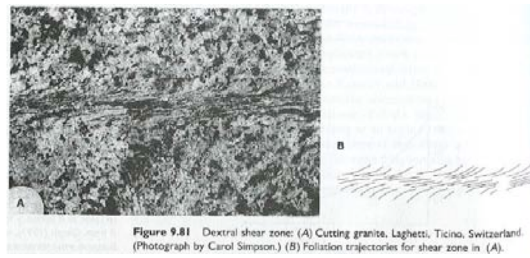
Lecture 22: ductile shear zones

websites from which images are drawn:

http://www.leeds.ac.uk/learnstructure/index.htm
http://www.rci.rutgers.edu/~geolweb/slides.html
http://www.earth.monash.edu.au/Teaching/mscourse
http://www.geolab.unc.edu/Petunia/lgMetAtlas/meta-micro
http://www.geo.unm.edu/teaching/microstructure/images
http://uts.cc.utexas.edu/~rmr/images
http://www.stmarys.ca/academic/science/geology/structural

ductile shear zone



from: http://www.ic.ucsc.edu/~casey/eart150/Lectures/ShearZones/15shearZns.htm

ductile shear zone:

"zone": tabular band of definable width in which there is considerably higher strain than in surrounding rock

"shear": large component of simple shear within shear zone
…rocks on one side of zone are displaced relative to those on the other side

"ductile" used to describe processes that operate inside zone (cataclastic flow; crystal-plastic mechanisms)

> ideal shear zone has planar and parallel boundaries outside of which there is no strain
> …in reality, boundaries typically are gradational

similar to faults in that displacement occurs, but *no through-going fracture forms*

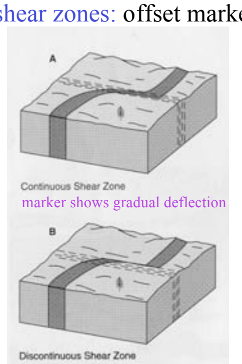
…consequence of higher temperatures and pressures
…produces metamorphism, foliations, lineations, folds

shear zones are longer and wider than they are thick…
…largest are hundred of kms long and tens of kms thick…
…smallest are cms long and mms thick…
…also can be observed in thin section…

> *all shear zones reflect localization/concentration of deformation into a narrow zone (strain in rock is heterogeneous)*

potentially can determine:
- sense of displacement
- amount of displacement
- amount of strain

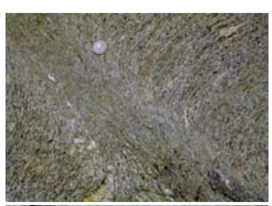
shear zones: offset markers



marker shows gradual deflection

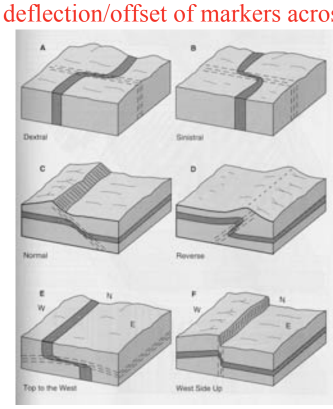
marker shows discrete offset

from: Davis and Reynolds, 1996



from: http://www.leeds.ac.uk/learnstructure/index.htm

deflection/offset of markers across shear zones

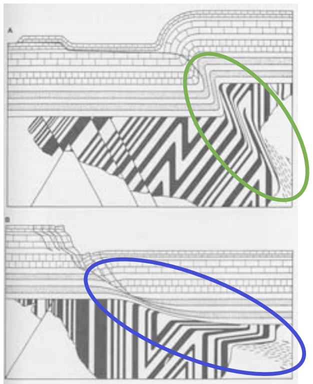


sense of shear

similar terminology to faults

> for subhorizontal to variably dipping shear zones--may specify motion of hanging walls--"top to the west"

from: Davis and Reynolds, 1996



relationship of shear zones at depth to faults near surface

thrust displacement

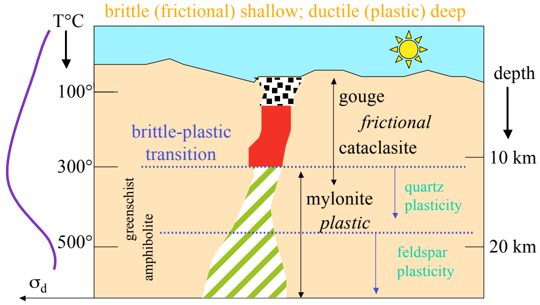
normal displacement

from: Davis and Reynolds, 1996

what does change from brittle to ductile reflect?

consider a fault from surface to depth

brittle (frictional) shallow; ductile (plastic) deep



relative crustal strength curve

fault rock

deformation mode

what is mylonite?

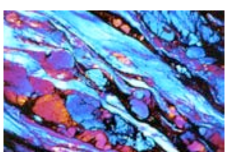
shear zone rock with crystallographic preferred fabrics

marble mylonite and quartz mylonite form at lower temperatures

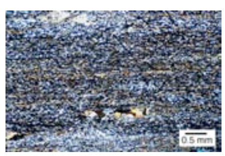
- dynamic recrystallization of calcite > 250°C
- dynamic recrystallization of quartz > 300°C

feldspar mylonites form at higher temperatures

- dynamic recrystallization of feldspar > 450°C



from: http://www.rci.rutgers.edu/~geolweb/slides.html



from: http://www.geolab.unc.edu/Petunia/lgMetAtlas/meta-micro

types of mylonites

protomylonite: matrix is < 50% of rock
ultramylonite: matrix is 90-100% of rock

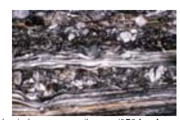
rocks with 50-90% matrix simply called mylonites

http://uts.cc.utexas.edu/~rmr/images

protomylonite

http://www.geo.umn.edu/teaching/microstructure/images/079.html

ultramylonite



mylonite

types of shear zones

shear zones form under many different conditions and in many different rock types

brittle deformation mechanisms:

--cooler temperature, lower pressure, faster strain rate, higher fluid pressure

ductile deformation mechanisms

--higher temperature, higher pressure, slower strain rate, lower fluid pressure

transition from brittle to ductile depends on rock type

…gypsum/halite deform ductilely when quartz/feldspar are brittle…

- "brittle" shear zones
- ductile shear zones
- semibrittle shear zones
- brittle-ductile shear zones

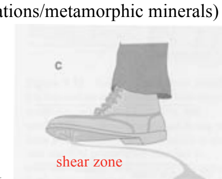
brittle shear zones

- form in shallow crust: 5-10 km depth
- reflect rapid strain rates (i.e. those during seismic events)
- contain closely spaced faults; brecciation; gouge

brittle shear zones are essentially fault zones

ductile shear zones

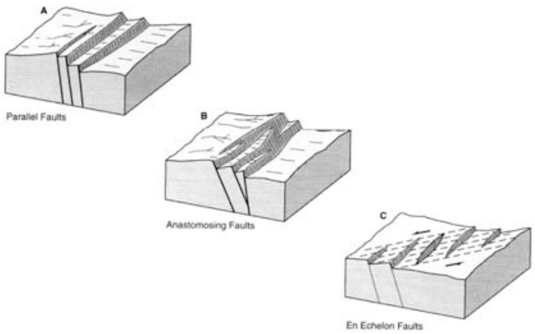
- form by shearing under ductile conditions (mid-lower crust)
- occur where temperature and pressures are high
- contain metamorphic rocks (foliations/metamorphic minerals)
  …e.g. mylonites…
- have no discrete physical break (markers do not lose continuity …gum after you step on it)



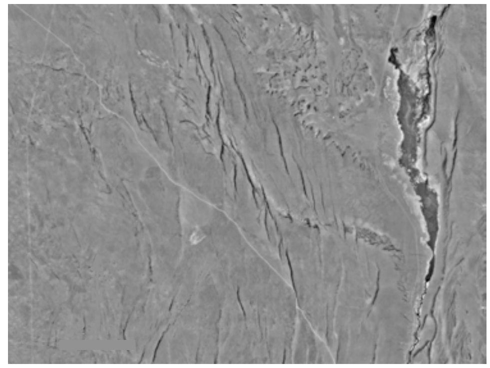
from: Davis and Reynolds, 1996

brittle shear zones

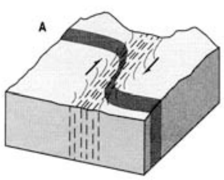
faults: parallel, anastomosing, en-echelon



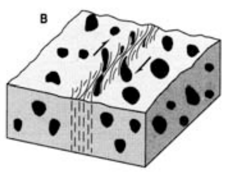
example: aerial photograph of volcanic tablelands



ductile shear zones



markers



xenoliths/plutons

example: sheared xenoliths

"hybrid" behavior:

brittle-ductile shear zones

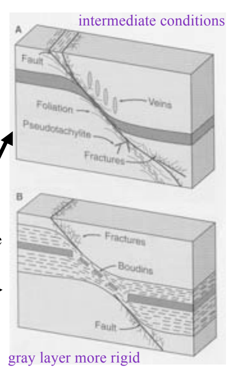
may have:

- mylonitic foliation
- boudins
- porphyroclasts
- tectonite matrix
- microfaults
- microbreccia/cataclasite

form when

- physical conditions allow brittle and ductile deformation at same time (A)
- different parts of rock have different mechanical properties (B)
- shear zone "strain hardens"
- short-term changes in physical conditions (i.e. strain rate) occur
- shear zone reactivates

intermediate conditions



gray layer more rigid

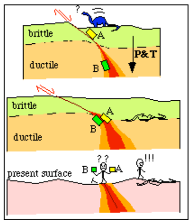
from: Davis and Reynolds, 1996

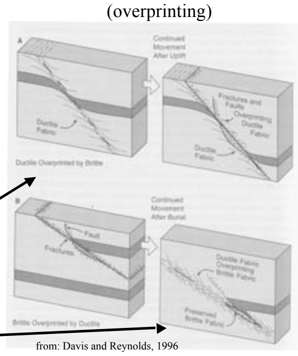
example: brittle-ductile shear zone

- brittle deformation - feldspar crystals
- ductile deformation - groundmass

brittle-ductile shear zones

may reflect changing conditions *such as uplift or burial* (overprinting)





--overprinting of ductile by brittle is easier to recognize …faults cut ductile feature…

--overprinting of brittle by ductile is harder to recognize …brittle structures may be "healed" by ductile processes

from: Davis and Reynolds, 1996

re-cap of controls on brittle vs. ductile deformation

	Brittle	Ductile
Temperature	Cooler	Hotter
Pressure	Lower	Higher
Strain Rate	Higher	Lower
Fluid Pressure	Lower	Higher

• mineralogy and grain size also important

why do shear zones form, thin, and thicken?

…formation requires concentration of deformation in thin zone

"softening" must occur processes in ductile shear zones

easier to deform rocks within zone

--grain size reduction
…localization of shear in finest rocks

--geometric softening
…preferred orientation of grains for slip

--reaction softening
…formation of new minerals (e.g. micas) that deform more easily

--fluid-related softening
…dissolution of grains that resist ductile deformation
…changing dominant deformation mechanism

--temperature softening (shear zone is hotter)

many shear zones are wide--why?

…e.g. shear zones with large displacements generally are wider than those with small displacements…

what happens?

for shear zones to broaden (thicken) during deformation, …it must be easier to deform rocks on boundaries of zone than it is to deform rocks in the zone

shear zone must undergo strain hardening

strain hardening: deformed grains can no longer deform (crystal lattices cannot adjust)

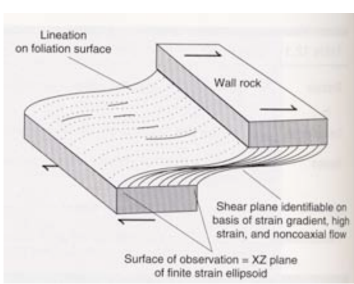
identifying sense of shear: shear-sense indicators

optimal surfaces are those *perpendicular* to shear zone boundaries

1) determine orientation of shear zone

2) find perpendicular (profile) plane

3) identify line of transport …direction along which relative displacement occurred… *(in perpendicular plane)*



perpendicular plane is sense-of-shear plane (SOS)

from van der Pluijm and Marshak, 1997

shear zone indicators: what are they?

• offset markers
• foliations
• S-C fabrics
• pressure shadows
• grain-tail complexes
• disrupted grains (mica fish)
• veins

shear zone indicators: offset markers

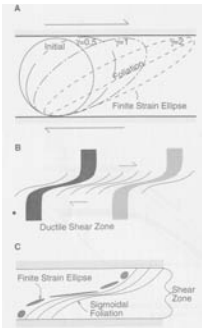
usually obvious
…make sure features on both are the same

from: http://www.leeds.ac.uk/learnstructure/index.htm

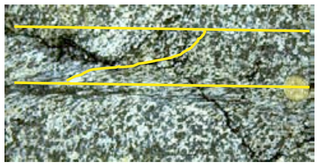
shear zone indicators: foliations

systematic variations in orientation across shear zone…

…reflects S_1S_2 (XY) plane of finite strain ellipsoid (simple shear)…



- leans in sense of shear direction
- sigmoidal pattern across shear zone
  (amount of shear increases to center)
- subparallel to shear zone boundaries in center of shear zone
  (shear highest in center)



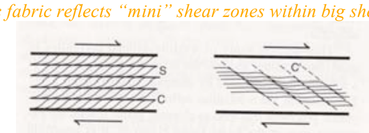
shear zone indicators: s-c fabrics

most shear zones have one foliation at angle < 45° to boundary;
this foliation is s-foliation (schistosité from French);
…crystal-plastic processes elongate crystals to extension

another foliation parallels shear zone boundaries;
this foliation is c-foliation (cisaillement from French);
…shear direction is within c plane

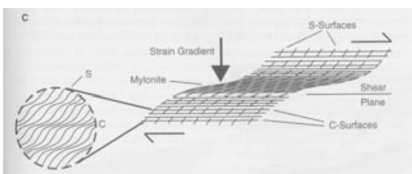
a third foliation may occur oriented oblique to boundary;
this foliation is c'-foliation and crenulates mylonitic foliation;
…shear bands…

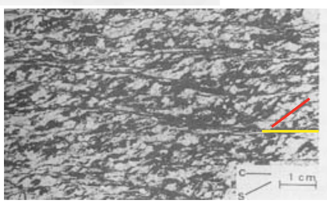
s-c fabric reflects "mini" shear zones within big shear zone



from van der Pluijm and Marshak, 1997

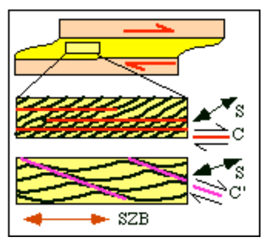
S-C pattern is similar to that for foliation in shear zone as a whole

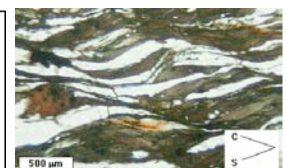


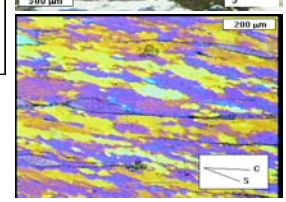


from: Davis and Reynolds, 1996

shear zone indicators: s-c fabrics



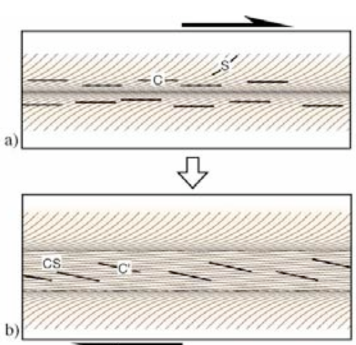




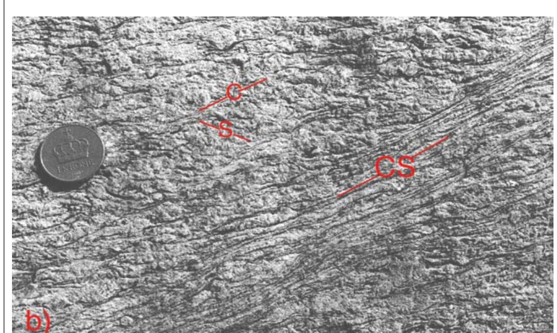
- s points in direction of shear
- c parallels shear direction
- c' displacement same as that of shear zone

from: http://www.earth.monash.edu.au/Teaching/mscourse

shear zone indicators: s-c fabrics



shear zone indicators: s-c fabrics

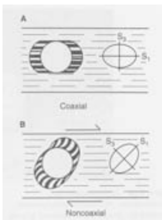


shear zone indicators: pressure shadows

form on flanks of rigid inclusions in shear zones
…rigid inclusion shields matrix on flanks from strain…
…crystallization of quartz, calcite, chlorite, etc.

most pressure shadows are microscopic--see in thin-section

growth accompanies each increment of extension



from: Davis and Reynolds, 1996

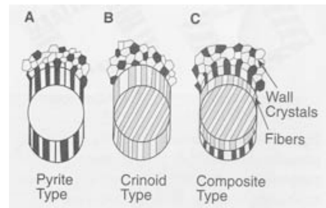
orientation of fibers depends on
coaxial
versus
noncoaxial (rotational)
strain

shear zone indicators: types of pressure shadows

pyrite: material mineralogically same as matrix
but different from inclusion
…fibers grow in crystallographic continuity with matrix

crinoid: material similar to inclusion not matrix
…fibers grow in crystallographic continuity with inclusion

composite: aspects of both



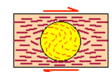
from: Davis and Reynolds, 1996

shear zone indicators: pressure shadow example

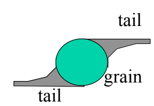
shear zone indicators: grain tail complexes

grains in matrix may have tails that form during deformation
…tails are distinguishable from matrix

…grains may be
…inclusions
…porphyroclasts (relics from protolith)
…porphyroblasts (grow during deformation)



…tails may be..
..attenuated, preexisting minerals
..dynamic recrystallization at grain rim
..synkinematic metamorphic reactions

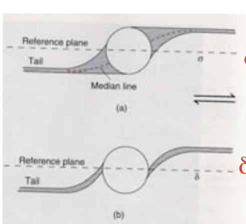


*grains are rigid bodies that **rotate** during deformation*
…tails give sense of displacement…

to use grain-tail complexes to indicate shear-sense,
need reference frame…relative to shear zone foliation..
…two "winged" types of tails: σ-type and δ-type

grain tail complexes: σ-type and δ-type

reference plane is shear zone foliation



from van der Pluijm and Marshak, 1997

σ wedge-shaped tails that do not cross reference plane when tracing tail away from grain; *looks like σ*

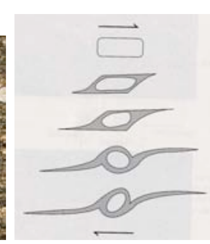
δ tails wrap around grain so they cross-cut reference plane when tracing tail away from grain; *looks like δ when rotated*

right-lateral (dextral) shear: clockwise rotation
left-lateral (sinistral) shear: counter-clockwise rotation

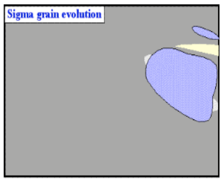
grain tail complexes: σ-type and δ-type

relationship between rate of crystallization and rotation of grain
…formation fast relative to rotation: σ-type
…rotation fast relative to formation: δ-type
(tail dragged and wrapped around grain)

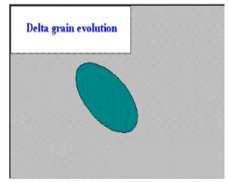
http://www.geo.umn.edu/teaching/microstructure/images/079.html



from van der Pluijm and Marshak, 1997

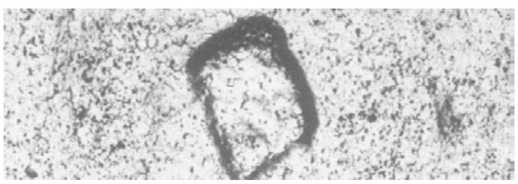


from: Structural Analysis, CD-ROM, DePaor



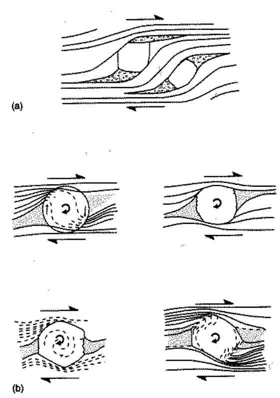
from: Structural Analysis, CD-ROM, DePaor

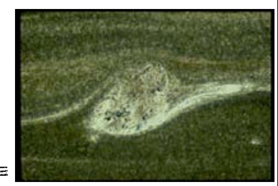
another animation…

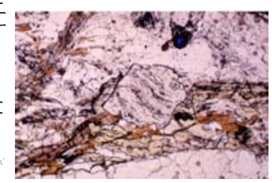


formation of grain-tale complex

animation from Allmendinger: http://www.geo.cornell.edu/geology/classes/RWA/GS_326/GEOL326.html#aa40

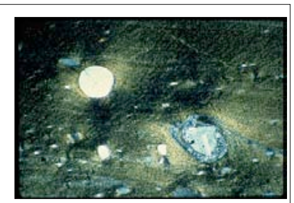


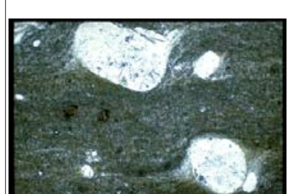


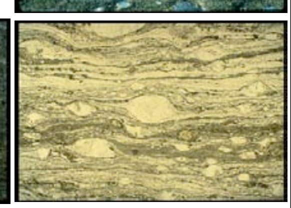


examples

determine:
type and sense of shear





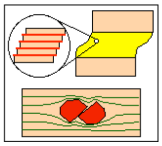


from: Simpson, Microstructures CD-ROM

shear zone indicators: disrupted grains

minerals may deform by fracturing (e.g. feldspar;quartz)

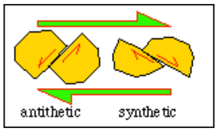
examine orientation of fractures relative to shear zone foliation

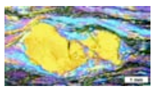


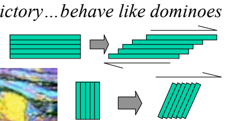
fracture < 45° to foliation: synthetic
displacement consistent with shear

fracture > 45° to foliation: antithetic
displacement opposite to shear

not contradictory…behave like dominoes







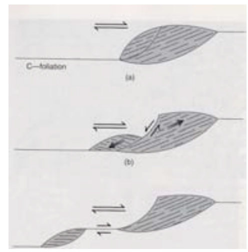
dominoes (tiling)

from: http://www.earth.monash.edu.au/Teaching/mscourse

shear zone indicators: mica fish

phyllosilicate grains (micas) connected by mylonitic foliation
…basal planes oriented at oblique angle to foliation…

grains have stair-step geometry in direction of shear

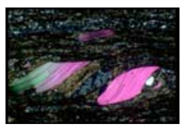


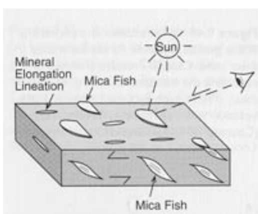
when large enough to see
in hand specimen,
…look like scales on a fish
("mica fish")

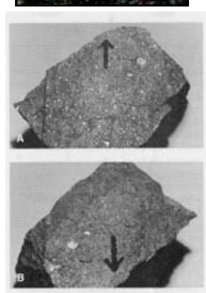
from van der Pluijm and Marshak, 1997

from: Simpson, Microstructures CD-ROM

asymmetry of mica fish gives shear
observe reflections in sunlight…
…fish flash…



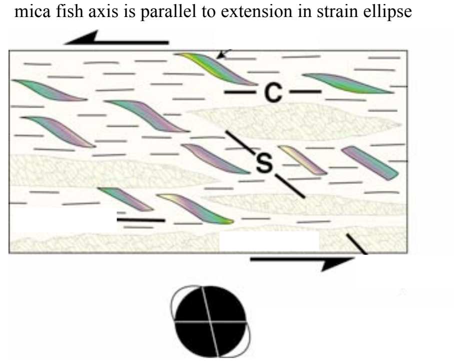




- mark north arrow on sample
- put back to sun and sample in front of you
- view parallel to lineation
- tilt sample
- note if flashy or dull

shear zone indicators: mica fish, s-c fabric, strain

mica fish axis is parallel to extension in strain ellipse

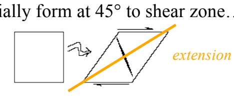


shear zone indicators: sigmoidal veins

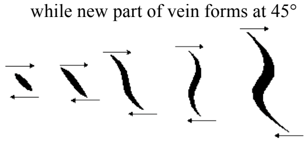
veins commonly associated with shear zones

…form perpendicular to *instantaneous extension*…

- initially form at 45° to shear zone…



- subsequently rotate to steeper angle
  while new part of vein forms at 45°

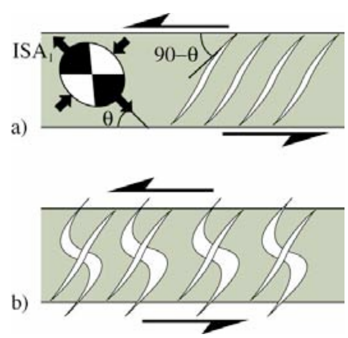


--foliations form perpendicular to instantaneous shortening--

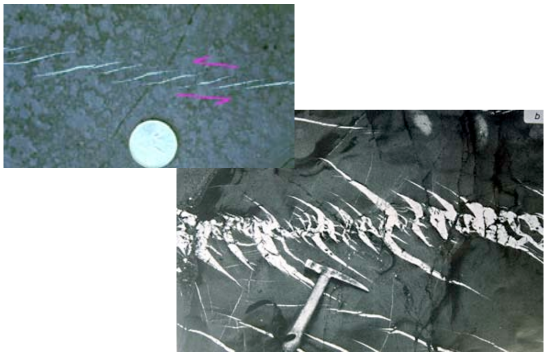
thus, veins and foliations will be perpendicular to each other in shear zone

shear zone indicators: sigmoidal veins

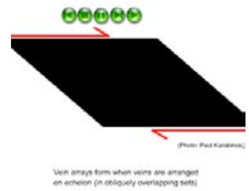
overprinting of early set (sigmoidal) by later



shear zone indicators: sigmoidal veins examples



from: http://www.science.ubc.ca/~eosweb/slidesets/keck



from: Structural Analysis, CD-ROM, DePaor