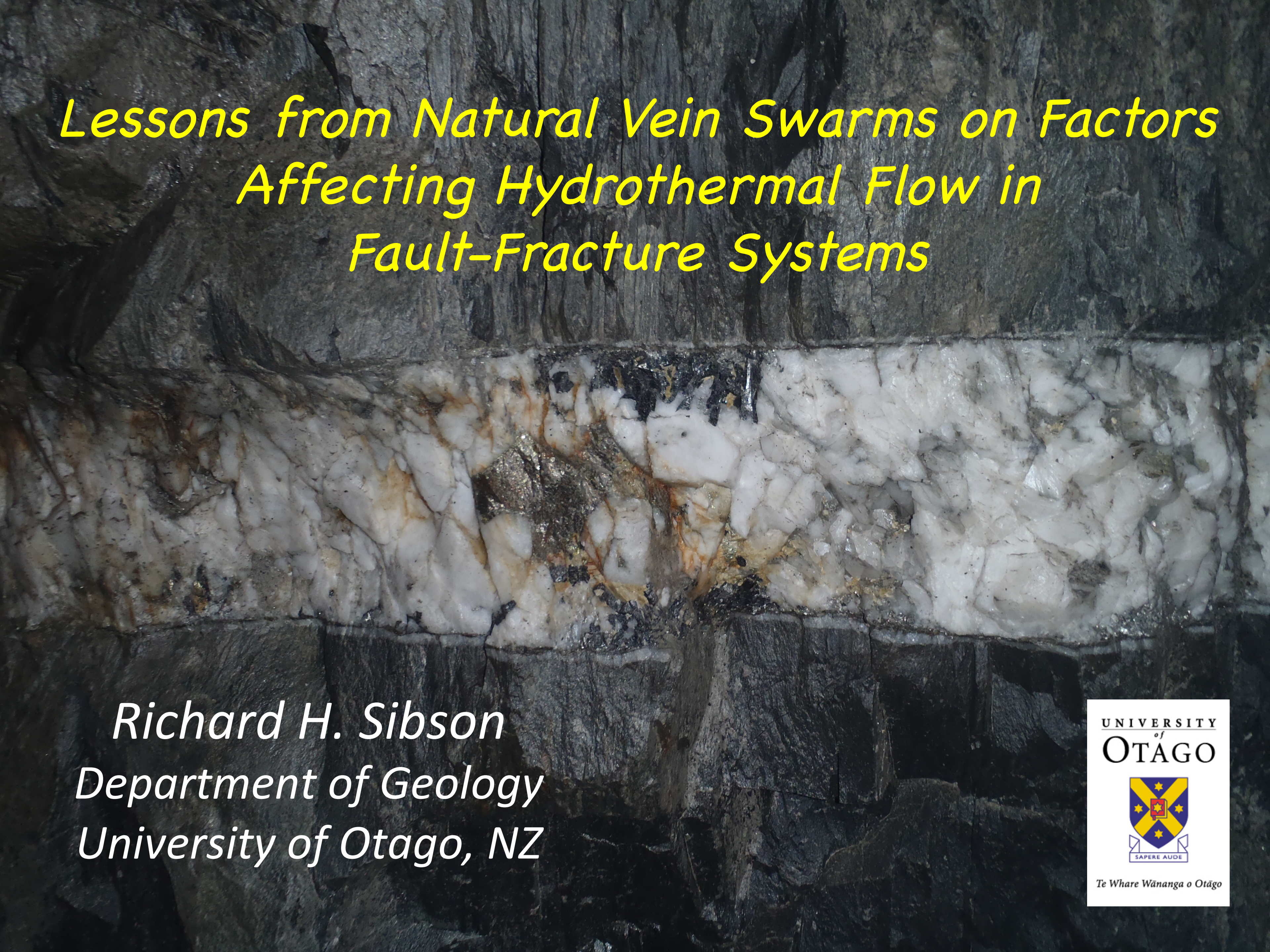


Lessons from Natural Vein Swarms on Factors Affecting Hydrothermal Flow in Fault-Fracture Systems

Richard H. Sibson
Department of Geology
University of Otago, NZ

- seismogenic crust is very heterogeneous

- much inherited structure (faults, fractures, folds, etc.)

'PAST IS THE KEY TO THE PRESENT'

M.N.I.A.B.

- look for simple signals that stand out through the noise and work some/most of the time

- mineralized fault-fracture systems = high-flux flow conduits

Au-Quartz Veins = Tracers for large-volume hydrothermal flow

Transport Solubilities

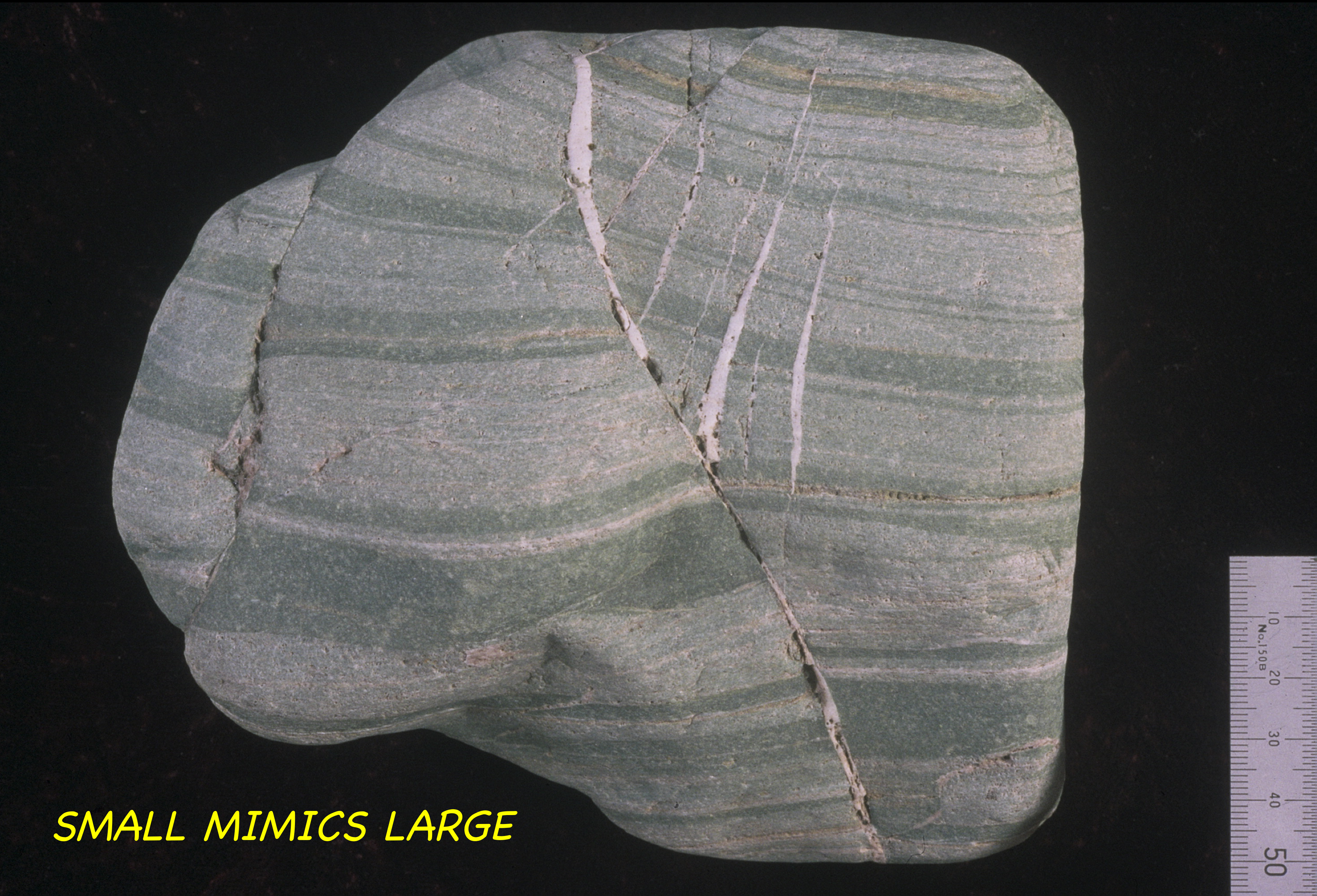
H_2O / Qtz ~ 10^3 - 10^4

H_2O / Au ~ 10^7 - 10^9

Ore Grades

1 < Au/Qtz < 1000 ppm

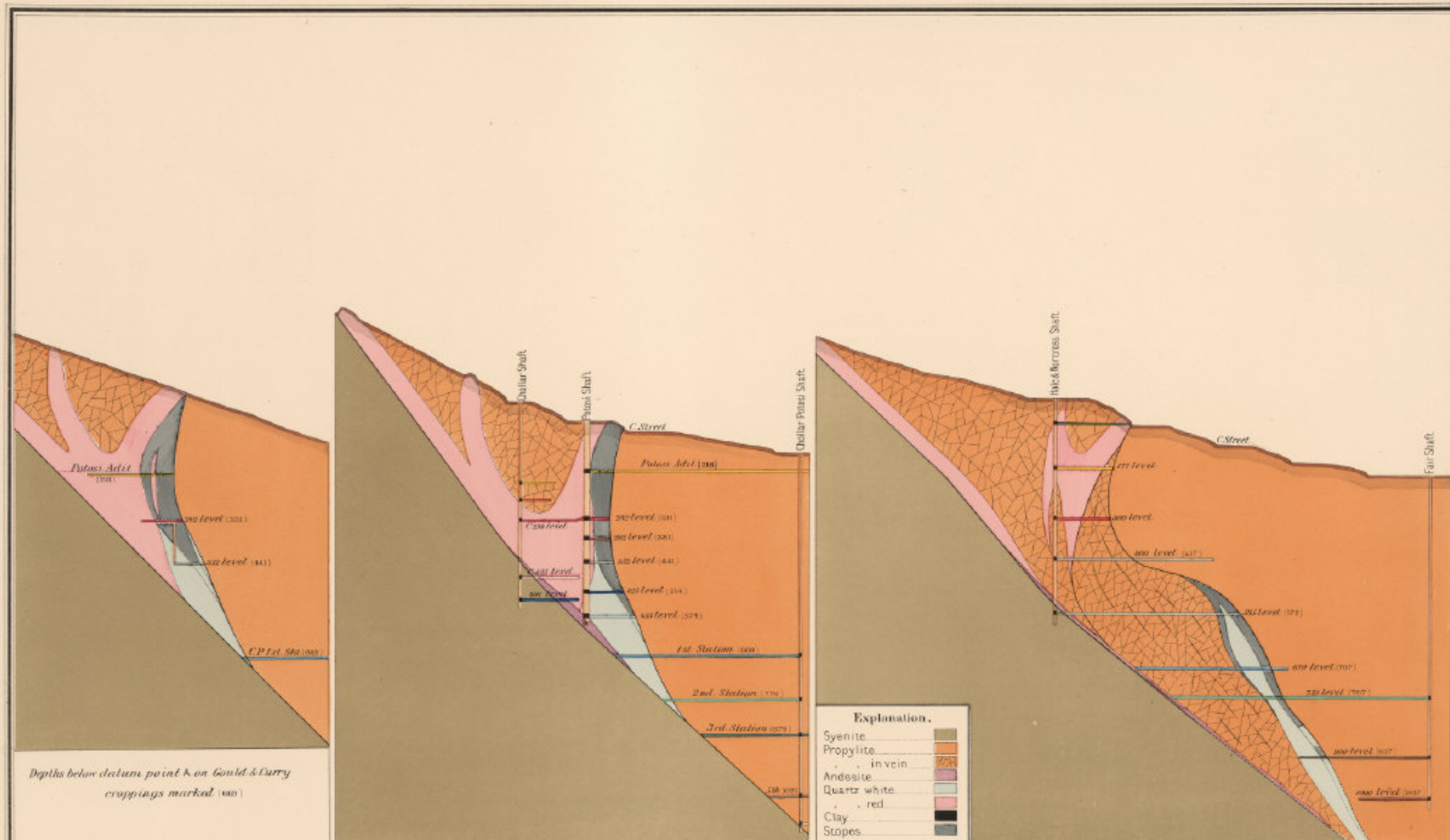
STRESS-CONTROLLED STRUCTURAL PERMEABILITY



CROSS SECTIONS VIRGINIA MINES, COMSTOCK LODE.

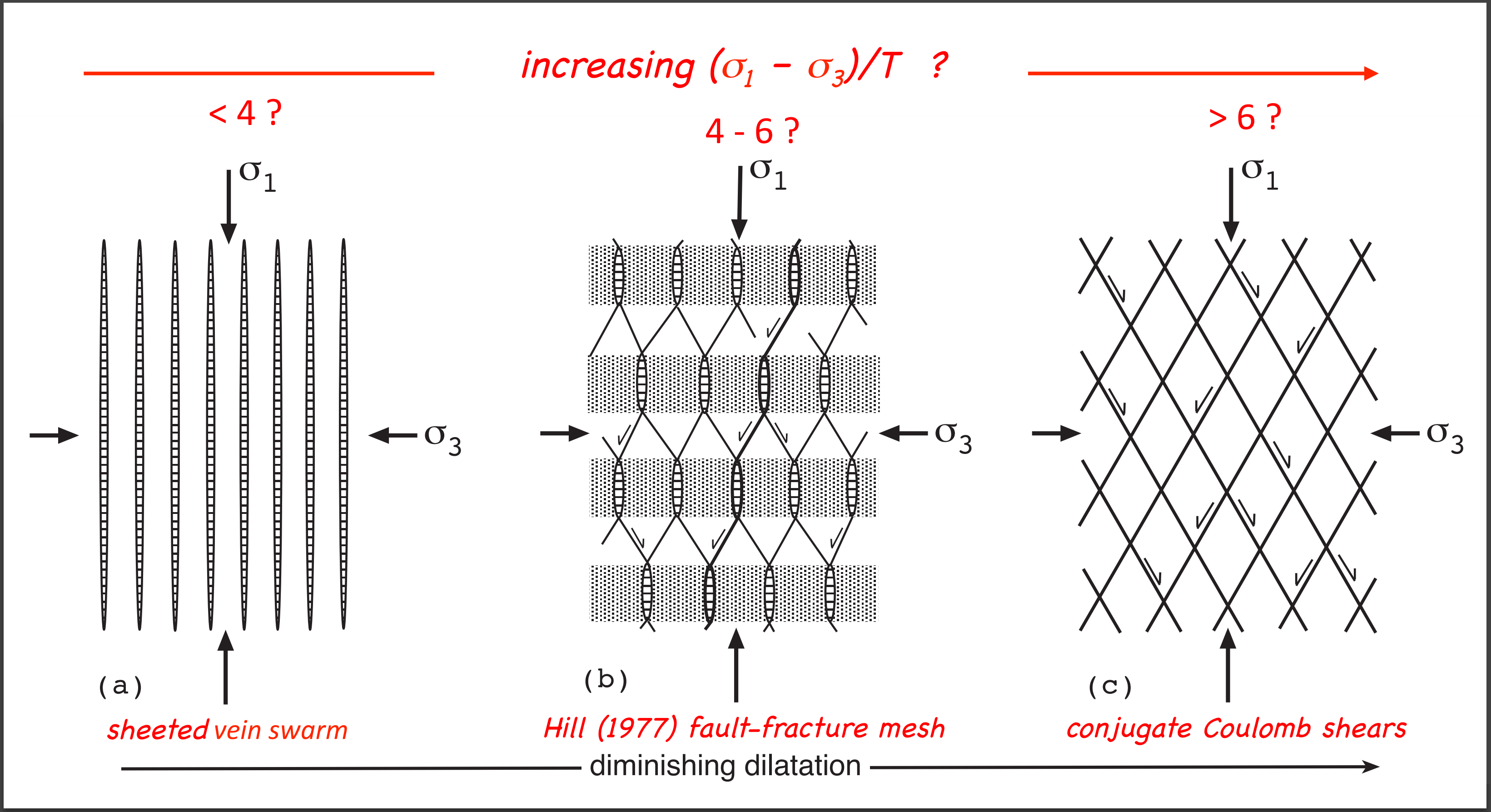
SCALE: 200 FEET TO ONE INCH.

Plate 9.



Through Potosi South Stope | Through Potosi Shaft | Through Hale & Norcross Shafts

Varieties of Fault-Fracture Mesh

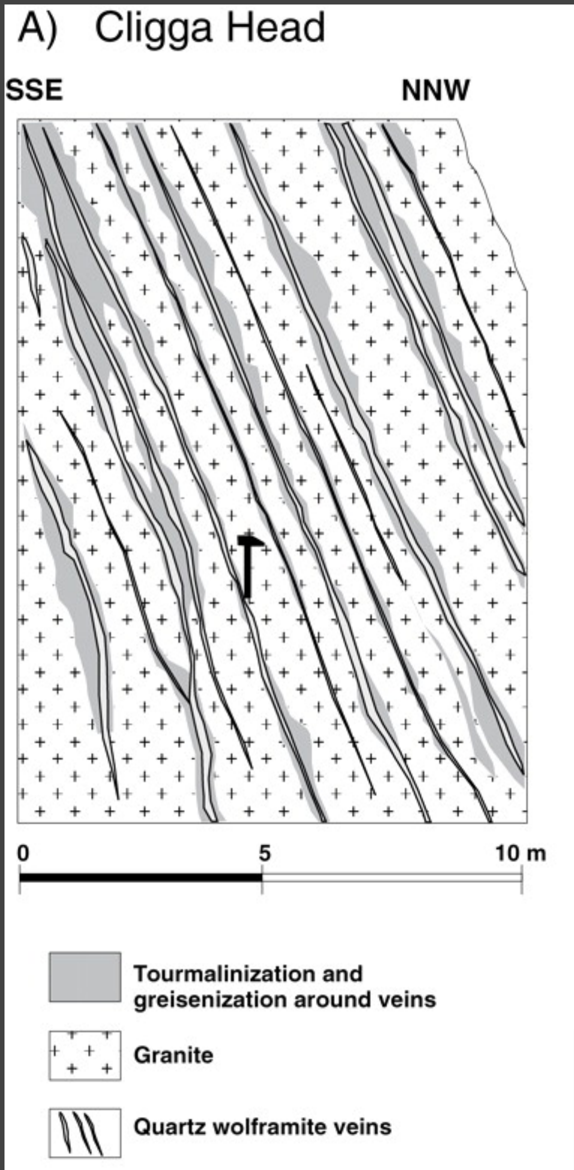


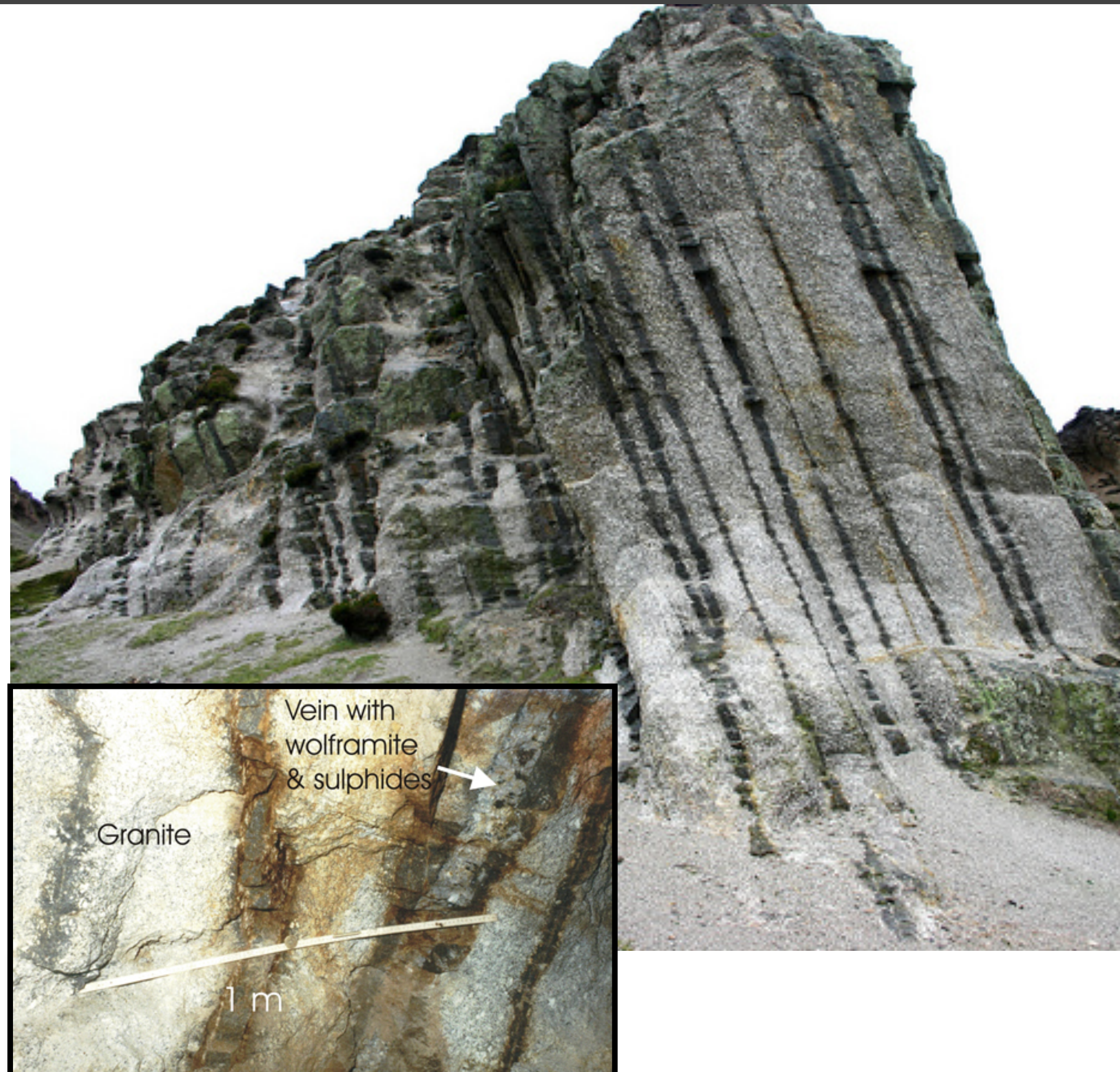
- implications for rupture growth and impedance?

Calcite Extension Veins in Jurassic Limestone, Kilve, Somerset

Quartz Extension Veins in Sandstone, N. Devon

Parallel Veins and Alteration Zones, Cligga Head

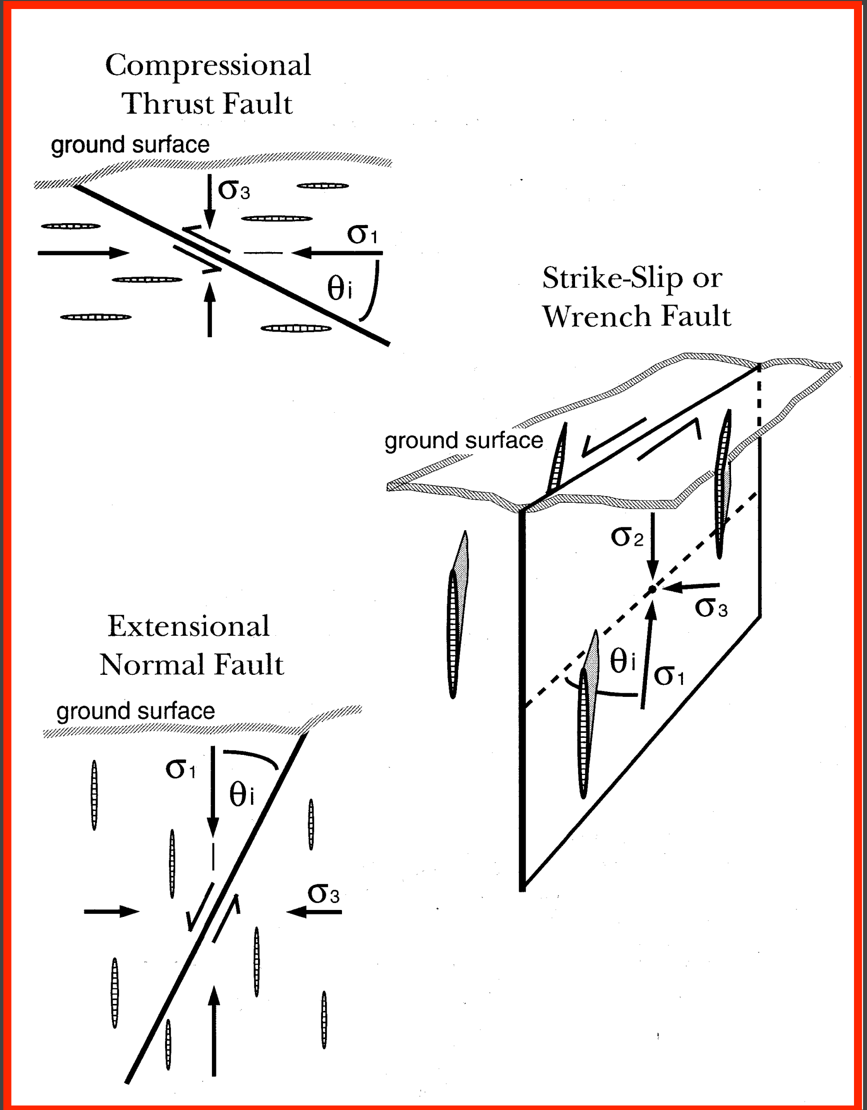




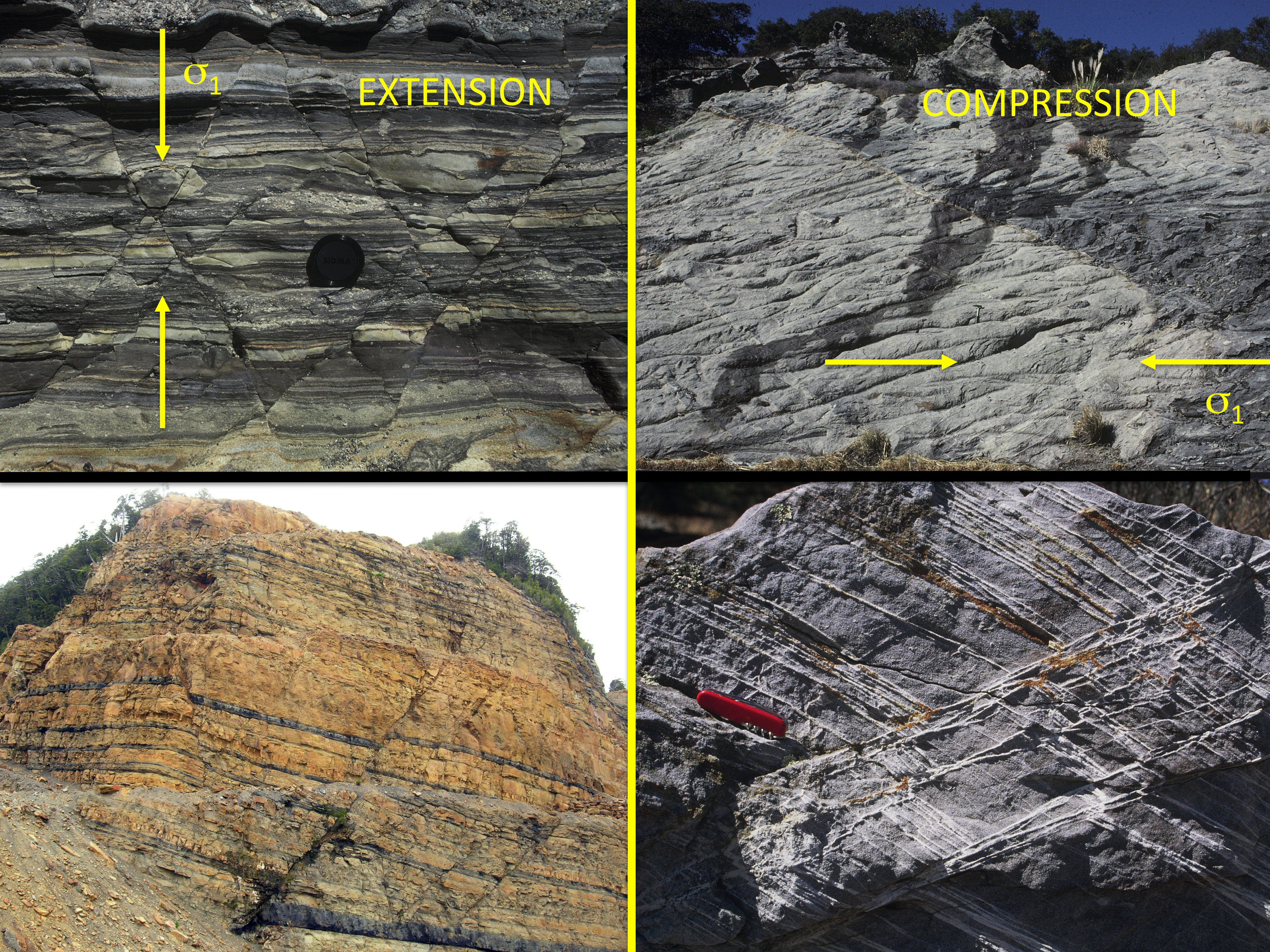
Extensional Fault-Fracture Mesh in Monterey Shales

E.M. Anderson's Theory of Faulting (1905)

- No shear stress along the rock-air interface at Earth's surface
- One principal stress must therefore be vertical with the other two in a horizontal plane
- There are therefore THREE fundamental stress regimes in the Earth's crust depending whether $\sigma_v = \sigma_1, \sigma_2$, or σ_3
- Faults develop in homogeneous, isotropic, intact crust in accordance with the Coulomb shear failure criterion, forming along planes containing σ_2 lying at c. 20-30° to σ_1
- THREE fundamental fault types: NORMAL Faults ($\sigma_v = \sigma_1$), THRUST Faults ($\sigma_v = \sigma_3$), and WRENCH (Strike-Slip) Faults ($\sigma_v = \sigma_2$).



- faults at initiation, or of low displacement



σ_1
EXTENSION
COMPRESSION
σ_1

Stress Ratio for Fault Reactivation (2D)
P_f Sensitivity

- for a cohesionless fault

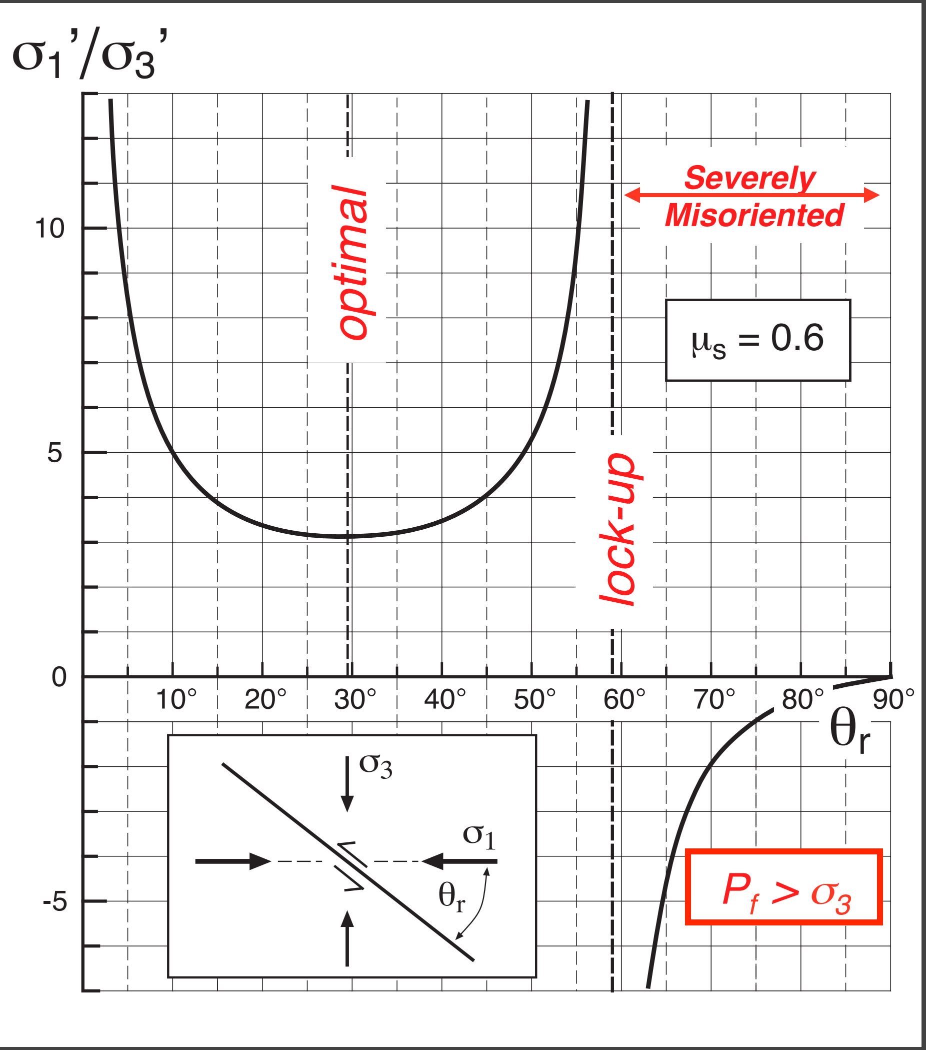
$$\tau = \mu_s.\sigma_n' = \mu_s(\sigma_n - P_f)$$

$$\frac{\sigma_1'}{\sigma_3'} = \frac{(\sigma_1 - P_f)}{(\sigma_3 - P_f)} = \frac{(1 + \mu_s \cot\theta_r)}{(1 - \mu_s \tan\theta_r)}$$

OPTIMAL - $\theta_r^* = 0.5\tan^{-1}(1/\mu_s)$
LOCK-UP - $\theta_r = 2\theta_r^* = \tan^{-1}(1/\mu_s)$

$\sigma_1'/\sigma_3' \rightarrow \infty$ if $\sigma_1 >>> \sigma_3$

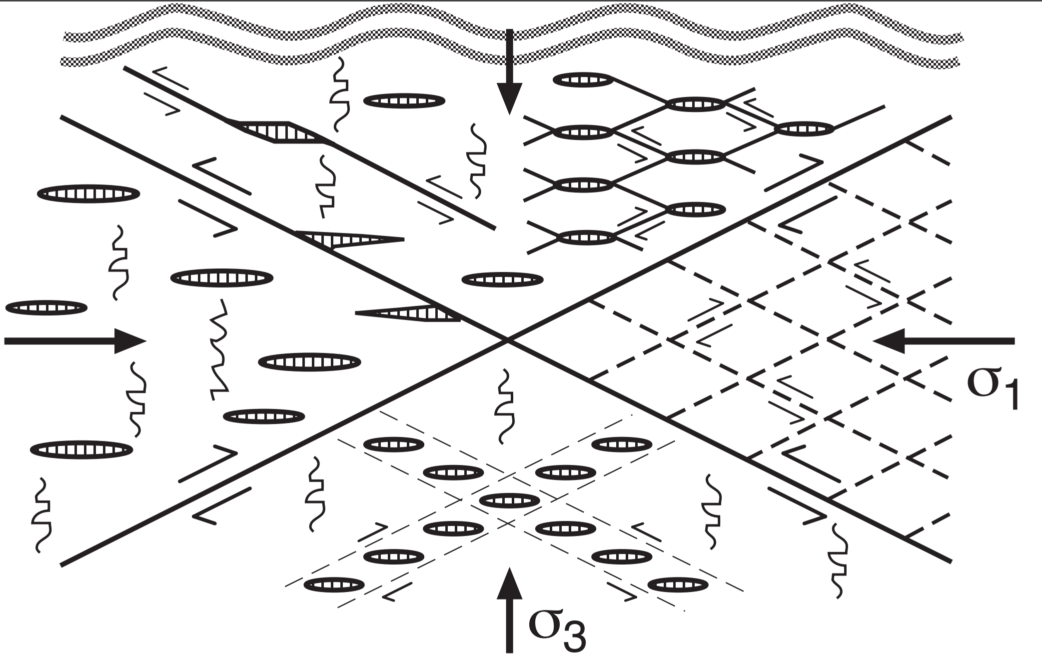
or if $\sigma_3' \rightarrow 0$ i.e. $P_f \rightarrow \sigma_3$



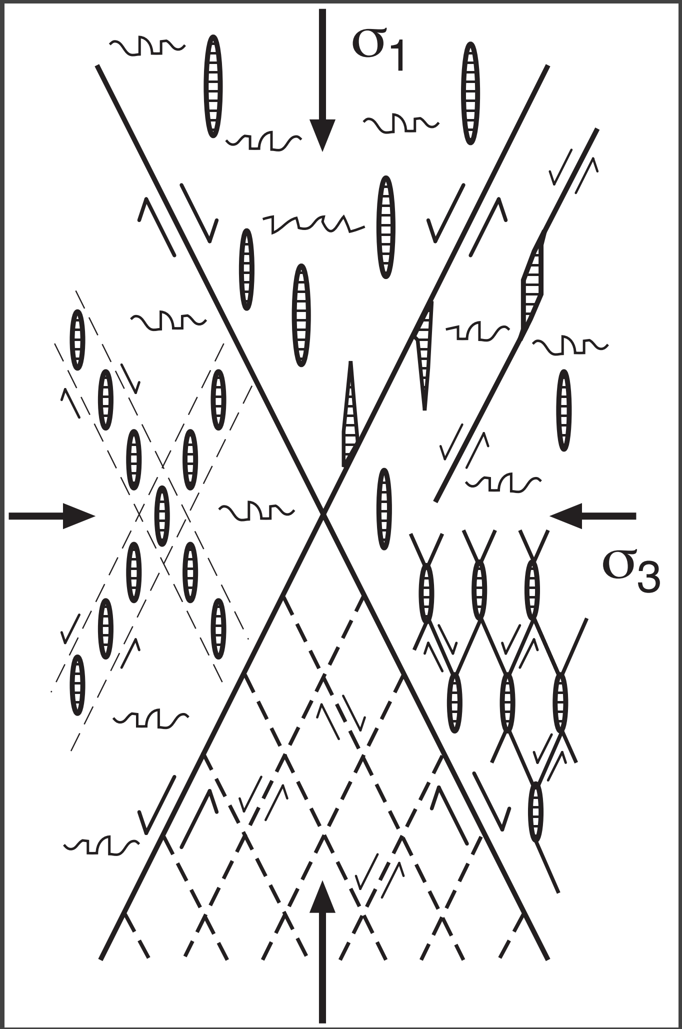
Elements of Stress-Controlled Structural Permeability

- *components dependent on stress and fluid-pressure conditions*

COMPRESSION



EXTENSION



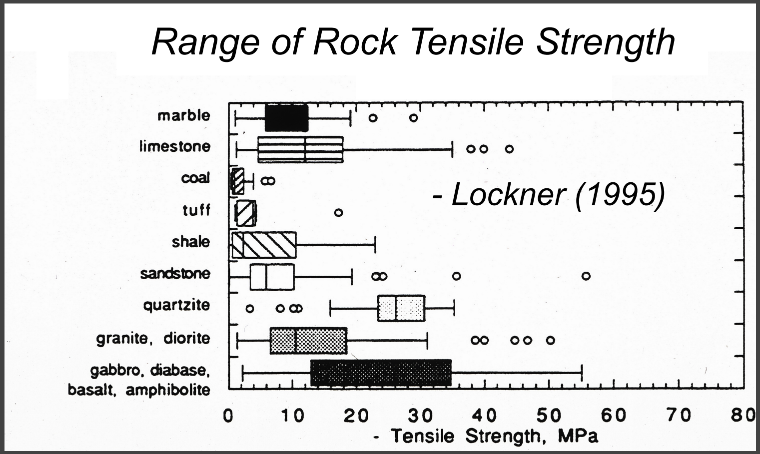
Conditions for Hydraulic Extension Fracturing

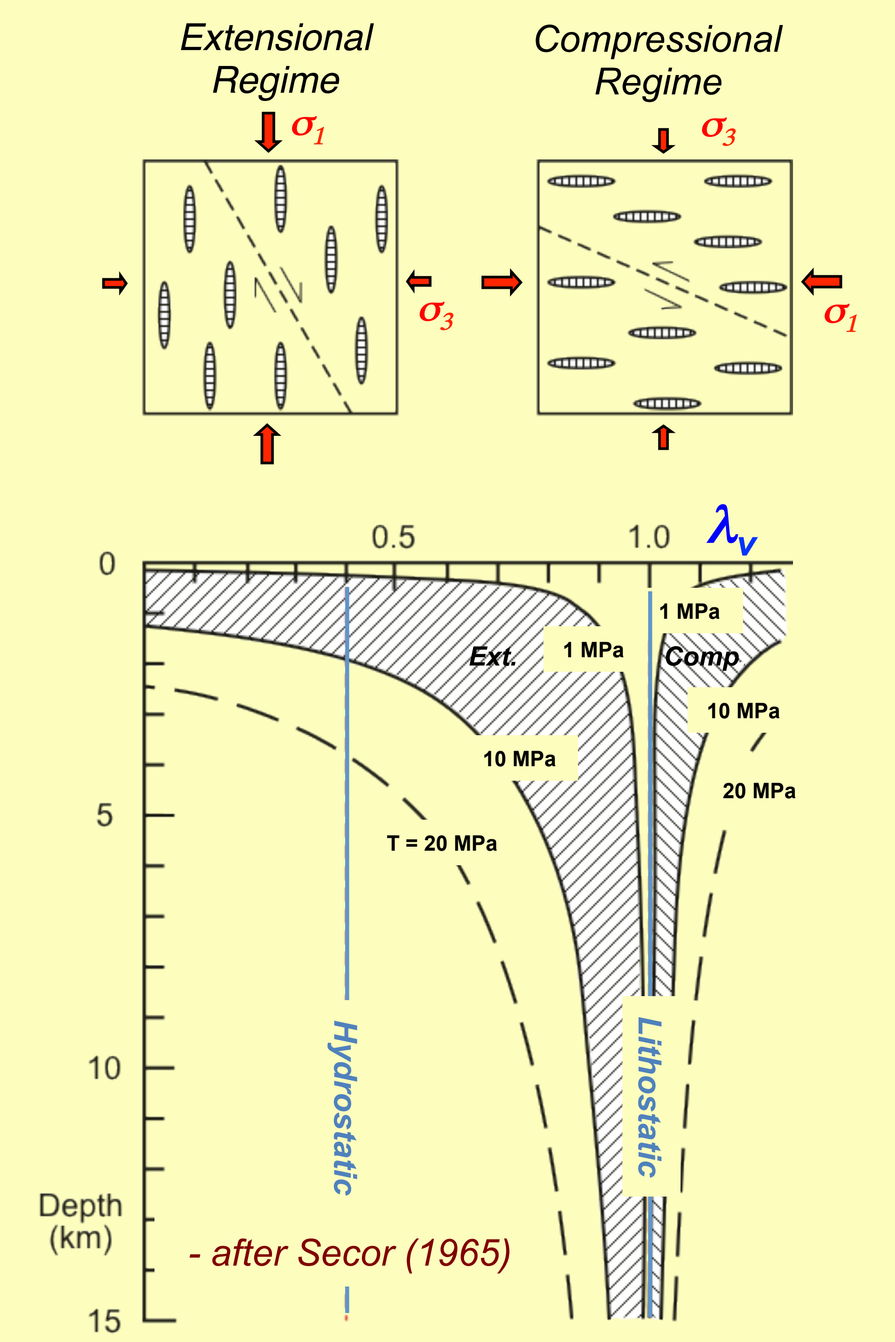
$P_f = \sigma_3 + T$

provided

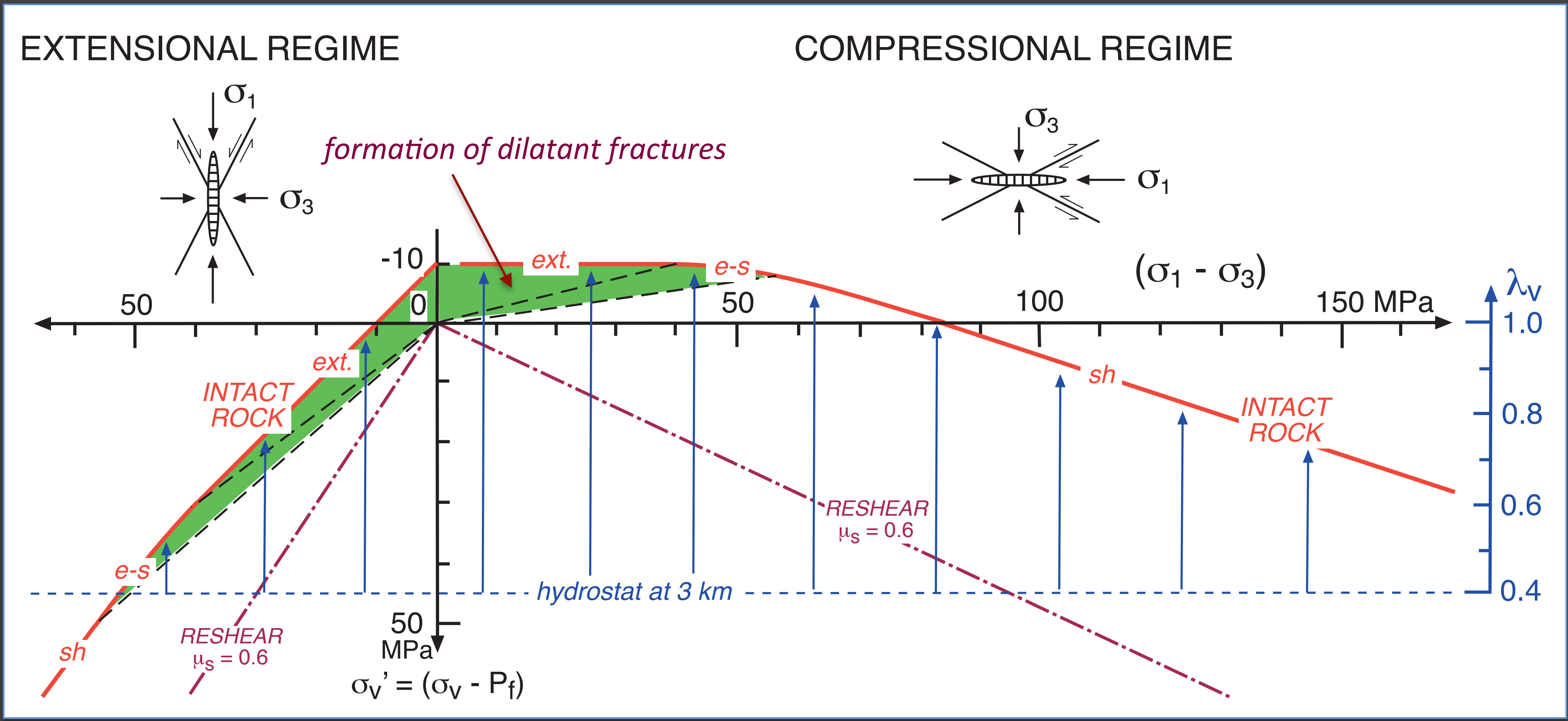
$(\sigma_1 - \sigma_3) < 4T$

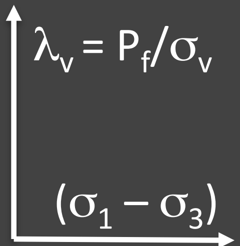
$\lambda_v = P_f / \sigma_v$





Conditions Promoting Brittle Failure in Extensional vs. Compressional Regimes



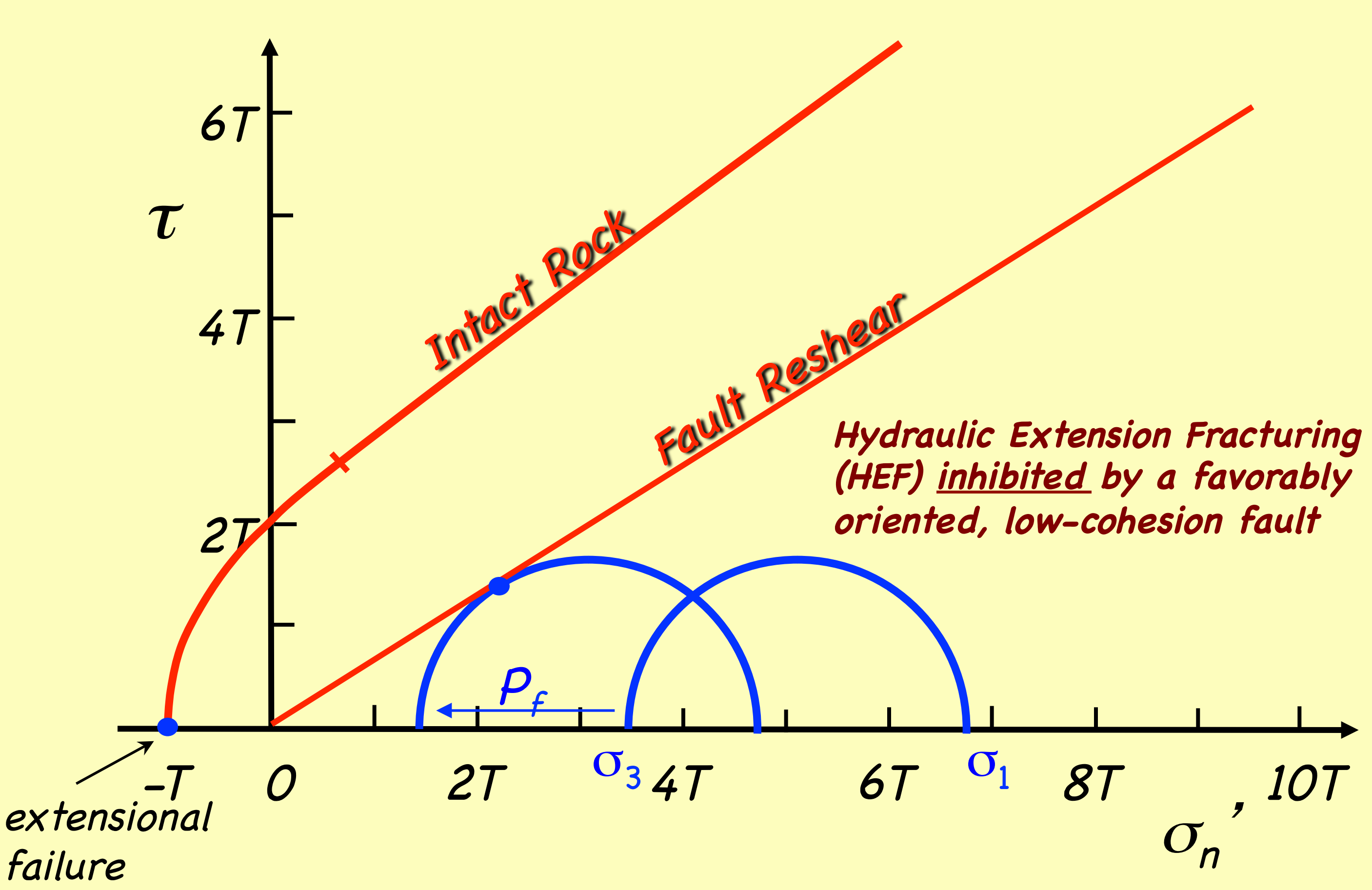


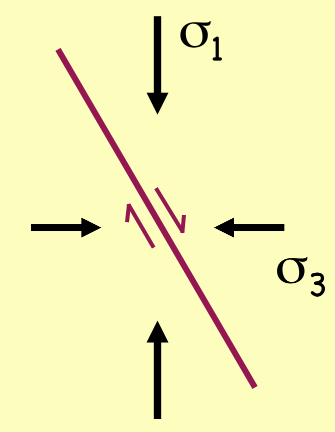
<u>Intact Rock</u>

'Andersonian' stress fields

T = 10 MPa; μ_i = 0.75

Inhibition of Hydraulic Extension Fracturing by an Existing Low-Cohesion Fault





ABSENCE of VEINS around faults does NOT mean absence of Overpressure

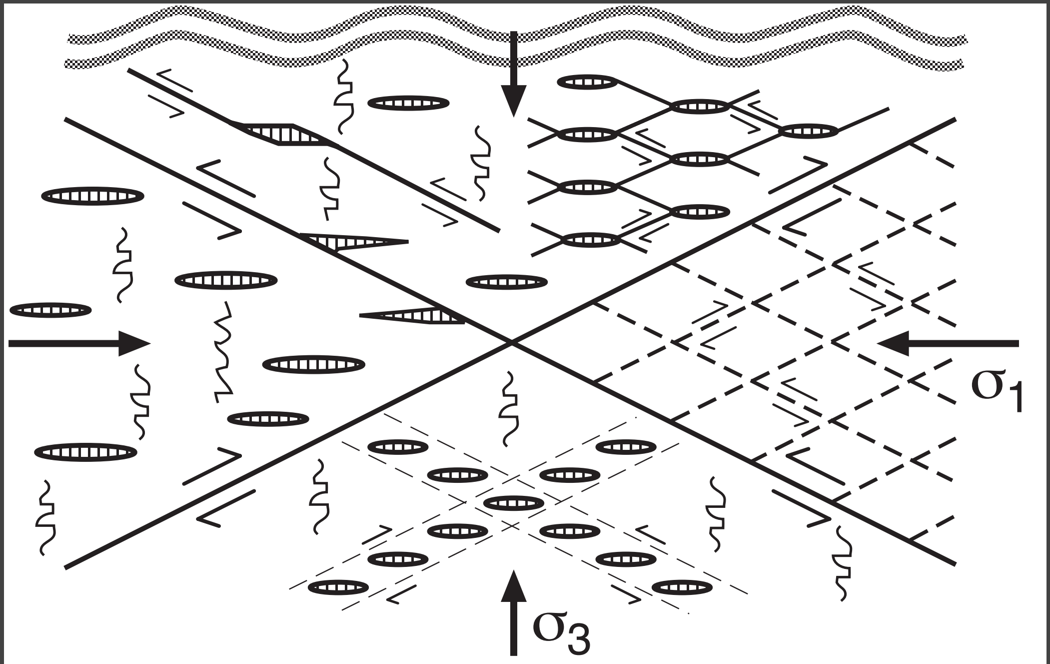
HEF can therefore develop:

1. **Within *intact rock***
2. **Around well-oriented faults with *cohesive strength* restored by hydrothermal cementation**
3. **In the vicinity of existing faults that are *severely misoriented* for reactivation**

COMPRESSIONAL REGIME

Reverse / Thrust Faulting

$$\sigma_v = \sigma_3$$

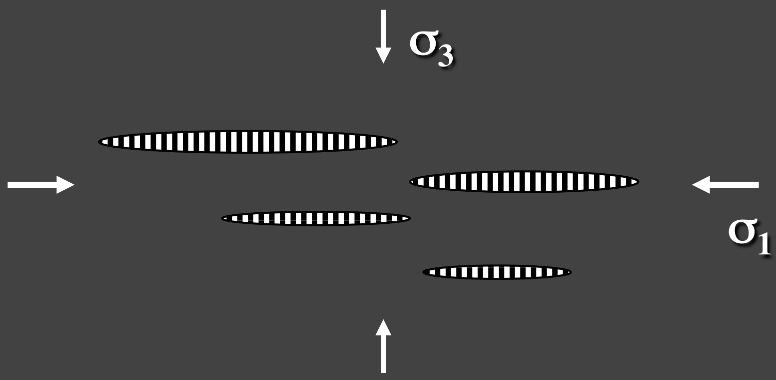


Minor Thrust with Extension Veins
Oguf Gynfor, Anglesey

Incipient Thrust Evolving from Extension Vein Array:

Torridonian Sst. in footwall of Moine Thrust

Flat-lying Hydrofractures in Proterozoic Metasediments and Metavolcanics, Damang Mine, Ghana



<u>Hydrofracture Condition</u>

$P_f = \sigma_3 + T$
with
$(\sigma_1 - \sigma_3) < 4T$

=> > *lithostatic* P_f if $\sigma_v = \sigma_3$

Au-Quartz Vein System, Damang Mine, Ghana

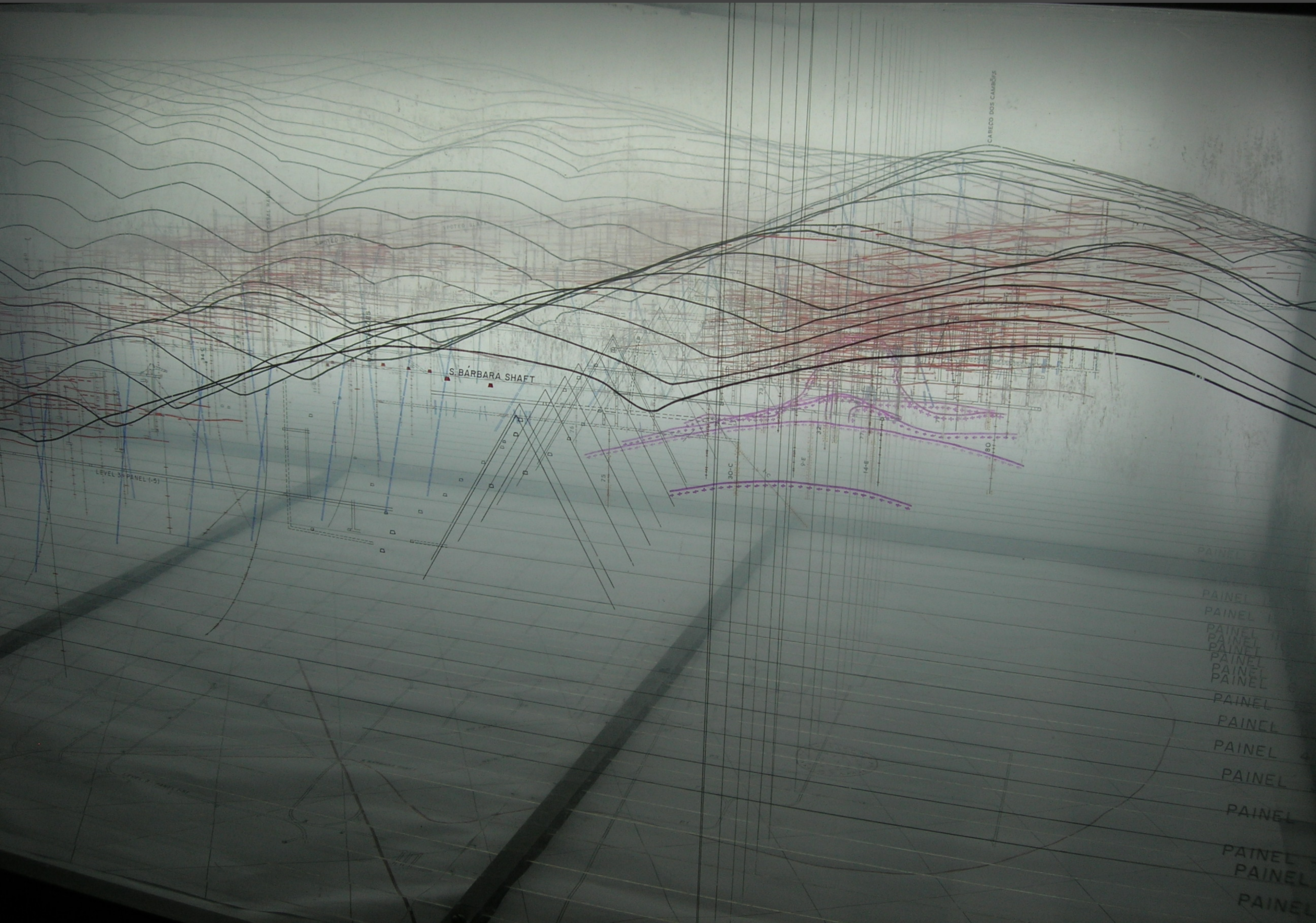
-photo by Andrew Tunks (see Tunks et al. 2004: J. Struct. Geol. 26, 1257-1273)

Localized 'Flats' in a Reverse Fault Dilational Stepover, Giant Mine, Yellowknife

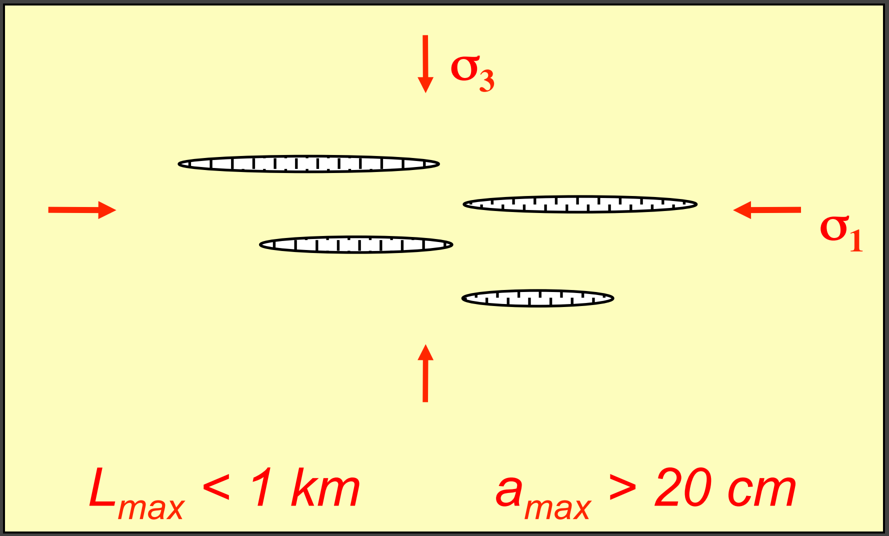
Self Organization of Extension Veins into a Thrust-Sense Shear Zone and Thrust Fault Damang Mine, Ghana

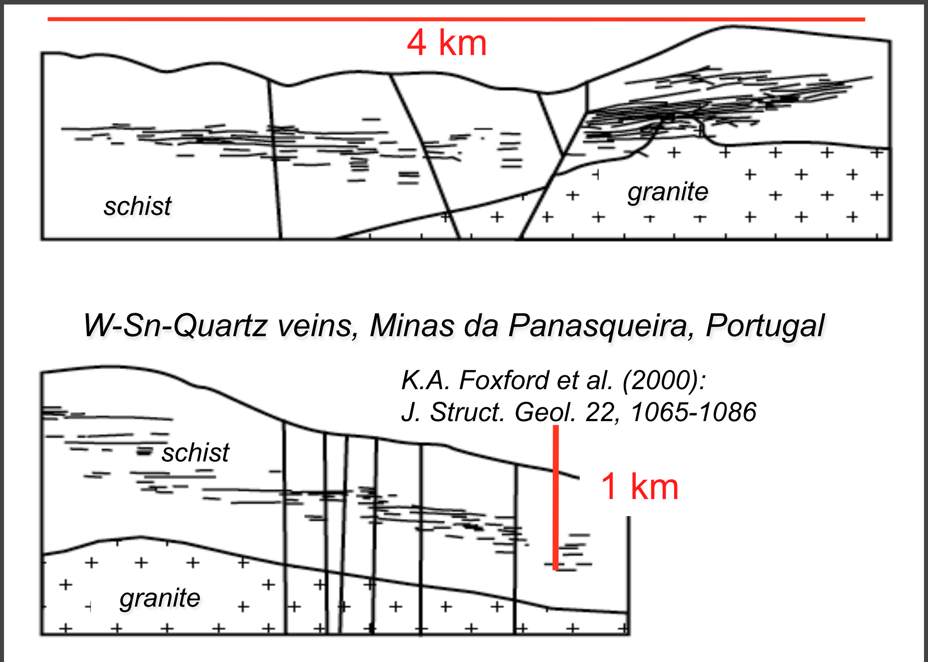
- photos from Andrew Tunks (Tunks et al. 2004: J. Struct. Geol. 26, 1257-1273)

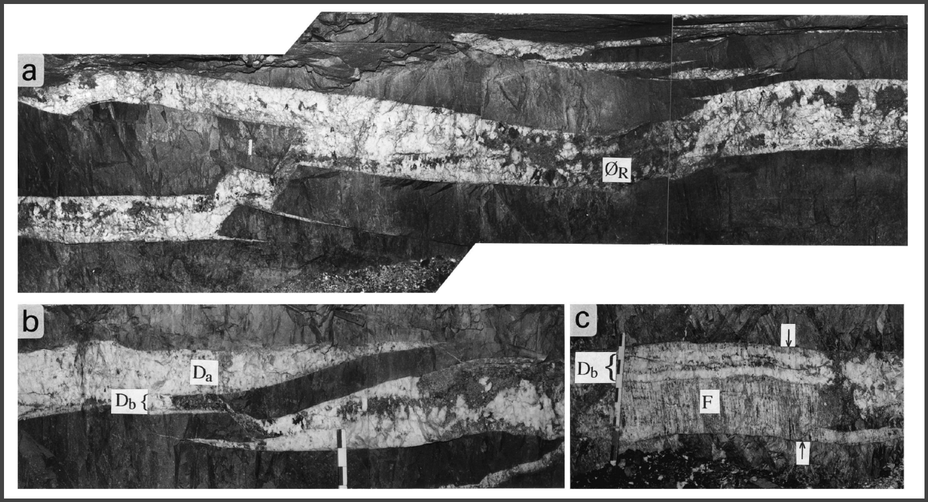
Minas da Panasqueira - 3D Mine Model



Flat-Lying W-Cu-Sn-Quartz Hydrofracture Array
Minas da Panasqueira, Portugal







HYDROTHERMAL FLUX:

V ~ 1000 km³

230°C < T < 360°C

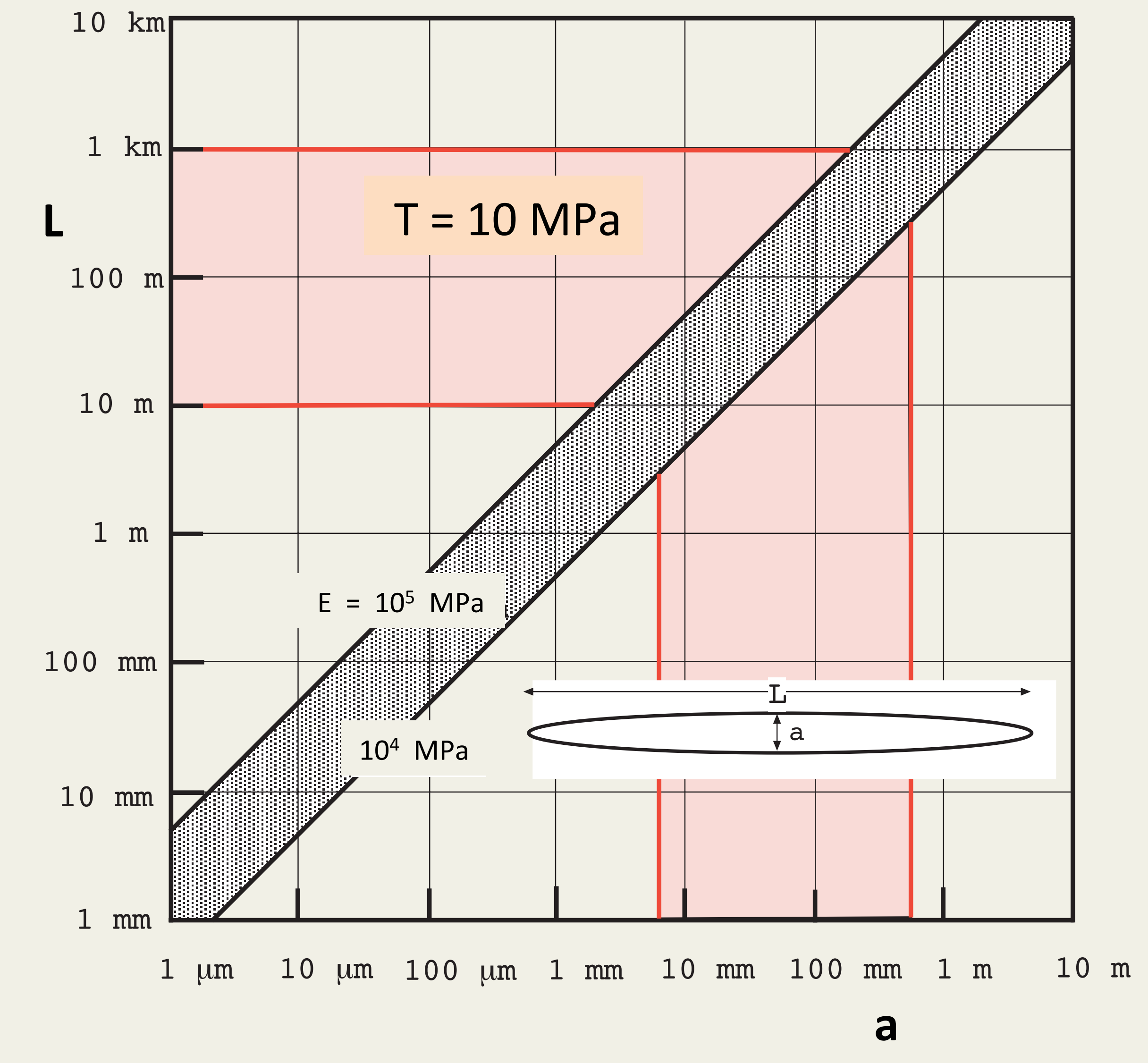
z = 1-2 km ?

c. 292 Ma (Late Hercynian)

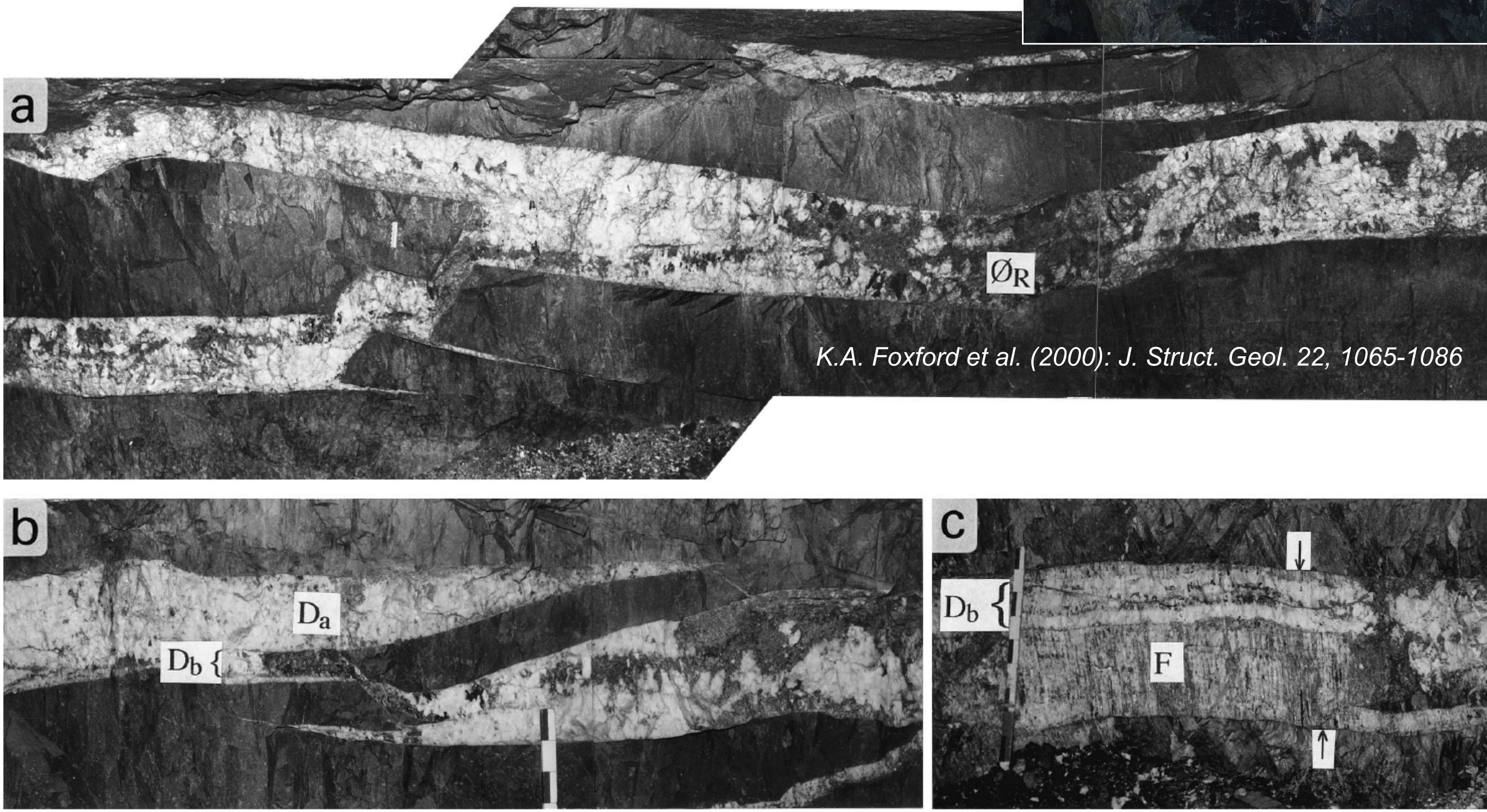
Polya (1989)

Elastic-Brittle Crack Model

$L/a \sim E/2T_o$



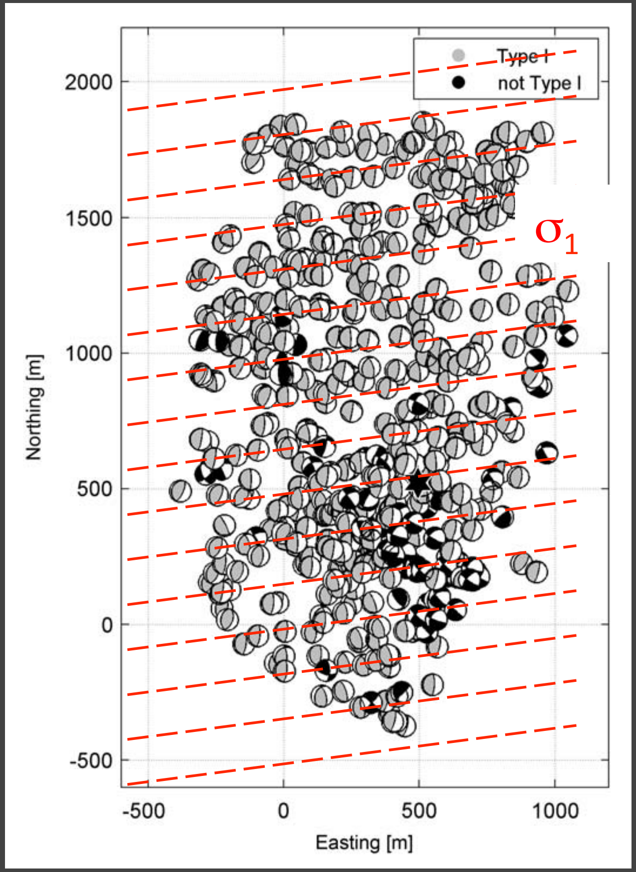
Minas da Panasqueira, Portugal
W-Sn-Quartz veins

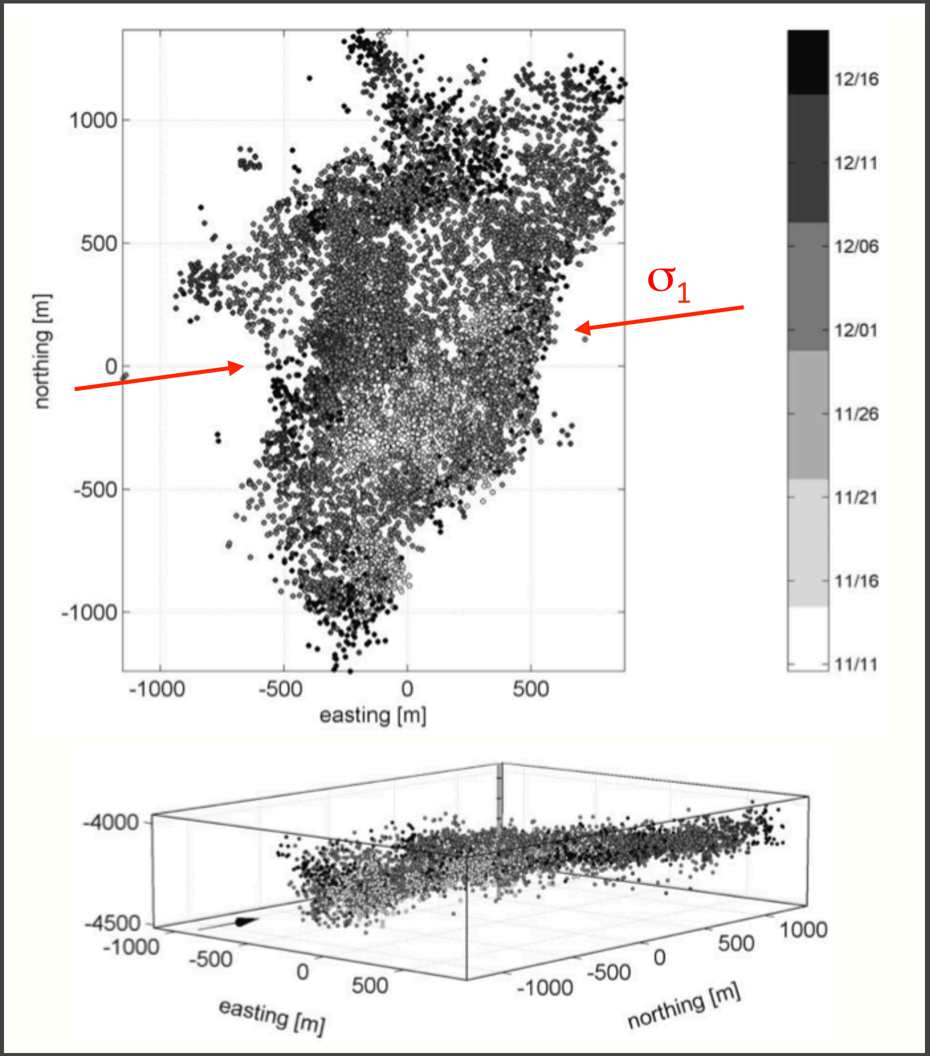


Minas da Panasqueira, - thrust truncating sub-horizontal extension fractures

Induced Seismicity in Carboniferous Granite, Habanero 1 Well, Cooper Basin, SE Australia

$P_f > \sigma_3$?

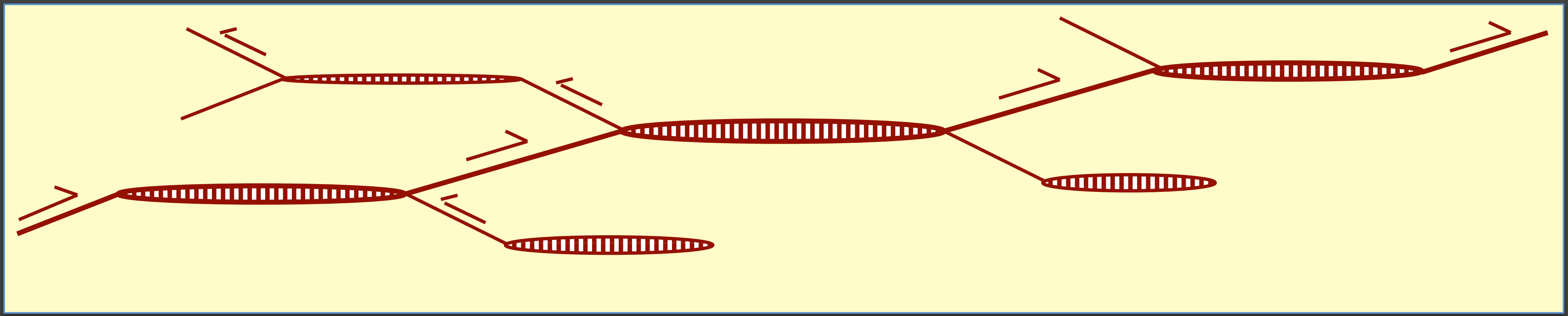




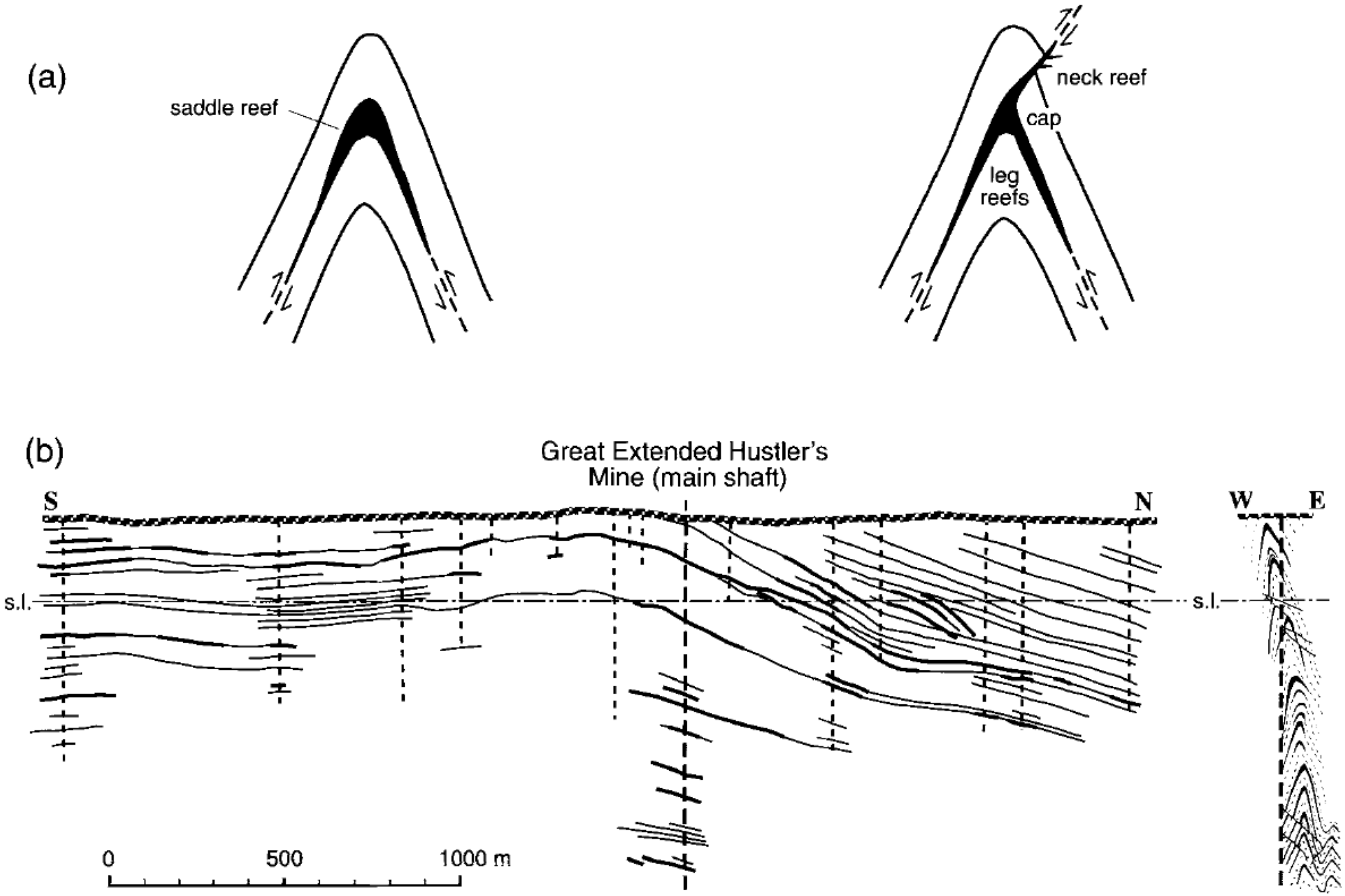
Baisch et al. 2006: BSSA 96, 2242-2256

Baisch et al. 2015: BSSA 105, 198-209

Low-Angle Thrust Fault-Fracture Mesh
Pilgrim's Rest, S. Africa



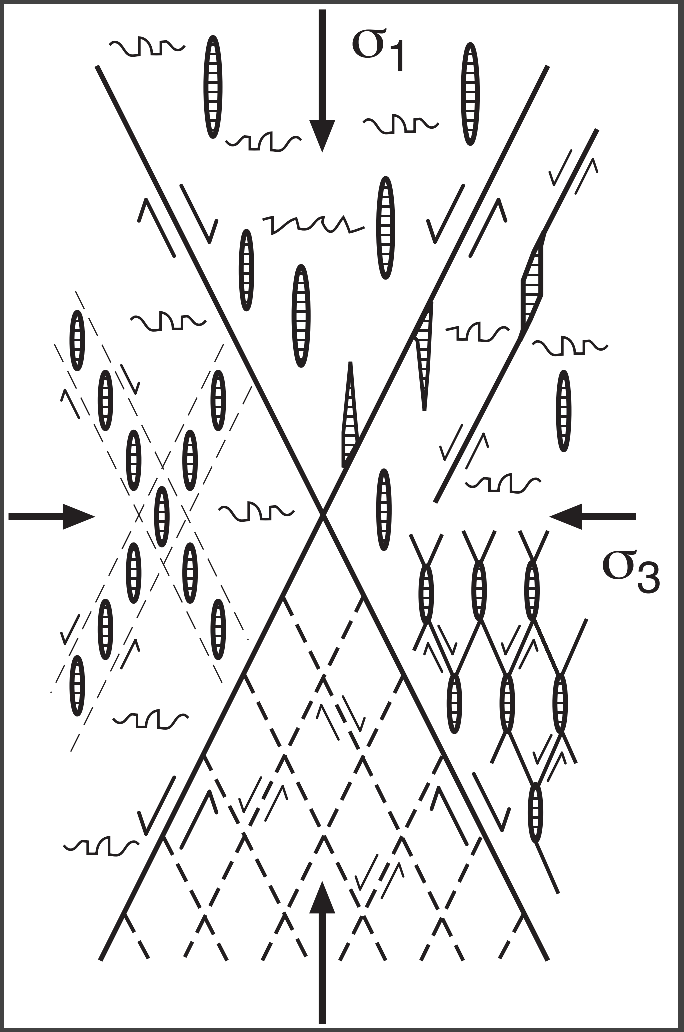
Flow Deflection Along Activated Anisotropy, Bendigo



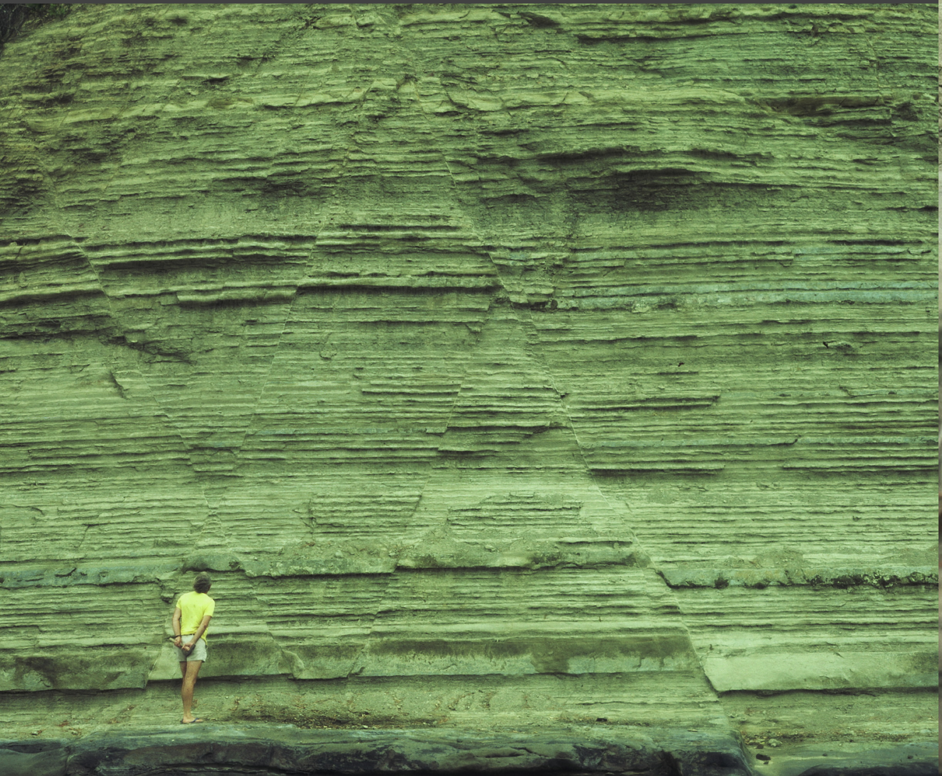
EXTENSIONAL REGIME

Normal Faulting

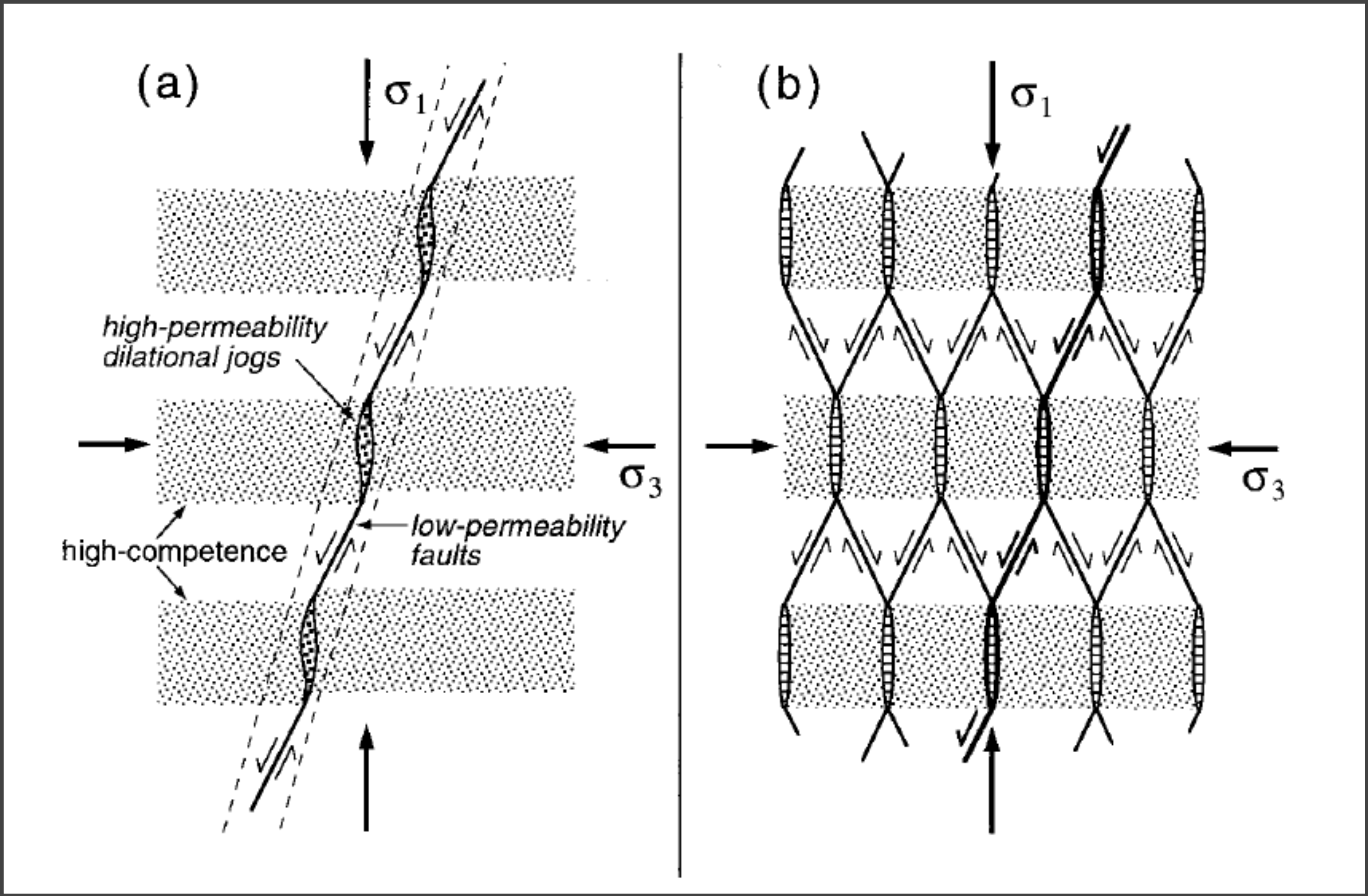
$\sigma_v = \sigma_1$



Enhanced Permeability at Intersections of Conjugate Normal Faults



Fault-Fracture Mesh



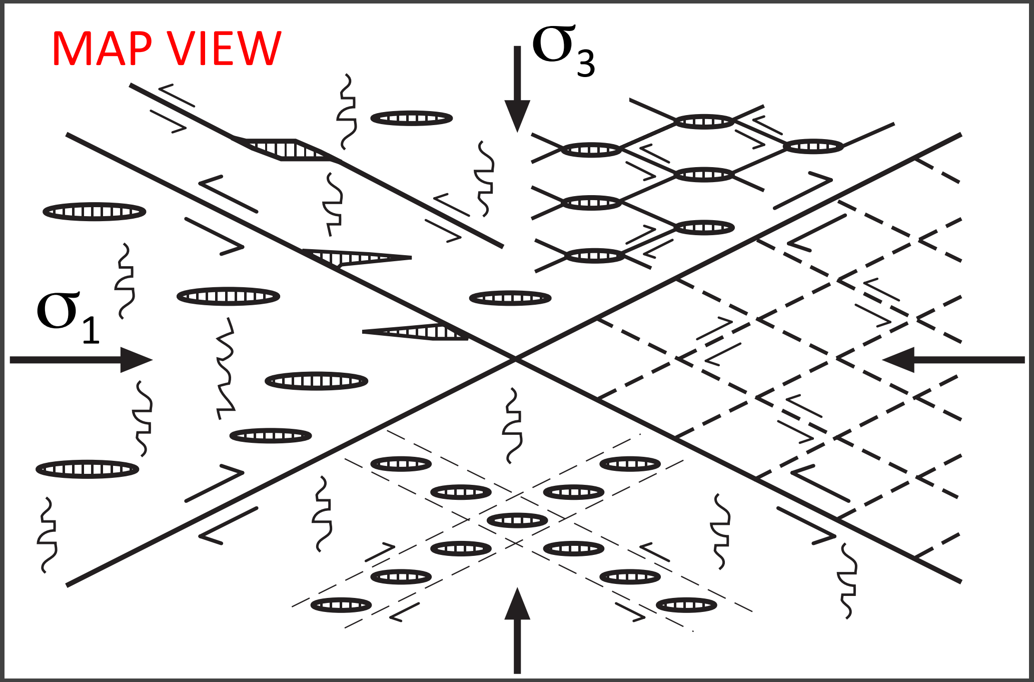
Extensional Fault-Fracture Mesh in Monterey Shales

Martha Au-Mine Epithermal Vein System

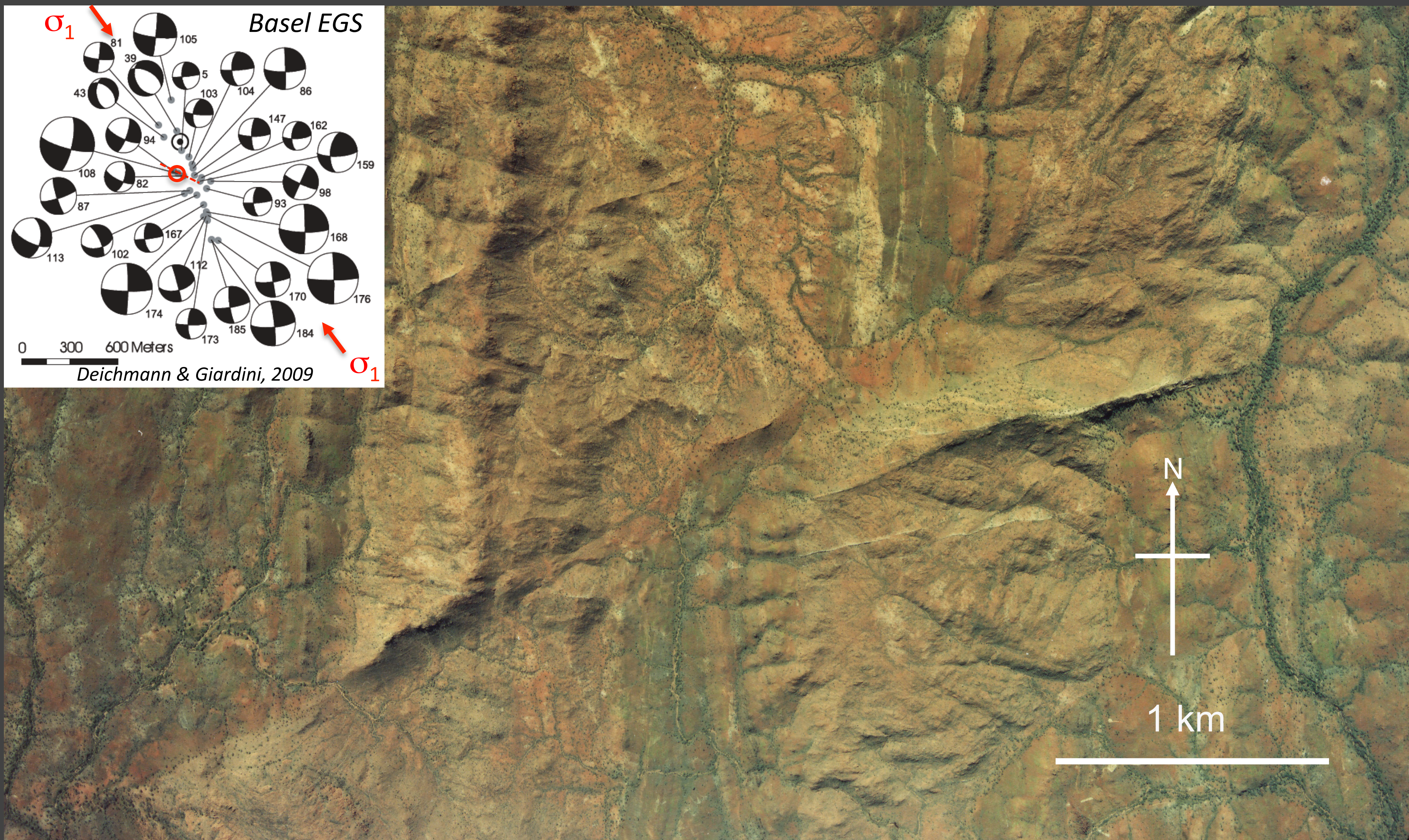
WRENCH REGIME

Strike-Slip Faulting

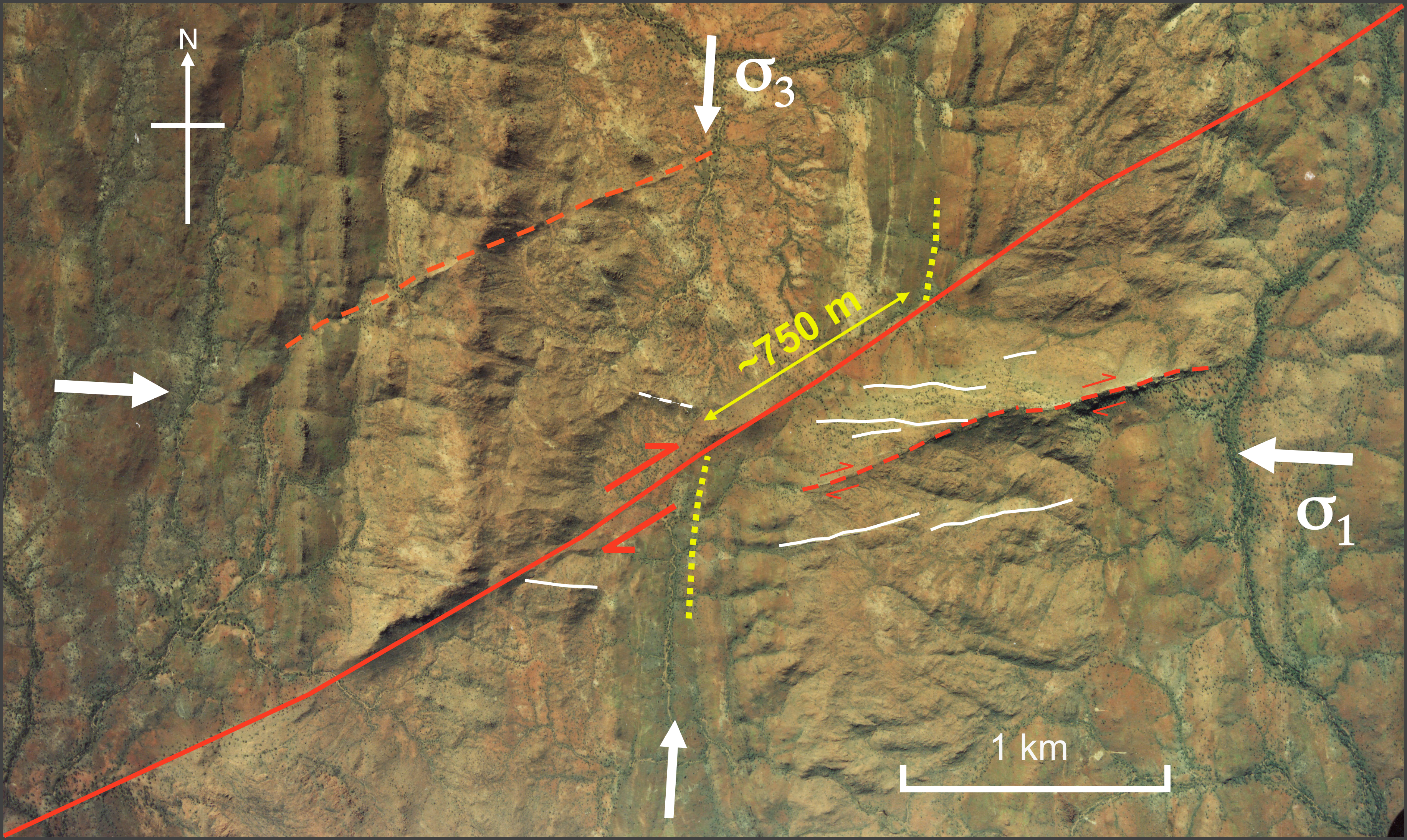
$$\sigma_v = \sigma_2$$



Spinifex Dextral Strike-Slip Fault and Related Quartz-Filled Extension Veins, Mt Isa Inlier

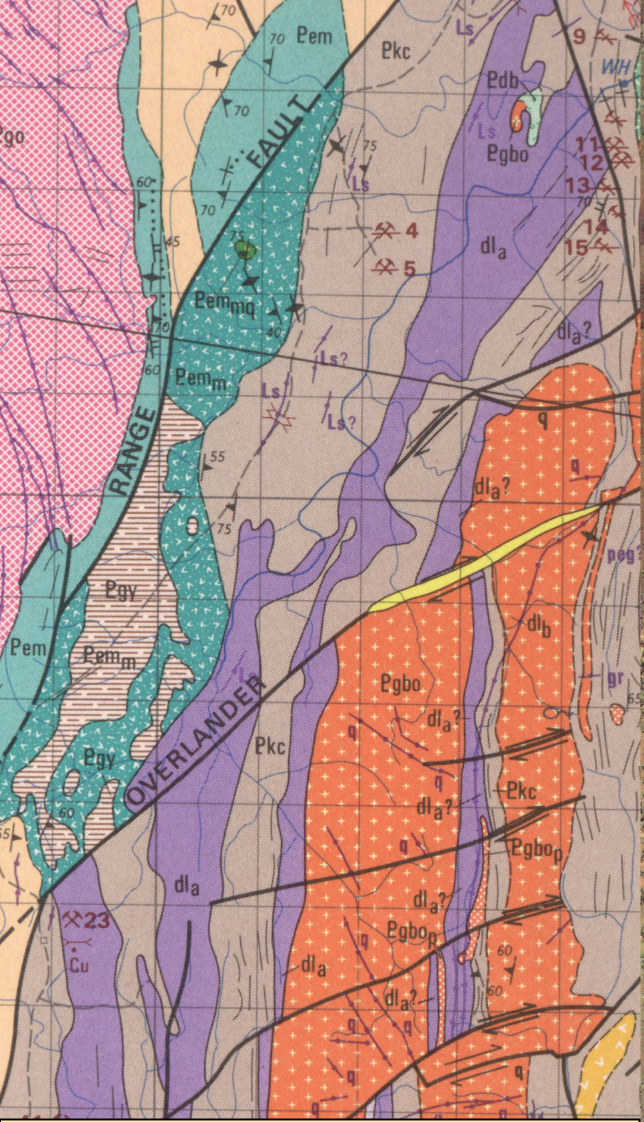


Spinifex Fault and Related Quartz-Filled Extension Veins, Mt Isa Inlier



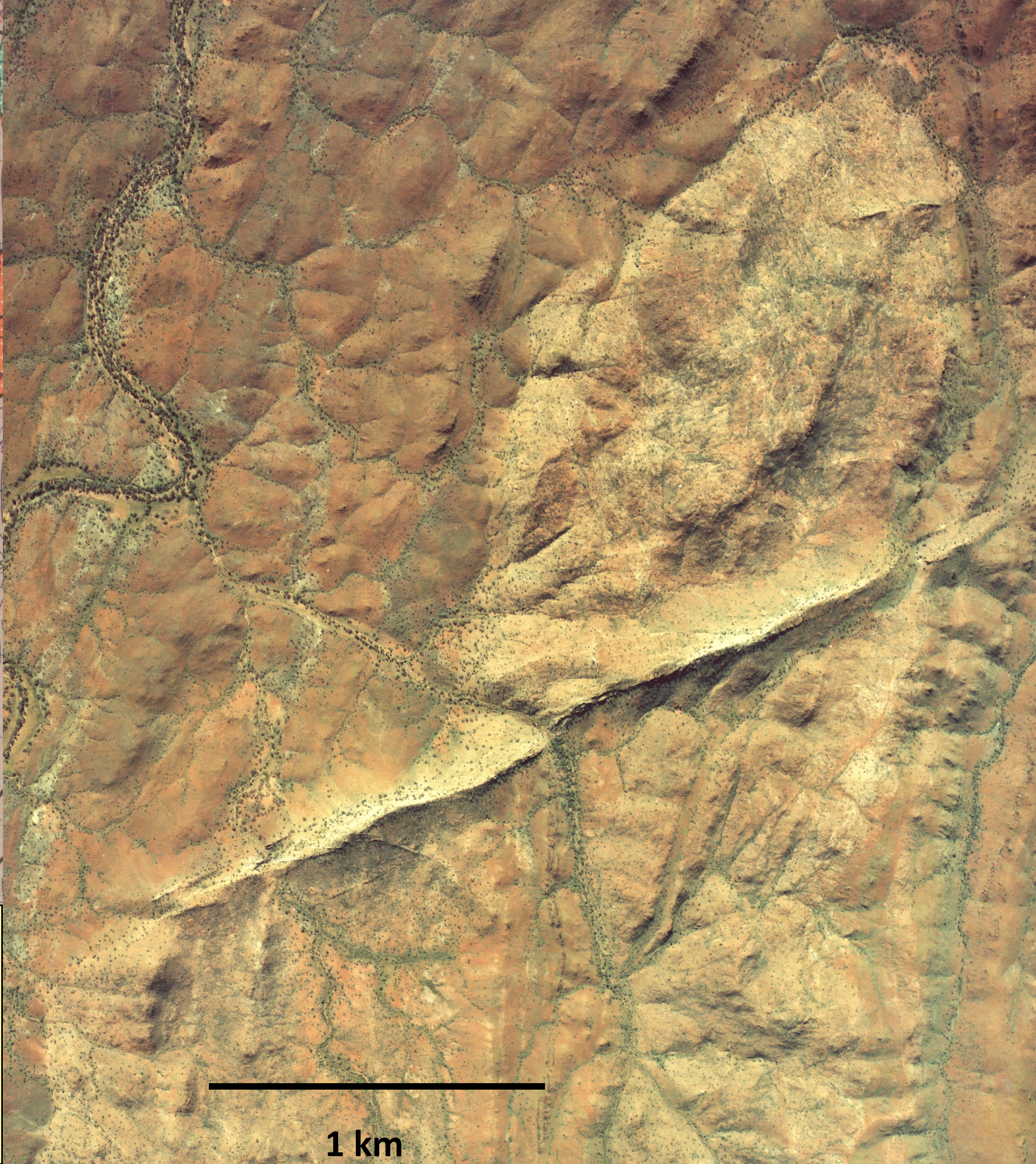
Quartz Extension Veins associated with dextral Spinifex Fault, Mt Isa Inlier

Ladder Network of Linking Extension Veins within a Dilational Stepover on a Dextral Strike-Slip Fault, Abitibi Belt, Quebec



Overlander Fault

(~1.5 km dextral slip)

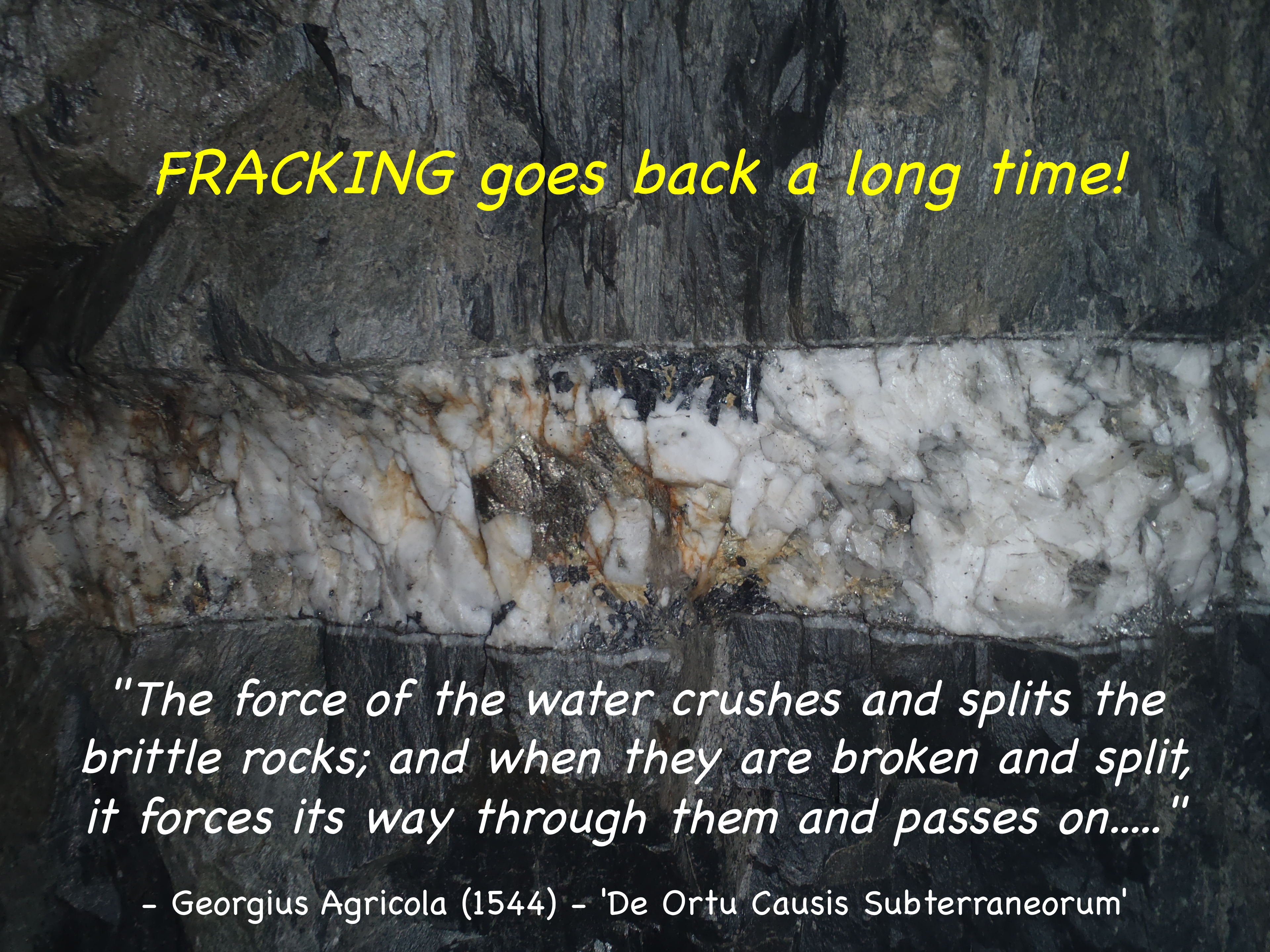



Overlander Fault
NNW
SSE


extensional dilation 15-20%

CONCLUSIONS

- *flow conduits range from **high-dilation extension fracture arrays** to **mixed fault-fracture meshes** to **low-dilation meshes of conjugate faults***
- *high-dilation fracture conduits may develop under **hydrostatic fluid-pressures** at shallow depth in extensional regimes but require **overpressures approaching lithostatic** in compressional regimes*
- *dilatant arrays of parallel extension fractures are unstable and degenerate into t.g. shear zones and faults*
- *presence of low-cohesion faults well-oriented for reactivation **inhibits formation of dilatant hydraulic extension fractures***
- ***Competence layering or heterogeneity** promotes local formation of high-dilation extension fractures*
- *formation of high-dilation extension fracture arrays requires: (1) INTACT ROCK, or; (2) FAULTS WITH RESTORED COHESIVE STRENGTH, or; (3) FAULTS THAT ARE SEVERELY MISORIENTED*
- ***Enhanced flow in dilational stepovers** from local stress heterogeneity*


FRACKING goes back a long time!
"The force of the water crushes and splits the brittle rocks; and when they are broken and split, it forces its way through them and passes on....."
- Georgius Agricola (1544) - 'De Ortu Causis Subterraneorum'