Let's Combust - Fossil Fuels

and if there is bit of time left

Fossils

Energy Resources Engineering

Institute for Computational & Mathematical Engineering
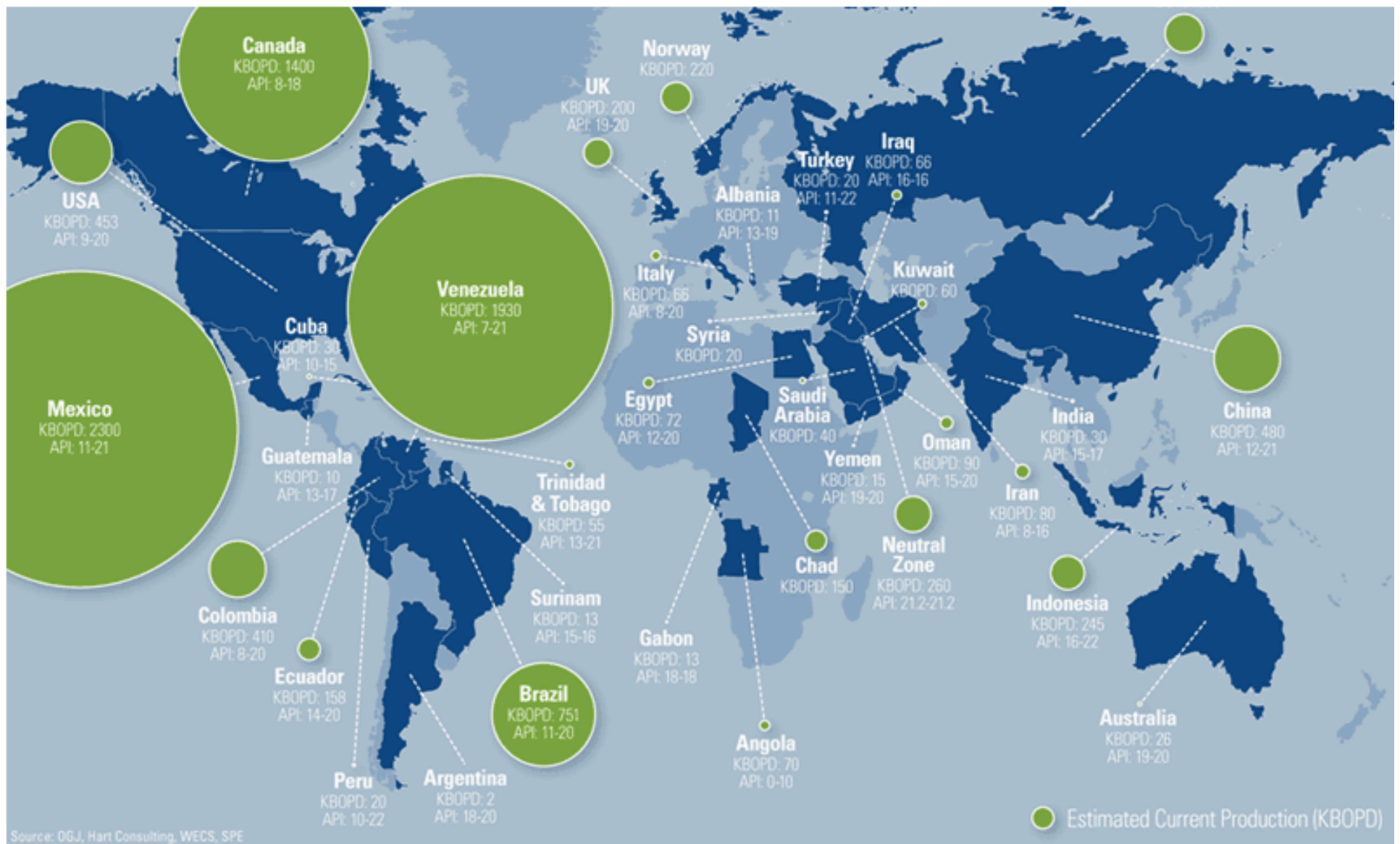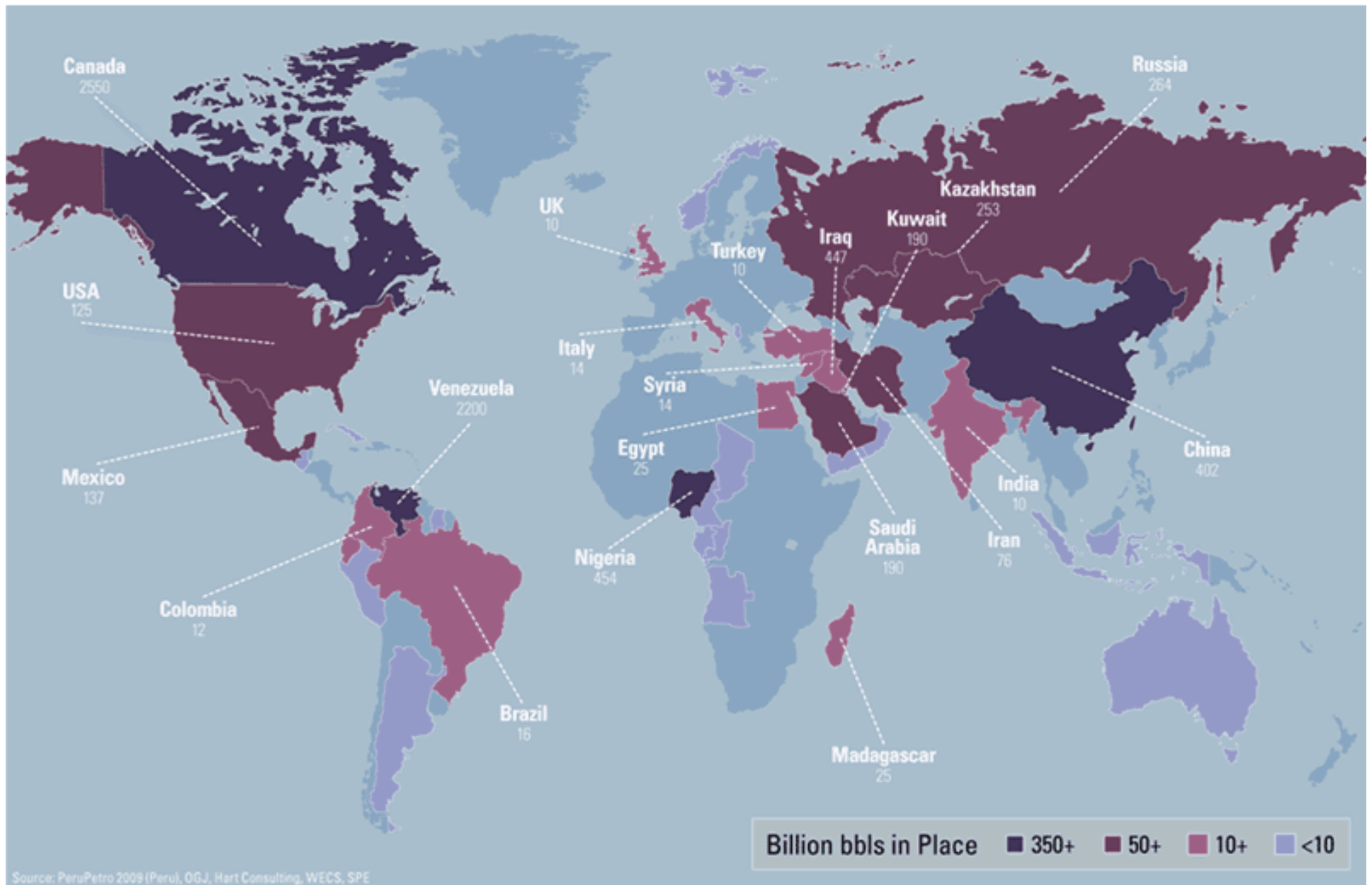
Stanford University

Woudschoten 2015

HEAVY
OIL

Decline of easiest to produce reservoirs pushes industry to

- Invest in Enhanced Oil Recovery (EOR) techniques
- Move into more hostile environments (off-shore, North)
- Explore and produce non-conventional oils, including heavy oils

Worldwide Heavy Oil Production by Country (www.slb.com)

Canada
KBOPD: 1400
API: 8-18

Norway
KBOPD: 220

UK
KBOPD: 200
API: 19-20

Turkey
KBOPD: 20
API: 11-22

Iraq
KBOPD: 66
API: 16-16

Albania
KBOPD: 11
API: 13-19

USA
KBOPD: 453
API: 9-20

Italy
KBOPD: 66
API: 8-20

Kuwait
KBOPD: 60

Venezuela
KBOPD: 1930
API: 7-21

Cuba
KBOPD: 30
API: 10-15

Syria
KBOPD: 20

Mexico
KBOPD: 2300
API: 11-21

Egypt
KBOPD: 72
API: 12-20

Saudi Arabia
KBOPD: 40

India
KBOPD: 30
API: 15-17

China
KBOPD: 480
API: 12-21

Guatemala
KBOPD: 10
API: 13-17

Trinidad & Tobago
KBOPD: 55
API: 13-21

Yemen
KBOPD: 15
API: 19-20

Oman
KBOPD: 90
API: 15-20

Iran
KBOPD: 80
API: 8-16

Colombia
KBOPD: 410
API: 8-20

Surinam
KBOPD: 13
API: 15-16

Chad
KBOPD: 150

Neutral Zone
KBOPD: 260
API: 21.2-21.2

Indonesia
KBOPD: 245
API: 16-22

Ecuador
KBOPD: 158
API: 14-20

Gabon
KBOPD: 13
API: 18-18

Brazil
KBOPD: 751
API: 11-20

Australia
KBOPD: 26
API: 19-20

Peru
KBOPD: 20
API: 10-22

Argentina
KBOPD: 2
API: 18-20

Angola
KBOPD: 70
API: 0-10

● Estimated Current Production (KBOPD)

Source: OGJ, Hart Consulting, WECS, SPE

Canada
2550

USA
125

Mexico
137

Venezuela
2200

Colombia
12

Brazil
16

UK
10

Italy
14

Syria
14

Egypt
25

Nigeria
454

Russia
264

Kazakhstan
253

Kuwait
190

Iraq
447

Turkey
10

Saudi Arabia
190

Iran
76

India
10

China
402

Madagascar
25

Billion bbls in Place ■ 350+ ■ 50+ ■ 10+ ■ <10

Worldwide Heavy Oil Resources by Country (www.slb.com)

Heavy Oils Require Stimulation

All heavy oils

1. are rather difficult to produce

2. are gucky

Thermal stimulation common

- Steam Flooding

- Steam-Assisted Gravity Drainage

- In-Situ Combustion

Give It Some Air and Combust
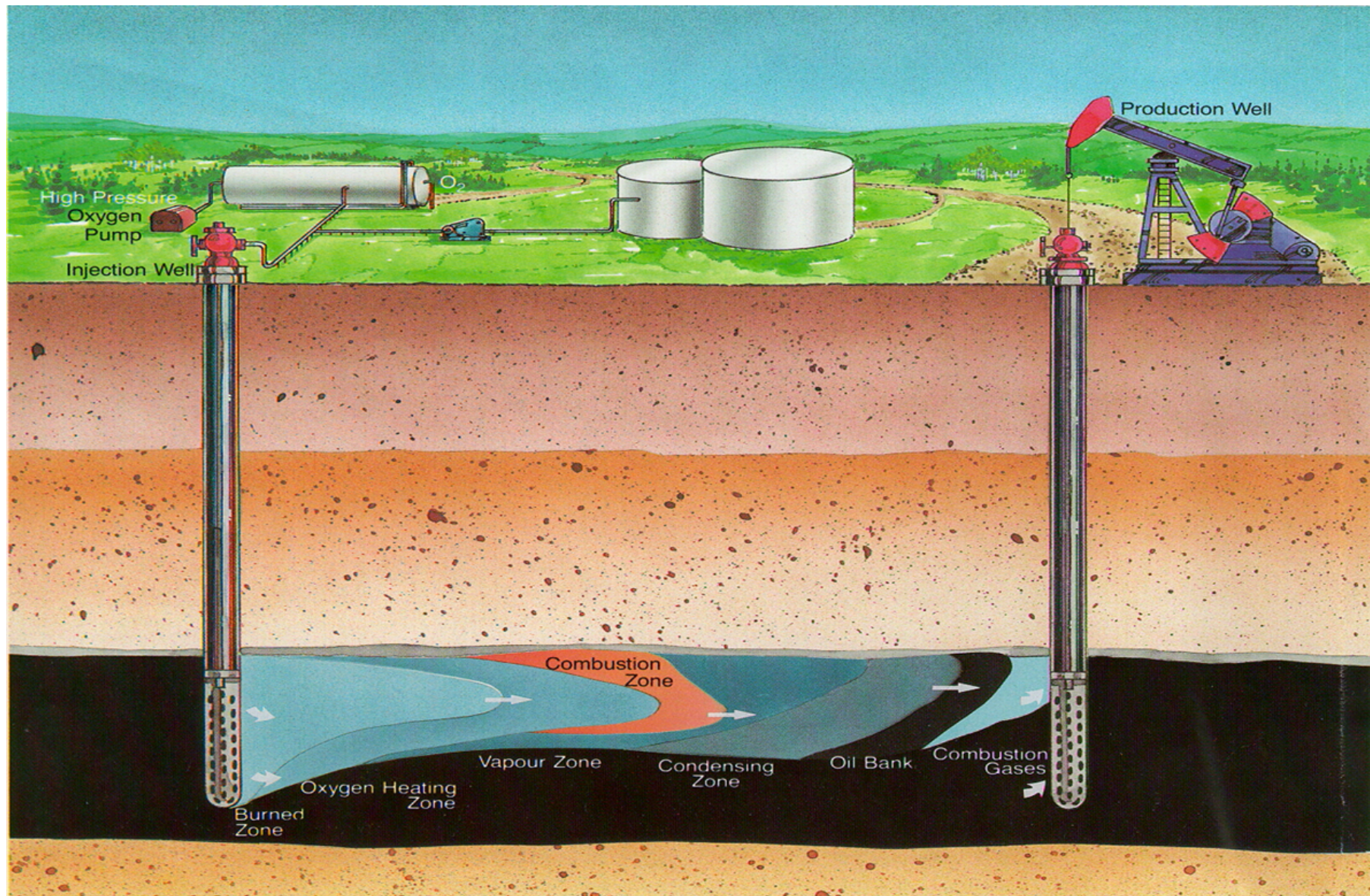
Great Idea, Big Headache

An attractive method for unlocking heavy-oil resources:

- Steam generated in-situ

- Oil upgrading possible

Tempr

Burned zone

Rx. zone

Steam/ hot water zone

Oil bank
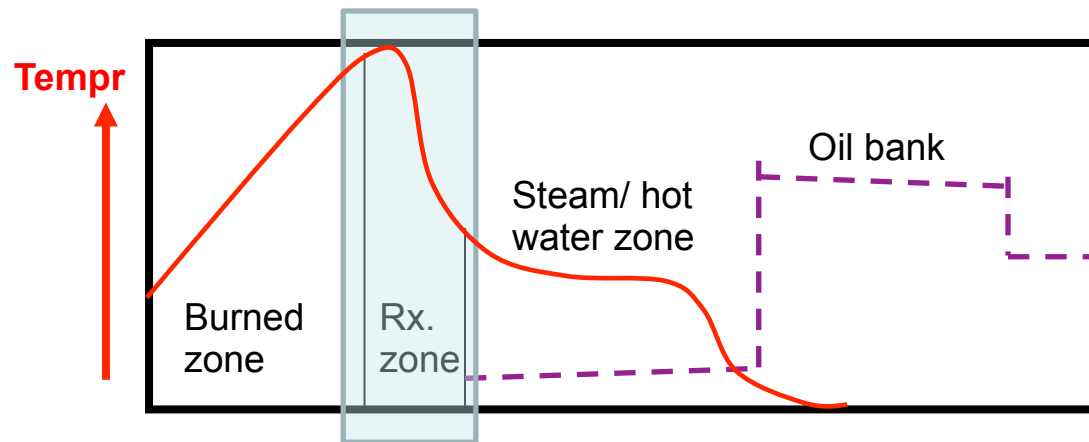
Thin reaction front, several inches

Reaction Front

Steam/Hot Water Front

Oil Bank Front

Burned Zone

Steam/Hot Water Bank

Oil Bank

t
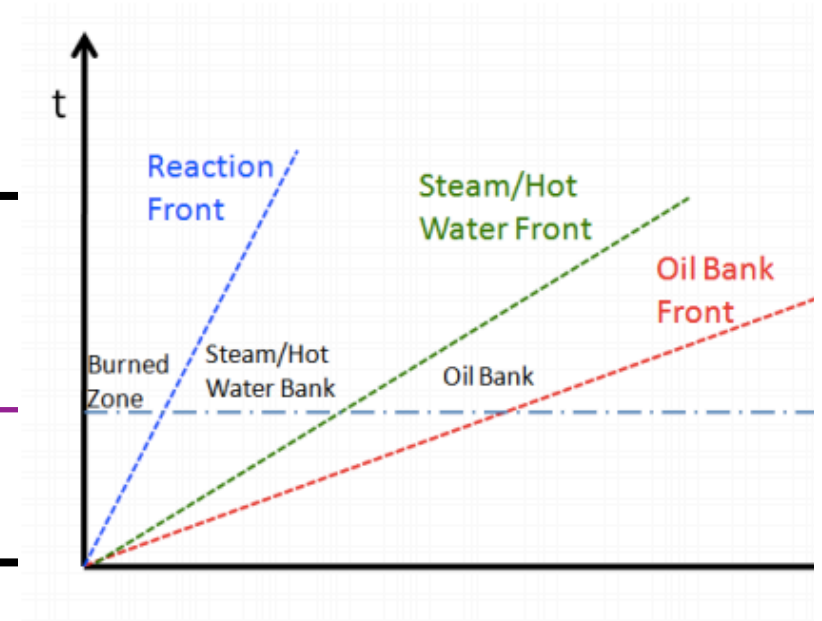
Multiple phases, multi-components, thermal, compressible, strongly nonlinear,

And most definitely and strongly multi-scale

Lab Tools & Virtual Lab Tools

- Kinetic Cells (100-5000 psi)

- Combustion Tube (up to 100 psi)

- X-ray CT scanning
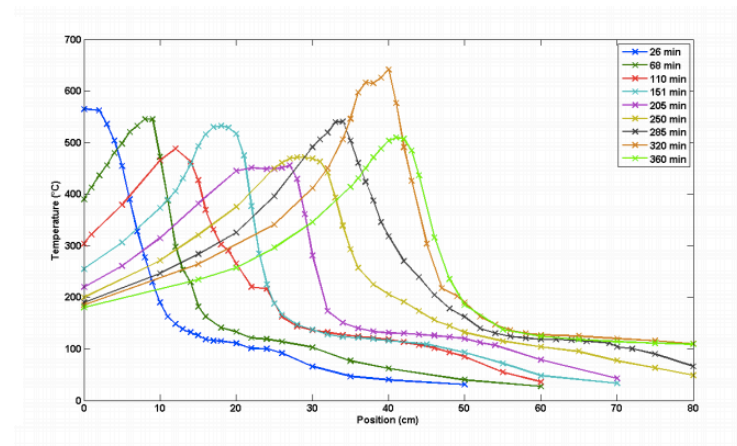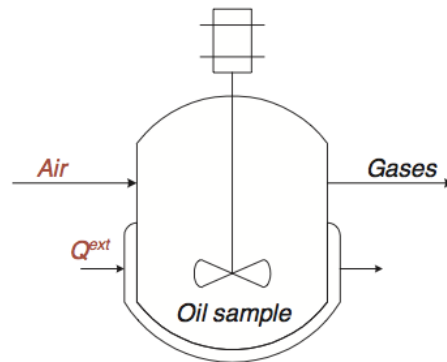
- Virtual Kinetic Cell (homebrew)

- Virtual Combustion Tube (homebrew)

- 2D small scale models (homebrew, commercial)

- 3D industrial scale reservoir model (in collaboration with 3DSL)

CAN WE CLUSTER REACTIONS?

Quite often we see three regimes

Low Temperature Oxidation Reactions

Forms heterogeneous gas/liquid of partially oxygenated compounds and

few carbon oxides. Increases oil viscosity and fuel content

Cracking/pyrolisis

Fuel "coke" formation (solid hydrocarbon, H/C 0.6-2), CO_2, CO

High Temperature Oxidation

Surface (and gas?) reactions of solid fuel. Highly exathermic

Needs to be maintained by sufficient air flux

What's Your Favorite Scheme?

Crookston Model (Crookston 1979) – no LTO/HTO distinction

Heavy Oil + O_2 $\rightarrow$ Inert Gas + Water   (Heavy Oil Oxidation)

Light Oil + O_2 $\rightarrow$ Inert Gas + Water   (Light Oil Oxidation)

Heavy Oil $\rightarrow$ Light Oil + Coke   (Heavy Oil Cracking)

Coke + O_2 $\rightarrow$ Inert Gas + Water   (Coke Oxidation)

Three Reaction Model (Dechelette 2006) – no light oil/heavy oil distinction

Oil + O_2 $\rightarrow$ Coke1   (Heavy Oil Cracking)

Coke1 + O_2 $\rightarrow$ CO + CO_2 + Water + Coke2   (Low Temperature Oxidation)

Coke2 + O_2 $\rightarrow$ CO + CO_2 + Water   (High Temperature Oxidation)

In each project, model is selected/calibrated based on lab data

Primary reactions, phase behavior, flow behavior (viscosity reduction), interaction with rock

Modeling at the Lab Scale

Transport & energy equations (accumulation = flow + well + reaction)

$$\frac{\partial C_i}{\partial t} + \nabla \cdot \mathbf{q_i^m} = Q_i^{m,well} + Q_i^{m,reac}$$
(Mass transport for i-th component)

$$\frac{\partial U_t}{\partial t} + \nabla \cdot \left(\mathbf{q^{h,adv}} + \mathbf{q^{h,cond}} \right) = Q^{h,well} + Q^{h,reac}$$
(Energy transport)

Combined with a volume balance equation (pressure equation)

and thermodynamic equilibrium equations

Components typically include heavy oil, light oil, O_2, CO_2, CO, H_2O

At lab scale chemical reactions modeled with Arrhenius

$$\frac{dC_f}{dt} = K\, p_{O_2}^a\, C_f^b, \quad K = A e^{-E_a / RT}$$

C_f = fuel concentration, p_{O_2} = partial pressure O_2, T = temperature

A = pre-exponential factor, E_a = activation energy

Hard to Resolve Front – Even in 1D

Temperature Profile (Crookston)

Combustion Tube Experiment

0.8 m long
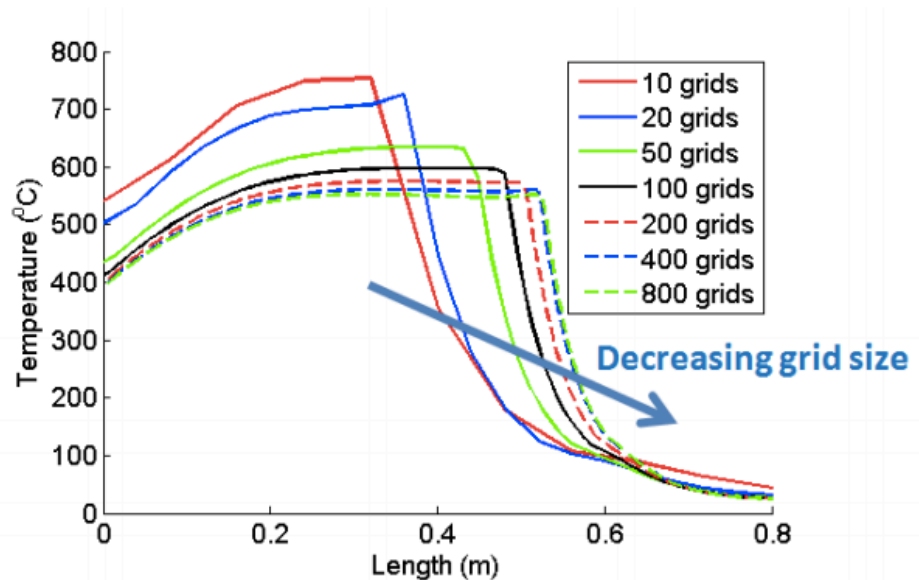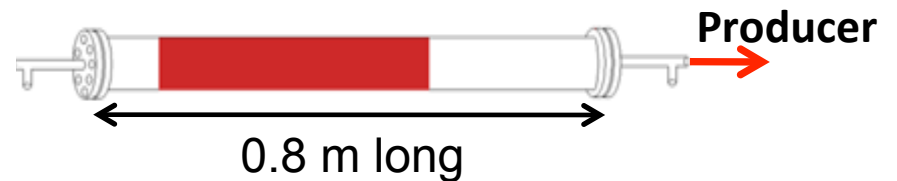
Resolving thin reaction front requires grid step sizes < 1cm

or *constant recalibration of reaction parameters*

Semi-affordable grid sizes in commercial reservoir simulation? ~ 10m

CHALLENGE 1: UPSCALE KINETICS

Da number   at laboratory scale ~$10^{3\text{-}4}$

at reservoir scale ~$10^{7\text{~}8}$

Typical approach is to use the lab reaction models at the reservoir scale

…. and twiggle the pre-exponential factors and reaction rates

Because of scale mismatch this leads to strong grid sensitivity

N = 600

N = 10

15.0   345.7   672.5   1001.2   1330.0

Temperature [°C]
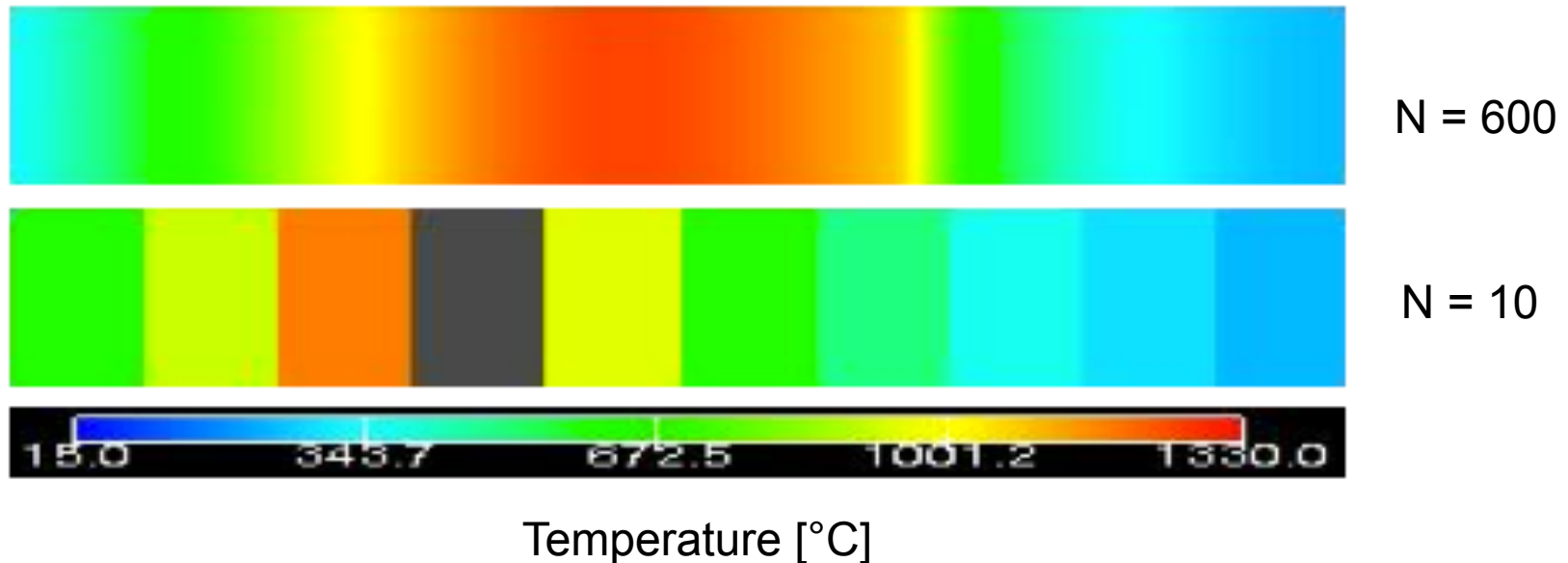
Challenge 2: Upscale permeability

- **ISC is essentially a gas drive**:

  Highly mobile gases (air, steam and inert gases) displace *hardly mobile oil*

- **Combustion/coking highly dependent on oxygen/steam transport**

| Permeability | Gas saturation | Oil saturation |

Quenches / *Burns*
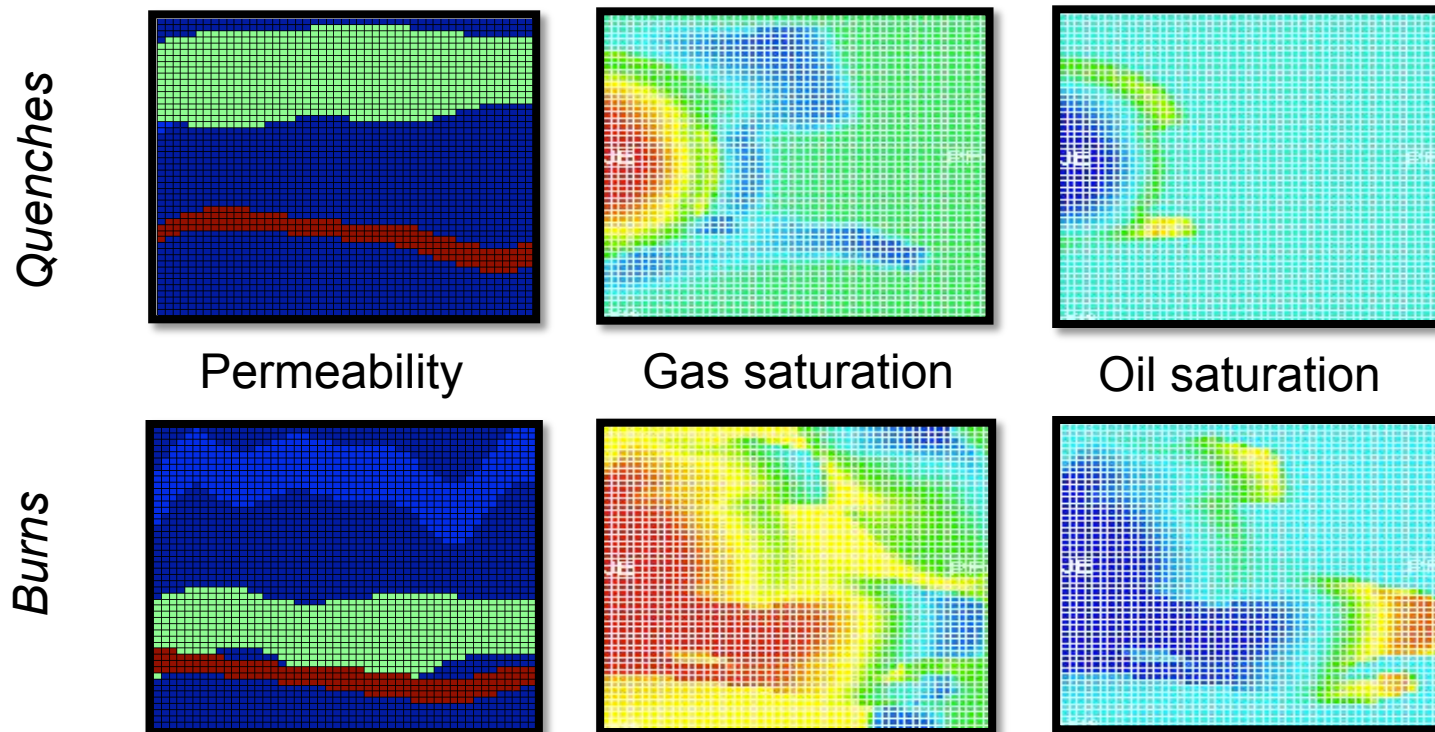
Challenge 3: Subgrid heterogeneity

Challenge 4, 5, 6, 7, ...

Sensitivity to initial oil, initial water, relative permeability,

Viscosity-temperature relations, phase behavior, …………
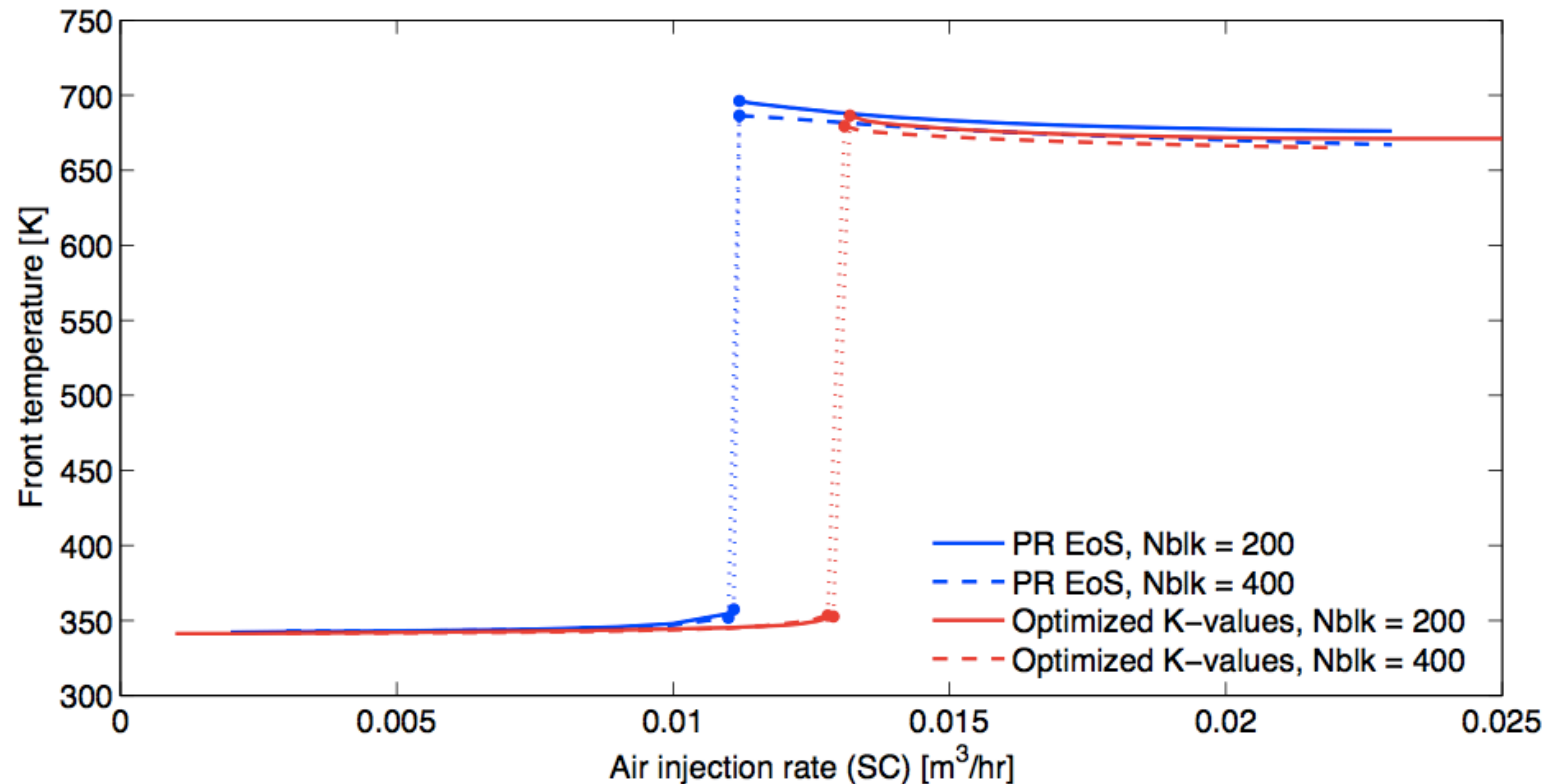
WHAT WERE WE THINKING (6-8 YEARS AGO)?

"We will tackle ISC in 4D. Easy"

- **Adaptive Mesh Refinement**
  - to resolve critical fronts (combustion, steam, oil bank)
  - to capture important perm variations

  Required flexible AMR method and appropriate permeability/
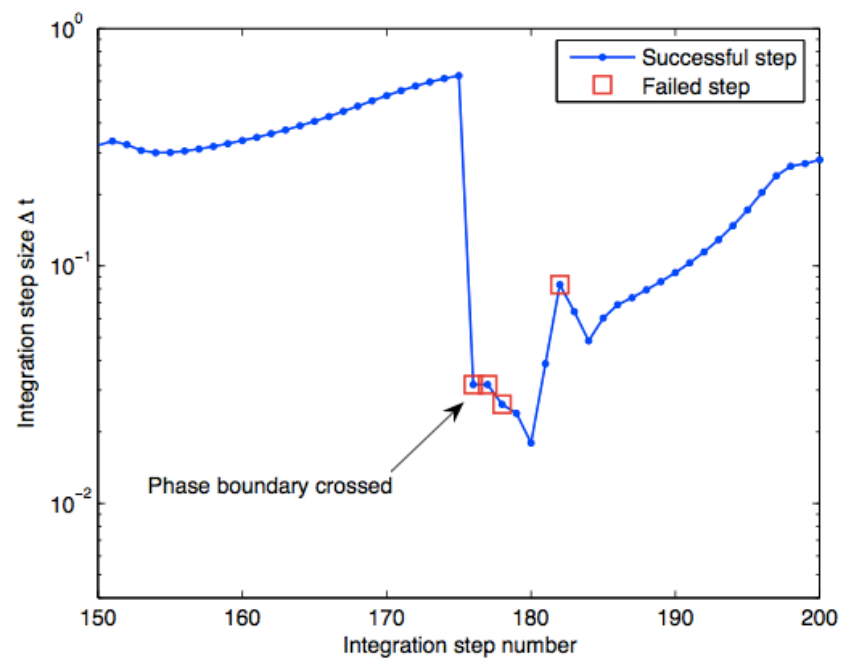 transmissibility upscaling techniques

- **Operator splitting**

  to separate fast kinetics from transport and reduce stiffness

- **Specialized kinetics integrators with phase change detection**

FINISH

Time level t_{n+1}

Pressure Eq.

Heat Eq.

Comp. conservation Eqs.

$P_{n+1}, T_{n+1}, \mathbf{C}^{(2)}$

Comp. conservation Eqs.

START

Time level t_n

$P_n, T_n, \mathbf{C}_n$

$P_{n+1}, T_n, \mathbf{C}_n$

$P_{n+1}, T_{n+1}, \mathbf{C}_n$

$P_{n+1}, T_{n+1}, \mathbf{C}^{(1)}$

Pressure

Temperature

Composition *(reaction)*

Composition *(transport)*
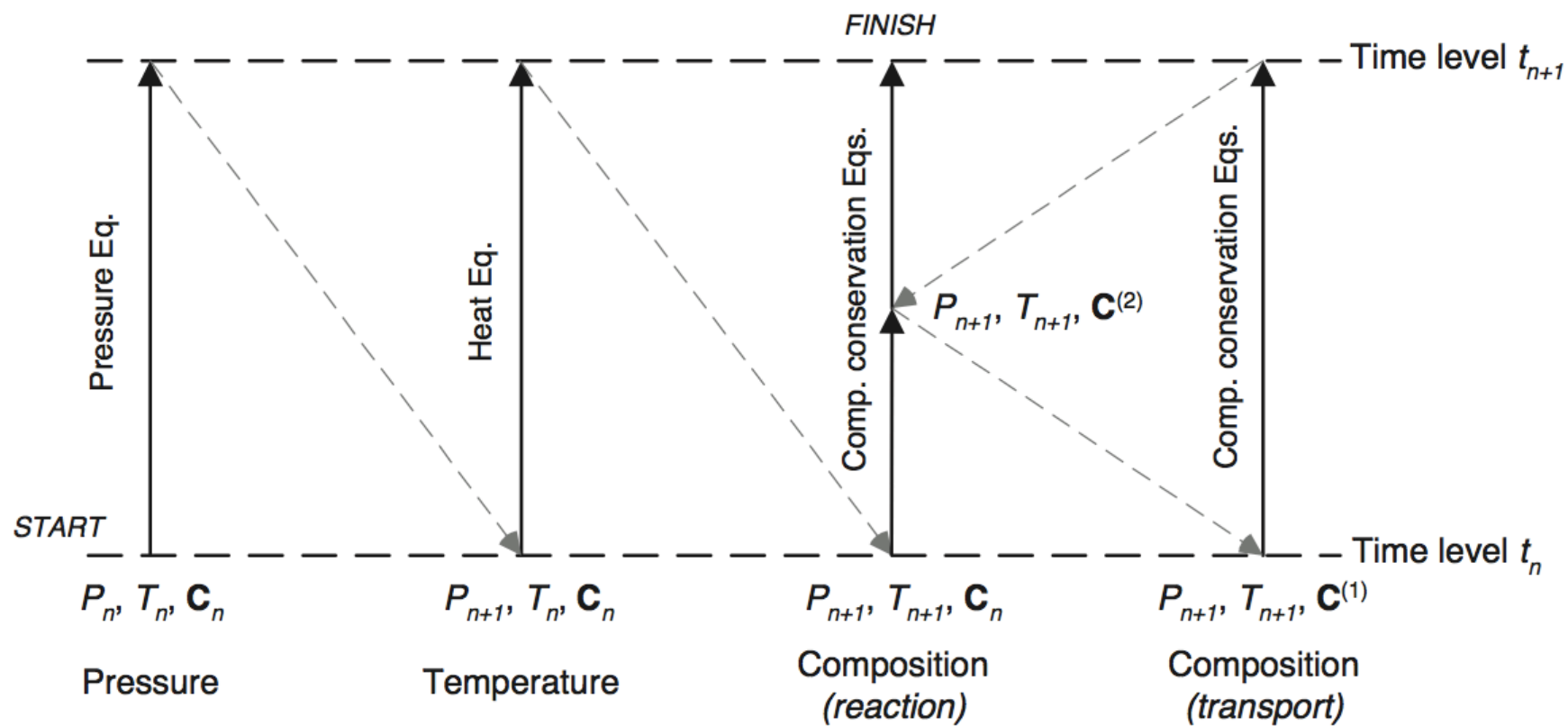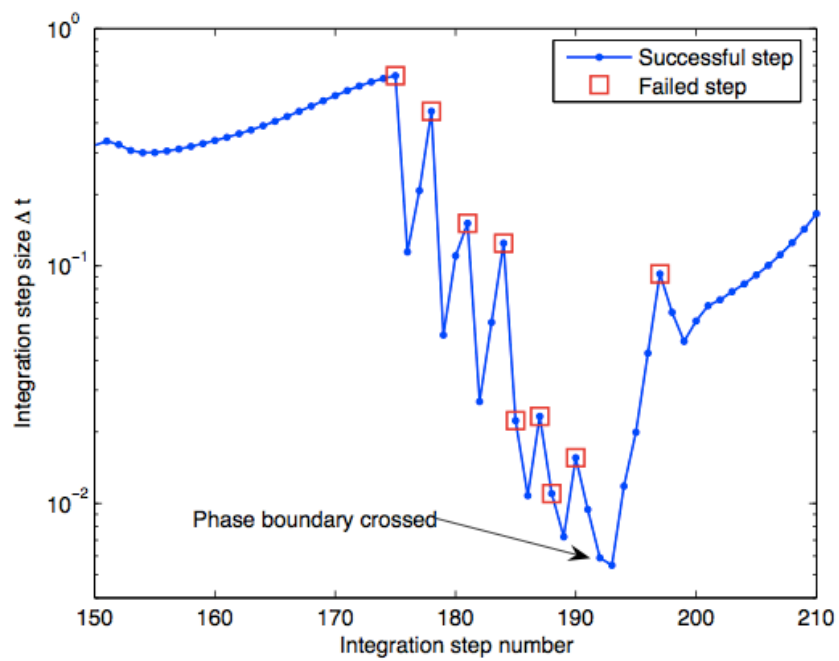
(a) Without phase change detection.　　(b) With phase change detection.

Musings about AMR for ISC

Is AMR with traditional models for kinetics an option at the reservoir scale?

- extreme coarsening/refinement to zoom in on combustion front

- high sensitivity to permeability variations leads to ragged front

- workload very skewed (fine cells much more expensive than coarse)

- time-stepping determined by fast kinetics, leading to severe stiffness

After musings and much work, we decided to approach kinetics differently....

Upscaling of Kinetics

Remove need to numerically model fast reactions

- Workload reduction for each time step

- Time step restrictions alleviated

Make kinetics treatment grid size insensitive

- Current "upscaling" done by twiggling until HTO sustained

- Calibration done on some grid size in 1D tests

- When grid step size changed, accuracy rapidly lost

Let's Think a Bit

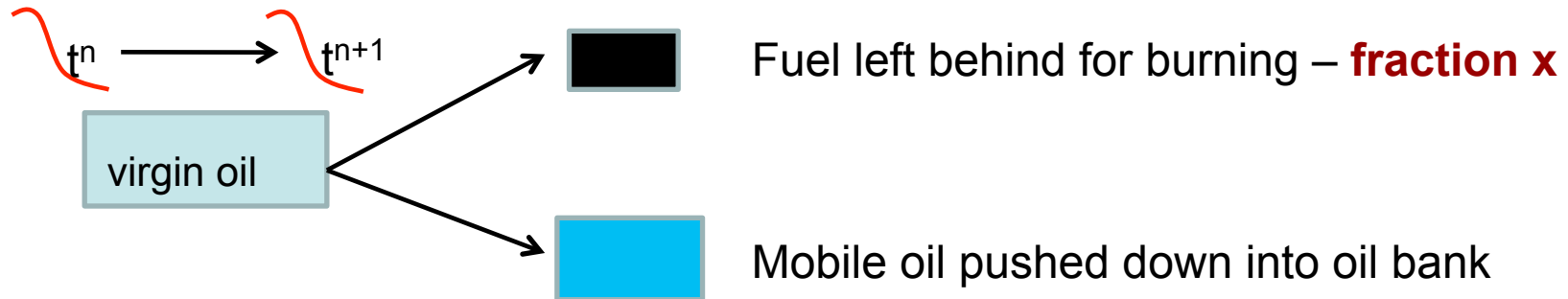**What are the essential kinetic impacts on**

- kinetics related sources/sinks in PDEs
- phase behavior
- composition
- viscosity
- rock structure

STUFF IS DEPOSITED, STUFF BURNS, STUFF IS HEATED, STUFF MOVES

t^n $\longrightarrow$ t^{n+1}

virgin oil

Fuel left behind for burning

Mobile oil pushed down into oil bank
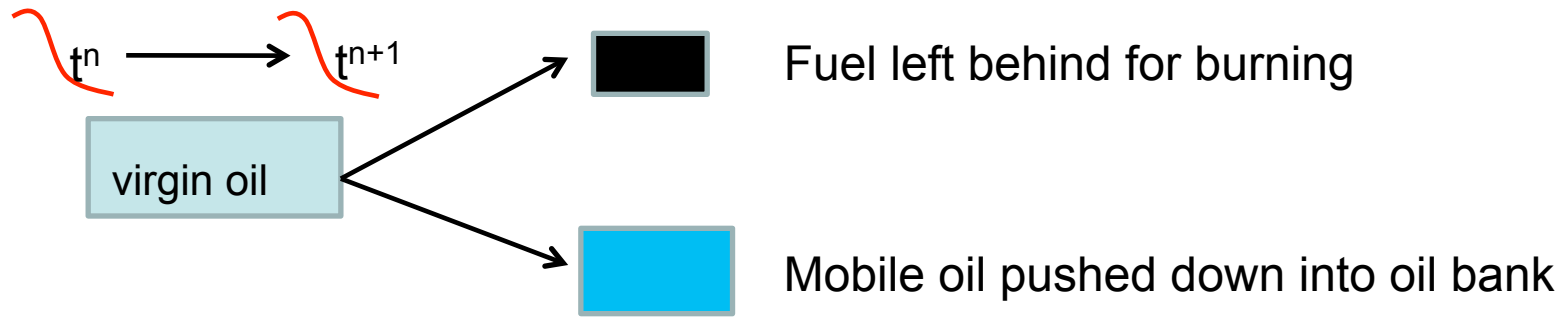
- 5-10% of the oil burns after fuel deposition
- Burn complete if air flux sufficient
- Remaining mobile oil flows downstream

Workflow based Upscaling for Grid Independence (WUGI) method

t^n ⟶ t^{n+1}

virgin oil

■ Fuel left behind for burning – **fraction x**

■ Mobile oil pushed down into oil bank

- Find the typical fraction of oil deposited as fuel (the "x")

- Assume sustained High Temperature Oxidation

- Replace kinetics sources in governing PDEs with appropriate heat release and changes in compositions

- Delivery of oxygen critical: otherwise keep PDEs intact

- Adapt (relative) permeability, porosity, viscosity as appropriate

X and Subgrid Heterogeneity

Case Number and Description	S_{ofuel}
1. White Noise	8.1%
2. Low Permeability Middle Square	9.0%
3. Low Permeability Squares	9.7%
4a. Layered System ($K_1/K_2 = 2$)	8.1%
4b. Layered System ($K_1/K_2 = 10$)	8.7%
5. Layer 1 of SPE 10 [23]	8.6%
6. Layer 51 of SPE 10 [23]	13%

Numerical experimentation shows sensitivities but not as strong as feared

In Quest for X, Lab and Numerics Support Each Other

kinetic cell experiments and numerical optimization

Combustion tube experiments and fine scale numerical validation

i-1 i i+1
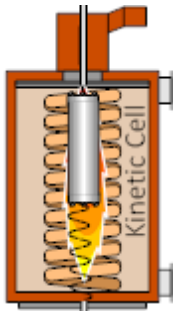
reaction models, reaction parameters
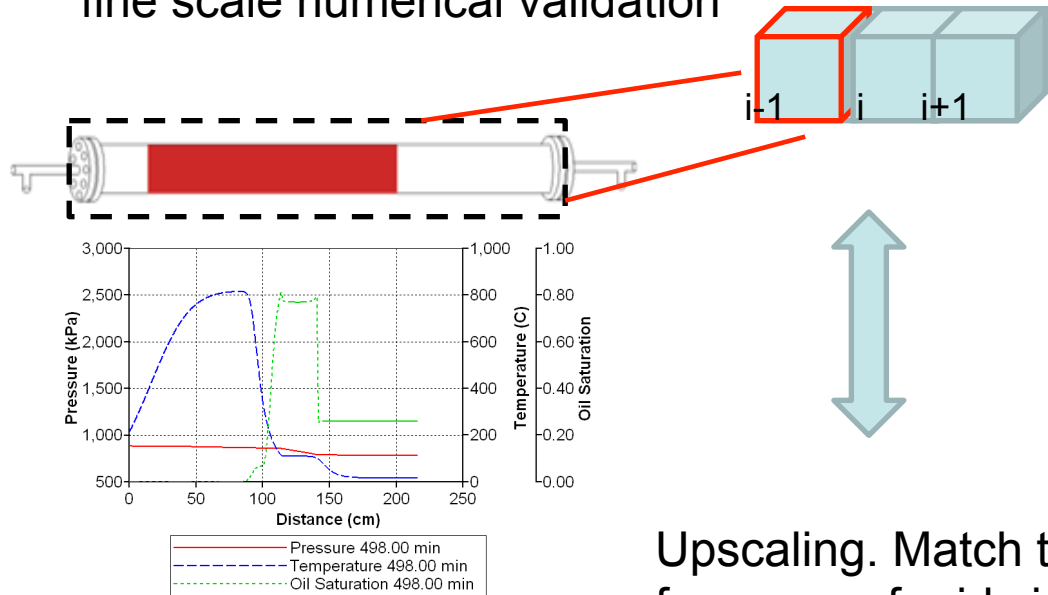
Upscaling. Match tube for range of grid sizes

Field-scale Simulation

virgin oil
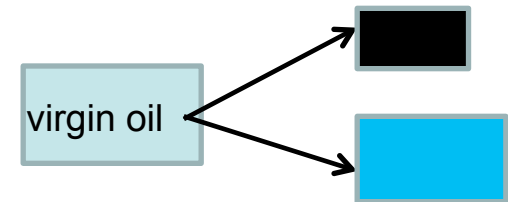
Find equivalent effects, adjust parameters

```
Kinetics cell experiment at different heating rates  →  Isoconversional fingerprint analysis  ✔ →  Combustion tube experiment to validate the prediction

Isoconversional fingerprint analysis  ✘ ↓  Not potentially a good candidate for ISC

Combustion tube experiment to validate the prediction  ↓  Compositional description and PVT properties of the crude-oil  ↓  Compositional simulation of kinetics cell experiment  ↓  Optimization method , matching kinetics experiment results  ↓  High-resolution reaction model

High-resolution reaction model  ←  Uncertainty evaluation  ←  Simulation of combustion tube test  ↓  Sensitivity analysis  →  Up-scaling the high-resolution model to field scale dimension

Bazargan et al. (2011)
```

IN ONE DIMENSION ALL LOOKS FINE

N=600 Kinetic | N=10 Kinetic | N=10 Upscaled | N=60 Upscaled

2.1m

Temperature [°C]

15 00   1000.00

N=600 Kinetic | N=10 Kinetic | N=10 Upscaled | N=60 Upscaled

Over coking

2.1m

O$_2$ Fraction

0.00000   0 05250   0.10500   0.15750   0 21000
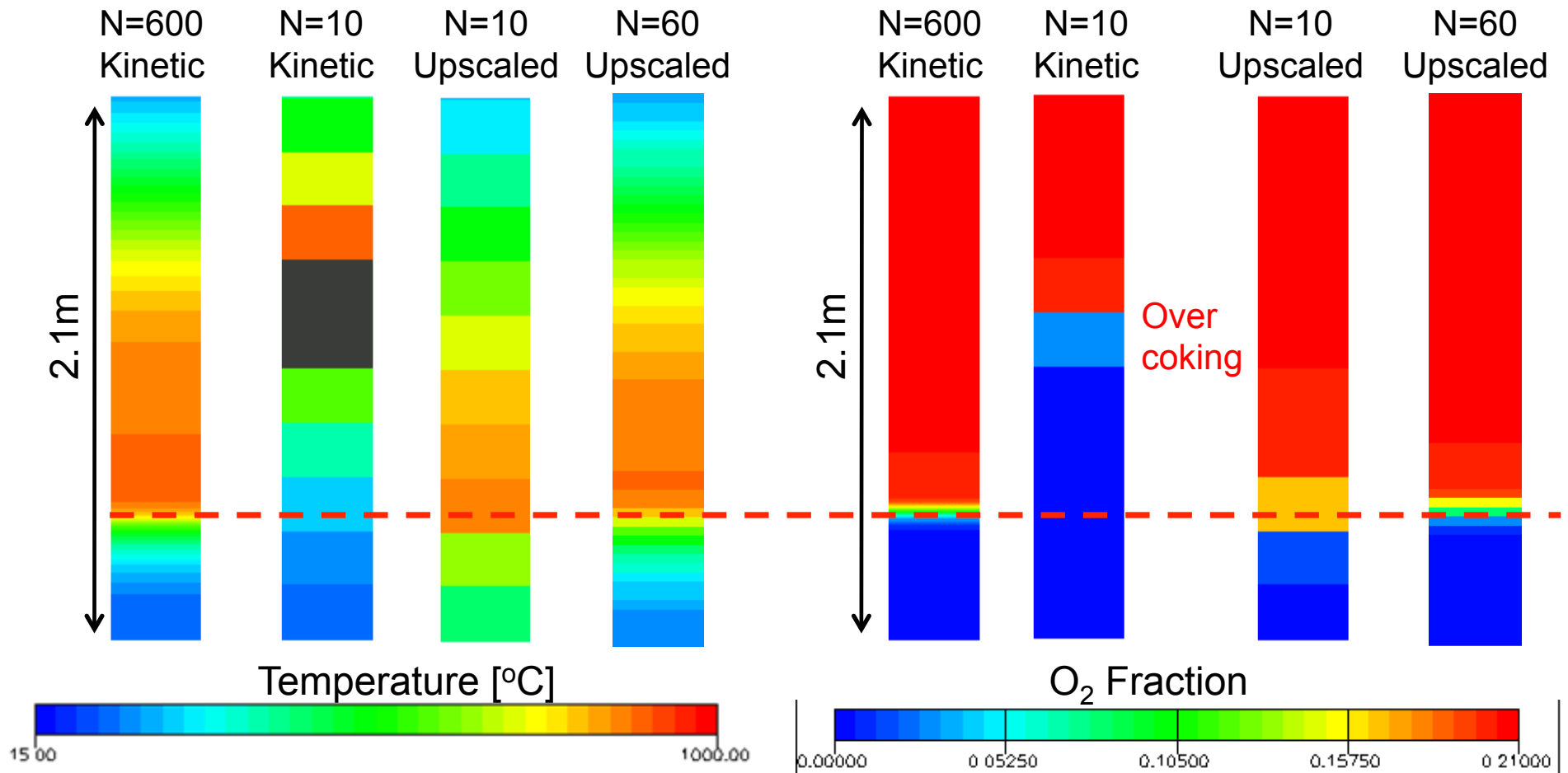
Upscaled ISC model predicts same front location as fine-scale kinetic simulation

TWO DIMENSIONS ALSO OK

O₂ Fraction
(200X200 Kinetic)

O₂ Fraction
(20X20 Kinetic)

O₂ Fraction
(20X20 Upscaled)

O₂ Fraction

Grid size 0.36cm

Grid size 3.6cm

0.72m

0.72m
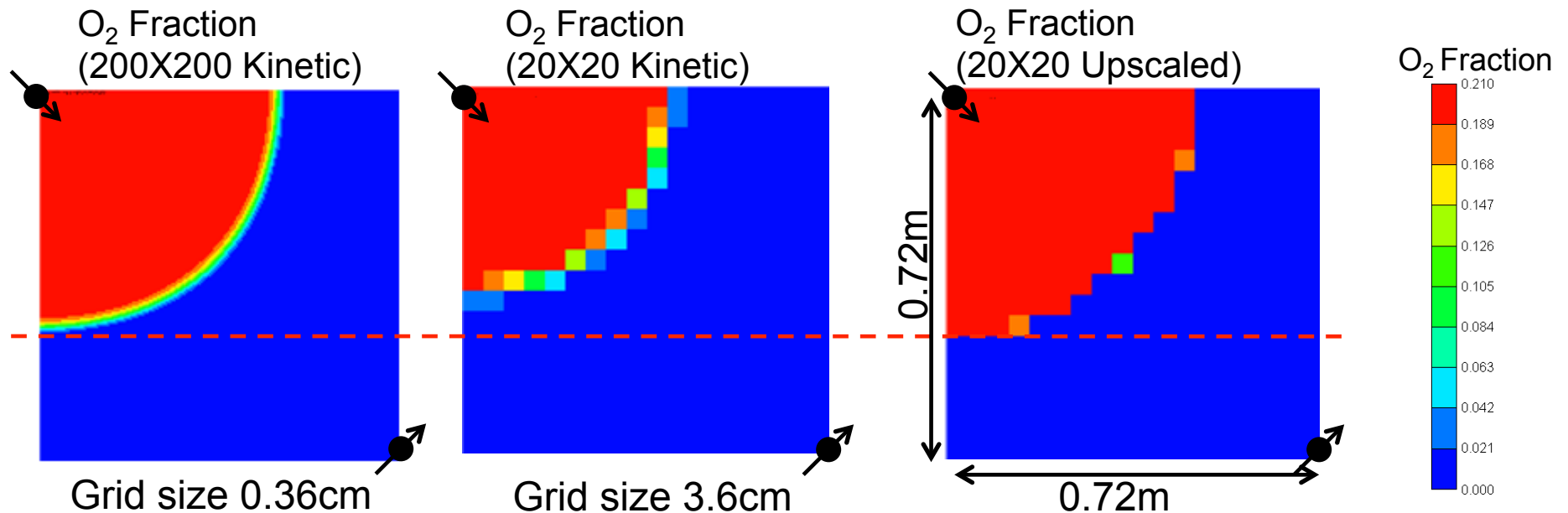
Homogeneous permeability, porosity (0.36) and initial oil saturation (0.4)

Upscaled model predicts similar front location as fine-scale kinetic model

Coarsening It Up a Bit More

O$_2$ Fraction
(200X200 Kinetic)

O$_2$ Fraction
(5X5 Kinetic)

O$_2$ Fraction
(5X5 Upscaled)

O$_2$ Fraction

0.210	
0.189	
0.168	
0.147	
0.126	
0.105	
0.084	
0.063	
0.042	
0.021	
0.000	

0.72m

0.72m

Grid size 0.36cm

Grid size 14.4cm
(Initial Ignition Problem)
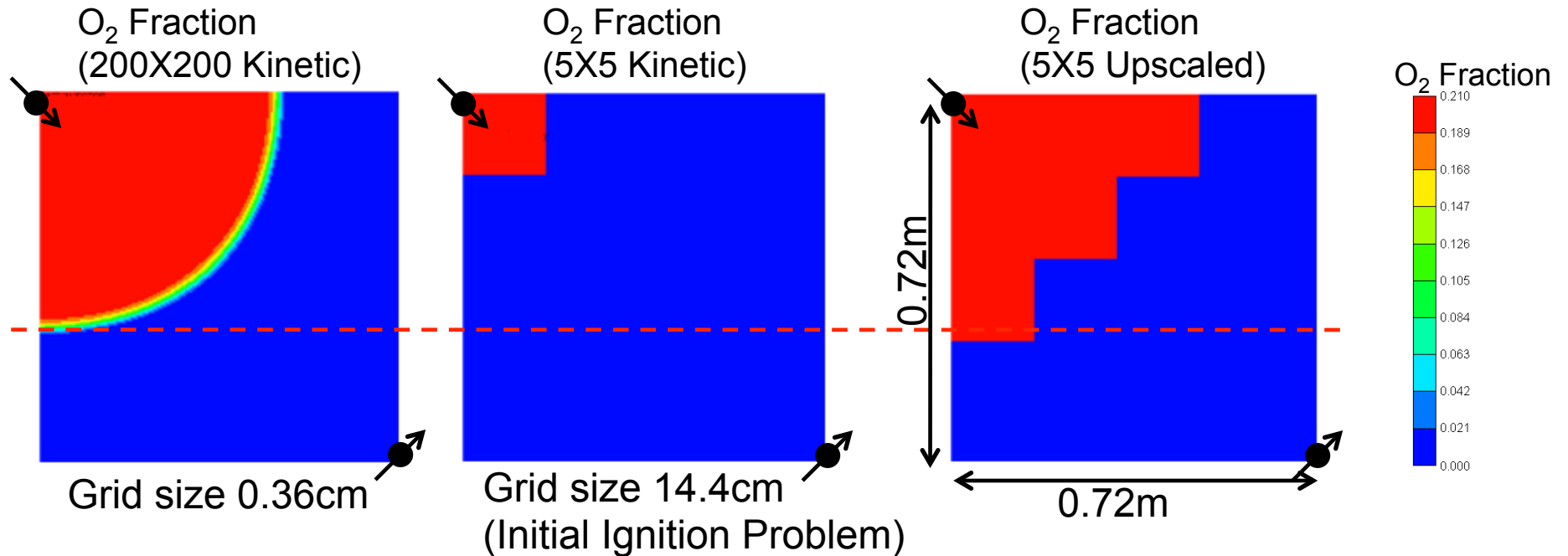
Front location still predicted correctly by the upscaled model

-> shows no or low grid sensitivity

Kinetic model shows excessive fuel generation and reduced front speed

50X50   100X100   200X200
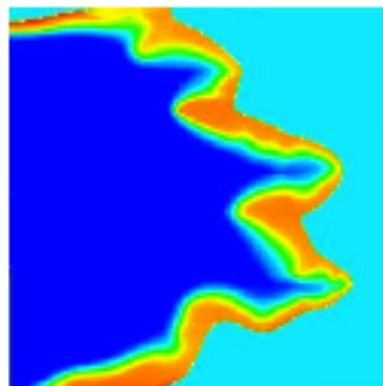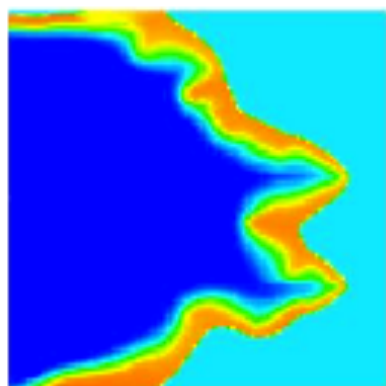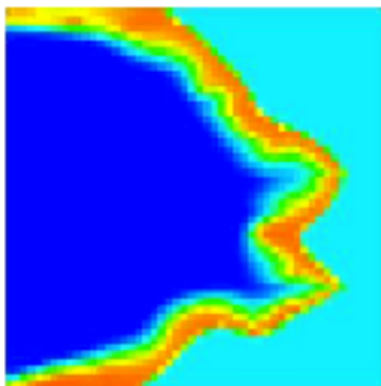
Oil saturation (upscaled model simulation)
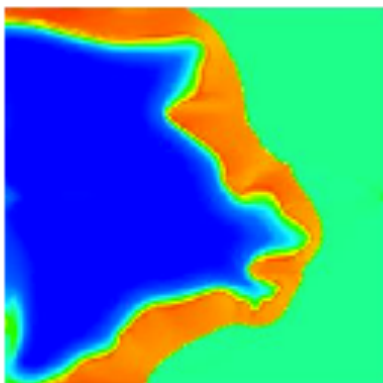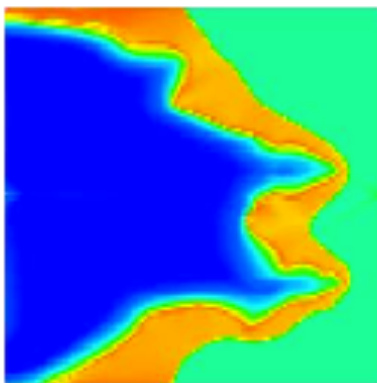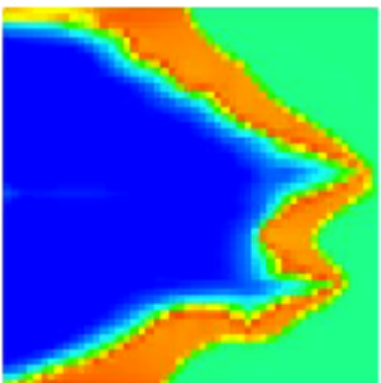
Oil saturation (kinetic model simulation)
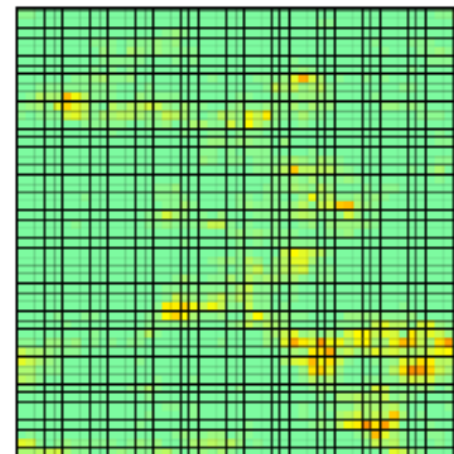
Permeability field
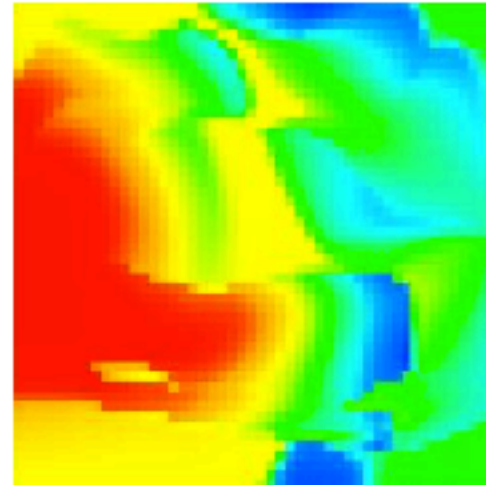
Quenching from Choking
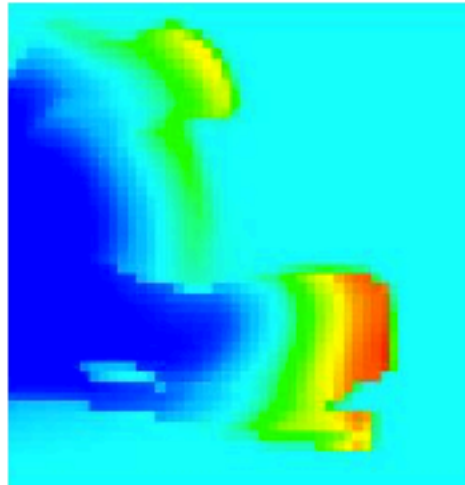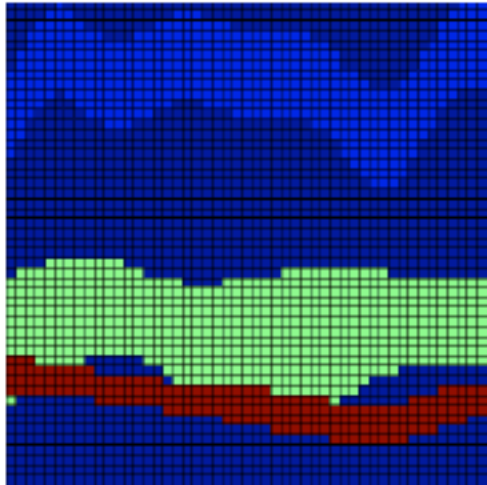

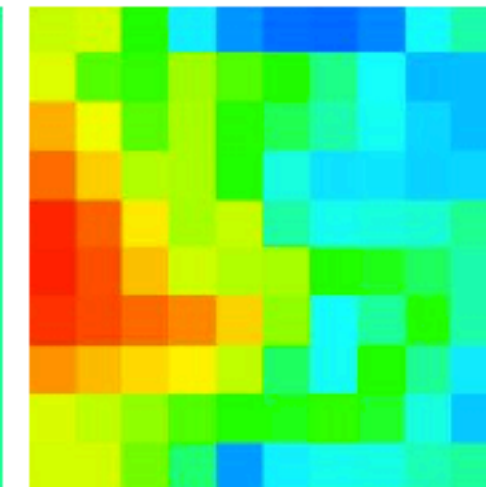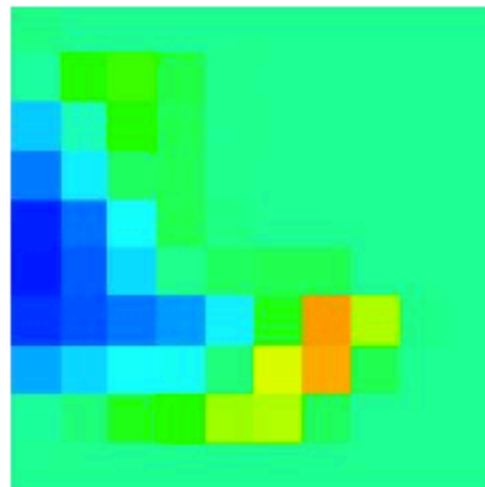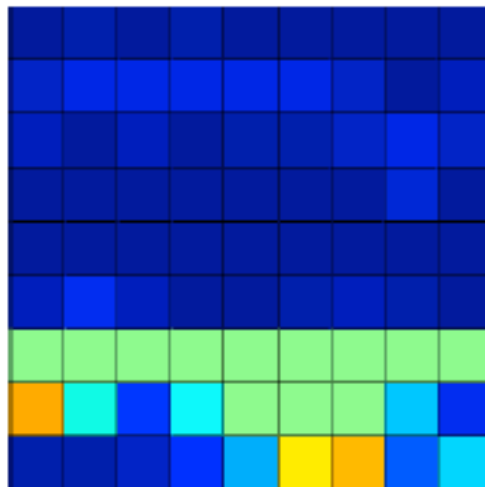|	
	50X50
	10X10

Permeability field   Oil saturation   Gas saturation
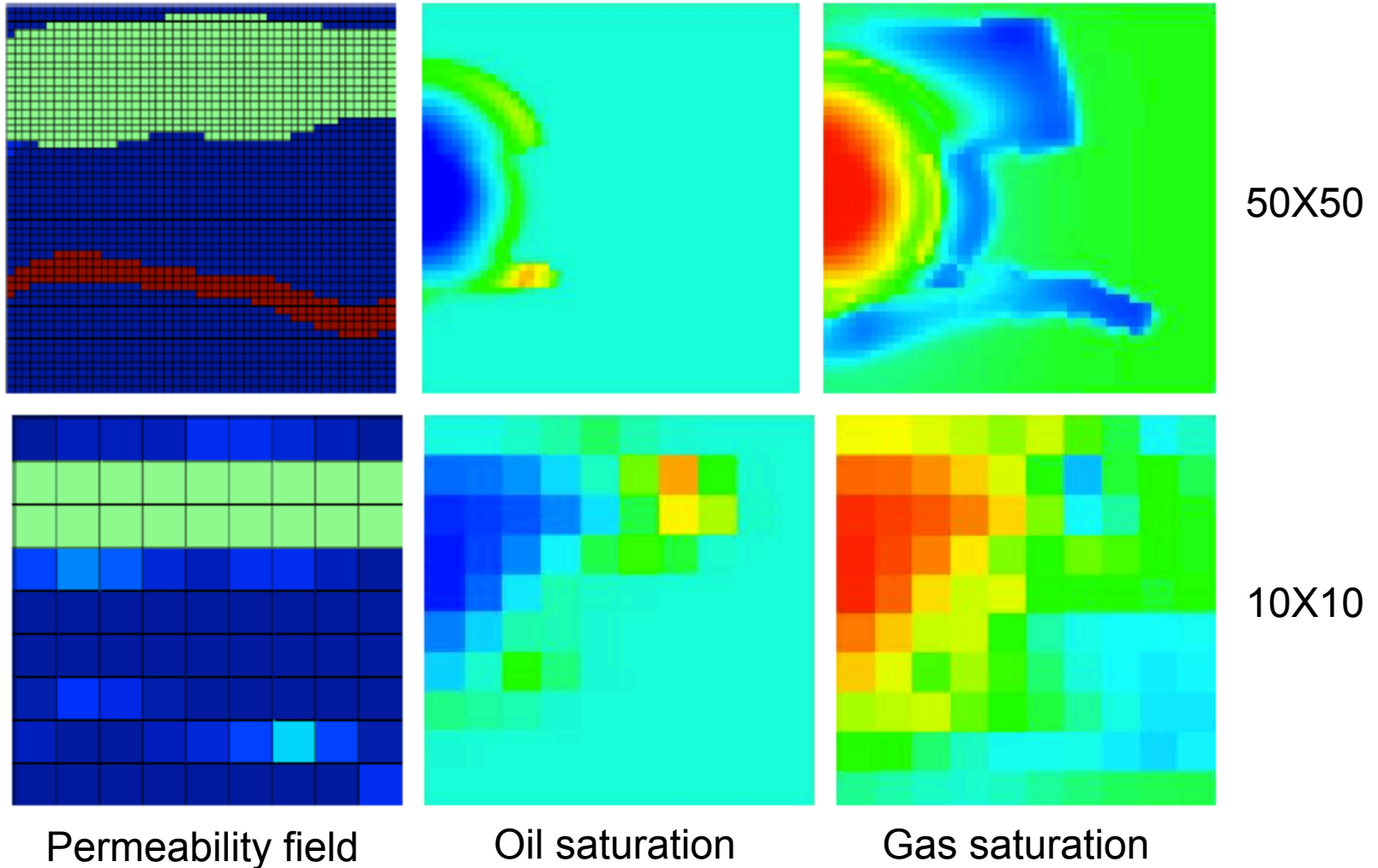
Small scale heterogeneity causes combustion to quench - coarse scale simulation does not capture this behavior

SUSTAINED FRONT

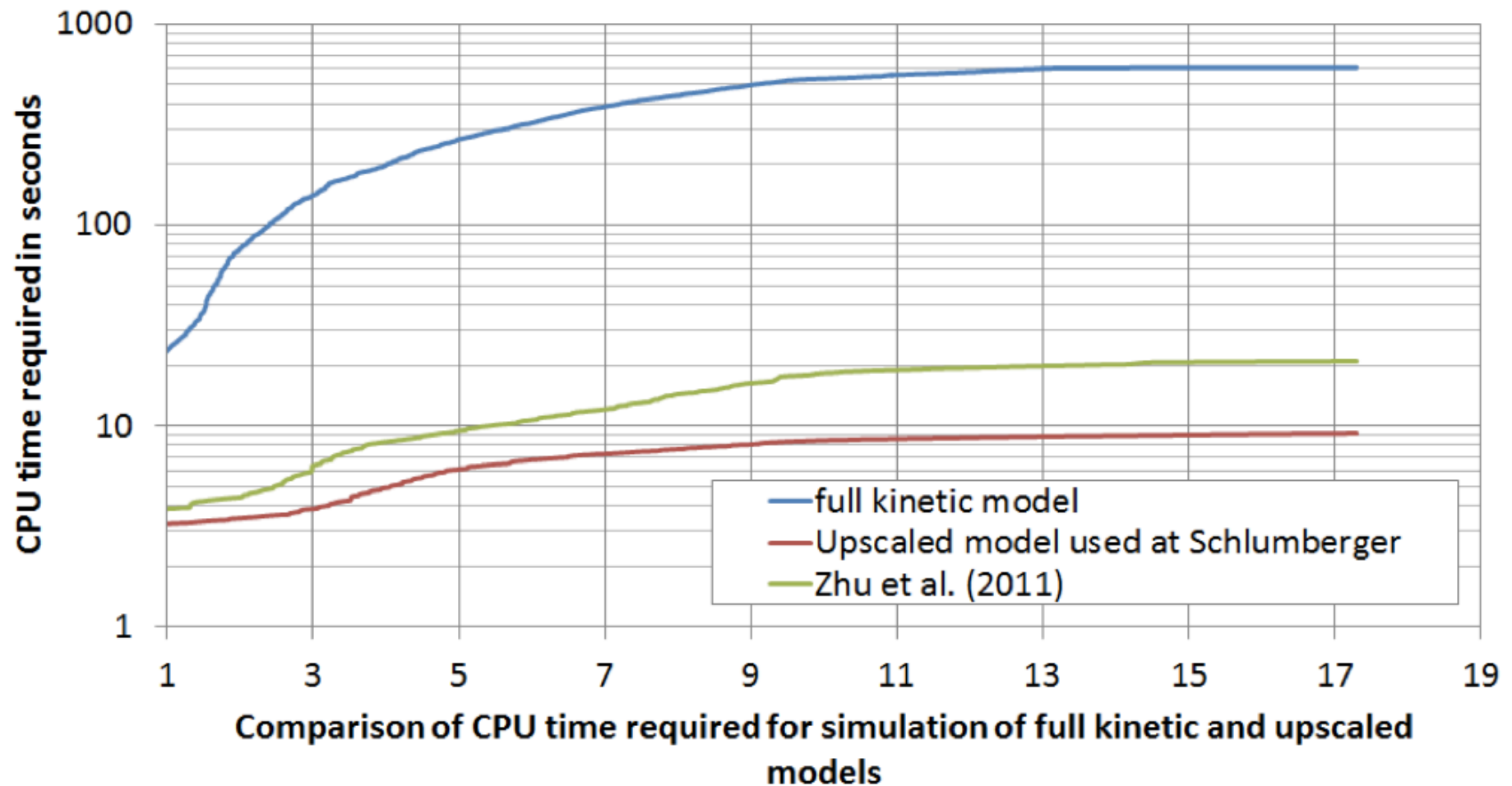|		
		50X50
		10X10
Permeability field	Oil saturation	Gas saturation

Schlumberger successfully applied WUGI to Suplacu field in Romania
Simulations were done using an improved fuel model in relatively
homogeneous permeability fields

Comparison of CPU time required for simulation of full kinetic and upscaled models

We should relax sustained HTO assumption

Minimal Air Flux threshold is emperical (Nelson 1961, Nodwell & Moore 2000)

Extinction/ignition studied using a Virtual Kinetic Cell (Kristensen & Gerritsen, 2008)

Fuel deposition to vary locally and as function of air flux

What impacts do subgrid scale heterogeneities have?

Does the combustion front "finger" or is it relatively smooth?

Does "choking" occur (swelling oil phase, solid fuel deposition) when

heat advection dominates?

What are next critical modeling issues?

Viscosity and relative permeability relations