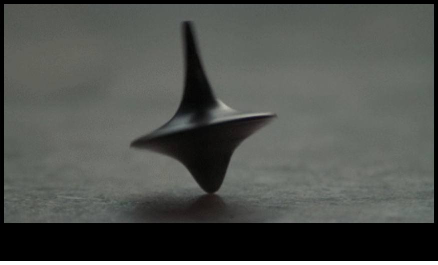
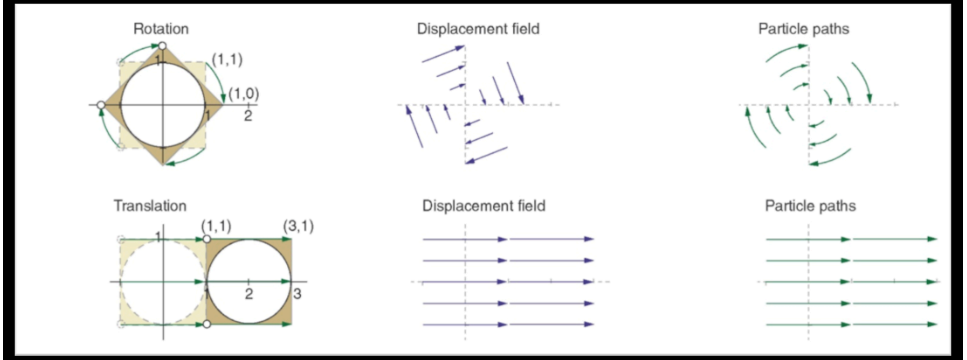
“Deformation”

- Any combination of:
  - Rotation
  - Translation
  - Volume change
  - Change in size or shape



Displacement vectors



- Each particle in the body we examine moves – each gets a vector.
- Characterize before/after displacements and actual path taken.

Strain

- Pre- to post-deformation

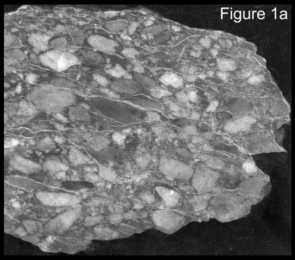


Figure 1a

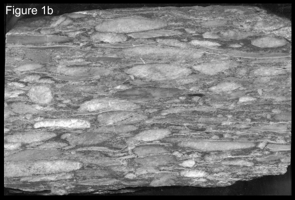
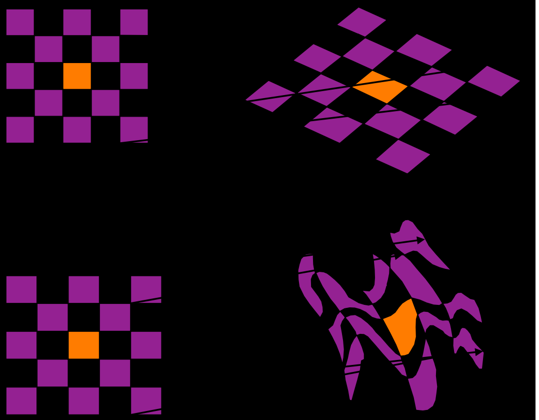


Figure 1b

Homogeneous vs. heterogeneous deformation

- We assume rocks deform as continuous fluids
- **Strain may vary**
- But it doesn't change abruptly - it varies smoothly and continuously

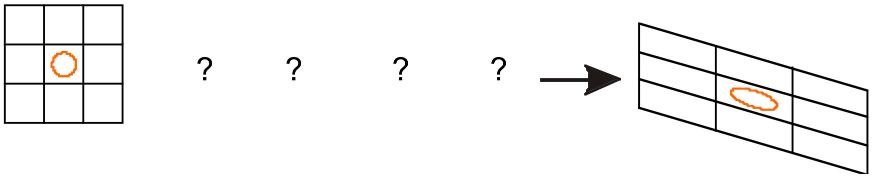


Strain – homogenous, or not?

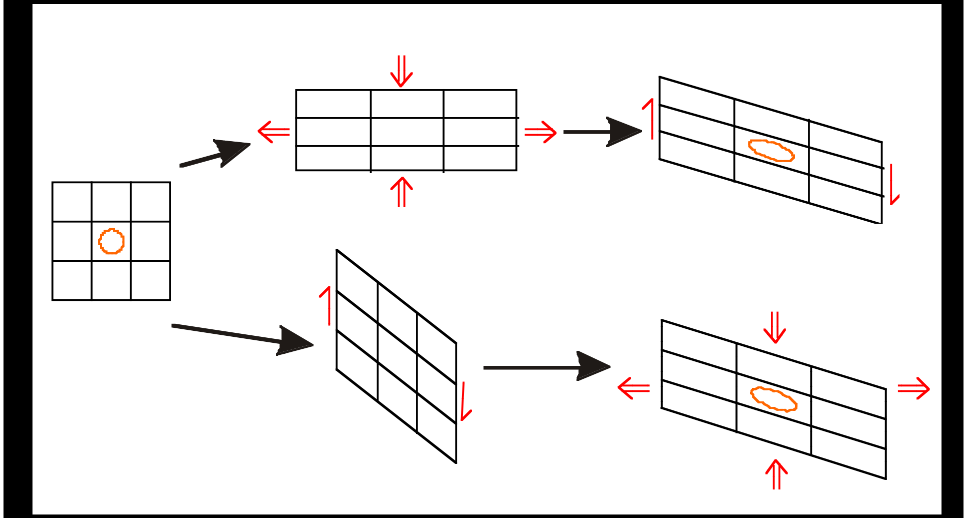
Photo from Casey Moore

Strained Conglomerate, Death Valley. Note limestone clasts are much more deformed than silicate clasts. Limestone deformation is similar to rock matrix.

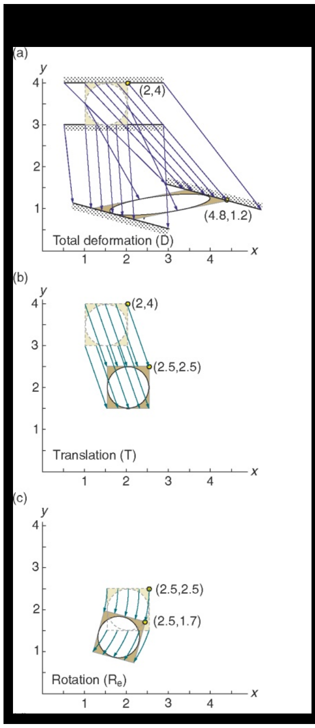
Strain is the change in shape…



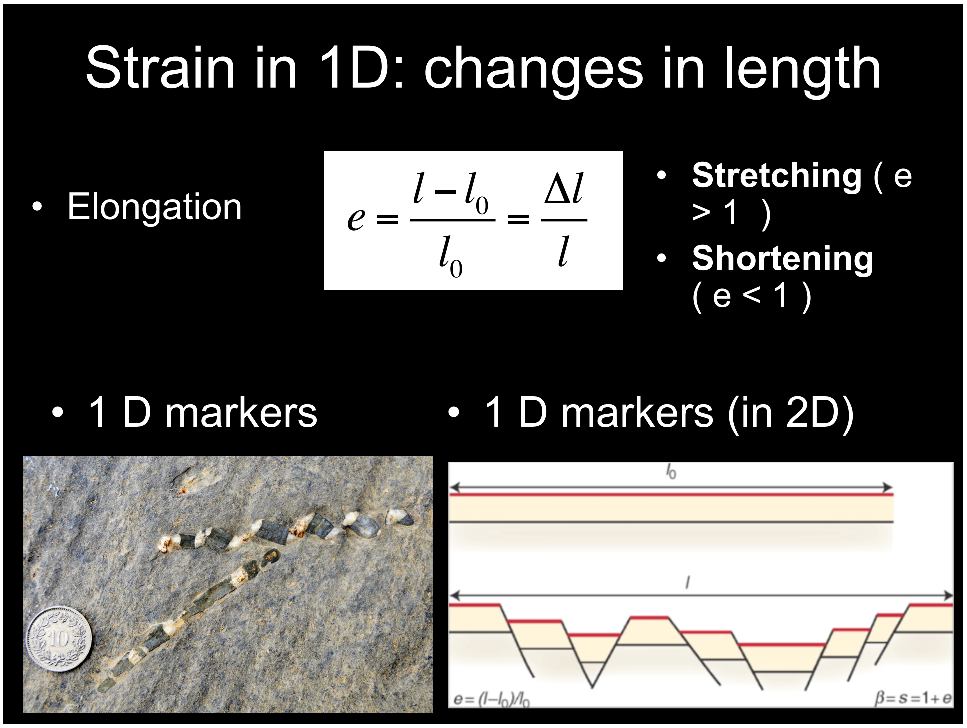
BUT strain ≠ deformation history



Deformation matrix



- Linear operators describe change in position of each point



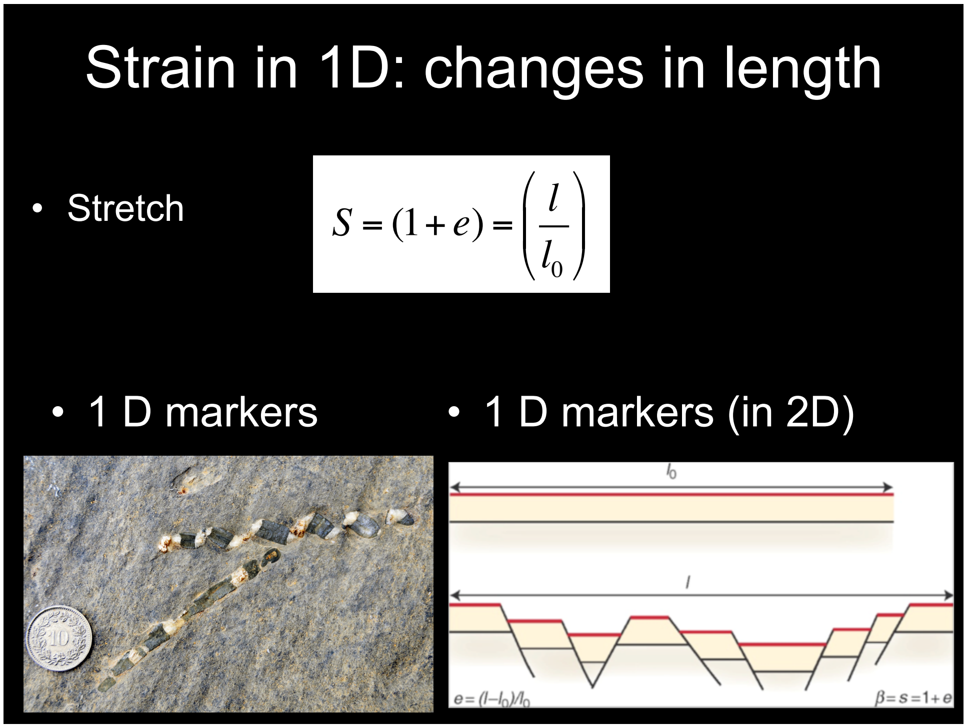
Strain in 1D: changes in length

- Elongation

$$e = \frac{l - l_0}{l_0} = \frac{\Delta l}{l}$$

- **Stretching** (e > 1)
- **Shortening** (e < 1)

- 1 D markers
- 1 D markers (in 2D)

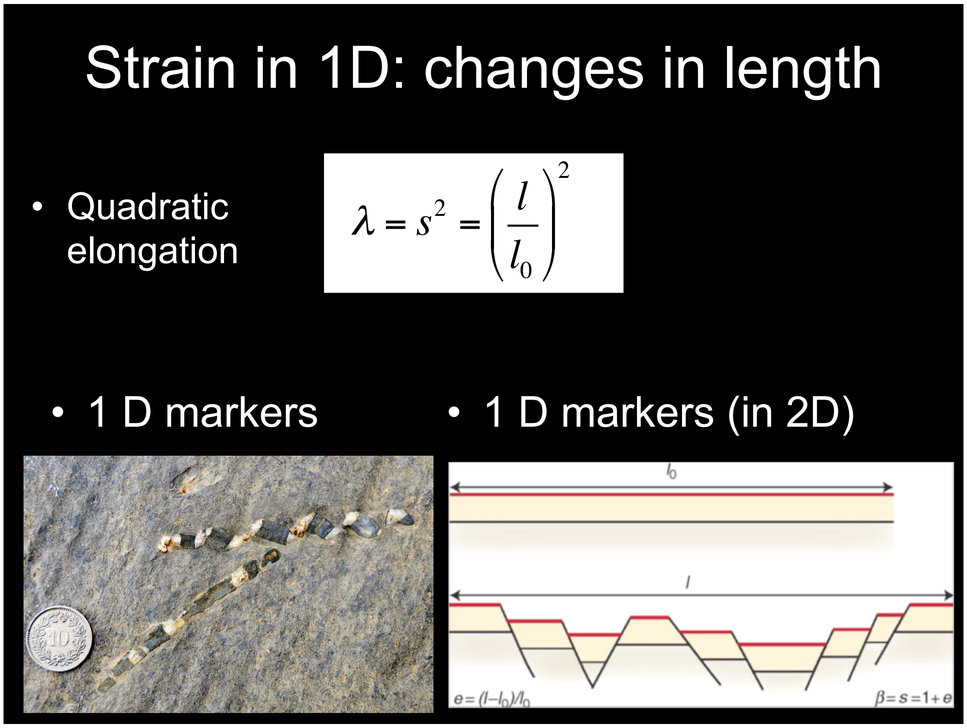


Strain in 1D: changes in length

- Stretch

$$S = (1 + e) = \left(\frac{l}{l_0}\right)$$

- 1 D markers
- 1 D markers (in 2D)

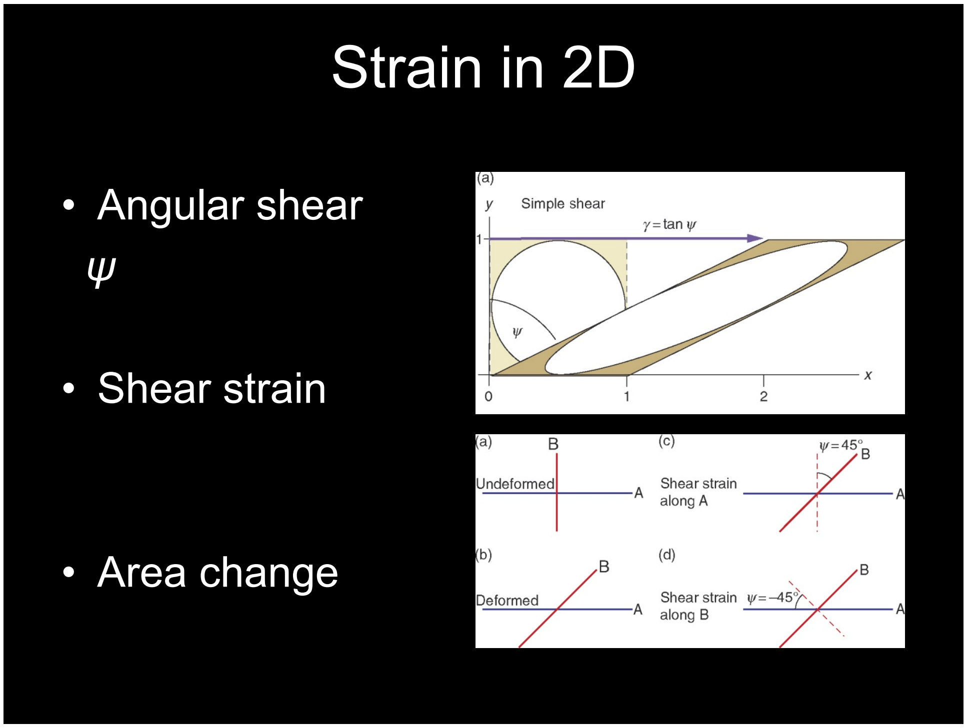


Strain in 1D: changes in length

- Quadratic elongation

$$\lambda = s^2 = \left(\frac{l}{l_0}\right)^2$$

- 1 D markers
- 1 D markers (in 2D)

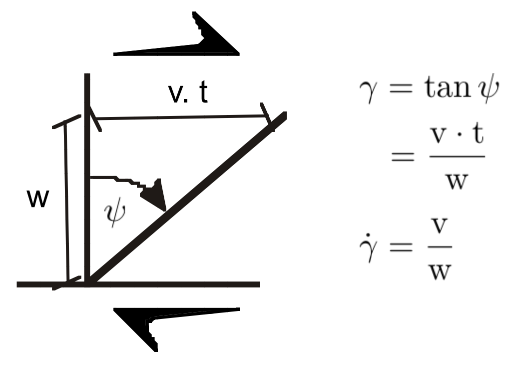


Strain in 2D

- Angular shear ψ
- Shear strain
- Area change

Strain rate

- Note that you will often read about strain rates – v. important parameter in geology!

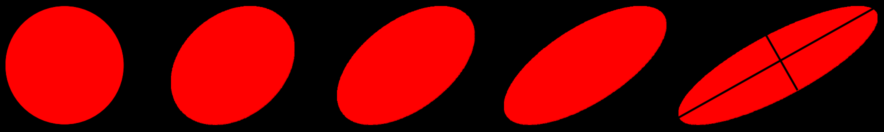


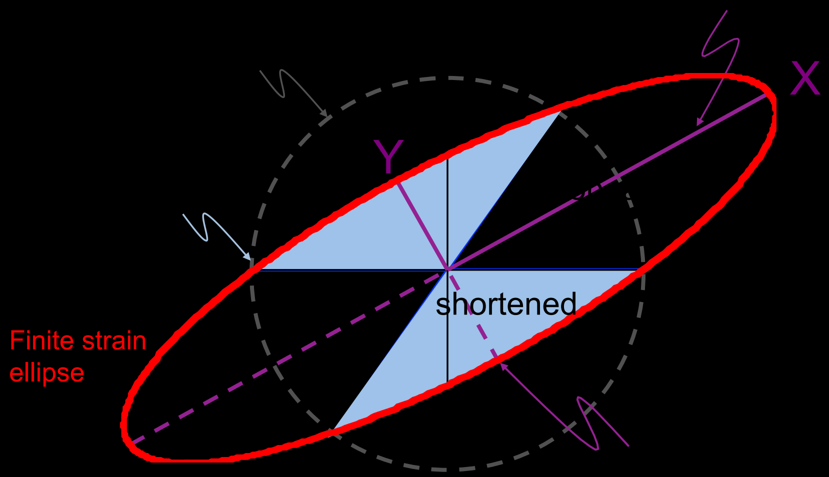
$$\gamma = \tan\psi = \frac{\mathrm{v}\cdot\mathrm{t}}{\mathrm{w}}$$

$$\dot{\gamma} = \frac{\mathrm{v}}{\mathrm{w}}$$

Strain in 2D: the strain ellipse

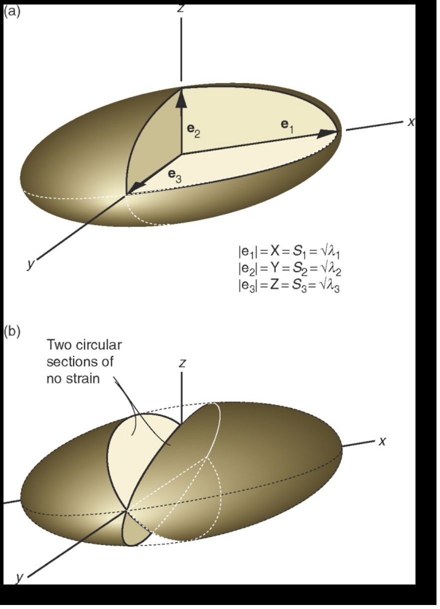
- Start with a circle
- Apply strain
- The resulting ellipse represents the elongation in any/all directions
- *For a region of homogeneous strain*



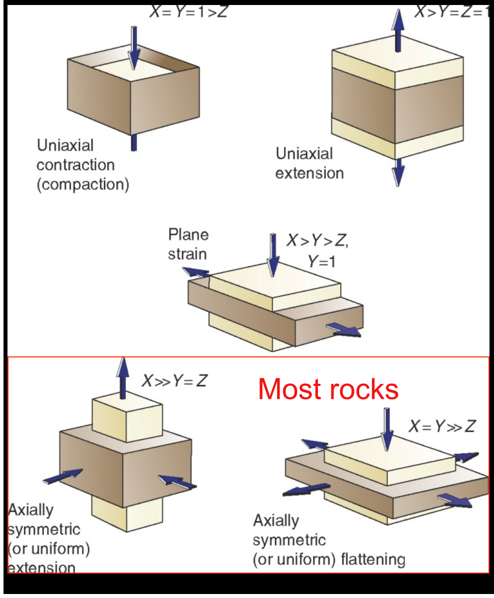


Strain in 3D

- Strain ellipsoid
- 3 principal strain axes
- Lines // to these are orthogonal and were originally orthogonal
- They have experienced no shear, only extension



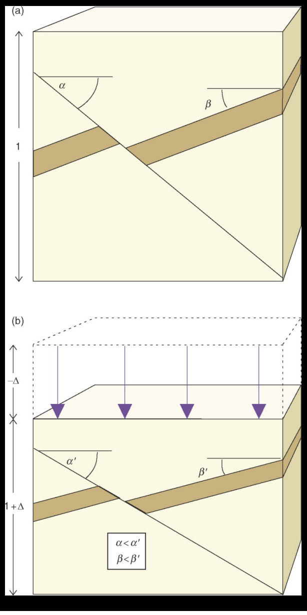
Plane strain



- 1D (Top): Uniaxial
  - Contraction or extension in only one direction.
- 2D: (Middle): **Plane Strain**
  - stretch in one direction (X) perfectly compensated for by contraction in (Z). Y=1.
- 3D: (Bottom) Uniform flattening/extension
  - compensated for oppositely in orthogonal plane.

Uniaxial contraction

- Contraction in vertical axis, no other axes change
- Requires vol. change
- e.g. COMPACTION
- Bedding dip changes

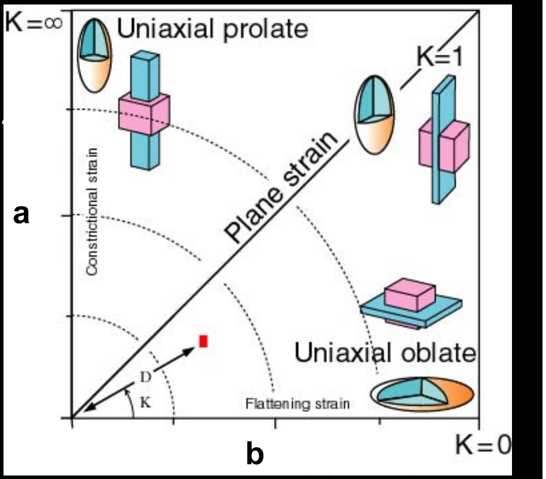


3D Strain classification

- Flinn diagram
  - Strain magnitude?
  - Deformation history?

For principal axes X, Y and Z:

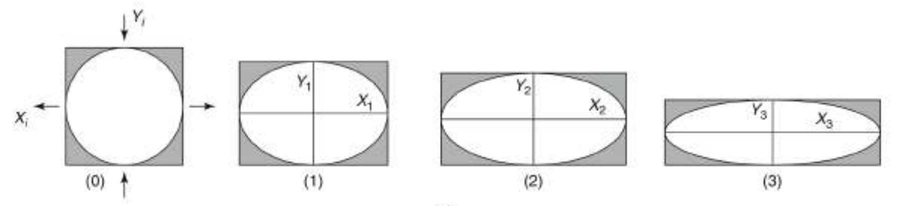
a = X/Y   b= Y/Z



D distance from the origin

K slope of the line

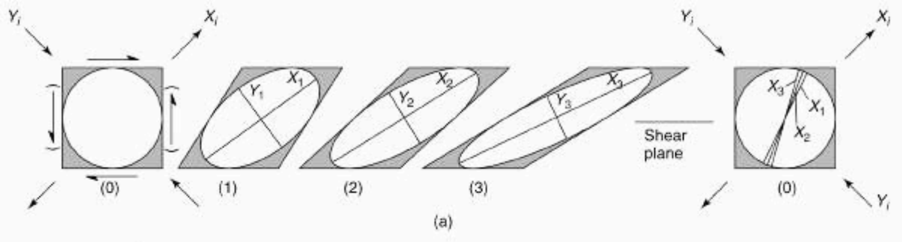
Coaxial deformation: Pure shear



- Principal axes have the same orientation before and after deformation
- Pure shear = plane strain, no vol. change:

k_x, k_y are stretch in X and Y

Non-coaxial deformation: Simple shear

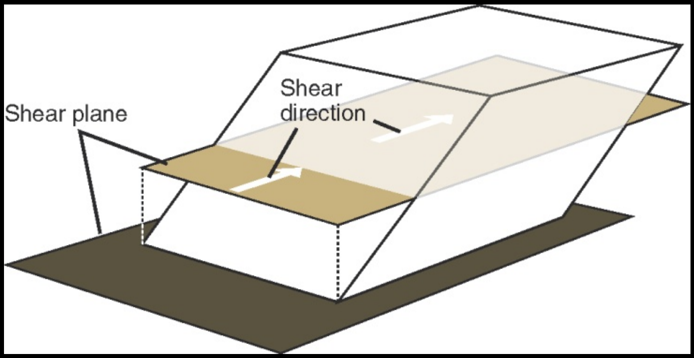


- Orientations of principal strain axes change as strain increases
- Simple shear = plane strain, no vol. change:

  γ is shear strain

  aka 'general shear'

Simple shear: the shear plane

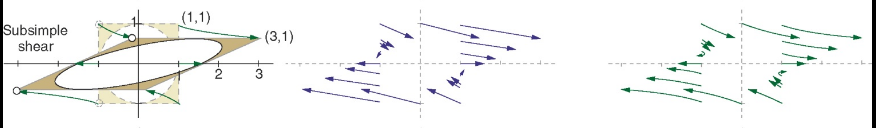


- Lines or planes parallel to the shear plane do not rotate – everything else does!

Non-coaxial or coaxial deformation?

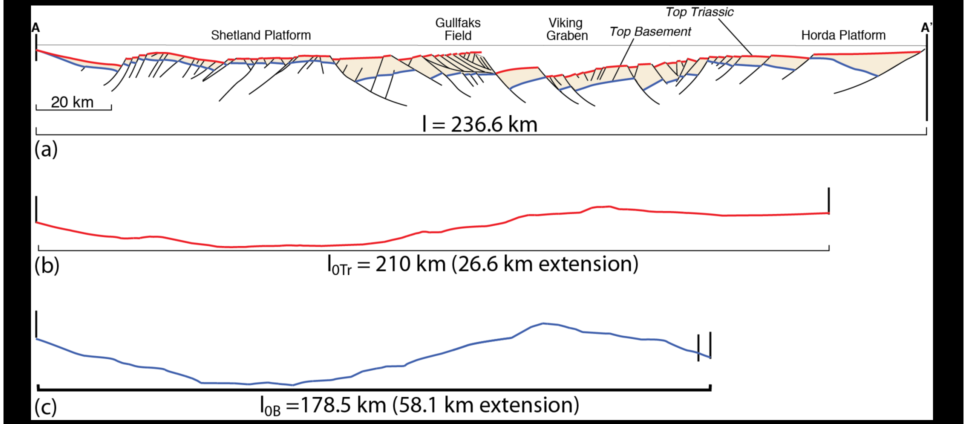
Subsimple shear

- Everything in between!

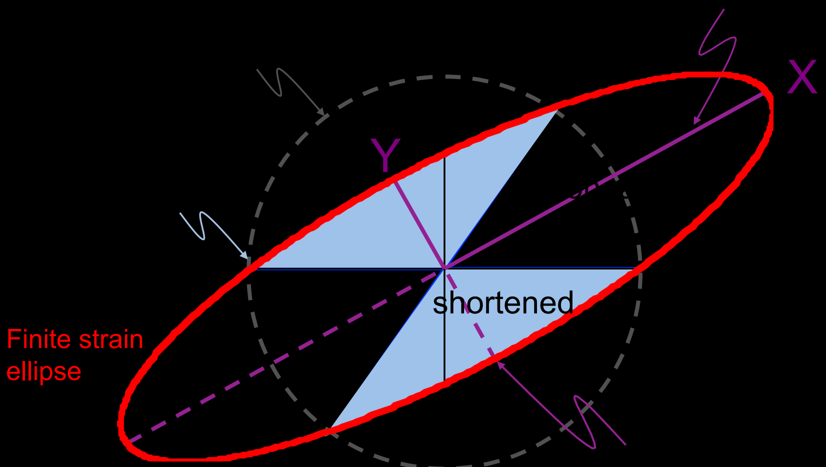


- A combination of pure and simple shear.

1D strain in the N Sea

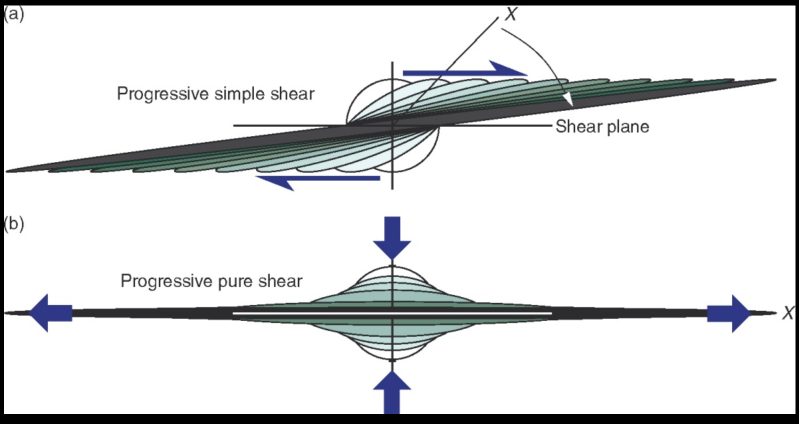


- How accurate are these results?

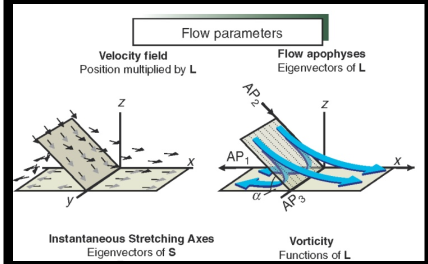


Progressive deformation

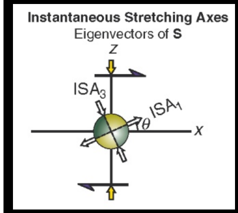
- Finite, incremental, infinitesimal strain
- DEFORMATION HISTORY

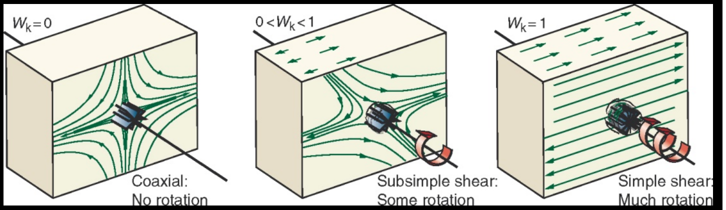


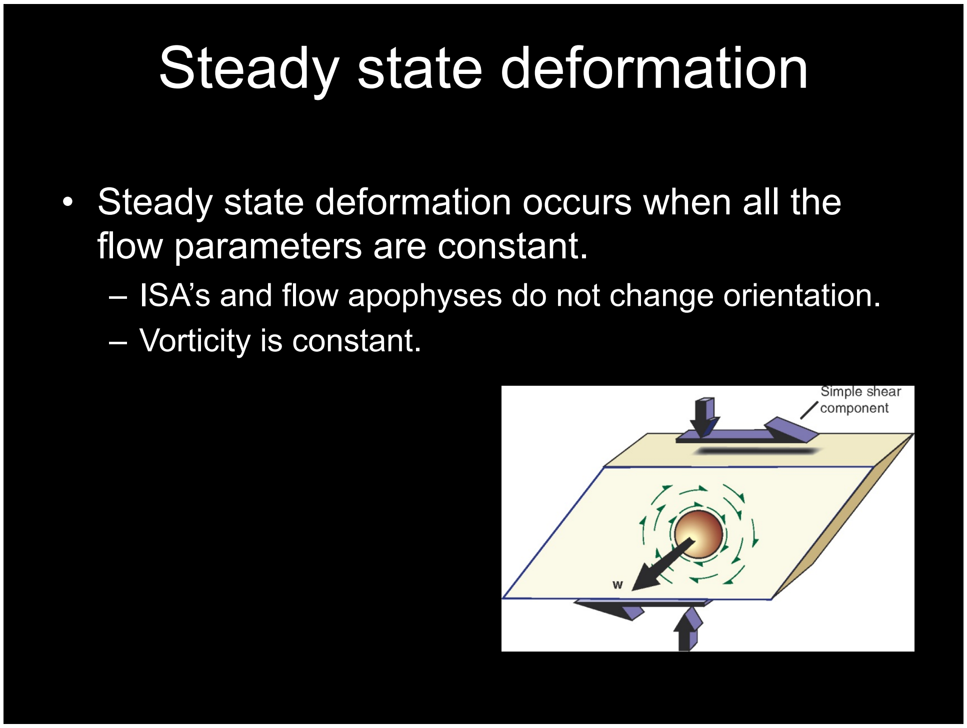
Flow parameters



- Continuous deformation is FLOW
- Velocity, flow apophyses, vorticity

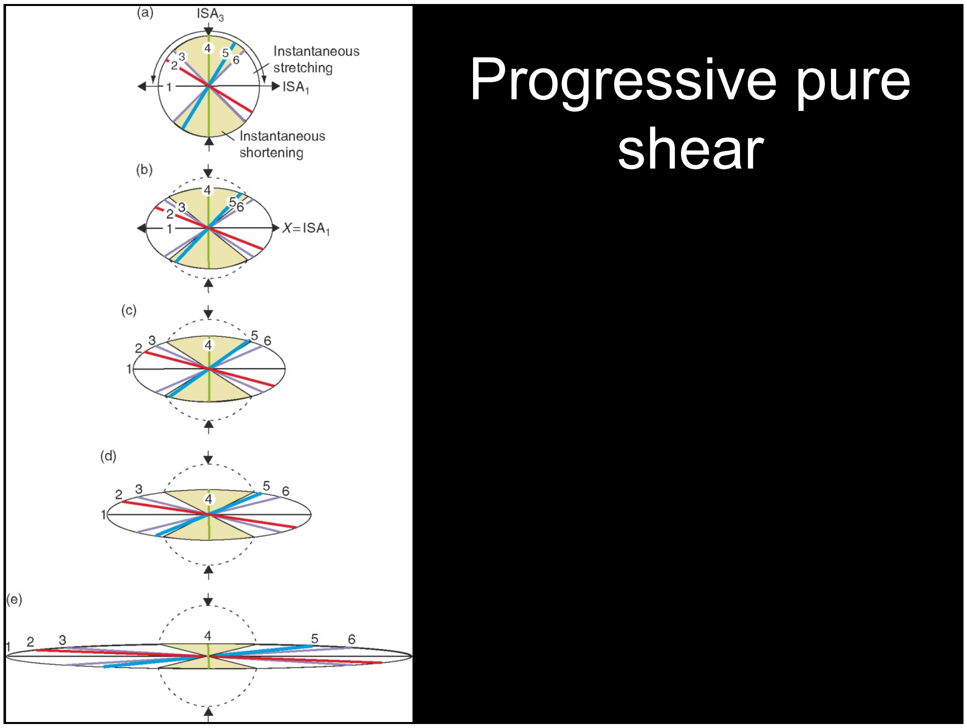






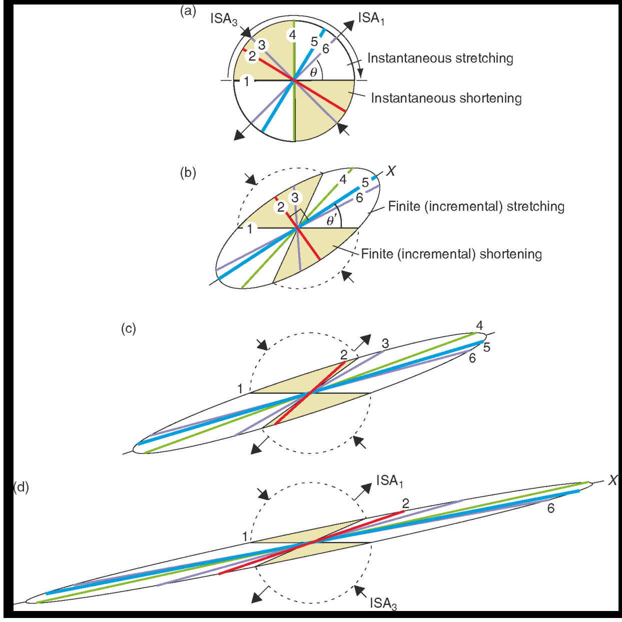
Steady state deformation

- Steady state deformation occurs when all the flow parameters are constant.
  - ISA’s and flow apophyses do not change orientation.
  - Vorticity is constant.



Progressive pure shear

Progressive simple shear



- Instantaneous stretching axes, ISA's
- Do not rotate
- Length changes fastest in the ISA$_1$ direction

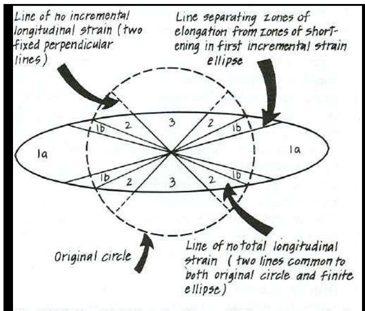


Fig. 14.18 Coaxial total strain ellipse with four zones, each of which has a different deformation history. After Ramsay (1967).

Zone

1a Lines that have been elongated only boudinage.

1b Lines that underwent early shortening followed by elongation (net lengthening). Remnants of disrupted folds and isolated fold hinges.

2 Lines that underwent early shortening followed by elongation (net shortening). Folds that are becoming unfolded and boudinaged.

3 Lines that have been shortened only. Folds with larg

How multiple deformations result from progressive coaxial shortening

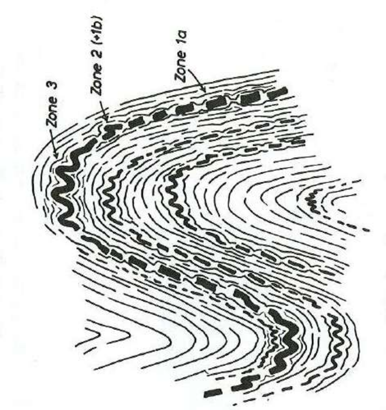
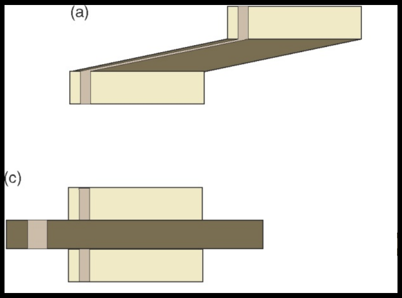
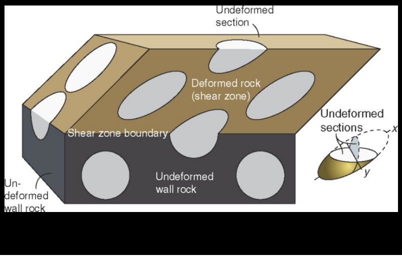


Fig. 14.19 Fold developed by coaxial strain showing structures in each zone. Maximum principal strain axis is vertical. From Ramsay (1967).

Boundary conditions

- Change in shape may require space
- For ‘compatibility’ the strain ellipses either side of a boundary must be the same





Strain markers

Reduction spots in slate. They are strained spheres of bleached rock that are elliptical in section and oblate (pancakes) in three dimensions.

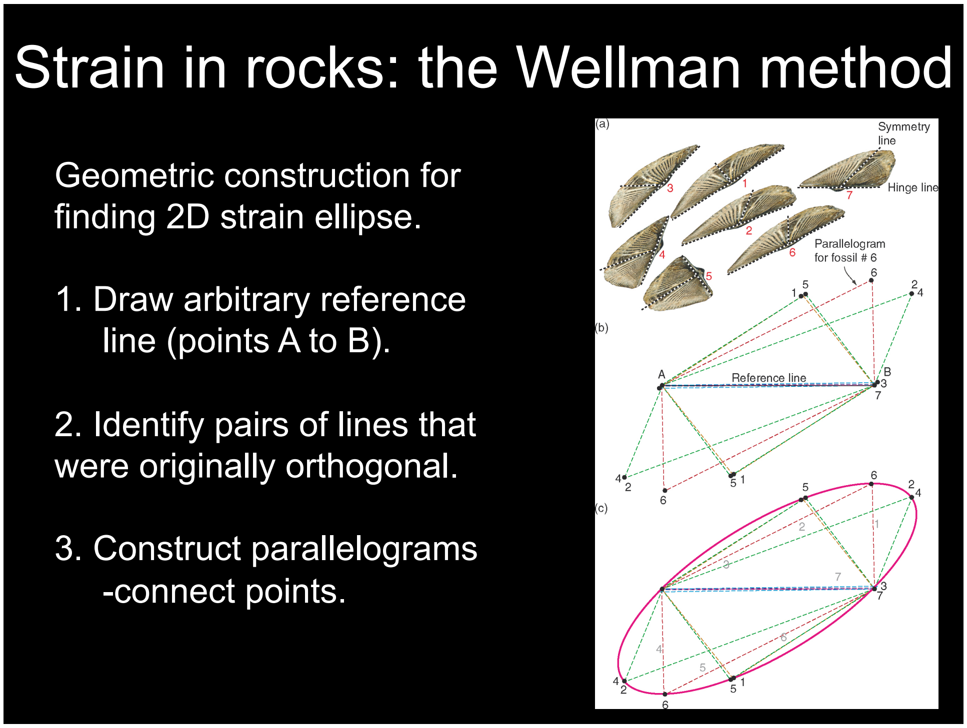
- Strain extracted from sections (2D) is the most common type of data.
- Combined to estimate 3D ellipsoid.
- <u>Others:</u> conglomerates, corals, vesicles

Strain markers: changes in angles

If the original orientation of lines is known, angular shear and shear strain can be obtained from deformed sets of lines.

<u>Others:</u> dikes, foliation and bedding sometimes found in undeformed and deformed states.

Undeformed trilobite contains orthogonal lines



Strain in rocks: the Wellman method

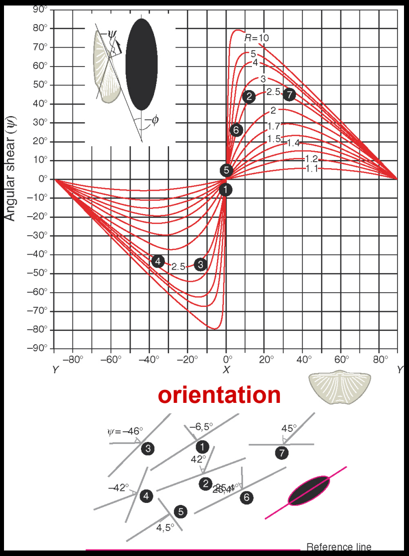
Geometric construction for finding 2D strain ellipse.

1. Draw arbitrary reference line (points A to B).

2. Identify pairs of lines that were originally orthogonal.

3. Construct parallelograms -connect points.

Strain in rocks: the Breddin graph

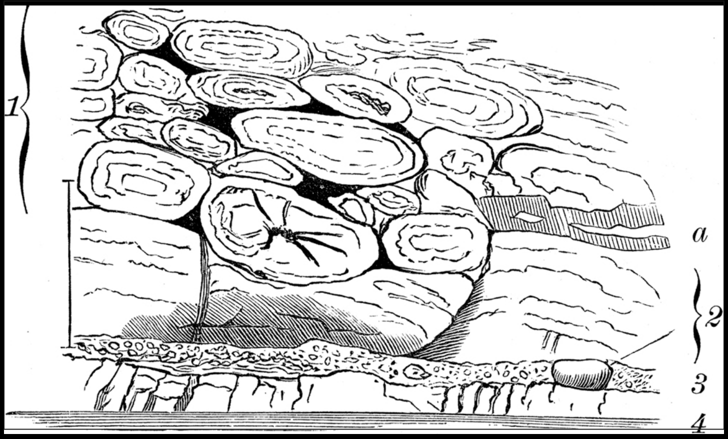


Based on understanding that the **minimum angular shear** occurs along lines nearest the principal strains

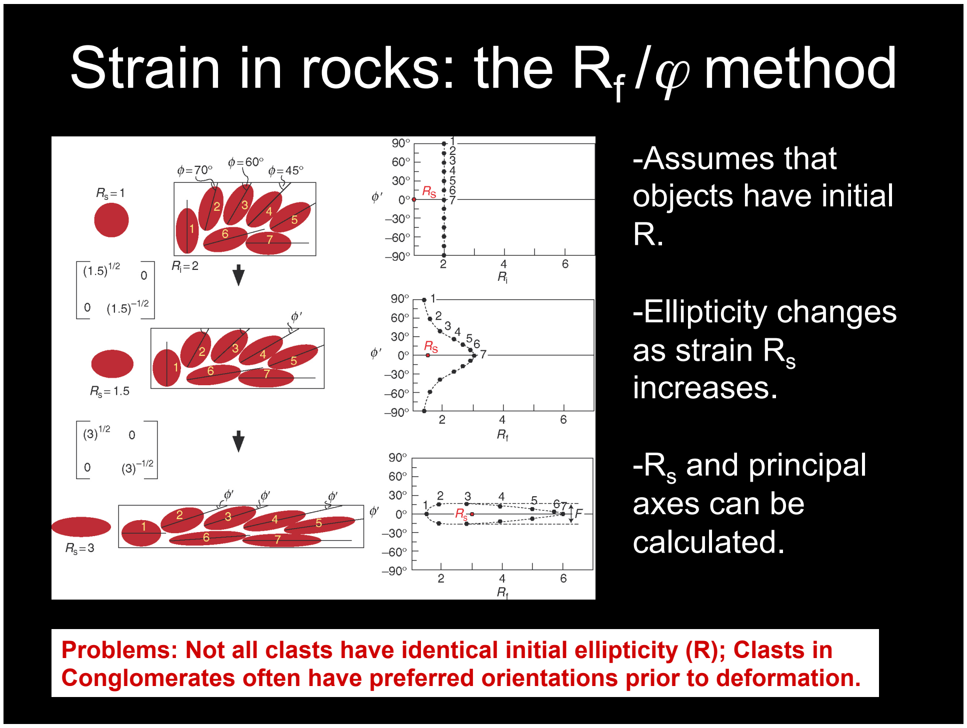
(+): R can be found with 1 or 2 observations if principal strain directions known.

(-): if strain directions not known, many observations needed.

Strain in rocks: the R_f/φ method



Circles (2D) and Spheres (3D) are relatively uncommon in nature. The R_f/φ Method accounts for this.



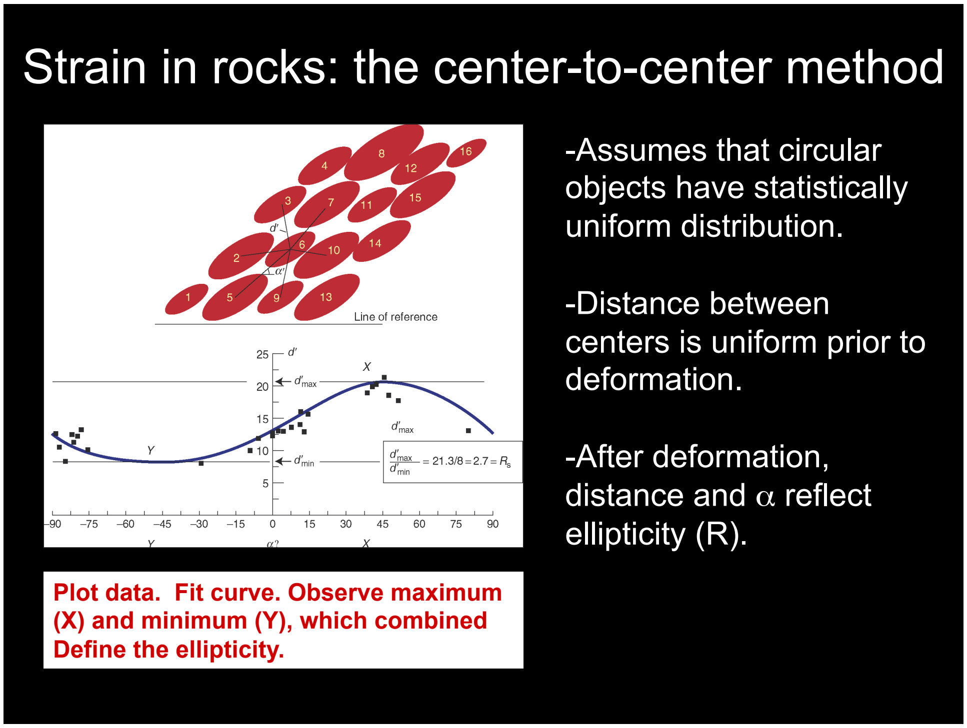
Strain in rocks: the R_f/φ method

-Assumes that objects have initial R.

-Ellipticity changes as strain R_s increases.

-R_s and principal axes can be calculated.

Problems: Not all clasts have identical initial ellipticity (R); Clasts in Conglomerates often have preferred orientations prior to deformation.



Strain in rocks: the center-to-center method

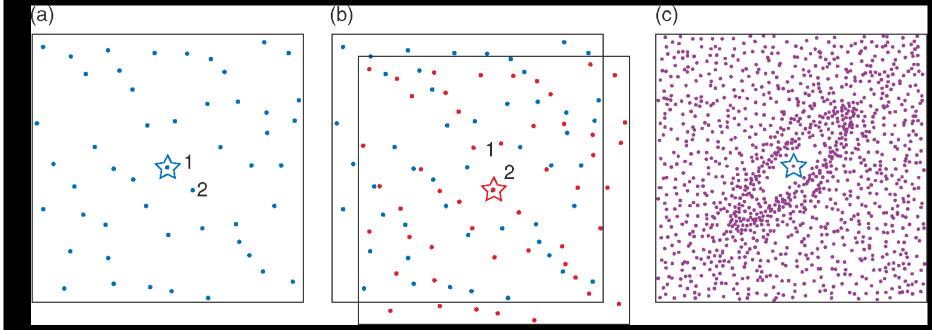
-Assumes that circular objects have statistically uniform distribution.

-Distance between centers is uniform prior to deformation.

-After deformation, distance and α reflect ellipticity (R).

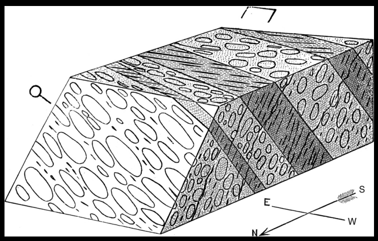
Plot data. Fit curve. Observe maximum (X) and minimum (Y), which combined Define the ellipticity.

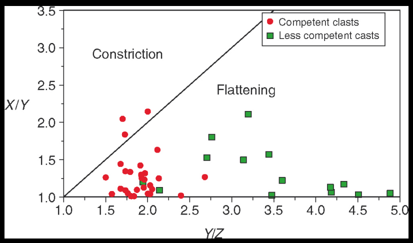
Strain in rocks: the Fry method



- Visualization of the center-to-center method.
- Overlays of distance between center points.
- Best done with computer program (e.g. Adobe Illustrator).

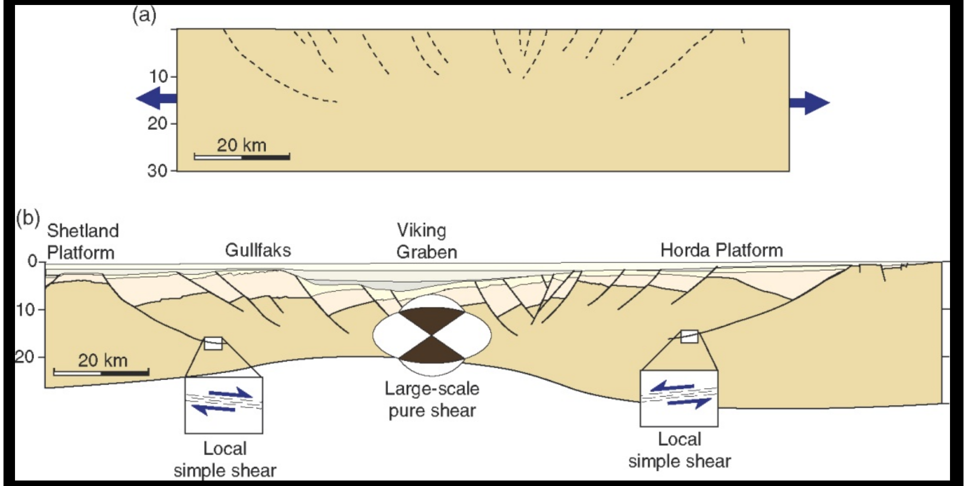
3D strain in the field





- 3D strain is found by combining strain estimates from two or more sections through the deformed rock volume.
- Shape of ellipsoid represented by Flinn diagram.
  - Assumes: heterogeneous strain that is evenly partitioned (rock properties).

Tectonics and scale dependent strain



Rheology

- The study of the mechanical properties of solids, fluids and gases
- Relates stress to strain through *constitutive equations*

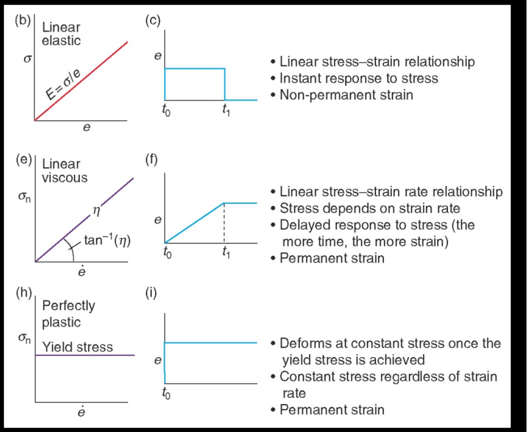
constant *activation energy*

strain rate $\dot{e} \propto \Delta\sigma^n e^{-Q/RT}$ *temperature*

differential stress (σ_1-σ_3) *gas constant*

3 idealized types of deformation

- Elastic (≠ brittle deformation!)
- Viscous
- Plastic



- Linear stress–strain relationship
- Instant response to stress
- Non-permanent strain

- Linear stress–strain rate relationship
- Stress depends on strain rate
- Delayed response to stress (the more time, the more strain)
- Permanent strain

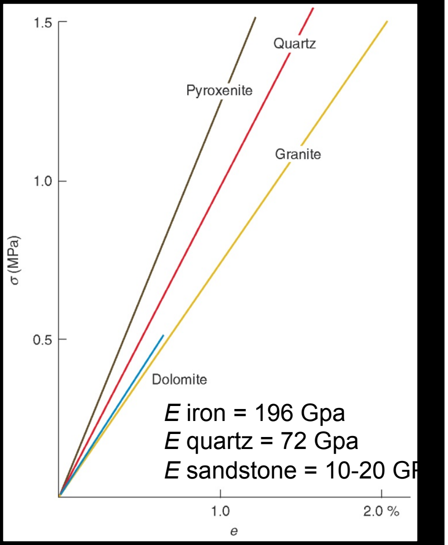
- Deforms at constant stress once the yield stress is achieved
- Constant stress regardless of strain rate
- Permanent strain

Elasticity (shallow crust)

- Elastic materials:
  - are solid or liquid
  - resist deformation
  - strain more as more stress applied
  - return to original shape after deformation
- For SMALL STRAIN, Elastic strain is RECOVERABLE

Elasticity

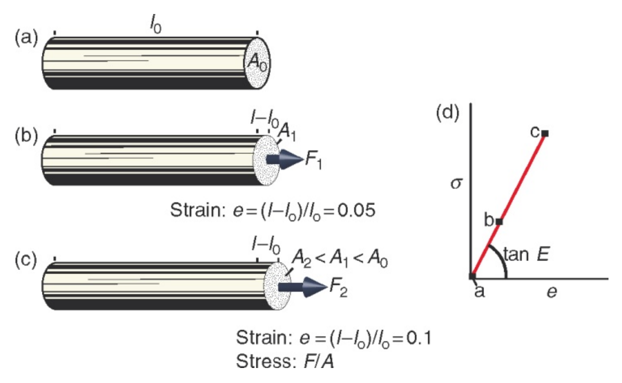
- **Hooke's** law:
- *E* is **Young's modulus**
- In shear:
- **Shear modulus**



E iron = 196 Gpa
E quartz = 72 Gpa
E sandstone = 10-20 G

Poisson's ratio (v)

- Ratio of horizontal to vertical strain for a given applied load = - e_x/e_z

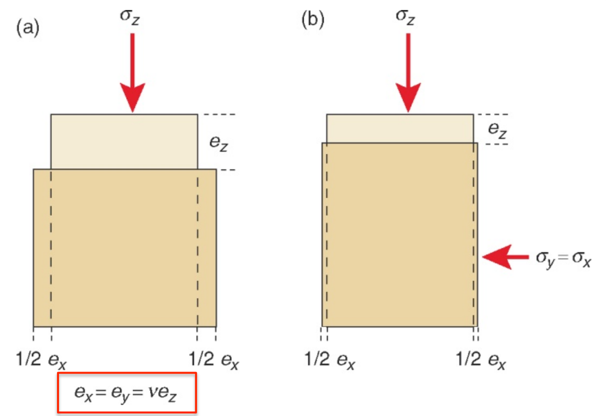


$e_z = -(e_x + e_y)$
$e_z = -2e_x$

For incompressible materials:
$0.5e_z = -e_x$
$v = -e_x/e_z$

Poisson's ratio (v)

- Uniaxial strain of a confined material



$\sigma_v = \rho g z$
Vertical Stress

Predicted Horizontal Stress
$\sigma_H = \sigma_h = \nu/(1-\nu)\sigma_v$

Rocks as fluids: permanent deformation

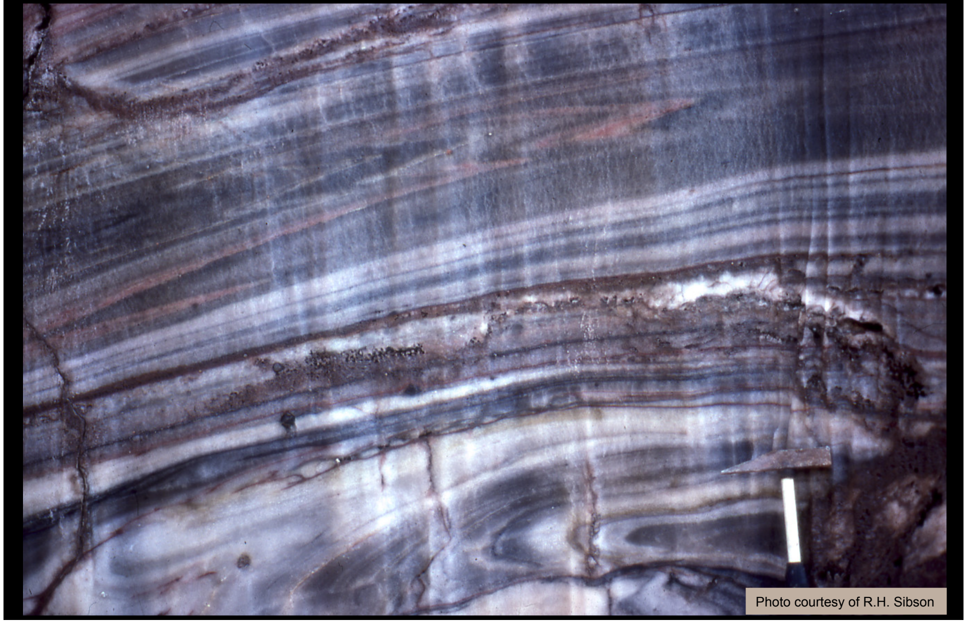
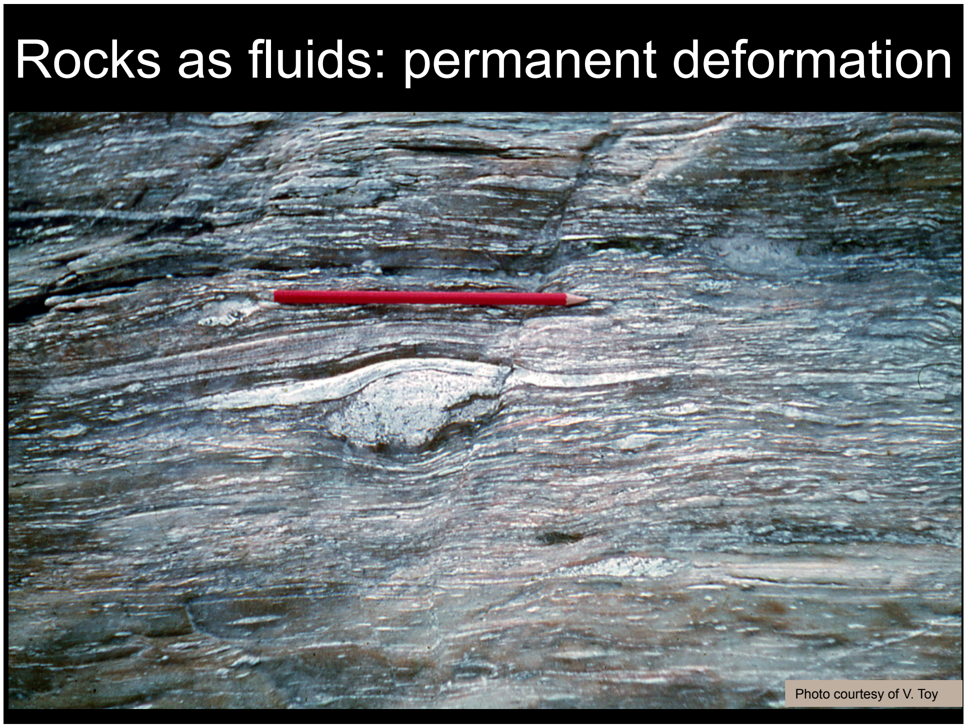


Photo courtesy of R.H. Sibson

Rocks as fluids: permanent deformation

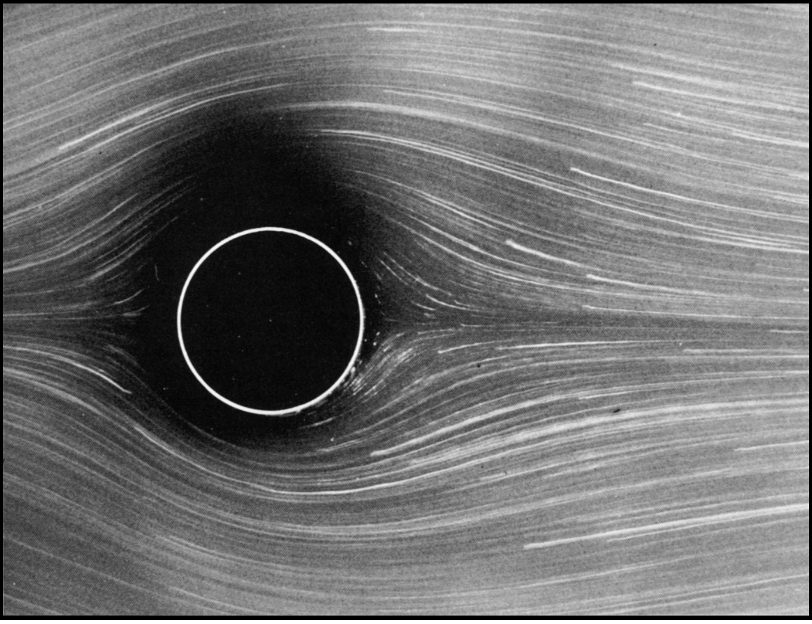
Photo courtesy of R.H. Sibson



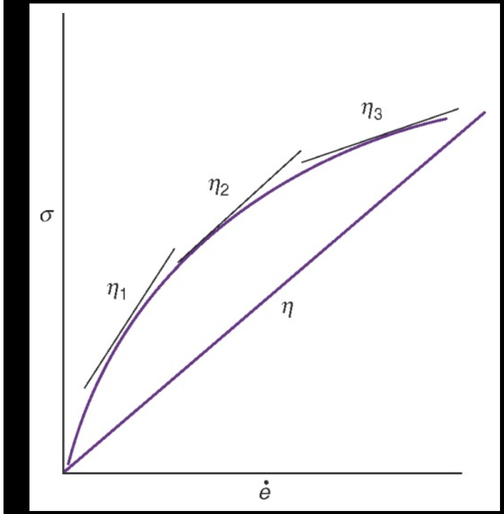
Rocks as fluids: permanent deformation

Photo courtesy of V. Toy

Flow lines in a channel flow



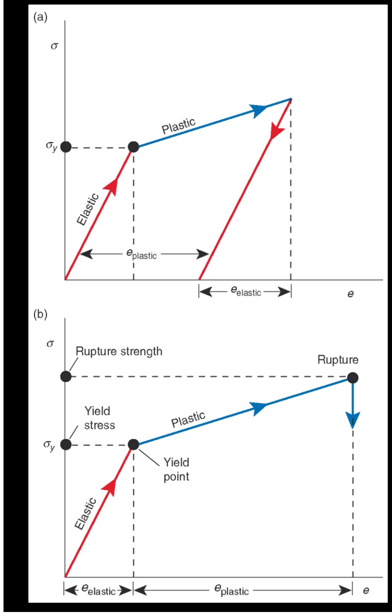
Viscous behavior



- Stress is proportional to strain rate
- η is viscosity (Pa.s)
- Higher stress means a faster flow or faster strain rate

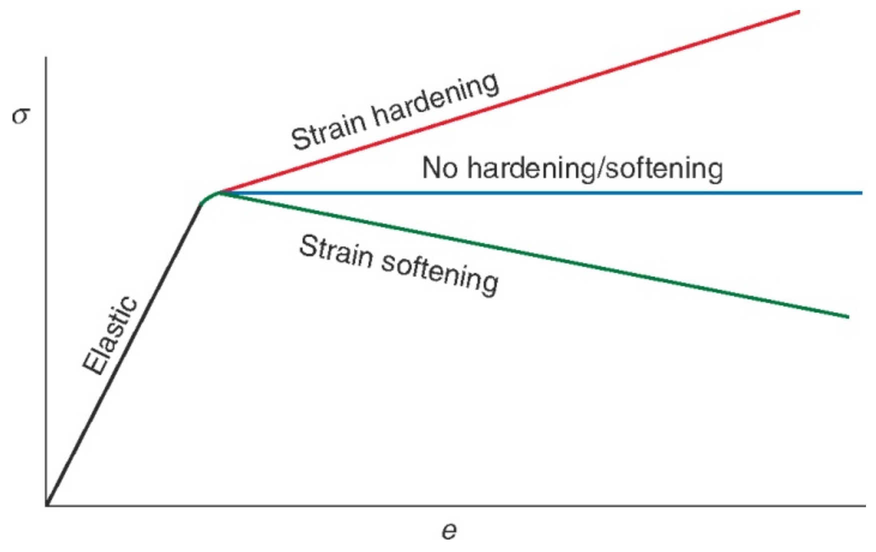
FLUIDS: magma, salt, overpressured mud

Plastic deformation

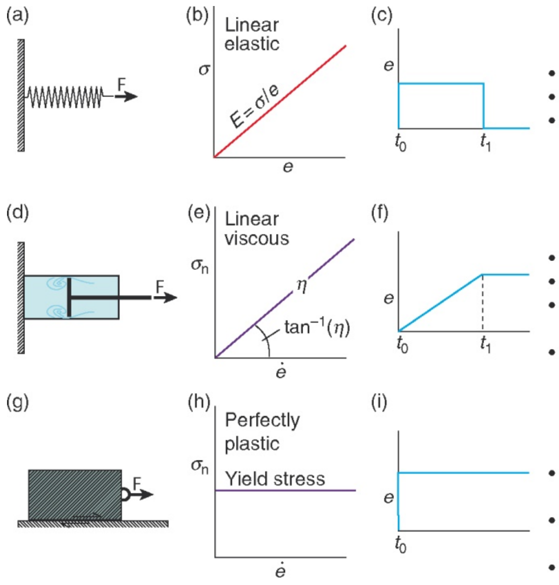


- *Permanent change in size/shape of a body* ***without fracture****, accumulated over time by a sustained stress beyond the elastic limit.*
- Described by flow laws

Strain hardening and softening



Conceptual models

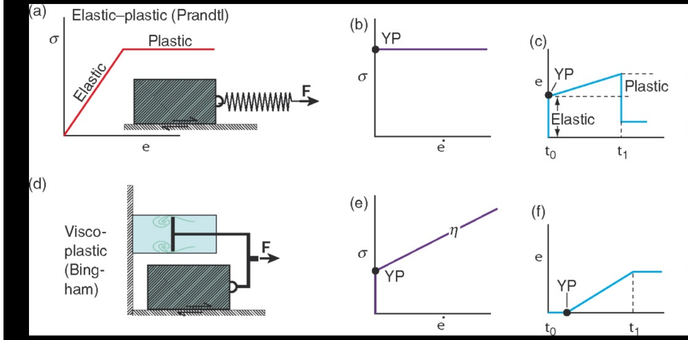


- Linear stress–strain relationship
- Instant response to stress
- Non-permanent strain

- Linear stress–strain rate relationship
- Stress depends on strain rate
- Delayed response to stress (the more time, the more strain)
- Permanent strain

- Deforms at constant stress once the yield stress is achieved
- Constant stress regardless of strain rate
- Permanent strain

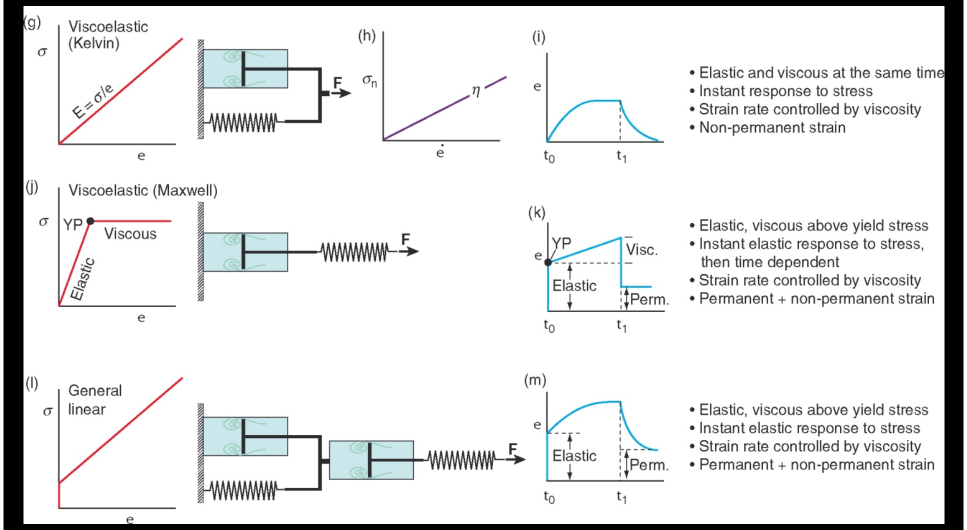
Combined models



- Elastic, then plastic stress–strain relationship
- Instant response to stress
- Permanent + non-permanent strain

- Linear viscous above YP
- No response to stress until YP, then time dependent
- Permanent strain

Combined models



- Elastic and viscous at the same time
- Instant response to stress
- Strain rate controlled by viscosity
- Non-permanent strain

- Elastic, viscous above yield stress
- Instant elastic response to stress, then time dependent
- Strain rate controlled by viscosity
- Permanent + non-permanent strain

- Elastic, viscous above yield stress
- Instant elastic response to stress
- Strain rate controlled by viscosity
- Permanent + non-permanent strain