Loading and Unloading – Compaction vs. Expansion Material Behaviour – Models (?)

by

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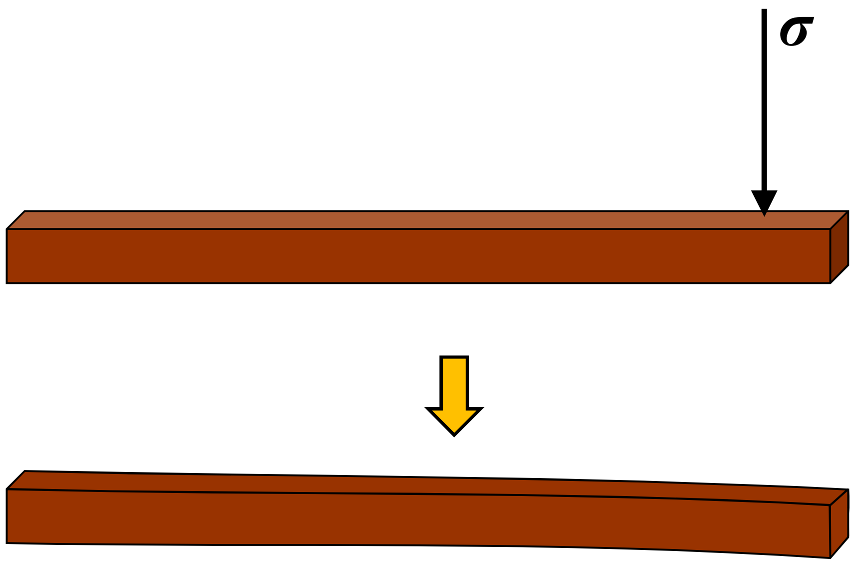
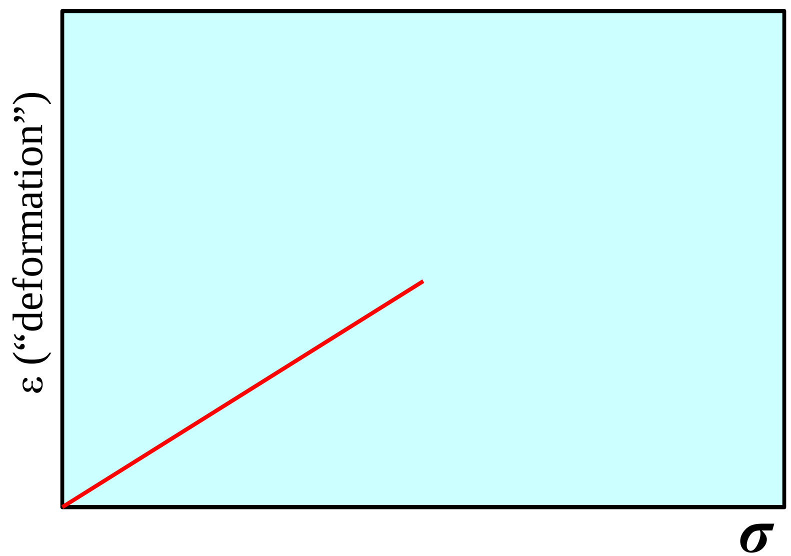
CO2 Workshop Bergen Nov 2011

Outline

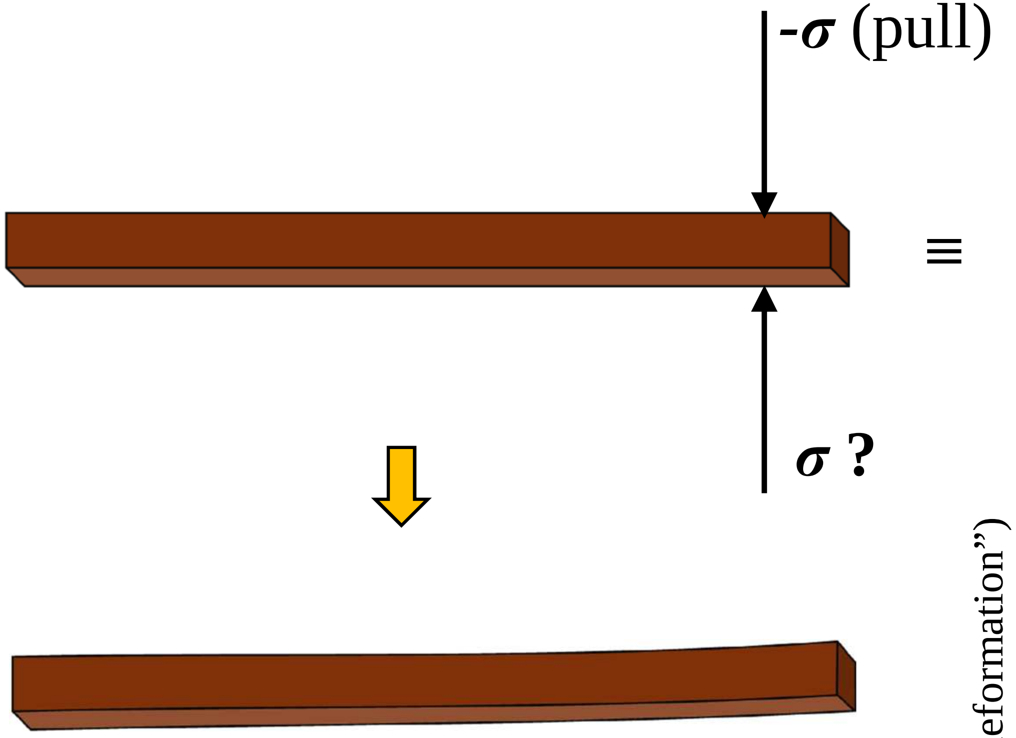
- ***Solids vs. Porous Rocks***
- ***Compaction of Porous Rocks***
- ***Can Compaction Models be Extended to the Expansion Regime?***
- ***Proposed Expansion Model***
- ***Reservoir – Overburden Interaction***

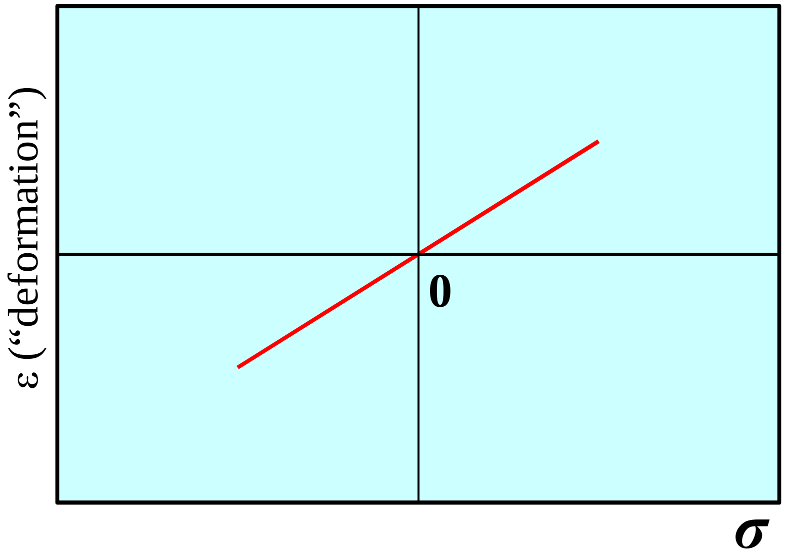
Strain (ε) vs. Stress (σ), Solid elastic deformation





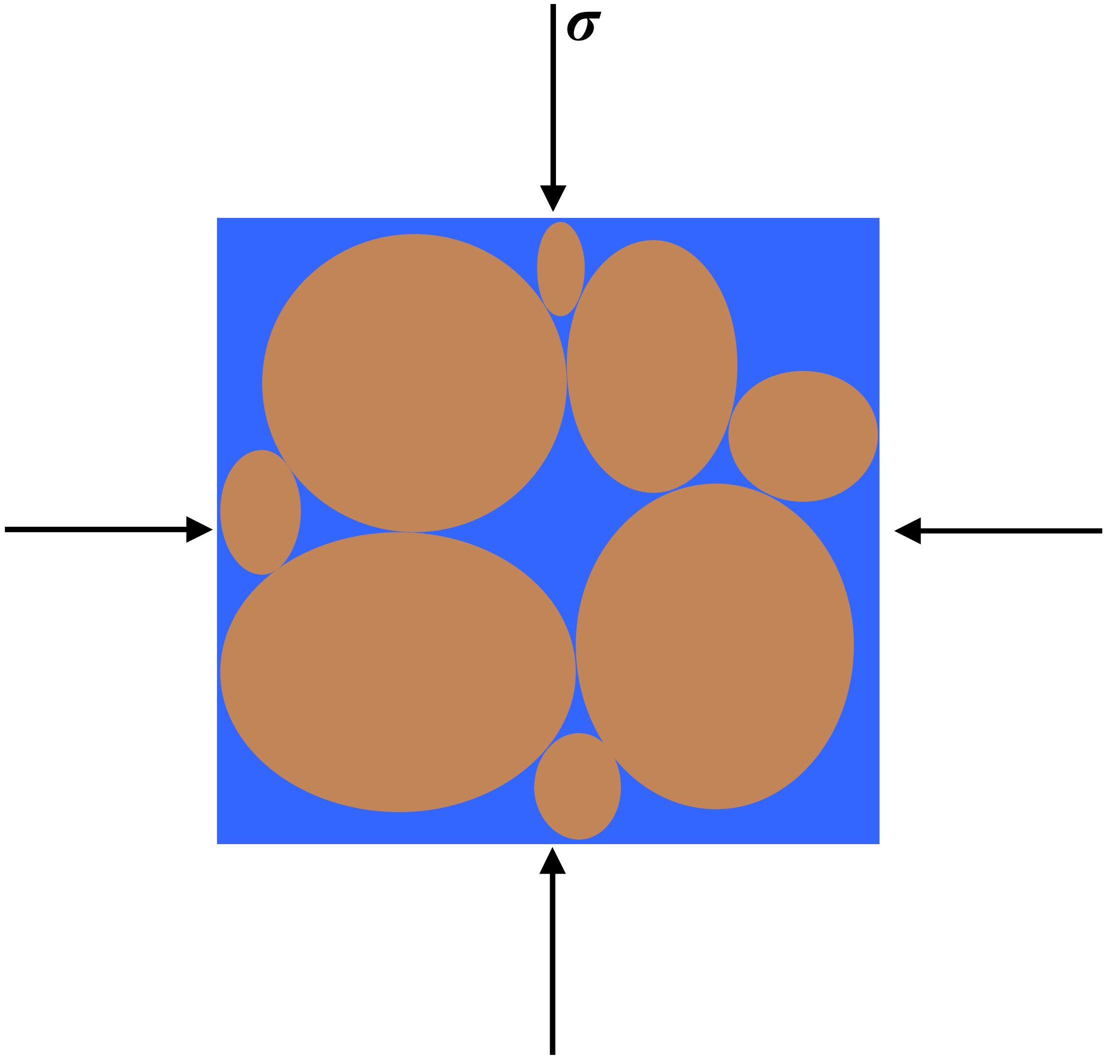
Strain (ε) vs. Stress (σ), Solid elastic deformation





Stress – strain symmetric

Stress – deformation in porous rocks



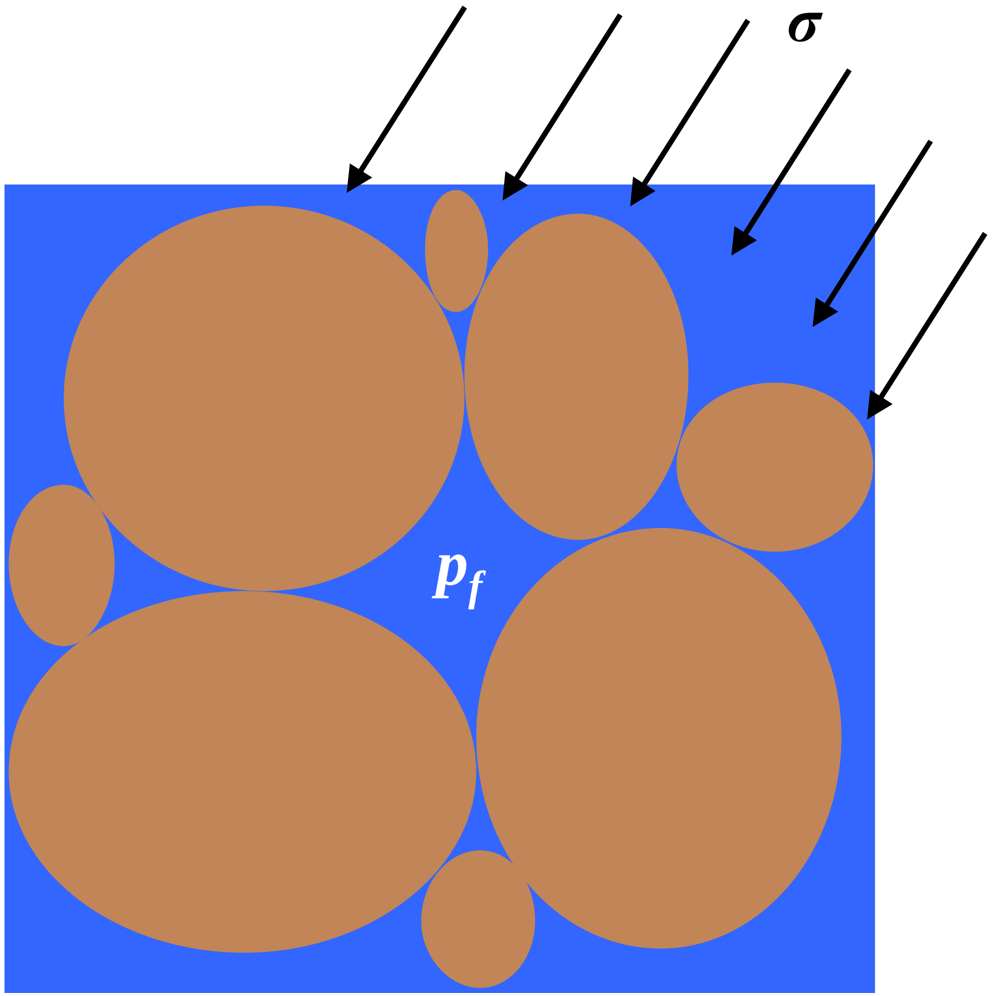
Consider a granular sample under compression.

Bulk compressibility is much larger than grain compressibility; for sands 2-3 orders of magnitude larger.

Grain compression is insignificant compared to pore volume reduction

→ The total compaction is (almost) completely due to change in pore volume

Effective Stress – intuitive definition



In a porous rock, the main mechanism is deformation of the pore space, not the solid itself.
The force acting on the *pore walls* is the external stress σ and an opposing force by the fluid pressure p_f.

The net force attempting to deform the pore wall is hence $\sigma' = \sigma - p_f$.

σ' is effective stress.

Volumetric deformation of porous rock

Governed by *mean effective stress;*

$p' = \frac{1}{3}(\sigma'_{xx} + \sigma'_{yy} + \sigma'_{zz})$

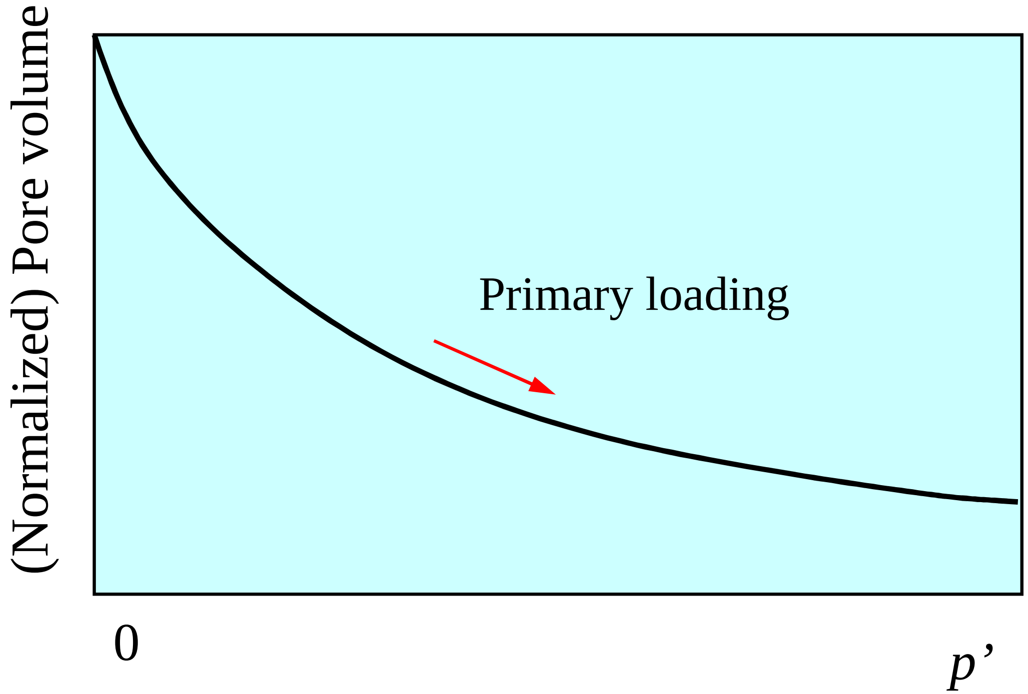
Deformation by *volumetric strain*:

$$\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

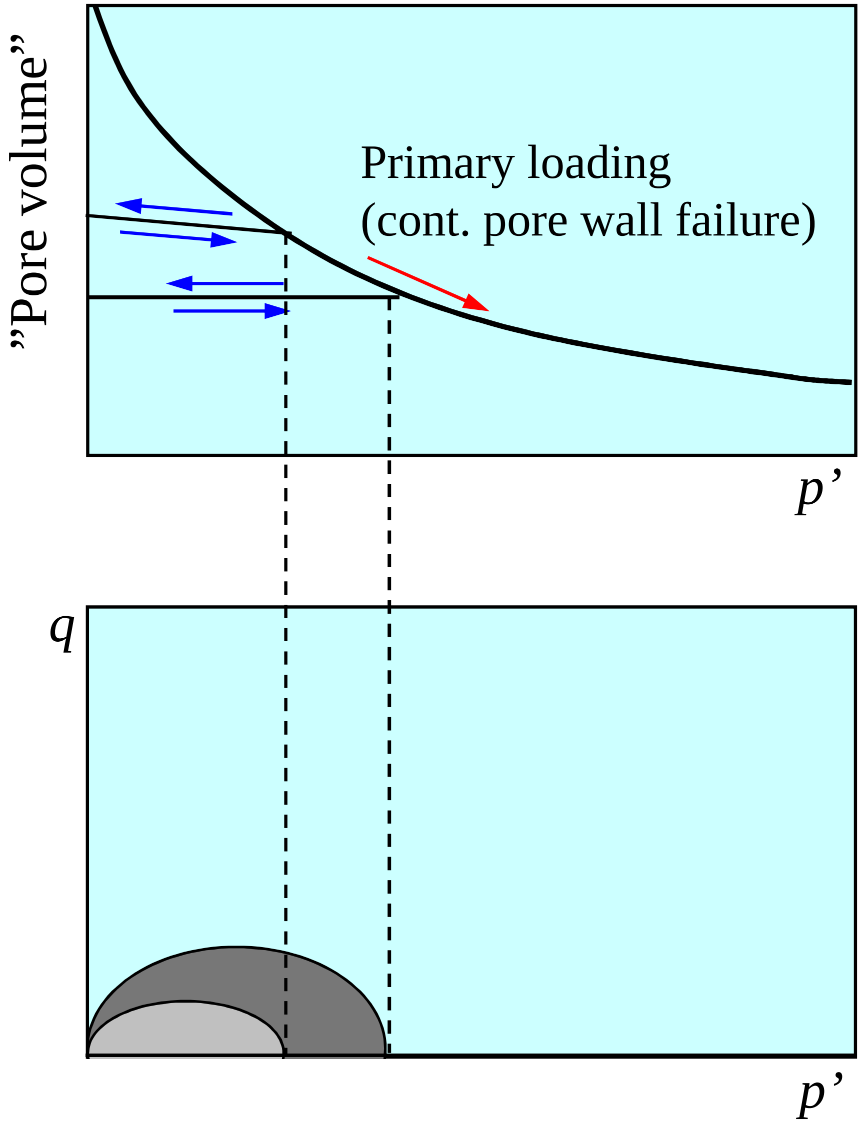
Also, q = deviatoric stress
(For cylinder symmetry $\sigma_a - \sigma_r$,
axial and radial stresses)

(Volume change determined by volumetric forces)

Qualitative soil response



In *p'* – *q* - space

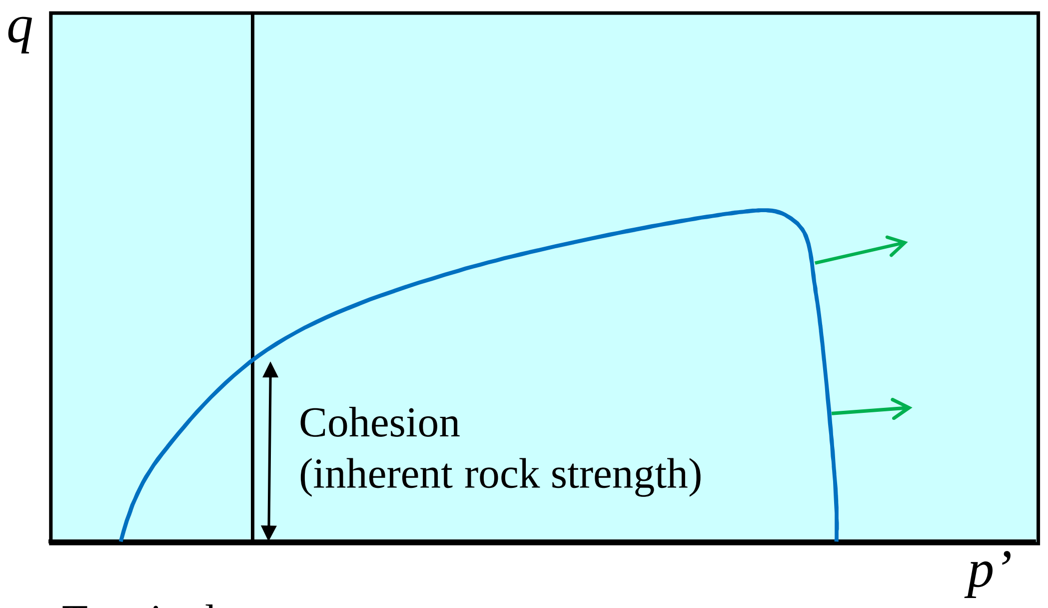


In stress-space (using *p'* and *q*), we have a "safe" region, where material behaves elastic (grey). Unloading – reloading is within this region.

To move down the primary load line, we must increase the size of the "current region", i.e. extend the *yield surface*.

Note that yield surface expansion is only in p' > 0 – interval.

General yield surface

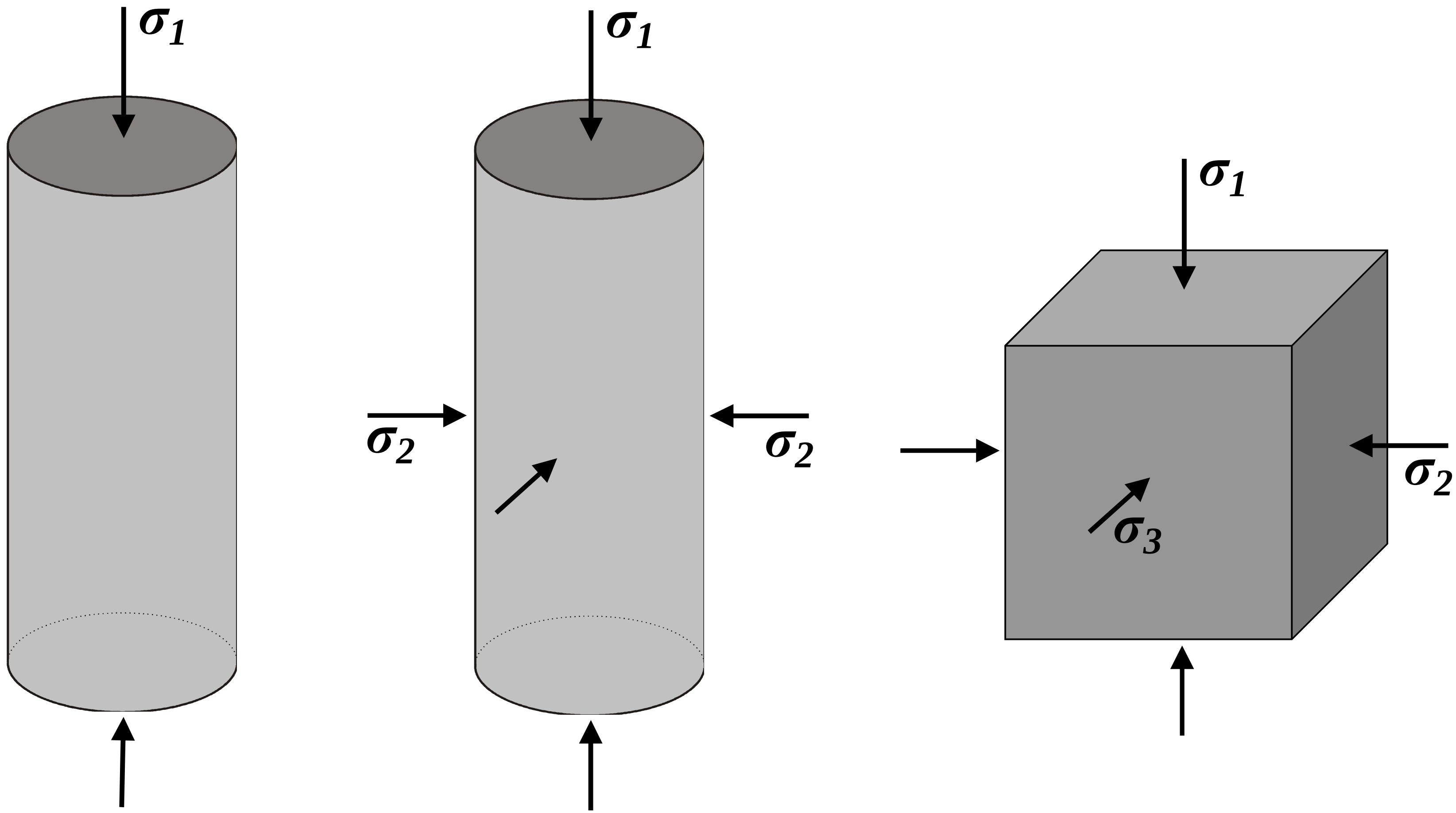


Terminology
"*p*' vanishes":
adjust for cohesion

Some surface in *p'* – *q* – space.
Rock behaves elastic within surface.
To reach a stress state exterior to surface, the yield surface must be expanded – determined by plastic flow and hardening rule.

Of interest here – these are "loading" concepts.

Common types of rock mechanics tests (loading!)



Uniaxial

$\sigma_2 = \sigma_3 = 0$

Triaxial

$\sigma_1 > \sigma_2 = \sigma_3$

Polyaxial

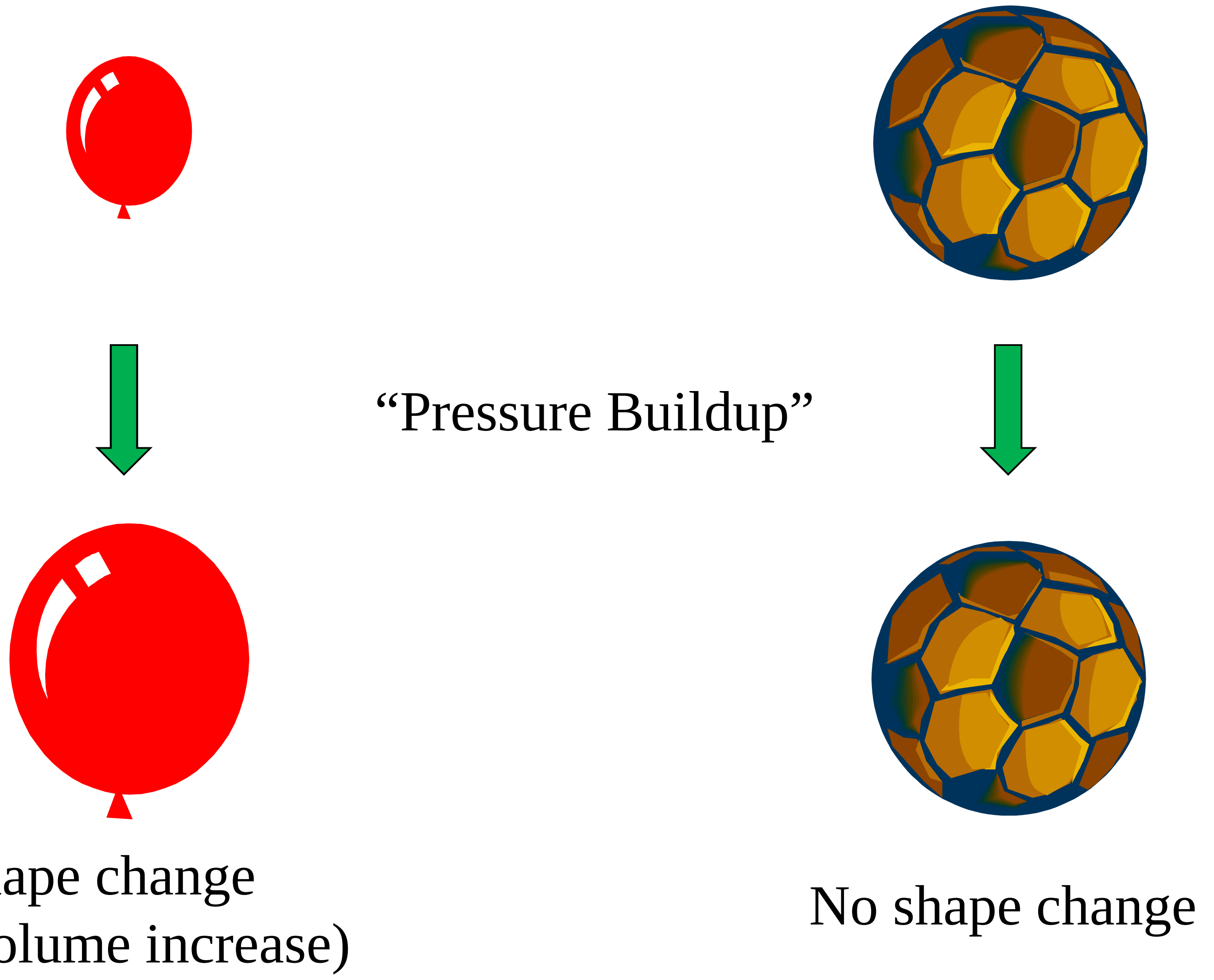
$\sigma_1 \neq \sigma_2 \neq \sigma_3$

Negative Effective Stress

Unlike the solids example,
negative effective stress has no symmetry analogy

(In the loading experiments, the applied loads *are* the boundary conditions. In an “expansion” experiment, what role do the BCs play?)

Expansion tests -- analogies

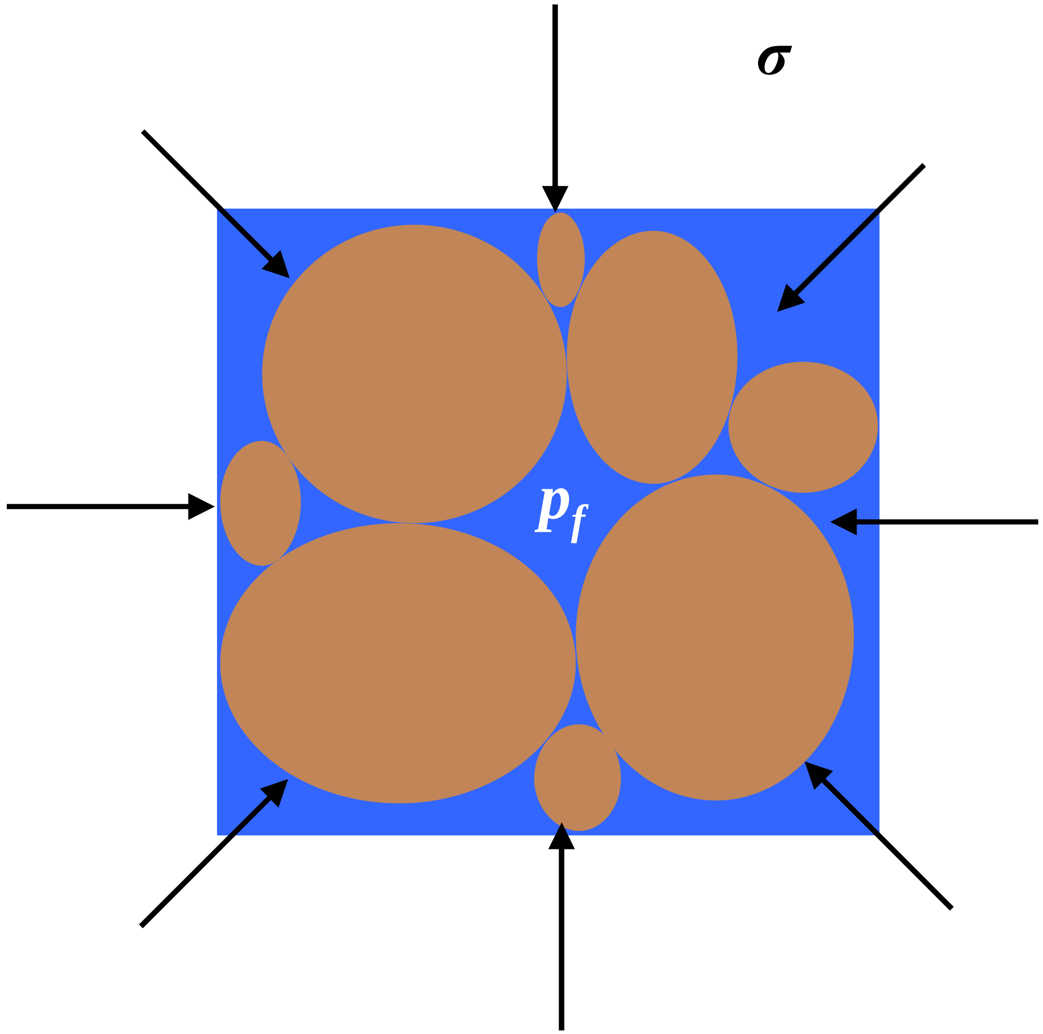


Expansion tests -- analogies

Final volume and interior pressure is determined
by material properties for the *bounding surface*,
not at all by the properties of the air inside the body.

If no bounding surface were present the air would
just go away – and not be bothered by increasing its
internal pressure.

Equilibrium

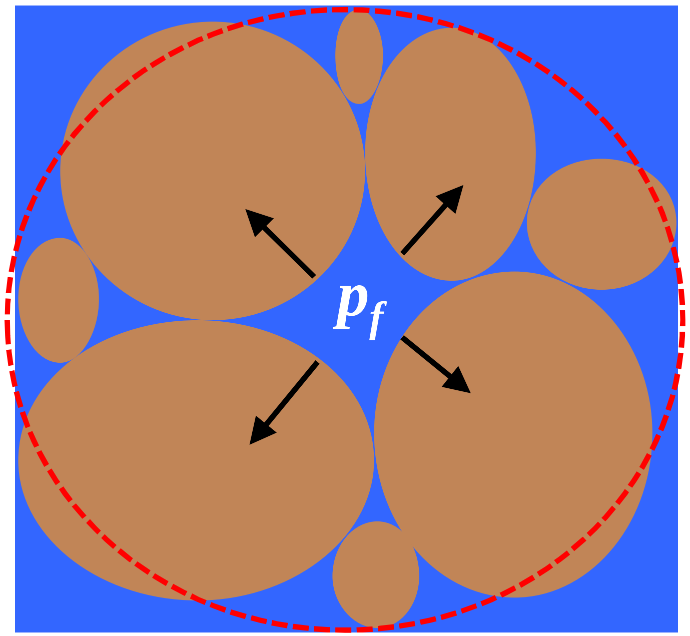


Surrounding mean stress equals fluid pressure :

No net forces acting on pore walls

Pore space & grains coexist in a state of equilibrium –
i.e., a state of total freedom.

Increasing p_f locally



Dashed circle:
Initial zone of influence

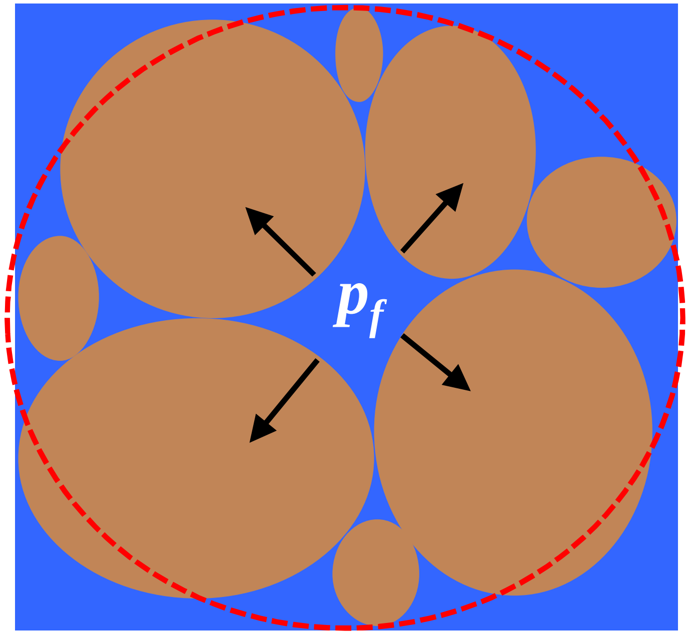
Net force attempts to push grains outwards from high-pressure pore

Balance:
Forces acting from “next layer” of grains, which resist being pushed outwards.

I.e., The local expansion attempt implies compaction to neighbour pores.

Recursive use of argument:
A compaction wave is generated

Increasing p_f locally



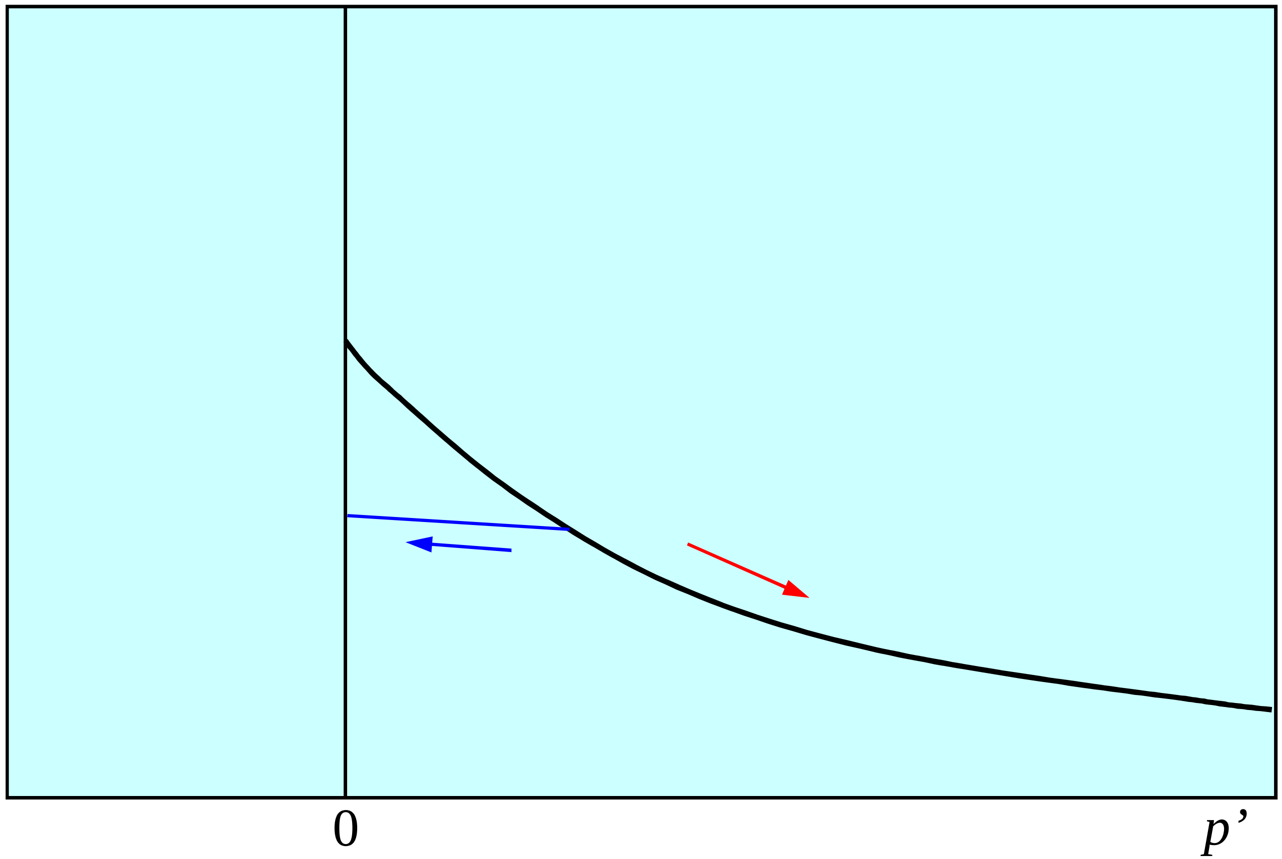
Dashed circle:
Initial zone of influence

Hence:
The local expansion is determined by the *compaction* properties of the neighbouring REVs.

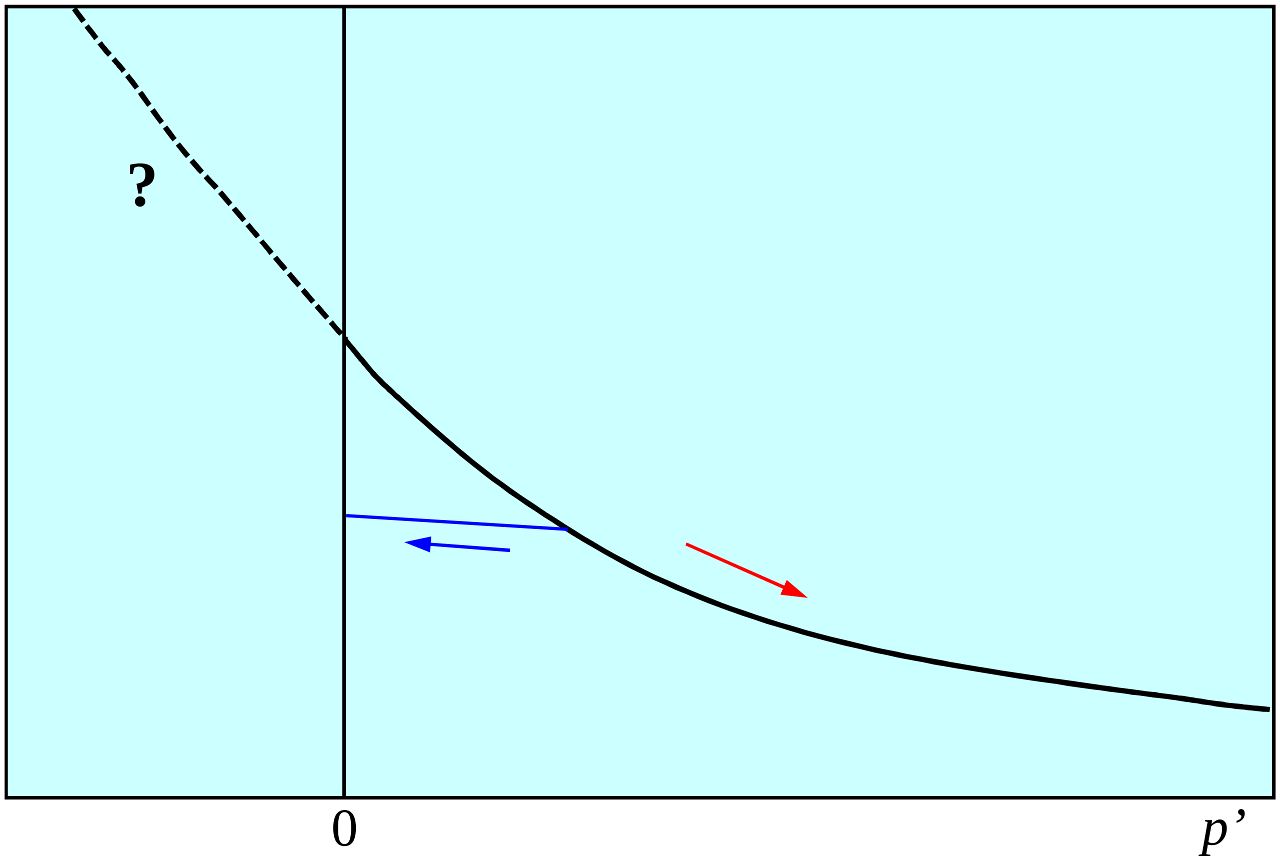
Expansion properties (if such exist) don't matter at all (the material has no resistance to expansion if not bounded by neighbouring material)

Extending *PV(p')* curve

Recall qualitative relation between mean effective stress and (normalized) pore volume

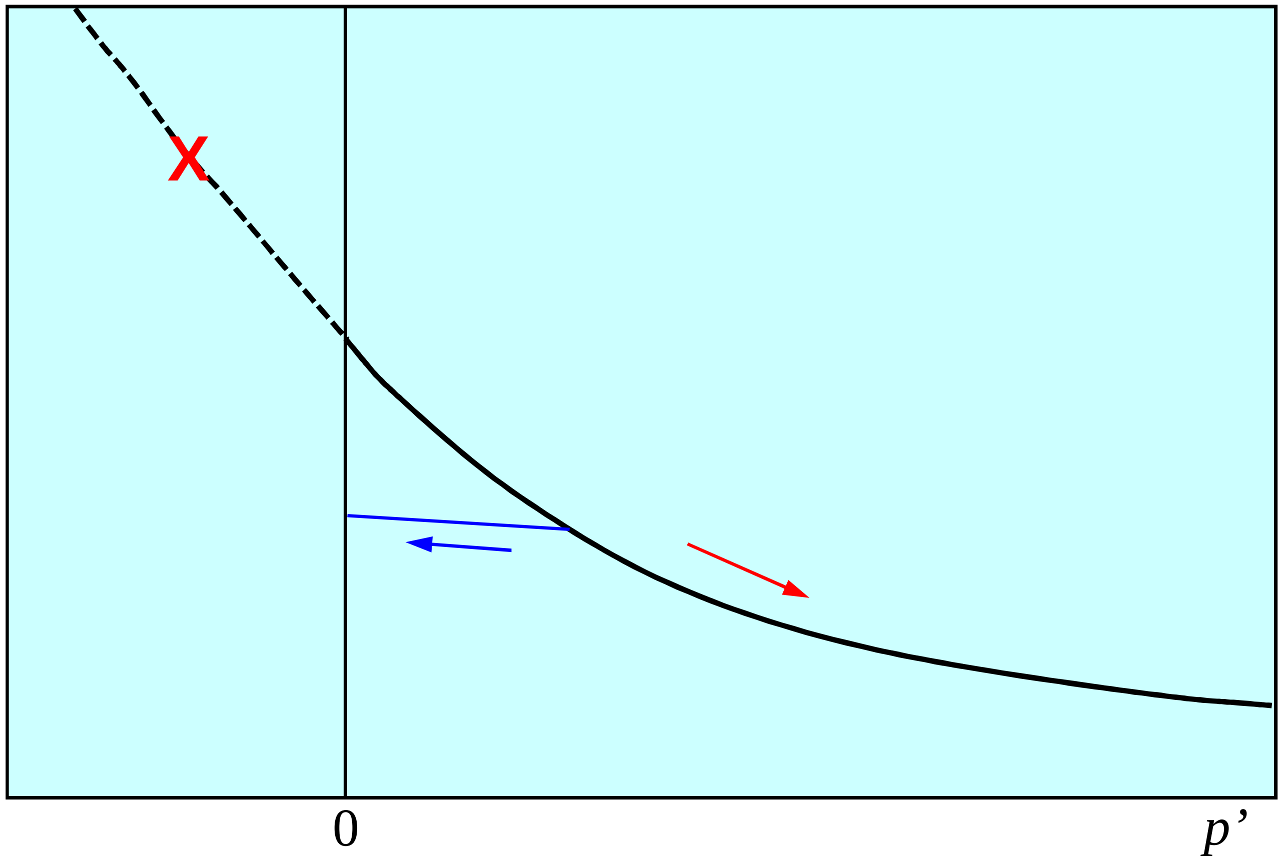


Extending *PV(p')* curve

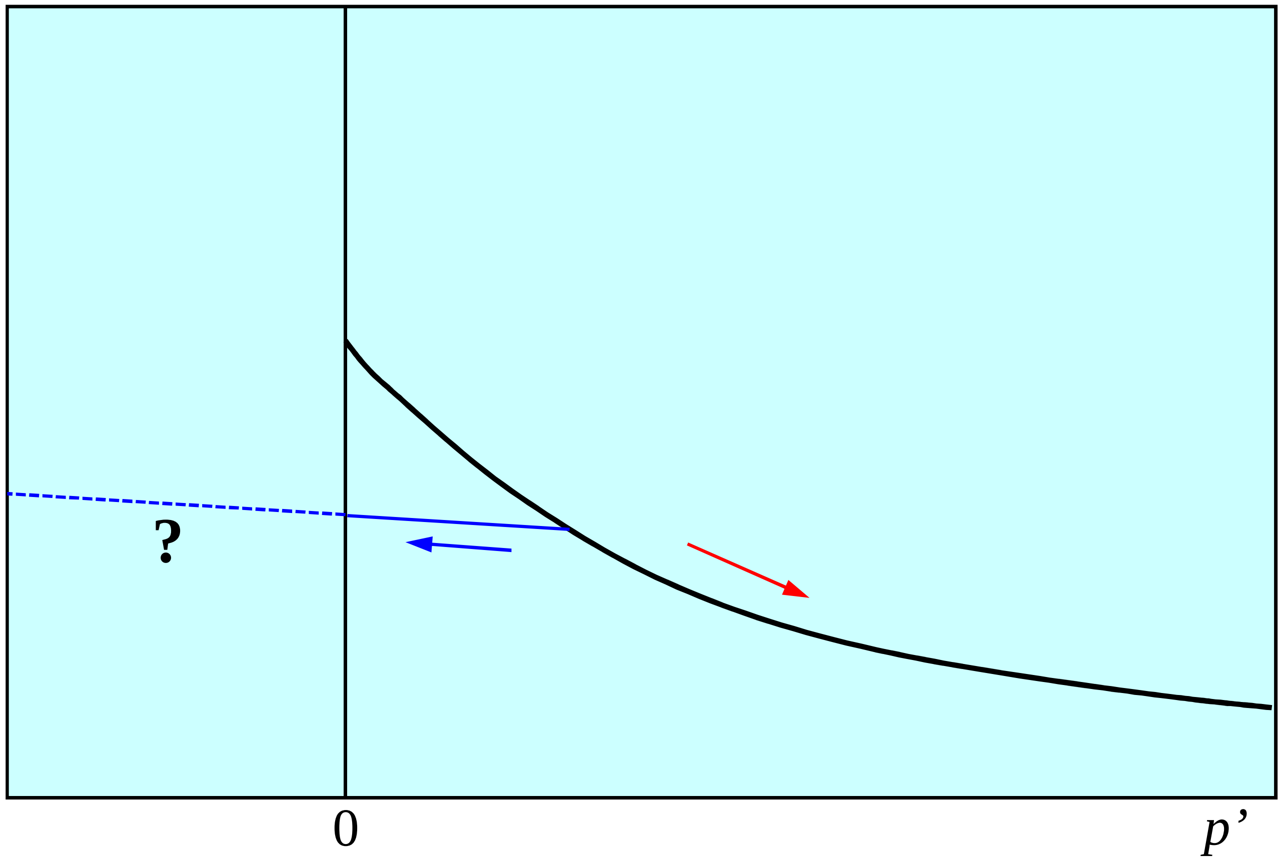


Extending *PV(p')* curve

Definitely wrong. Primary loading curve is only valid for *increasing* mean effective stress

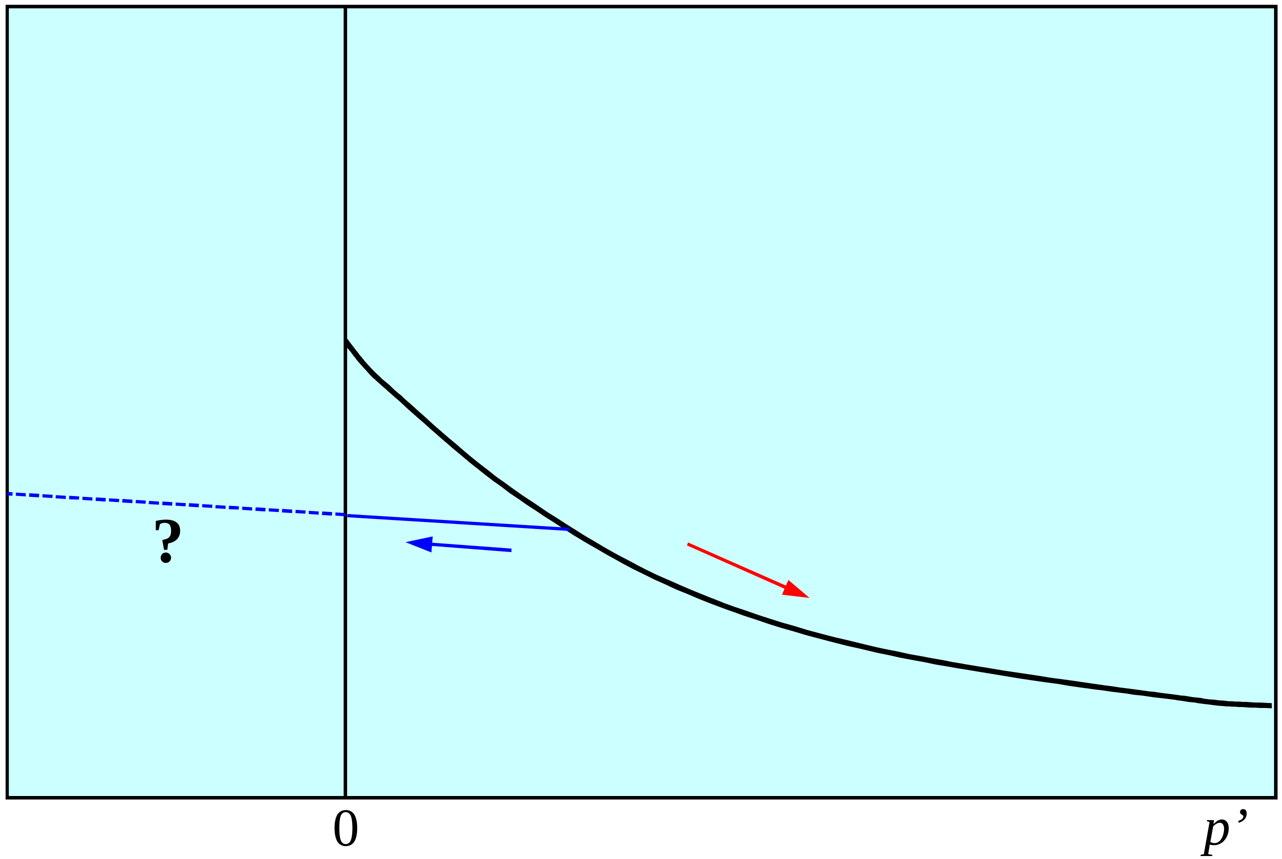


Extending *PV(p')* curve

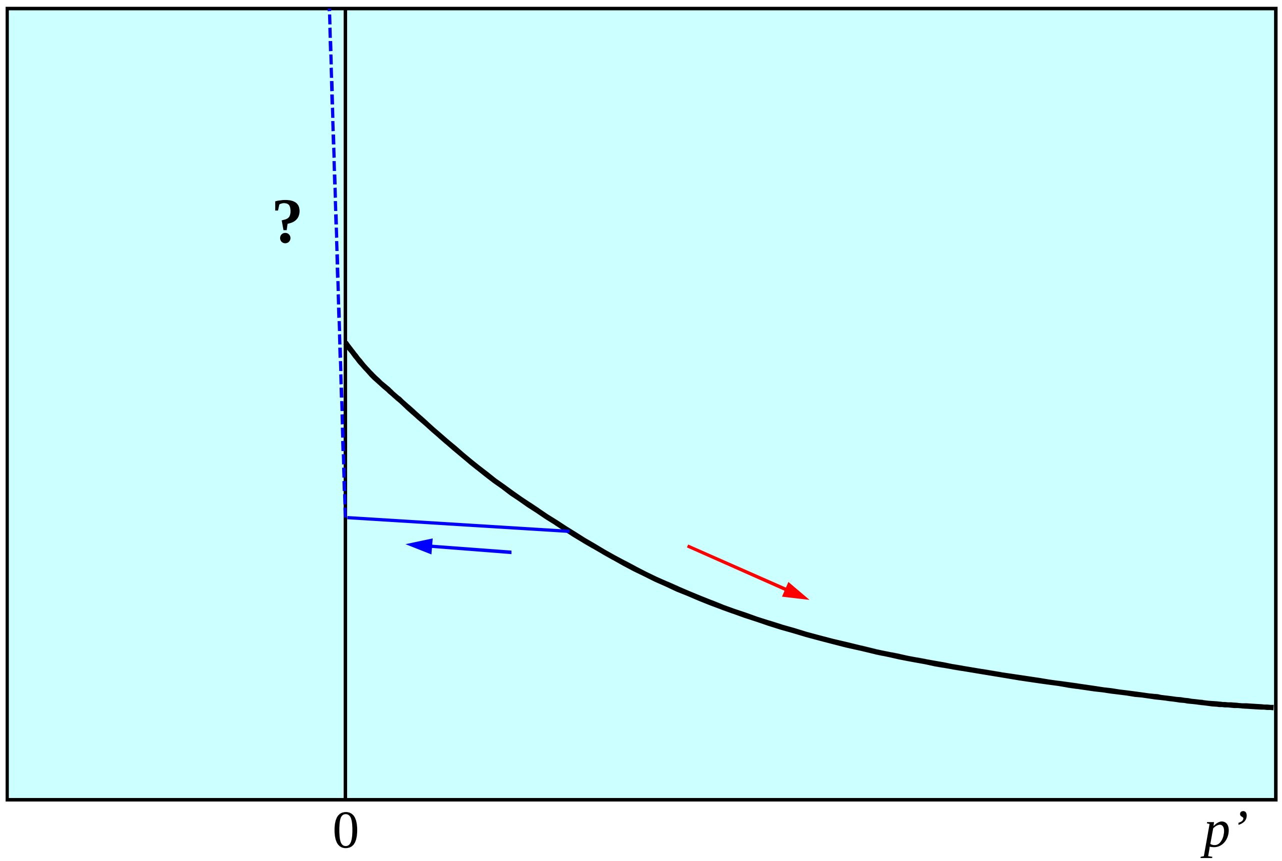


Extending *PV(p')* curve

Maybe... Probably valid for solids at least
Doesn't agree with my understanding of what's going on.



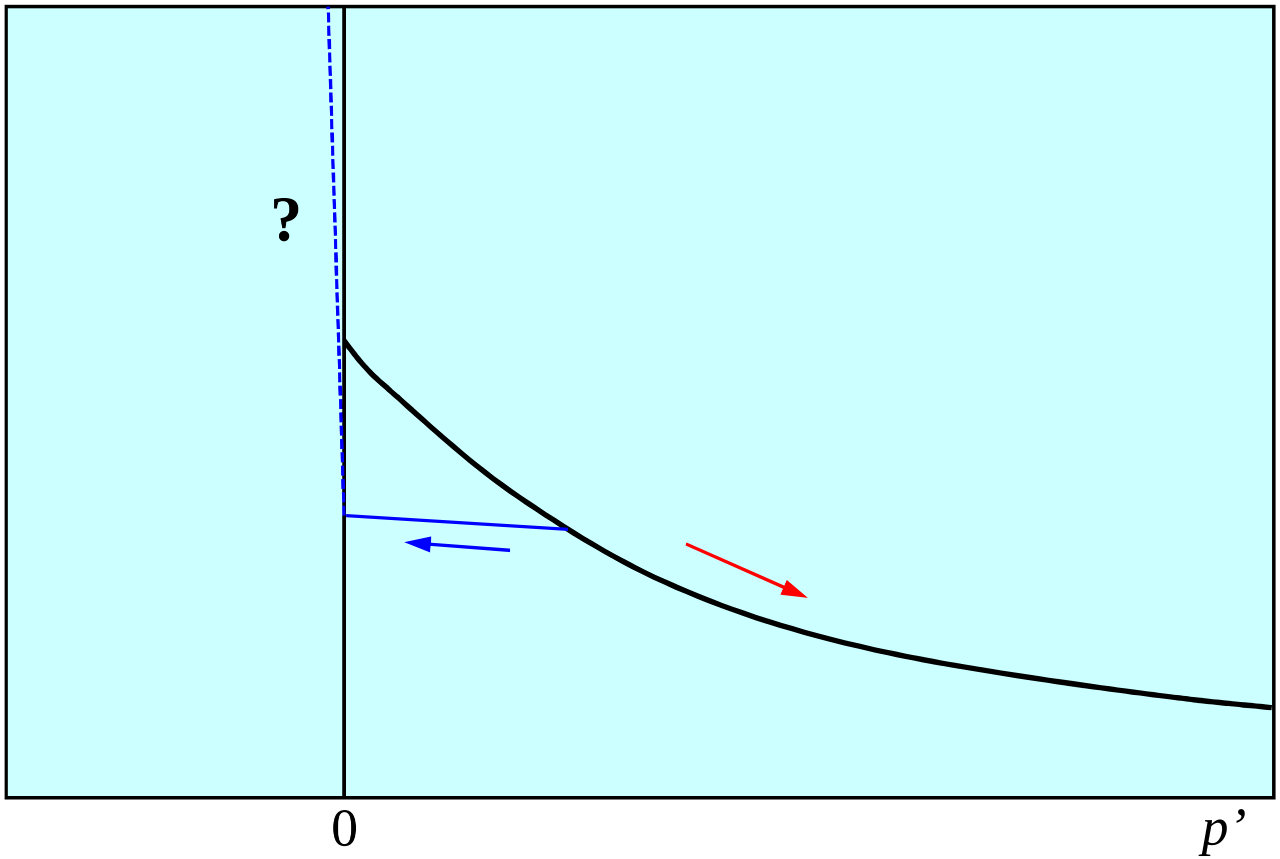
Extending *PV(p')* curve



Extending *PV(p')* curve

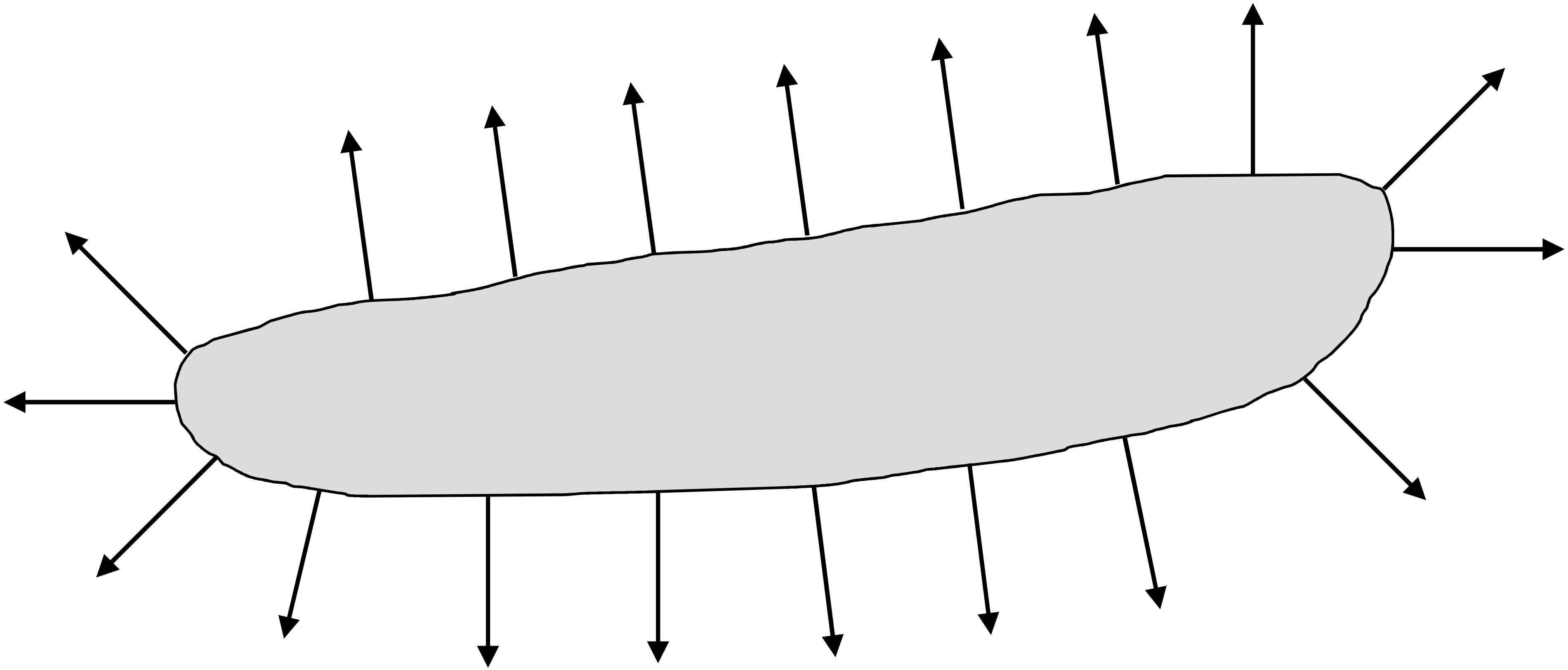
Infinite response. – Interpretation:

Free expansion, governed by BCs (neighbour materials prop's)



Application to overpressured reservoir

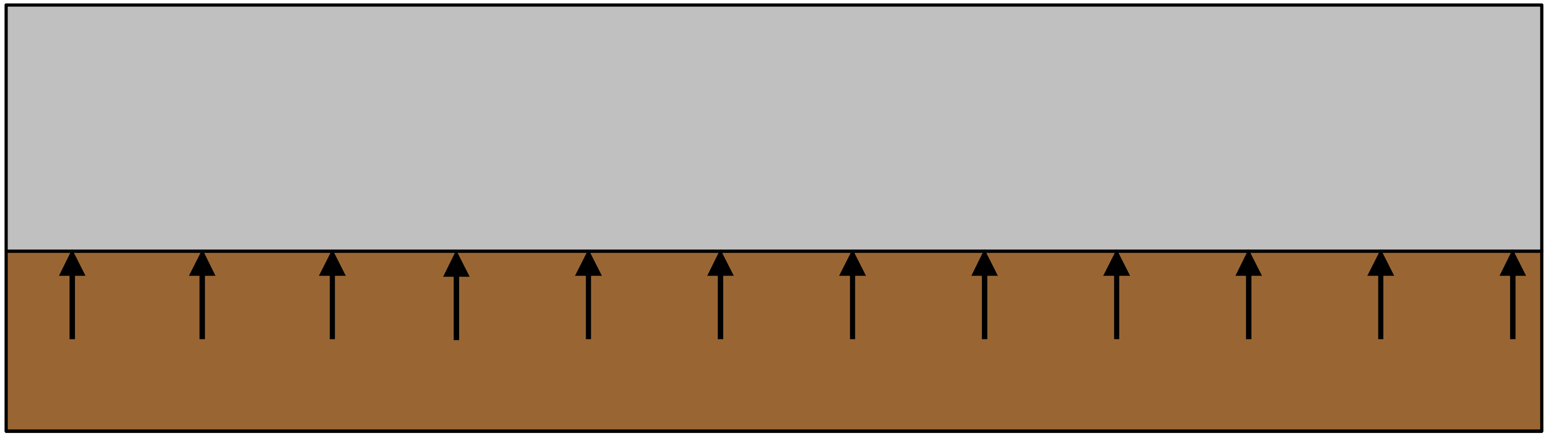
Assume pressure increases slowly (semi-stationary):
Pressure potential is constant within reservoir.
Then internal forces cancel, and the overpressure results in a net force acting outwards on reservoir boundary.



Interaction with overburden

A standard load-problem, resulting in uniform compaction of overburden – described by compaction characteristics of overburden material.

Reservoir material properties don't matter at all



Interaction with overburden

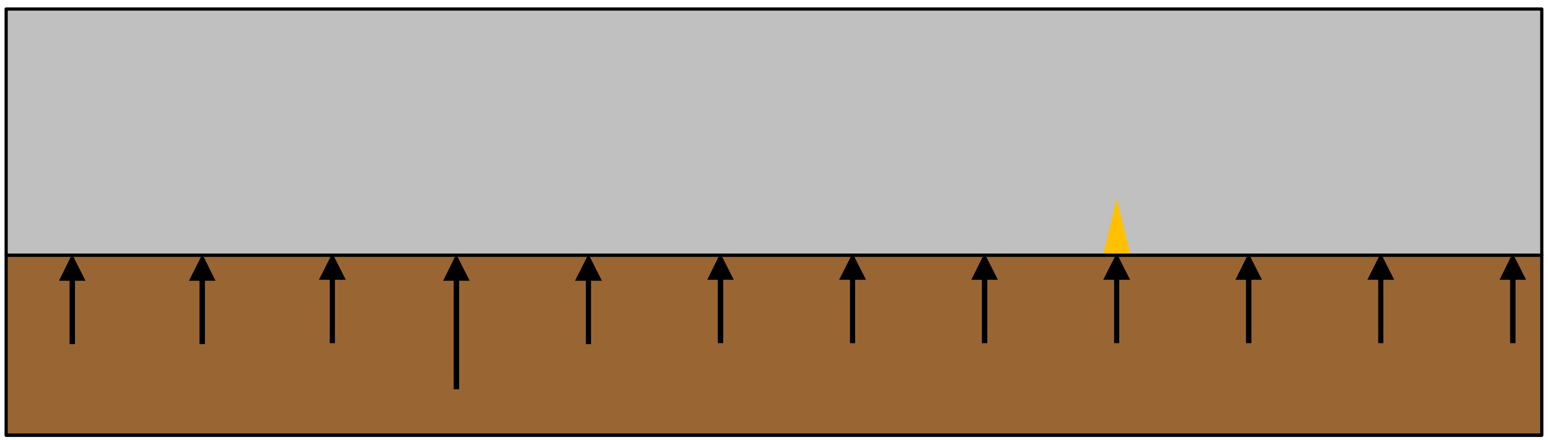
Non-uniformity;

Local load-variation or material weakness:

Experience from analogue cases:

Fracturing or local compaction wave

Model is very sensitive to small impurities



Compaction waves in overburden will follow "paths of weakness" to surface. These can develop as part of the process

Modelling of overburden deformation

Requires,

- Good material description for overburden materials,
  - heterogeneities
  - initial stress distribution
  - failure characteristics

- Accurate pressure distribution and development in reservoir

(which implicitly requires a good rock mechanics model for the reservoir. But apart from that the reservoir material props are really not needed…)

Modelling of overburden deformation

As overburden material description is rarely
(or not) readily available
(not prime priority in e.g. oil companies) –
we face an extremely tough inverse problem
(when surface observations are available)

or struggle completely in the dark.

Or??

Thank you!