Intro. to Brittle Deformation and Fractures

I. Introduction

A. Fractures = brittle rupture of rock medium in response to stress

1. Most common geologic structure;
2. cracks in rocks/minerals in which cohesion of material is lost.

B. Geological importance of fractures;

1. Conduits for fluids (water, gas, oil),

a. increase permeability,
b. avenues for enhanced weathering,
c. influence fluid flow to wells,
d. Serve as planes of weakness for construction/mining
(1) "hydrofracing" in petroleum/groundwater industry
e. Increase risk of slope failure/rock slides

C. Terminology

1. joints: cracks in rock in which no appreciable displacement has occurred
2. faults: cracks in rock in which appreciable displcacement has occurred

D. Types of fractures

1. Extensional Fractures

a. Mode 1=extensional fracture where relative motion is perp. to fracture plane,

(1) known as joints, gashes, veins.
(2) Fracture planes are parallel to maximum force.

2. Shear Fractures: relative motion parallel to fracture plane (i.e. faults)

a. Mode 2=slides perp. to edge of fracture = Strike Slip

(1) motion parallel to strike of fracture plane

b. Mode 3=slides parallel to edge of fracture = Dip-Slip

(1) motion parallel to dip of fracture plane

c. Oblique extension fracture or mixed mode fracture

(1) Hybrid between Modes 2 and 3

E. Methods of Observation and Analysis

1. Distribution of geometry of fracture system
2. surface morphology of fractures
3. Cross-cutting relations between fractures
4. Geometric relationship between fractures and other structures

II. Joints: Mode I Fractures

A. Joints Defined

1. unfilled mesoscopic fractures exhibiting no evidence of shear
   a. Most common structural element at every outcrop.
   b. Commonly joints form before faults which are later reactivated in shear.
   c. In sedimentary rocks most joints are vertical or bed normal,

B. Geometry of Natural Mode I Fractures

1. Joint Types: Terminology

   a. Joint Set: adjacent fractures of similar geometry
      (1) strike orientation and dip

   b. Joint System

      (1) two or more joint sets affecting the same body of rock

   c. Systematic and nonsystematic joints
      (1) Systematic joints
         (a) planar
         (b) parallel
         (c) regular spacing
      (2) Non-systematic joints
         (a) "curvy cross-joints"
         (b) curviplanar, irregular in geometry
         (c) irregular spacing
         (d) commonly abut against older fractures

   d. Sheet joints/Exfoliation joints
      (1) curved extension fractures
      (2) "release" fractures due to removal of overburden via erosion
      (3) subparallel to topographic form
      (4) exfoliation domes: onion-like appearance due to sheeting joints

   e. Columnar joints
      (1) vertical fractures that form hexagonal or pentagonal forms
      (2) form from cooling of igneous bodies/shrinkage

f. Veins
   (1) mineral filled fractures
      (a) calcite, quartz fillings most common

g. Gash joints
   (1) en echelon organization
   (2) commonly mineral filled
   (3) may be S or Z shaped
   (4) commonly form in response to shear motion

h. Pinnate Fractures
   (1) secondary fractures form in response to shear along fault planes
   (2) form acute angles with fault
   (3) show relative shear sense of fault motion

III. Geometry of Mode I Fracture Systems in Three Dimensions (Geometric Analysis)

A. Orientation of Fractures

1. Strike and dip measurements
2. Joint Sets: Fractures of similar orientation in space
   a. Must. I.D. sets in field
3. Joint orientation vs. Lithology
   a. mechanical properties of varying lithology can result in deviation of fracture orientation in uniform stress field
4. Problem: curving fractures
   a. if fracture not planar, must take care in measuring and interpreting orientation of "curvy cross joints".

B. Scale and Shape of Fractures

1. Lateral and vertical extent of fracture
   a. vertical terminations at bed contacts? or through-going?
   b. lateral extent
2. Nature of fracture termination (shape)
   a. branching
   b. en echelon
   c. curving/overlap

3. Scale of fracture
a. megascopic
b. mesoscopic
c. microscopic

C. Spacing of Fractures

1. Distance between fractures of a given set, measured perpendicular to the fracture surface

2. Known Controls

a. systematic vs. nonsystematic
(1) systematic = regular spacing
(2) nonsystematic = irregular spacing
b. Bed Thickness in Layered Rock
(1) As Bed Thickness >, Fracture spacing > logrithmically (and vice versa)

c. Lithology
(1) Rheologic properties of rock will affect fracture spacing
(a) e.g. coal vs. shale

D. Spatial Pattern and Distribution of Fracture Systems
1. Map plots of fracture orientation (strike and dip)
a. Relation to other structure
(1) bedding attitude
(2) folds, faults

2. Form Line Map
a. Plot fracture orientation at individual outcrop locations
b. extend lines between data points to created a continuous "form line"
(1) allows greater visual recognition of patterns in map view over large areas

IV. Features of Mode I Fracture Surfaces

A. "Fractography" - analysis of morphology on the surface of fractures

1. Plumose Markings or Hackle Plume

a. Hackle- regular pattern of subtle ridges and grooves on surface of fracture
(1) commonly shows radiating pattern from a point or central axis
(2) Most commonly displayed on fine-grained lithologies (mudstone, chalk)
(a) hard to find on coarse sandstone

b. Rib Marks

(1) ripple shaped ridges that form transverse to hackle lines

c. Hackle Markings and Fracture Propagation

(1) Plumose structure = distinct evidence of mode I extension
(2) plumose structure forms in response to rapid fracture propagation upon cracking
(3) the direction of divergence of the hackle plume points in the direction of propagation
(4) Rib Marks = arrest lines, where fracture propagation temporarily halted.

d. Slickenside Lineations or "Slickenlines"

(1) Grooved striations that form on fracture surface in response to shear
    (a) result from abrasive/polishing action of crushed rock caught in shear zone
    (b) distinct evidence that fractures are either of Mode II or Mode III origin

e. Mineralized fracture surfaces (calcite, quartz commonly)

(1) Suggest fluids driving force of rock fracture
(2) fracture served as fluid conduit

V. Abutting Relations / Cross-cutting Relations

A. Fracture termination against another fracture

1. first-formed fracture through-going
2. second-formed fracture propagates to first fracture and stops due to break in mechanical properties of the rock

B. Fractures that cut through one another

1. timing ambiguous
2. fracture 1 may have been cemented allowing fracture 2 to propagate through

C. Law of Cross-cutting Relations (relative timing)

1. If structure A cross-cuts another structure B, then structure A must be younger

    a. e.g. mineralization on fracture surface implies that the fracture must have been present first
    b. fractures that cut an igneous intrusion, must have formed after the

igneous intrusion

c. igneous intrusions found along fracture planes, must have occurred after the fracturing

VI. Relationships of Mode I Fractures to Other Structures

A. Subsidiary fractures associated with faults

1. Conjugate shear fractures

a. Mode III fractures that form in response to secondary shear along a larger scale fault system

b. classic pattern: two fracture sets oriented at ~60 degrees with respect to one another

(1) 60-65° between fractures, one set of which is parallel to fault

(2) form by shear/sliding and cracking of rock

2. Gash fractures, pinnate fractures = Mode I secondary fractures associated with larger scale faulting

a. pinnate fractures: en echelon arrays along a shear fracture

(1) acute angle points in the direction of relative motion of block containing fract.

B. Mode I fractures associated with folds

1. Commonly find mode I fractures in association with folded rocks

a. Transverse fractures or "dip fractures"

(1) strike of fracture cross-cut the fold axis, or is oriented parallel to the dip direction of the fold limbs

b. Fold-parallel or "strike fractures"

(1) strike of fracture is parallel to the fold axis, or is parallel to the strike direction of the fold limbs

VII. Intro to Fracture Mechanics

A. Mechanics:

1. fracture planes will strike parallel to maximum force of compression

a. Tensile stress forms at right angles to maximum compression resulting in Mode I fracture

(1) absolute tension (dry)
 (a) very rare in tectonic/lithospheric environment

(2) Relative internal tension
 (a) burial compression with pore fluids
 (b) primary driving process for fractures?

B. Visualization of Crack Propagation
 1. Initial Crack = Penny shape

 a. Fracture propagation until crack tip hits bedding plane or other mechanical boundary

 (1) Bedding planes serve as vertical limiting factors
 (2) Crack will be forced to grow horizontally.

VIII. Summary: Outcrop Characterization of Fractures

A. Lithology
 1. Rheologic property of beds (e.g. shale vs. limestone vs. sandstone)
B. Joint characterisation
 1. Type: systematic vs. non-systematic
 2. orientation: strike and dip
 a. correlation of joints and shear fractures with other structures
C. shape
 1. Implications for mechanics
 a. joints prop. normal to least principal stress
D. Fracture height, outcrop length
 1. controlled by bed thickness
E. Fracture spacing perpendicular to surface
 1. proportional to bed thickness, thicker=greater spacing
F. Aperture width dimensions of fracture opening
G. Cross-cutting / abutting relationships
 1. Secondary joints will abut and terminate against earlier-formed fractures
H. Fractography: details of surface morphology of fracture
 1. plumose morphology, hackle geometry
 2. <u>Recracking</u> - reactivating a rupture after it has come to a complete halt, which forms arrest lines.
 a. Process indicates that stress magnitudes change with time. forms plumose surfaces.
I. <u>Crack and seal veins</u> : hydraulic fracturing by episodic build up of fluid pressure in excess of tensile strength of vein or host rock).
 1. Vein mineral composition (calcite, quartz)
J. <u>En echelon cracks</u>
 1. commonly form in shear zones that are oriented 10-45 degrees from the vein trace
K. <u>Pinnate joints</u>, large scale versions of microcracks (feather fractures) forming an

acute angle with the fault zone. Apex of acute angle is direction of shear.

IX. Summary of Fracture Discussion

A. Fractures are ubiquitous geologic features, and are significant to many processes in the geologic environment

B. Fracture identification and analysis is essential for geometric models and can be useful for kinematic and mechanical models if systematic.

C. The first step in this process is to construct accurate geometric models by compiling surface and subsurface data into maps, cross sections and stereographs.

D. The overall objective of structural analysis is to restore deformed materials to original state.