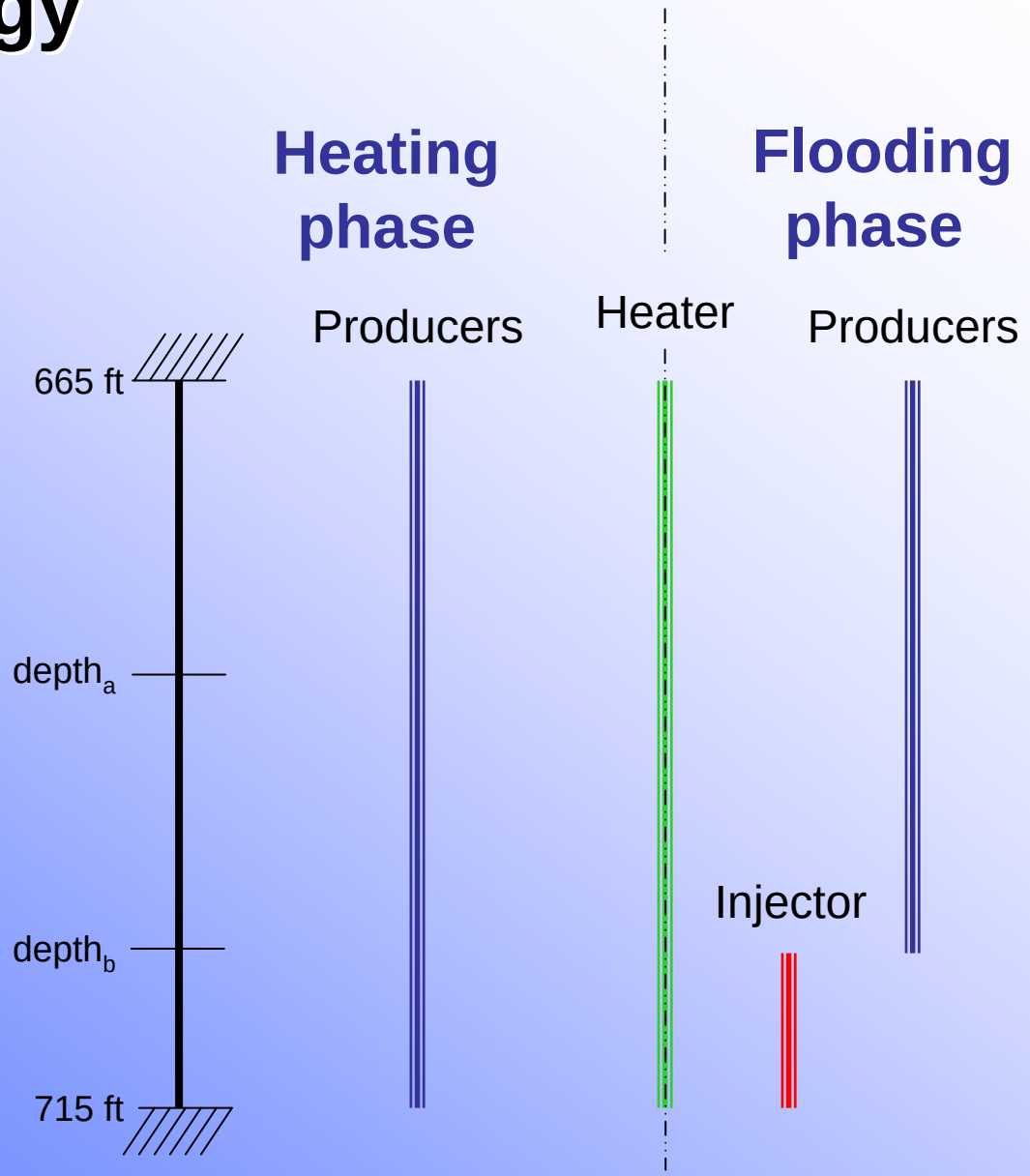
BC: $$\begin{cases} \left(\overline{Cp}\dfrac{\partial T}{\partial t}\right)_{\bar{z}=0} = \left(\lambda_c \dfrac{\partial^2 T}{\partial \bar{z}^2}\right)_{\bar{z}=0} \\ T(\bar{z} = \infty) = T_{ini} \end{cases}$$

$$q_L = \lambda_c \left(\frac{T_{res} - T_{ini}}{d} - p\right)$$



Recovery strategy

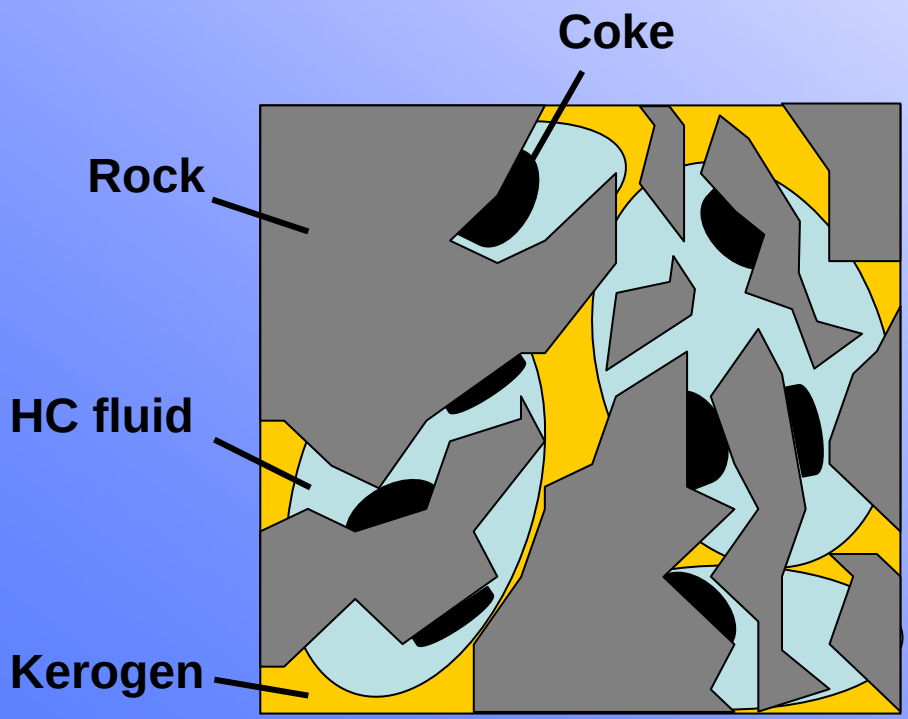


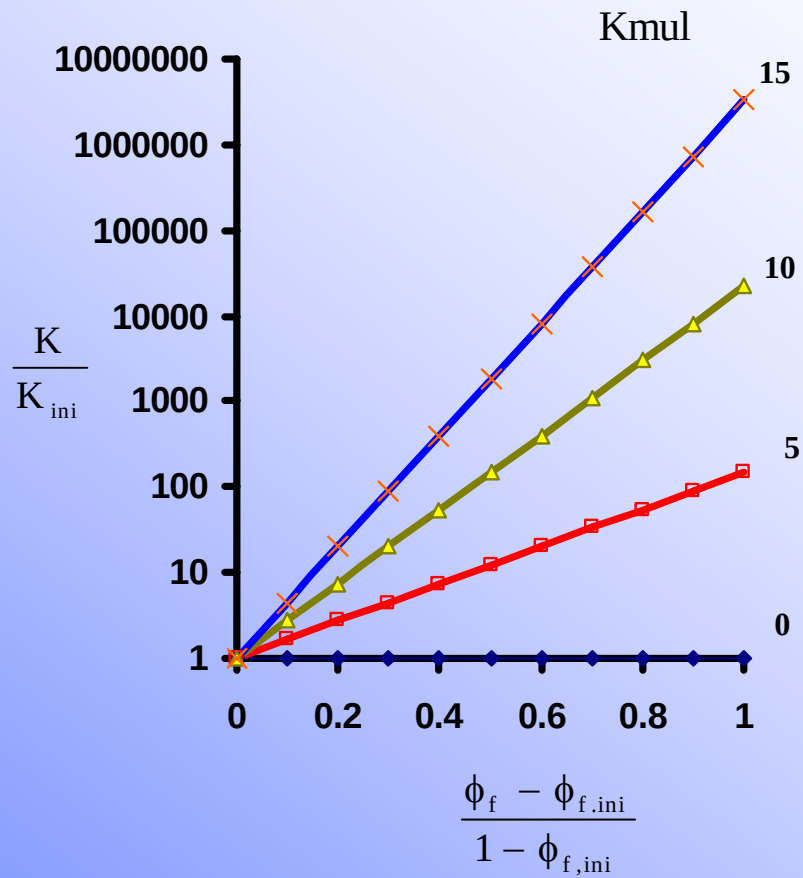


Permeability creation model

Assumption:
Permeability (K) is created when pore volume is occupied by more fluid.

$$K = K_{ini} \exp\left[Kmul\left(\frac{\phi_f - \phi_{f.ini}}{1 - \phi_{f,ini}}\right)\right]$$





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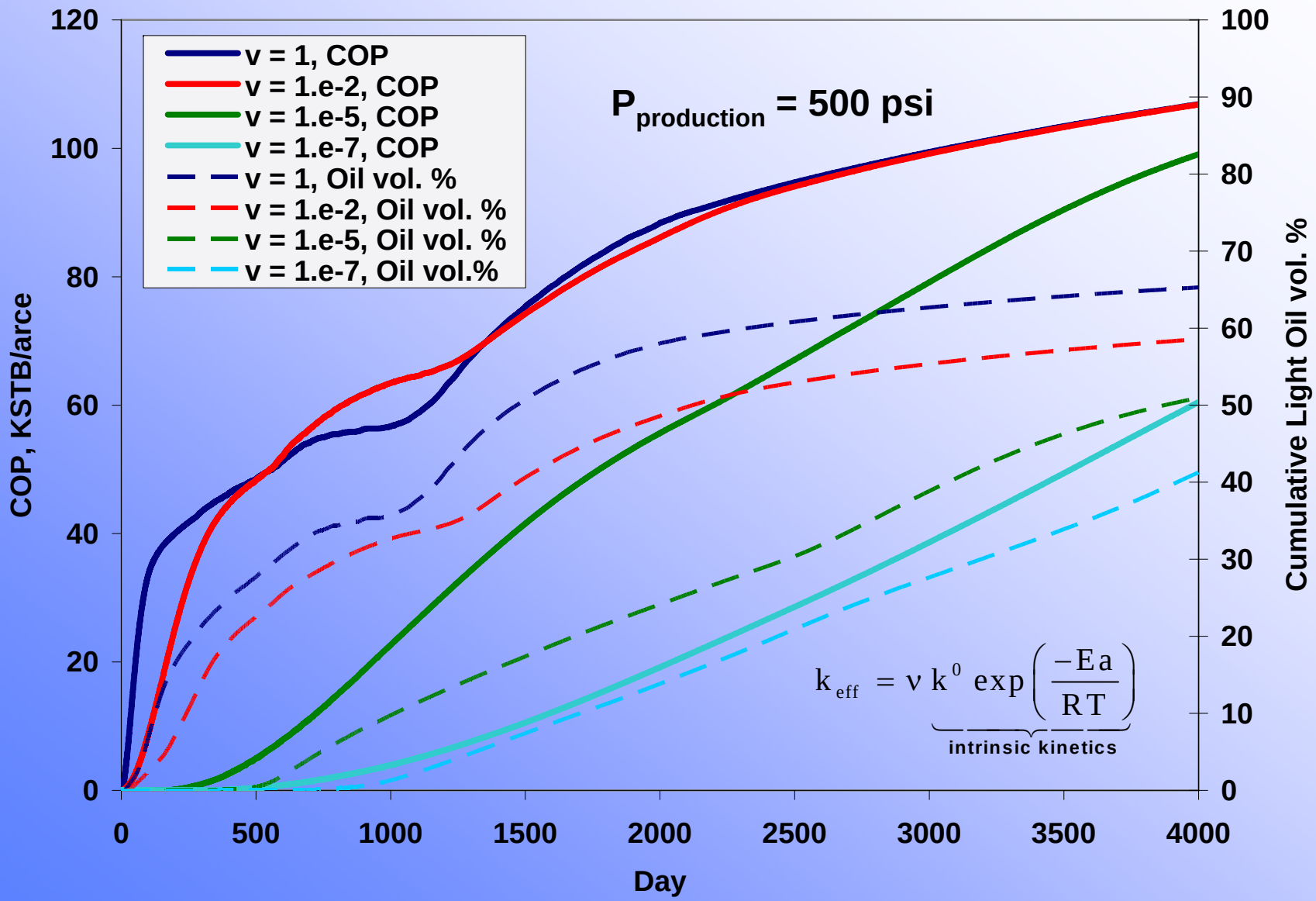
Modeling results

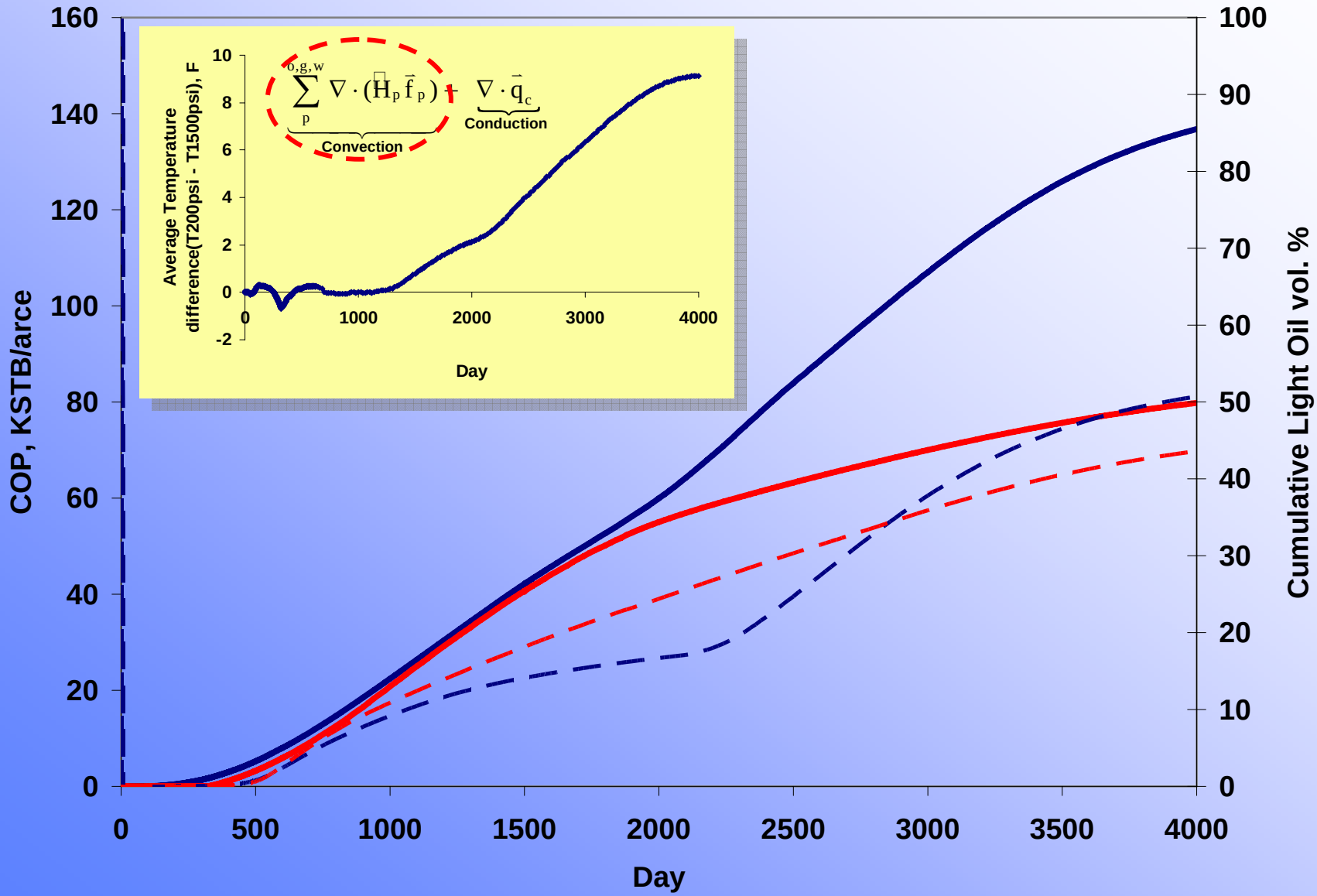
1. Effective reaction coefficient
2. Sensitivity of reservoir pressure
3. Influence of permeability creation
4. Sensitivity of reaction factor ratio k_2/k_1
5. Waterflooding

$P_{initial}$ = 200 psi at the top the reservoir

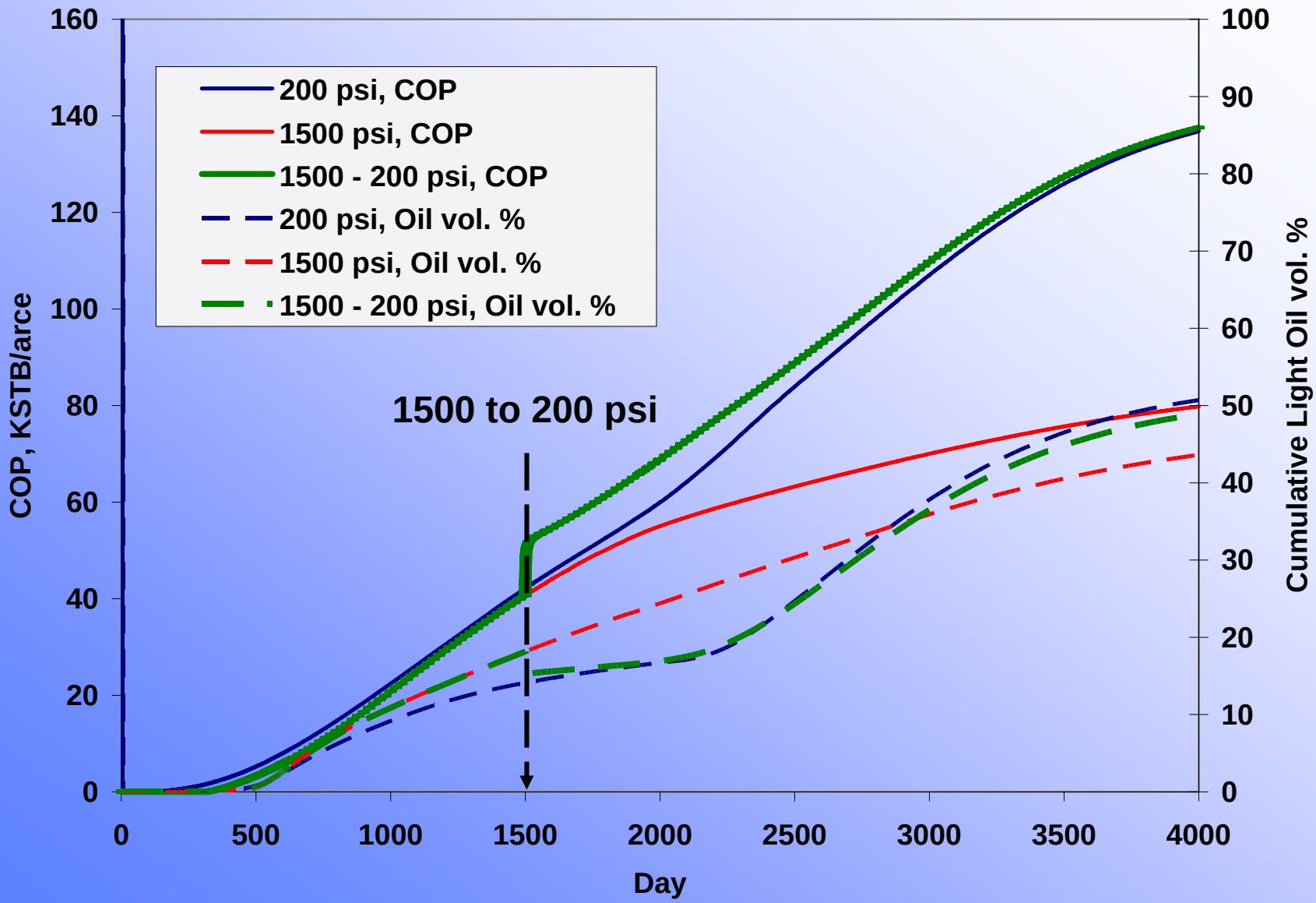
Effective reaction coefficient:



Sensitivity of reservoir pressure:

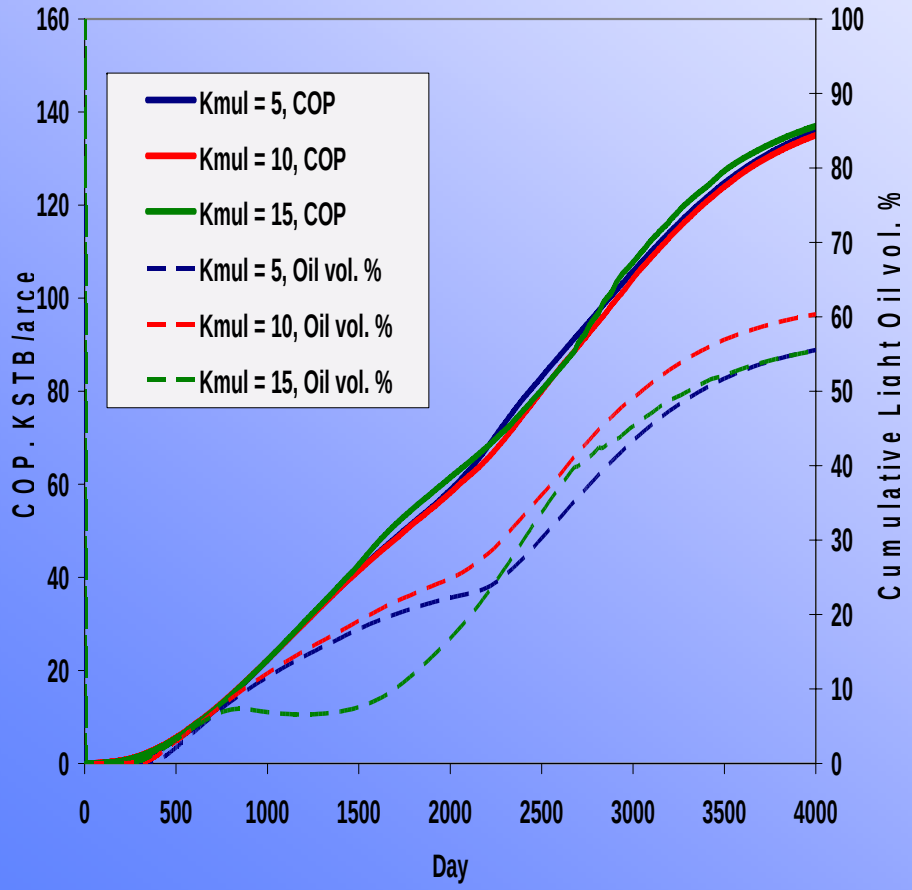


Switch from high pressure to low pressure:

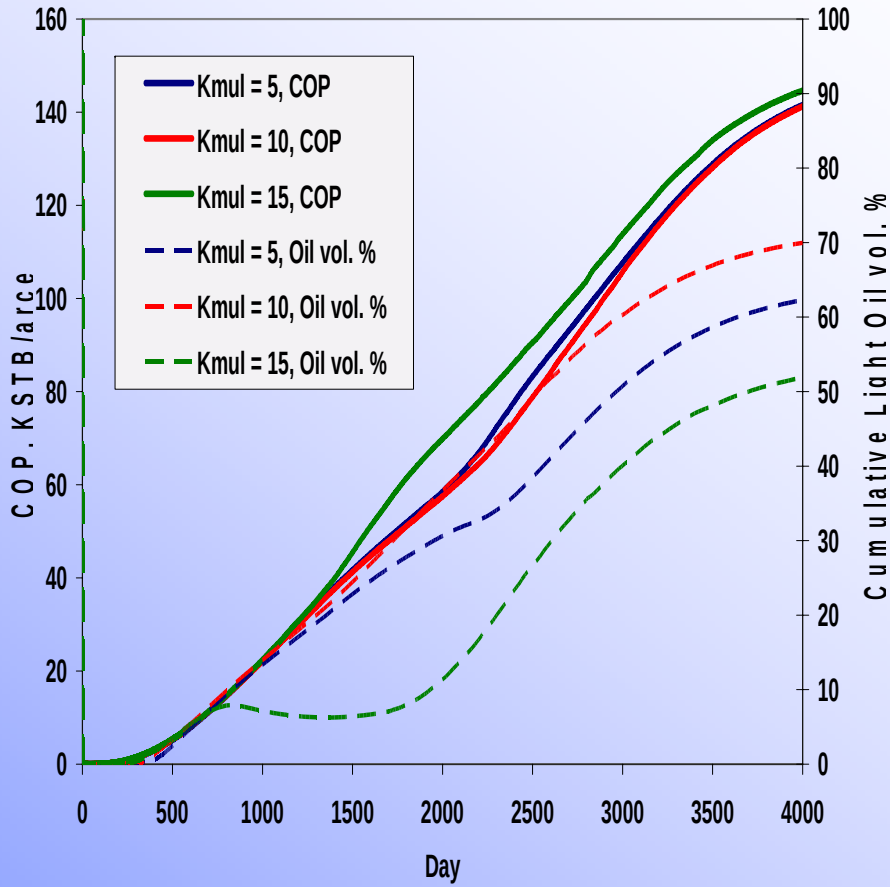


Influence of permeability creation:

With 13% coking

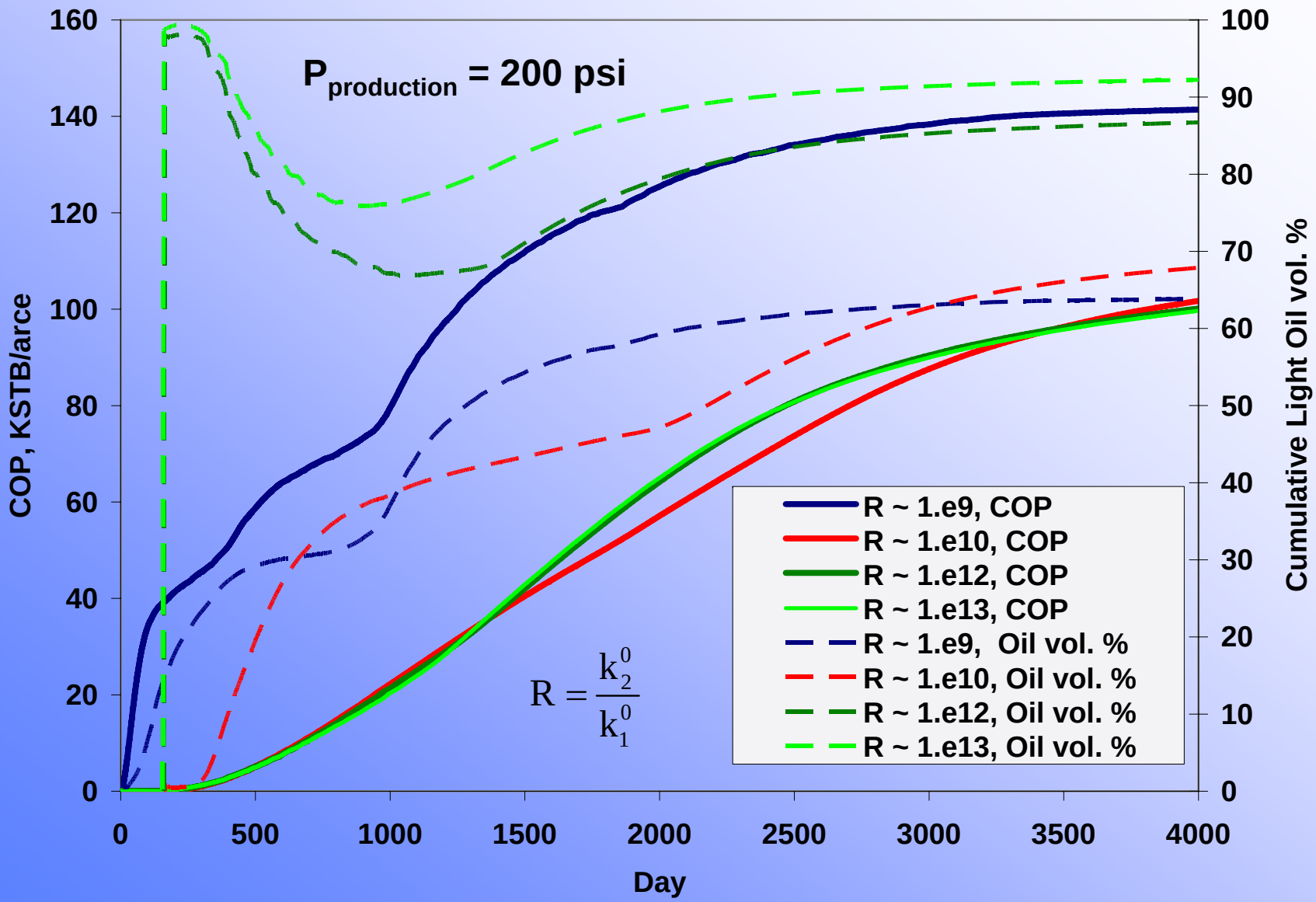


With 5% coking

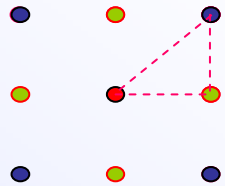


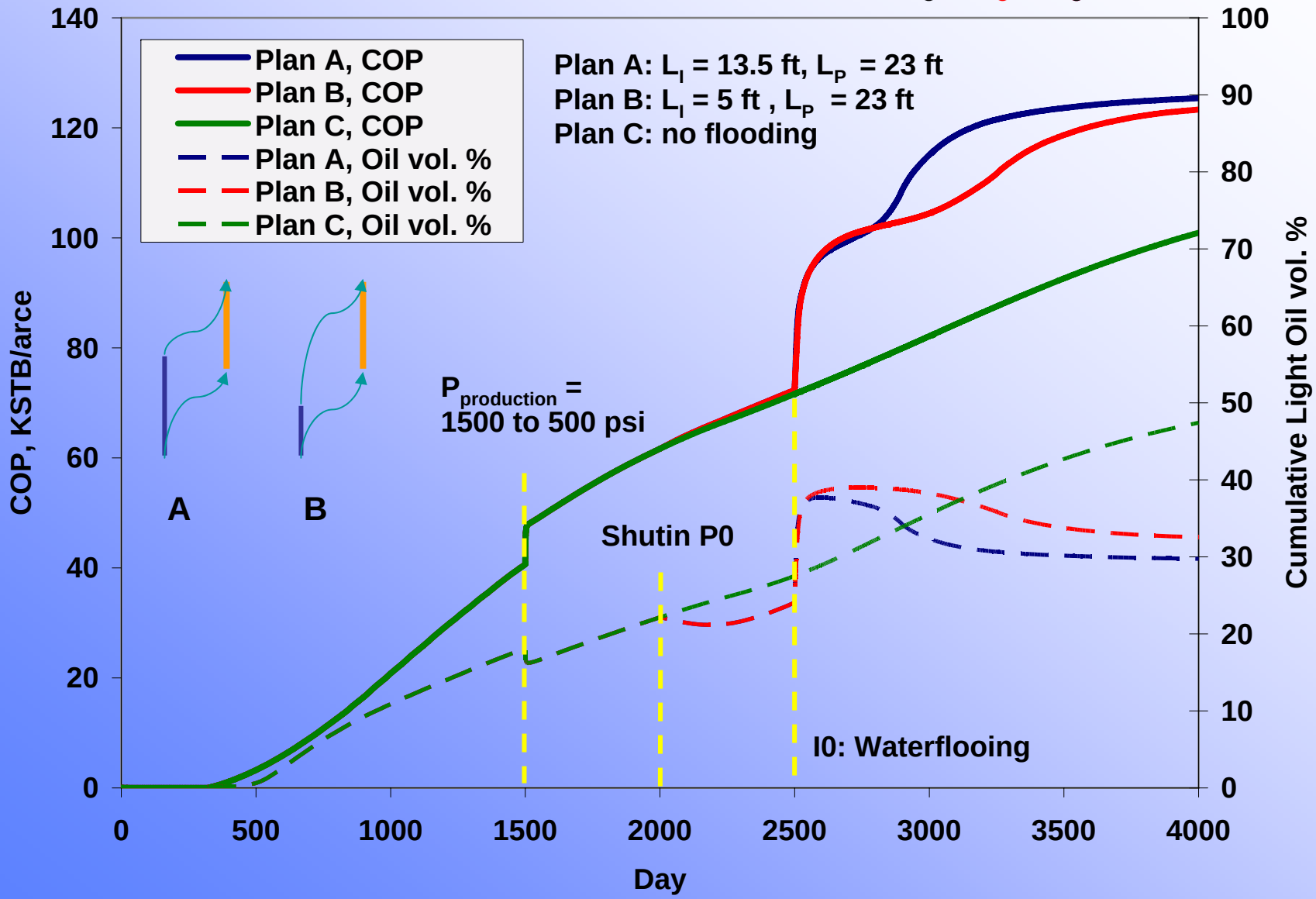
$P_{production}$ = 200 psi

Sensitivity of reaction factor ratio k_2/k_1:



Waterflooding (with ν = 1e-5)





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Summary

1. Reservoir pressure can be dramatically increased by volume expansion which acts as the most important driving force to deplete oil.
2. In low pressure production, the heat transfer is improved by convection flow, resulting in more light oil product.
3. The influence of permeability creation on the production is significant especially when coking rate is low.
4. The conditions selected indicated the 2^{nd} reaction is dominant in determining the product distribution.
5. Total production and light production could be less than predicted by intrinsic kinetics.
6. Waterflooding is a possible alternative to shorten the length of the project; however, HC might remain due to multiphase interaction.

Acknowledgements

- US DOE for financial support for Depositional Heterogeneity and Fluid Flow Modeling of the Oil Shale Interval of the Upper Green River Formation, Eastern Uinta Basin, Utah
- Utah Heavy Oil Center
- Computer Modeling Group for Academic Licenses for CMG Software