Compaction Modelling by Coupled Rock Mechanics and Reservoir Simulation

by

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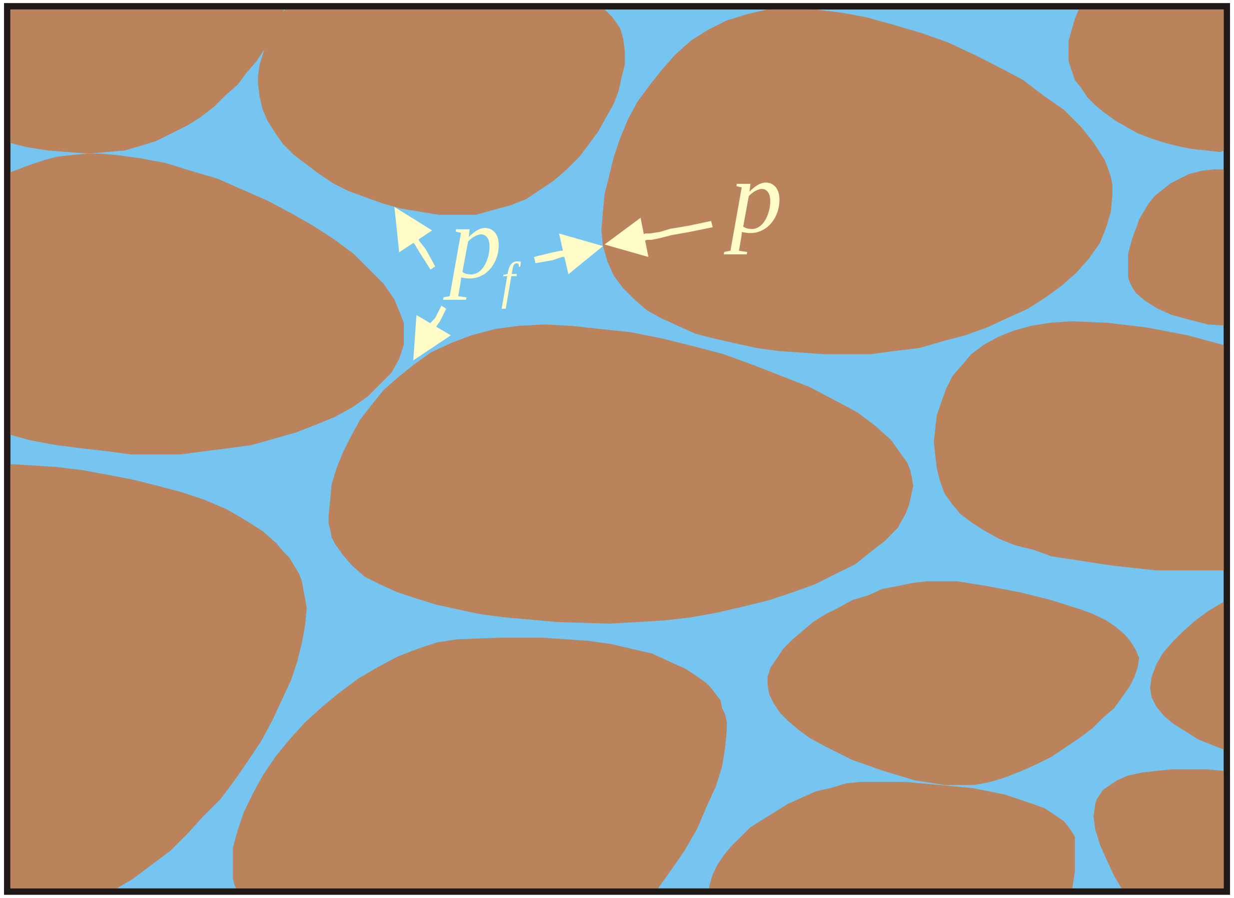
Outline

- ***Why***
- ***How***
- ***Recent Developments***

Compaction: Deformation of pore space.

Net force on pore wall:
Difference betweeen confining pressure (stress)
and fluid pressure



Effective stress:

$\sigma' = \sigma - p_f$

(Disregarding grain compression)

Compaction Modelling

- Compaction is a function of *effective stress*, σ'.
- **The Reservoir Simulator** computes compaction from *fluid pressure*, p_f
  - ✓ only available compaction energy
  - ✓ approximation – how good is it?
    - Investigate relationship $\sigma' \leftrightarrow p_f$
    - Utilise to speed up simulations

Measure for Compaction

Pore volume multiplier m:

In each grid cell,

$$m(t) = \frac{\text{Cell pore volume at time } t}{\text{Initial cell pore volume}}$$

$m_{pf}(t)$: Computed from fluid pressure (table look-up)

$m_{\varepsilon}(t)$: Computed from volumetric strain

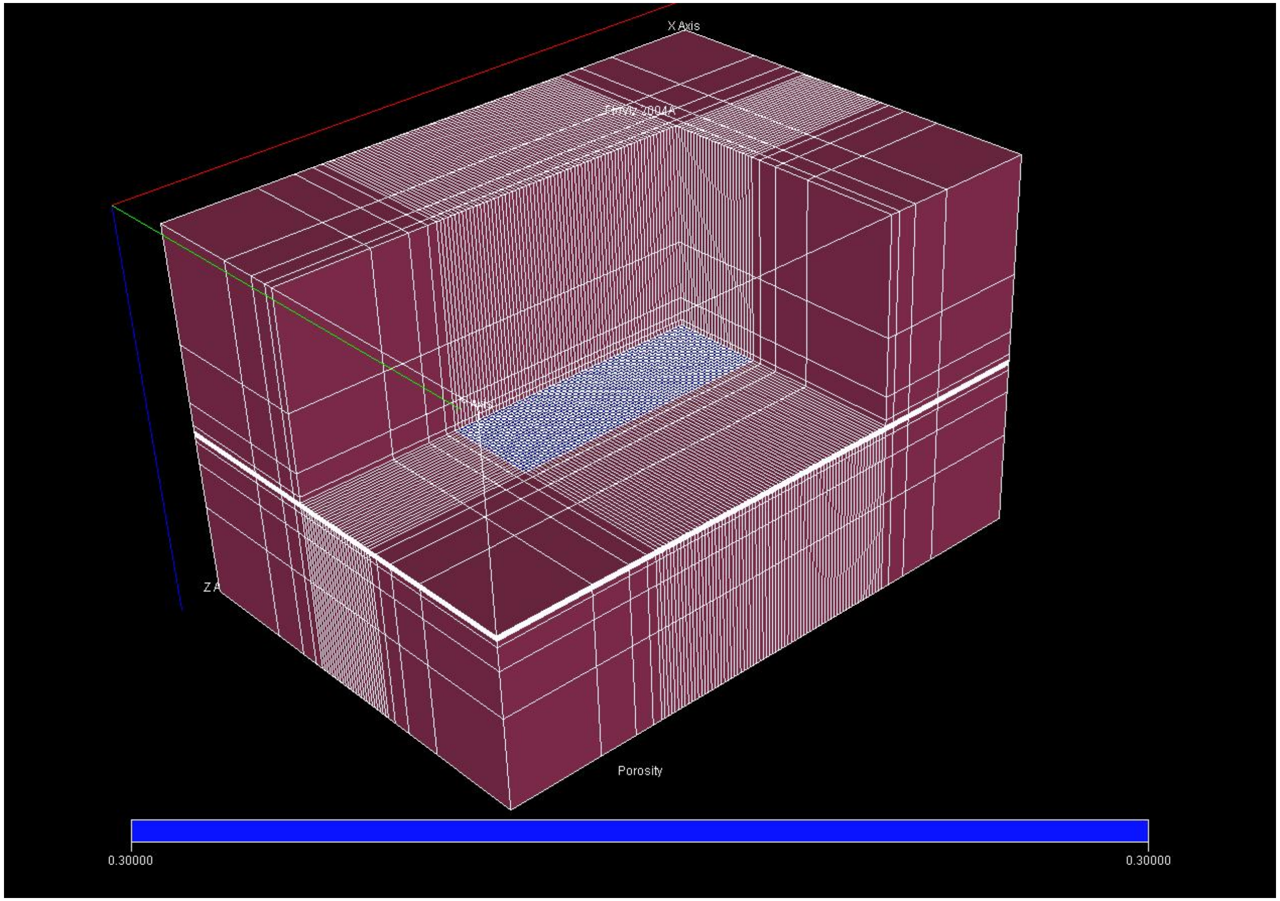
$$m_{\varepsilon}(t) = e^{-\Delta\varepsilon_{\text{vol}}}$$

Coupling

Since *fluid pressure*, *stress*, and *compaction* are inter-related, correct reservoir state can only be achieved by performing **coupled flow and rock mechanics simulations**

Coupling: Boundary Conditions

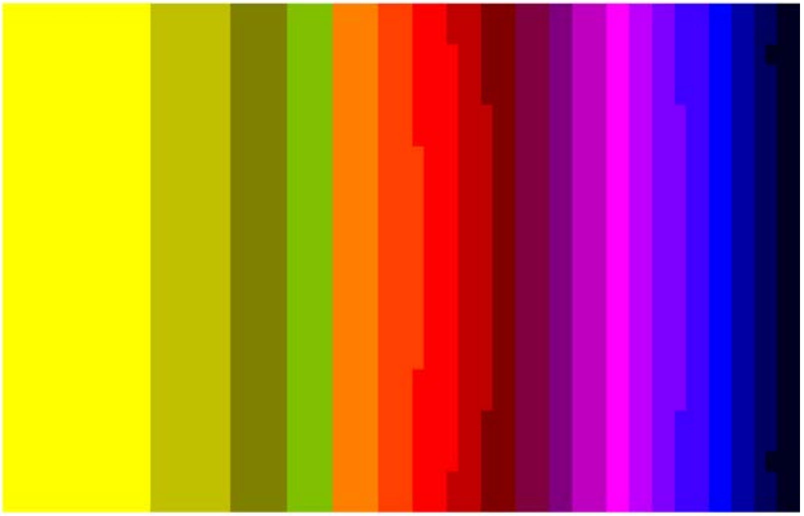
Reservoir embedded in a volume of surrounding non-porous rock (Overburden, underburden, sideburdens)



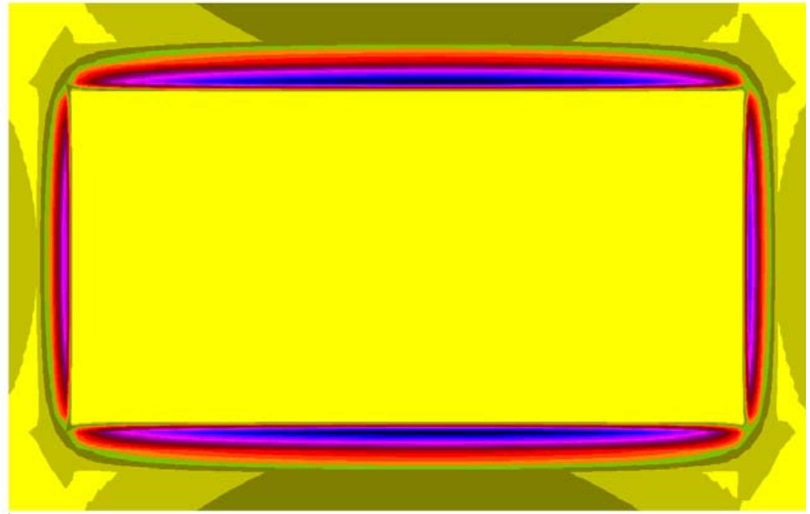
Flow-sim BC:
No-flow on edge of porous rock
IC:
Equilibrium

Rock mech BC:
Free top surface, else rigid edges.
IC: Vertical stress by soil weight

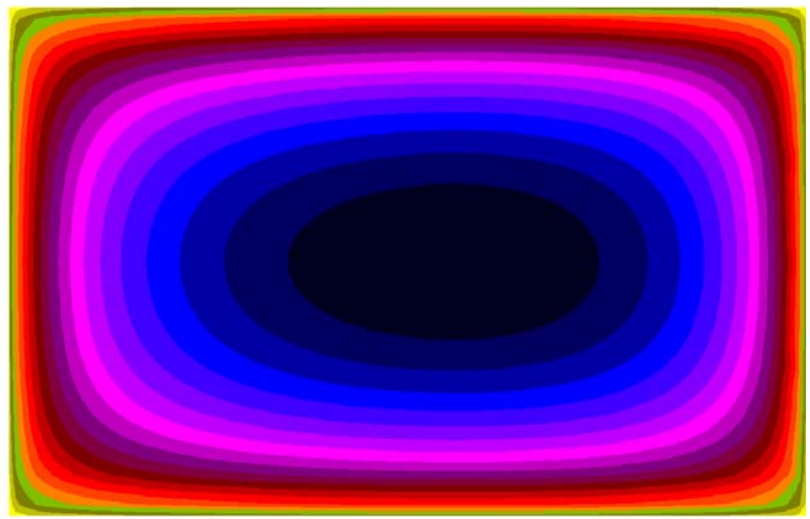
Can p_f be used in place of σ' ?
Iso-contours, homogeneous (single material) reservoir



Fluid pressure from flow-sim

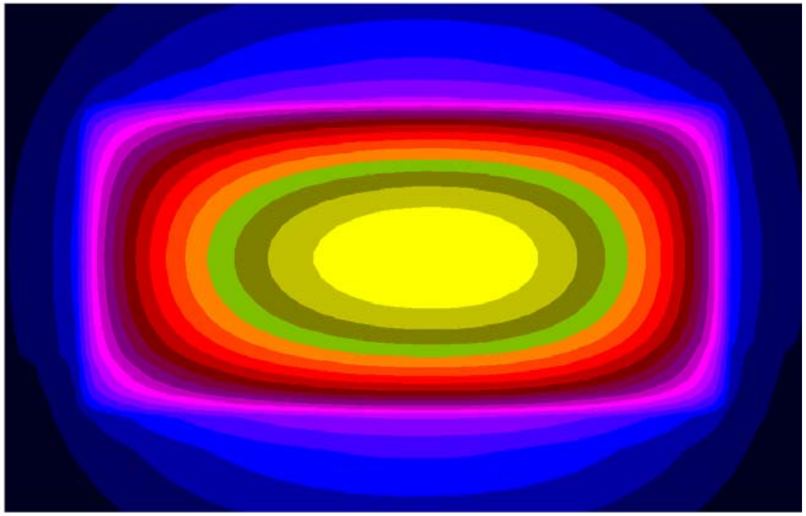


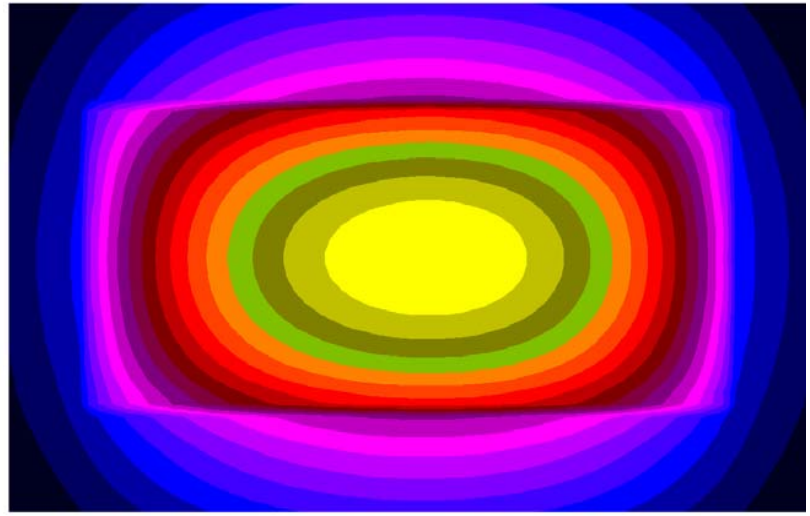
Mean eff. stress,
part of sideburden included

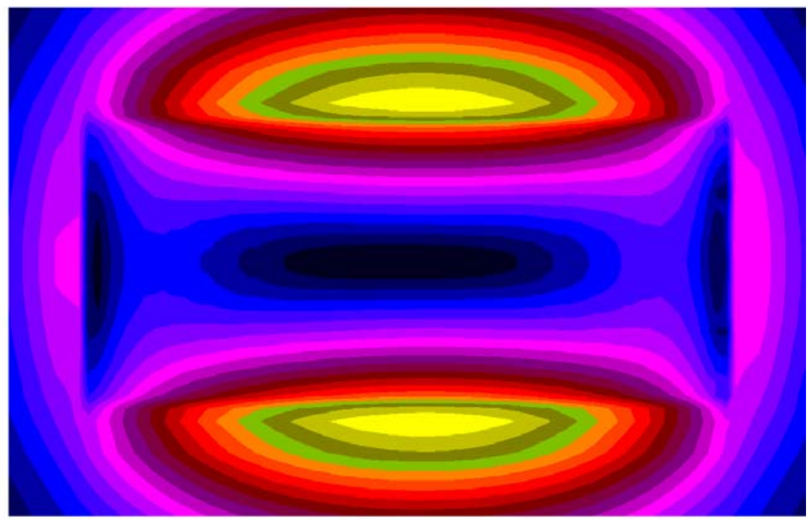


Mean eff. stress,
zoomed in on reservoir only

Total (node) displacement





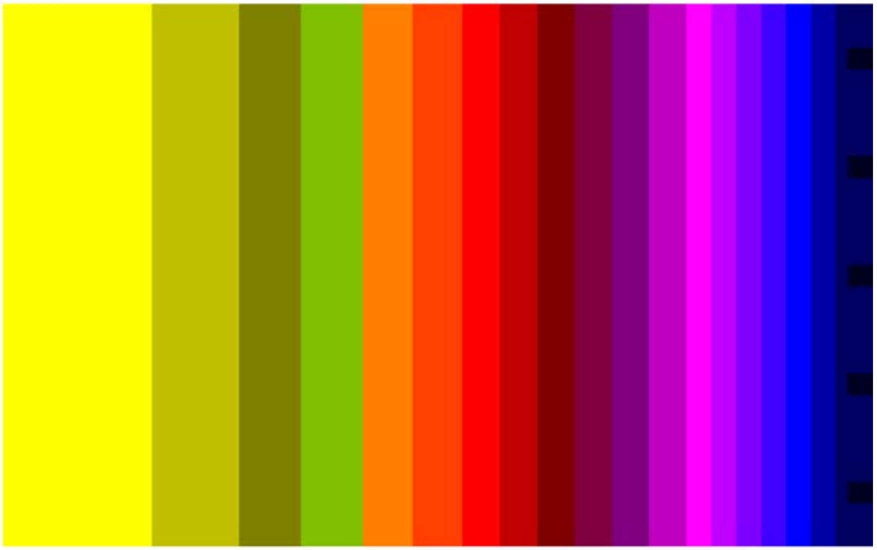


Top, max DS = 810 mm

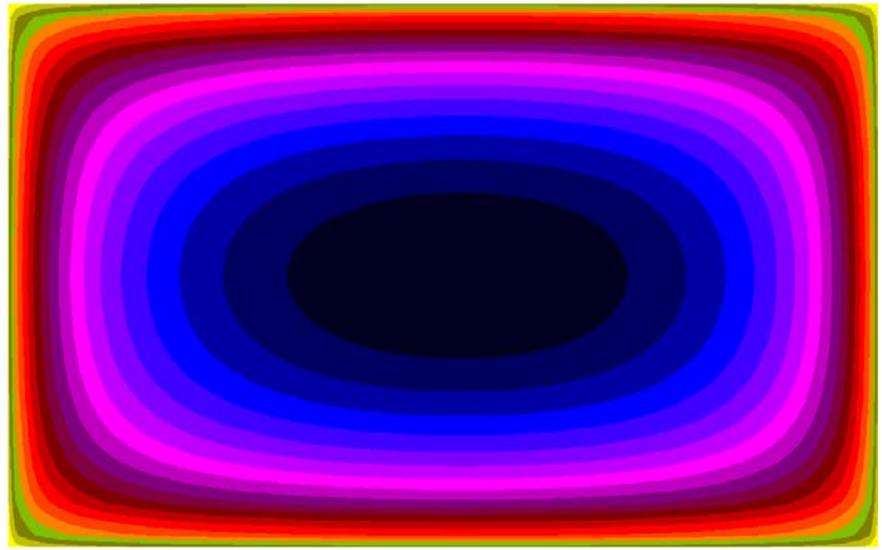
Middle, max DS = 465 mm

Base, max DS = 200 mm

Computed compaction



Eclipse:
From fluid pressure, m_{pf}

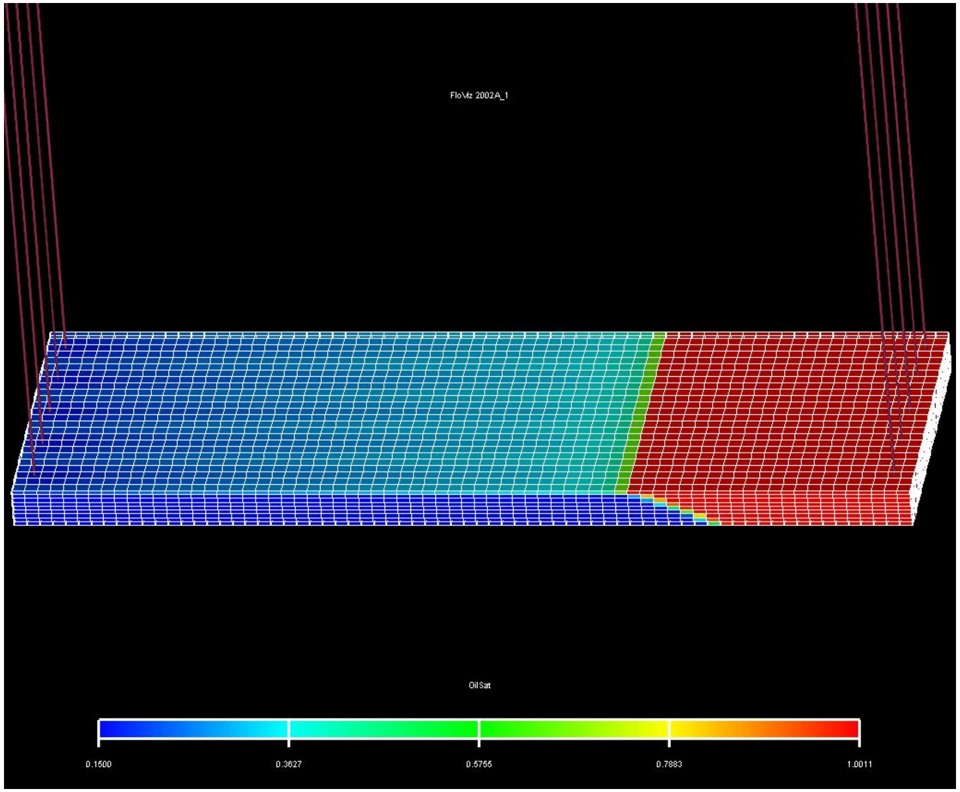


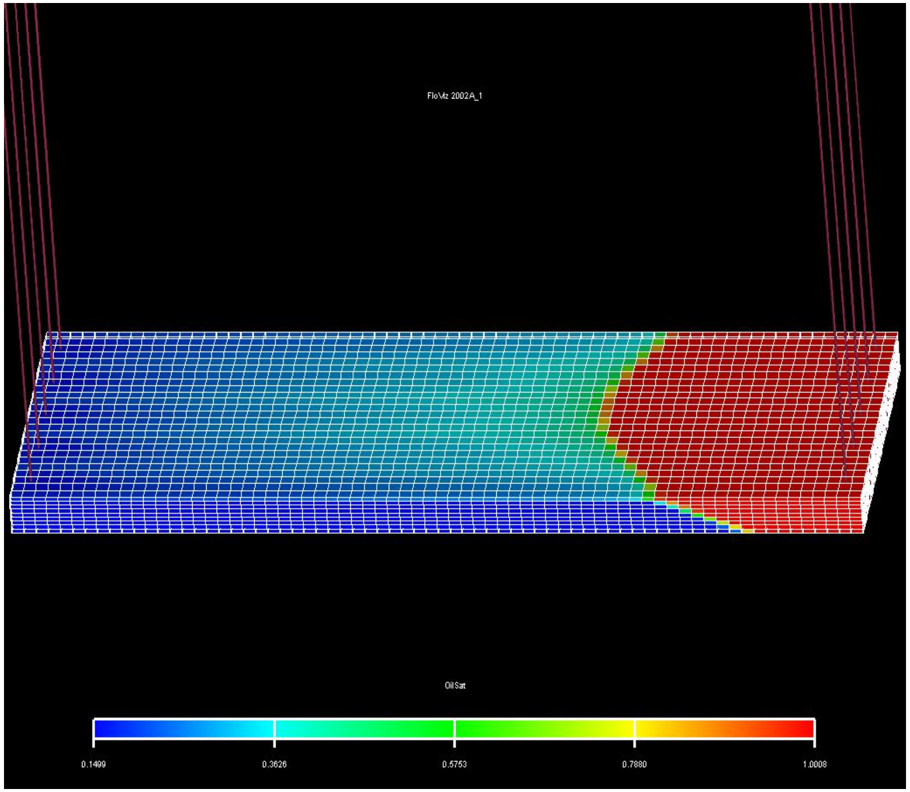
”Correct”;
From vol. strain, m_{ε}

Consequence for flow

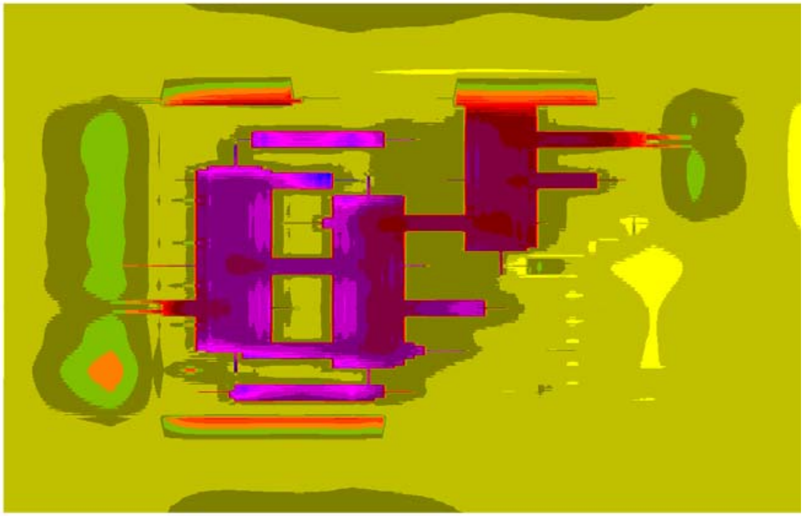
- Compaction is largest far from boundaries ("arching effect" – bowl shape)
- Permeability is generally lower in compacted volumes
  - increases towards boundaries
- Should expect lower flow rates in centre of reservoir

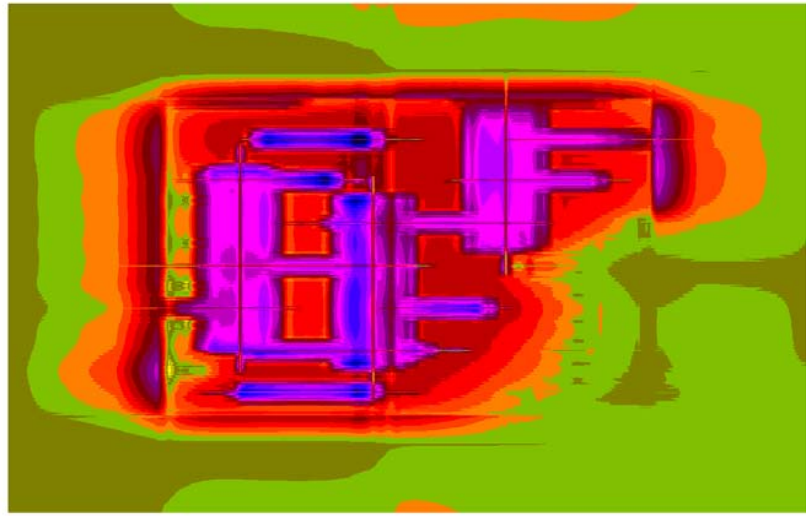
Simulated Oil Saturation, from m_{pf} and m_{ε}





For comparison: Fractured heterogeneous chalk

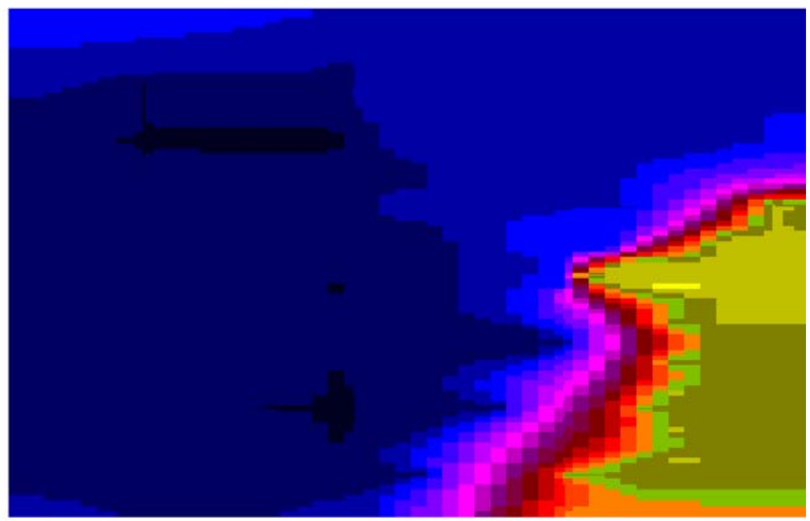




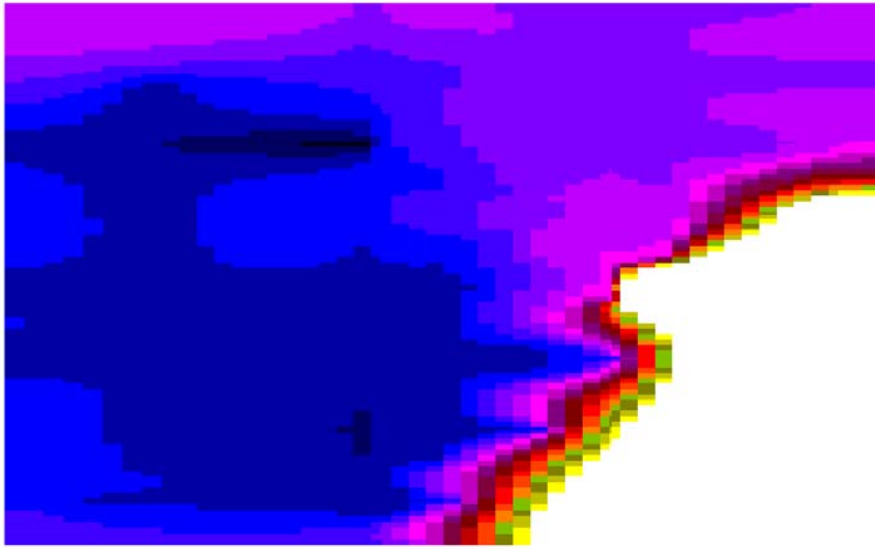
Mean eff. stress, central layer

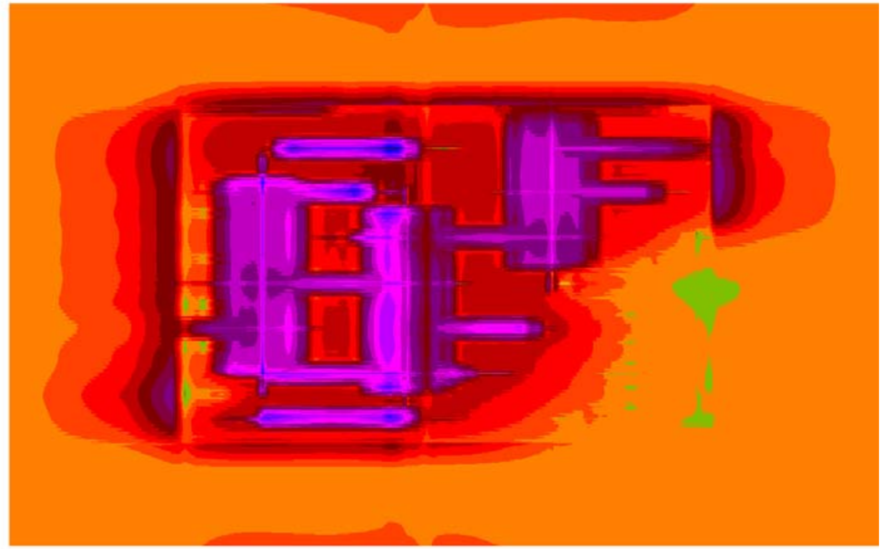
Mean eff. stress, base of reservoir

Fluid pressure from flow-sim, base of reservoir



Computed compaction





Eclipse:
From fluid pressure, m_{pf}

"Correct";
From vol. strain, m_{ε}

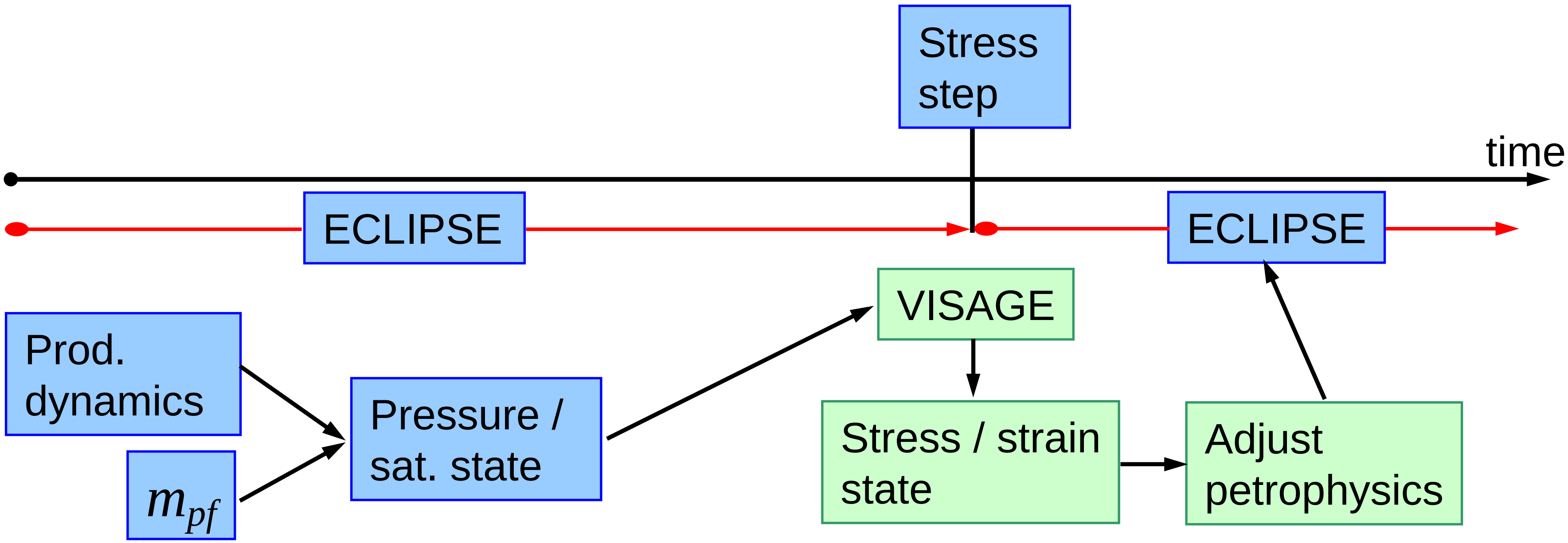
Fully Coupled Simulation

- Full system of fluid flow and rock mechanics equations solved simultaneously at each time step
  - Most accurate solution
  - Takes long to run
  - No fully coupled simulator includes all options that exist in commercial flow simulators or rock mechanics simulators

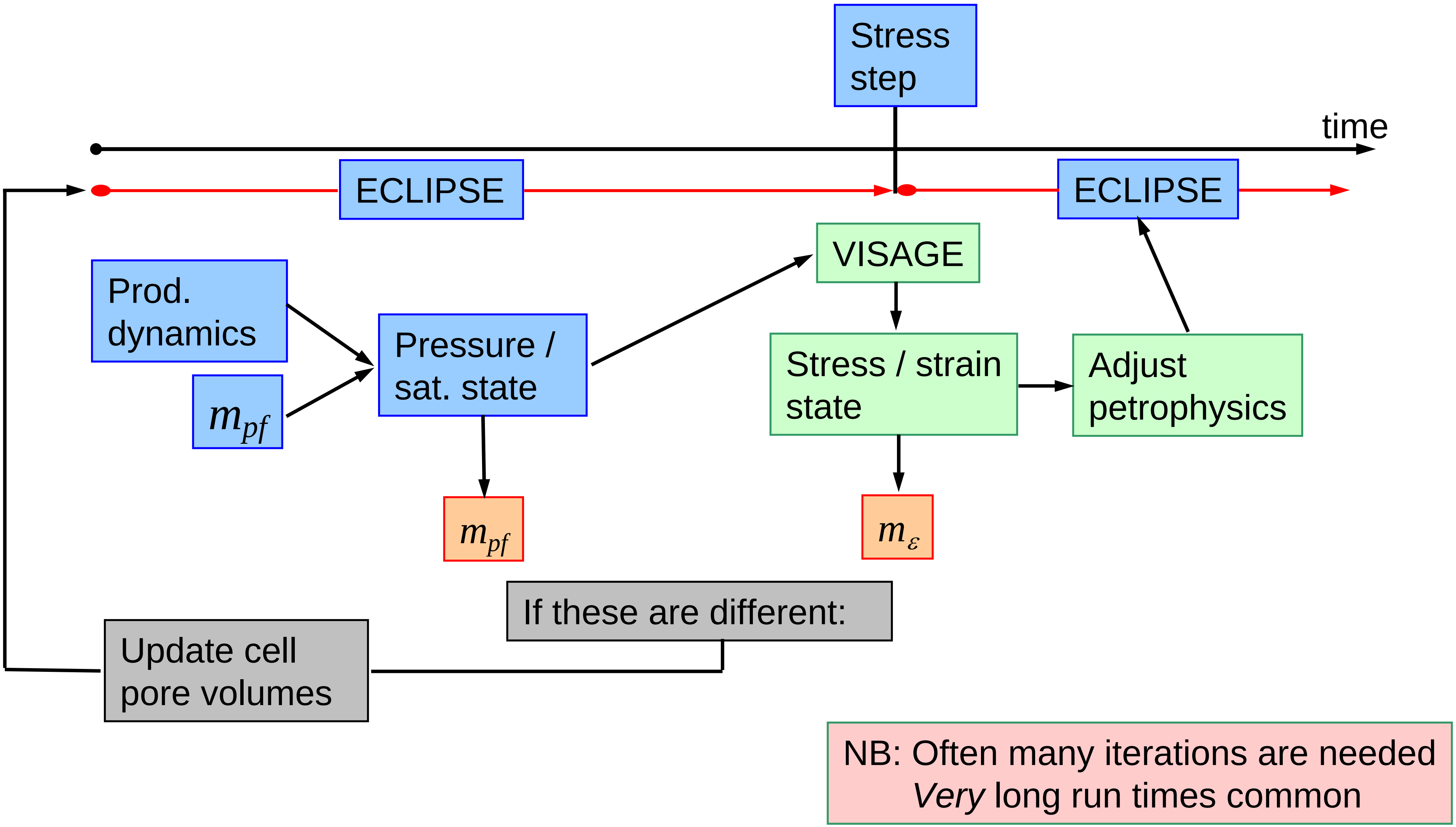
Sequential Coupling

- Flow simulator (Eclipse) and Rock Mech simulator (Visage) operate in turns
  - ✓ Access to bells & whistles in Eclipse and Visage
  - ✓ Data Exchange – No code modification

Coupling Scheme – Explicit



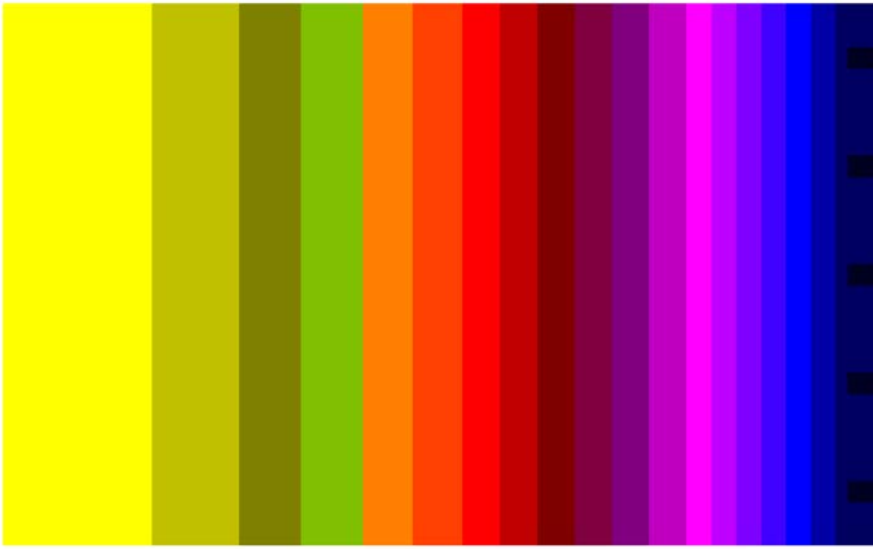
Coupling Scheme – Iterative

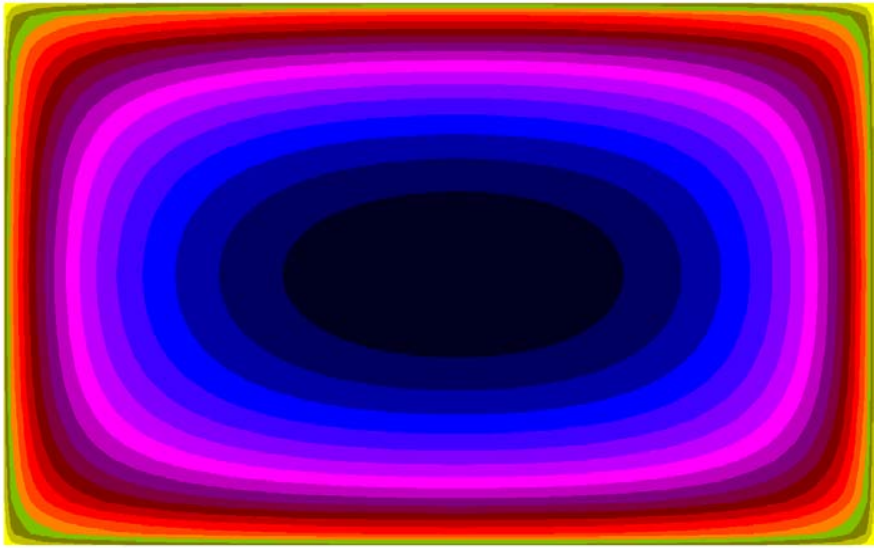


Comments

- At the start of each stress step, the flow-sim computed state (p_f, m_{pf}) is used as “initialiser” for the stress computations
- Since m_{pf} is wrong anyway, most reported schemes either don’t use it, or use a simple form
- Pore volumes (and p_f) are correct only after each stress step, not in flow sim calculations between

Stress step: Computing the compaction variation





With this m_{pf} as ”initial guess”

the stress simulator has a tough job

to converge to this solution, m_{ε}

And, although qualitatively OK, the compaction *level* is probably wrong (pore volume iterations needed)

Key Question

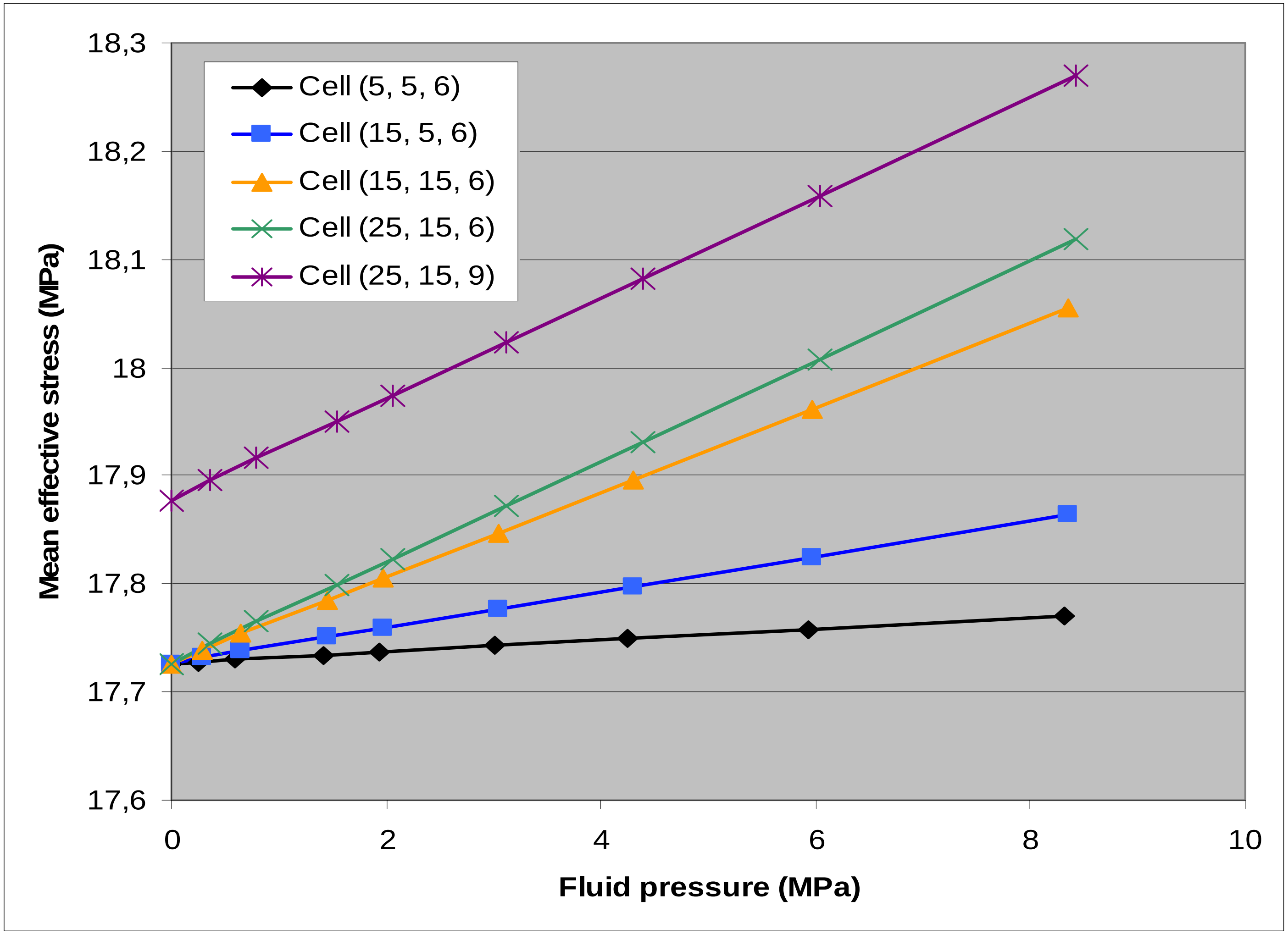
Can we *a priori* construct rules for deriving cell pore volumes, used by the flow simulator, which are closer to the ”true” volumes?

From previous discussion

- Compaction is a function of mean effective stress, p'
  - ✓ Measured or derived from poro-elasto-plastic model
- There is no simple relation between p' and p_f.
- Lack of correlation appears to be primarily due to geometry ("arching effect")

➢ Can p' and p_f be related *locally*?

p' vs. p_f in some cells



Constructing appropriate $m(p_f)$

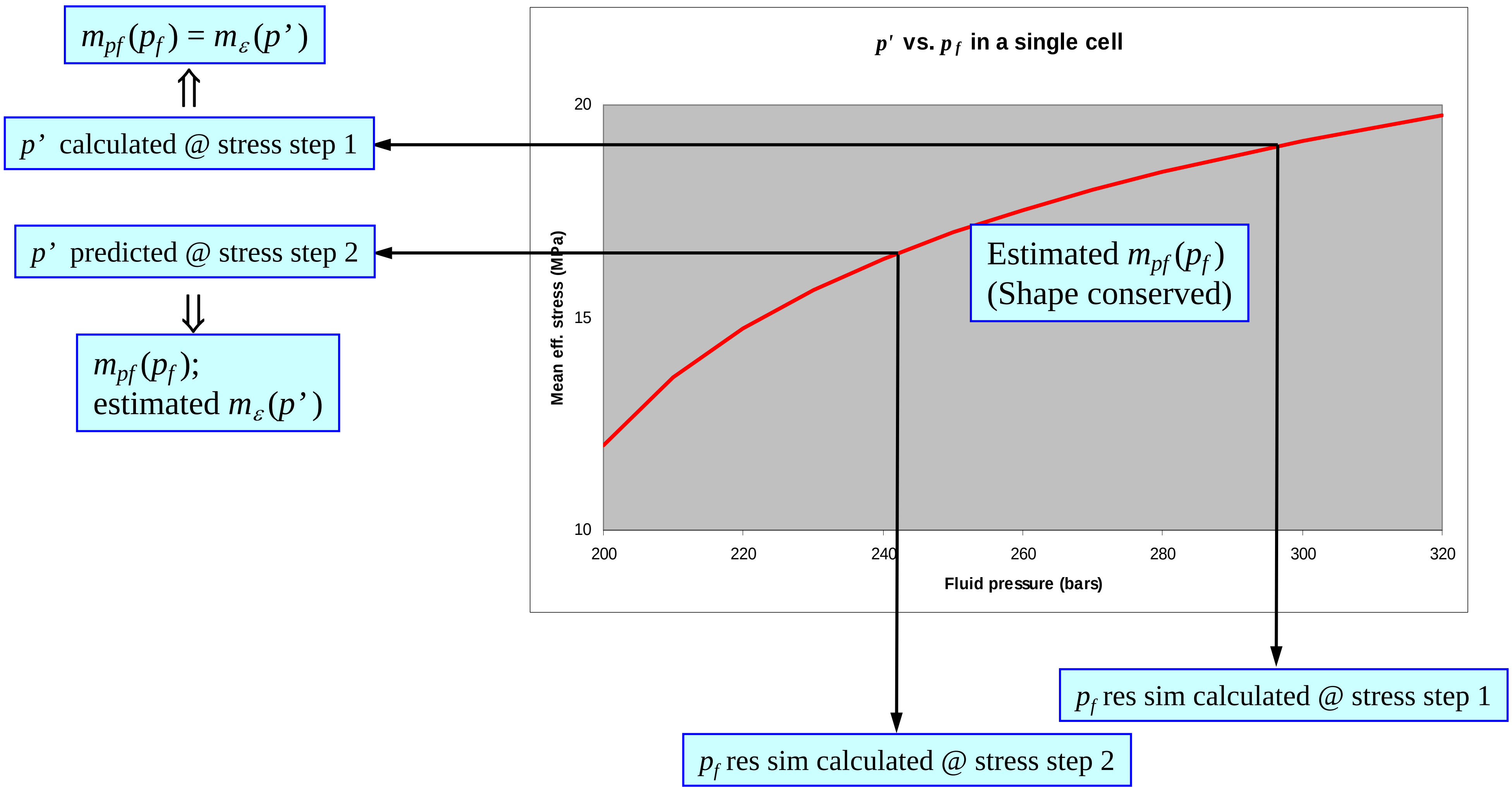
- At stress step 1, in each cell:
  - Get p_f and p' (or m_{pf} and m_ε)

- Assumption:
  In each cell,
  i. $p' = p'(p_f)$
  ii. $m_{pf}(p_f)$ can be found from $m_\varepsilon(p')$ by scaling

- If assumption OK:
  - Cell pore volume can be found (exact) on a later stress step t_{s2}:

$$p_f^2 = p_f(t_{s2}) \rightarrow m_{pf}(p_f^2) = m_{pf}\left[m_\varepsilon[p'(p_f^2)]\right]$$

Calculating compaction at a later stress step

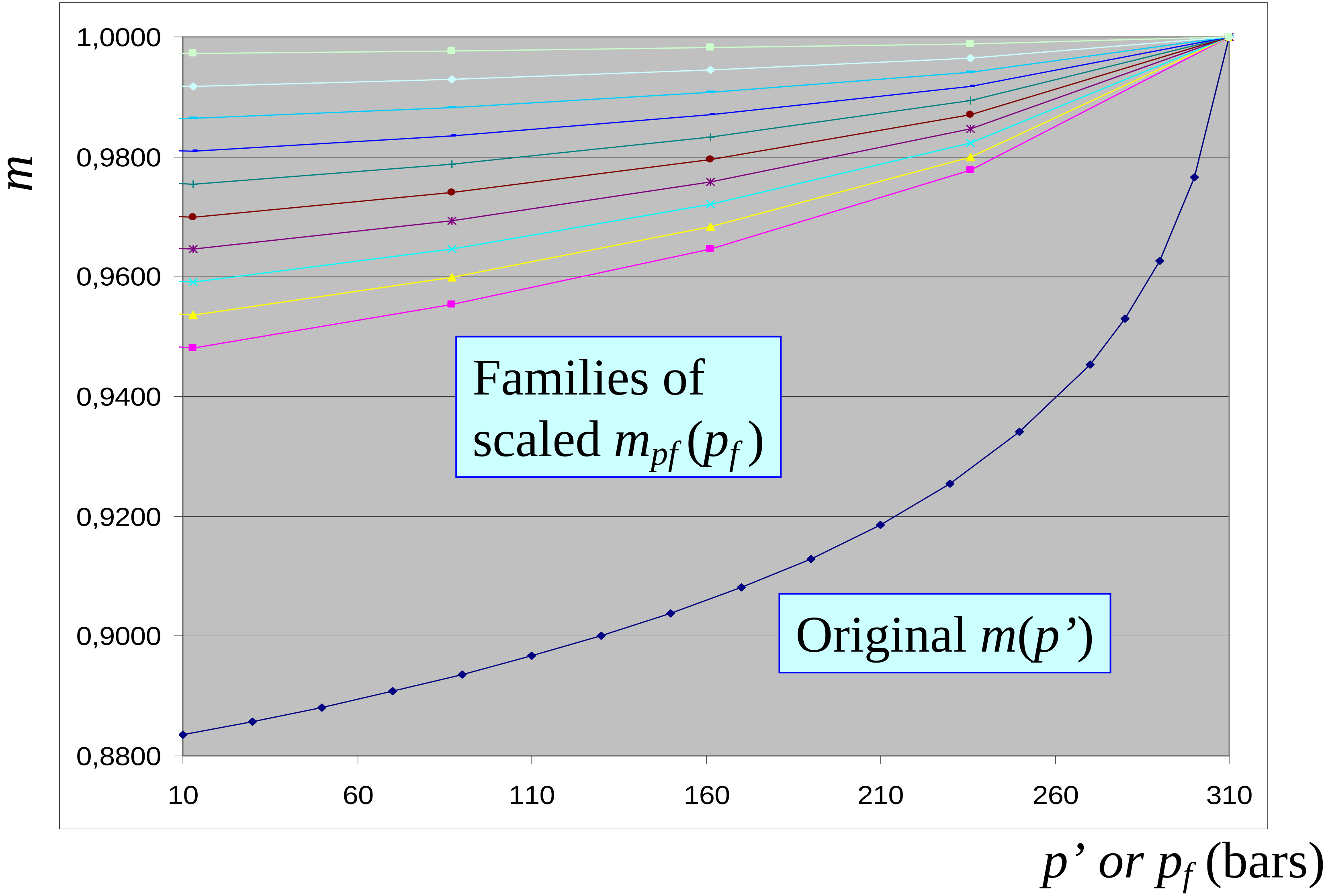


Comments

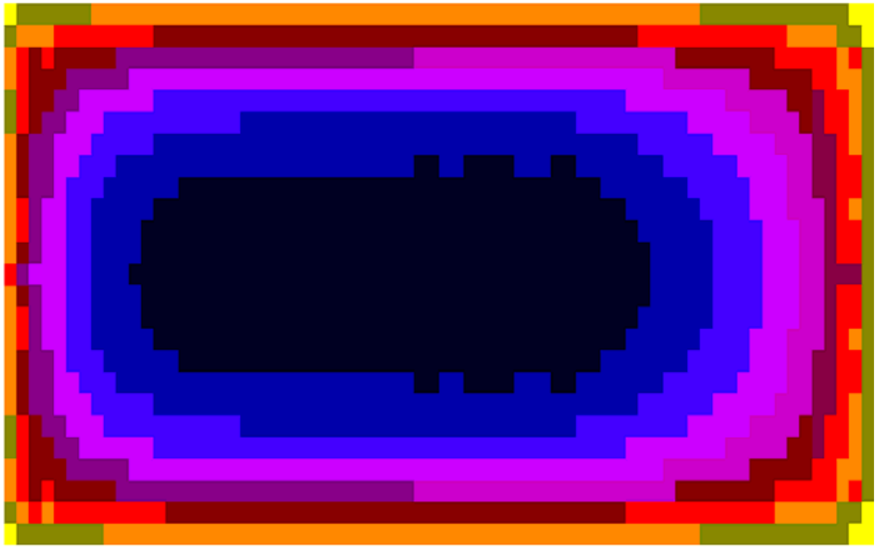
- Obviously the assumption cannot be true in general
- Computed $m_{pf}(t_{s2})$ is a (good) approximation to m_{ε}
  - Predictor for stress simulator
- In practice, we don't use one m_{pf}-table per cell, but group almost equal tables in material regions.
- Most of the hard work done at first stress step
  - Predictor is updated (improved) at each stress step (explicitly)
- The m_{pf} is "good enough" that pore volumes and p_f are accurate in flow simulator between stress steps

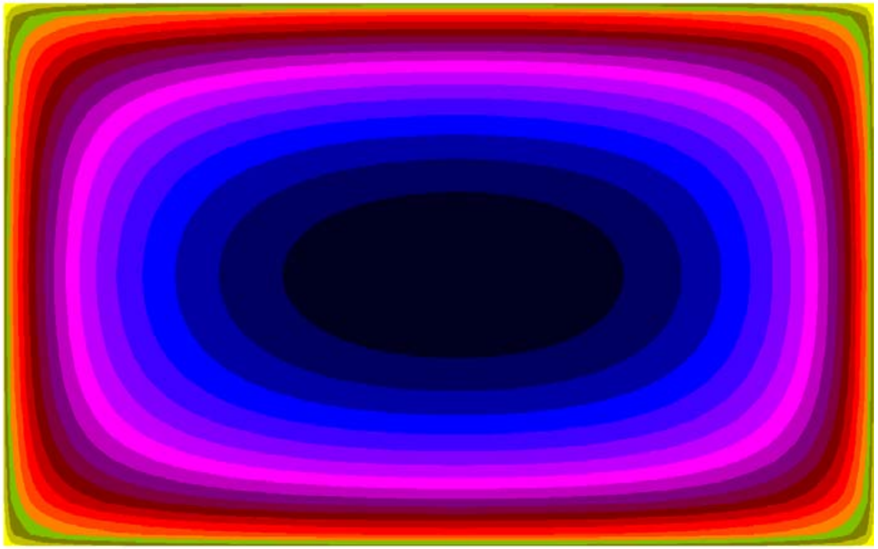
Ex. Grouping in Material Regions, XY View

Derived (pseudo) compaction functions



Computed compaction after redefinition





Eclipse:
From fluid pressure, m_{pf}

"Correct";
From vol. strain, m_{ε}

Computation after redefinition – simple case

- CPU time for each stress step calculation was reduced by more than 50% due to better “initial” pressure and compaction state
- No pore volume iterations were needed
- Total gain:
  - ✓ Large reduction of CPU time (can be >95%)
  - ✓ Accurate stress / compaction / fluid pressure field
  - ✓ Accurate pressure / pore volumes in flow simulator between stress steps
- The procedure has been fully automated for simple processes, but (still) requires Res. Eng. assistance for more complex problems

Conclusions

- For many reservoirs (especially weak sand, chalk) rock mechanics has a significant influence on flow pattern and production
- Should be investigated by coupled simulations
- A predictor scheme with improved efficiency and accuracy has been presented