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Can We Model Stimulation Processes in Naturally Fractured Geothermal Reservoirs?

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NFR

- The Naturally Fractured Rock (Reservoir) mass to be "stimulated"

What Controls Stimulation?

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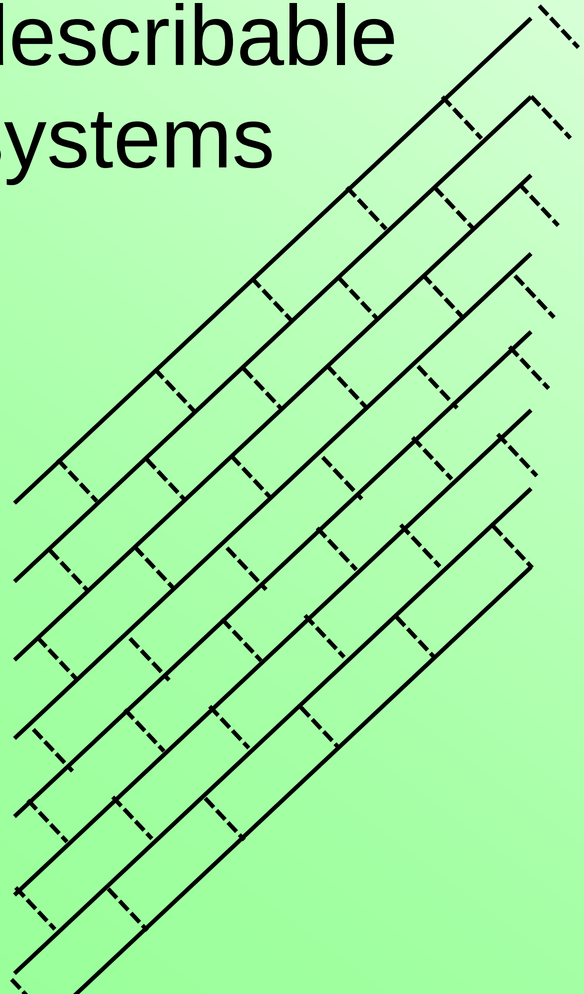
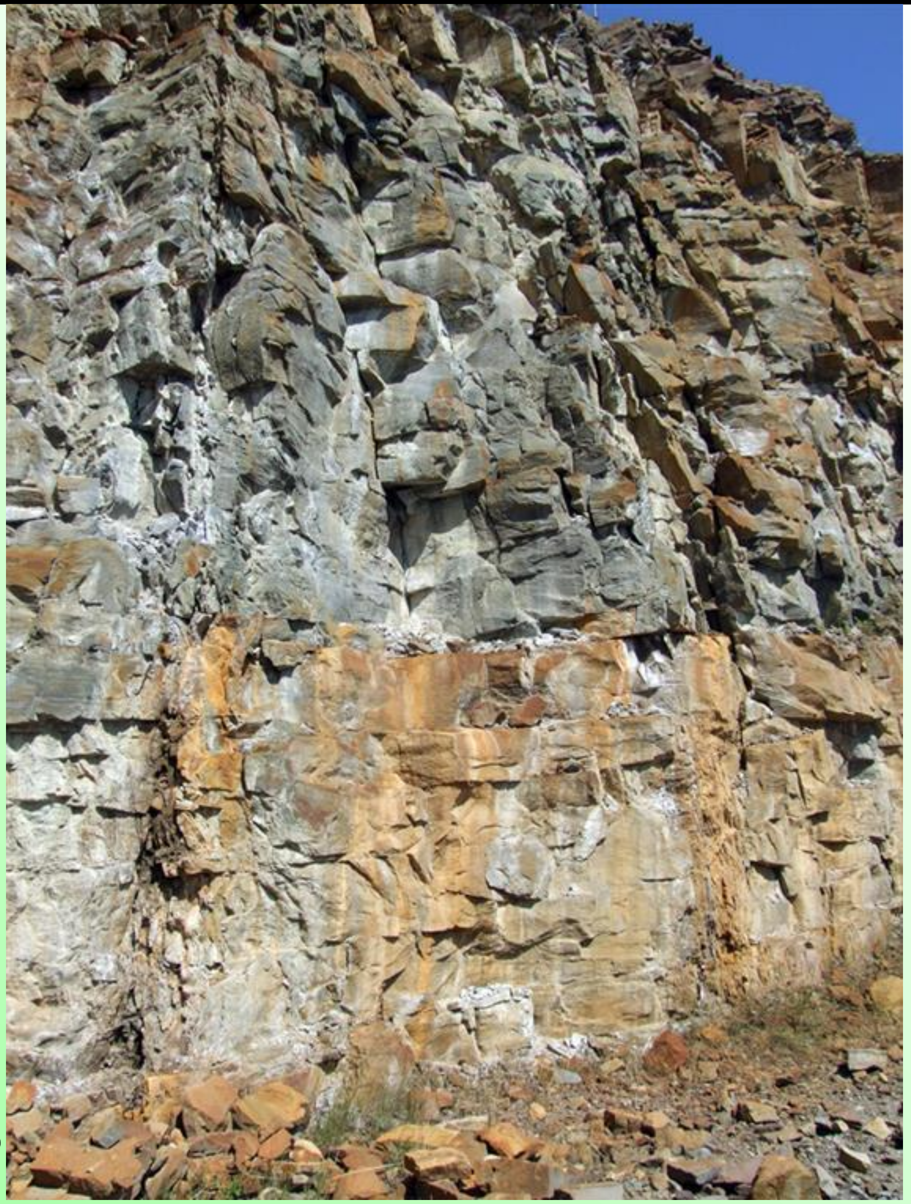
NFR Fabric Geometry
NFR Joint Properties
In Situ Stresses
Stimulation Rate
Fluids Used in HF
…and some others

Naturally Fractured Rock Mass

Regular, describable systems



Real rock mass



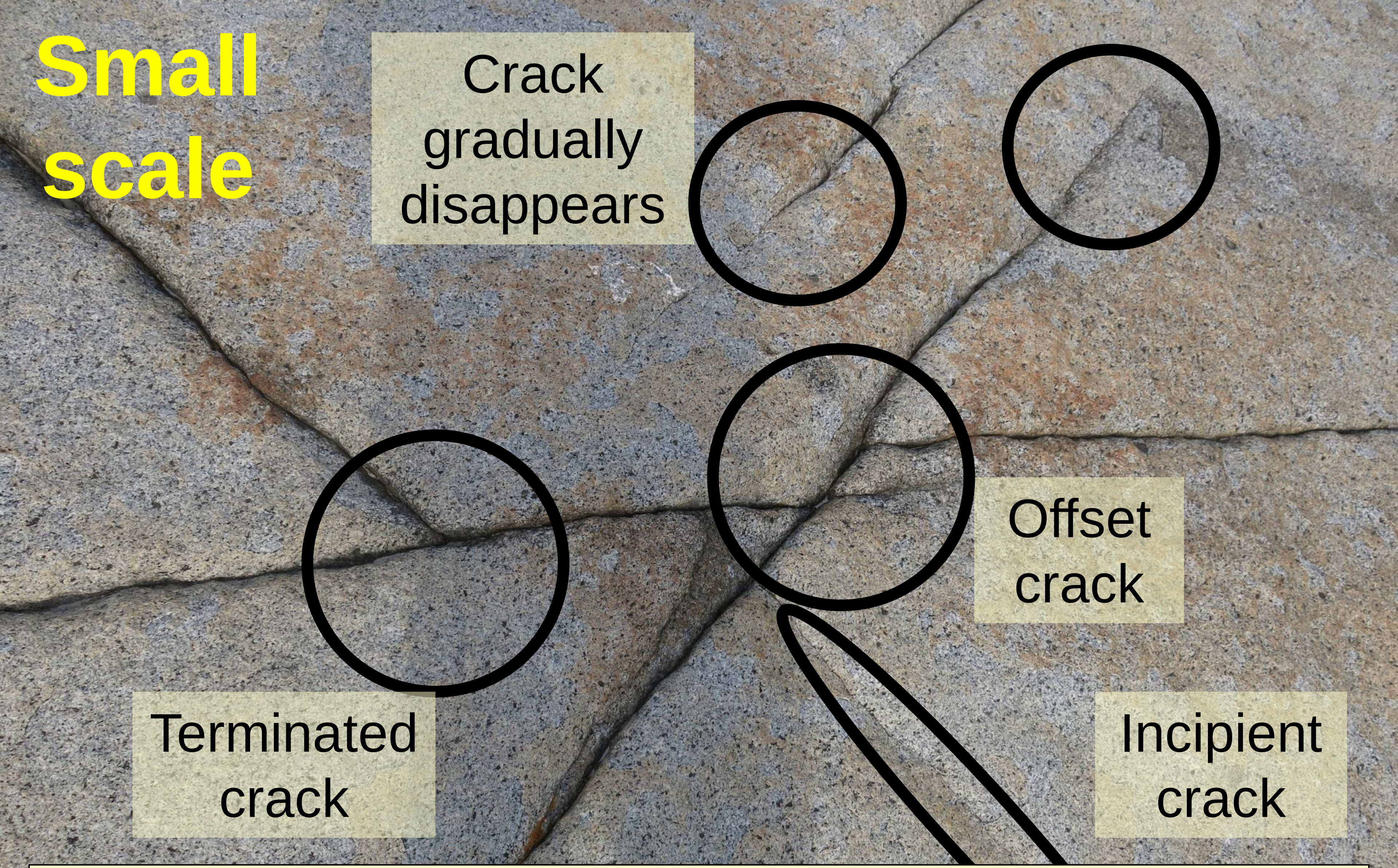
Utica Shale, note the consistent natural fracture fabric

Natural Fractures

- Natural fractures are largely "closed"
- …we want to open & connect the natural fractures by HF & HS
- So, NFR properties are very important but we don't know how to incorporate them easily into models:
  - ⇨ Cohesion, frictional behavior, ductility
  - ⇨ Fabric (frequency, orientation, sets, etc.)
  - ⇨ Fracture compressibility & conductivity
  - ⇨ Changing stresses & fracture aperture
  - ⇨ And so on…


How regular
is spacing?


What about 3 km deep?



…and irregular orientations, varying aperture, different roughness, etc. etc.

A Stochastic Approach?

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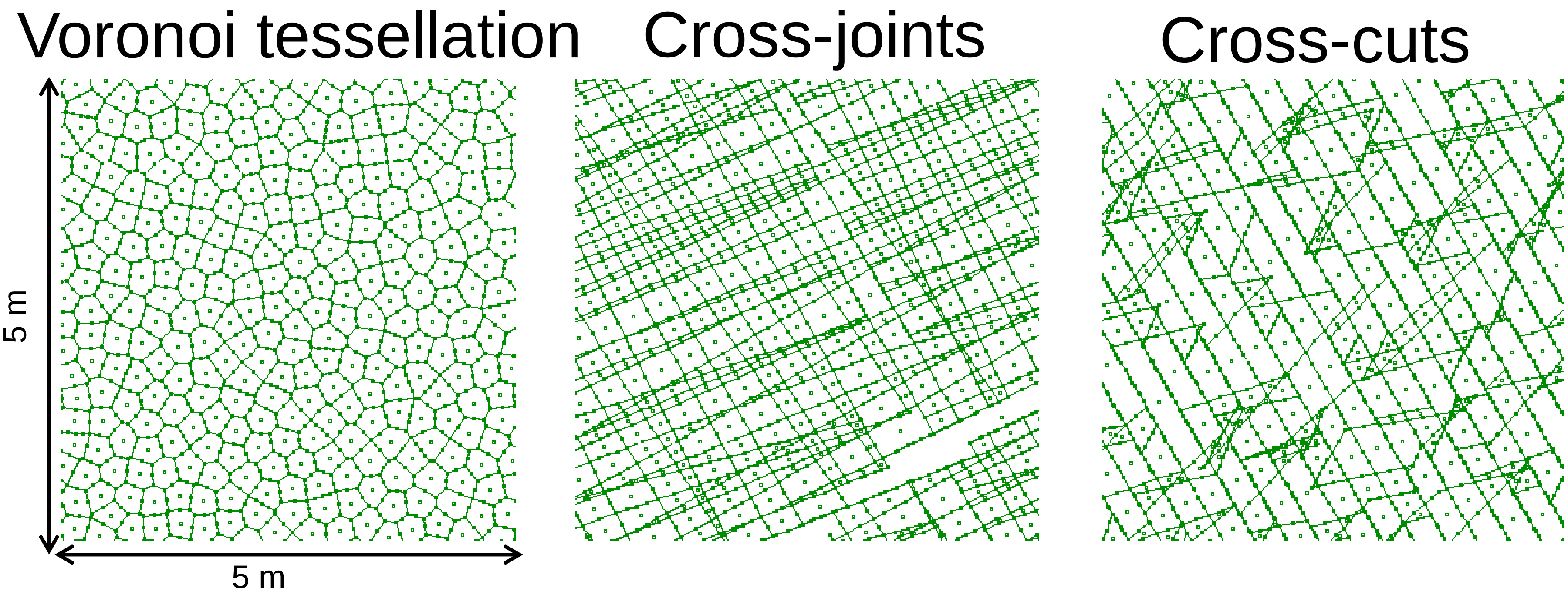
- Natural fabric variability uncertainty
- Our tools to "see" the fabric in a NFR at depth are very limited (core, acoustics)
- Which parameters are most important?
- Spacing, scale, persistence, distributions…? Of what types?
- We need input from some sophisticated people who understand NFR fabric

Representative Geometries?

- Fabric is a highly complex subject
- Can we choose “representative” geometries for HF simulations?



Joint Mechanical Properties

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- Even a "simple" DEM approach needs…
- **Cohesion** (An "average"? Or local? Scale)
- **Friction** behavior (= f(roughness))
- **Stiffness** (invariably = $f(\sigma'_n)$)
- **Shear stiffness** (= $f(\tau$, roughness))
- **Conductivity** (= f(apparent aperture))
- **Dilation** function…

Each parameter is stochastic, linked to others, highly non-linear, f(scale)

Are Joints Rough or Smooth?

Source: N. Barton and A. Makurat


smooth
rough
Are fractures smooth or rough?

Joint Properties Description

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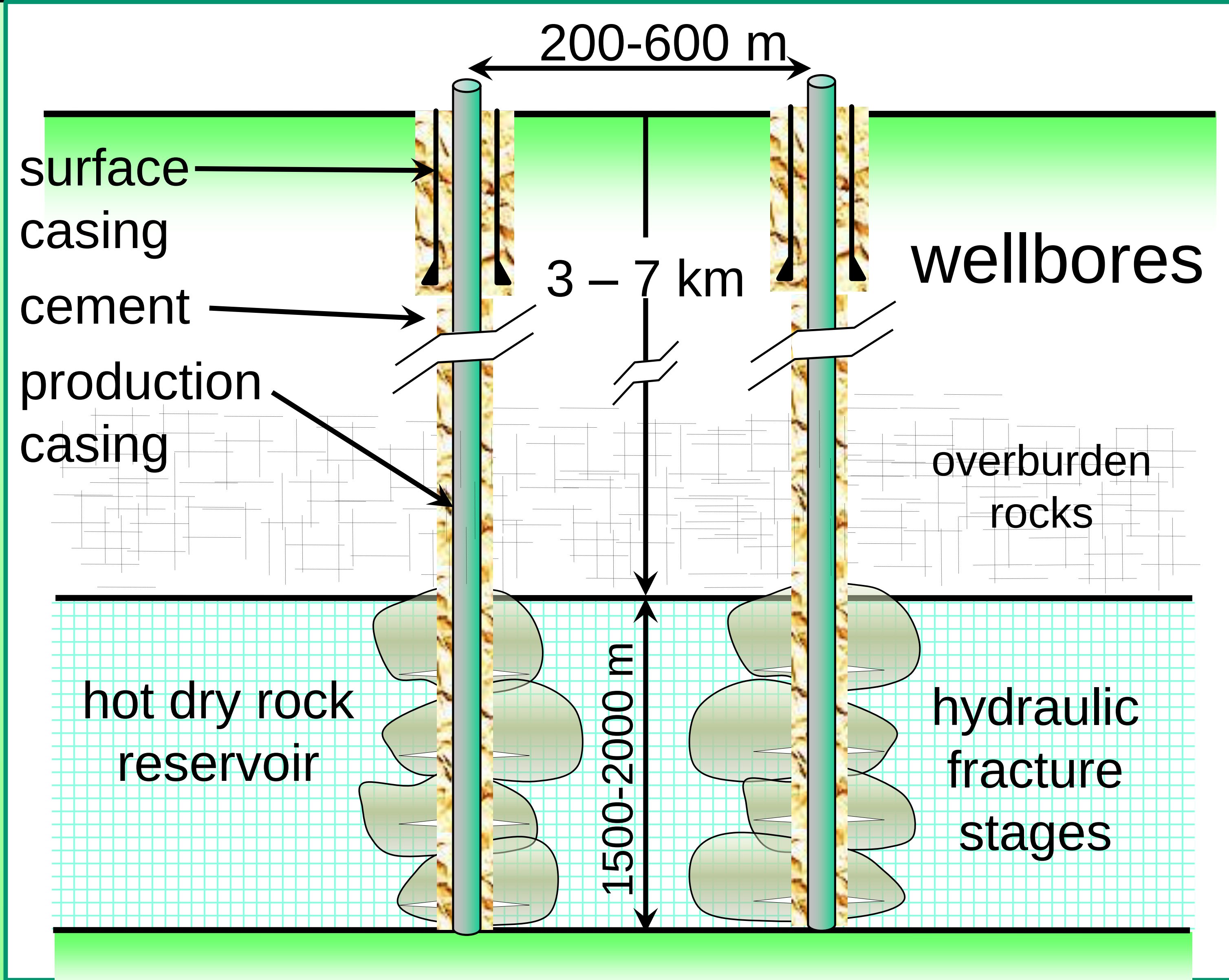
- How to describe the distribution of non-linear parameters like c′, ϕ′?
- Measuring values? Distributions?
  - For each joint set?
  - …scale effects?
- Clearly, there is no realistic chance to get precise answers
- So, do we determine the dominant parameters and focus only on them?

Rock Mass Stimulation and Well Connection

Interwell Communication…

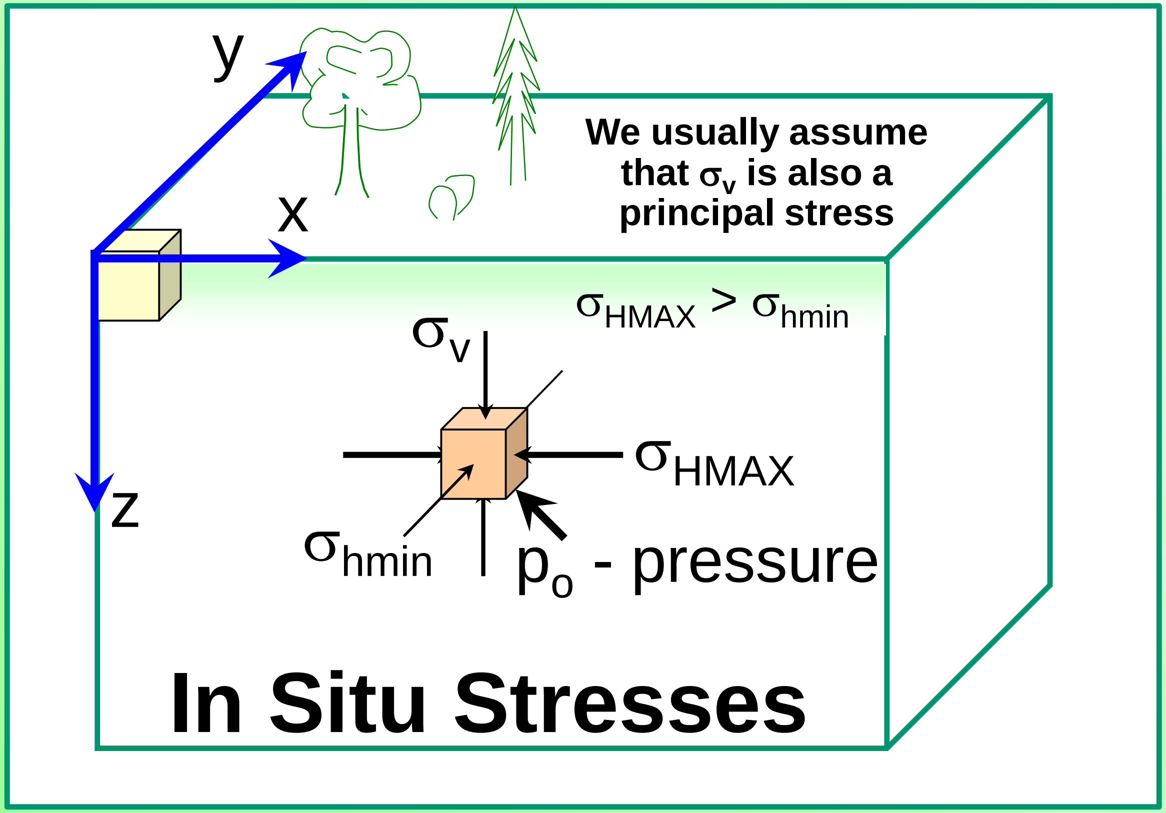


The Main Issues…

- *In Situ* Stresses
- Naturally Fractured Rock Mass Properties
- Stimulation Process (rates, pressures, time)
- Exploitation Schedule

In Situ Stresses

- The stress state in the ground is a fundamental factor in stimulation
- A three-dimensional stress state exists



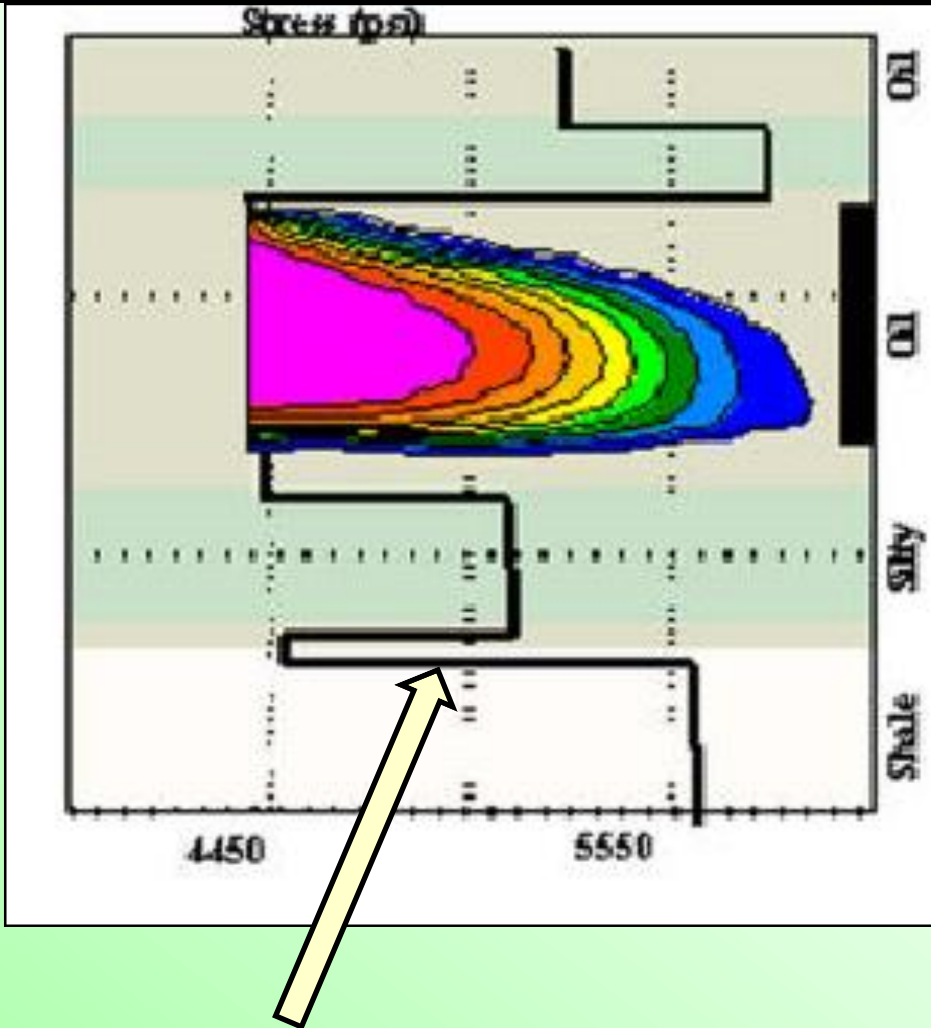
Stresses and Stimulation

- Value of σ_3 dominates HF behavior
- Orientation of σ_3 controls direction
- Fractures rise, generally
- Deviatoric stress (σ_1 - σ_3) magnitude and stress ratio (σ'_1/σ'_3) control shearing
- And rock & joint properties also…
- …& **stresses change during stimulation**!

We understand HF better these days, but not truly predictively.

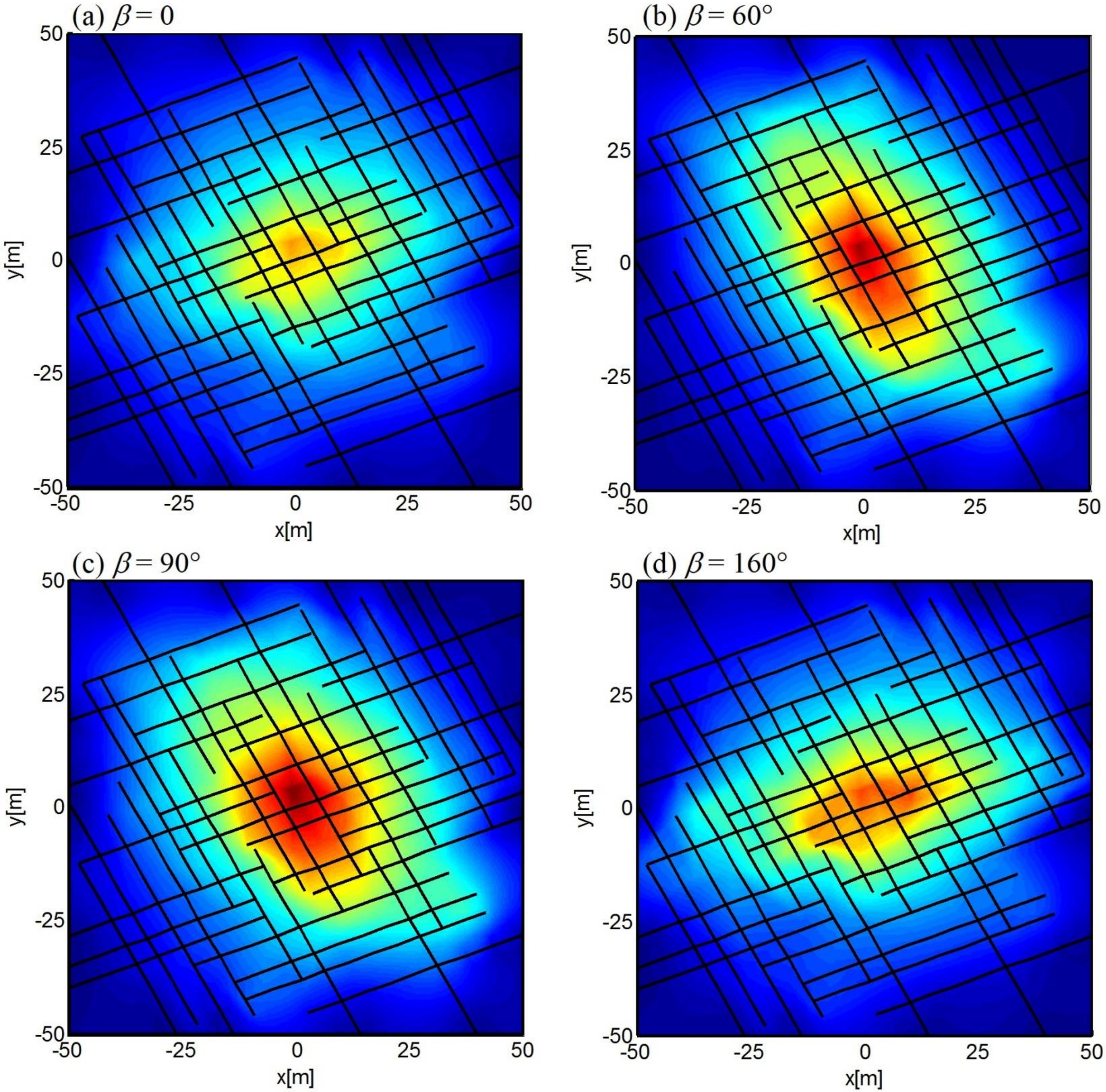
Stresses and Simulation

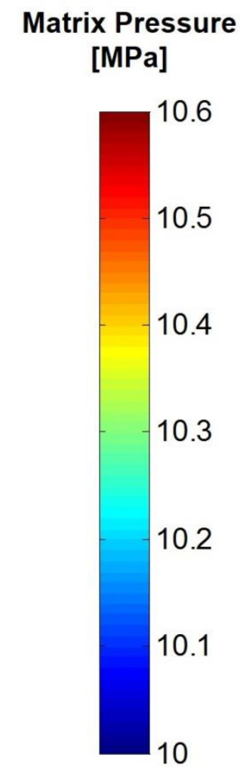
- We often assume a homogeneous [σ_{ij}]
- But we know that initial σ_h stresses are different from bed to bed…
- …and the transitions are not abrupt
- …and there are lateral variations too



Assumed σ_h in HF model

Impact of Stress Angle

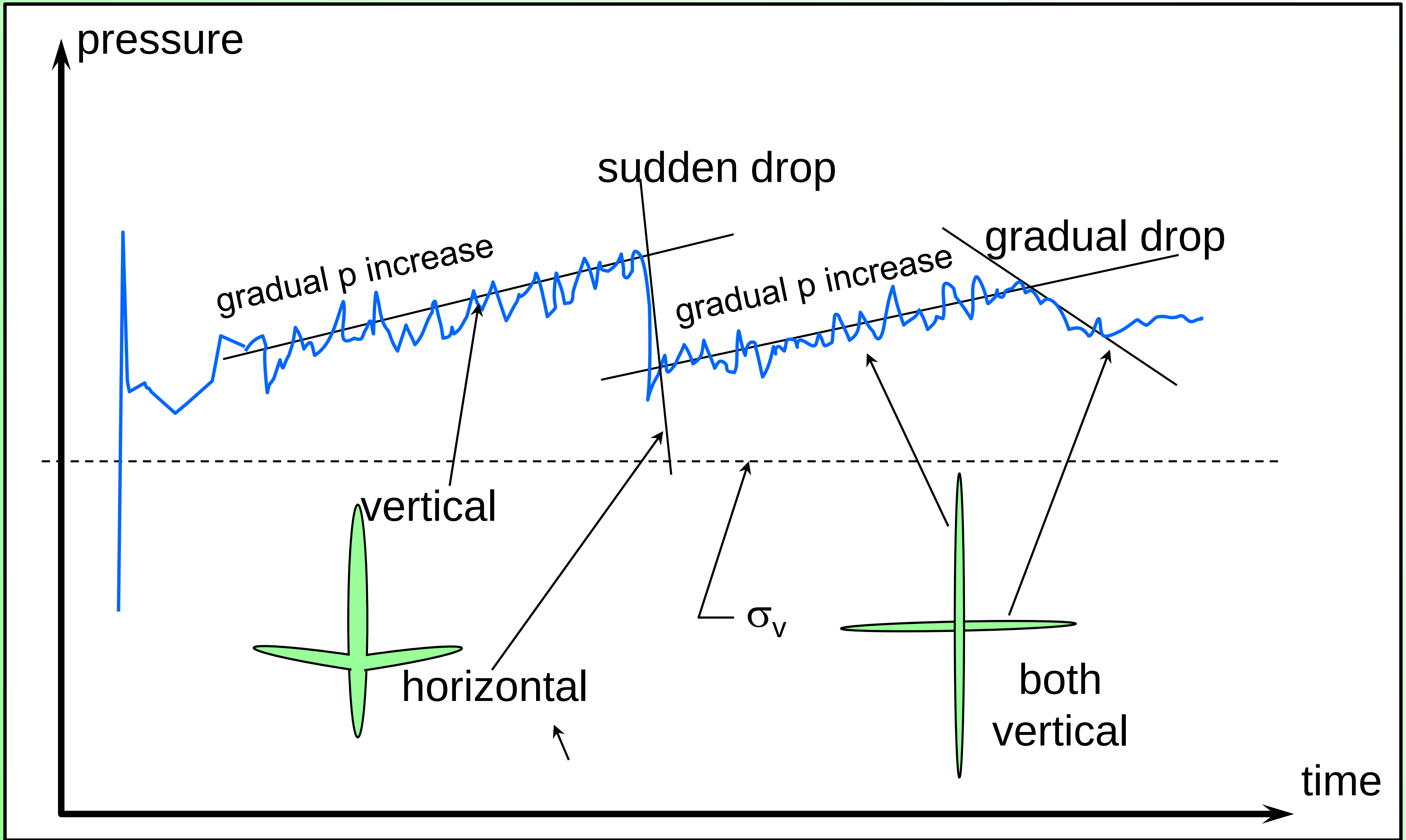




http://www.kilty.com/trip.htm

Pressure Records Show Δσ/Δt

- Pressure drops = changes in orientation



Simulation of Stimulation

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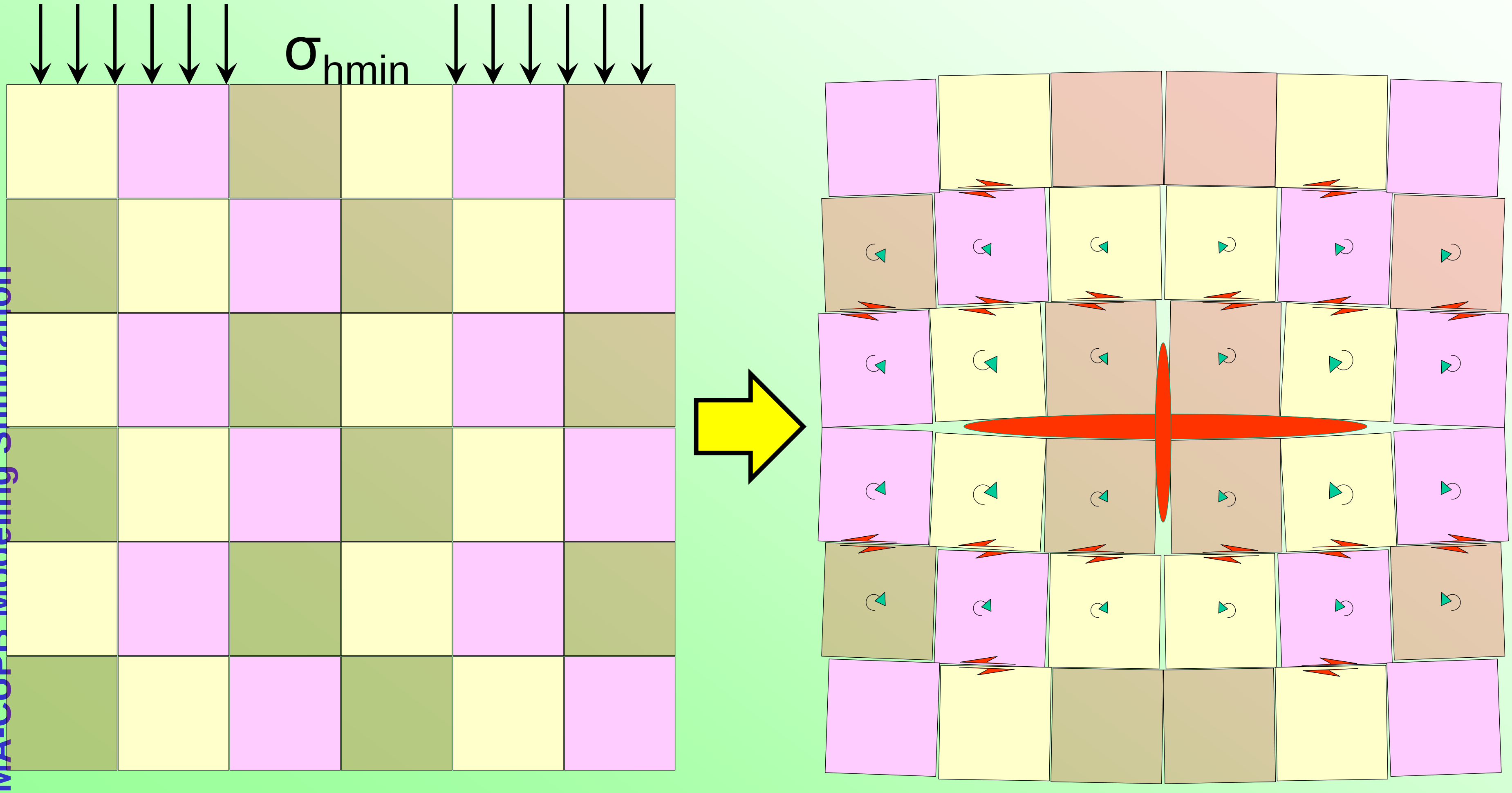
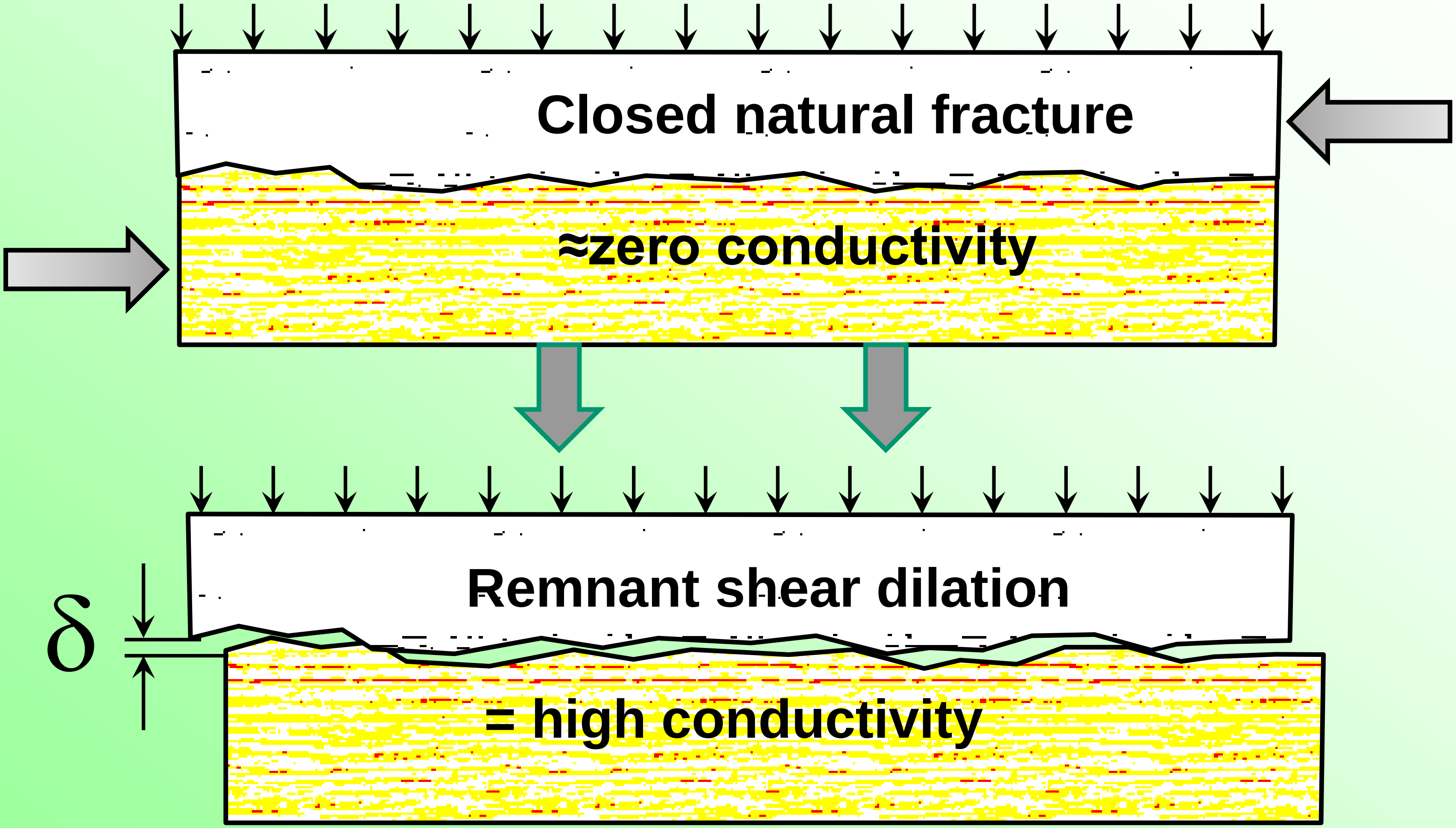
- The effect of HF and Hydroshearing

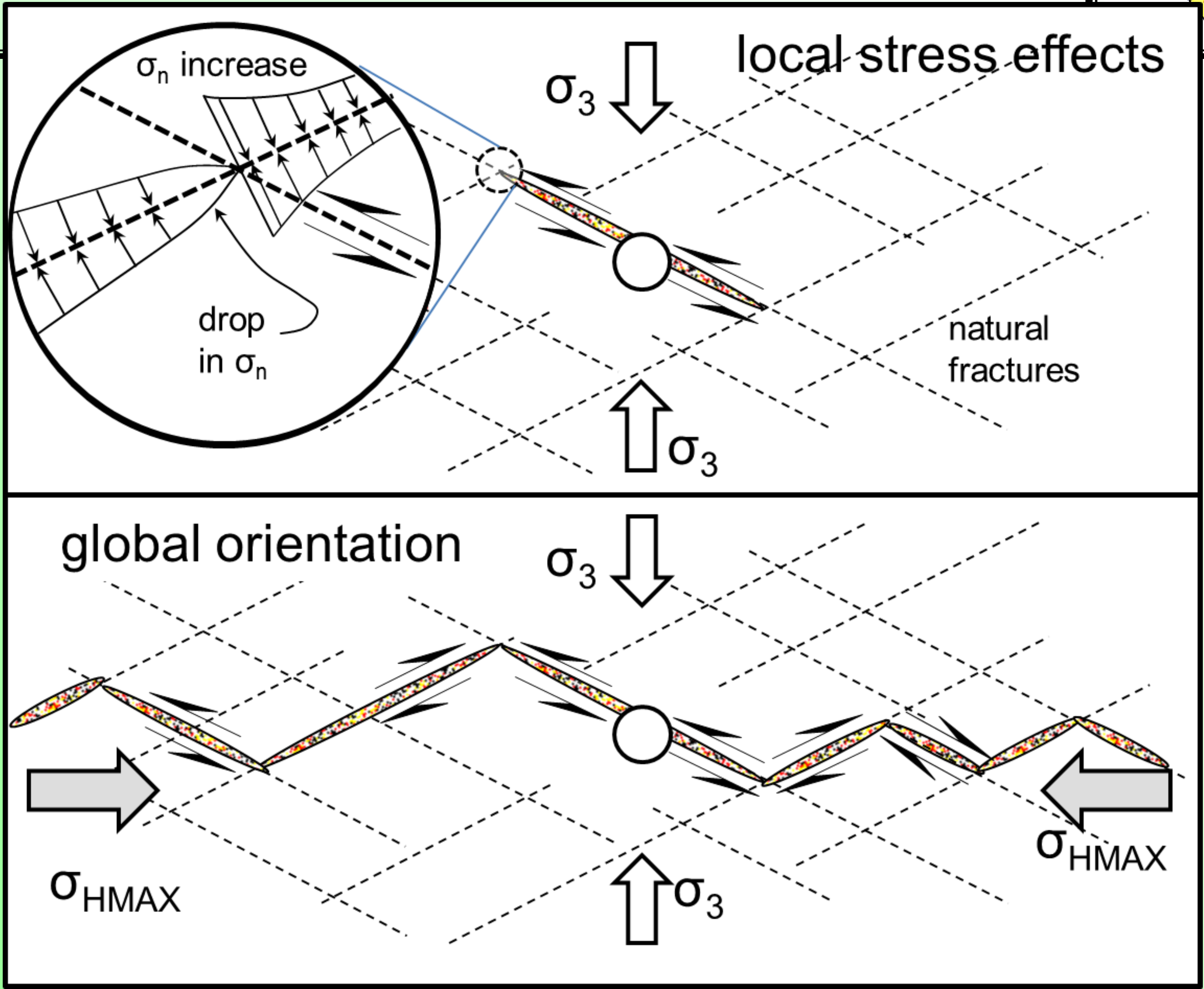


Shear Dilation



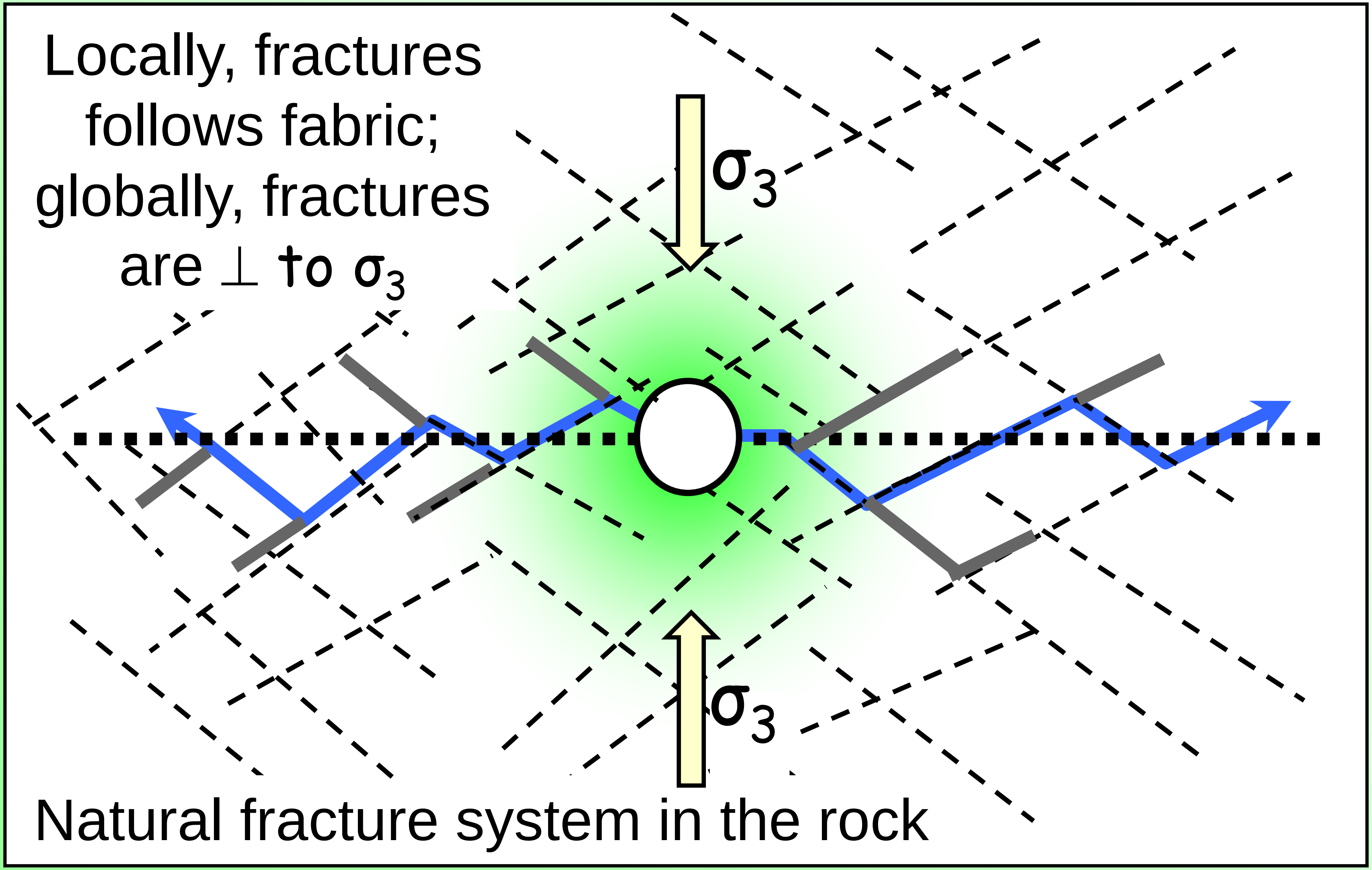
Shear Dilation in Stimulation

Local HF Reorientation…

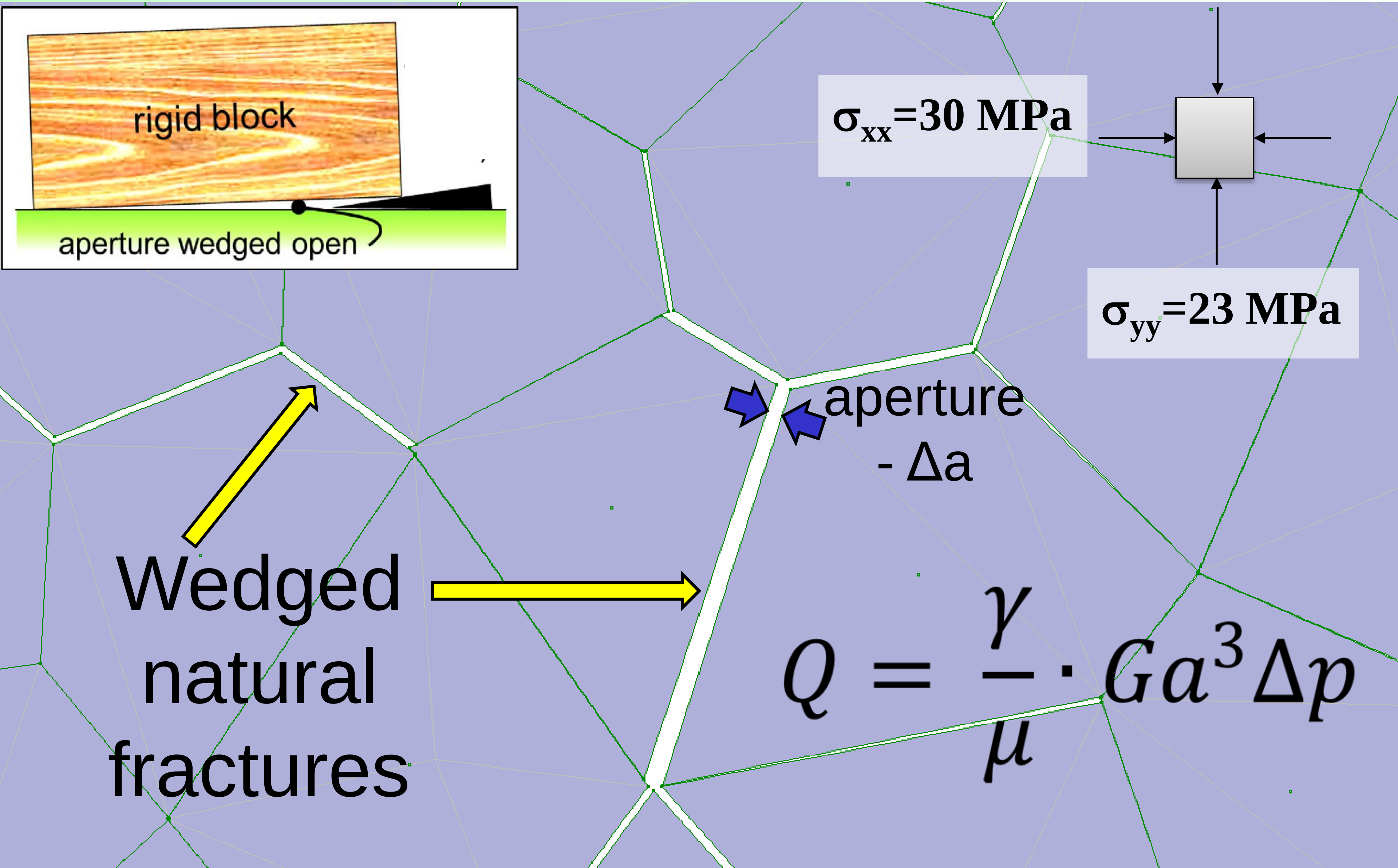


ARMA-CUPB Modeling Stimulation

Large-Scale HF Propagation

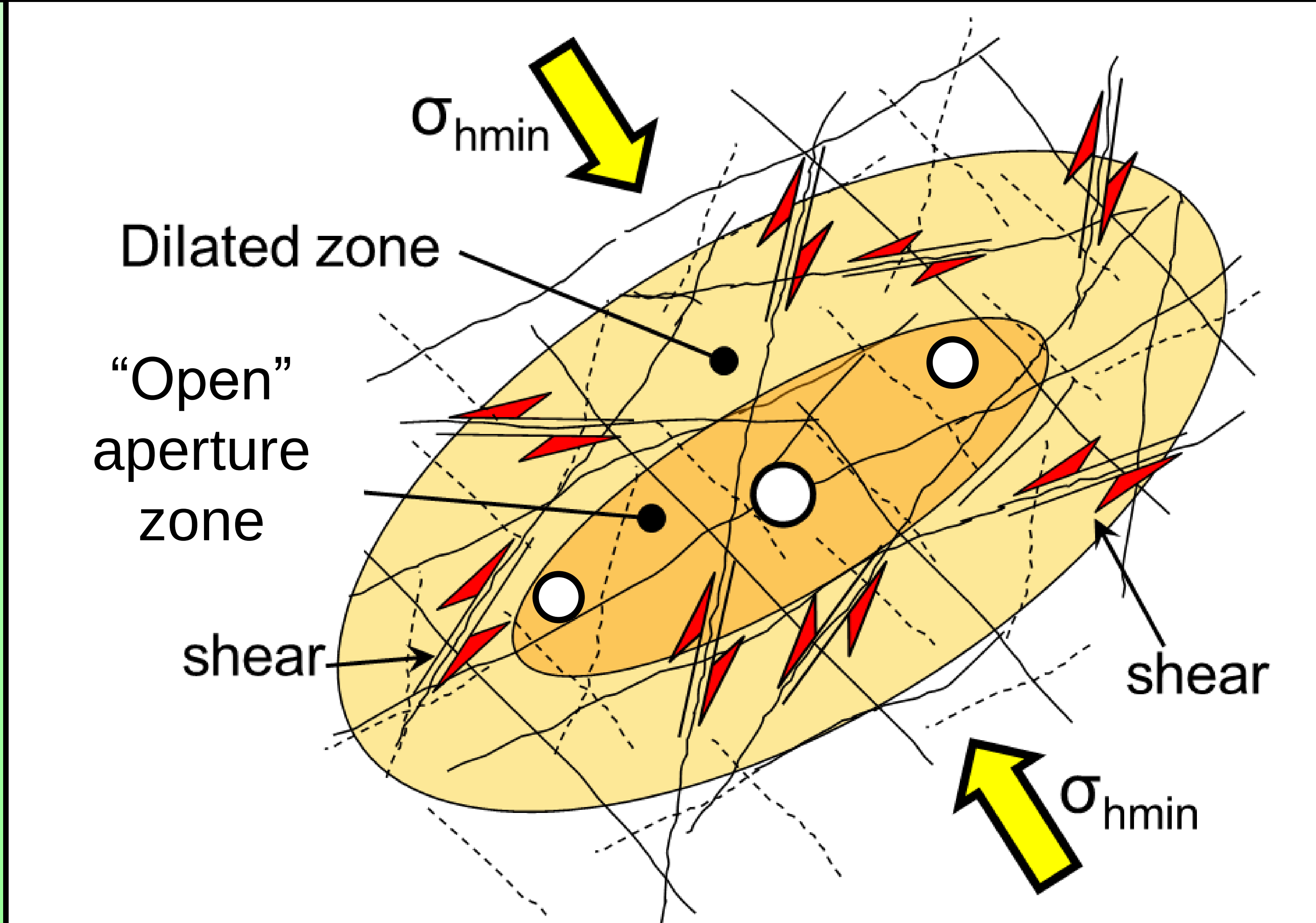


Aperture Impact

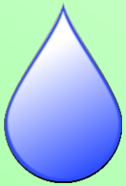


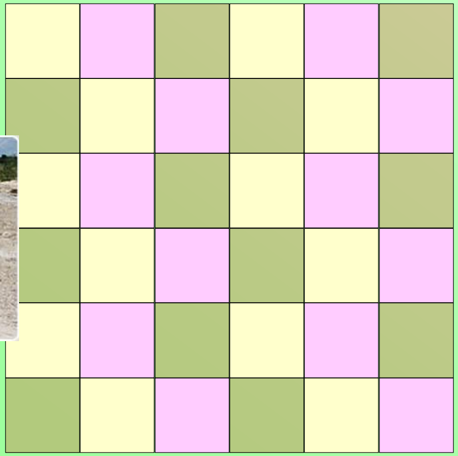
$$Q = \frac{\gamma}{\mu} \cdot G a^3 \Delta p$$

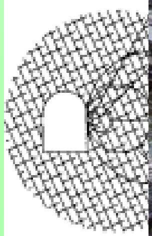
The Stimulated Volume



Scale and Analysis (Simulation)







Wang, Zhao
Engineer

Simulation and Uncertainty

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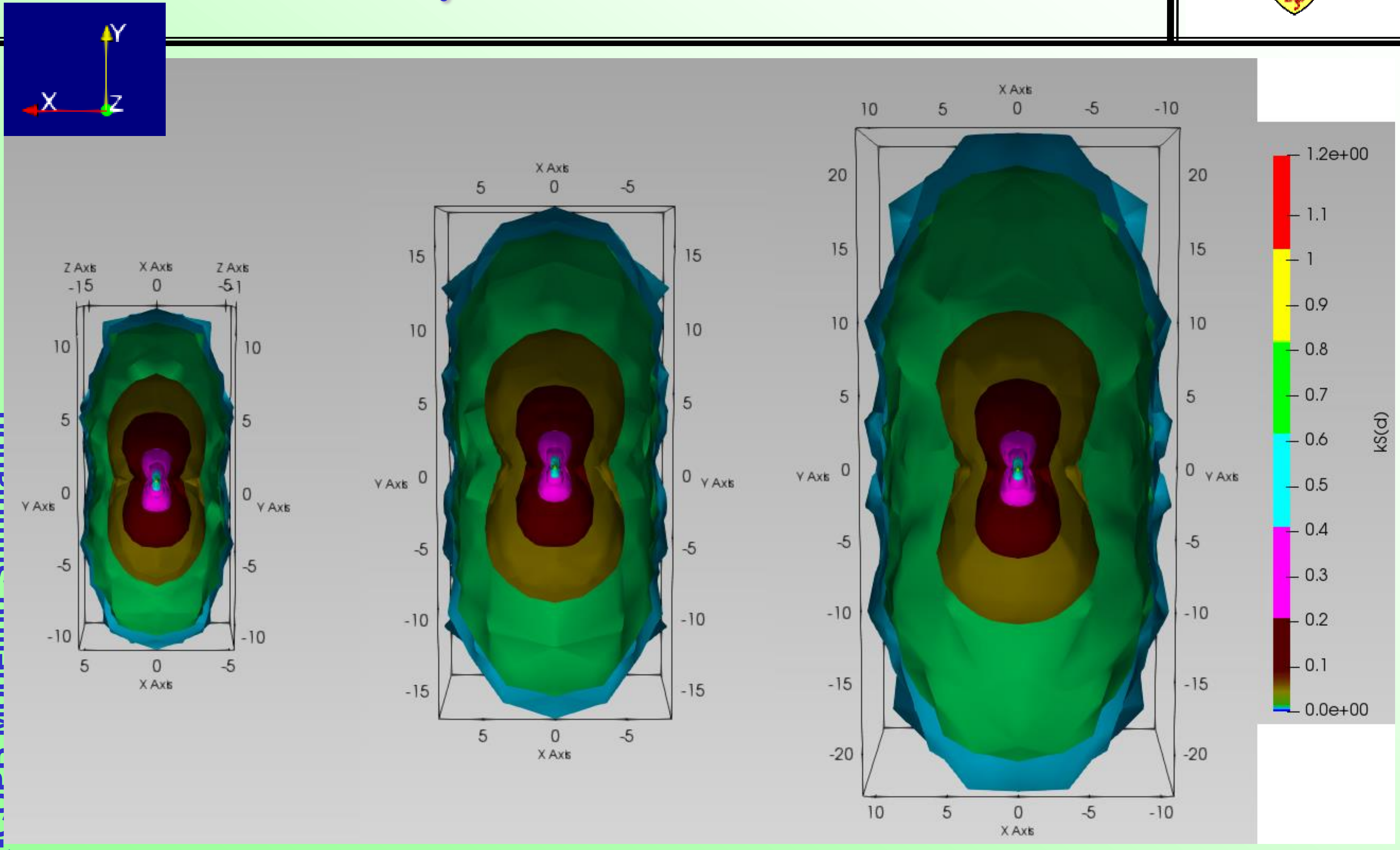
- Simulating HF & HS is challenging
- Because of uncertainty…
- …no one can closely predict stimulation outcomes *a priori* with only simulation
- I believe up-scaled models are vital, and
- …fabric and system variability must be simplified and better accommodated
- …real-time monitoring is important
- …field calibration remains vital

Permeability Evolution



t=80 s **t=200 s** **t=460 s**

Monitoring Stimulation

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- P, T, rate are standard measures…
- Microseismic monitoring is good, but…
- We need **deformations** in order to:
  - Track what is going on at depth
  - Calibrate and use geomechanics models
- Options?
  - Precision tilt measurements
  - Fibre-optics cables in shallow slim holes
  - 3-D active seismics (stress changes)

Conclusions

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- Many variables, unknown distributions
- Rock fabric and scale impacts
- Natural & induced stress inhomogeneity
- We will never fully constrain these parameters. So…
- …predicting stimulation outcomes in the absence of monitoring data is improbable
- …predicting stimulation outcomes in the absence of calibrations is improbable

What Shouldn't we Model?

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- Tip processes?
  - Too dominated by local effects
  - Tip process zone is small compared to the HF scale – St. Venant's Principle
- Individual joint responses?
  - Huge constitutive uncertainty for each joint, we must adopt an upscaled "law"
  - Huge changes in fracture conductivity, we must adopt a non-linear "k" = f(damage?)
- Avoiding deterministic fabric models?
- What use is fracture toughness?

But These are also Challenges!

- Many useful subjects for research and ideas for implementation in the field
- We will never be able to "predict" in a deterministic manner…
- …but we should get much better at predicting "ranges of outcomes"

Addressing these challenges will drive future EGS implementation, but modesty in our ability to "predict" remains appropriate

Acknowledgements

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