Sandstone Compaction Modelling and Reservoir Simulation

by

Øystein Pettersen

EAGE, Madrid, June 2005

Outline

- State of the art
- Model for sandstone compaction
- Adapt to simulation
- Improved coupled simulation
  (rock mechanics ↔ flow simulation)

Compaction Modelling

- **Reservoir Simulator**: Compaction is a function of fluid pressure, $C_r = C_r(p_f)$
- **Reality**: Compaction is a function of effective stress
  → the difference between (confining) total stress and fluid pressure

- Measure for compaction in a simulator grid cell, **Pore Volume Multiplier**,

$$PVmult = \frac{\text{current cell pore volume}}{\text{initial cell pore volume}}$$

Computing *PVmult*

- From reservoir simulator:
  $PVmult(p_f)$ from $C_r(p_f)$ (table look-up)

- From rock mechanics simulator
  $PVmult(\text{strain}) = \exp(-\Delta \text{ vol. strain})$

Fluid Pressure and Stress

For practical purposes,

$$\sigma' = \sigma - p_f$$

where

σ' and σ are effective and total stress

p_f is fluid pressure

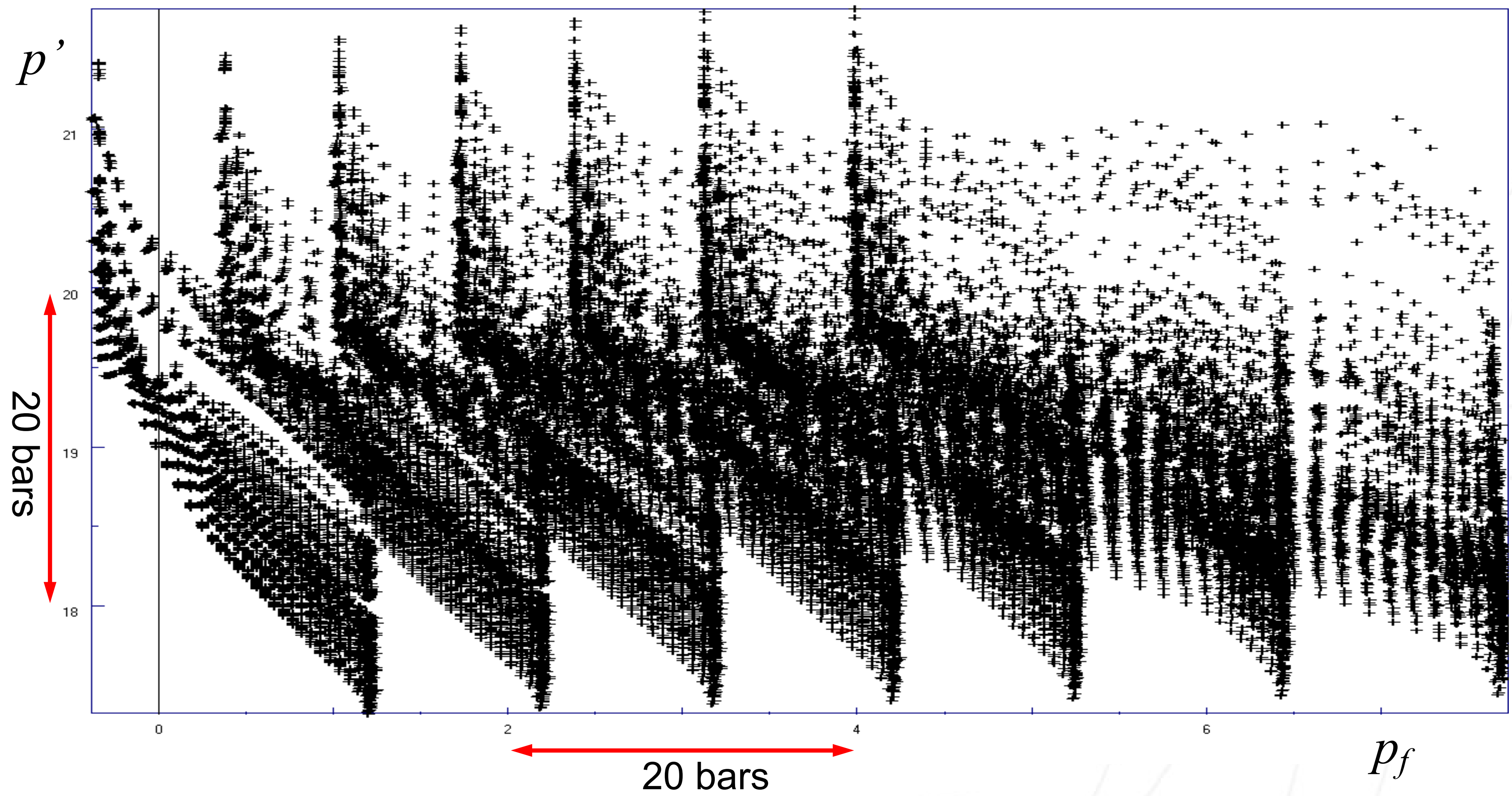
I.e.: Assuming compaction is a function of fluid pressure

is equivalent to assuming total stress is constant,

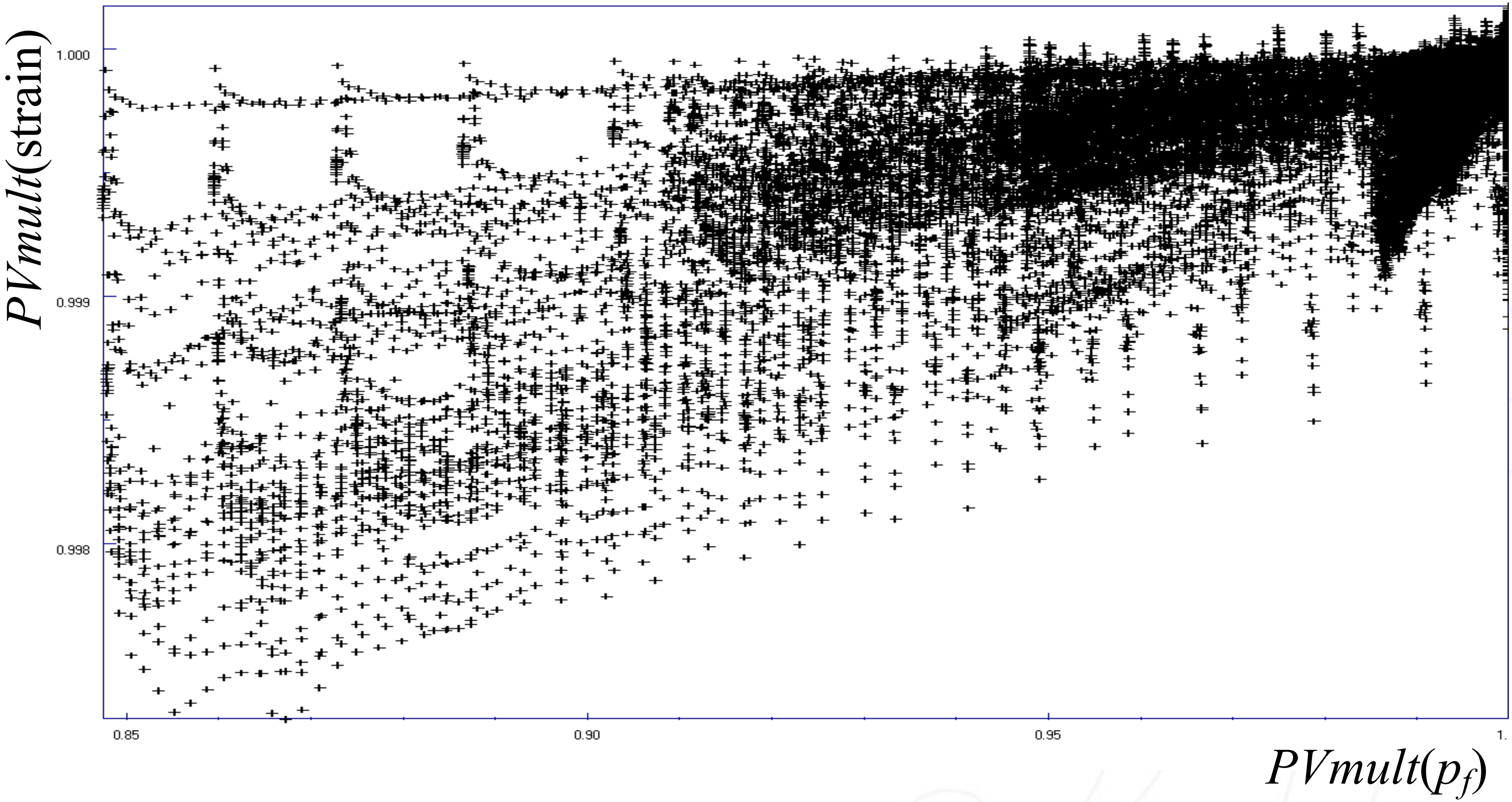
or

mean effective stress vs. fluid pressure is a straight line

Correlation: Mean Eff. Stress vs. Fluid Pressure

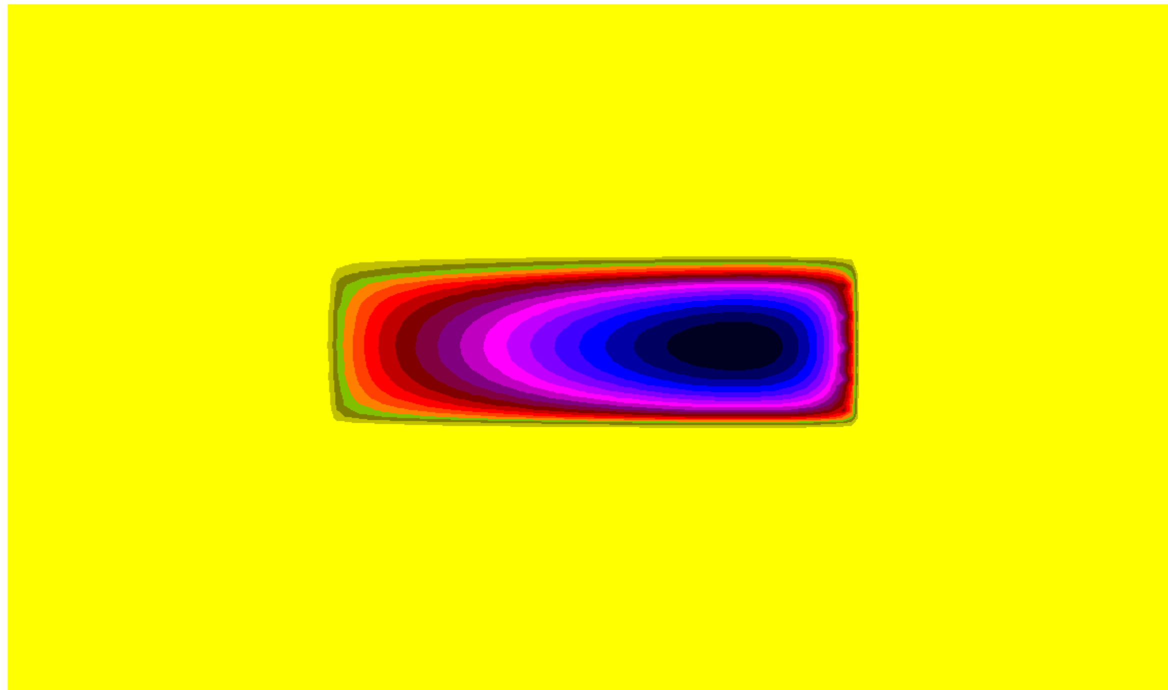


Correlation *PVmult*: "Correct" vs. from p_f



The main reason for the discrepancy is that the reservoir simulator knows nothing about actual soil displacement in the reservoir. (Boundary effects – “arching”)

$PVmult(p_f)$
(Reservoir only)



$PVmult(\mathrm{strain})$ (Reservoir and sideburdens)

There is a growing awareness that

- Dynamic reservoir stress state often has significant influence on petrophysics and fluid production
- These processes can only be understood by performing coupled simulations
(Rock mechanics simulator – Reservoir simulator)

In this study:

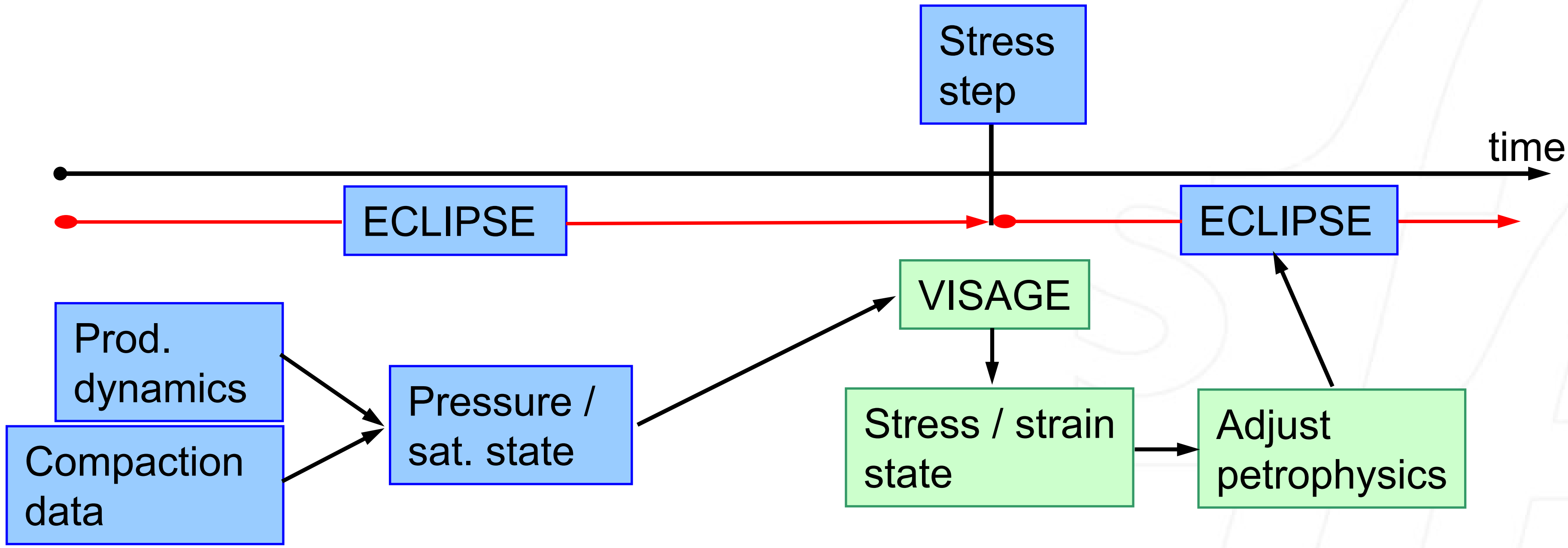
Finite Difference Reservoir simulator:
ECLIPSE from Schlumberger

Finite Element Rock Mech. simulator:
VISAGE from V.I.P.S Ltd.

Coupling Modes

- Fully coupled
  - 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

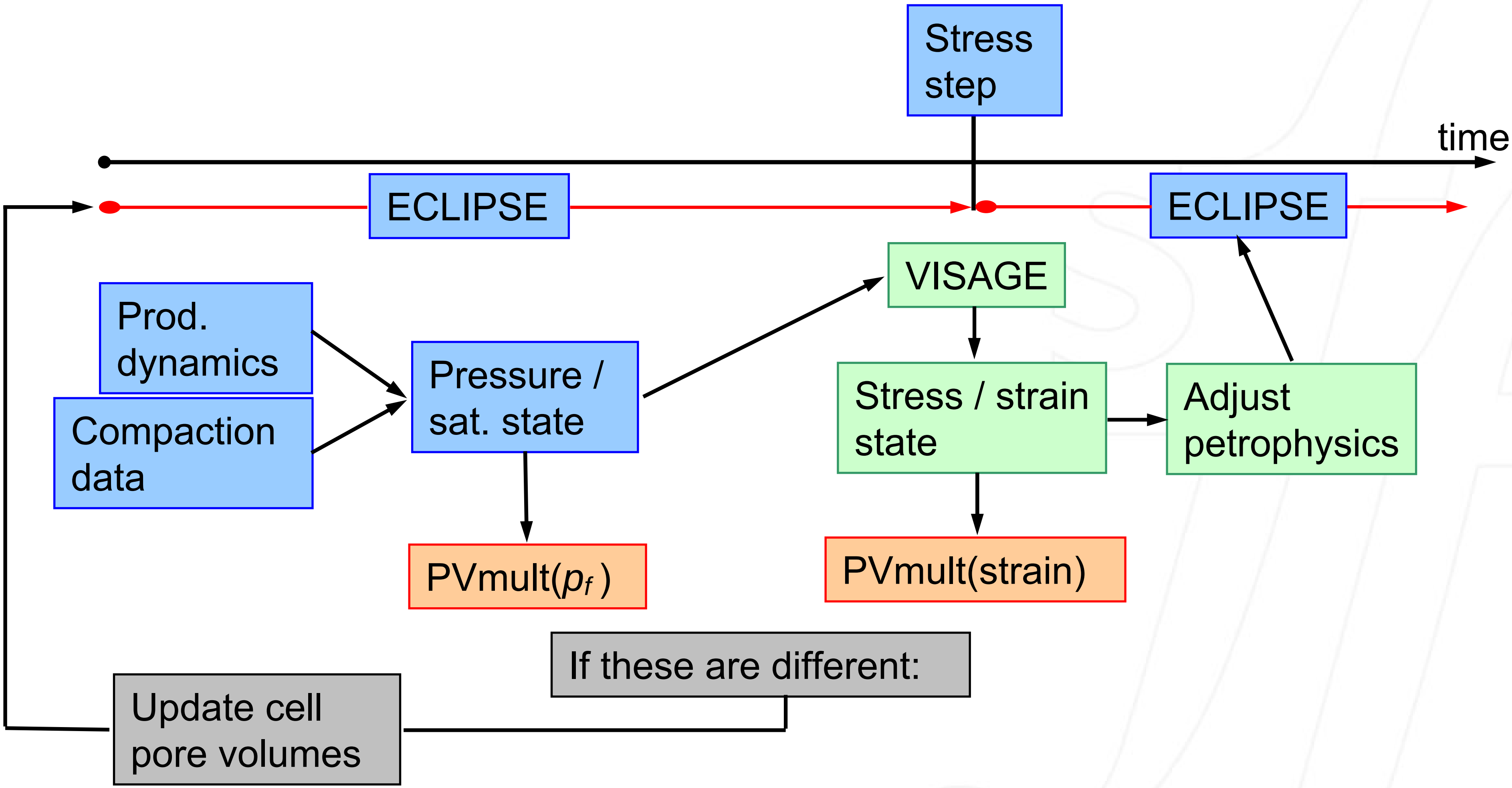
Coupling Modes: Explicit Coupling



Explicit Coupling

- 👍 Relatively fast
- 👍 Provides reasonably good reservoir stress state *distribution* (but not *level*)
- 👎 Questionable accuracy w.r.t. compaction modelling

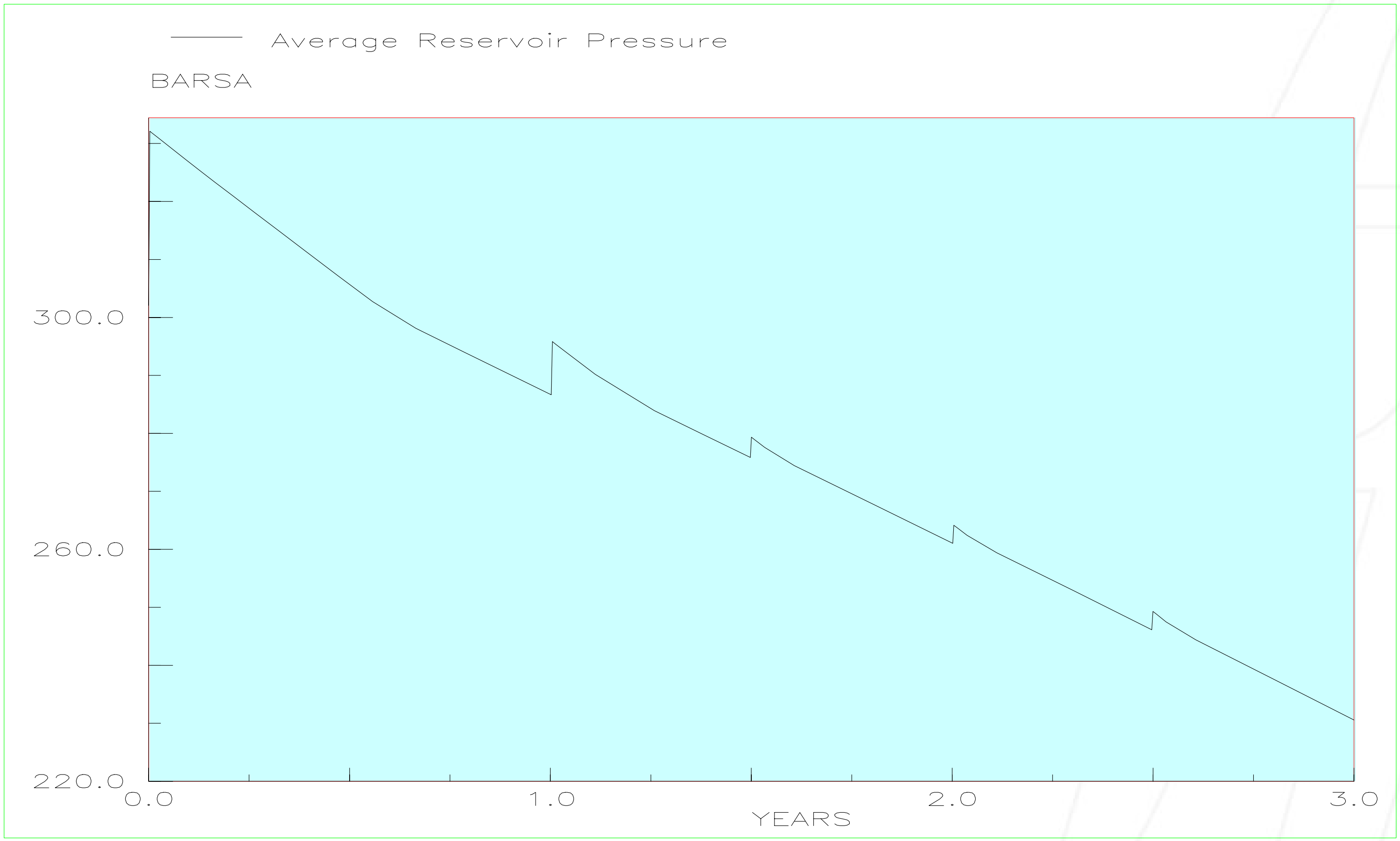
Coupling Modes: Iterative Coupling



Iterative Coupling

- Good reservoir stress state *distribution* and *level,*
  - Accurate compaction
- Can take long to run
- Updates performed only on stress steps
  - Pressure discontinuities

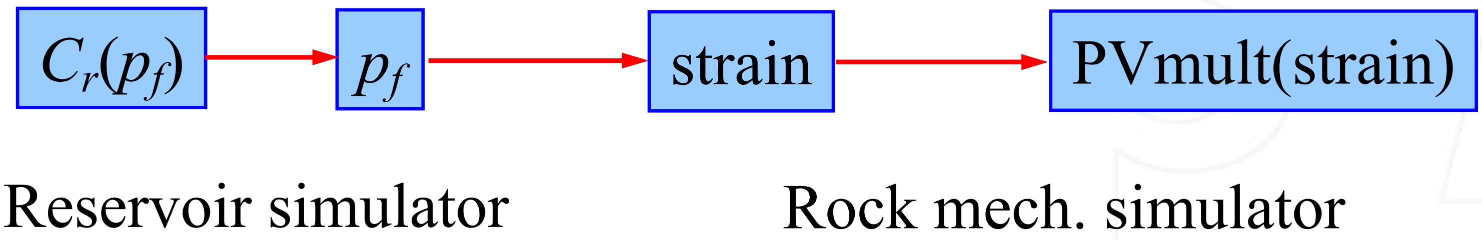
Pressure vs. Time in Iterative Coupled Run



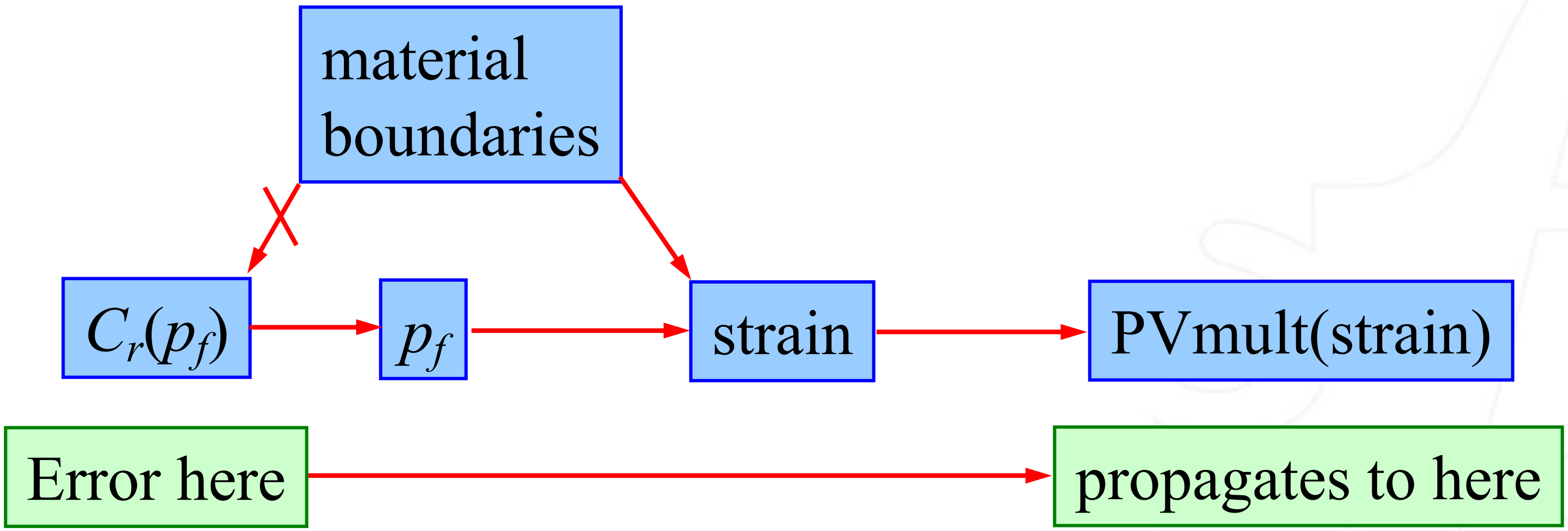
Discontinuties at stress steps

Improved Coupling Scheme

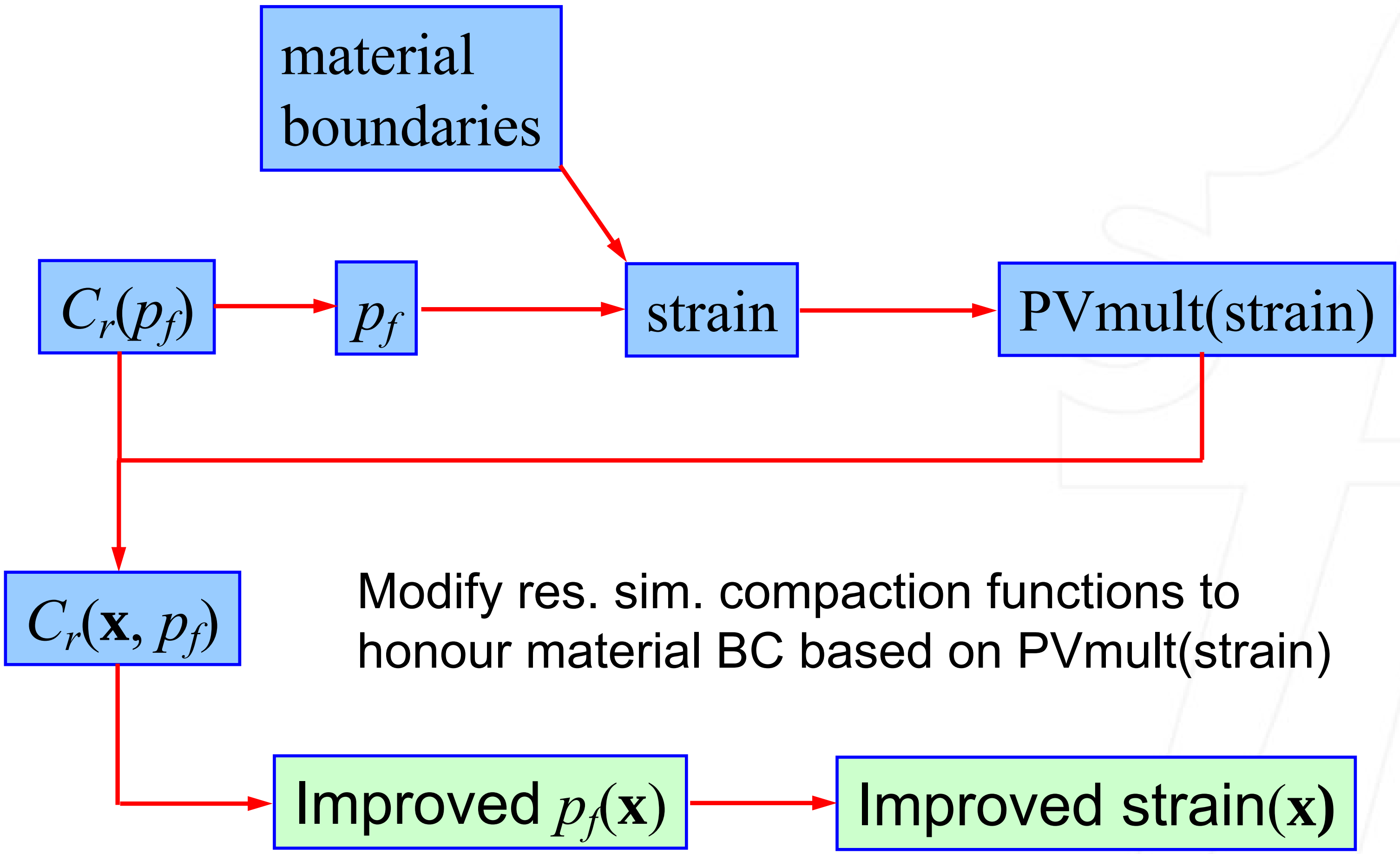
Evaluation chain:



Improved Coupling Scheme



Improved Coupling Scheme



Modify res. sim. compaction functions to honour material BC based on PVmult(strain)

Improved Coupling Scheme

- extend trends in $C_r(\mathbf{x}, p_f)$ in space and time to get a better predictor for stress simulations
- Modifications done on res. sim. data: Cont. pressure

Goal

- ☺ Faster than iterative coupling
- ☺ More accurate than explicit coupling

Consistent Compaction Model

- To proceed we need a compaction model which is "equivalent" in VISAGE and ECLIPSE

- Definition:
  A compaction model is consistent if the flow simulator compaction function is derived from the rock mechanics poro-elasto-plastic model.

(Idealized) Grain Pack Model for Sand / Sandstone

Basis – Pure Geomechanical Compaction

- Typical measured bulk compressibilities for sands / sandstones are much smaller than grain compressibility
  - ✓ Grain (quartz): K ~ 38 GPa
  - ✓ Sands: K = 100 MPa – 1 GPa
  - ✓ Sandstones: K = 5 – 15 GPa

Basis – Pure Geomechanical Compaction

- Typical measured bulk compressibilities for sands / sandstones are much smaller than grain compressibility
  - ✓ Grain (quartz): K ~ 38 GPa
  - ✓ Sands: K = 100 MPa – 1 GPa
  - ✓ Sandstones: K = 5 – 15 GPa

➢ Bulk compressibility cannot be explained by grain compression alone

Basis – Pure Geomechanical Compaction

- Typical measured bulk compressibilities for sands / sandstones are much smaller than grain compressibility
  - ✓ Grain (quartz): K ~ 38 GPa
  - ✓ Sands: K = 100 MPa – 1 GPa
  - ✓ Sandstones: K = 5 – 15 GPa

- Bulk compressibility cannot be explained by grain compression alone

- Pore space compaction in a skeleton of *rigid grains* can only be caused by grain reorganization

Basis – Pure Geomechanical Compaction

- Typical measured bulk compressibilities for sands / sandstones are much smaller than grain compressibility
  - ✓ Grain (quartz): K ~ 38 GPa
  - ✓ Sands: K = 100 MPa – 1 GPa
  - ✓ Sandstones: K = 5 – 15 GPa

- ➢ Bulk compressibility cannot be explained by grain compression alone

- ➢ Pore space compaction in a skeleton of *rigid grains* can only be caused by grain reorganization

- Principle of Stable Settlement:
  When grain packing changes, it will always seek a more stable packing pattern.

Consequences

- Each stress state corresponds to a stable packing configuration
  - the tightest possible packing at that state

Consequences

- Each stress state corresponds to a stable packing configuration
  - the tightest possible packing at that state

- As packing becomes tighter, further packing will be increasingly more difficult to achieve
  - each “packing level” is more stable than previous levels
  - Compressibility increases with load

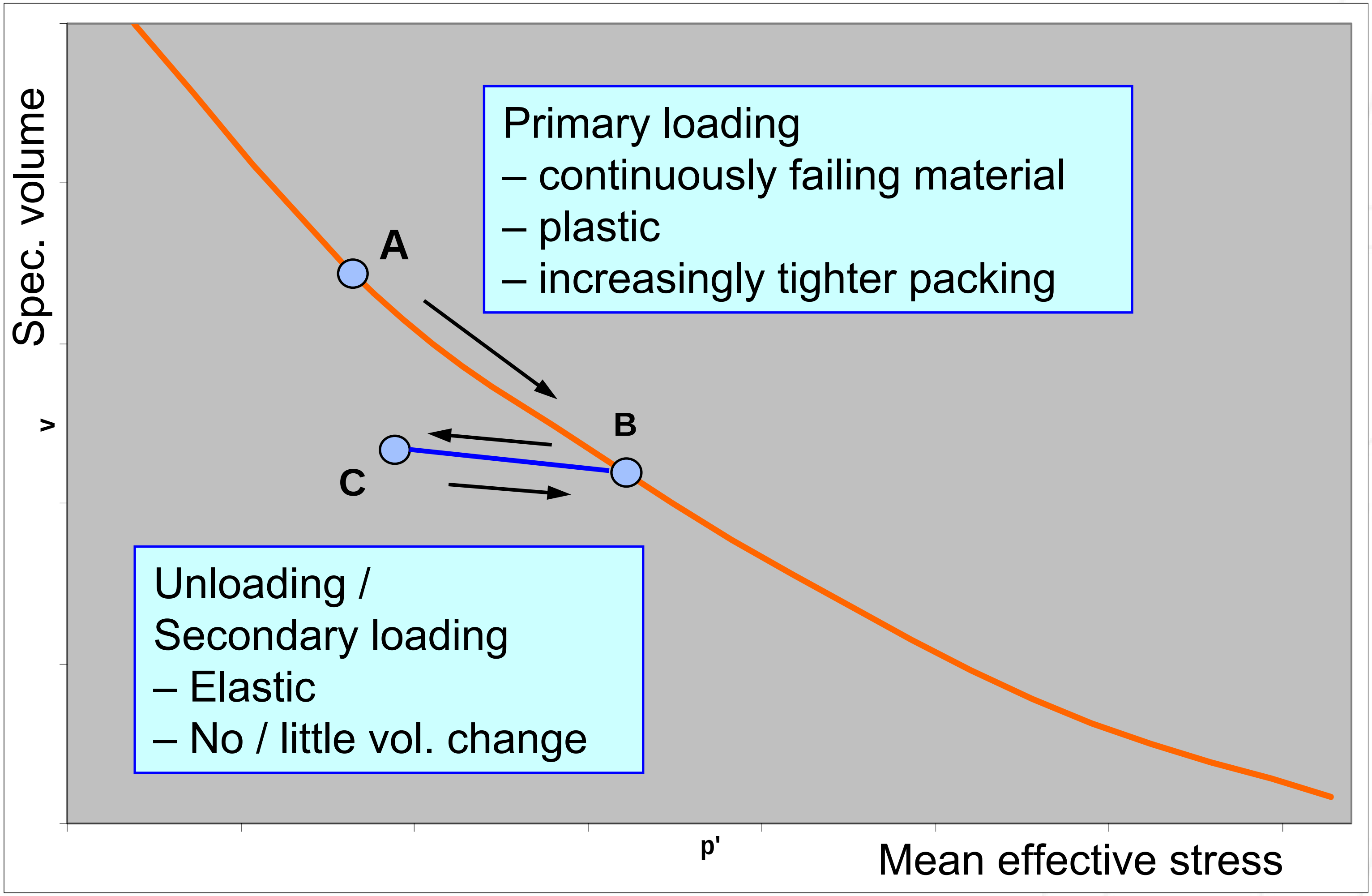
Consequences

- Each stress state corresponds to a stable packing configuration
  - the tightest possible packing at that state
- As packing becomes tighter, further packing will be increasingly more difficult to achieve
  - each "packing level" is more stable than previous levels
  - Compressibility increases with load
- Relieving stress will *not* return the soil to a previous, *less stable* packing level

Implications

- At pore level, continuous pore wall failure is taking place during compaction
- At bulk level, compaction will be observed as permanent deformation of pore space (plasticity)
- The soil has *no memory* of its past stress history
  - each packing level can be seen as a “new” material with its own poro-elasto-plastic parameters

Characteristics of Grain Pack Model



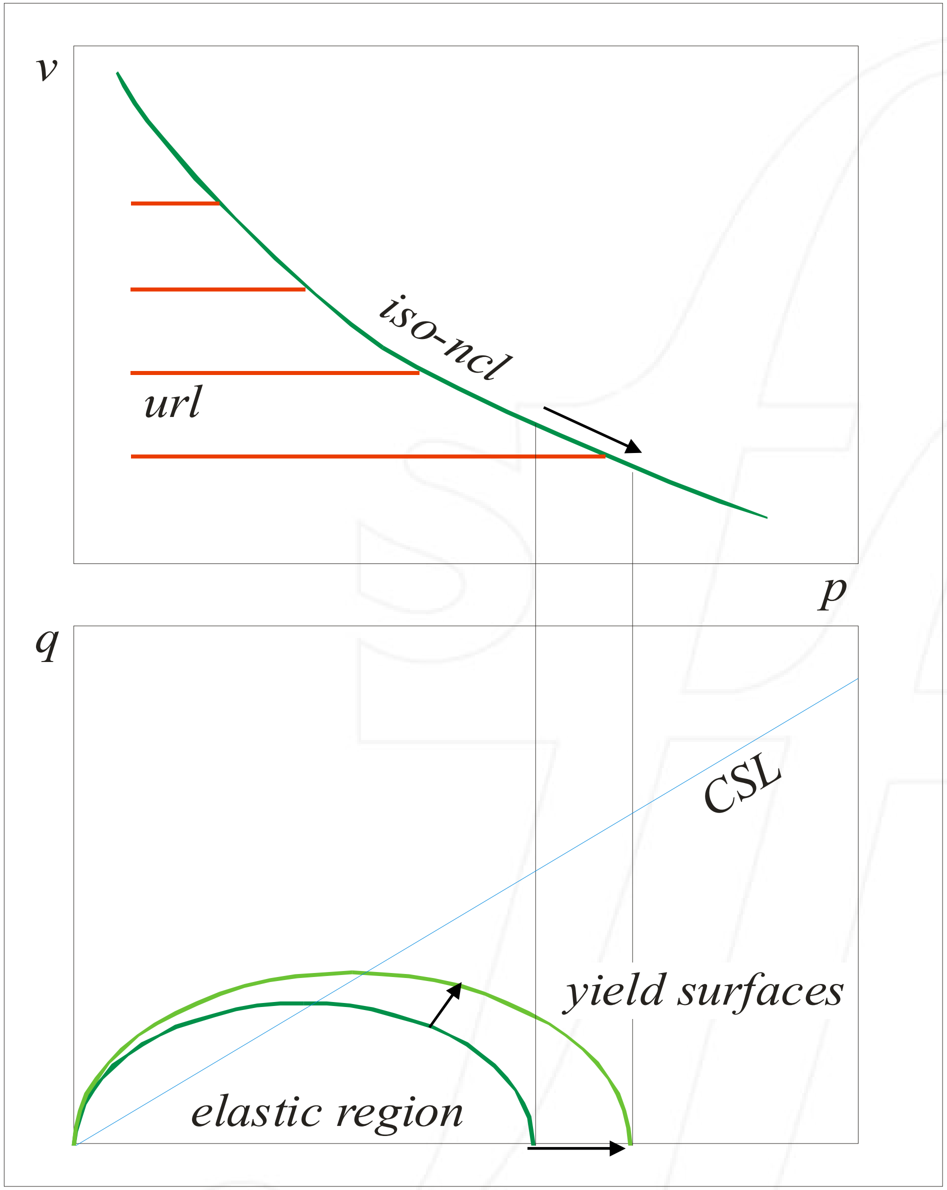
Hence, the grain pack model behaves according to Critical State Theory:

Change of *v* along iso-ncl (isotropic normal compression line) is determined by expansion of yield surface in the stress plane

Movement along url's (unloading-reloading lines) occurs in the elastic region in the stress plane

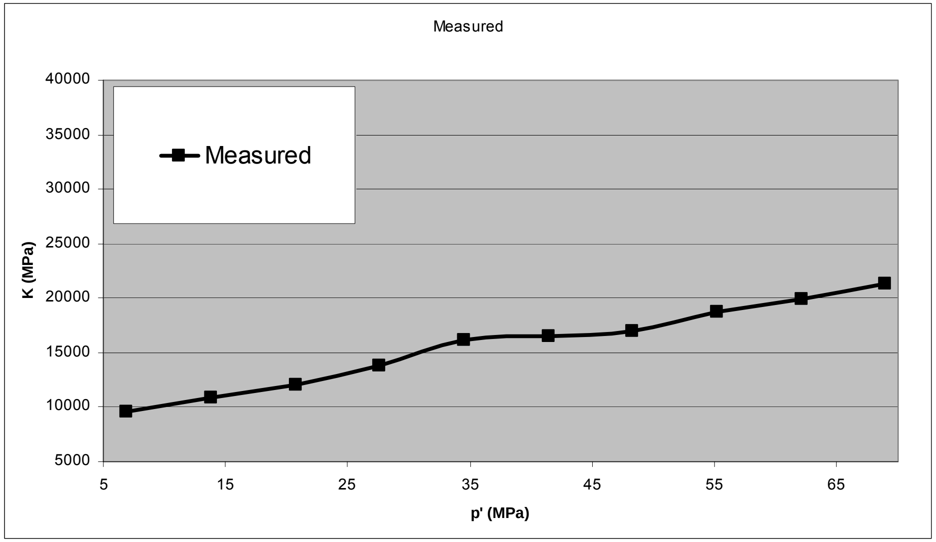
Yield surface expansion is determined by the hardening rule

$$\frac{\partial p}{\partial \varepsilon_p} = p \frac{v}{v_0} H$$



- **For sands / sandstones, Critical State Theory is *the* appropriate failure model to use.**
  - Not e.g. Mohr-Coulomb (the most popular choice).
  - Definitely not linear elastic
  - In practice we use the special case: Cam Clay Model

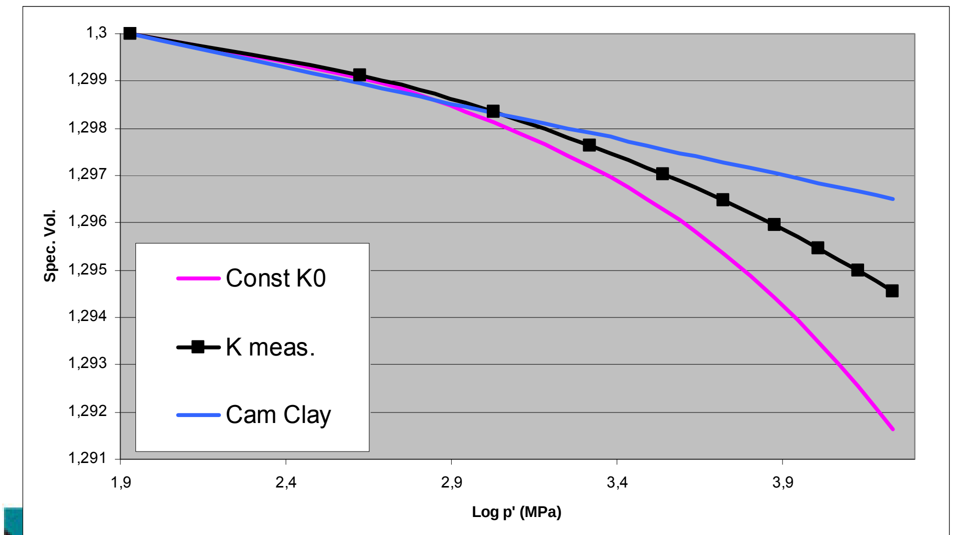
$K(p') \rightarrow C_r(p')$ (Med. Strength Sandstone)

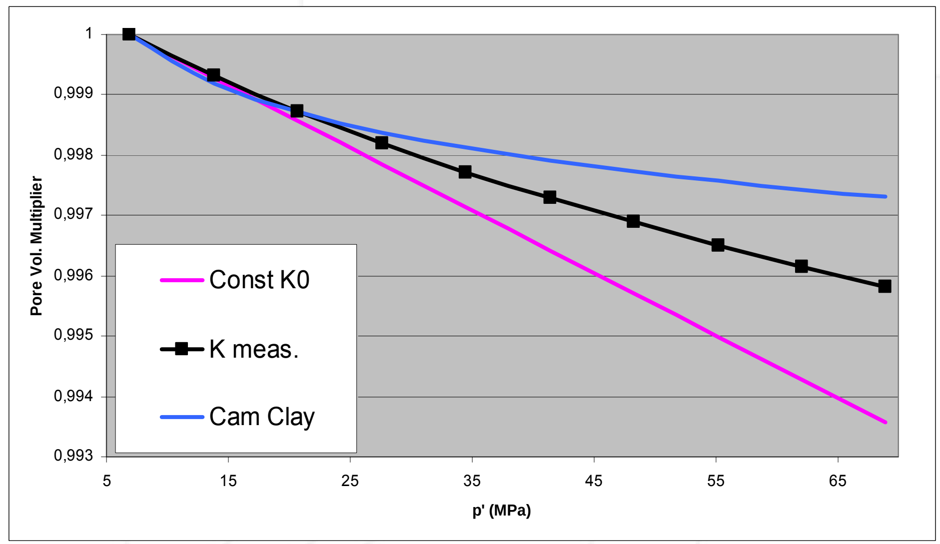


K(p')

v(p')

PVmult(*p'*)





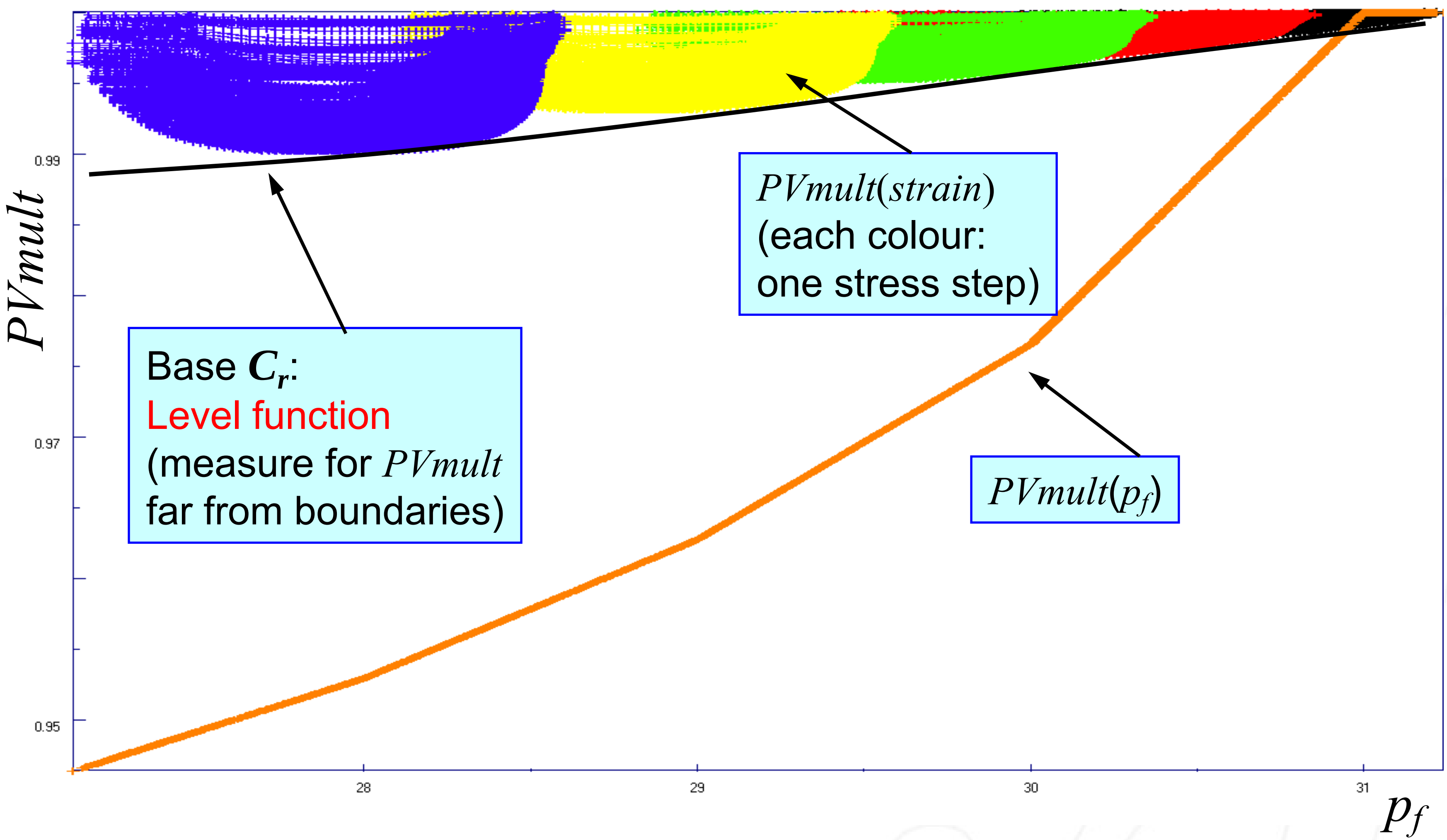
Calculating compaction distribution, Step by step

Rock Mech. Failure Model: Critical State (Cam Clay)

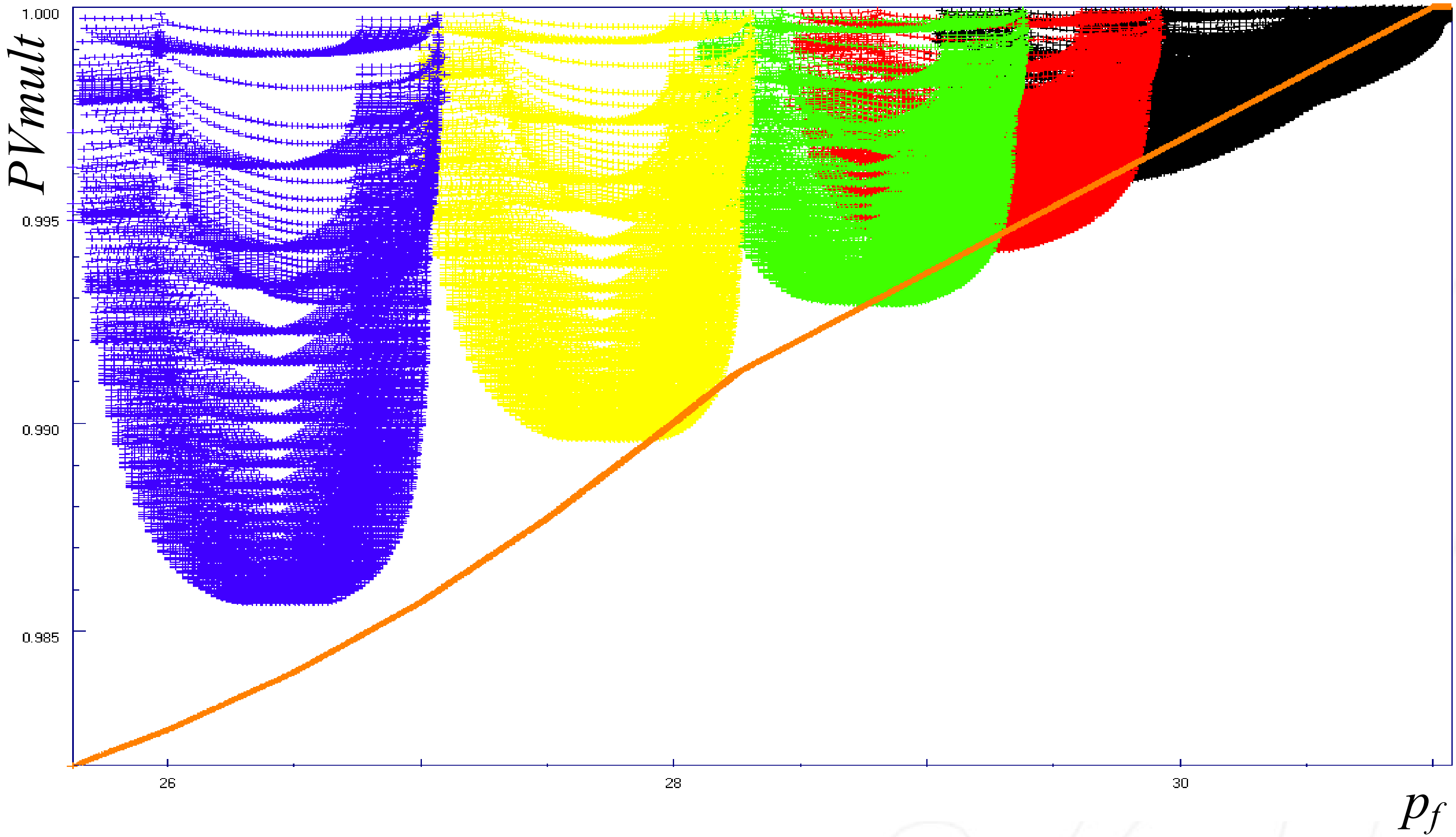
Flow Sim. Compaction function: Derived from Cam Clay

All calculations done on stress step 2; but complete simulation performed at each iteration, for illustrative purposes

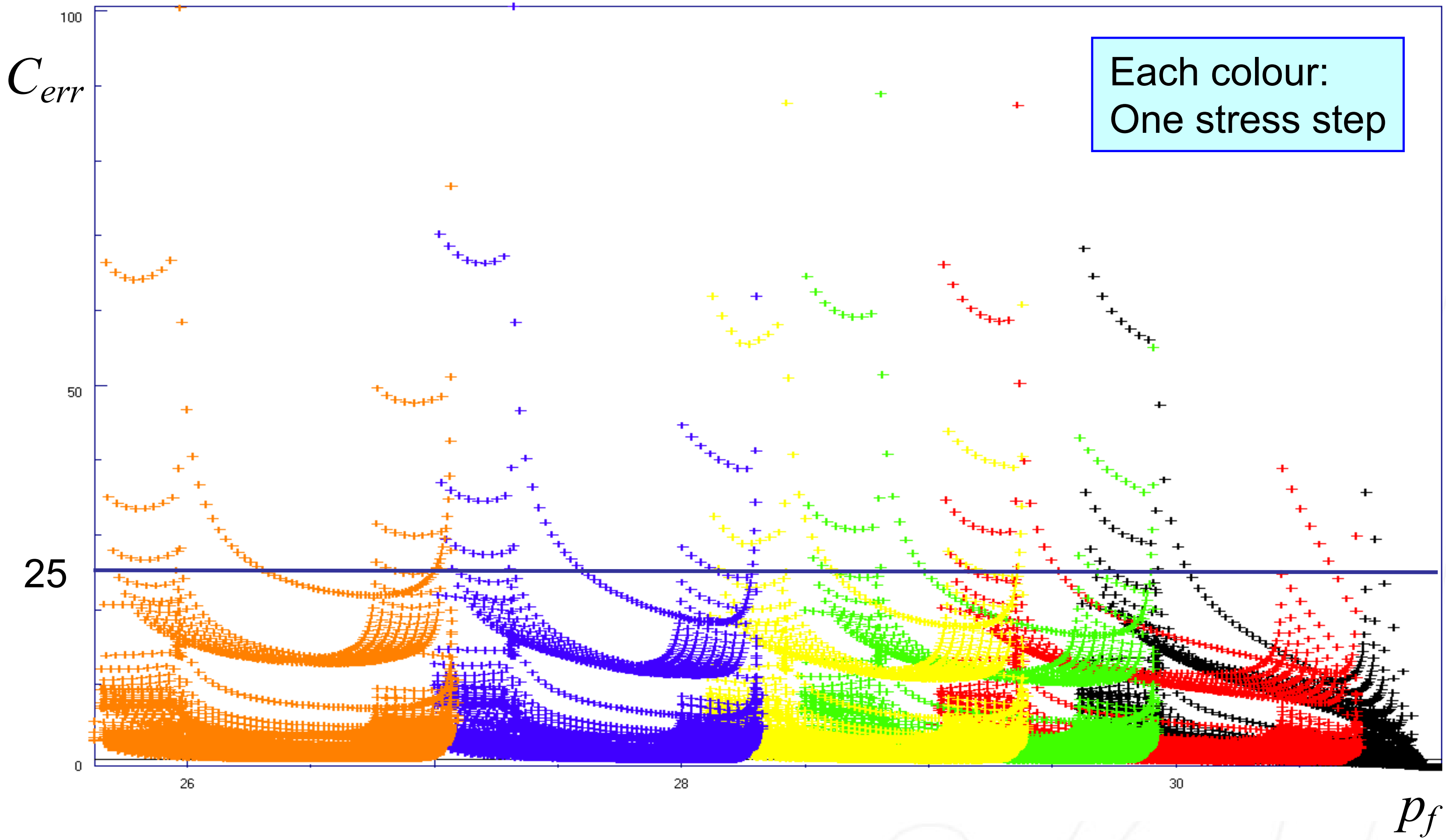
Iteration Step 1: Using $C_r(p_f)$ instead of $C_r(p')$



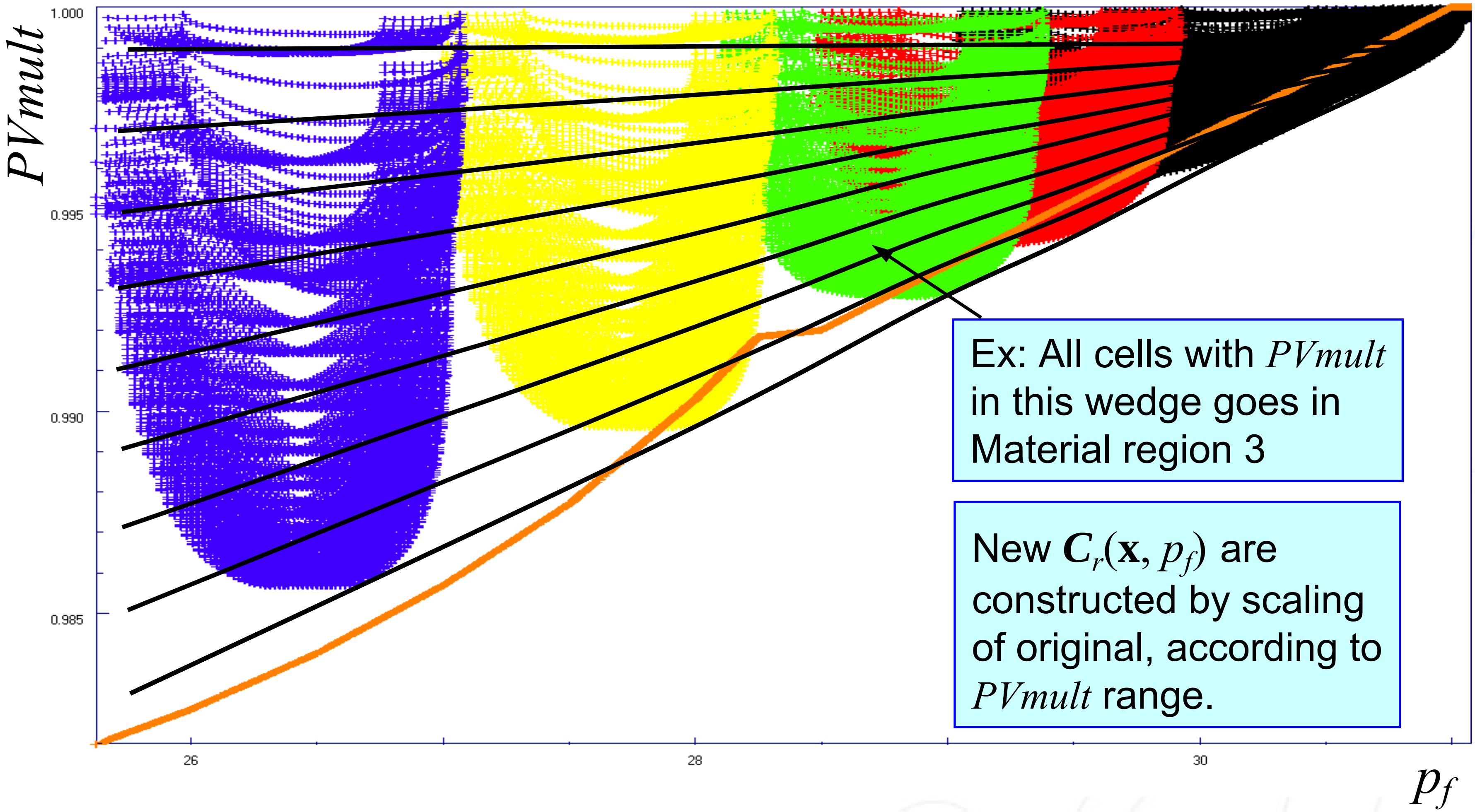
Iteration Step 2: Scale $C_r(p_f)$ to Level Function



Error in Compaction Computation



Iteration Step 3:
Subdivide Reservoir into new Material Regions

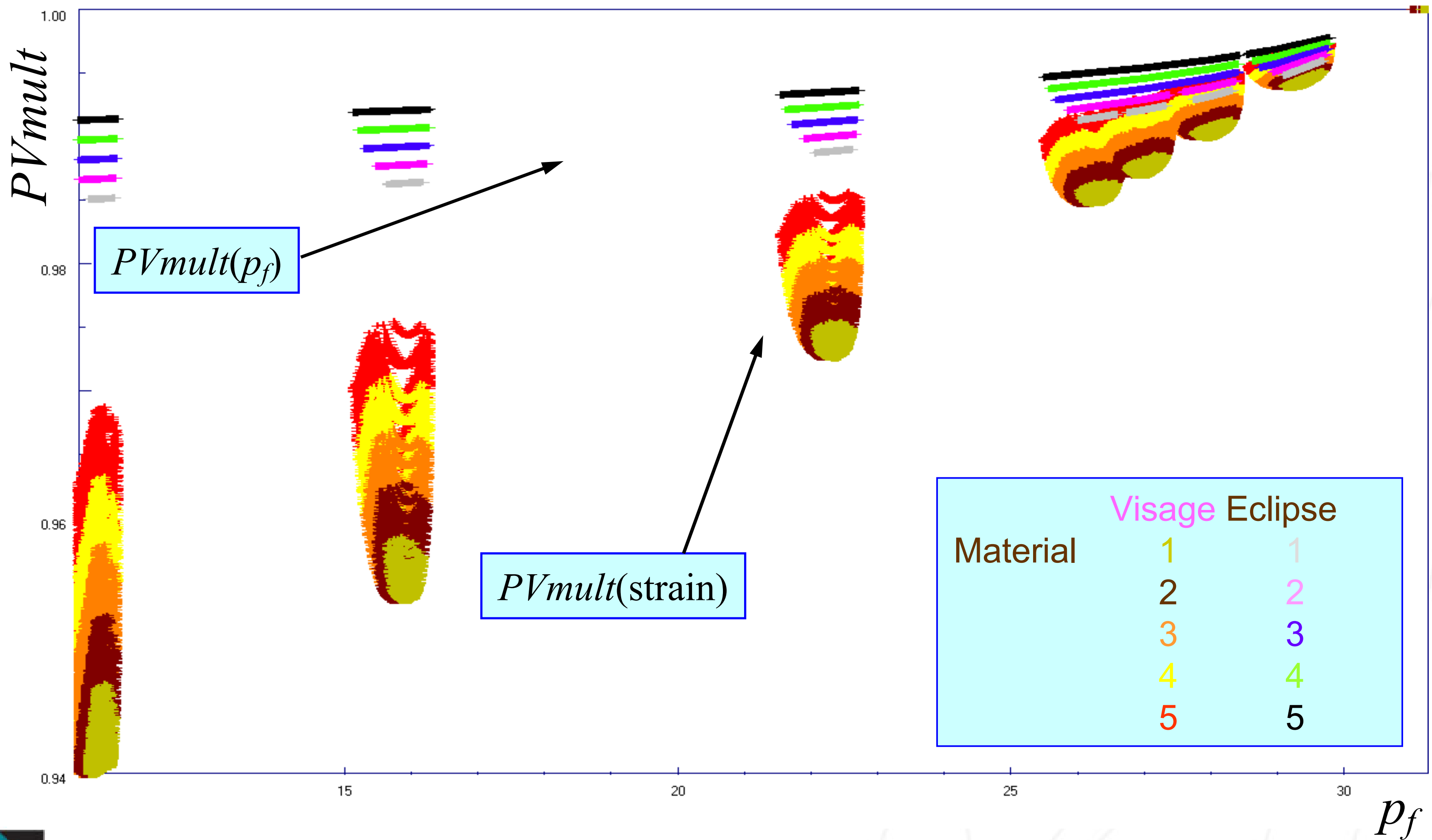


Ex: All cells with *PVmult* in this wedge goes in Material region 3

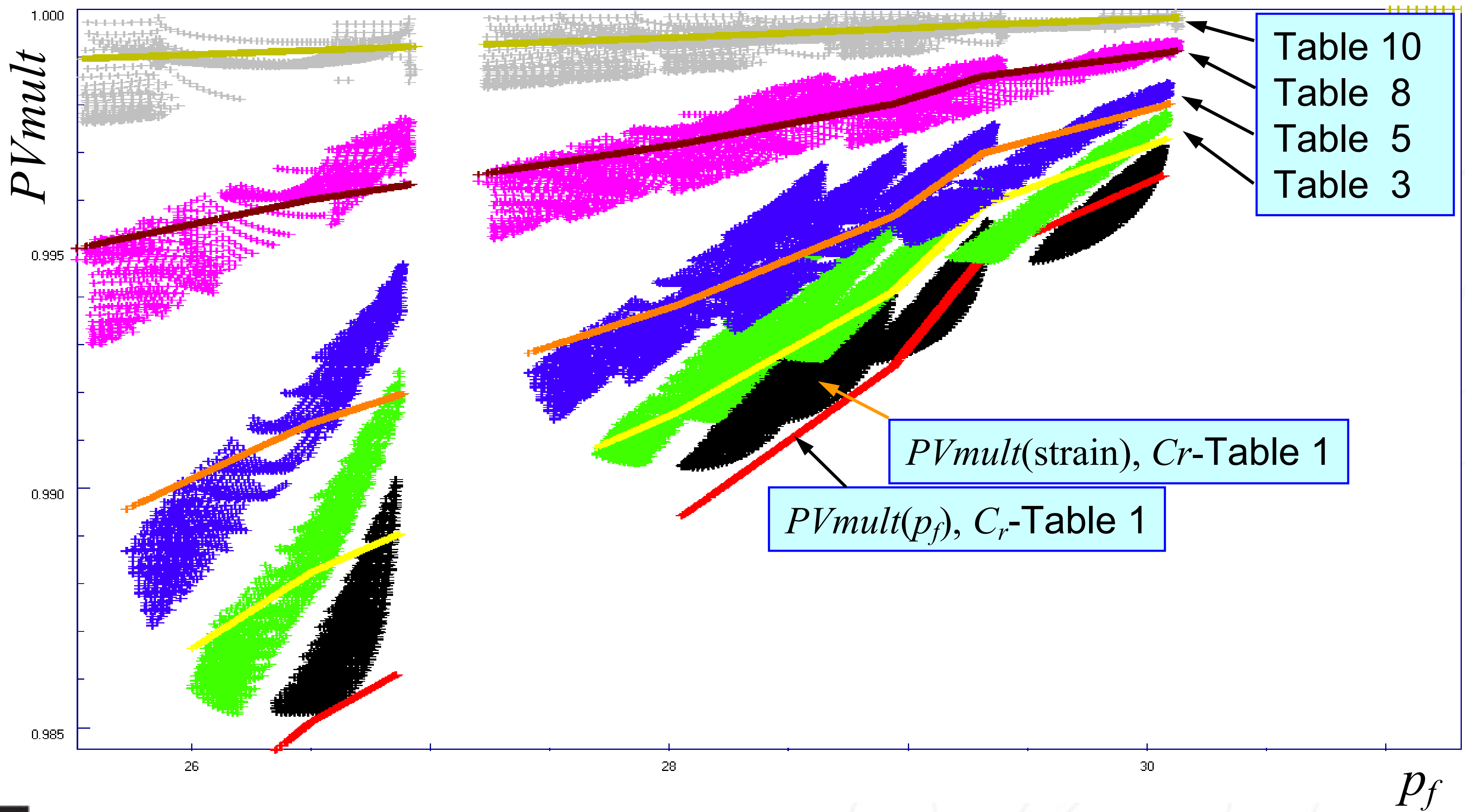
New $\boldsymbol{C}_r(\mathbf{x}, p_f)$ are constructed by scaling of original, according to *PVmult* range.

New Material Regions, XY View Middle Layer

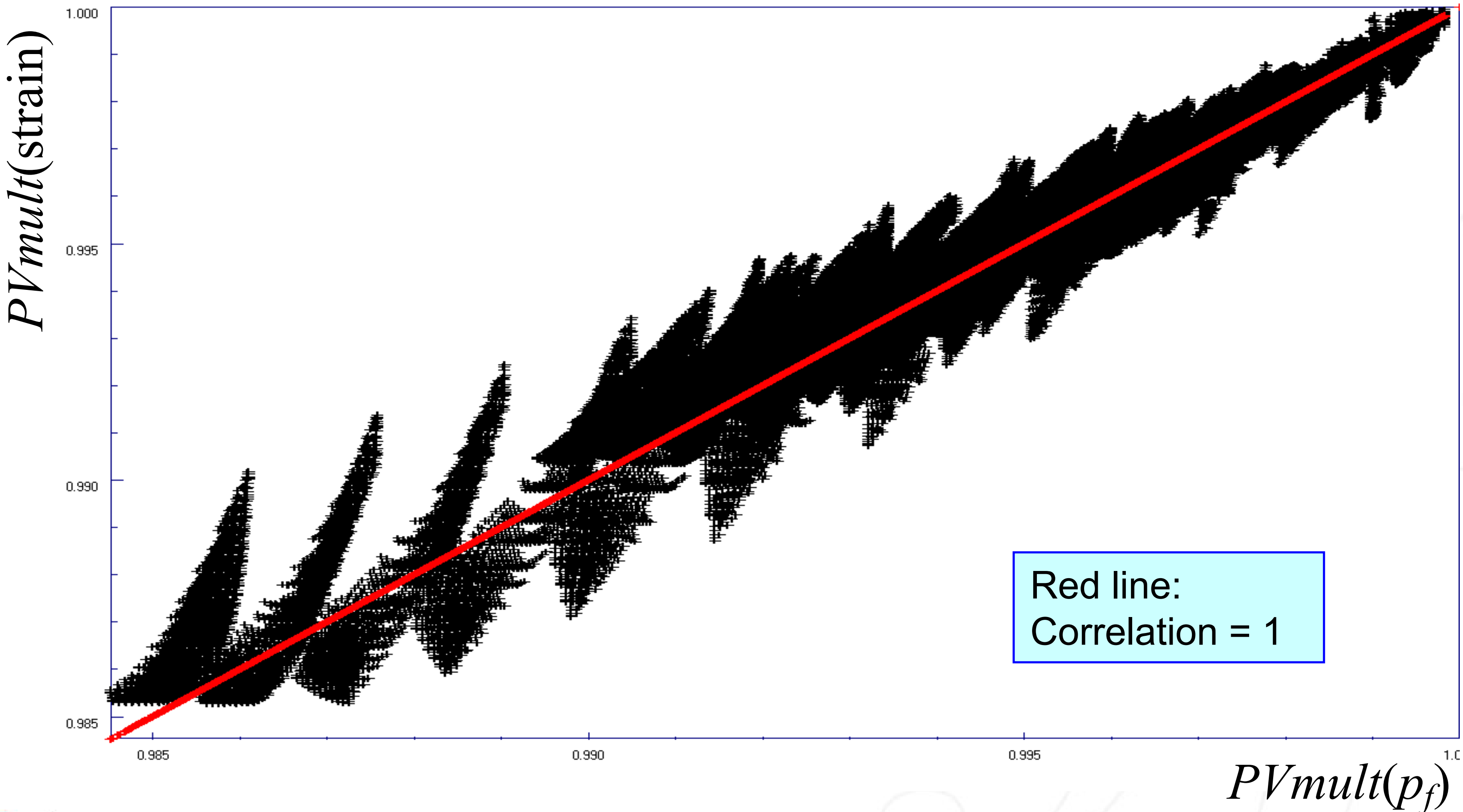
Example Using 10 Material Regions.
Compaction Energy Changed → Level Invalid



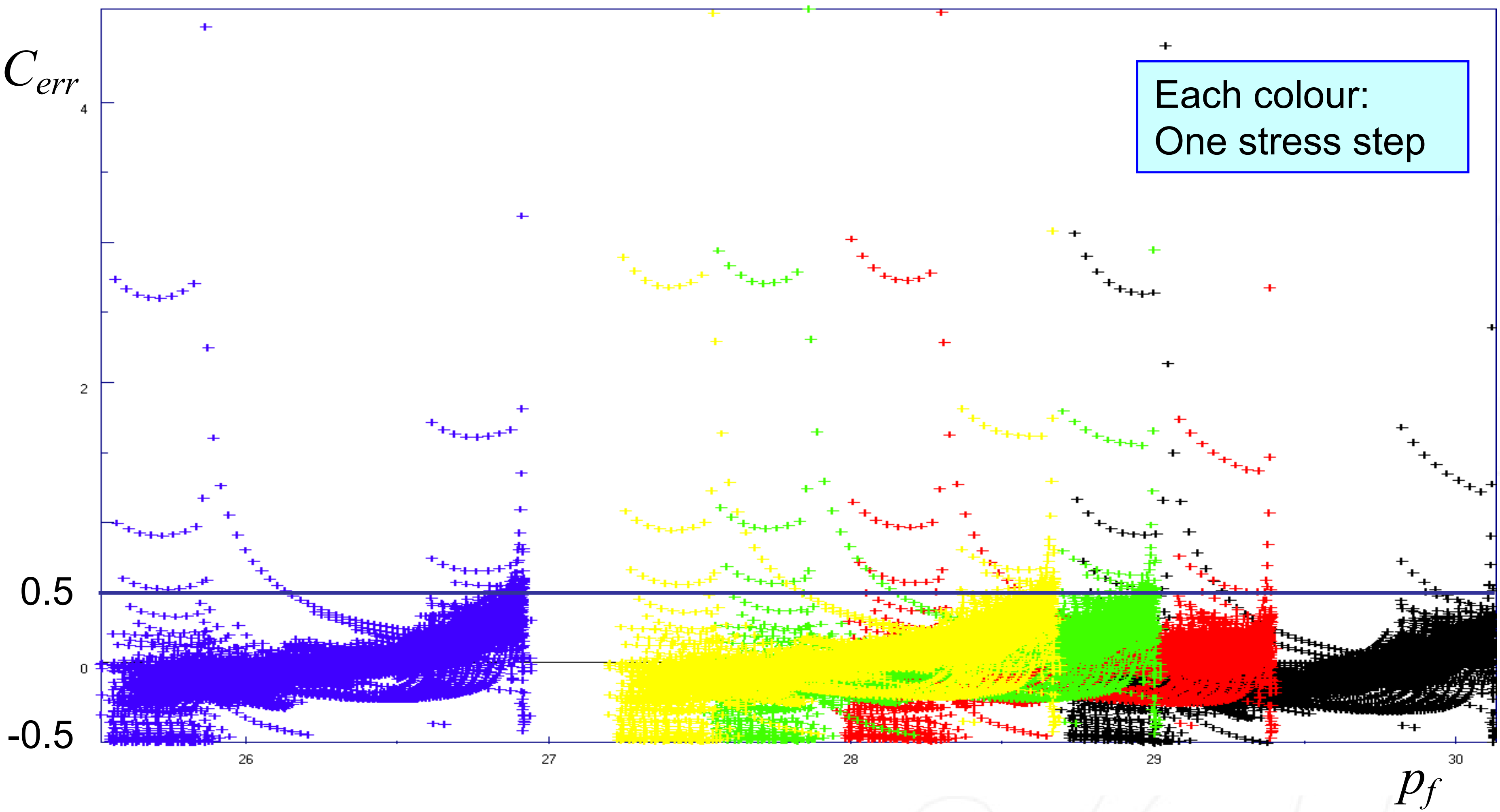
Iteration Step 4:
Adjust Level for all 10 Compaction Functions



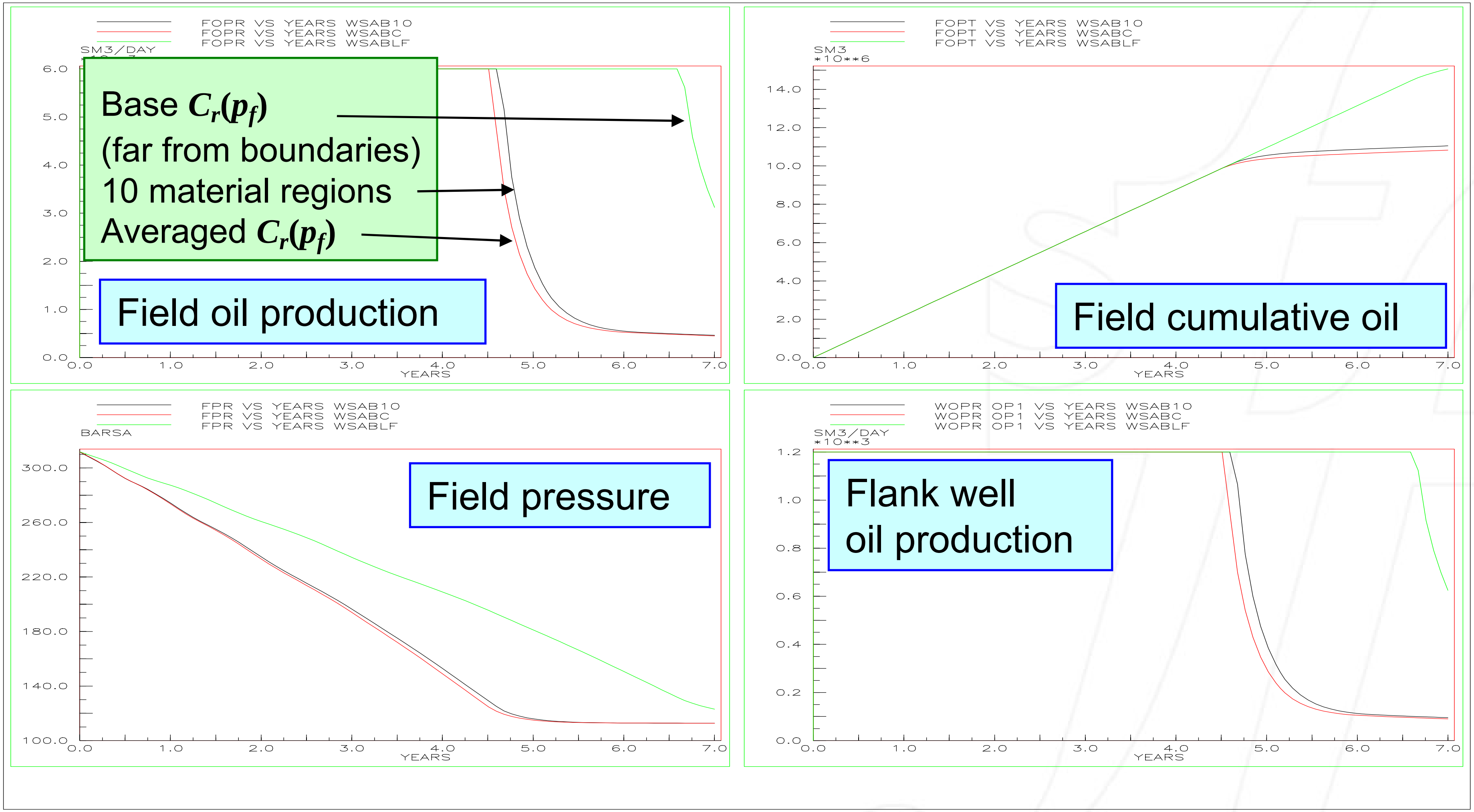
PVmult(strain) vs. *PVmult*(p_f)



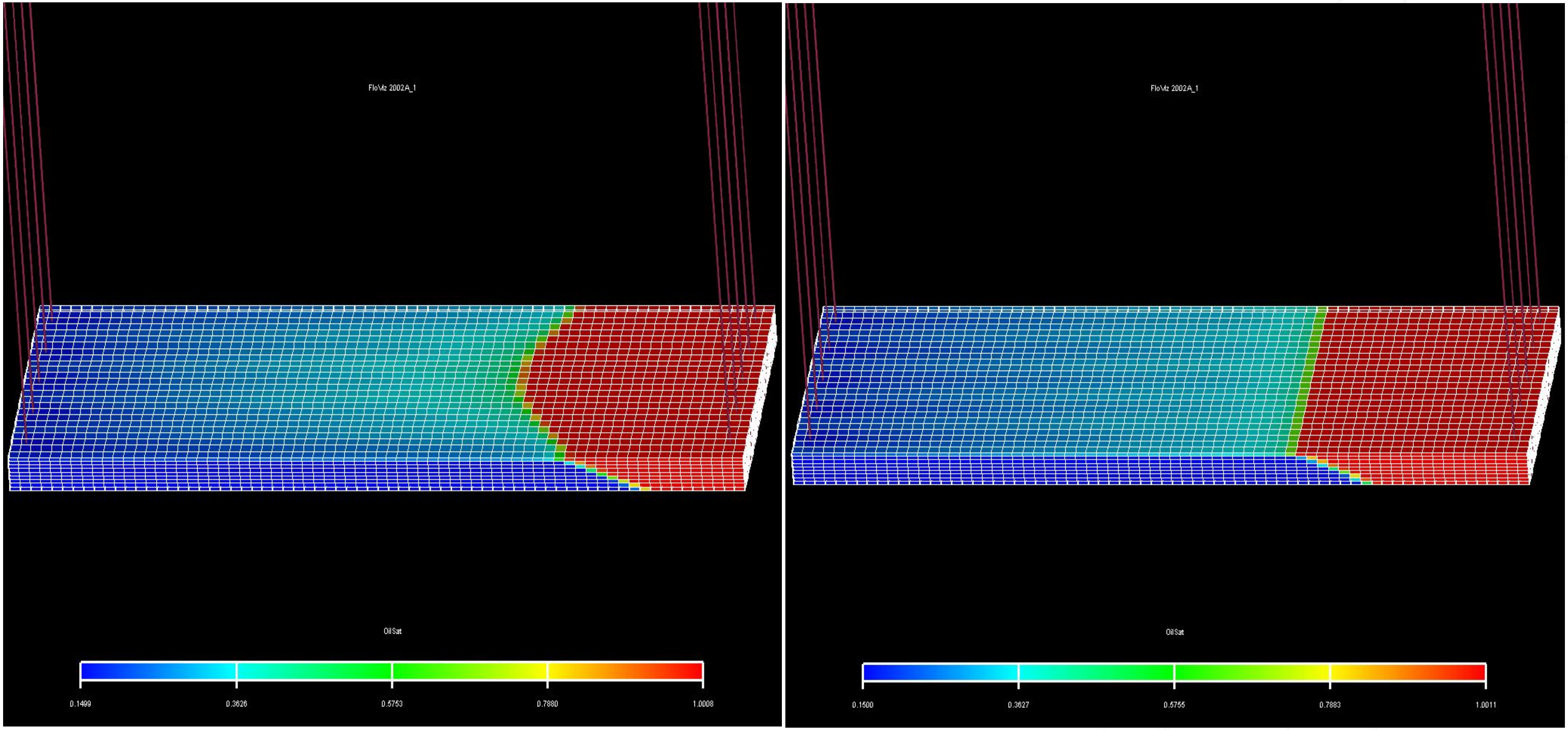
Error in Compaction Computation



Does it Matter? – Simulated Production



Oil Saturation, 10 Material Regions and Averaged $C_r(p_f)$



Comments

- Rock Tables & Material Regions only needs redefining at *some* stress steps
  - ✓ Example run: All updates based on results from stress step no. 2

Comments

- Rock Tables & Material Regions only needs redefining at *some* stress steps
  - ✓ Example run: All updates based on results from stress step no. 2
- New material regions can be accurately determined in one, or a few iterations

➢ Total number of Visage runs considerably reduced

Comments

- Rock Tables & Material Regions only needs redefining at *some* stress steps
  - ✓ Example run: All updates based on results from stress step no. 2
- New material regions can be accurately determined in one, or a few iterations
- ➢ Total number of Visage runs considerably reduced

☺ Improved reservoir simulator compaction functions reduces Visage run time:

- Example run, CPU time per stress step
- ➢ Iteration step 1: ~15 minutes
- ➢ Iteration step 2: 7-8 minutes
- ➢ Iteration steps 3 & 4: 1-2 minutes

Improved Coupling Scheme:

- Accuracy comparable to fully coupled
- Efficiency comparable to explicit coupled, often better (good predictor)
  - 1-10% of fully coupled run times

Conclusions

- By compaction of sand / sandstone
  - material grows stronger due to tighter packing
  - pore space is permanently deformed
  - ➢ Critical State Theory

- Disregarding stress state boundary effects (“arching”) can lead to grave errors, especially for weak materials

- Understanding compaction requires coupled simulations

- An improved coupling scheme has been presented