

ESS 411/511 Geophysical Continuum Mechanics Class #19

Highlights from Class #18 – Chloe Mcburney

Today's highlights on Monday – Alexandria Vasquez-Hernandez

Check out these websites about measuring stress in the Earth:

<https://www.eoas.ubc.ca/courses/eosc433/lecture-material/L7-InSituStress.pdf>

http://www.hydrofrac.com/hfo_home.html

Also see slides on class web site about Measuring Stress in the Earth

https://courses.washington.edu/ess511/NOTES/SLIDE_SHOWS/PDF/stress_class_show_2017_all.pdf

Your short CR/NC Pre-class prep writing assignment (1 point) in Canvas

- It will be due in Canvas at the start of class.
- I will send another message when it is posted in Canvas.

Mid-course class evaluations

- Did you get a notice?
- Your comments will be helpful for me
- Thanks!

Midterm take-at-home

- Any concerns?

ESS 511 term-project reports

- Can you upload reports to Canvas now?

ESS 411/511 Geophysical Continuum Mechanics

Broad Outline for the Quarter

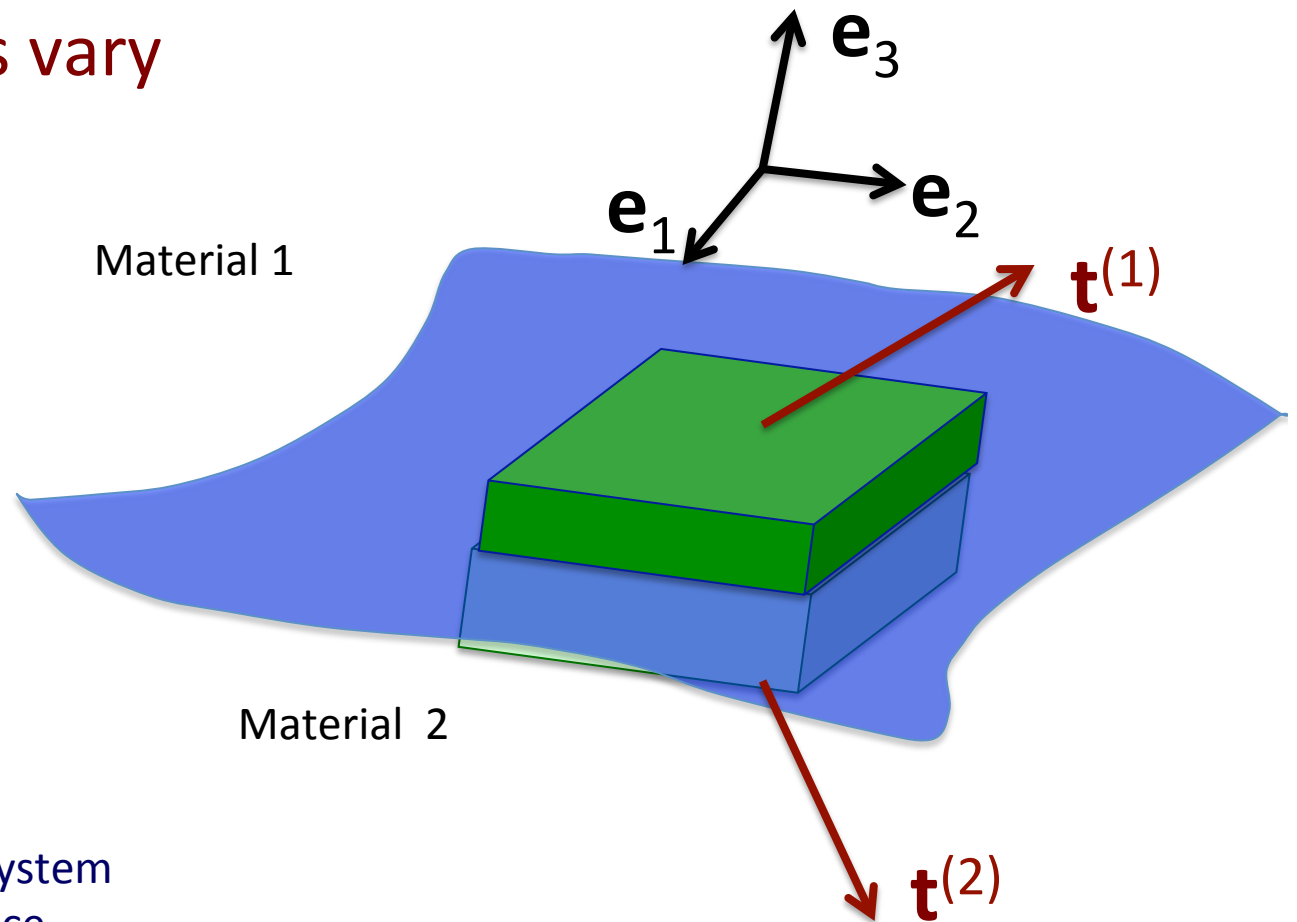
- Continuum mechanics in 1-D
- 1-D models with springs, dashpots, sliding blocks
- Attenuation
- Mathematical tools – vectors, tensors, coordinate changes
- Stress – principal values, Mohr's circles for 3-D stress
- Coulomb failure, pore pressure, crustal strength
- Measuring stress in the Earth
- Strain – Finite strain; infinitesimal strains
- Moments – lithosphere bending; Earthquake moment magnitude
- Conservation laws
- Constitutive relations for elastic and viscous materials
- Elastic waves; kinematic waves

Measuring Stress in the Earth

I - Stress boundary conditions

- What happens to stress when 2 continua are stuck together?

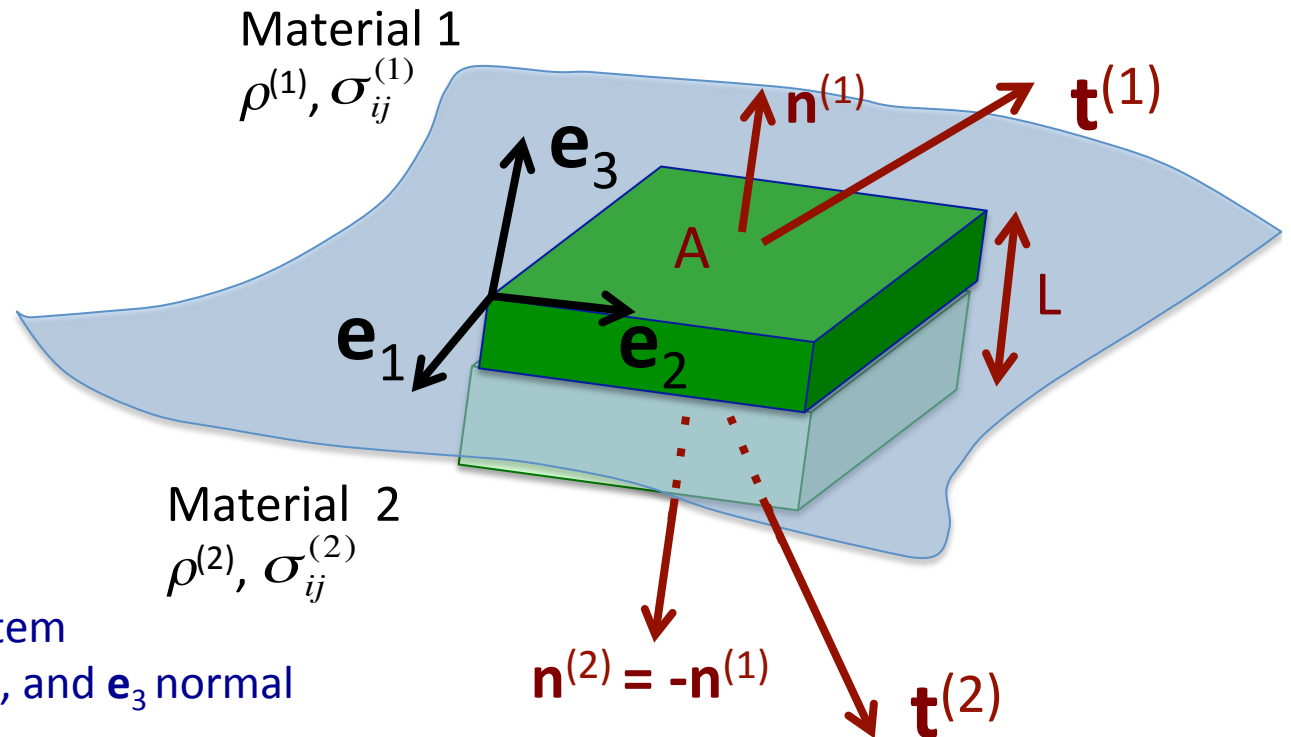
How do stresses vary
across material
boundaries?



Let's choose a coordinate system
with \mathbf{e}_1 and \mathbf{e}_2 in the interface

- now calculate all the forces on the little box
- Let the thickness of the box go to zero

How do stresses vary across material boundaries?



Let's choose a coordinate system with \mathbf{e}_1 and \mathbf{e}_2 in the interface, and \mathbf{e}_3 normal to the interface

- Now add up all the forces on the surface of the little box
- For equilibrium, $\sum f_j = 0$
- Let the thickness L of the box go to zero, so the areas of the sides go to zero

The only remaining nonzero forces are:

$$f_i^{(top)} = A t_i^{(n^{(1)})} = A \sigma_{ij}^{(1)} n_j^{(1)}$$

$$f_i^{(bot)} = A t_i^{(n^{(2)})} = A \sigma_{ij}^{(2)} n_j^{(2)} = -A \sigma_{ij}^{(2)} n_j^{(1)}$$

How do stresses vary across material boundaries?

$$f_i^{(top)} = A \sigma_{ij}^{(1)} n_j^{(1)}$$

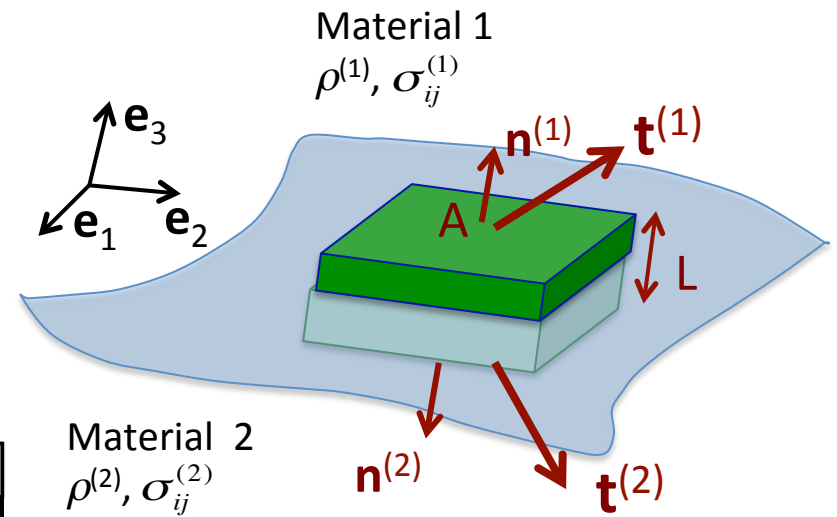
$$= A \begin{bmatrix} \sigma_{11}^{(1)} & \sigma_{12}^{(1)} & \sigma_{13}^{(1)} \\ \sigma_{12}^{(1)} & \sigma_{22}^{(1)} & \sigma_{23}^{(1)} \\ \sigma_{31}^{(1)} & \sigma_{32}^{(1)} & \sigma_{33}^{(1)} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = A \begin{bmatrix} \sigma_{13}^{(1)} \\ \sigma_{23}^{(1)} \\ \sigma_{33}^{(1)} \end{bmatrix}$$

$$f_i^{(bot)} = -A \sigma_{ij}^{(2)} n_j^{(2)}$$

$$= A \begin{bmatrix} \sigma_{11}^{(2)} & \sigma_{12}^{(2)} & \sigma_{13}^{(2)} \\ \sigma_{12}^{(2)} & \sigma_{22}^{(2)} & \sigma_{23}^{(2)} \\ \sigma_{31}^{(2)} & \sigma_{32}^{(2)} & \sigma_{33}^{(2)} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} = A \begin{bmatrix} -\sigma_{13}^{(2)} \\ -\sigma_{23}^{(2)} \\ -\sigma_{33}^{(2)} \end{bmatrix}$$

$$f_i^{(top)} + f_i^{(bot)} = 0$$

$$\Rightarrow \left\{ \begin{array}{l} \sigma_{13}^{(1)} = \sigma_{13}^{(2)} \\ \sigma_{23}^{(1)} = \sigma_{23}^{(2)} \\ \sigma_{33}^{(1)} = \sigma_{33}^{(2)} \end{array} \right\}$$



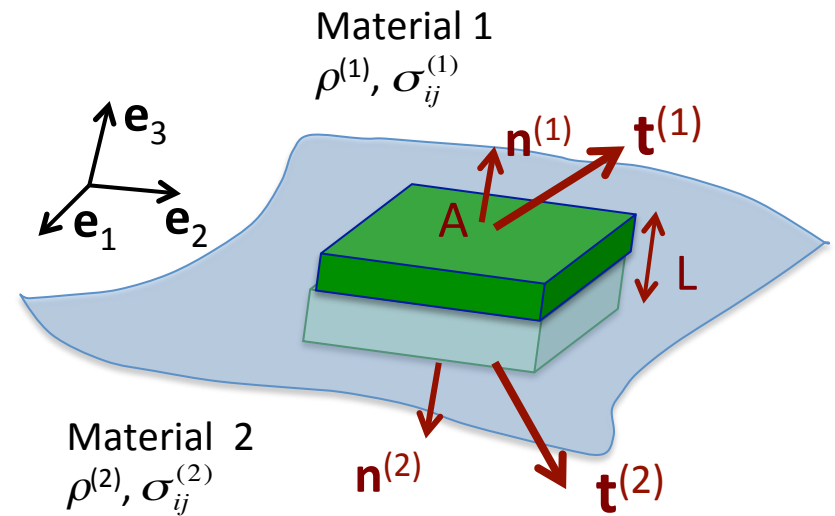
How do stresses vary across material boundaries?

$$f_i^{(top)} + f_i^{(bot)} = 0$$

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So σ_{13} , σ_{23} , and σ_{33} must be continuous across the interface.

- σ_{31} and σ_{32} are also continuous, since σ_{ij} is symmetric



There are no restrictions on σ_{11} , σ_{12} , σ_{21} , or σ_{22} .

- They act only within their own material.
- This is the principle of stress guides

How do stresses vary across material boundaries?

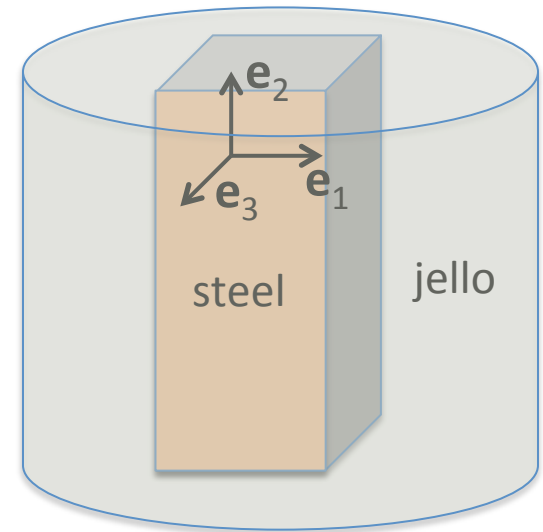
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- They act only within their own material.
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Is σ_{22} continuous across the jello/steel interface?
What about σ_{33} ?



Why do we care about stresses in the Earth?

Measuring stress around an excavation

- Mine shaft
- Tunnel
- Well
- Others?

Let's take a break for some flatjacks with syrup ...

Class-prep questions (Break-out rooms)

For Class #19 (Friday Nov 13). Due before class.

Check out these websites about measuring stress in the Earth:

<https://www.eoas.ubc.ca/courses/eosc433/lecture-material/L7-InSituStress.pdf>

http://www.hydrofrac.com/hfo_home.html

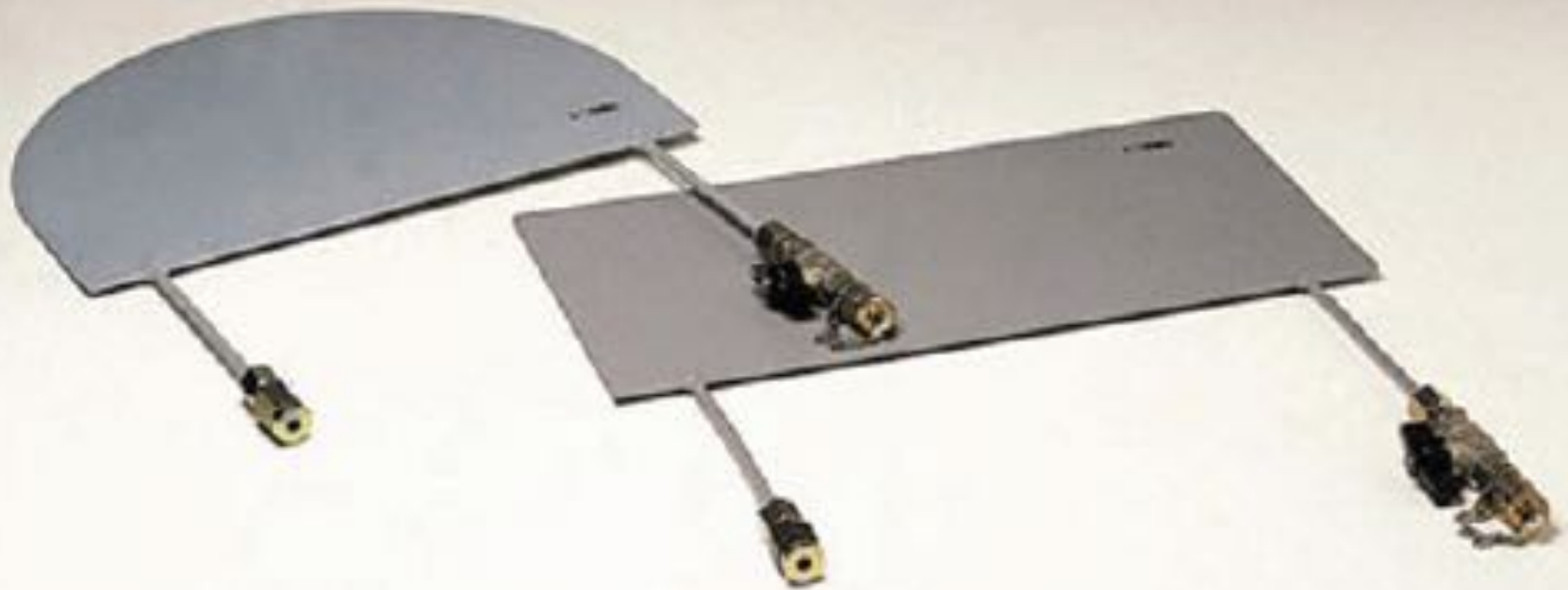
https://courses.washington.edu/ess511/NOTES/SLIDE_SHOWS/PDF/stress_class_show_2017_all.pdf

Assignment:

What is a flatjack?

How can a flatjack be used to measure stress?

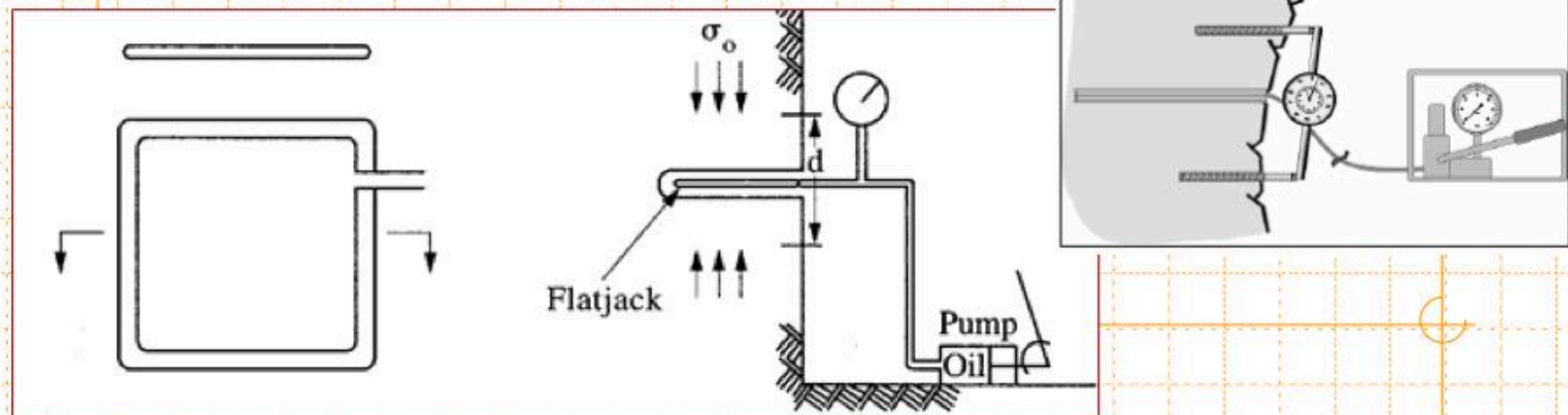
Flatjack Tests



- What do you think the test might measure?

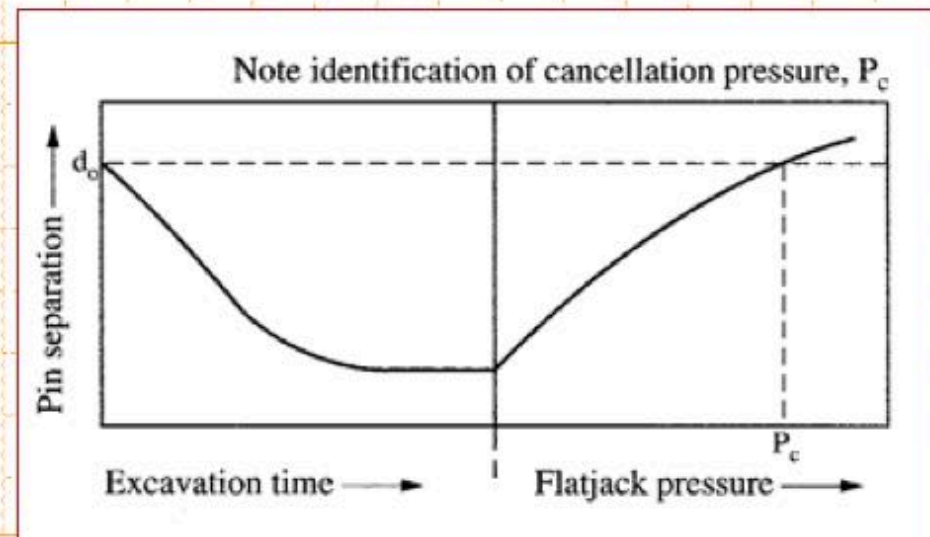
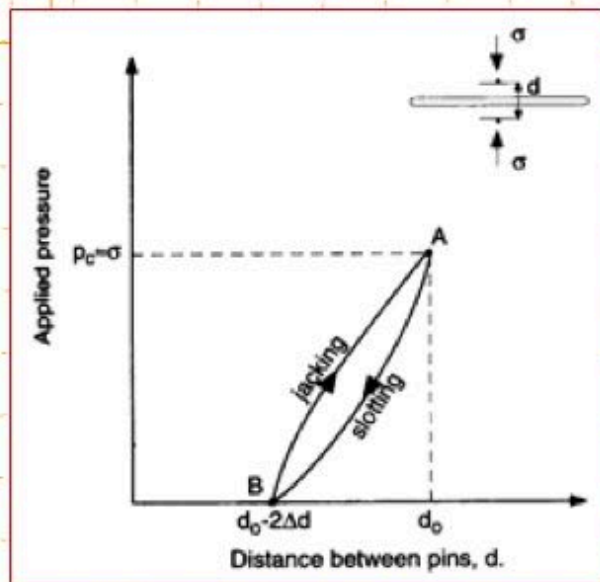
Flatjack Method

The flatjack method involves the placement of two pins fixed into the wall of an excavation. The distance, d , is then measured accurately. A slot is cut into the rock between the pins. If the normal stress is compressive, the pins will move together as the slot is cut. The flatjack is then placed and grouted into the slot.



Flatjack Method

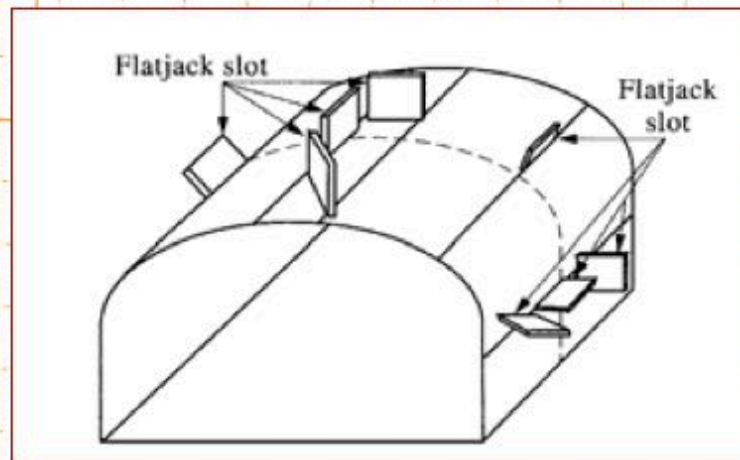
On pressurizing the flatjack, the pins will move **apart**. It is assumed that, when the pin separation distance reaches the value it had **before** the slot was cut, the force exerted by the flatjack on the walls of the slot is the same as that exerted by the pre-existing normal stress.



Hudson & Harrison (1997)

Flatjack Method

The major disadvantage with the system is that the necessary **minimum number of 6 tests**, at different orientations, have to be conducted **at 6 different locations** and it is therefore necessary to distribute these around the boundary walls of an excavation.



1. Flatjack

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \text{Symm.} & \sigma_{yy} & \tau_{yz} \\ & & \sigma_{zz} \end{bmatrix}$$

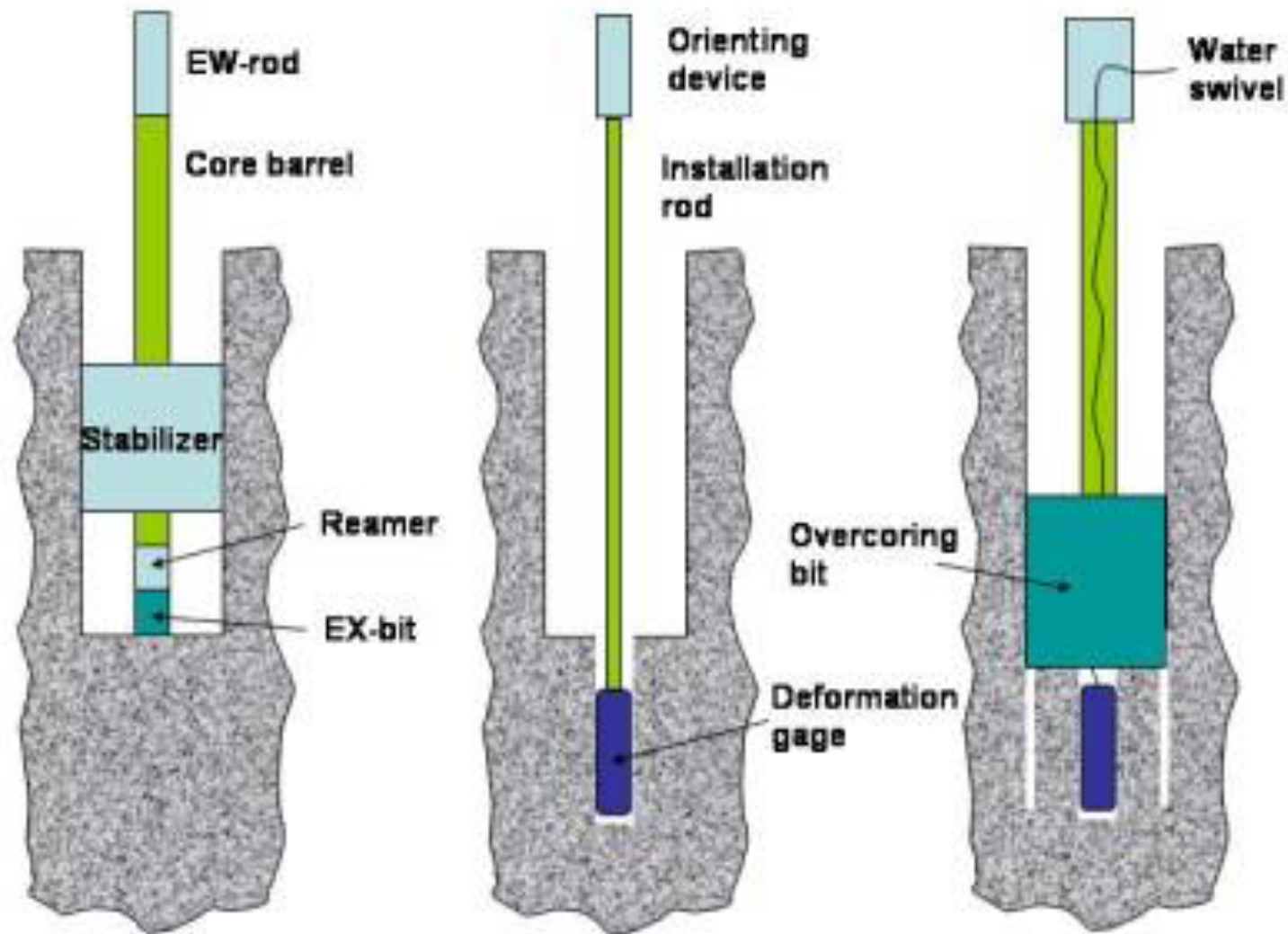
One normal stress component determined, say parallel to x-axis.

Hudson & Harrison (1997)

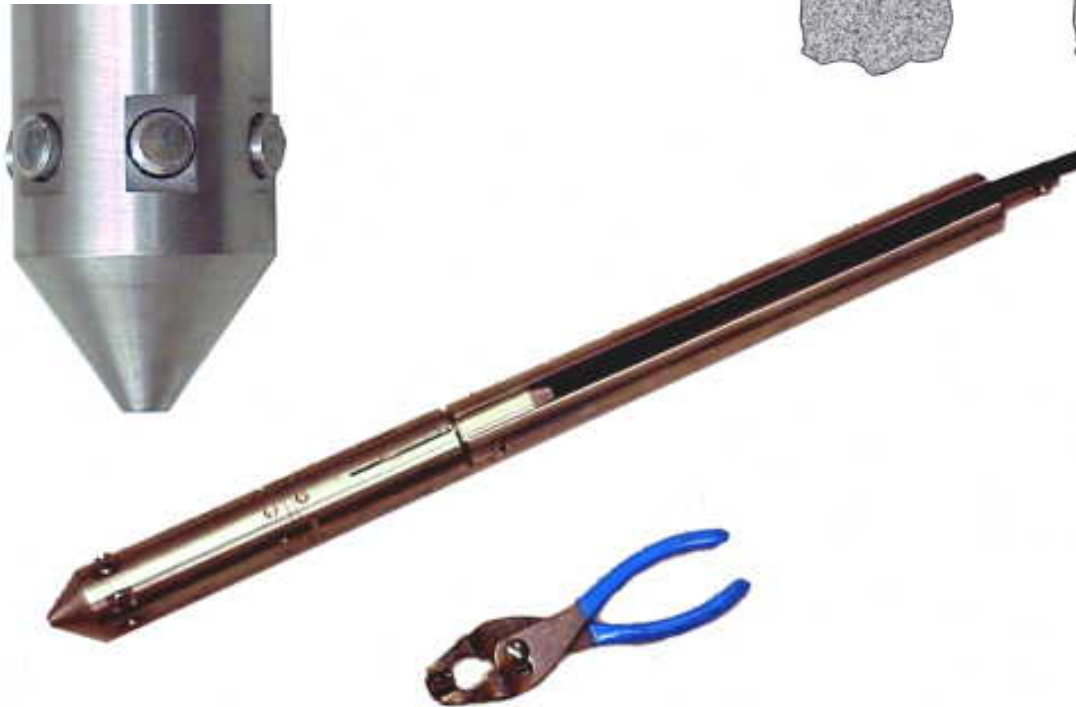
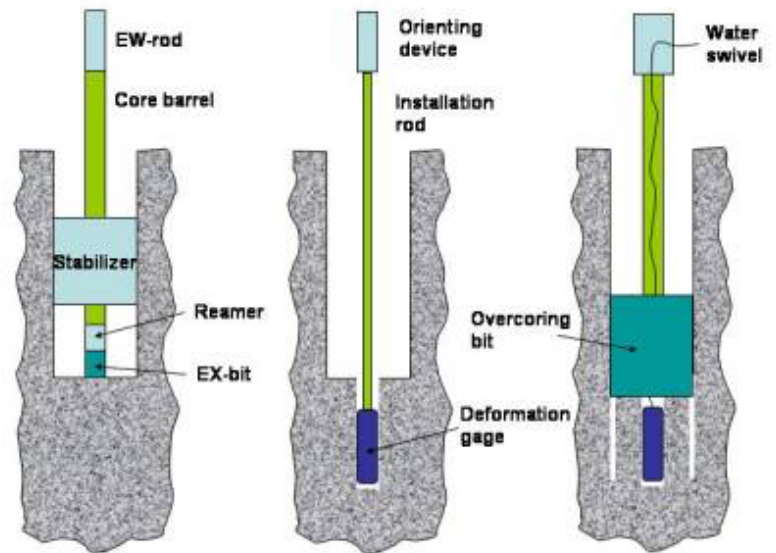
It is also important to note that the excavation from which the tests are made will disturb the pre-existing stress state, and so the new redistribution of stresses should be accounted for.

Over-coring

Overcoring – the operation



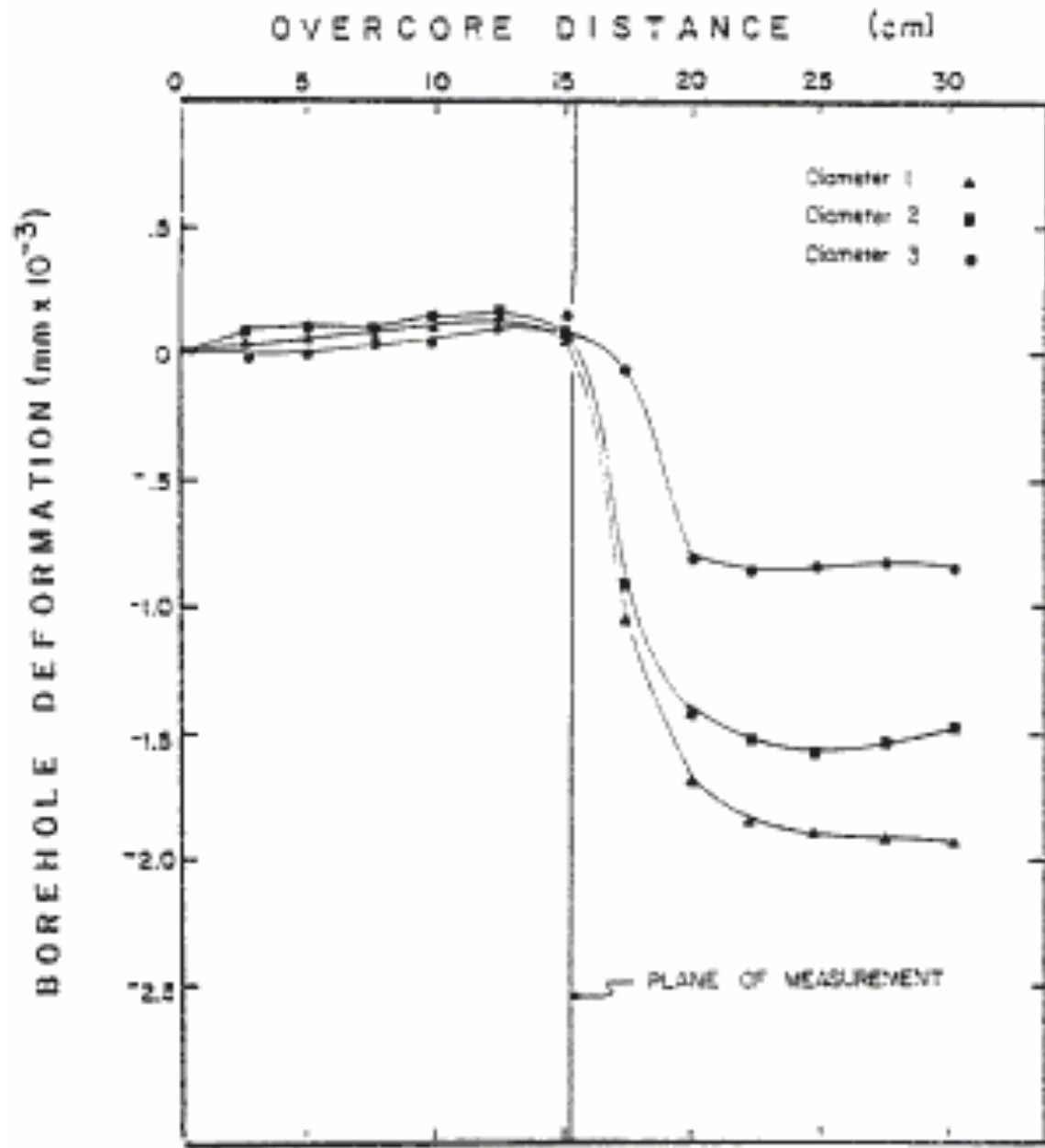
Overcoring – the tool



http://www.hydrofrac.com/hfo_home.html

Overcoring – the data

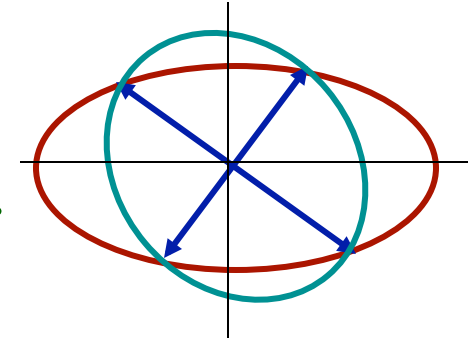
Three channels of diametral deformations logged continuously as the deformation gage is overcored. As the overcoring bit passes through the plane of measurements, the stresses are relieved and the results are shown as diametral deformations.



Why 3 sensors at 120°?

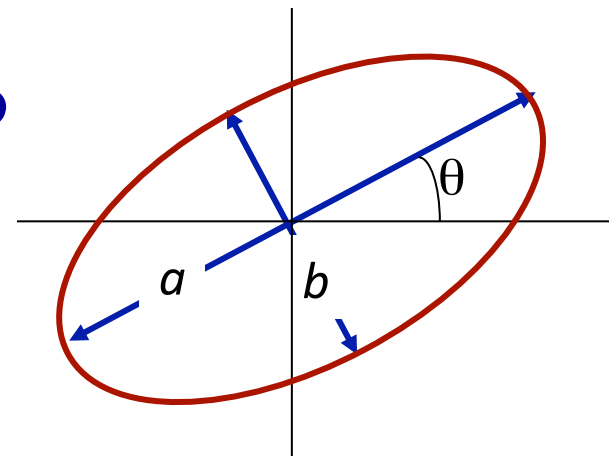
Why not 2 sensors at 90°?

- The hole will deform into an ellipse.
- Many ellipses can fit 2 diameters.

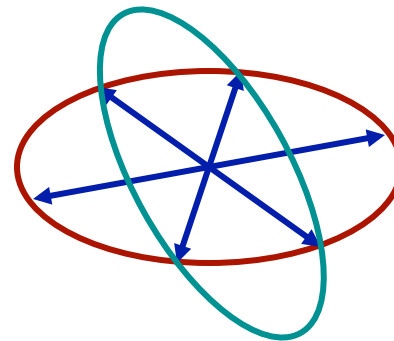


How many parameters are needed to describe an ellipse?

- Major axis a
- minor axis b
- orientation angle θ



With 3 diameters, there is a unique ellipse solution



Overcoring - calibration

Now we know the deformation of the hole, but not the stress in the surrounding rock.

What's next?



Rheological properties

- Pressure tests and tri-axial tests on the recovered cores to relate measured strain to relieved stress.

http://www.hydrofrac.com/hfo_home.html

Modes of fracture

Modes of Cracking

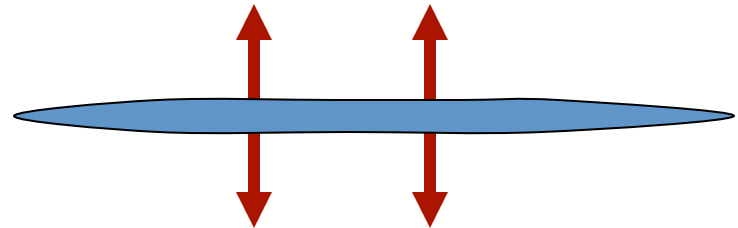
Coulomb model represents failure in shear.

- The 2 sides of a crack slide past each other without opening large gaps.
- Mode II or Mode III in fracture mechanics



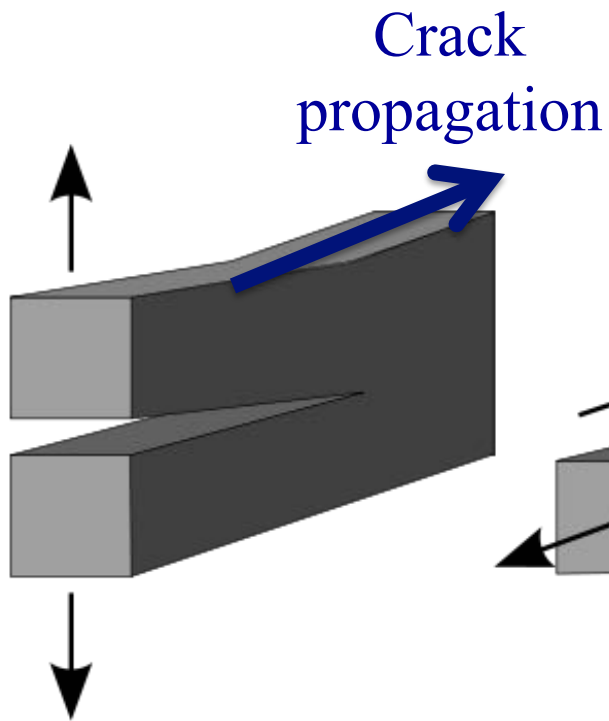
But materials can also fail in another mode.

- The 2 sides of a crack do not slide past each other
- Large gaps can open.
- Mode I

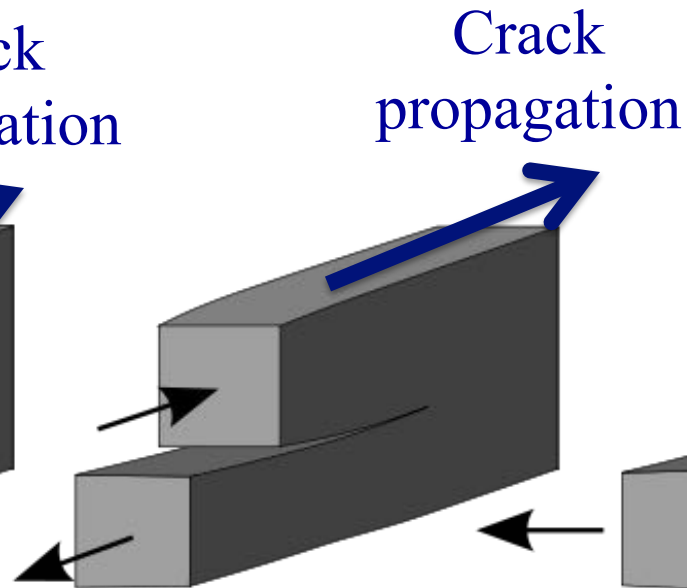


Modes of Cracking

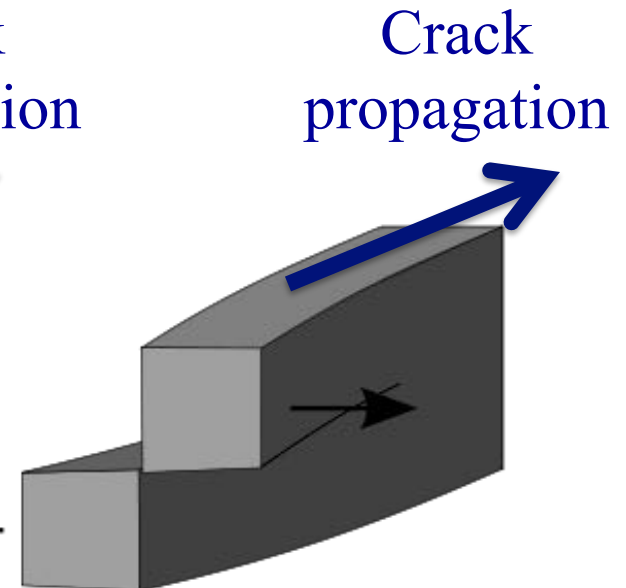
Mode I:
Opening



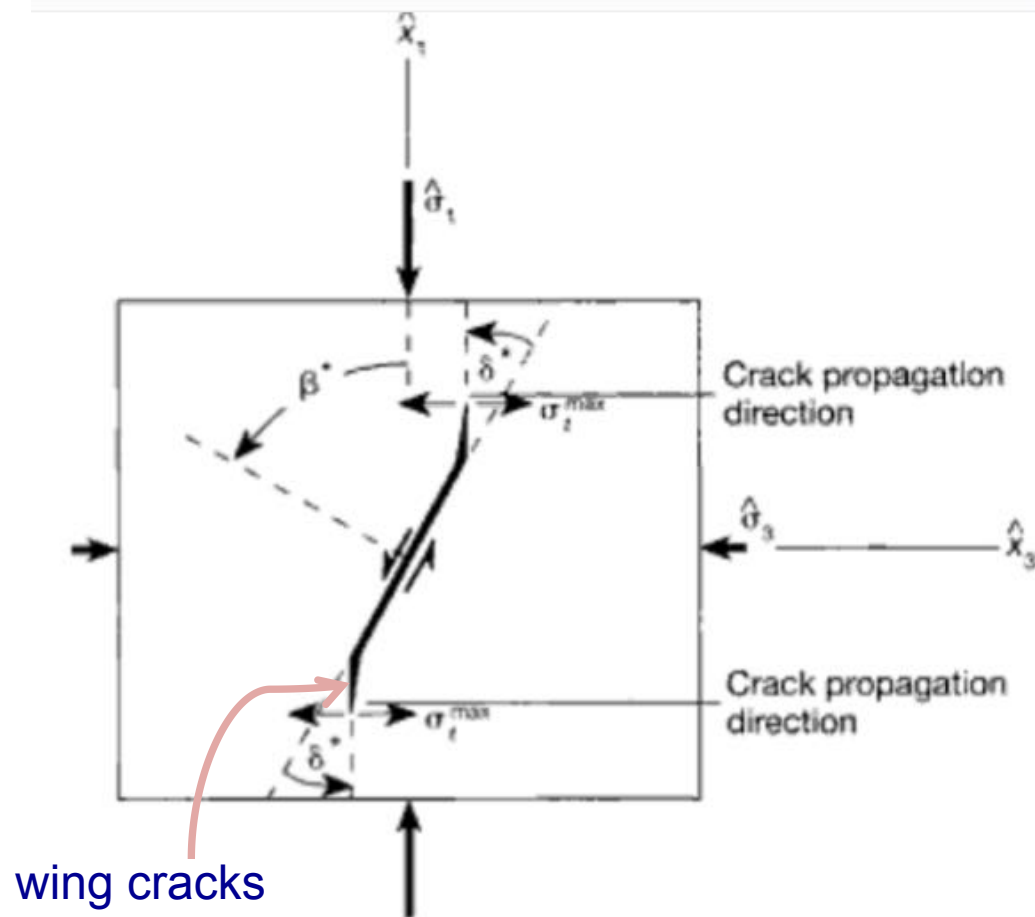
Mode II:
In-plane shear



Mode III:
Out-of-plane shear



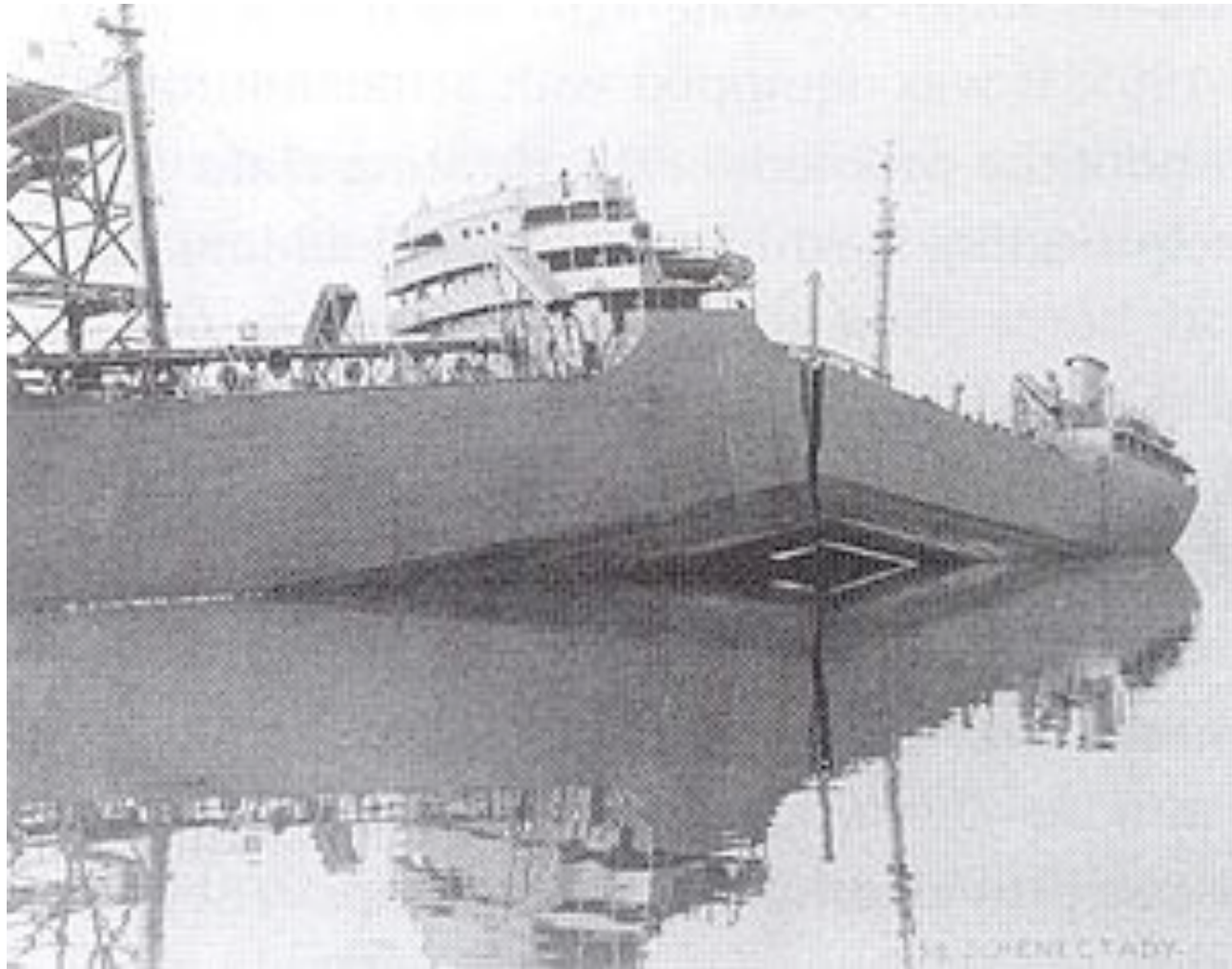
How shear cracks grow – not in own plane



Shear cracks (Modes II or III) need “process zone” to grow.
Wing cracks are part of that process zone.

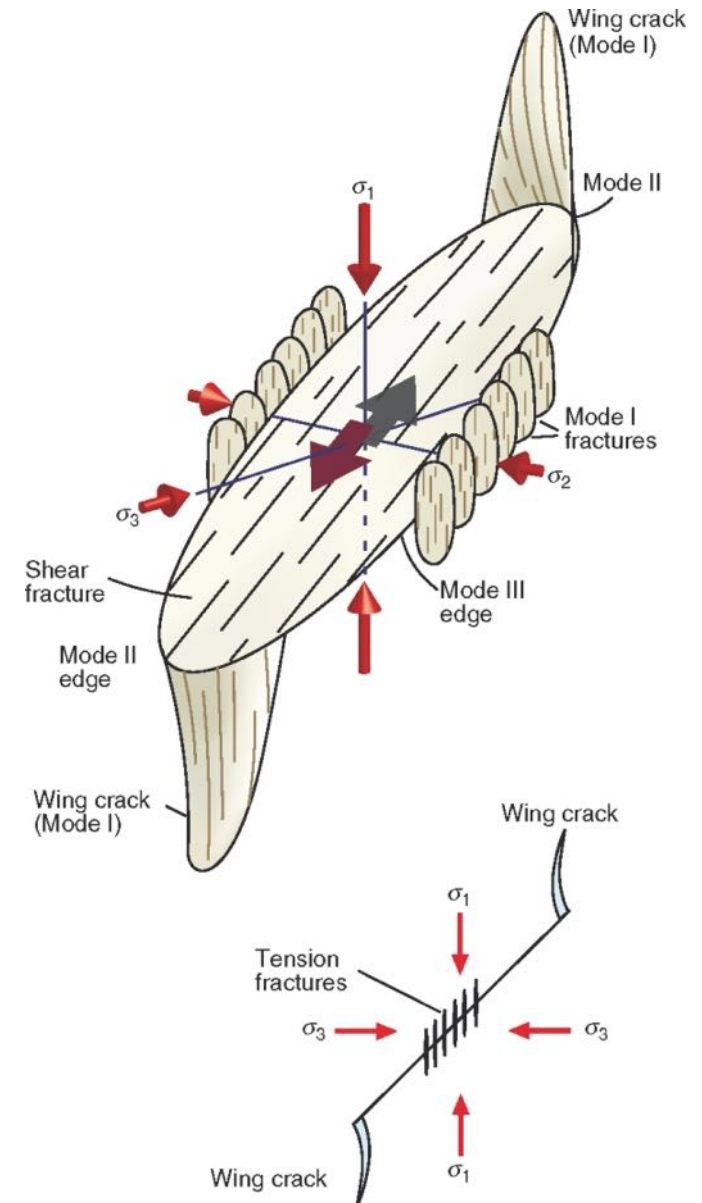
S.S. Schenectady

- Portland OR, 16 January, 1943



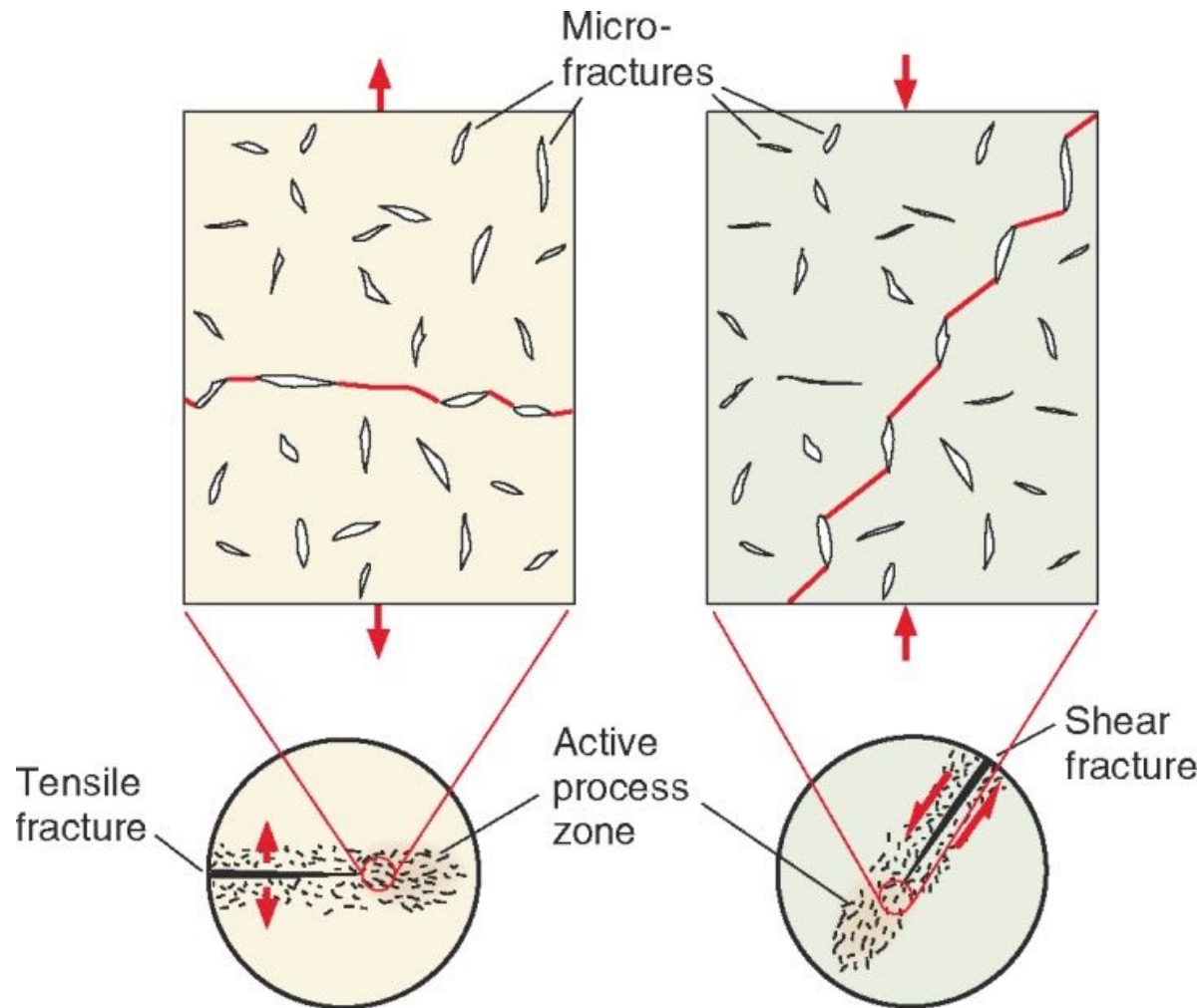
Fracture growth and wing cracks

- A shear crack cannot propagate in its own plane
- A shear crack has Mode II and Mode III edges
 - On the Mode II edges, **Mode I wing cracks** form
 - On the Mode III edges, **arrays of Mode I cracks** form



Growth and propagation of extension and shear fracture

- Linkage of tensile microcracks (flaws)

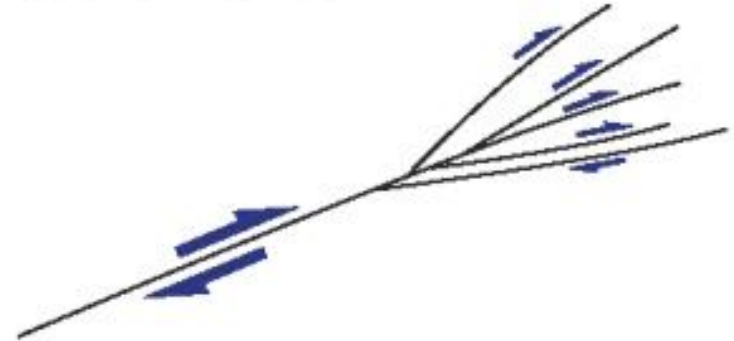


Minor fractures at the termination of shear fractures

(a) Wing crack



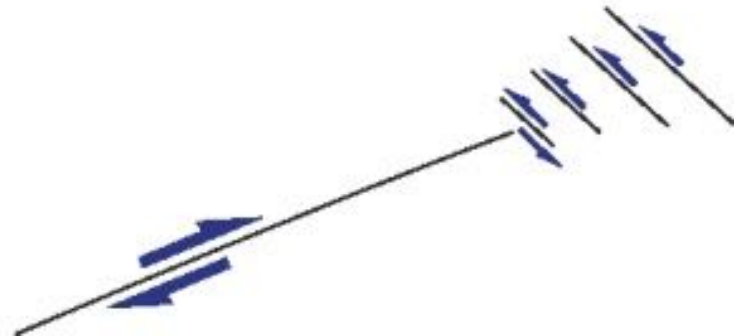
(c) Splaying



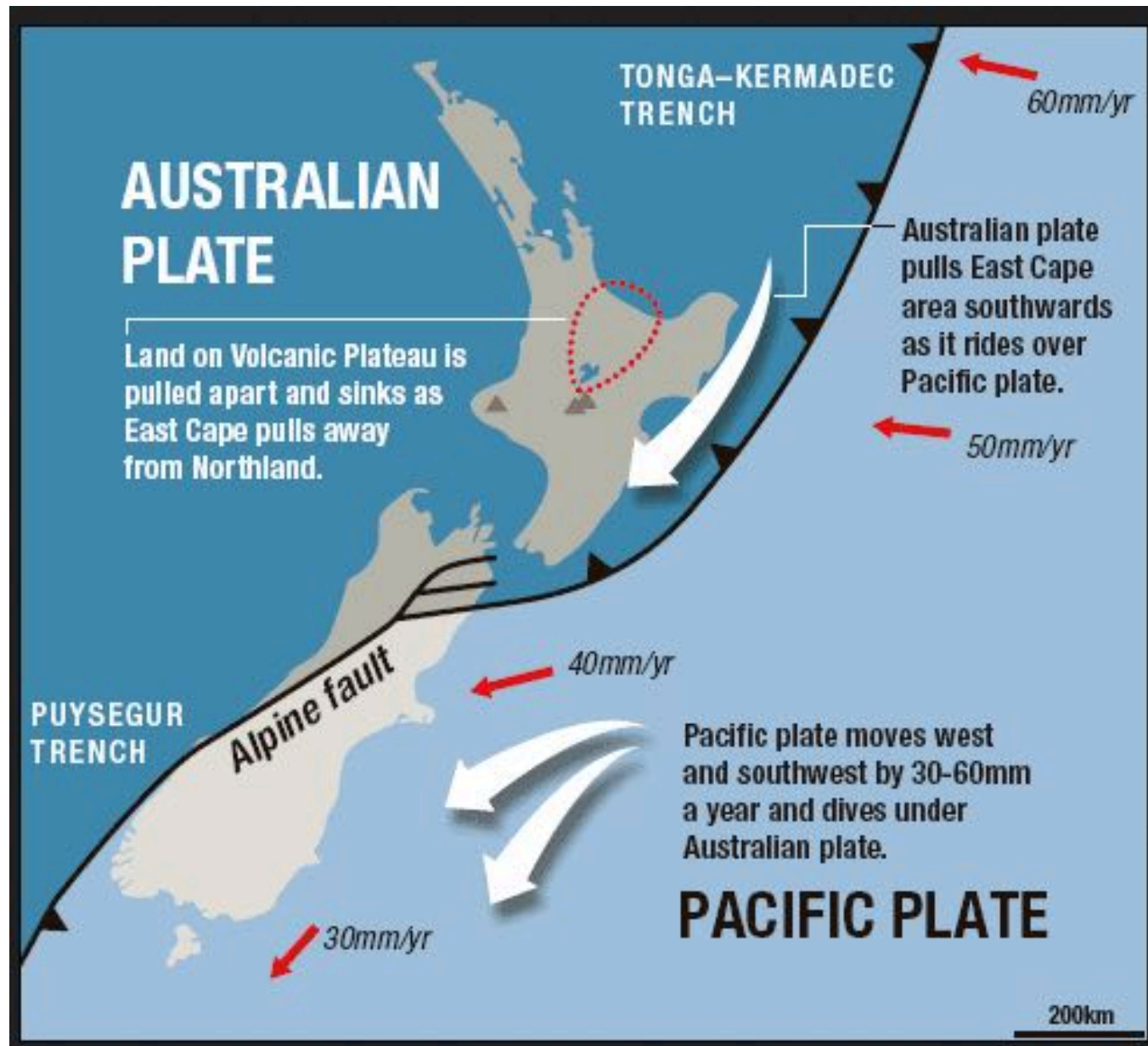
(b) Horsetailing



(d) Antithetic shear fractures



Also see numerous fracture patterns in Kim, Peacock, Sanderson,
J. Structural Geology (2004).



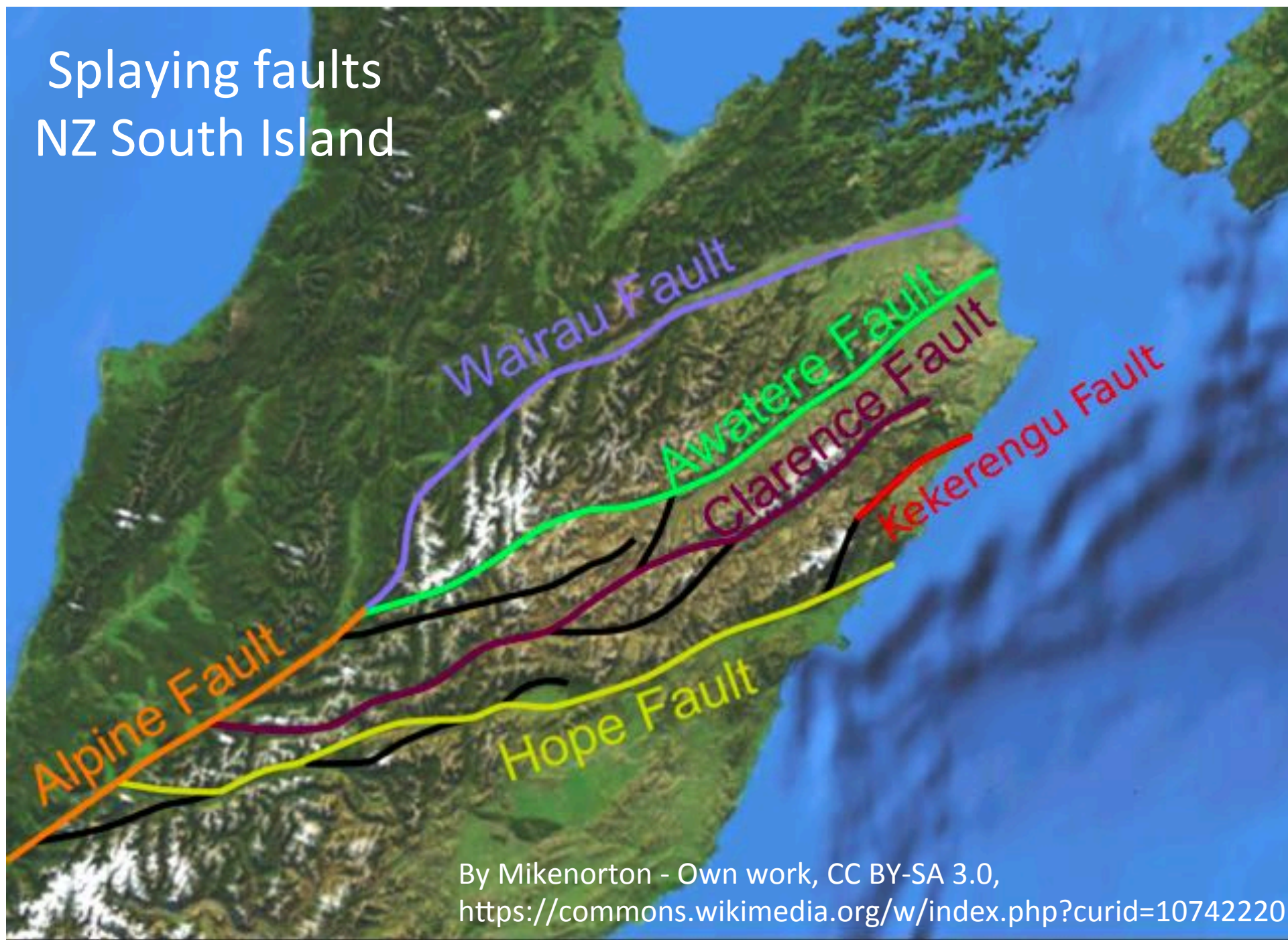
<https://theextinctionprotocol.wordpress.com/2015/03/25/new-zealand-community-told-to-prepare-for-major-quake-along-dangerous-alpine-fault/>



Kaikoura
14 November 2016

7.8 M_w

Splaying faults NZ South Island



By Mikenorton - Own work, CC BY-SA 3.0,
<https://commons.wikimedia.org/w/index.php?curid=10742220>

Let's talk about fluid pressure ...

Recall discussion of fracking (hydrofracturing) in
Problem session yesterday

- Shut-in pressure \Rightarrow horizontal stress state?
- Breakdown pressure \Rightarrow horizontal stress state?

