Main Topics

• Planar geologic structures (mostly fractures)
• Folds
• Fabrics: grain-scale structure

Main Theme

• Geometry, kinematics, and mechanics essential for how we understand geologic structures
Planar Geologic Structures

- Geologists classify fractures based on kinematics (i.e., by the relative displacement of points that were originally neighbors on opposing faces of a fracture), not by genesis or geometry.

Joints

Relative displacement is perpendicular to fracture walls
Joints near French Lake (~400m), Sierra Nevada, California

Fractures commonly occur in parallel sets and impart anisotropy (directional variability) to rocks.

Sheeting Joints
Shuteye Peak, CA (from Huber)
Water Weeping From Sheeting Joints

Exceedingly important in crustal mechanics and fluid flow

Dikes
Opening Mode fractures
Dikes:
Opening Mode Fractures

- Geometry
- Thin relative to their in-plane dimensions (~1:1000+)
- Bounded in extent
- Grossly planar (usually)

Dikes
Opening Mode fractures

Dike traces have ends

[Diagram of dike traces with ends and explanation of opening mode fractures]
Planar Geologic Structures

- A fracture is classified according to its kinematics (i.e., by the relative displacement of points that were originally neighbors on opposing faces of a fracture) and not by genesis or geometry.

Faults: Shearing Mode Fractures

- Relative displacement parallels fault
- Geometry
  - Thin relative to their in-plane dimensions (~1:1000+)
  - Bounded in extent
  - Grossly planar (usually)
Geologic Classification of Faults

• Based on orientation of slip vector (vector joining offset neighboring points) relative to the strike and dip of a fault

Strike-slip Fault

• Slip vector is predominantly horizontal (i.e., parallel or anti-parallel to the line of strike)
• Right lateral: in map view across a fault, a marker is offset to the right
• Left lateral: in map view across a fault, a marker is offset to the left
Dip-slip Fault

- Slip vector is parallel (or anti-parallel) to dip
- 1: hanging wall ("upper face" moves down relative to footwall ("lower face")
- 2: **Thrust fault:** hanging wall moves up relative to footwall

![Dip-slip Fault Image](http://volcanoes.usgs.gov/imgs/Jpg/Photoglossary/fault1_large.jpg)

Normal Faults

Hanging wall ("upper face" moves down relative to footwall ("lower face")

![Normal Faults Images](http://volcanoes.usgs.gov/images/glossary/fault.php)
Thrust Fault

Hanging wall moves up relative to footwall

http://www.pitt.edu/~cejones/GeoImages/7Structures/ReverseFaults/AbnormalReverseFaultSml.jpg

Dike Intruded Along a Fault

Relative displacement is perpendicular to fracture walls
Oblique-slip Fault

Combination of strike slip and dip slip

http://upload.wikimedia.org/wikipedia/commons/0/0a/Oblique_slip_fault.jpg

Slip vs. Separation

Contrast between slip and separation

After slip, Before erosion

After slip, After erosion

After driveway removal, After new home construction
Planar Geologic Structures

- A fracture is classified according to its kinematics (i.e., by the relative displacement of points that were originally neighbors on opposing faces of a fracture) and not by genesis or geometry.

Shear Zones

- Thin structures across which deformation is continuous and relative displacement parallels the structure
- Rock within shear zones commonly is foliated
- Common in plutonic & metamorphic rocks
Shear zone Between Two Faults

Most faults are probably surrounded by annular shear zones
Fracturing Along Strike-slip Faults

Conceptual Model of Secondary Fracturing in Three Dimensions Around a Small Fault
Formation of Faults

Area of active research, but faults commonly exploit pre-existing weaknesses (e.g., bedding, joints, and dikes)

Fault and Joint, Sierra Nevada, CA
Map of Faults and Joints, Sierra Nevada, CA

Folds

- Surfaces which have experienced, at least locally, a change in their normal curvature (rate at which a unit tangent or a unit normal to a surface changes with respect to distance along a surface)

http://jupiter.ethz.ch/~kausb/Crete_folds.jpg
Folds

- Most readily identified in rocks that are layered or bound by parallel discontinuities; folds occur in all rocks, *including plutonic rocks*!
- Folding commonly causes bedding planes to slip
- Historical 2-D conceptualization of folds

Cylindrical Fold (2D)
2D Fold Classification Factors

- Direction of opening of a fold (i.e., direction of curvature vector)
- Relative curvature of inner and outer surfaces of a fold
- Axial surface orientation (axial surface connects points of tightest curvature)
- Fold axis orientation (fold can be "generated" by fold axis)

Common Fold: Syncline

- Youngest rocks in center of fold
- Usually "U-shaped" (i.e., they open down)

hgp://www.grossmont.edu/judd.curran/images/synclinePhoto.jpg
**Common Fold: Anticline**

![Anticline Image](http://rst.gsfc.nasa.gov/Sect5/OilAnticline.jpg)

Oldest rocks in center of fold
Usually "A-shaped" (i.e., they open down)

**Common Fold: Recumbent Fold**

![Recumbent Fold Image](http://en.wikipedia.org/wiki/File:Caledonian_orogeny_fold_in_King_Oscar_Fjord.jpg)

Anticline: Oldest rocks in center of fold
Syncline: Youngest rocks in center of fold
2D Fold Classification Factors

- Direction of opening of a fold (i.e., direction of curvature vector)
- Relative curvature of inner and outer surfaces of a fold
- Axial surface orientation (axial surface connects points of tightest curvature)
- Fold axis orientation (fold can be "generated" by fold axis)

2D Fold Classification Scheme
2D Fold Classification Factors

- Direction of opening of a fold (i.e., direction of curvature vector)
- Relative curvature of inner and outer surfaces of a fold
- Axial surface orientation (axial surface connects points of tightest curvature)
- Fold axis orientation (fold can be "generated" by fold axis)

Fold Terminology

- Axial surface orientation (axial surface connects points of tightest curvature)
Cylindrical Fold (2D)

- Fold axis: Line parallel to the surface of a cylindrical fold.

2D Fold Classification Scheme
2D Fold Classification Scheme

3-D Characterization of Folds

http://www.le.ac.uk/geology/wdc2/calcsilicate%203d%20folds.jpg
3-D Characterization of Folds

http://upload.wikimedia.org/wikipedia/commons/4/45/shar_pei_welpen.jpg

3-D Characterization of Folds

http://image.shutterstock.com/display_pic_with_logo/9916/9916,1122427430,2/stock-photo-wrinkled-cloth-450464.jpg
Curvature of a Plane Curve

- In global reference frame
  \[ k = \frac{\frac{d^2y}{dx^2}}{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2}} \]

- In local reference frame
  \[ k = \frac{d^2y}{dx^2} \]

Principal Curvatures of a Surface

- Matrix of 2nd partial derivatives of surface \( z \) in local reference frame
  \[
  k = \begin{bmatrix}
  \frac{\partial^2 z}{\partial x^2} & \frac{\partial^2 z}{\partial x \partial y} \\
  \frac{\partial^2 z}{\partial y \partial x} & \frac{\partial^2 z}{\partial y^2}
  \end{bmatrix}
  \]

- Matrix of 2nd partial derivatives of surface \( z \) in principal local frame
  \[
  k = \begin{bmatrix}
  \frac{\partial^2 z}{\partial x^2} & \frac{\partial^2 z}{\partial x \partial y} \\
  \frac{\partial^2 z}{\partial y \partial x} & \frac{\partial^2 z}{\partial y^2}
  \end{bmatrix}
  \begin{bmatrix}
  k_1 & 0 \\
  0 & k_2
  \end{bmatrix}
  \]
3D Fold Classification Scheme of Lisle and Toimil (2007)

Fold Classification Scheme of Lisle and Toimil (2007)

3D Fold Classification Scheme of Mynat et al. (2007)

Fold Classification Scheme of Mynat et al. (2007)
Folding Along Faults

From Grasemann et al., 2005

Folding Along Faults

From Martel and Langley, 2005
“Fault” in Foam Rubber, Before Slip

“Fault” in Foam Rubber, After Slip
Other Mechanisms for Folding

Flexure over intrusions

From lateral shortening

GK Gilbert’s first sketch of a laccolith

Experimental device of Bailey Willis

Fabrics

- **Grain-scale structure** (metamorphic rocks & igneous rocks)
- **Foliation**: preferred alignment of minerals (e.g., mica) parallel to a plane;
- **Lineation**: preferred alignment of minerals parallel to a line;
Fabrics
Grain-scale Structure

- Foliation: preferred alignment of minerals (e.g., mica) parallel to a plane

- Lineation: preferred alignment of minerals parallel to a line
Mechanisms for Fabric Development

• Strain
  – Flattening
  – Stretching

• Rigid body rotation in a flow