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Thermal Recovery Processes in Clastic and Carbonate Rock

January 31, 2013

Contents

Sub-Surface

- Principles of SAGD and CSS
- Pressure and Temperature
- Steam Properties
- Bitumen Phase Behavior
- Geo-Mechanics
- Relative Permeability Hysteresis
- Numerical Simulations
- SOR vs. RF or NPV vs. Cash Flow
- Carbonates

Not Addressed:

- impact of temperature cycles on well failure
- operation of cycles with increasing duration
- higher P/T conditions in facility
- H_2S, CO_2

DISCLAIMER
(for the experts)

- simplification
- generalization

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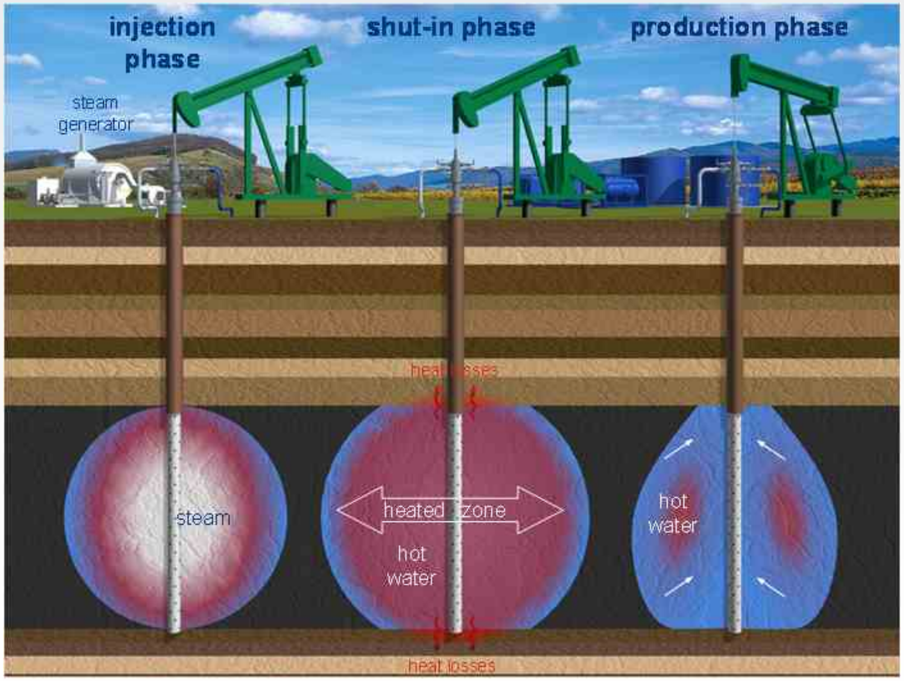
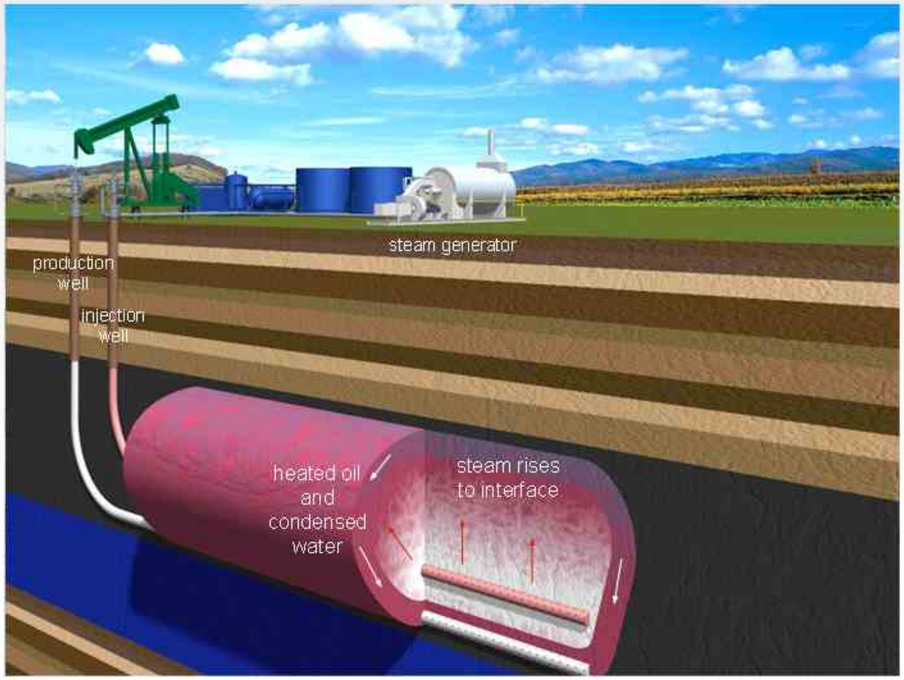
Principles





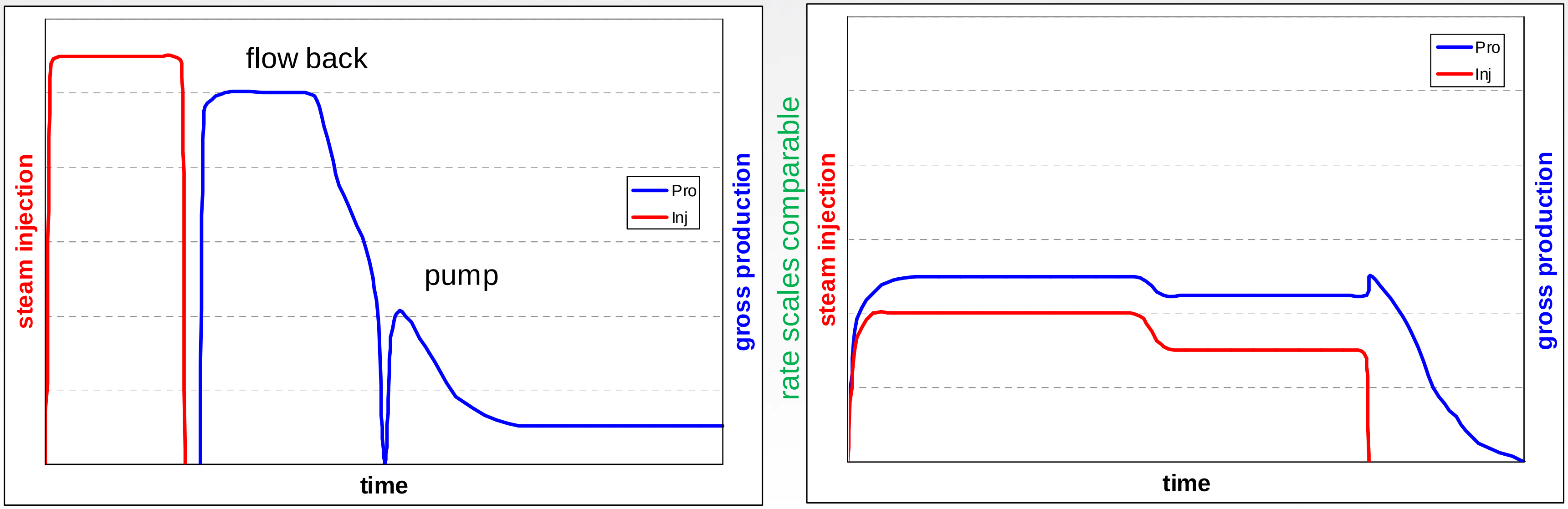
CSS – Cyclic Steam Stimulation

- injection-soak-production
- vertical or horizontal wells
- dilation compaction
- solution gas drive
- gravity drainage (if mature)

SAGD – Steam Assisted Gravity Drainage

- balanced injection and production
- horizontal wells
- gravity drainage

Injection and Production



time scales not comparable

CSS – Cyclic Steam Stimulation

- soak period after injection
- flow back initially restricted
- late production in mature CSS: gravity drainage

SAGD – Steam Assisted Gravity Drainage

- balance injection and production
- produce most injected steam as water

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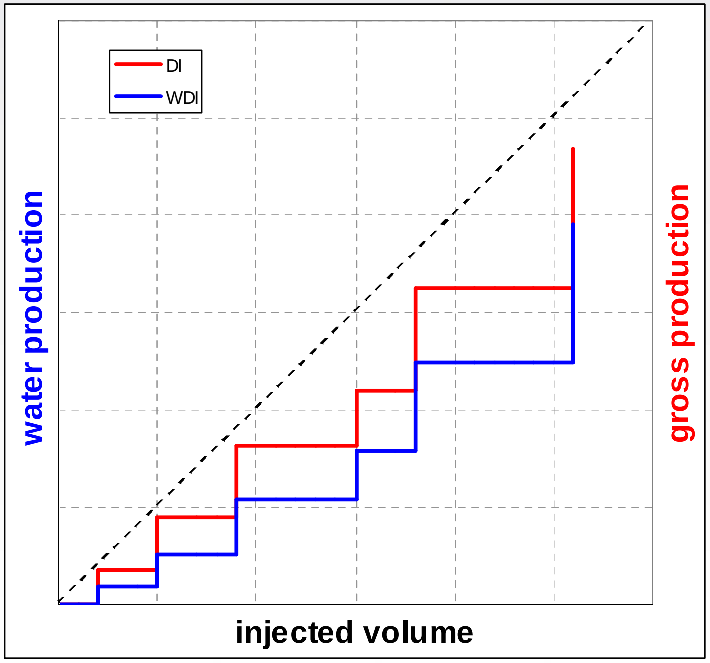
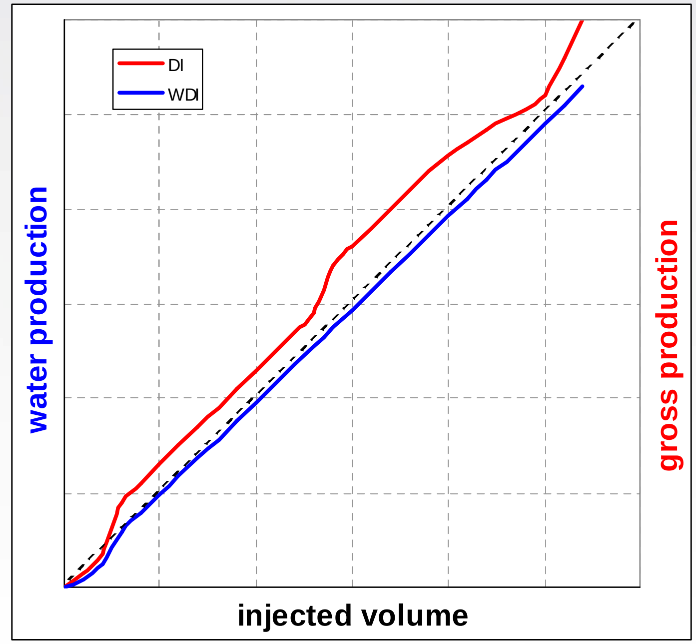
Material Balance



volume scales not comparable



volume scales not comparable

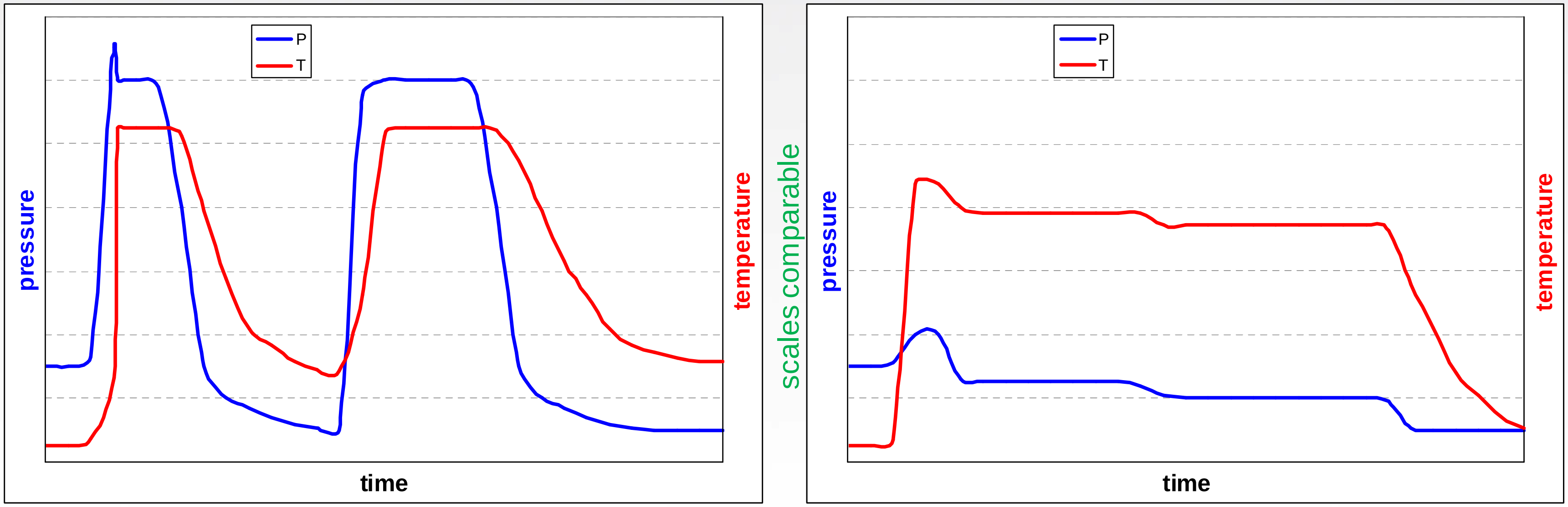
CSS – Cyclic Steam Stimulation

- 1 > DI > WDI
- liquid volume is left behind
- irreversible porosity increase
- loss to the outside

SAGD – Steam Assisted Gravity Drainage

- DI > 1 ≈ WDI
- liquid volume is missing
- void occupied by gas (H_2O, HC)

Pressure and Temperature



time scales not comparable

CSS – Cyclic Steam Stimulation

- steam volumes increase
- initial flow back, then pump
- cycles get longer

SAGD – Steam Assisted Gravity Drainage

- operating pressure determines the temperature
- blow-down in late life

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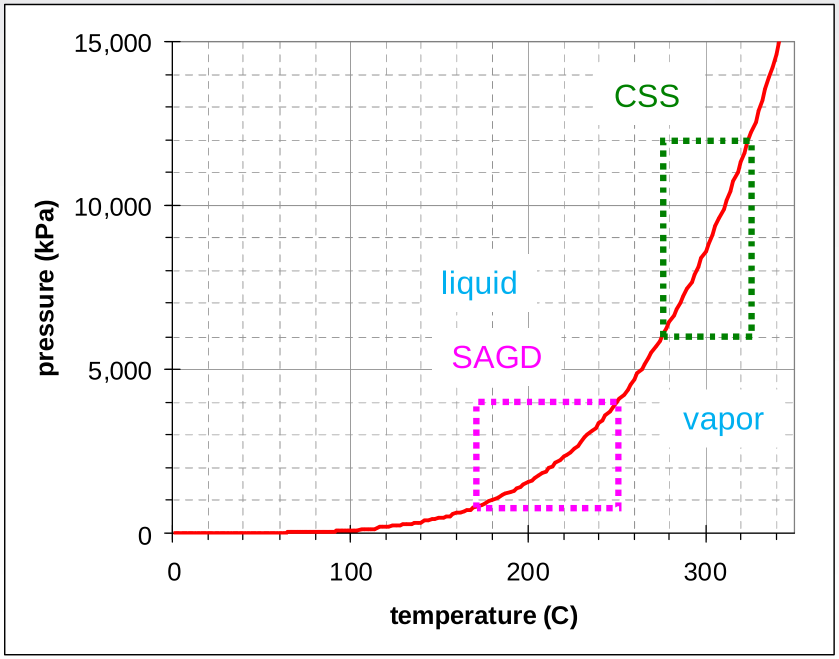
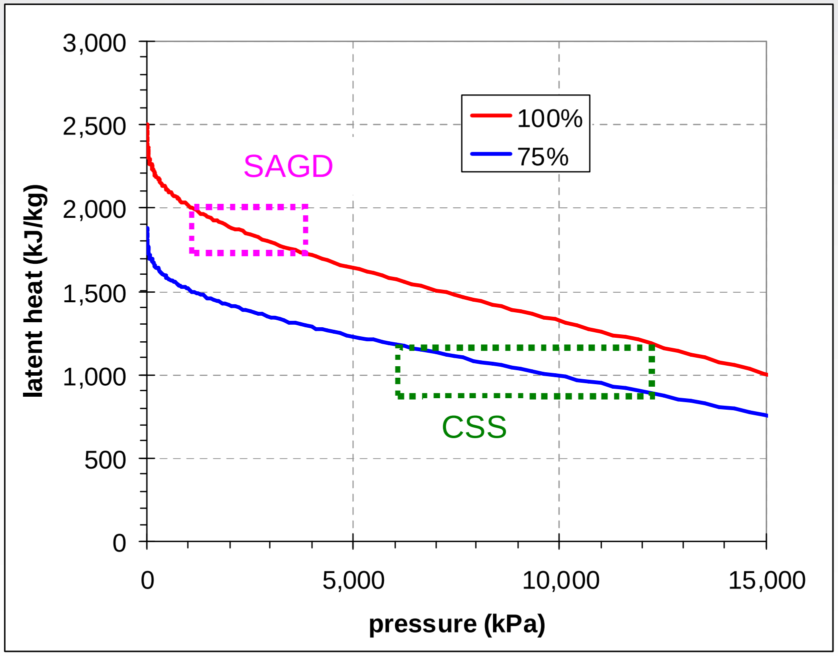
Steam Properties





CSS – Cyclic Steam Stimulation

- higher steam P&T
- lower quality (variable P_{inj})
- reduce viscosity
- main drive mechanism: dilation/re-compaction
- create volume

SAGD – Steam Assisted Gravity Drainage

- moderate steam P&T
- less volume required for latent heat
- reduce viscosity
- main drive mechanism: gravity drainage
- maintain gas phase in chamber

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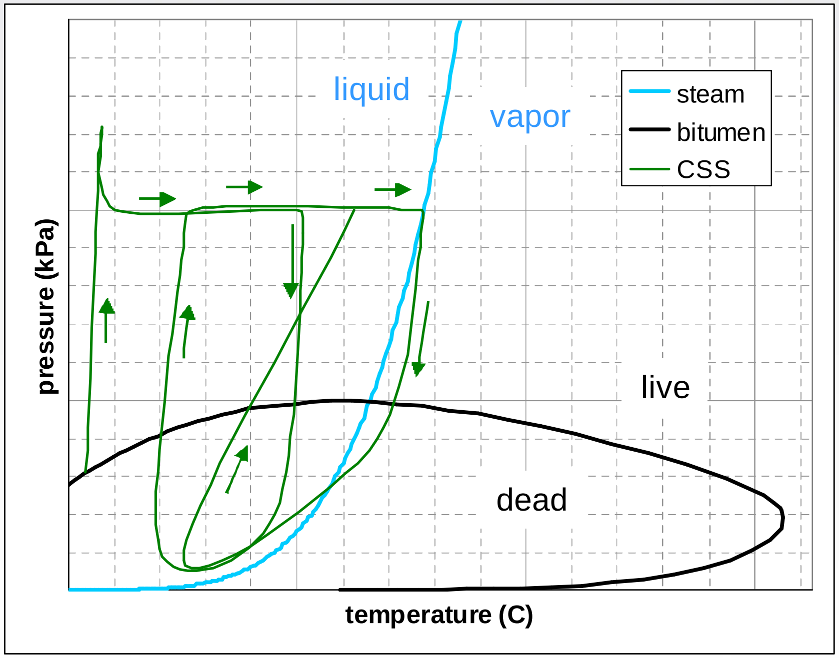
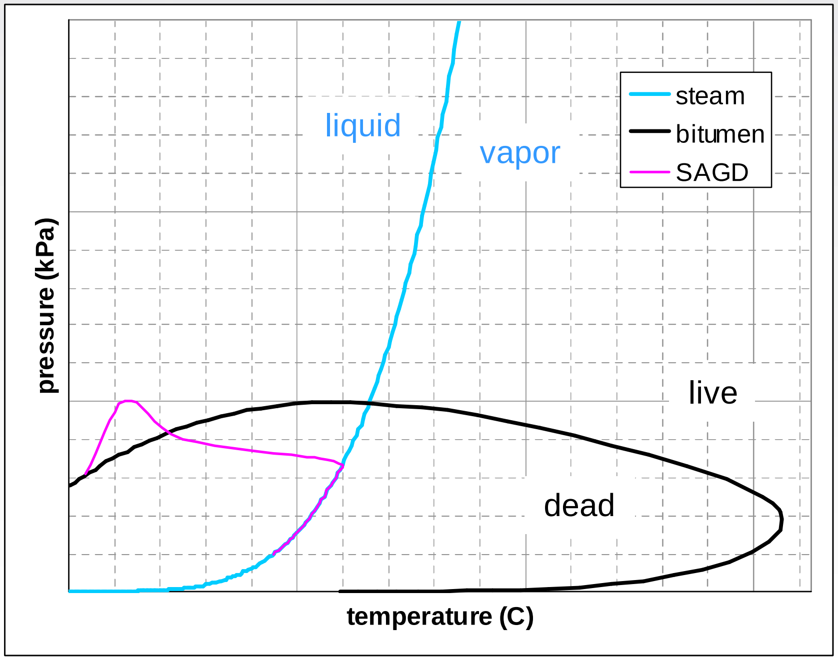
Phase Behavior





CSS – Cyclic Steam Stimulation

- high P keeps bitumen live during 1st cycle injection
- if gas is abundant, bitumen can re-saturate

SAGD – Steam Assisted Gravity Drainage

- temperature leads to dead bitumen fast
- no potential re-saturation

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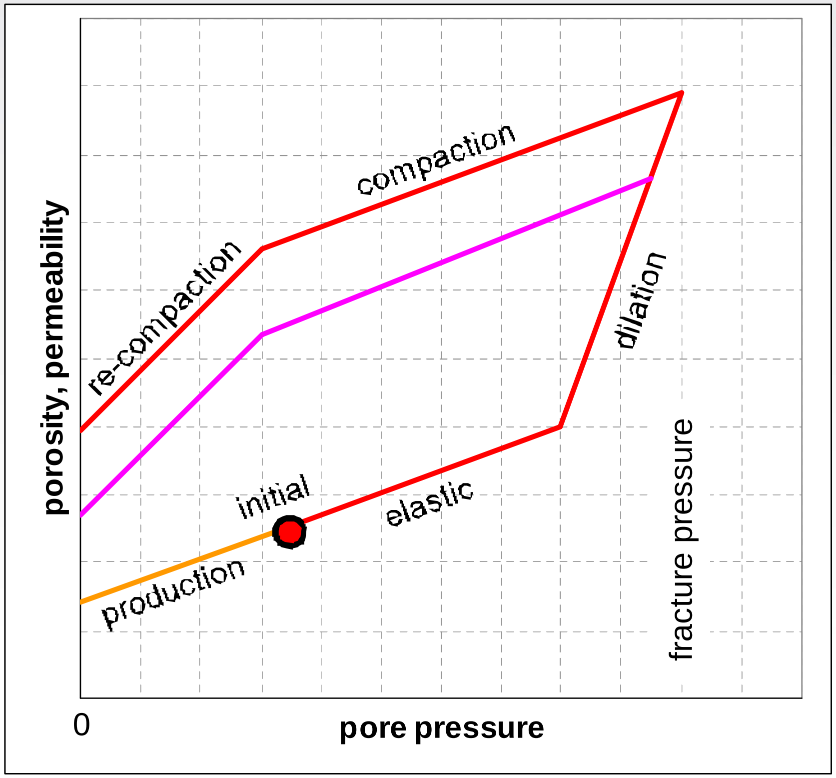
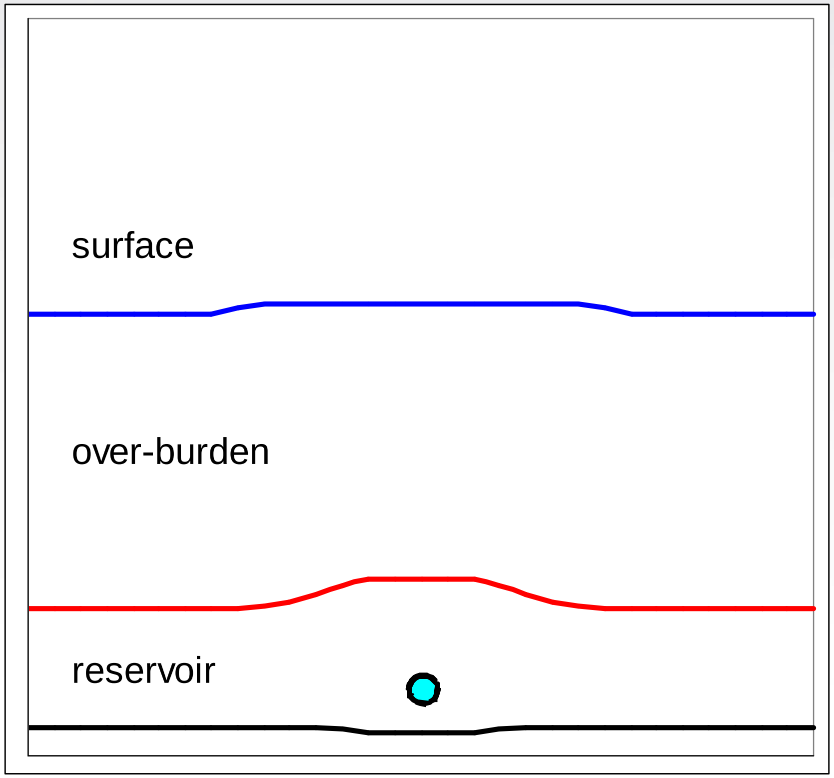
Deformation





CSS – Cyclic Steam Stimulation

- full range of pressure cycle
- compaction is main drive mechanism
- irreversible dilation $\Rightarrow$ DI < 1

SAGD – Steam Assisted Gravity Drainage

- low range of pressure
- thermal expansion

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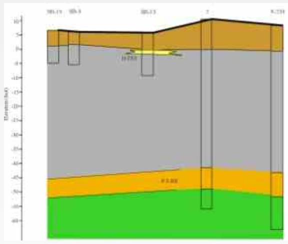
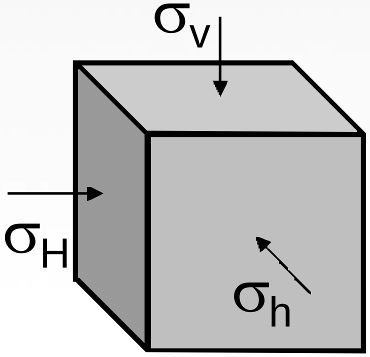
Fracturing

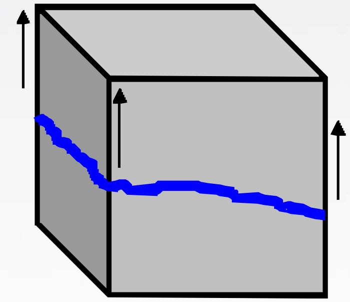
overburden weight

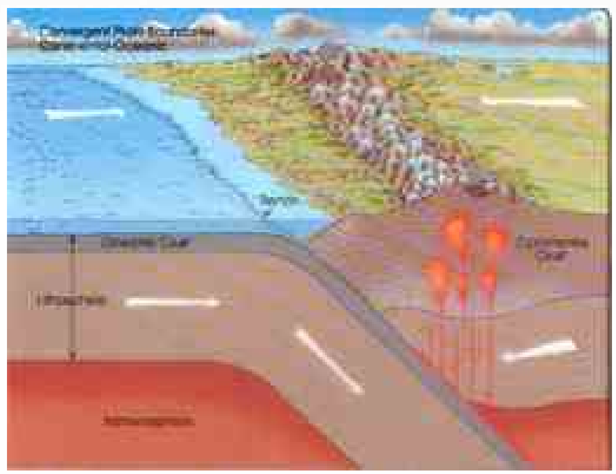




once the pore pressure exceeds
the smallest stress, and
the rock strength is overcome,
the rock will break

$\sigma_v < \sigma_h$





$\sigma_h < \sigma_v$

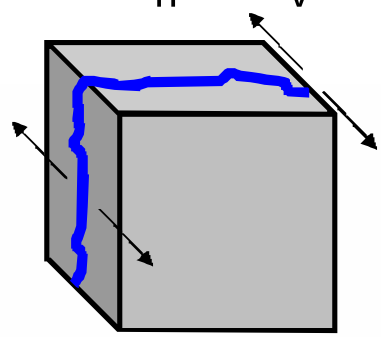


plate tectonics

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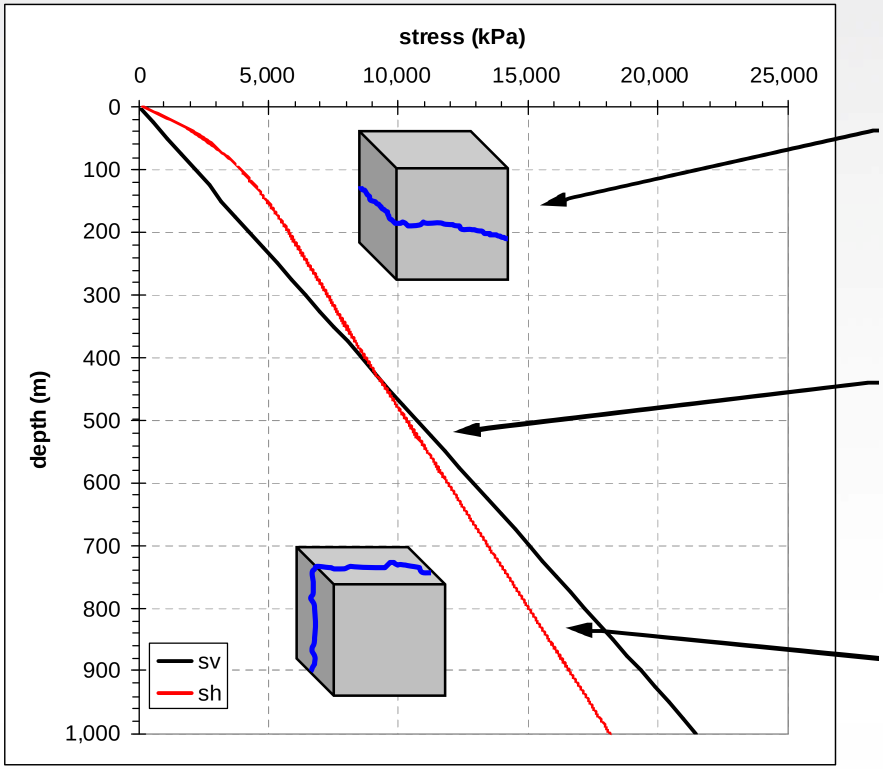
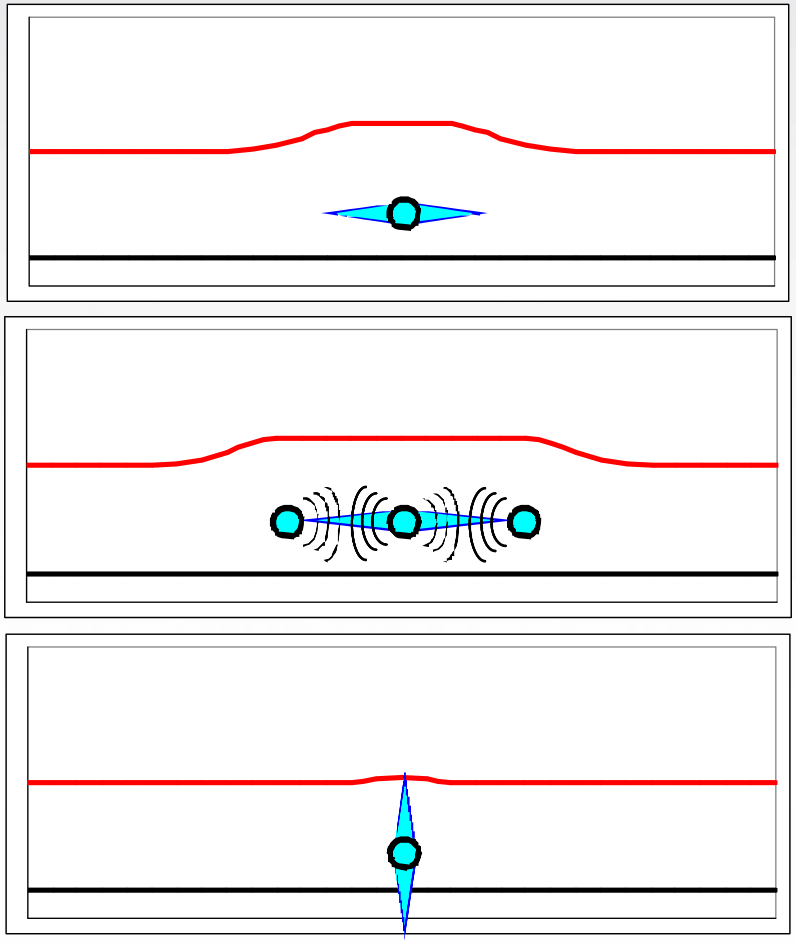
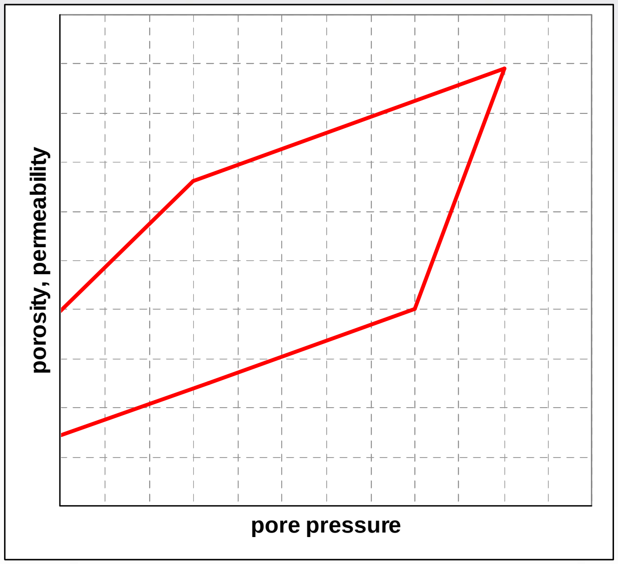
Fracturing cont'd

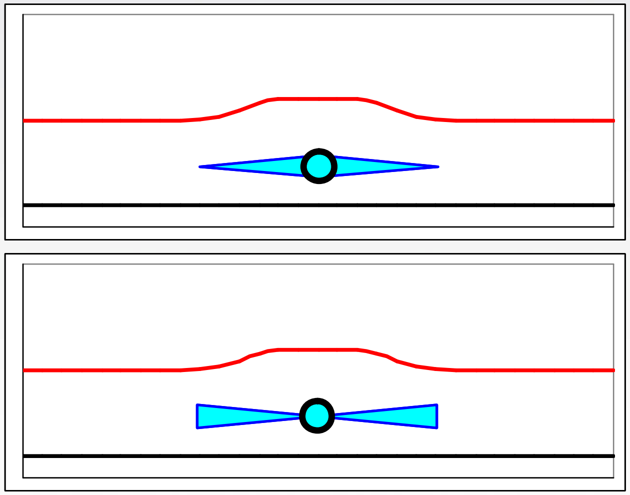


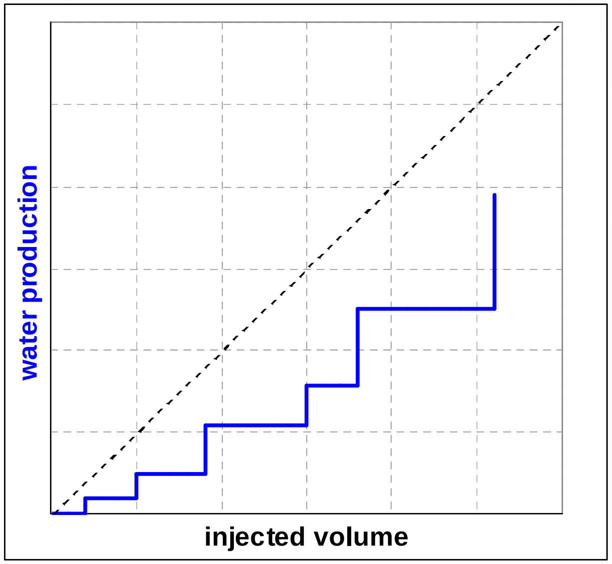


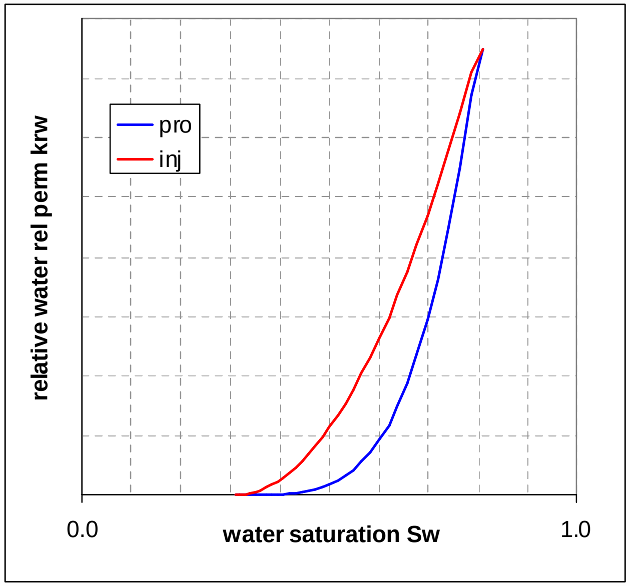
thermo- and poro-elastic effects of multiple wells can turn fracture orientation from initially vertical to horizontal

Relative Permeability Hysteresis









Numerical Simulations

CSS	SAGD
inj/pro cycles, unstable	balanced inj/pro
large range of P&T	small range of P&T
sand-face steam quality	no issue
bitumen phase behavior	mainly dead bitumen
large cycles of S_w and S_o	stable S_w and S_o changes
critical gas saturation	initial gas saturation
rel perm hysteresis	not necessary
dilation hysteresis	not necessary
fracture initiation, growth	not necessary
fracture flow	not necessary

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Performance Comparison

CSS (CNRL)

Pads 29-31

Primrose South

- Clearwater
- 12 m net pay
- 3 pads, each
  2 x 8 hor wells
- spacing 190 m
- length 1,200 m
- since 2004

SAGD (Suncor, CNRL)

Burnt Lake Pilot

Primrose East

- Clearwater
- 25 m net pay
- 3 SAGD well pairs
- spacing 80 m
- length 700; 900,1000 m
- since 1997

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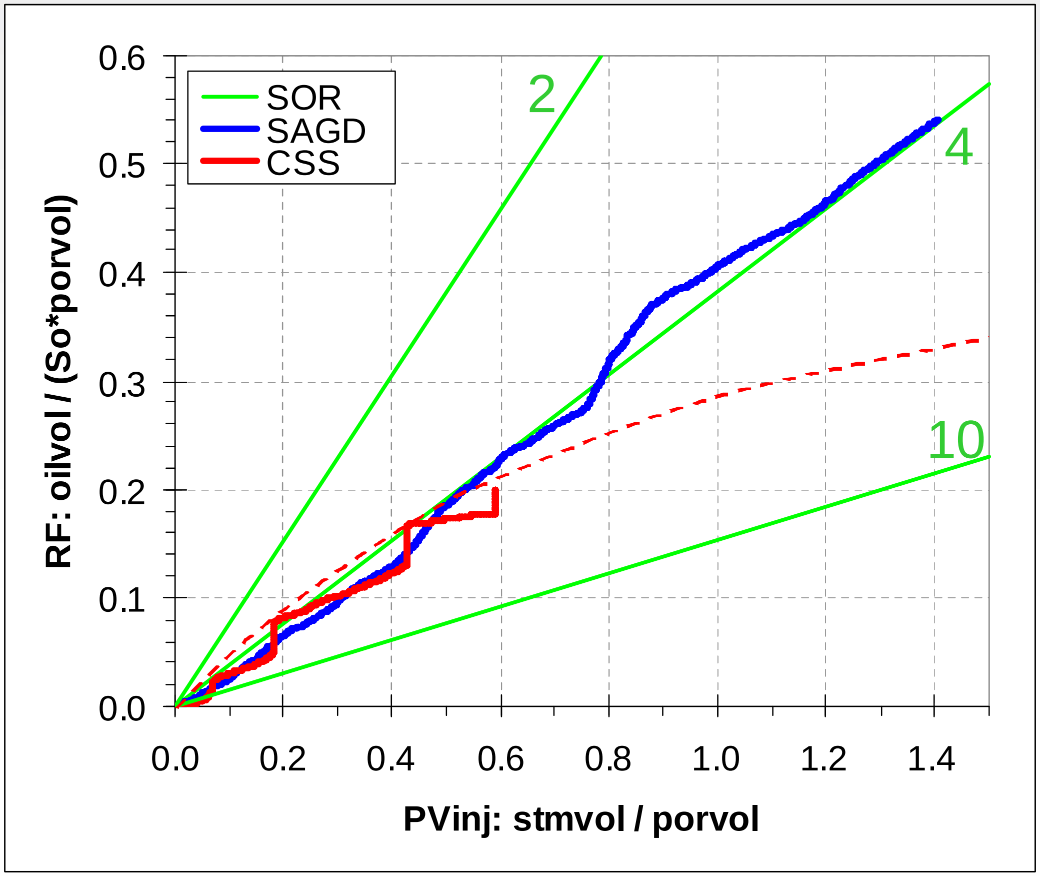
Recovery Factor

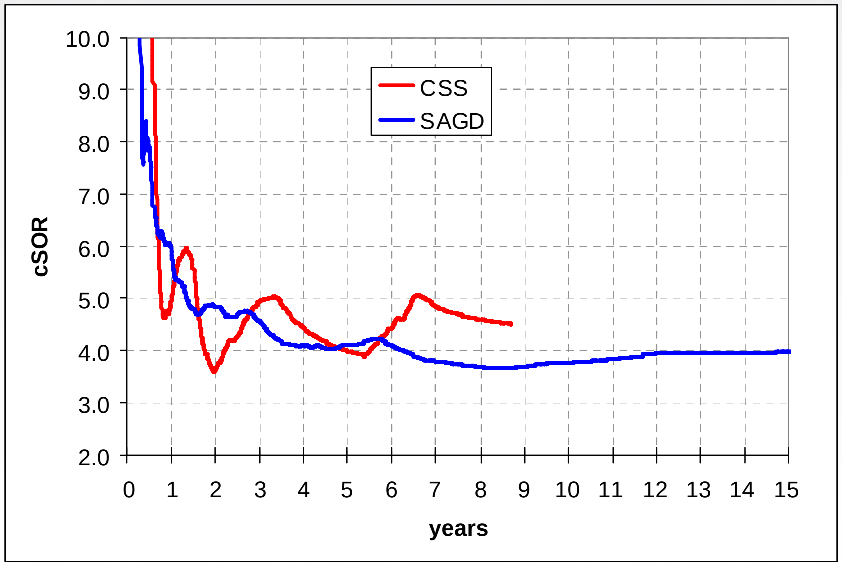
CSS:
- RF is not a fixed number
- cut-off SOR is economic decision

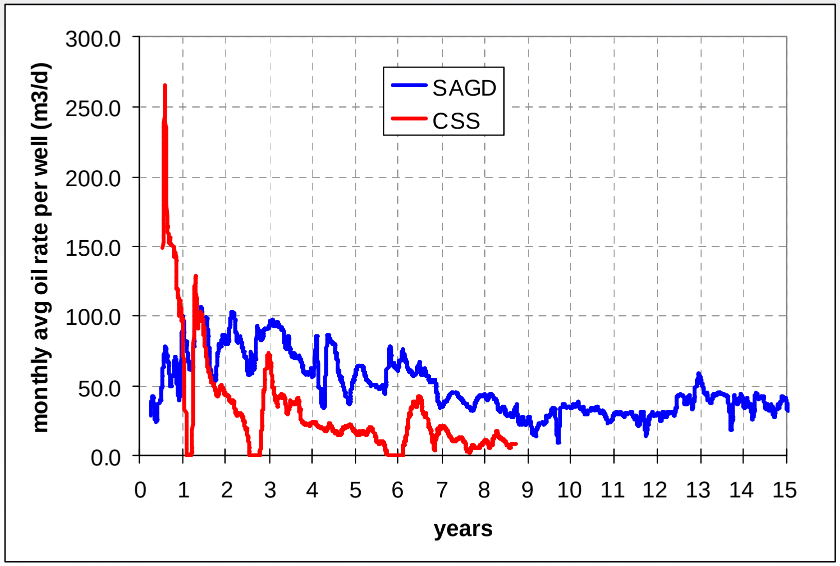
SAGD:
- stable thermal efficiency
- RF > 60 possible at stable SOR



no time relation

Time Dependent





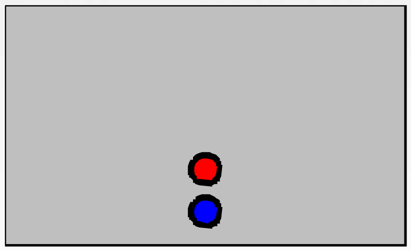
full pad performance

CSS:
- lower SOR after Cy1 and Cy2
- equivalent SOR after Cy3
- higher SOR after Cy4+

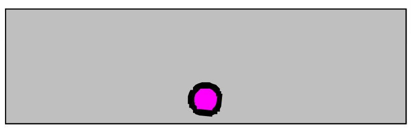
individual well performance

CSS:
- 3-6 x rates in Cy1
- equivalent rates in Cy2
- much lower rates in Cy3+

Economic Difference



- 2x net pay
- 2x wells
- higher SOR after 2 yrs
- lower oil rates in 1st yr
- SOR stable for 10+ yrs
- RF > 60% achievable in 10+ yrs



- ½ net pay
- ½ wells
- lower SOR after 2 yrs
- 3-6 x oil rates in 1st yr
- cut-off SOR at 20% RF

CSS:	lower capital and fast return –	**NPV**
SAGD:	sustainable SOR and high RF for additional 5-10 yrs –	**cash flow**

Consider this ...

- start dev't with CSS to maximize NPV
- transform mature CSS to SAGD to maximize RF
- attempts by IOL, CNRL, SCAN
- risk of CSS in shallow reservoirs is over-rated
  - stress regime favors horizontal fractures
  - initial SAGD injection pressures are comparable to CSS requirements for dilation
  - CSS vs. SAGD operation strategy in case of increased injectivity
- SAGD has advantage of control over operation pressure
  - now high or low pressures required
  - gas cap
  - top/bottom water
- permeability may be too high for CSS
  - high pressures not achievable
  - example: fractured carbonates

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What to do in Carbonates?

- fractures in carbonates increase effective permeability
- high permeability is good for SAGD but for CSS, this may prevent reaching injection pressures that cause dilation - the second 'S' in CS**S**
- very high permeability may cause uncontrollable shortcut between injector and producer of classic SAGD pair
- distributions of primary and secondary porosity vary within the Grosmont, and the recovery process has to be adapted
- conceptual process for carbonates in two phases

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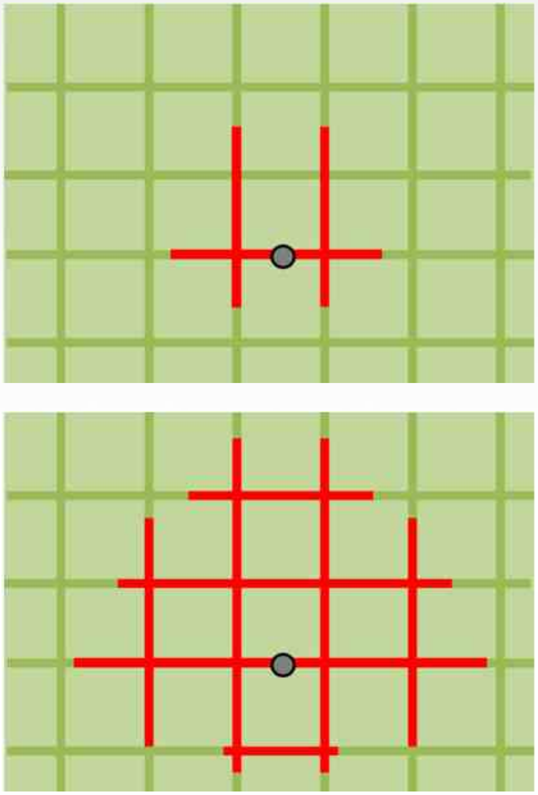
Phase 1:
Cyclic SAGD



<u>Cyclic</u>

objectives:

- **heat fracture system by convection**
- **recover bitumen in fractures**

recovery mechanisms:

- **fractures**
  - **gravity**
  - **thermal expansion**
- **matrix**
  - **thermal expansion**
  - **solution gas drive**

decreasing contribution to total bitumen production

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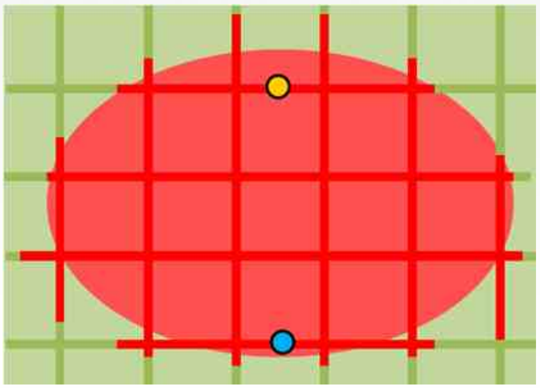
Phase 2: Continuous SAGD



requires dedicated injector and producer

multiple options for configurations

<u>**Continuous**</u>

objectives:

- **maintain heat in fractures**
- **heat matrix by conduction**

recovery mechanisms:

- **matrix**
  - **imbibition**
  - **gravity**
- **fractures**
  - **serve as collectors**

similar contribution to total bitumen production

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Matrix Contributions

Spontaneous Imbibition

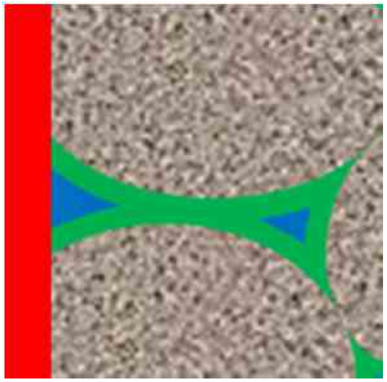
<u>Initial (10-20 °C)</u>
oil wet:

- bitumen is continuous phase
- cold bitumen is immobile
- water is immobile (non-continuous)
- hot water (condensed steam) will not enter matrix
- bitumen only move into fracture by thermal expansion
- heat will penetrate into matrix by conduction

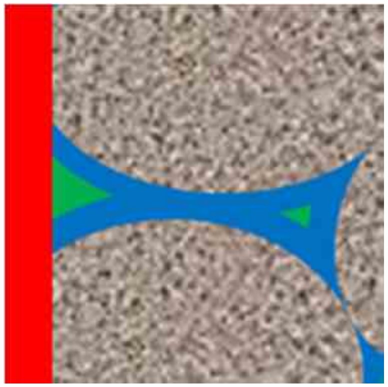
<u>Hot (> 150 °C)</u>
changes to water wet:

- water is continuous phase
- water is mobile (continuous)
- hot bitumen is mobile
- hot water (condensed steam) will be sucked into matrix
- bitumen will be pushed out of matrix into fracture
- heat will penetrate into matrix by conduction and convection
- confirmed in lab tests
- reported for Qarn Alam, Oman

SPE 71866, SPE 153812



green - **bitumen**
blue - **water**
red - **steam**



Matrix Contributions

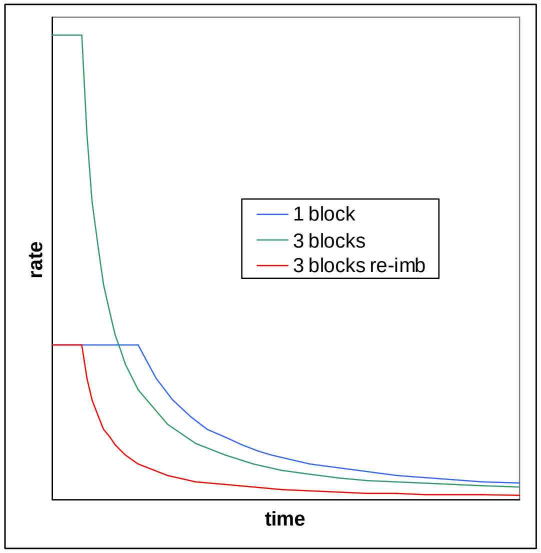
Gravity Drainage

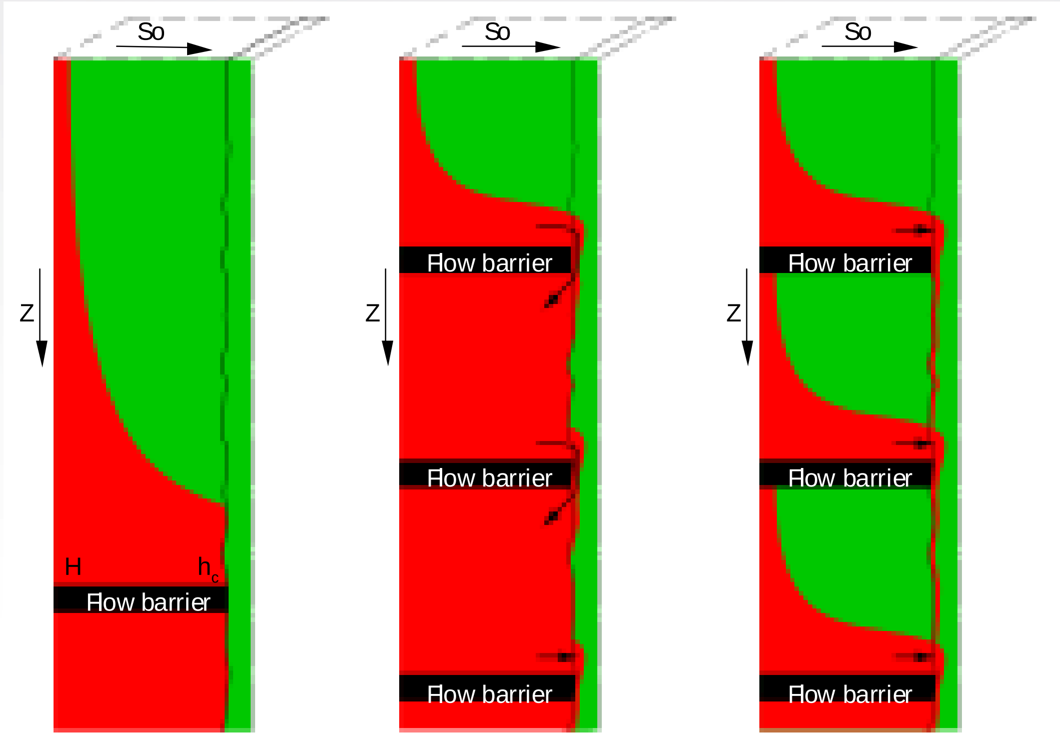
gravity drainage rate depends on:

- density contrast steam/bitumen
- vertical permeability
- oil viscosity

example:

- 1,000 m well length
- 100 m well spacing
- 100 mD matrix vertical permeability
- 100 cP viscosity
- 700 m^3/d drainage rate (theoretical)





SPE 111403

red- **bitumen**
blue - **water**
green - **gas or steam**

Summary

- Conventional SAGD in Clastic Reservoirs
  - relies on gravity
  - usually associated with a well pair at the bottom and 5-8 m vertical distance
  - oil rates and SORs are stable over a long time, allowing high RF
- Conventional CSS in Clastic Reservoirs
  - relies initially on dilation and re-compaction; later on gravity
  - usually associated with single well operated at high pressures
  - oil rates peak in first 1-3 cycles; then performance is below SAGD
- Cyclic SAGD in Carbonates
  - dilation unlikely; no CSS benefits; relies on gravity
  - targets bitumen in fractures
- Continuous SAGD in Carbonates
  - gravity drainage and spontaneous imbibition
  - targets bitumen in matrix

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