I. Basic Concepts

A. Strain Defined

1. Strain = deformation of material in response to stress

a. deformation = change in size and shape

(1) change in length, diameter, volume of material

b. Extensional Strain = lengthening/stretching
c. Compressional Strain = shortening/flattening
d. Rotational vs. nonrotational strain

B. Types of Strain

1. Homogeneous: changes in size and shape are proportionately identical from smaller scale to larger scale in rock body

a. planar surfaces remain planar after deformation
b. lines remain straight
c. parallel lines remain parallel

2. Inhomogeneous: changes in size and shape vary from place to place in rock body

a. straight lines become curved
b. planes become curved
c. parallel lines are not parallel after deformation

d. Example Folding:

(1) On large scale: inhomogeneous ductile deformation

(2) On small scale: homogeneous strain

C. Other Terms and Concepts of Strain

1. Progressive Deformation: time series of motion that carries body from undeformed state to final deformed state

a. strain path: steps or path of progressive deformation

b. strain state: any given instant of strain, final strain state yields no information about strain path

2. 3-D strain: examination of shape/size changes in 3-dimensions

3. Plane Strain: examination of shape/size changes in 2-dimensions

4. Material objects used to identify strain

a. bedding planes
b. fossils, oolites, nodules

II. Measures of Strain

A. Linear Strain (change in length during deformation, strain in 1-dimension)

1. volume of material: measure of size of material, that may be subject to change during strain

a. volume of cube = l x l x l (e.g. cu. cm)

2. Stretching: measure of ratio deformed length (L2) to original length (L1)

$Sn = L2/L1$

3. Extension: measure of ratio of change in length (dL) to original length (L1)

$e = dL/L1 = (L2-L1)/L1 = Sn - 1$

a. Positive value of extension = lengthening
b. negative value of extension = shortening

B. Volumetric Strain (change in volume during deformation, i.e. change in length in 3-D)

1. volumetric stretch: $Sv = v2/V1$

2. volumetric extension: $Ev= dV/V1 = (V2-V1)/V1 = Sv-1$

C. Shear Strain: change in shape without change in volume

1. e.g. deformation of cube into rhombohedron, or sphere into ellipsoid

2. Measured by changes in internal angle of axis of volume

III. Strain Ellipse

A. Strain Ellipse Defined (2-dimensions)

1. Convenient to imagine a circle being deformed into an ellipse in 2-D.

a. consider example of compression with sigma1 > sigma3
b. diameter of circle shortened parallel to sigma1
c. diameter of circle lengthened parallel to sigma3

B. Strain Ellipsoid (3-dimensions)

1. similar to strain ellipse only in 3-D, with a sphere deformed into an ellipsoid

C. Principal Axes of Strain Ellipsoid

1. defined by three mutually perpendicular axes of strain ellipsoid

a. e1 >/= e2 >/= e3

(1) e1 = long axis of strain ellipsoid

(a) parallel to sigma3 of stress ellipse

(2) e2 = intermediate axis of strain ellipsoid

(a) parallel to sigma2 of stress ellipse

(3) e3 = shorth axis of strain ellipsoid

(a) parallel to sigma1 of stress ellipse

2. In 2-D commonly look at e1-e3 plane of strain ellipse

a. analysis of plane strain only

3. In deforming a sphere to an ellipsoid...

a. lengthening along e1
b. shortening along e3

D. Strain Markers

1. General technique, analyze geologic markers of known original shape, and compare to current strain state as found in outcrop

a. quantitatively derive strain ratios through geometric analysis

2. Types of strain markers commonly used in strain studies

a. Ooids (concentric carbonate spheres)
b. Radiolaria / Foraminifera (spherical microfossils)
c. Brachiopod fossils
d. spherical pebbles and cobbles
e. spherical chert nodules
f. mudcracks (Pinto, MD stop 1)

g. boudinage: result from stretching and lengthening parallel to layer

IV. Examples of Homogeneous Strain

A. Pure Strain

1. principal axes of strain maintain constant orientation

    a. e.g. pure shear
    b. uniform dilation
    c. simple flattening or extension

B. Uniform Dilation

1. Pure volumetric change with no change in shape of deforming body
    a. e.g. cube stretched by same value in all directions, results in cube with larger volume

C. Simple Extension

1. lengthening parallel to one of the axes of strain

D. Simple Flattening

1. shortening parallel to one of the axes of strain

E. Uniaxial Strain

1. 2 of principal strain axes remain equal and unchanged
2. 1 of the principal strain axes either lengthened or shortened.

F. Simple Shear vs. Pure Shear

1. Simple Shear Defined (rotational)

    a. rotation of principal strain axes
    b. e.g. plane square deformed into parallelogram
    c. no volume change, but change in shape

2. Pure Shear Defined (non-rotational)

    a. no rotation of principal strain axes
    b. simple volume change, no change in shape
    c. parallel lines remain parallel

V. Focus on Elastic Deformation

A. Types of Material Response to Stress

1. Elastic Deformation: deformation of body is recoverable upon removal of stress

2. Brittle Deformation: non-recoverable deformation through brittle fracture

    a. fracture occurs once elastic strength is exceeded

3. Plastic Deformation: non-recoverable, permanent ductile deformation

B. More on Elastic Deformation...

1. Elastic Deformation:
   a. stress and strain are in 1:1 relation
   b. as stress is removed, strain is diminished to 0

2. Extensional strain (uniaxial)

   a. e_n = dL/L1 = (L2-L1)/L1

3. Young's Modulus: relation of stress to strain under elastic deformation conditions

   a. Sigma = E(e_n) i.e. stress = E(strain)

where, Sigma = stress, E = Young's modulus, e_n = extensional strain

(1) E = young's modulus = stress/strain

(2) Young's modulus characterizes the elastic behavior of a given material

(a) compressive stress (+) produces shortening (-strain)

(b) Tensile stress (-) produces lengthening (+ strain)

(c) values of E: -0.5 EE5 to -1.5 EE5 MPa

4. Poisson Ratio

   a. Relations of compressible materials under uniaxial stress

(1) compressive stress applied to body

(a) shortening parallel to axial stress
(b) extension perpendicular to axial stress

   b. Poisson's Ratio: measure of ratio of extension normal to axial compressive stress to shortening parallel to axial compressive stress

(1) v = abs. value [e1/e2]

where v = poisson's ration, e1 = extension normal to axial compressive stress, e2 = shortening parallel to axial compressive stress

(a) v: for ideal isotropic elastic material = 0.5
(b) common v values in rocks: 0.25-0.33

VI. Observations of Strain in Deformed Rocks

A. General

1. Concepts of strain history and progressive deformation

a. Field relations: it is only possible to observe final strained state of rock as preserved in outcrop

(1) Must infer initial undeformed state

b. Strain history: unraveling the history of strain and deformation of rock bodies

(1) Progressive strain: motion of deforming particles in a rock body as a function of time

(a) incremental strain: defined increments of strain followed by periods of non-deformation

(b) continuous strain: strain ellipse defined for every instant of time

(2) Technique: reconstruct strain history using deformation fabrics in rocks

(a) cross-cutting relations
(b) radiometric dating where possible

(3) Field problems

(a) time as an eternal missing variable
(b) unknown original shape of geologic feature

i) remember: need to compare deformed state to original state to calculate strain

(c) Goal: find familiar geologic structures whose initial size and shape can be approximated, then compare to deformed state to calculate strain

B. Delineation Techniques for Plane Strain (2-D resolution)

1. Strain of circular geologic features

a. examples

(1) ooids, radiolaria, foraminifera
(2) crinoid discs, burrows
(3) flattened spherical pebbles

b. Needed: measure of large sample population and apply statistical techniques to account for inhomogeneous strain and methodology errors.

2. Strain of linear geologic features

   a. Examples

      (1) linear mineral crystals
         (a) tourmaline, amphibole, rutile

      (2) linear fossils
         (a) belemnites

      (3) Boudinage structures

3. Strain of polygonal geologic features

   a. example: flattened mud cracks, e.g. Pinto MD

4. Sheared orthogonal lines

   a. orthogonal = approximately perpendicular

   b. examples of perpendicular geologic lines

      (1) hinge line and symmetry line of brachiopod shells
      (2) body segments of trilobites