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/macourse
http://www.geolab.unc.edu/Petunia/IntroGeo/met_microimages_dir
http://uts.cc.utexas.edu/~rmr/images
http://www.stmarys.ca/academic/science/geology/structural
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

Ductile shear zones are longer and wider than they are thick …largest are hundreds 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

Continuous shear zone: marker shows gradual deflection

Discontinuous shear zone: marker shows discrete offset

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”
relationship of shear zones at depth to faults near surface

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

what does change from brittle to ductile reflect?

consider a fault from surface to depth

brittle (frictional) shallow; ductile (plastic) deep

brittle-plastic transition

gouge

frictional cataclasite

mylonite plastic

quartz plasticity

feldspar plasticity

depth

10 km

20 km

relative crustal strength curve

fault rock deformation mode

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

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)

shear zone rock with crystallographic preferred fabrics

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types of mylonites

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

rocks with 50-90% matrix simply called mylonites

brittle shear zones
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brittle shear zones are essentially fault zones

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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

from: Davis and Reynolds, 1996
brittle shear zones

faults: parallel, anastomosing, en-echelon

example: aerial photograph of volcanic tablelands

ductile shear zones

markers

gxenoliths/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

example: brittle-ductile shear zone

- brittle deformation - feldspar crystals
- ductile deformation - groundmass

from: Davis and Reynolds, 1996
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

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)

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

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)

re-cap of controls on brittle vs. ductile deformation

<table>
<thead>
<tr>
<th></th>
<th>Brittle</th>
<th>Ductile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Cooler</td>
<td>Hotter</td>
</tr>
<tr>
<td>Pressure</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Strain Rate</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Fluid Pressure</td>
<td>Lower</td>
<td>Higher</td>
</tr>
</tbody>
</table>

• mineralogy and grain size also important
shear zone indicators: foliations

systematic variations in orientation across shear zone…
…reflects $S_{1}S_{2}$ (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

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

shear zone indicators: s-c fabrics

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

shear zone indicators: s-c fabrics

shear zone indicators: s-c fabrics

from: Davis and Reynolds, 1996
from: http://www.earth.monash.edu.au/Teaching/mscourse
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

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

shear zone indicators: pressure shadow example
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: \( \sigma \)-type and \( \delta \)-type

shear zone indicators: grain tail complexes
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formation of grain-tale complex

animation from Allmendinger: http://www.geo.cornell.edu/geology/classes/RWAA15_126/GEOL126.html#aa40

another animation...


determine:
  type and sense of shear

examples
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)

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")

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
mica fish axis is parallel to extension in strain ellipse
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

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

Source: Structural Analysis, CD-ROM, DePaor