I. Introduction to Ductile Deformation

A. Ductile Deformation = "solid state flow"

1. Permanent, coherent solid-state deformation
2. no loss of cohesion at scale of mineral crystals
3. no evidence of brittle fracturing

a. e.g. glacial / ice deformation
b. metal rolling in steel plants

B. Ductile Characteristics

1. smoothly varying deformation
2. no evidence of discontinuities
3. no indication of discrete shear planes or fracture planes
4. excludes soft sediment deformation, since sediments are not yet consolidated in coherent state

C. General Process Conditions

1. Thermally activated process (Temps = 50% melting point)
2. deformation processes
    a. dislocations through crystal lattices
    b. solid-state diffusion (molecular transport)

D. Fold Deformation dramatic evidence of ductile deformation processes

II. Description of Folds

A. Introduction

1. folds: wave-like undulations of rock layers

a. Commonly result from ductile deformation of sedimentary strata

2. Fractal nature of folds

a. microscopic to mesoscopic to megascopic

3. Folds common to large-scale orogenic belts

a. Fold and thrust complexes

(1) Appalachian valley and ridge
(2) Canadian Rockies
(3) Himalaya
(4) Alps

b. Outer zone of orogenic belts = fold and thrust

c. Inner zone of orogenic belts

(1) > depths, > temperatures
(2) metamorphic mountain cores

4. Other occurrences of folds

   a. glacial ice
   b. salt dome complexes
   c. folded beds, veins, dikes, igneous complexes

5. Importance of folds

   a. traps for oil and gas
   b. influence deep hydrologic regime
   c. economic mineral accumulations
   d. record of tectonic process

B. Fold Geometries and Morphology

1. Single folded surface (e.g. bedding contact)

   a. crests and troughs of wave form
      (1) crest = convex up
      (2) trough = concave up
   b. Inflection line
      (1) Pt. of change in curvature from convex to concave
   c. Fold Train
      (1) series of folds of alternating curvature
         (a) alternating crests and troughs
      (2) Antiforms: convex up fold
      (3) Synforms: concave up fold
   d. Fold System
      (1) series of folds of similar geometry and common origin
   e. Curvature: measure of change in orientation per unit distance along fold structure

      (1) circle = constant radius of curvature
      (2) flat plane = 0 radius of curvature

   f. Hingeline or hinge: imaginary line connecting points of maximum curvature along a fold
      (1) hinge may be curved or straight
      (2) hinge may vary in magnitude of curvature

      (3) Hinge zone = vicinity of max. curvature

   g. Limbs of fold = regions of lowest curvature on folds

   h. Crest line: line connecting points of highest elevation on structure

   i. Trough line: line connecting points of lowest elevation on structure

(1) Culiminations: crest lines at max. el.
(2) Depressions: trough lines at min. el.

j. Fold Profile
(1) shape of fold examined in plane perpendicular to hinge line

k. Fold Types
(1) cylindrical folds: folds in which lines can be moved parallel to the fold surface without losing contact with the surface

(a) Fold Axis: unique, imaginary reference line of constant orientation that can be moved along the fold surface without losing contact with the surface

i) 0 degree angle between fold axis and any part of fold

(2) Non-cylindrical folds: do not possess fold axis

(a) essentially undulatory surfaces

2. Parts of Folded Layers and Multilayers

a. Multilayers: nested stack of two or more folded surfaces

(1) Inflection surfaces: planes connecting inflection lines on multiple fold levels
(2) Axial Plane: plane connecting mult-level hinge lines
(3) Axial Surface Trace: Axial surface intersects ground surface as a line.

b. Anticlines and Synclines

(1) Anticline: antiform structure with oldest rocks on concave side of fold

(2) Syncline: synform structure with youngest rocks on concave side of fold
(a) Overturned anticline = upside down “synformal” anticline
(b) Overturned syncline = upside down “antiformal” syncline

C. Fold Scale and Attitude

1. Components of scale

a. wavelength: crest to crest distance

(1) controls: commonly according to bed thickness
(a) > thickness, > wavelength
(b) < thickness, < wavelength

b. amplitude
   (1) median surface: line connecting inflexion points on fold
   (2) A = distance between crest or trough, and median surface (i.e. “height” of fold”)

2. Attitude of Folds: Descriptive Terminology

   a. Classification based on Axial Surface (axial plane if planar)
      (1) upright: axial plane vertical
      (2) steeply, mod., gently inclined: axial plane between horizontal and vertical
      (3) recumbent: axial plane horizontal

   b. Classif. based on plunge of hinge line
      (1) gently, mod., steeply plunging = inclined plunge
      (2) horizontal: plunge = 0 degrees
      (3) vertical plunge = 90 degrees
      (4) Doubly plunging fold: hinge line plunges in two directions

   c. Domes and Basins
      (1) Dome: antiformal, dome structure
      (2) Basin: synformal, bowl structure

   d. Other Terms
      (1) Homocline: uniformly dipping beds with no change in dip over a regional area
      (2) Monocline: fold pair with long limbs of similar dip, and a short step of increased dip
      (3) Overturned folds: one of the limbs of the fold is inverted upside down (stratigraphy inverted)

D. Elements of Fold Style (form description)

1. Measures of folding

   a. fold angle:
      (1) angle between two lines drawn perpendicular to inflection points of fold

   b. Interlimb angle
      (1) angle between two lines drawn as tangents to the inflections points of fold
      (2) angle < with increasing tightness of fold

2. Cylindricity
   a. measure of degree to which fold approximates ideal cylindrical fold

      (1) practical measure: on stereonet, how closely do poles to planes of fold fit a great circle distribution?

3. Symmetry

a. symmetric folds: in profile, shape on one side of hinge is mirror image to that on other side of hinge
   (1) limbs on both sides of fold have same dip angle

b. asymmetric folds: no mirror plane symmetry in profile view

   (1) Z-folds: looking down plunge, fold profile has shape of Z
   (2) S-folds: looking down plunge, fold profile has shape of S

      (a) m-folds: small scale M-shaped folds found in the core of larger scale folds

   (3) Vergence: up dip direction of axial surface on an asymmetric fold

4. Style of Folded Surface (quantitative descriptors)
a. Aspect Ratio =
   Amplitude/distance between inflection pts

   (1) wide, broad, equant, short, tall

b. Tightness = measure of degree of acuteness of interlimb angle
   (1) gentle, open, close, tight

c. Bluntness = radius of curvature of fold at point of closure

   (1) sharp, rounded, blunt

5. Ramsay's Fold Classification

a. Basic Concepts

   (1) dip isogon: line drawn across the folded layer connecting two points of equal dip

   (2) orthogonal thickness: thickness of layer measured perpendicular to bedding planes

   (3) axial trace thickness: thickness of folded layer measured parallel to axial trace of fold

b. Ramsay's Classification

Class	Dip Isogon Geometry (from convex to concave)	Orthgonal Thick (from hinge to limb)	Axial trace thick. (from hinge to limb)

1	convergent		increases
1A	convergent	increases	increases
1B	convergent (parallel fold)	constant	increases
1C	convergent	decreases	increases
2	parallel (similar fold)	decreases	constant
3	divergent	decreases	decreases

(1) Class 1 Folds:

(a) dip isogons converge toward the concave side of the fold
(b) axial trace thickness increases from hinge to limb

(2) Class 2 Folds:

(a) dip isogons are parallel to one another and parallel to axial surface
(b) axial trace thickness decreases from hinge to limb

(3) Class 3 folds:

(a) dip isogons diverge toward the concave side of fold

6. Style of folded multi-layer

a. harmony
(1) harmonic fold: continuous along axial surface (in vertical profile)
(2) disharmonic: folding dies out along axial surface (in vertical profile)

b. axial surface geometry

(1) planar axial surface
(2) curving axial surface

E. Scaling and Order of Folds (fractal approach to fold scale)

1. First oder folds: large scale, regional
2. second to higher order folds: on outcrop to hand sample scale

3. nested folds = "parasitic folds" = smaller scale higher order folds

F. Structural Associations of Folds

1. Parallel Folds

a. ramsay's class 1 B fold
b. commonly plunging structures, e..g Valley and Ridge province of Appalachians

2. Similar Folds

a. ramsy's class 2 fold
b. fold nappes: large-scale, recumbent isoclinal folds

3. Other
a. Chevron: sharp angular folds
b. Kink Folds: step folds
c. Ptygmatic folds: common disharmonic folds found in met. rocks; "convolute folding", axial surface is curved
d. Box folds: box shape fold geometry

Summary of Fold Geometries

Hinge Line	Axial Surface	Tightness	Symmetry	Shape	Size	Class
plunging Nonplunging	upright inclined recumbant	open tight	Symmetric Asymmetric	kink circular chevron box	λ+ amp.	concentric similar parallel disharm. flow

III. Kinematic Models of Folding

A. Introduction

1. 2-dimensional deformation models

a. homogeneous deformation: straight and parallel lines remain straight and parallel after deformation
b. Inhomogeneous deformation: straight and parallel lines become curved and nonparallel after deformation
c. Simple Shear- two-dimensional, constant volume deformation

(1) Simple shear = rotational shear

(2) analogy: sliding cards in a deck

(a) homogeneous: square sides become parallelogram after deformation
(b) Inhomogeneous: sides become curved

d. Pure Shear = "flattening"

(1) Pure Shear = Non-rotational shear

(2) analogy: flattening a square

(a) max compression = direct shortening
(b) min stress = lengthening, NO ROTATION

2. Competence - measure of rheology of rock material = "resistance to ductile deformation"

a. Competent material: deforms ductilely at relatively low rate (resistant) (e.g. sandstone)
b. Incompetent material: deforms ductilely at relatively high rate (non-resistant) (e.g. shale)

B. Flexural Folding of a Layer

1. Flexural Folding: orthogonal thickness of a given rock layer remains constant throughout the folding process

a. Produces "Parallel folds"
b. Stress Processes

(1) Bending = Non-compressional stress

(a) Vertical torque stress

i) opposing stress components that produce equal and opposite pressure that bend the layer into a fold

ii) No horizontal compression or tension is felt by layer

(b) Sources of vertical bending

i) magmatic uplift
ii) draping over faulted basement rocks

(2) Buckling = active compressive stress parallel to layer

(a) e.g. fold-thrust complexes

i) complex bending and buckling as beds are ramped up onto thrust planes

c. Strain Response in Folding

(1) Orthogonal Flexure

(a) lines drawn perpendicular to bedding planes, remain perpendicular after folding

i) Stretching of convex sides of fold
ii) shortening of concave sides of fold
iii) bed thickness remains constant before and after folding

(b) Net Result: fanning of lines about the fold

i) common in competent rocks, with folds of low radius of curvature

(2) Flexural Shear

(a) Folding accommodated by shear along bedding planes, parallel to bedding planes

i) e.g. bending deck of cards

ii) Beds on convex side of fold move towards hinge of fold

(b) Net Results

i) Bed thickness remains constant before and after folds
ii) lines perpendicular to bed plane, do not remain perp. after folding.
iii) No stretching or shortening of convex/concave portions of folds

(c) Common Occurrence

i) in multilayer systems of varying competence
ii) e.g. Pinto MD field trip
iii) Field evidence: bedding plane slickensides

2. Flow Folding (aka passive shear folding)

a. Results in "Similar Folds"

(1) thickness of bed changes throughout fold structure

(a) shear perpendicular to bedding plane

(2) common in highly incompetent layers (e.g. shale)

(a) inhomogeneous simple shear (rotational shear)

(b) Shear motion cross-cuts layer
i) (not parallel to layer as in flexure shear above)

(3) Fold Characteristics

(a) axial surface of fold parallel to shear planes of deformation
(b) Orthogonal thickness of layer changes across fold
(c) thickness of layer parallel to shear planes remains constant
(d) shape of fold is same on both convex and concave side of fold

3. Volume-Loss Folding

a. Process: solution and removal of rock material, results in shortening and folding of layers

(1) Discrete zones of volume loss due to solution

C. Flexure Shear and Flow Folding of Multilayers

1. Problem: complexity of multilayered rock systems

a. varying competence between interbeds (e.g. chert, shale, sandstone, limetone)

(1) Each lithology possesses unique rheology and competence

(2) Net result: complex fold systems with mixed modes

2. Scenario 1: stack of rocks with high competence of similar magnitude (e.g. stack of sandstone beds)

a. mechanical model: rheologic isotropy

b. Flexure-slip folding

(1) each competent layer slips over the other via shear along bedding planes

(a) shear greatest on limbs
(b) shear = 0 at hinges
(c) sense of shear reverses at hinge

i) convex side of fold: shear converges from both limbs toward the hinge

ii) concave side of fold: shear diverges along both limbs away from hinge

3. Scenario 2: stack of mixed competence rocks (high competence contrast between layers... e.g. sandstone and shale interbeds)

   a. mechanical model: rheologic anisotropy
   b. Processes

      (1) Competent layers slip as coherent mass
      (2) Incompetent layers become zones of shear accommodation
         (a) deformed greatest on limbs
         (b) flattening at hinge zone

   c. If thickness of competent layer > incompetent layer

      (1) disharmonic, ptygmatic folds may develop in incompetent layer

4. Scenario 3: multilayer system comprised entirely of incompetent rocks (e.g. shales)

   a. mechanical model: rheologic isotropy

   b. Net process: flow folding (passive shear folding)

      (1) similar folds

D. Formation of Kink and Chevron Folds

1. what are they?

   a. Kink folds: symmetric folds with sharp angular hinges and straight limbs
   b. Chevron Folds: asymmetric folds with sharp angular hinges and straight limbs

2. Kink Folds

   a. Kink band: one short limb between two axial surfaces

   b. process models

      (1) kink band propagation with axial surfaces migrating into undeformed material

      (2) Stationary kinks develop in response to simple shear in hinge zones

3. Chevron Folds

   a. Intersection of two kink bands

b. Flexure slip / crinkling of layers into chevron folds

E. Fold-thrust systems

1. Complex interaction of thrust faults and layer folding

2. Two primary mechanisms of thrust-folding

a. "Fault-bend folds" - Thrust ramping and buckling of over-riding layer

b. Fault-propagation folds:

(1) thrust- tip begins to propagate up section

(a) anticlinal fold develops in lee of thrust-tip during propagation
(b) thrust undercuts behind fold structure as both propagate and develop

F. Drag Folds

1. Drag fold implications

a. shear velocity along fault zone establishes localized stresses in the fault blocks
b. fault-stress transfer results in fold development above and/or below the fault planes

G. Folding and Multiple Deformation Events

1. Process: refolding of earlier formed folds (multi-deformation)

a. superposed folding: multiple sets of folds superposed on one another

b. Process:

(1) fold 1 = folding of original bedding planes
(2) fold 2 = folding of axial plane of fold 1
(3) fold 3 = folding of axial plane of fold 2... etc.

(a) common in deep-seated cores of orogenic complexes

2. Notation Used in Deciphering Multiple Deformation Patterns

a. S = surfaces
(1) So = bedding plane surfaces
(2) S1, S2, S3... Sn = axial surfaces of folds
b. f = fold hinges

(1) f1, f2, f3... fn

c. Examples

(1) F1So = first generation of axial plane of original bedding planes

3. Complex fold patterns

a. Type 1

(1) fold 1 upright, fold 2 upright, axial surfaces at right angles
(2) net pattern = "egg carton"

b. Type 2

(1) fold 1 recumbent, fold 2 upright, axial surfaces at right angles
(2) net pattern= crescents, mushrooms or m-shape patterns

c. Type 3

(1) Fold 1 inclined, fold 2 upright, axial surfaces not at right angles
(2) net pattern = wavy s-patterns

H. Diapiric Flow

1. Diapirs defined

a. circular or elliptical structures
b. process: bouyant uplift of elliptical mass via density constrasts (Density of diapir < density of country rock)

(1) net effect: rising diapiric mass, sinking country mass
(a) e.g. lava lamp

c. Common diapiric materials

(1) salt / salt domes
(2) shale / shale diapirs
(3) magma diapirs (granites) / gneiss domes

2. Folding and Diapirs

a. internal folding, deformation and shear flowage within diapir
b. uplift and buckling of country rocks above diapir
(1) faulting of country rock as well.