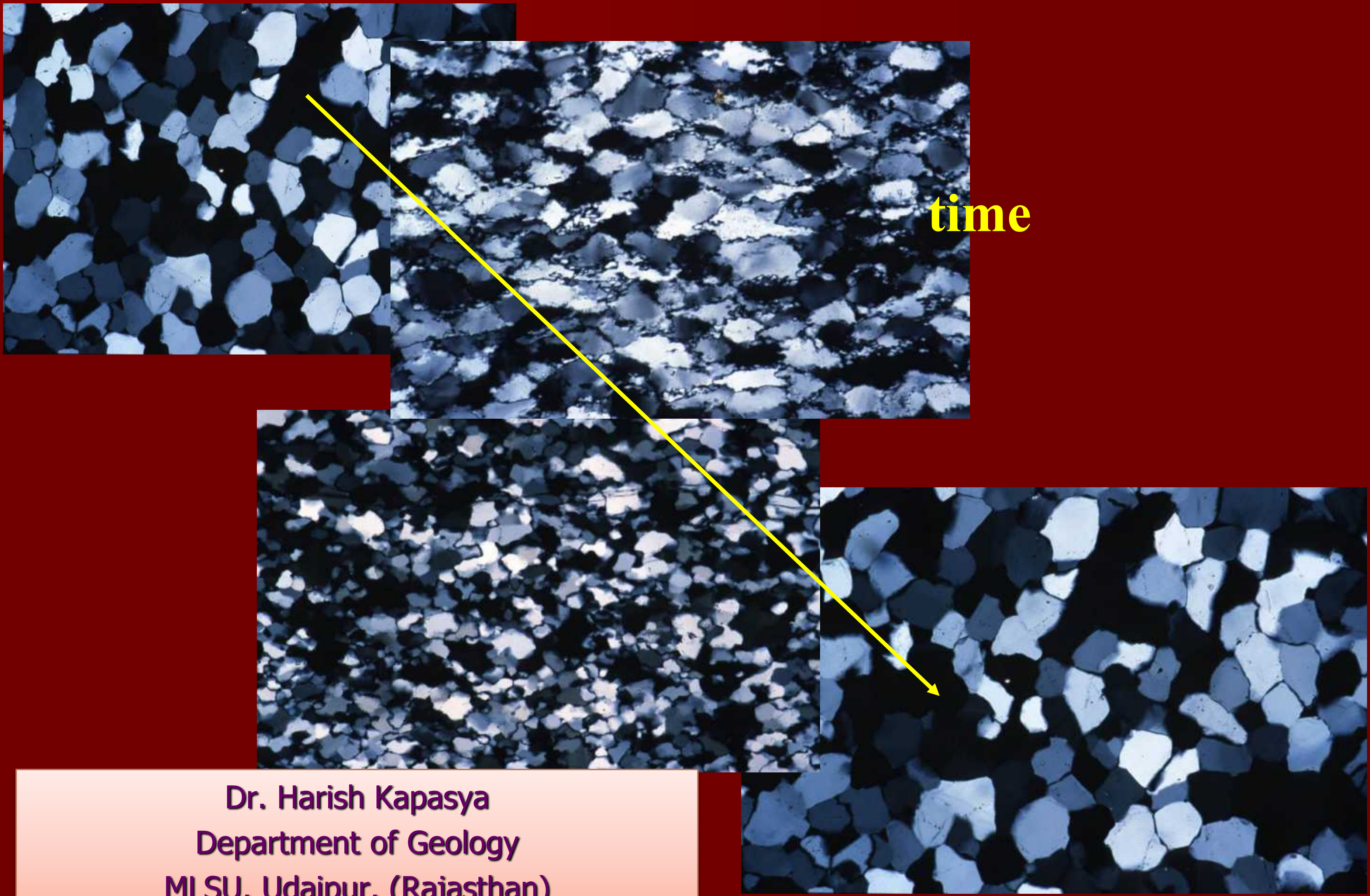
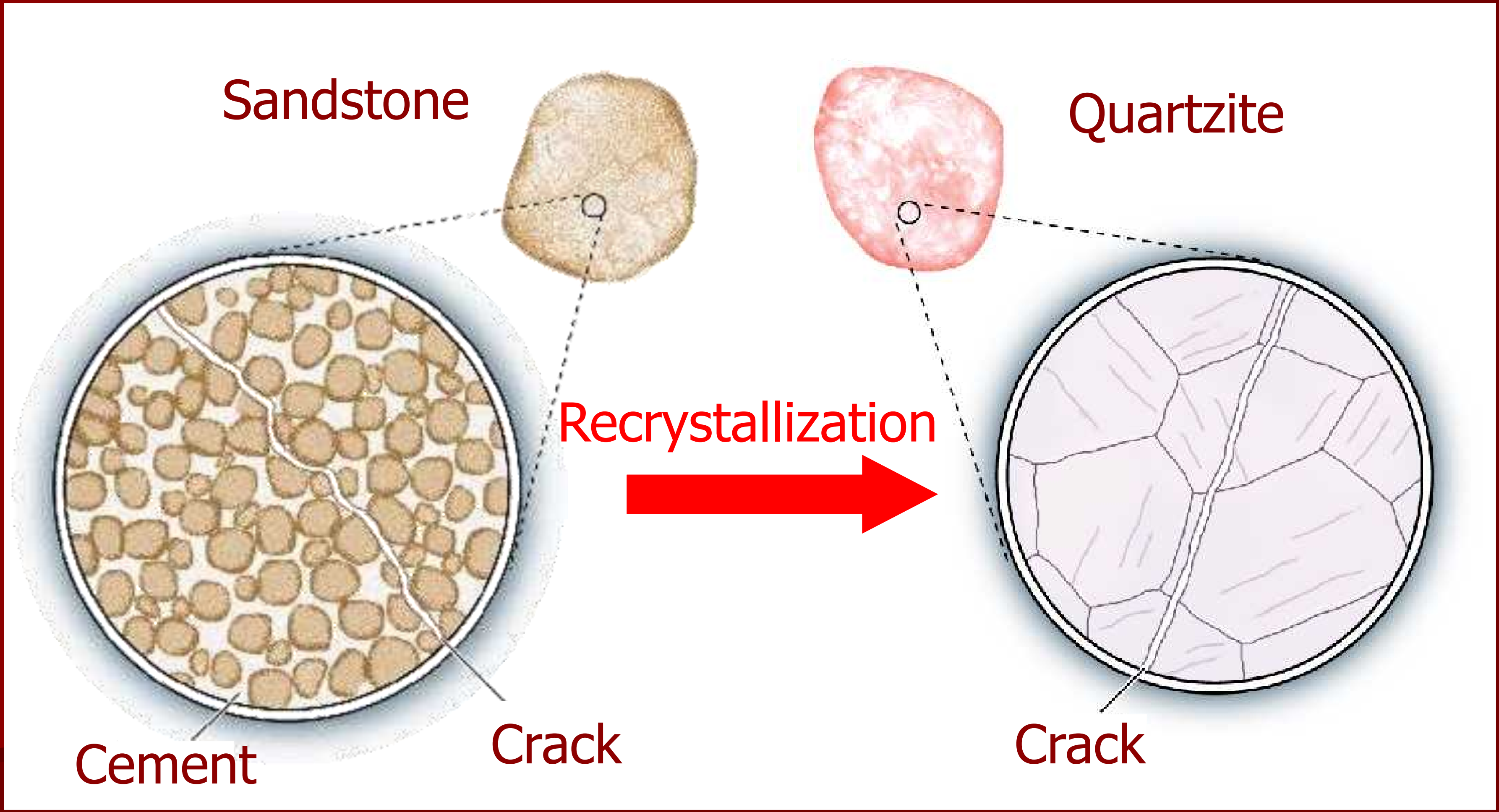
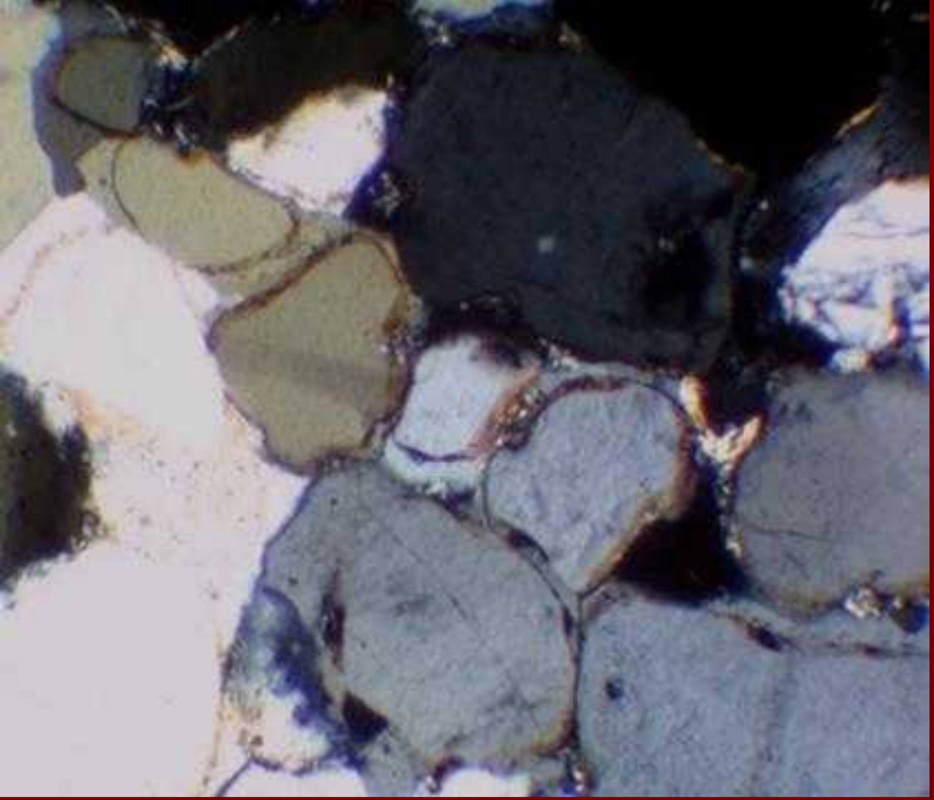
Relationships between deformation and metamorphism



Dr. Harish Kapasya
Department of Geology
MLSU, Udaipur, (Rajasthan)

Recrystallization: Minimization of Interfacial Free Energy by Minimizing Surface Area

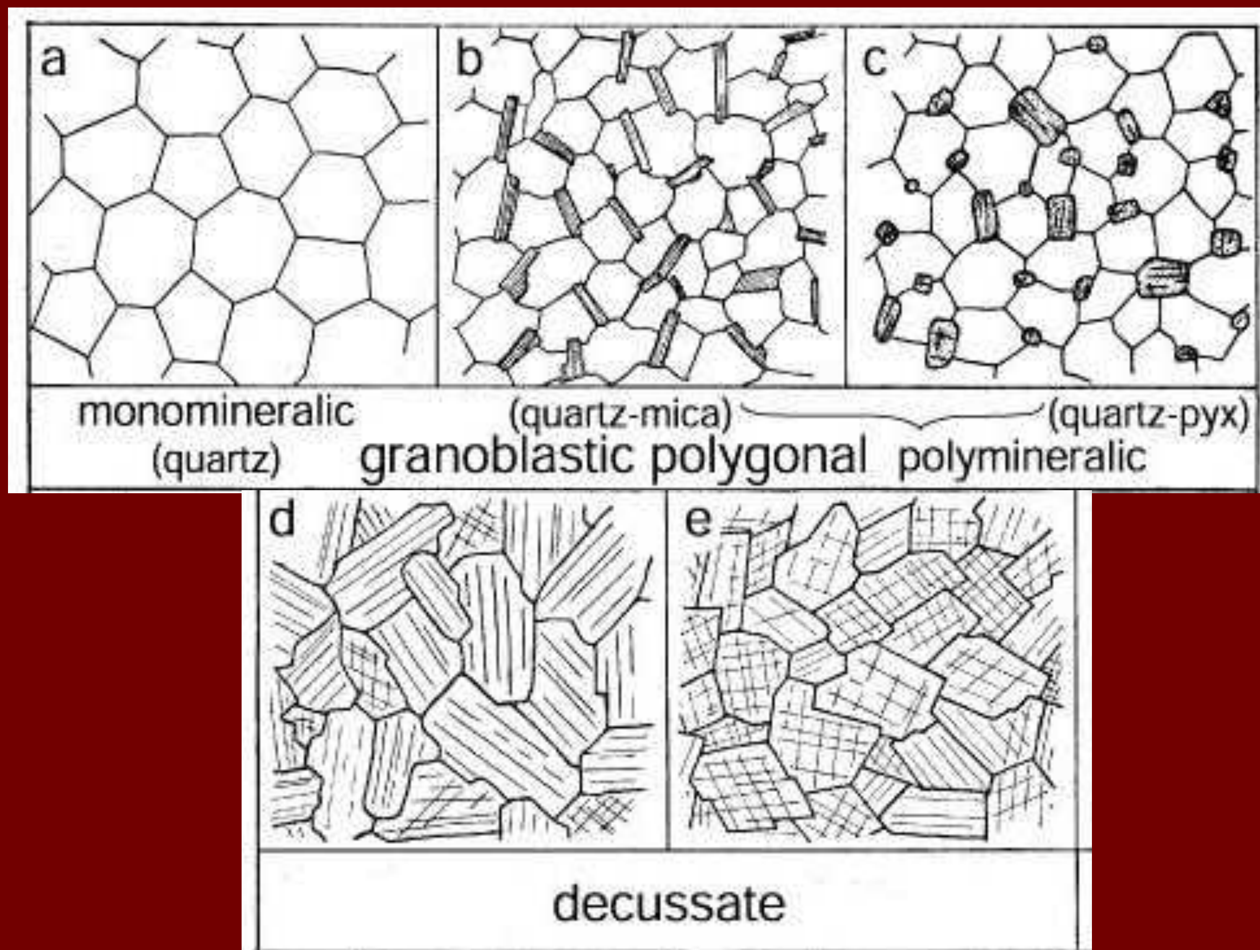




Sandstone texture

Quartzite texture

Granoblastic/Decussate Textures (Characteristic of Contact or Thermal Metamorphism)



Fold Generation:

folds that formed at approximately the same time
...commonly find several fold generations in an area...

each generation labeled by letter F (fold) and number;
number reflects *relative* order of formation...

F_1 (first); F_2 (second); F_3 (third), etc.

several fold generations may fold during an orogenic phase

Orogenic Phase:

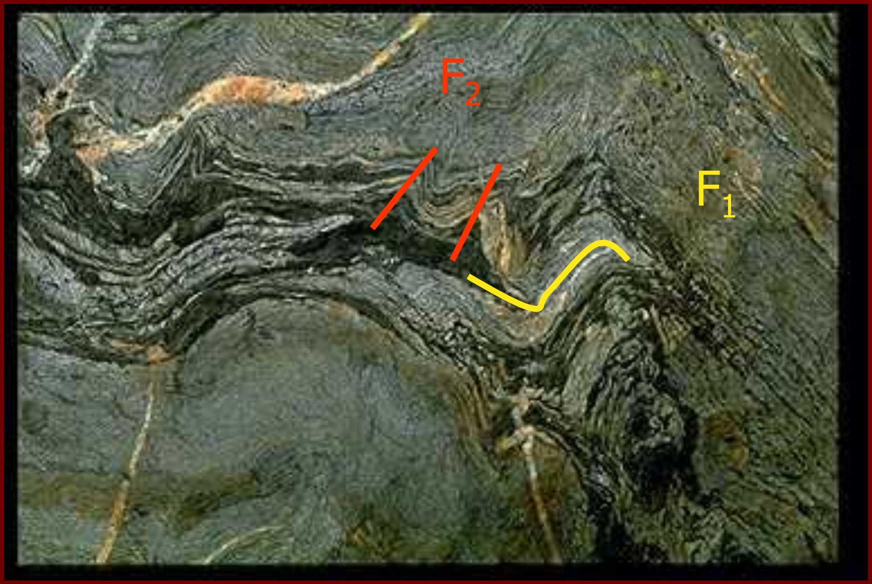
mountain-building event;
given letter D (deformation) (D_1, D_2, D_3, etc.)

to distinguish folds of different generations use principle of superposed folding...

...later generations are superposed on, or overprint, earlier ones

fold superposition creates specific patterns --requires careful geometric analysis

simple rule: a superposed fold is younger than structure it folds

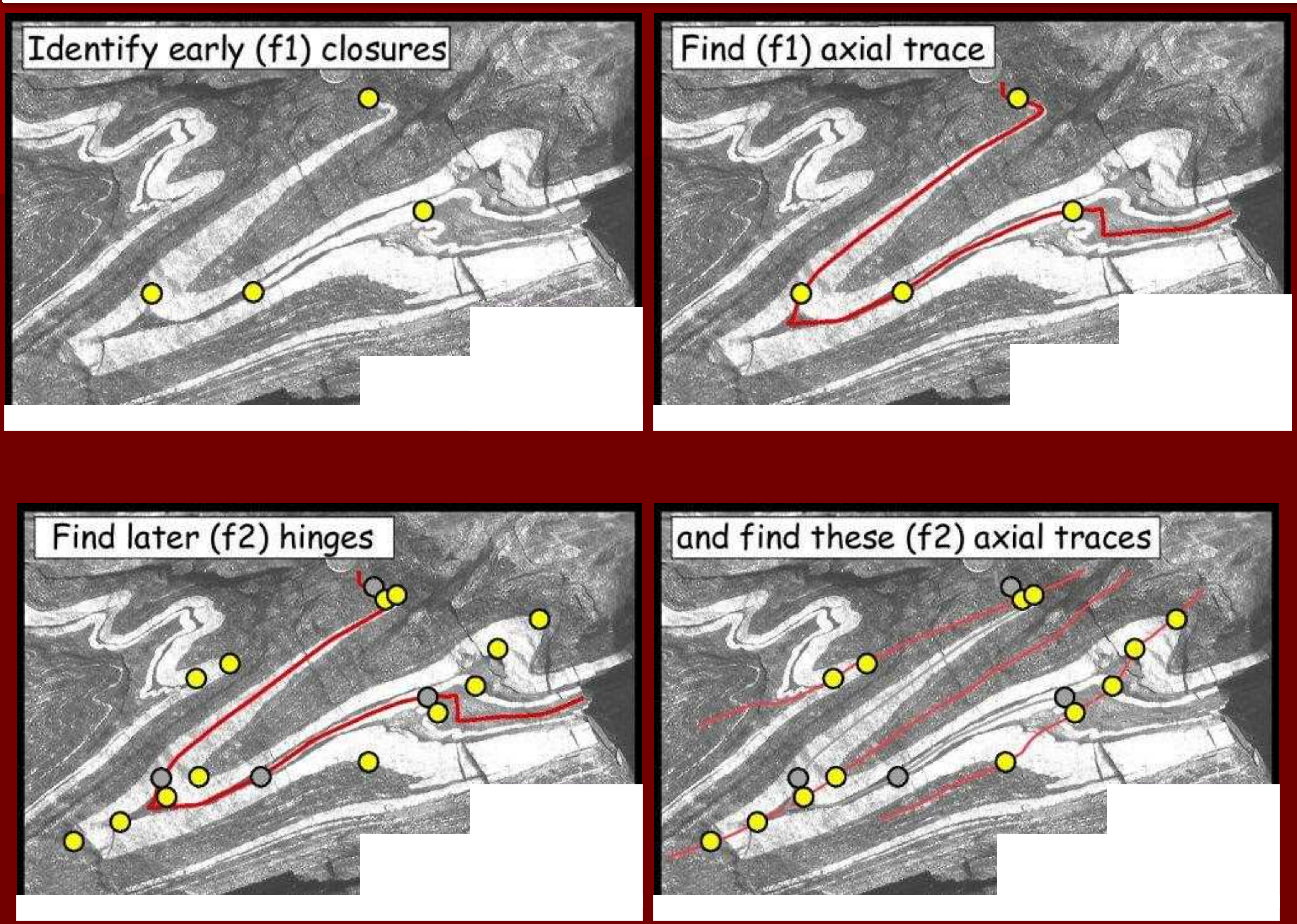


examples of superposed folding

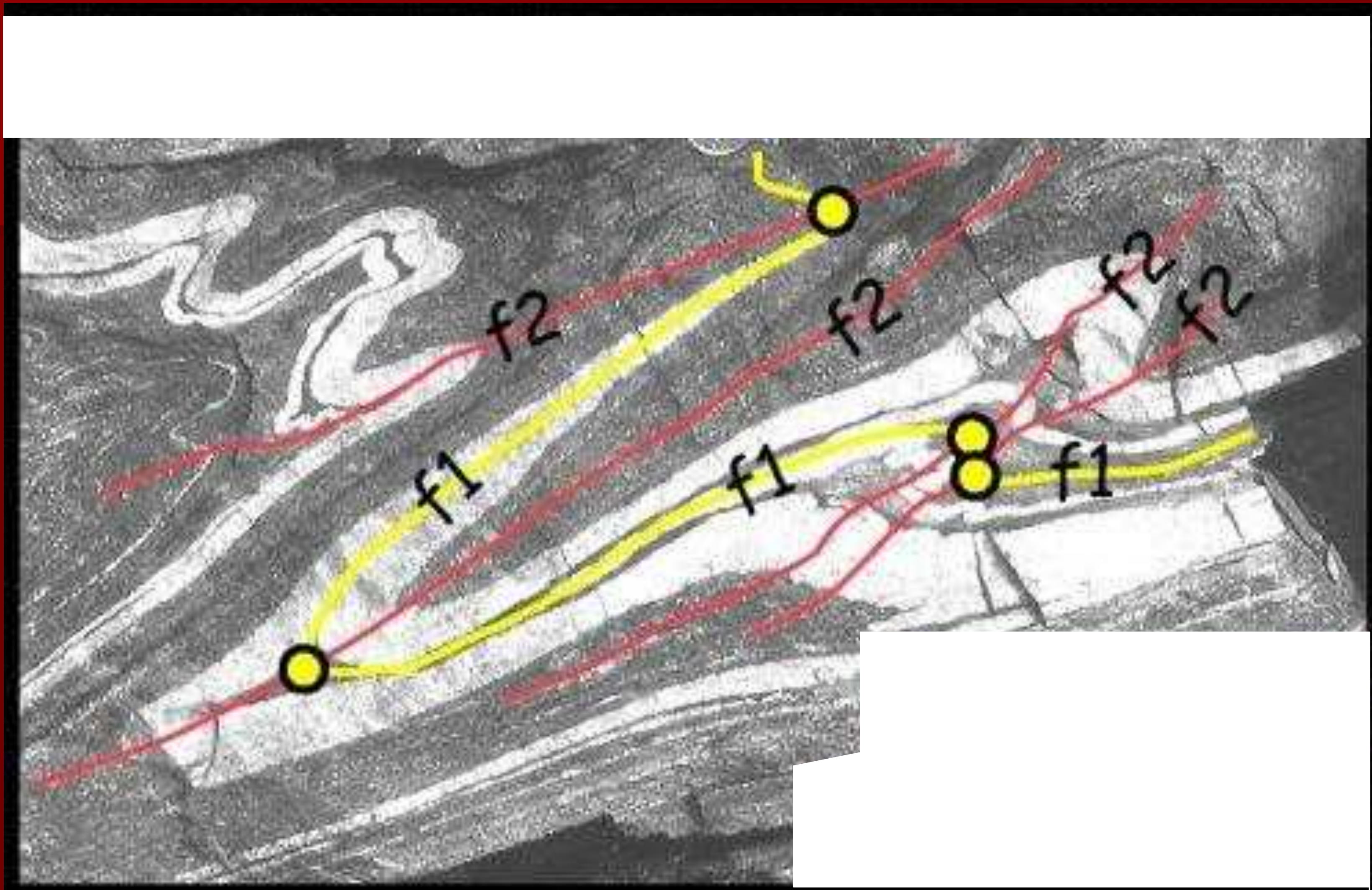
note axial surface of early fold is folded, later axial surface is not

we will examine right image more closely...

PROCEDURE FOR EXAMINING SUPERPOSED FOLDS

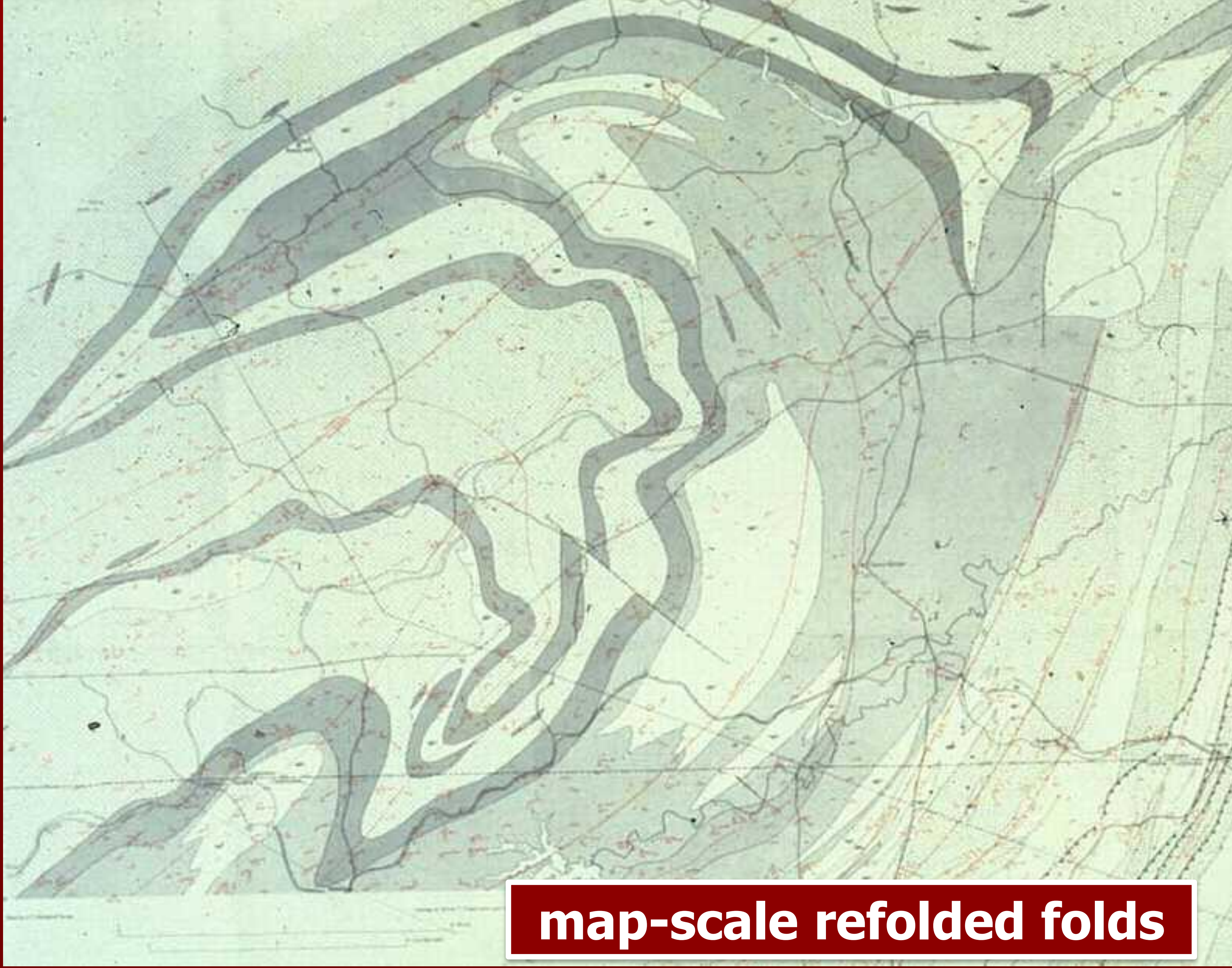


both folds identified…



F_1 axial surface is folded; F_2 is not. rule of superposition shows that F_2 is younger than F_1

more folded folds…



map-scale refolded folds

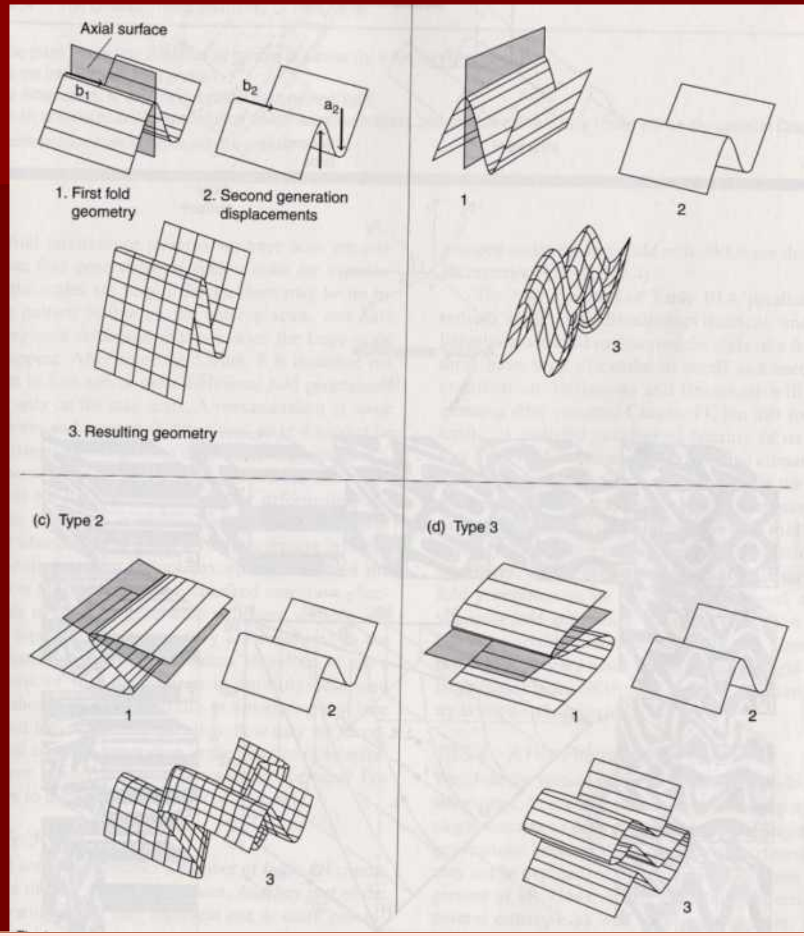
4 basic endmember interference patterns are seen from superposition of upright F_2 folds on F_1 folds of variable orientation

type 0

type 1

type 2

type 3



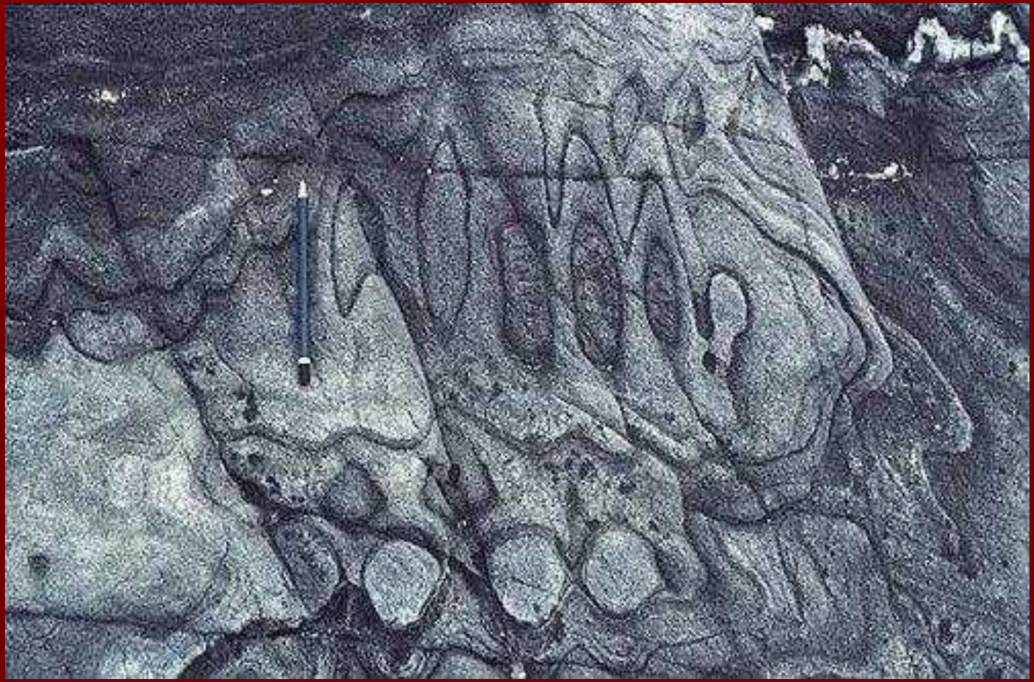
type 0: cannot see as inteference type; axial surfaces parallel
type 1: "dome-and-basin" structure; egg-carton; axial surfaces normal
type 2: most difficult to visualize; "mushroom"
type 3: "refolded folds" (all types are refolded)

type 1 interference: egg-carton; dome-and-basin

type 2 interference; mushroom

type 3 interference

fold interference patterns



more interference patterns

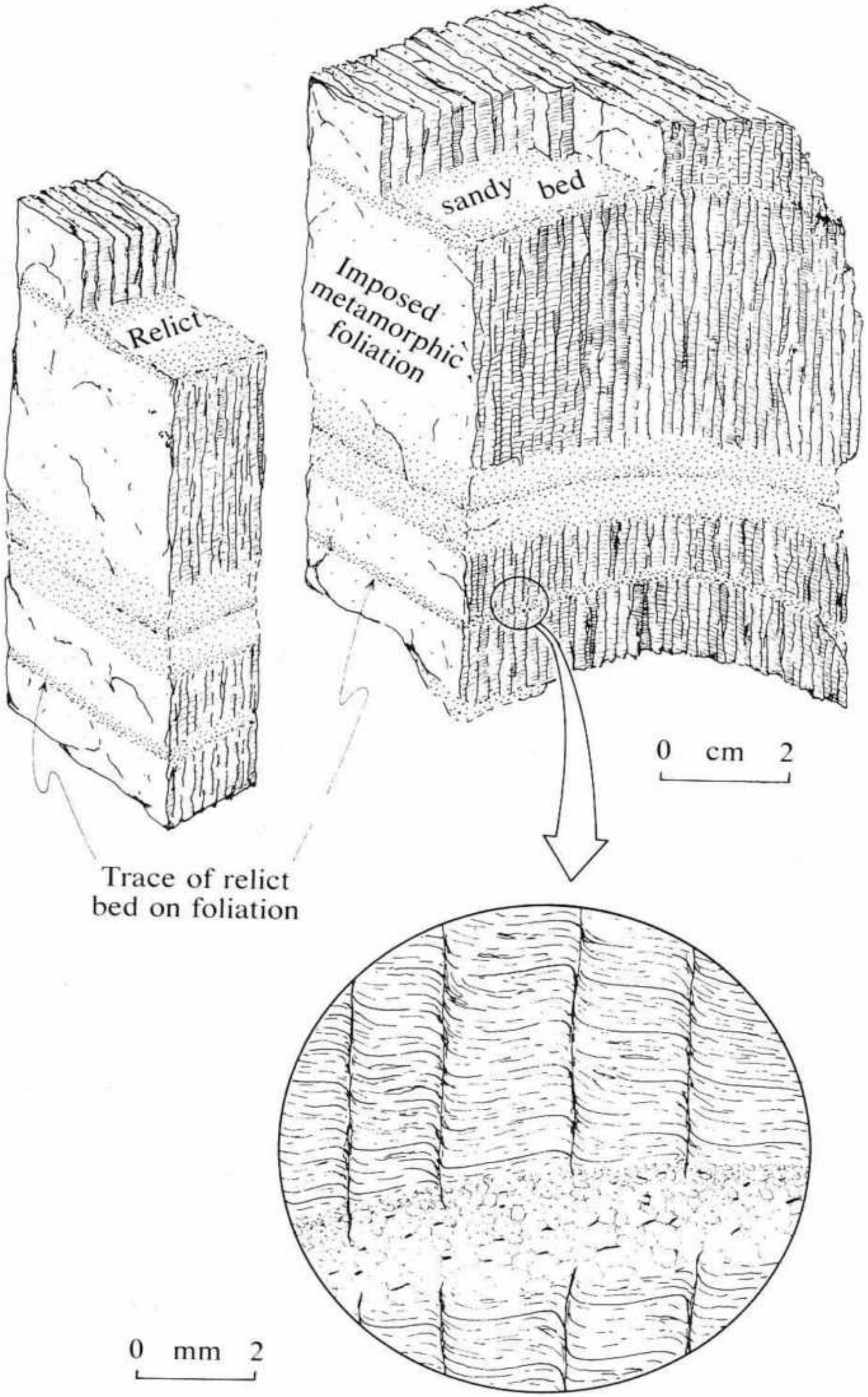
Metamorphic Textures

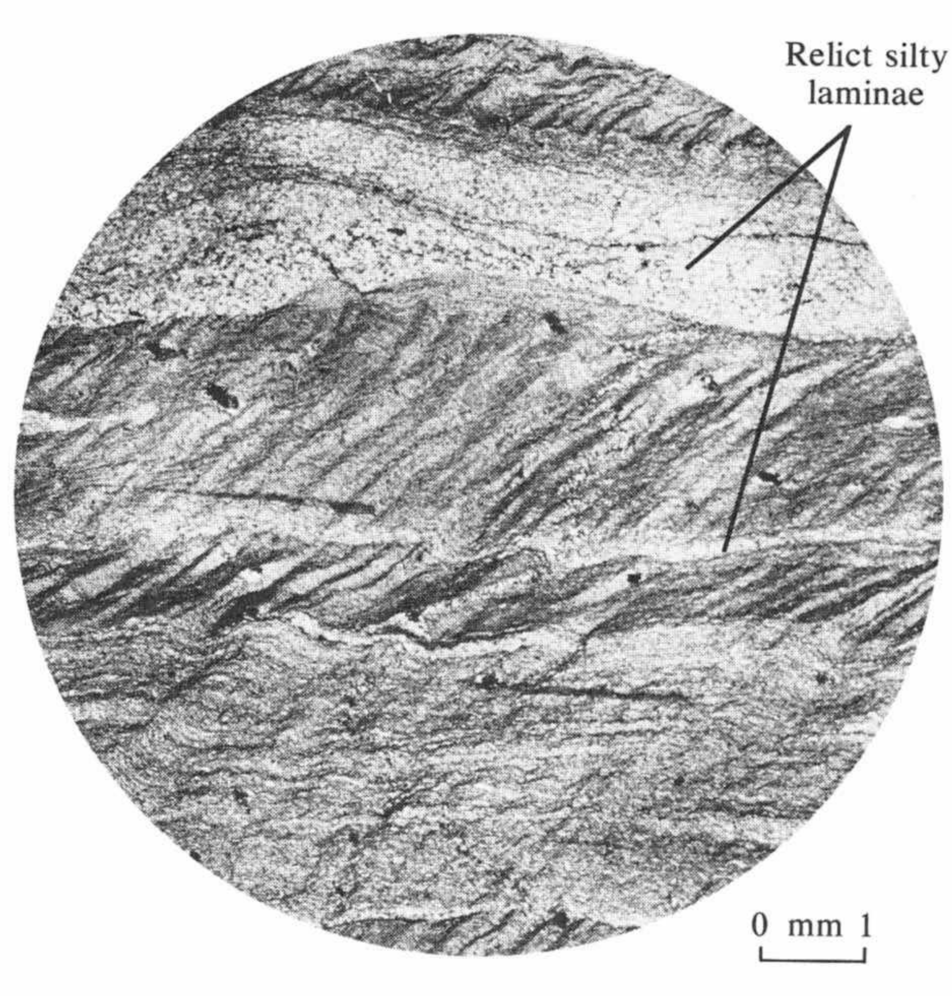
Textures of Regional Metamorphism

- Dynamothermal (crystallization under dynamic conditions)
- Orogeny- long-term mountain-building
  - May comprise several Tectonic Events
    - May have several Deformational Phases
- May have an accompanying Metamorphic Cycles with one or more Reaction Events

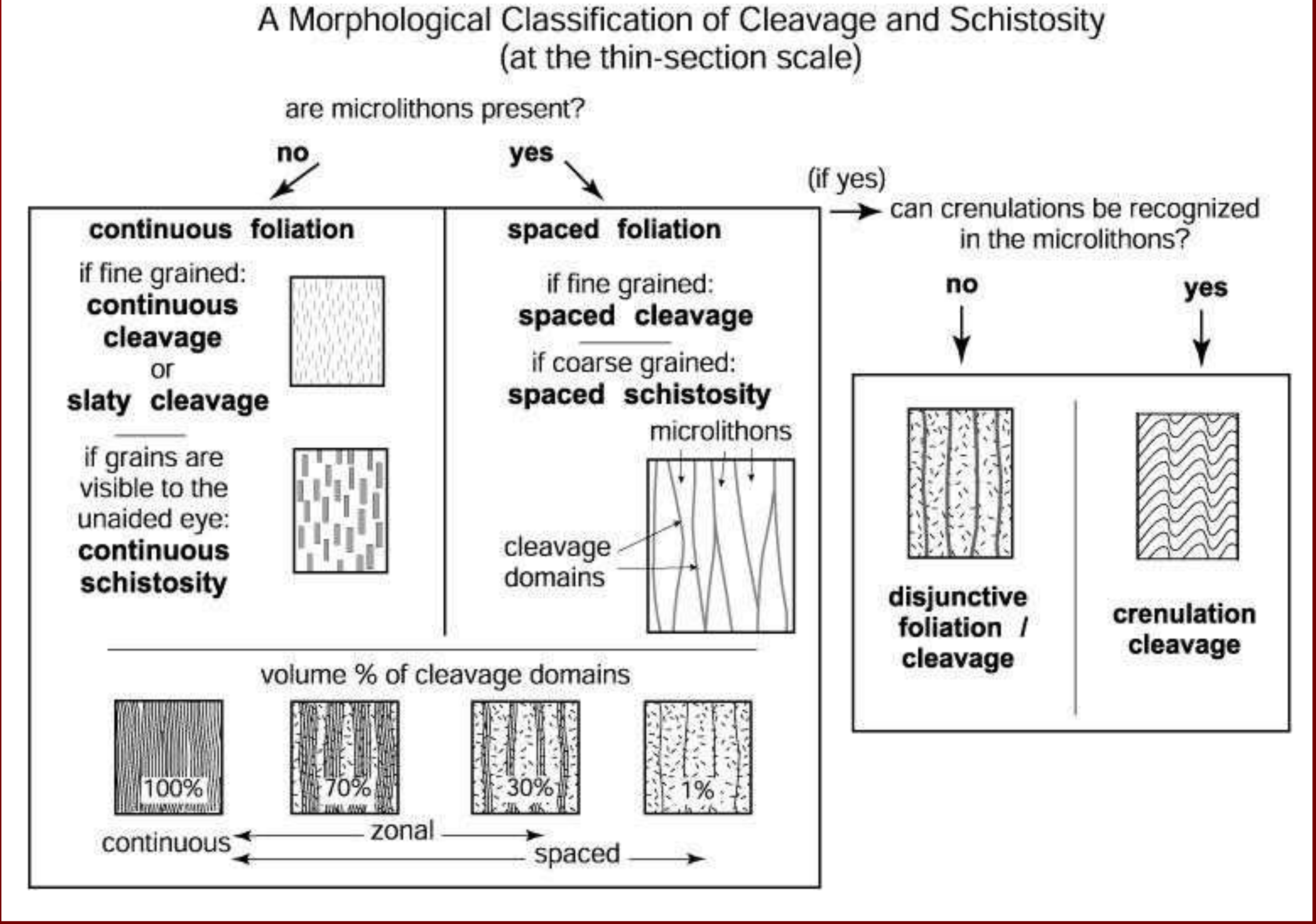
Textures of Regional Metamorphism

- Tectonite- a deformed rock with a texture that records the deformation
- Fabric- the complete spatial and geometric configuration of textural elements
  - Foliation- planar textural element
  - Lineation- linear textural element





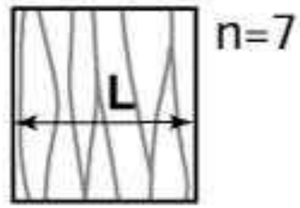
Development of an axial-planar cleavage in folded metasediments. Circular images are microscopic views showing that the axial-planar cleavage is a crenulation cleavage, and is developed preferentially in the micaceous layers.



A morphological (non-genetic) classification of foliations. After Powell (1979)

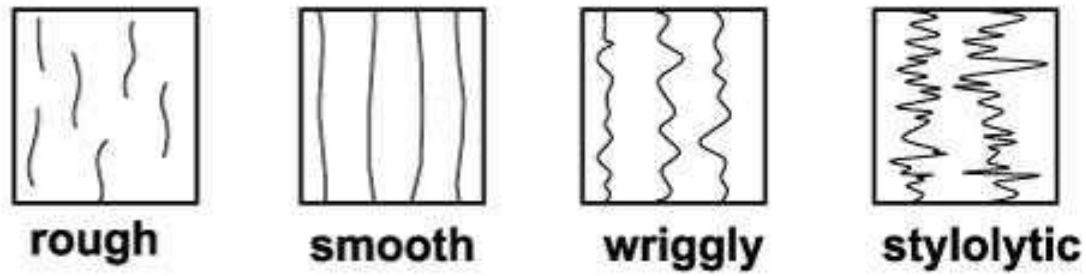
Other Useful Criteria to Describe Spaced Foliations

1. Spacing



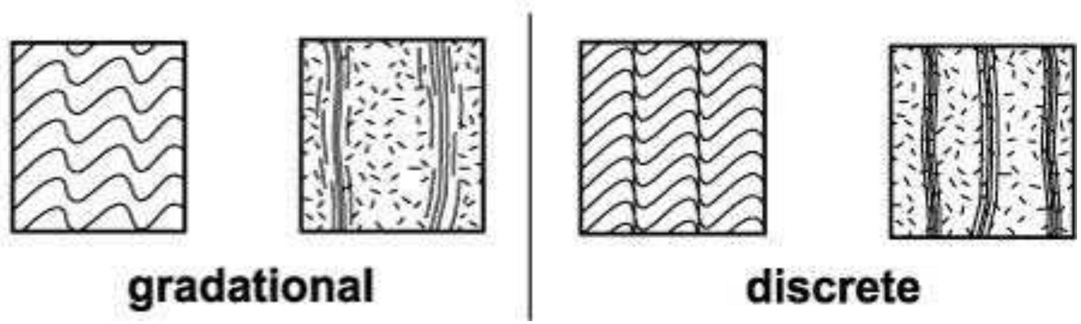
Spacing = length (L) divided by the number of cleavage domains (n) crossed in the length

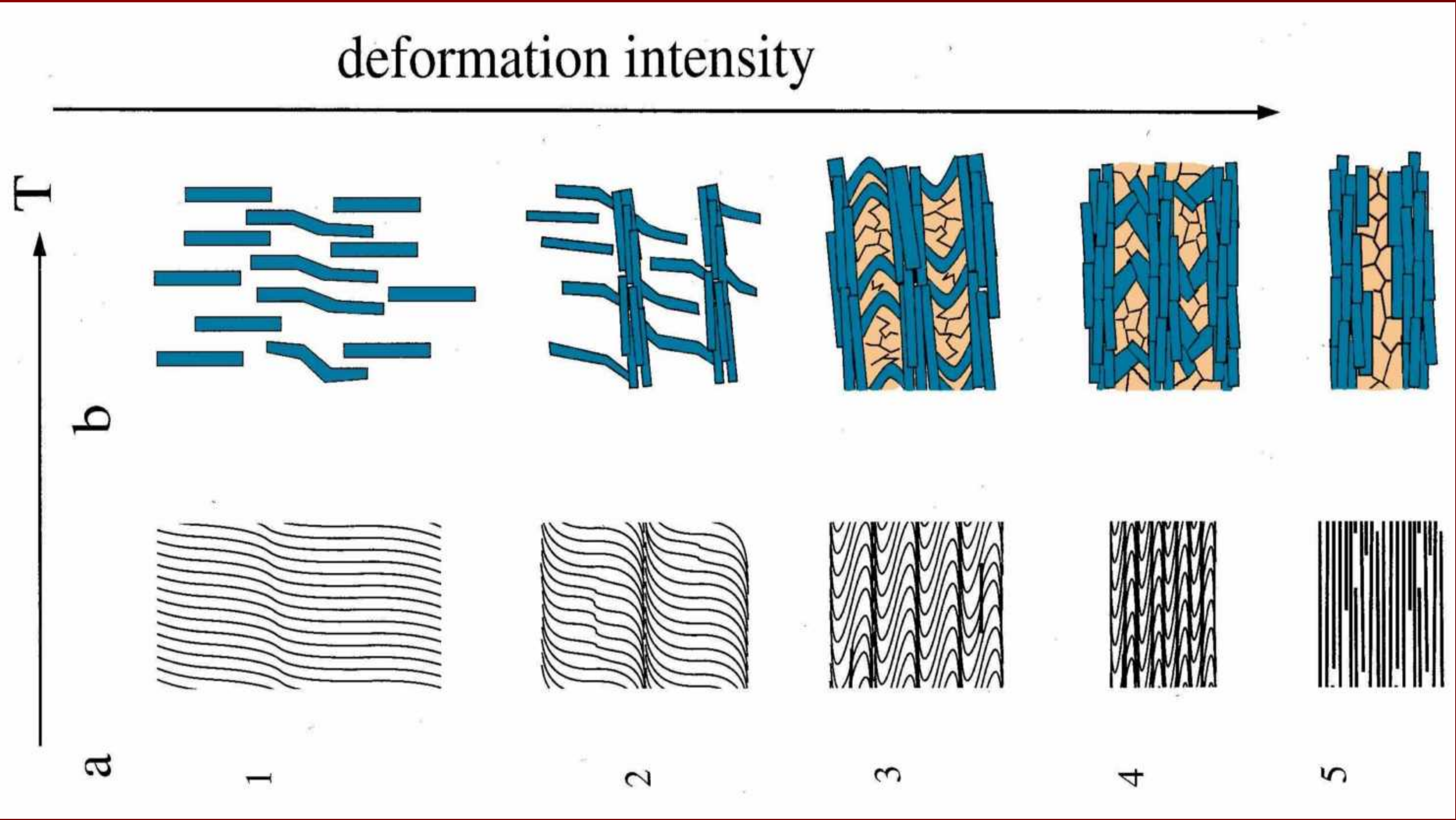
2. Shape of cleavage domains



3. Spatial relation between cleavage domains

4. Transition between cleavage domains and microlithons

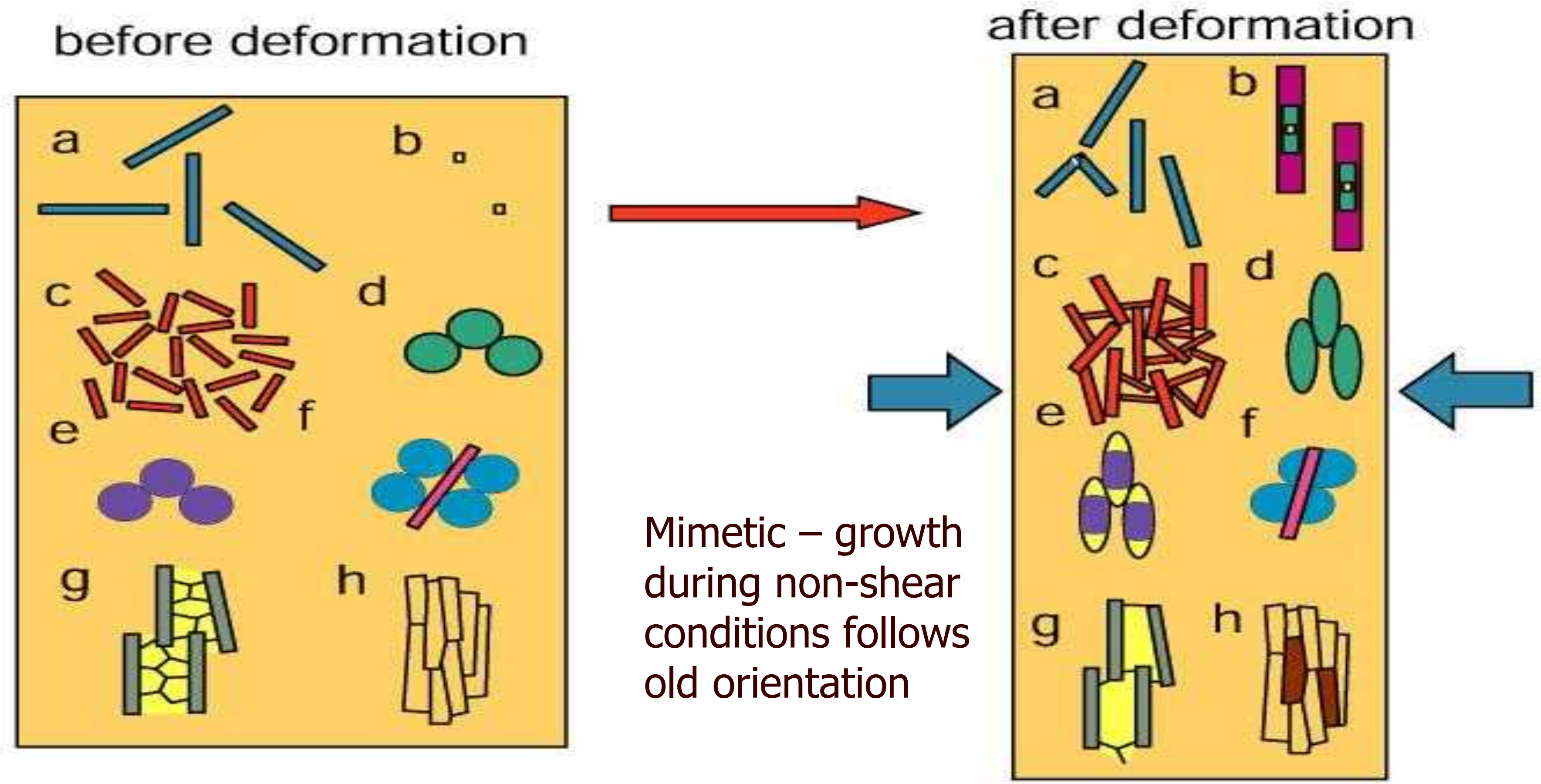




Development of S_2 micas depends upon T and the intensity of the second deformation

. Proposed mechanisms for the development of foliations

a. Mechanical rotation. **b.** Preferred growth normal to compression. **c.** Grains with advantageous orientation grow whereas those with poor orientation do not (or dissolve). **d.** Minerals change shape by ductile deformation. **e.** Pressure solution. **f.** A combination of a and e. **g**. Constrained growth between platy minerals. **h.** Mimetic growth following an existing foliation.



Mimetic – growth during non-shear conditions follows old orientation

Development of foliation by simple shear and pure shear (flattening)

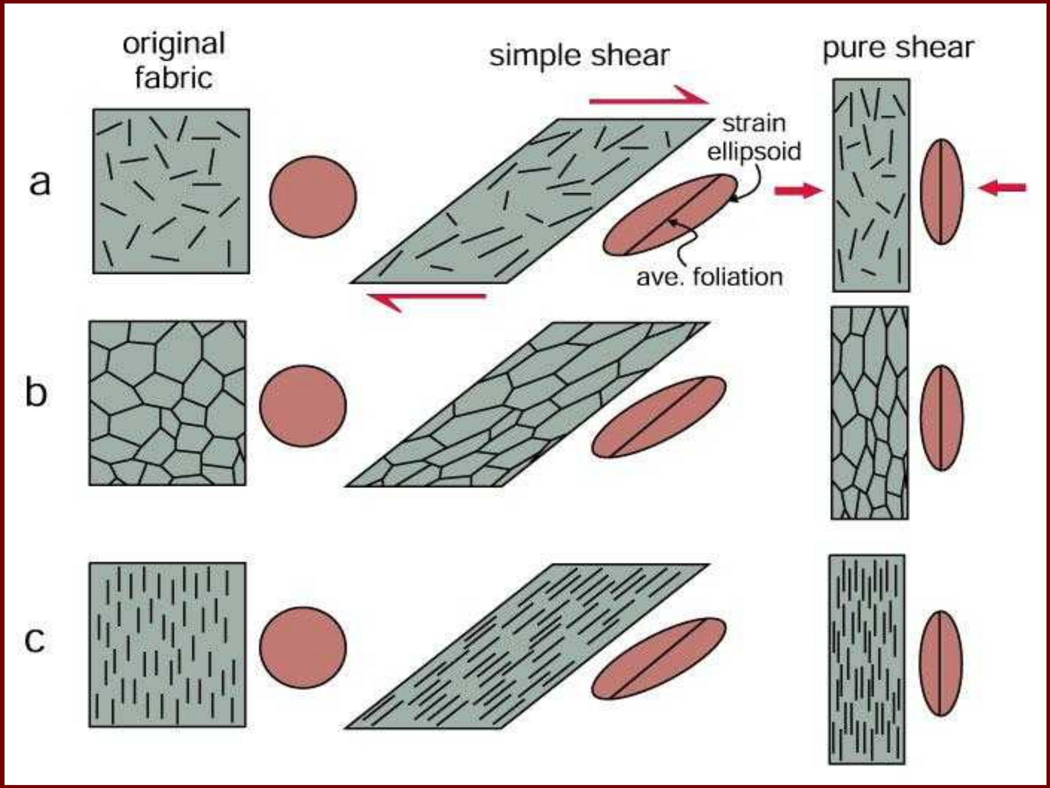
a. Beginning with randomly oriented planar or linear

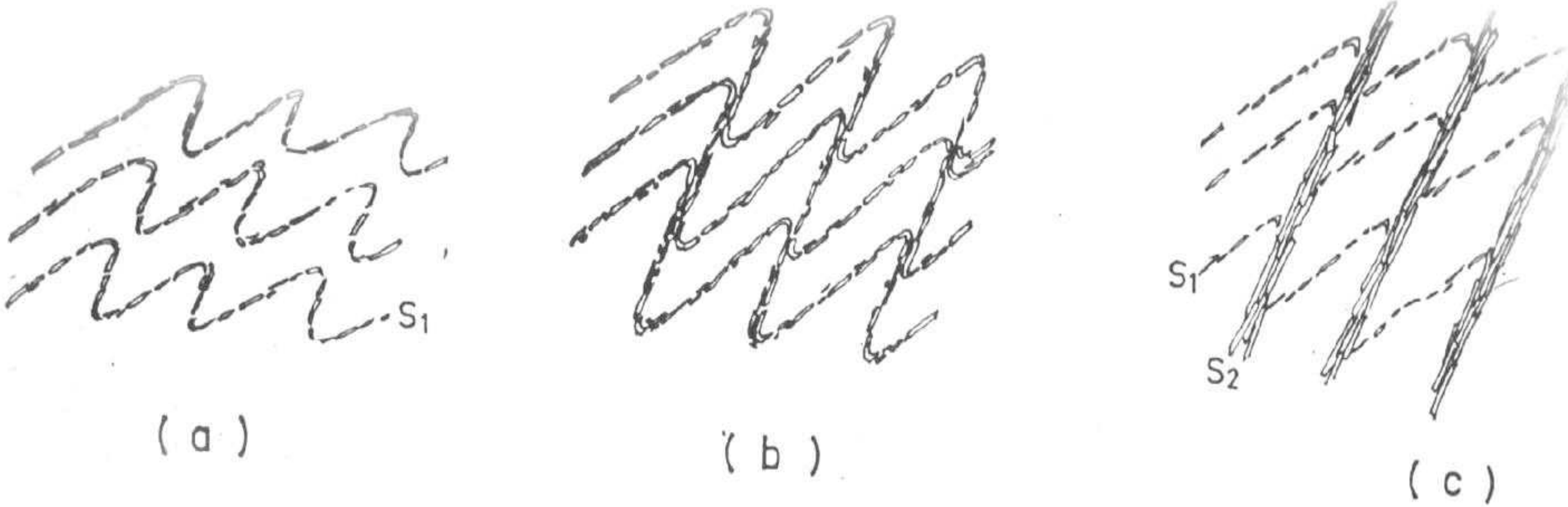
b. Beginning with equi-dimensional crystals

c. Beginning with pre-existing foliation

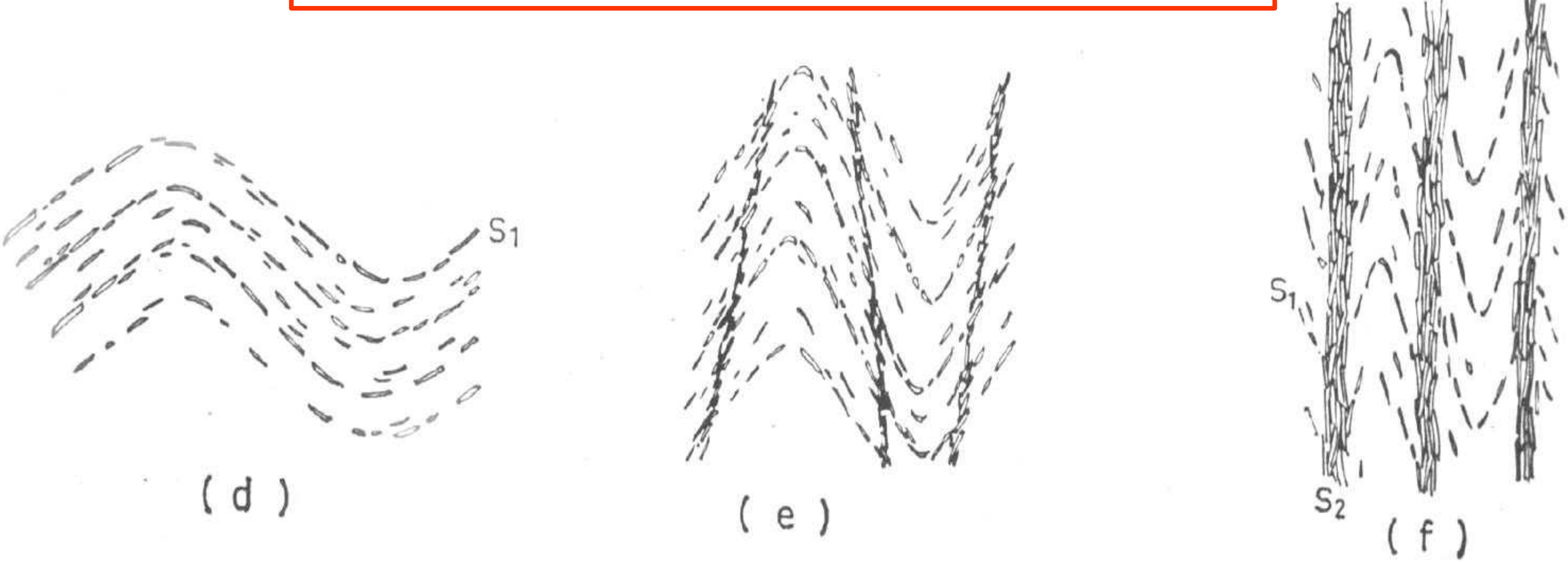
Shaded figures represent an initial sphere and the resulting strain ellipsoid

Development of foliation by simple shear and pure shear (flattening).



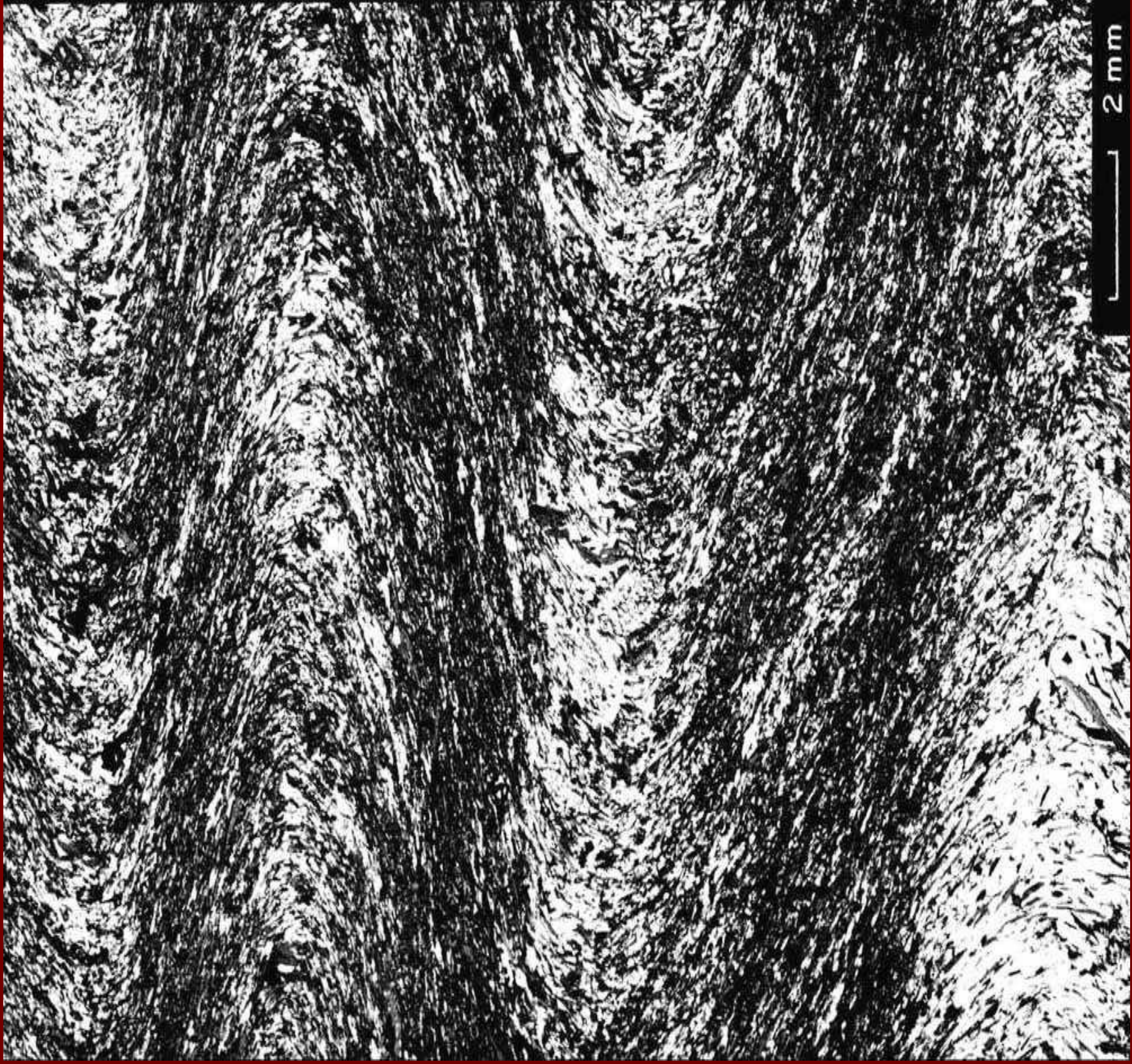


DEVELOPMENT OF CRENULATION CLEAVAGES

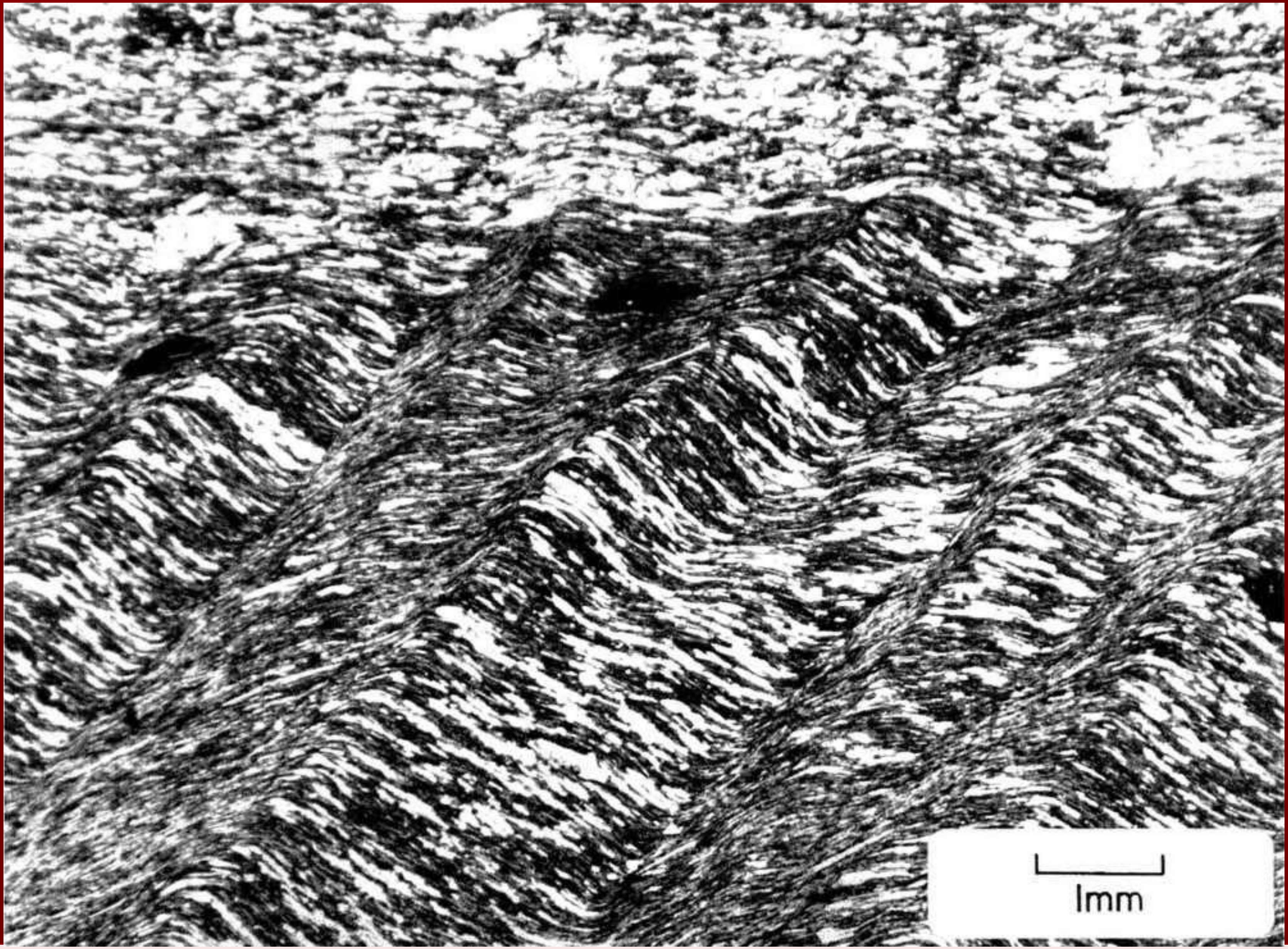


Crenulation: A slaty cleavage or schistocity that becomes microfolded

Quartz grains commonly dissolve by pressure solution from the steep limbs and precipitate in the hinge



Symmetrical crenulation cleavages in amphibole-quartz-rich schist. Note concentration of quartz in hinge areas.



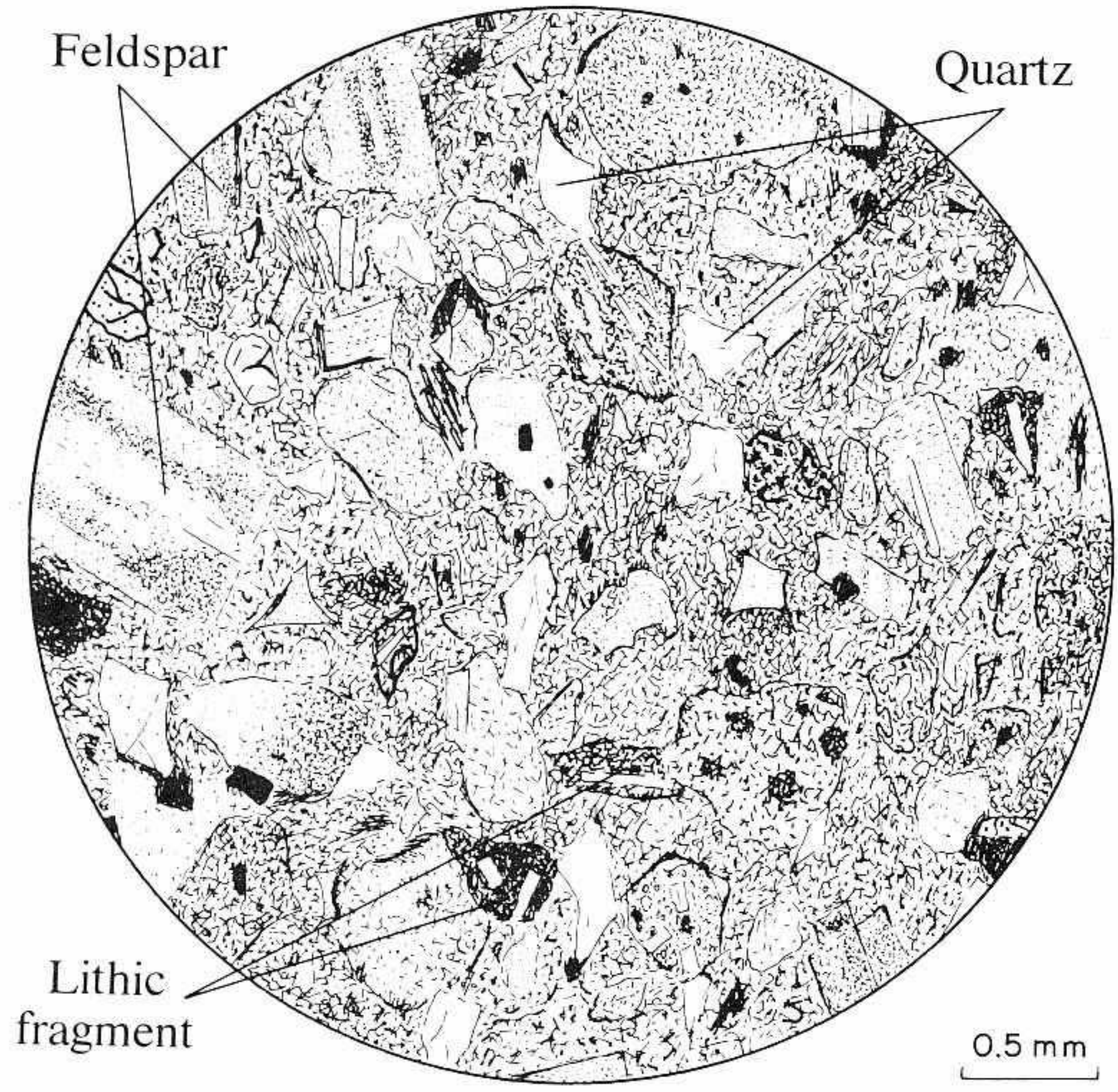
Asymmetric crenulation cleavages in mica-quartz-rich schist. Note horizontal compositional layering (relict bedding) and preferential dissolution of quartz from one limb of the folds.

- Progressive Syntectonic Metamorphism of a volcanic graywacke.

Phase 1: Both plag and Kfs in isotropic matrix

- Feldspars altered to fine sericite and secondary Ca-Al silicates

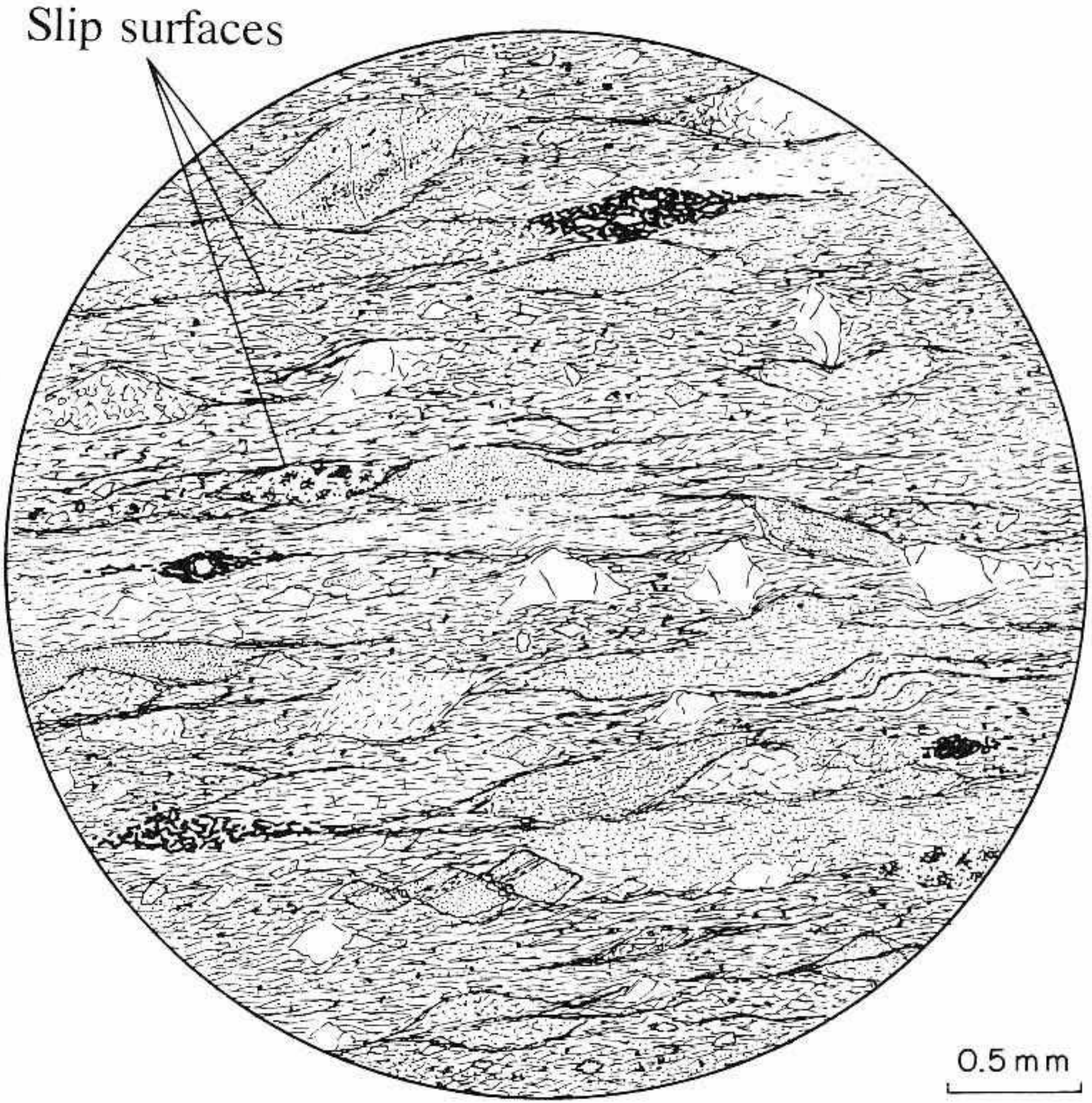
- Sericite is a fine grained mica, either muscovite or Illite. Sericite is a common alteration mineral of orthoclase or plagioclase feldspars



Progressive syntectonic metamorphism

Phase 2: Pervasive foliation develops due mostly to shear

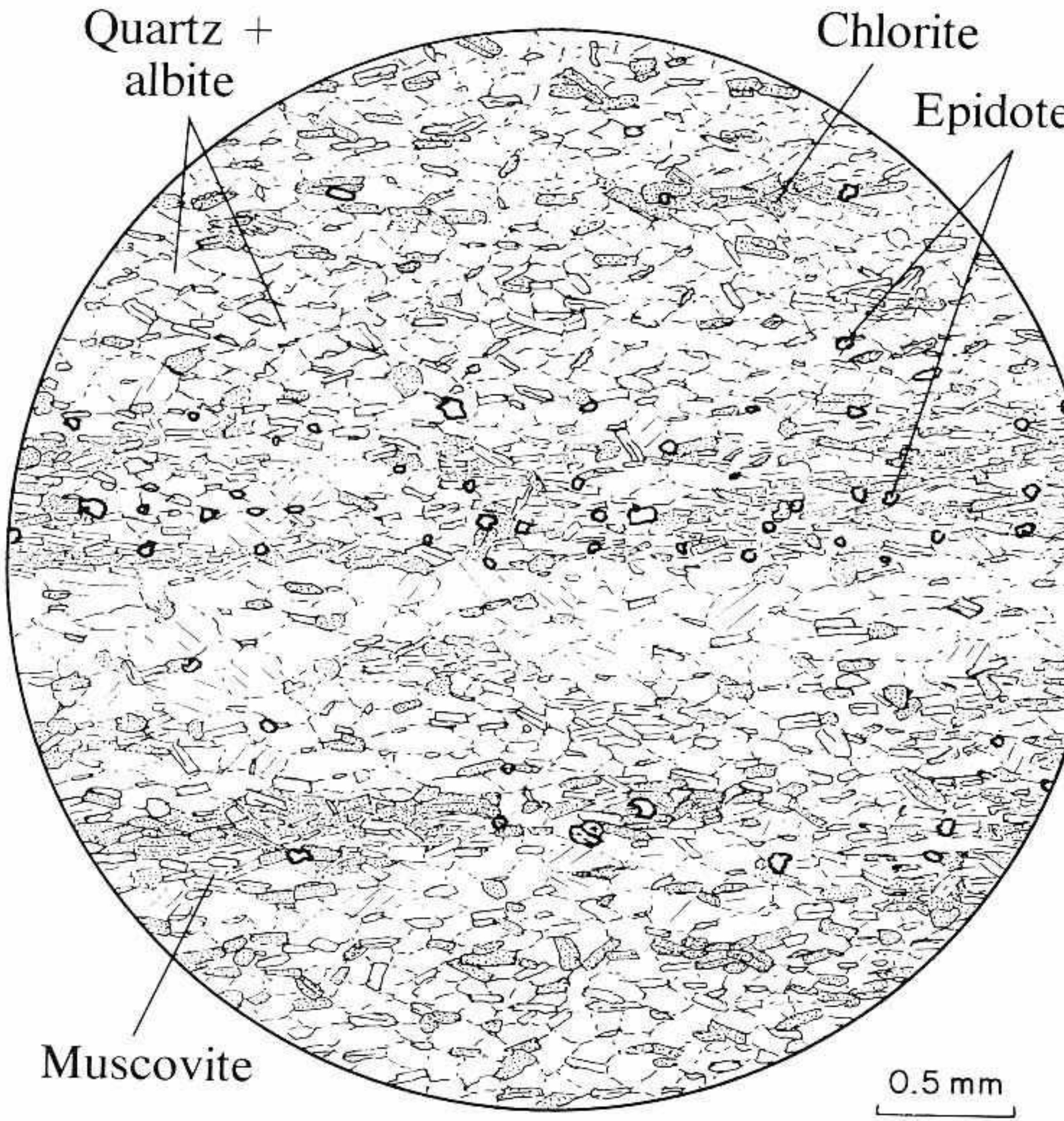
- Grain size reduction
- Porphyroclasts common and rounded
- Matrix recrystallized and new minerals form (Qtz, Ep, Sericite, Ab, Chl)
- Chl & Ser enhance foliation



Progressive syntectonic metamorphism

Phase 3: Fine-grained schist with larger crystals- no relict textures
- Good muscovite and biotite define schistosity
- Some metamorphic differentiation to layering
- Qtz and Ab are polygonal mosaic in mica-free layers

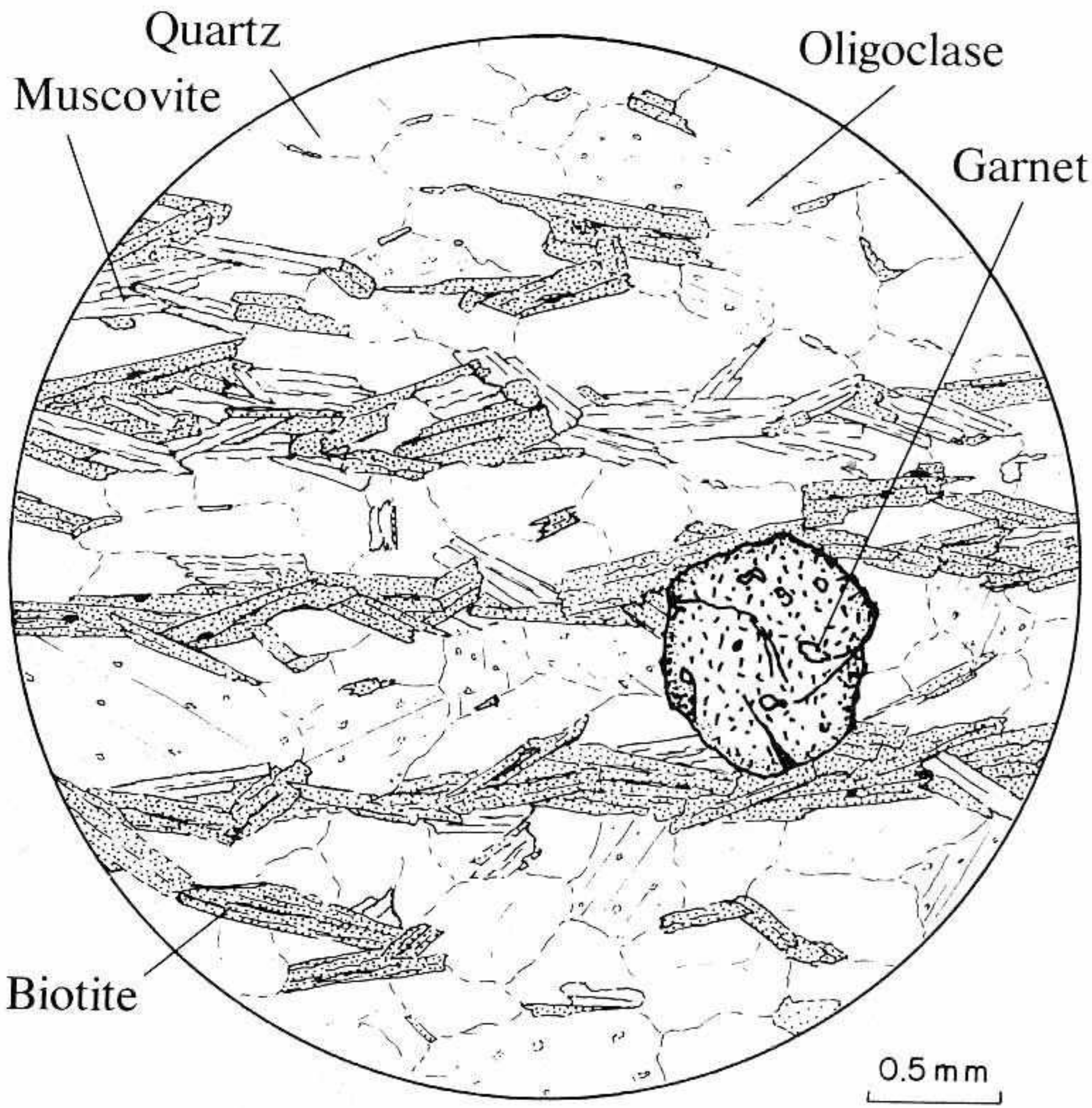
Progressive syntectonic metamorphism



Phase 4: Good schist with coarser grains

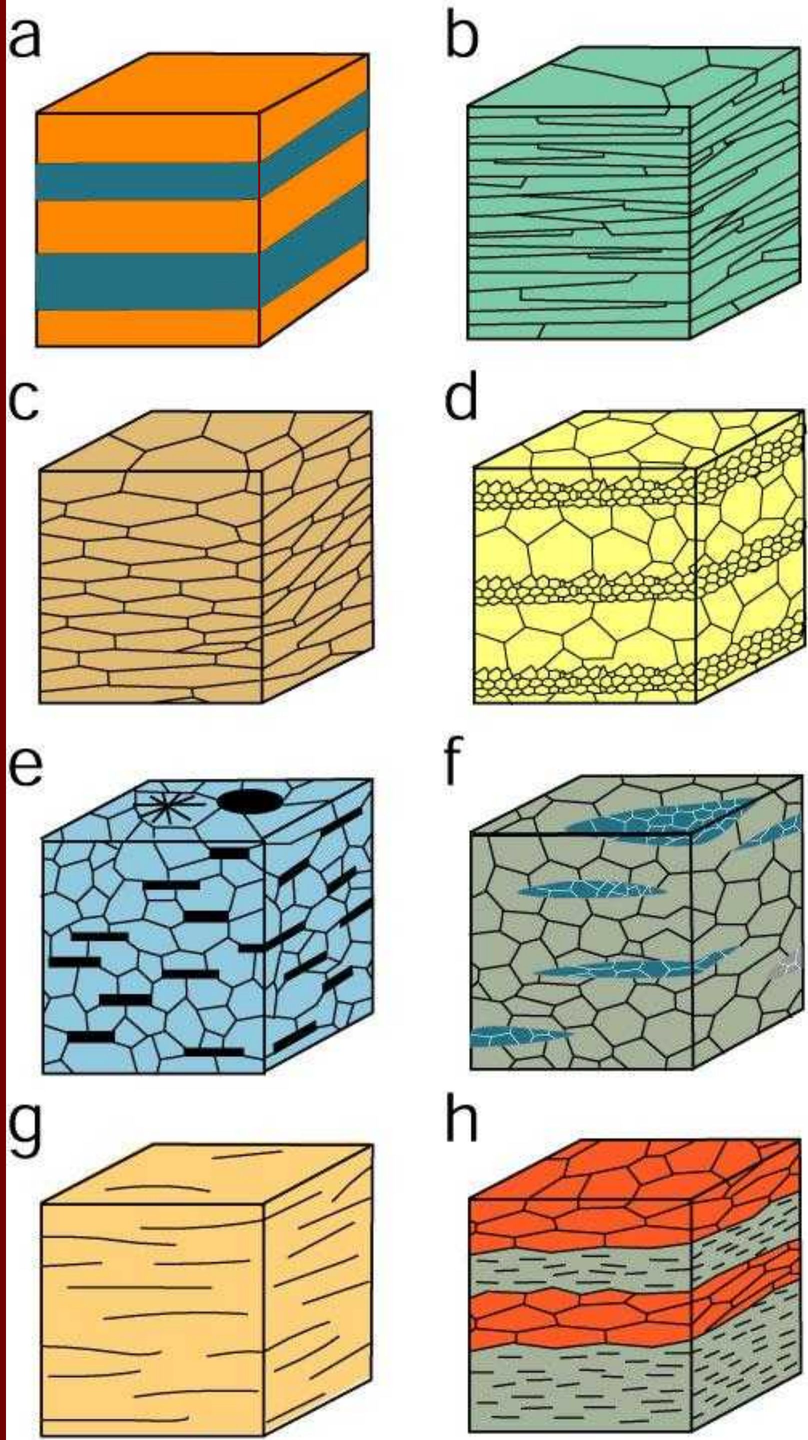
- More enhanced segregation into layers
- Plag no longer Ab- accepts more Ca at higher T
- Garnet is a new isograd mineral

Progressive syntectonic metamorphism of a volcanic graywacke,



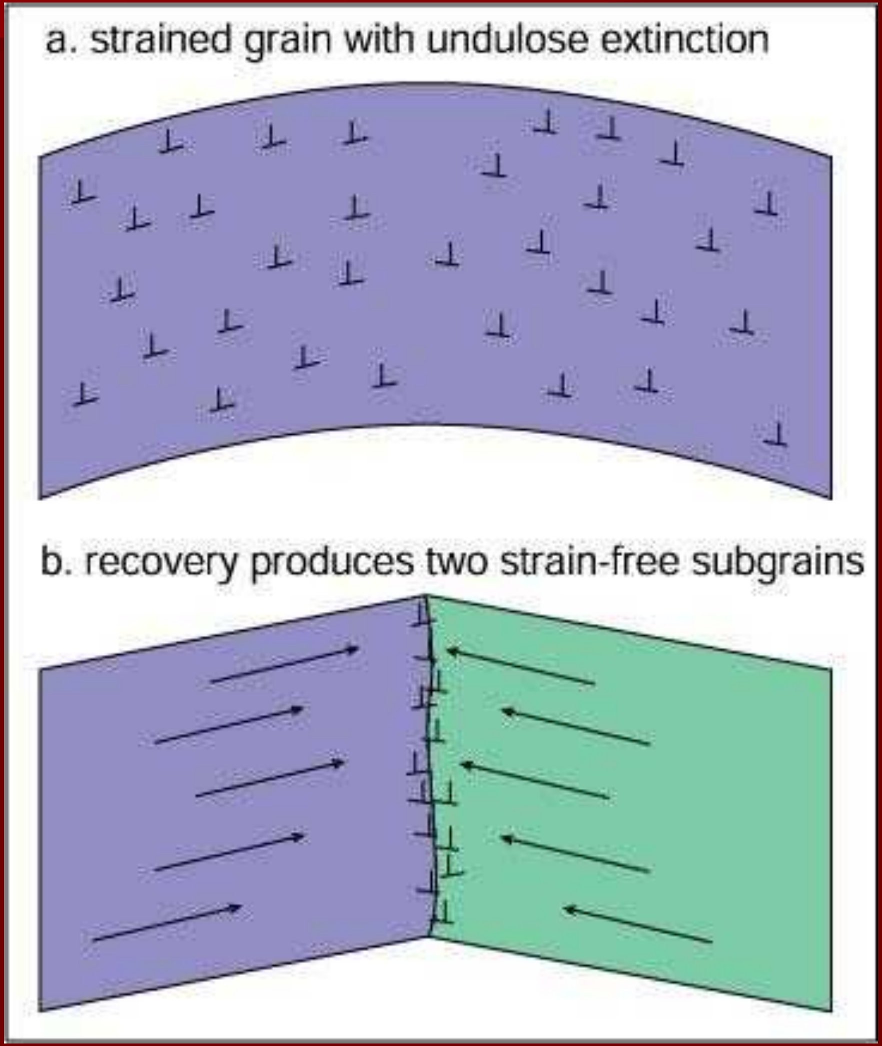
Types of foliations

a. Compositional layering
b. Preferred orientation of platy minerals
c. Shape of deformed grains
d. Grain size variation
e. Preferred orientation of platy minerals in a matrix without preferred orientation others
f. Preferred orientation of lenticular mineral aggregates
g. Preferred orientation of fractures
h. Combinations of the above



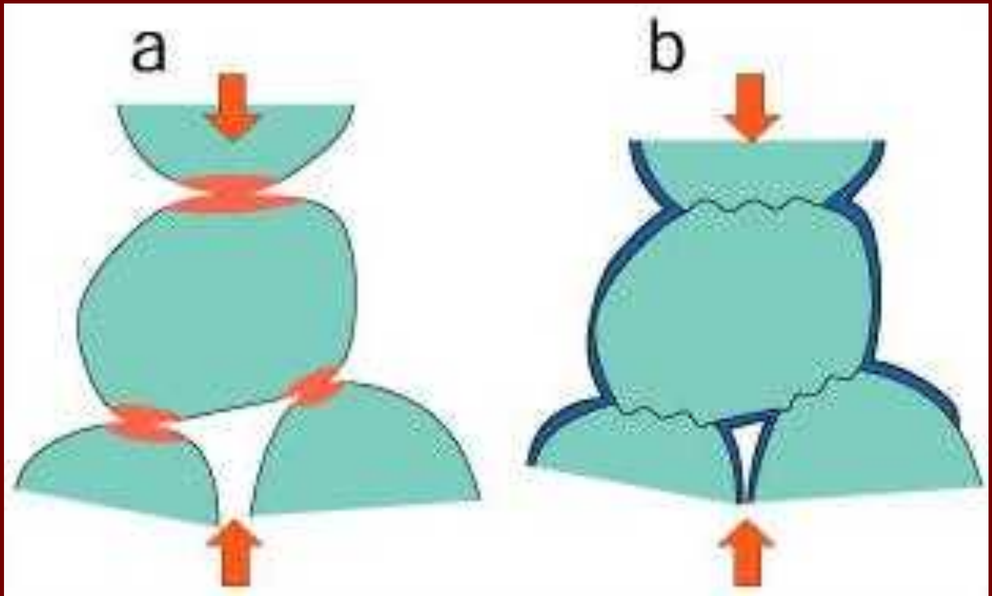
Textural Effects of Differential Stre

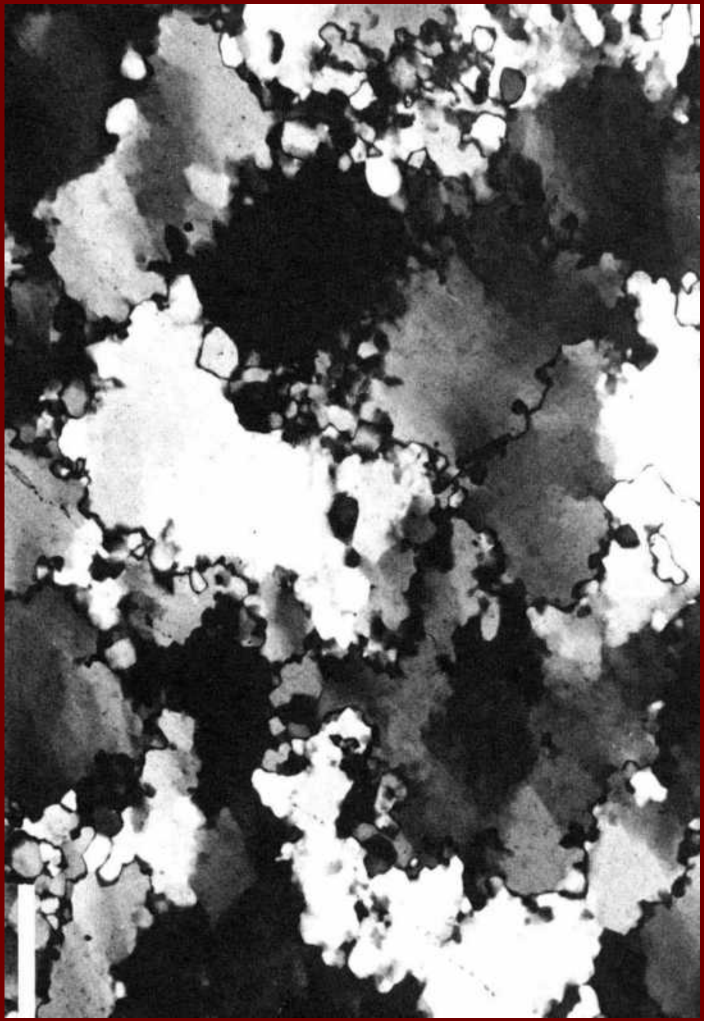
Stressed grains store strain energy released during metamorphism
clearing defects and dislocations (polygonization)



Pressure Solution

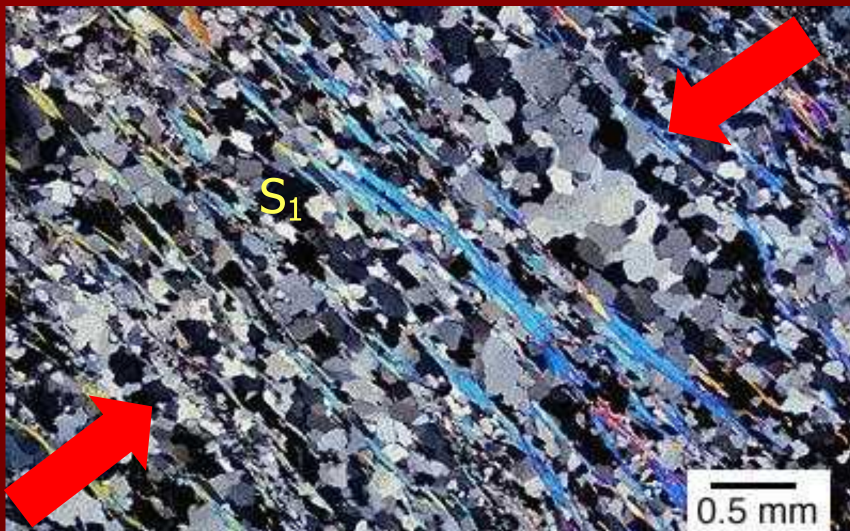
Differential stress produces serated grain boundaries

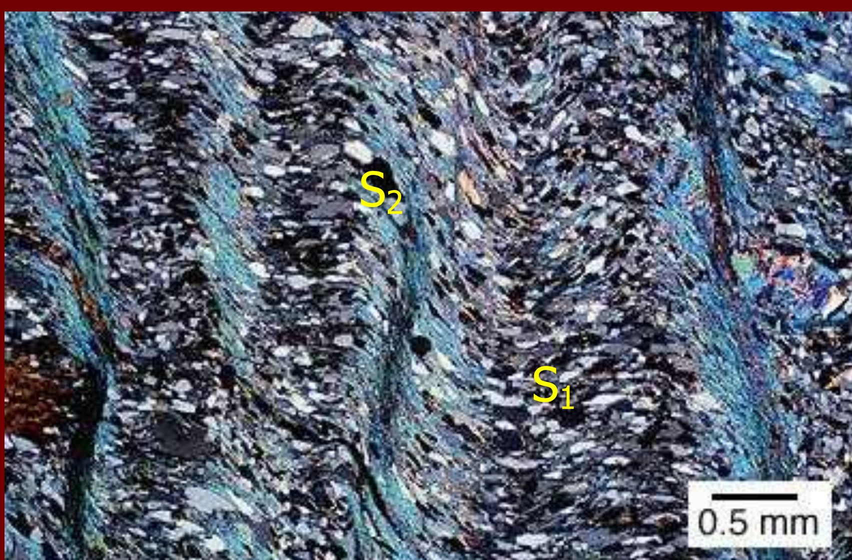




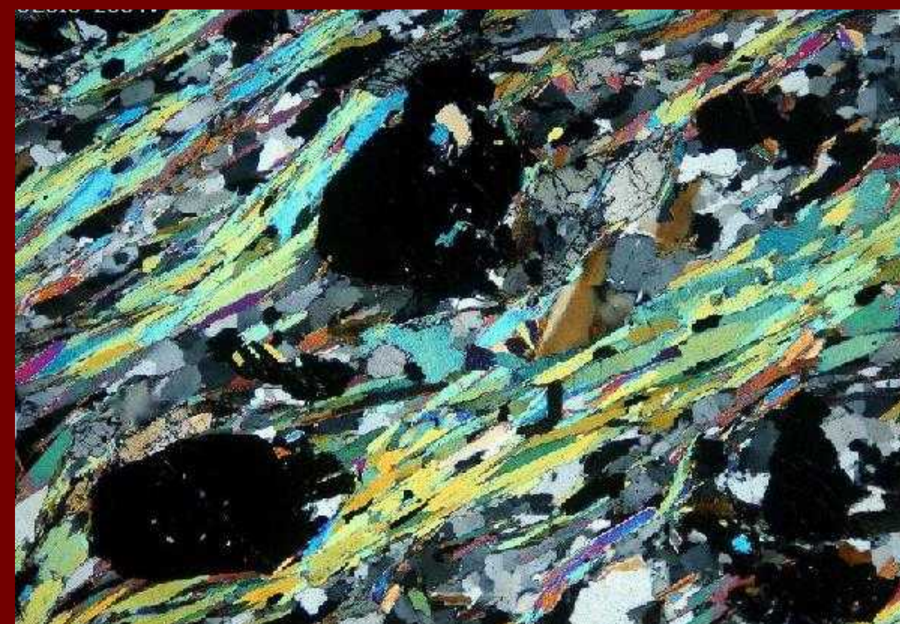
Foliation Development

σ_1





Schistocity S_1 flattened around garnet porphyroblasts



Crenulation cleavage S_2 developed by folding S_1

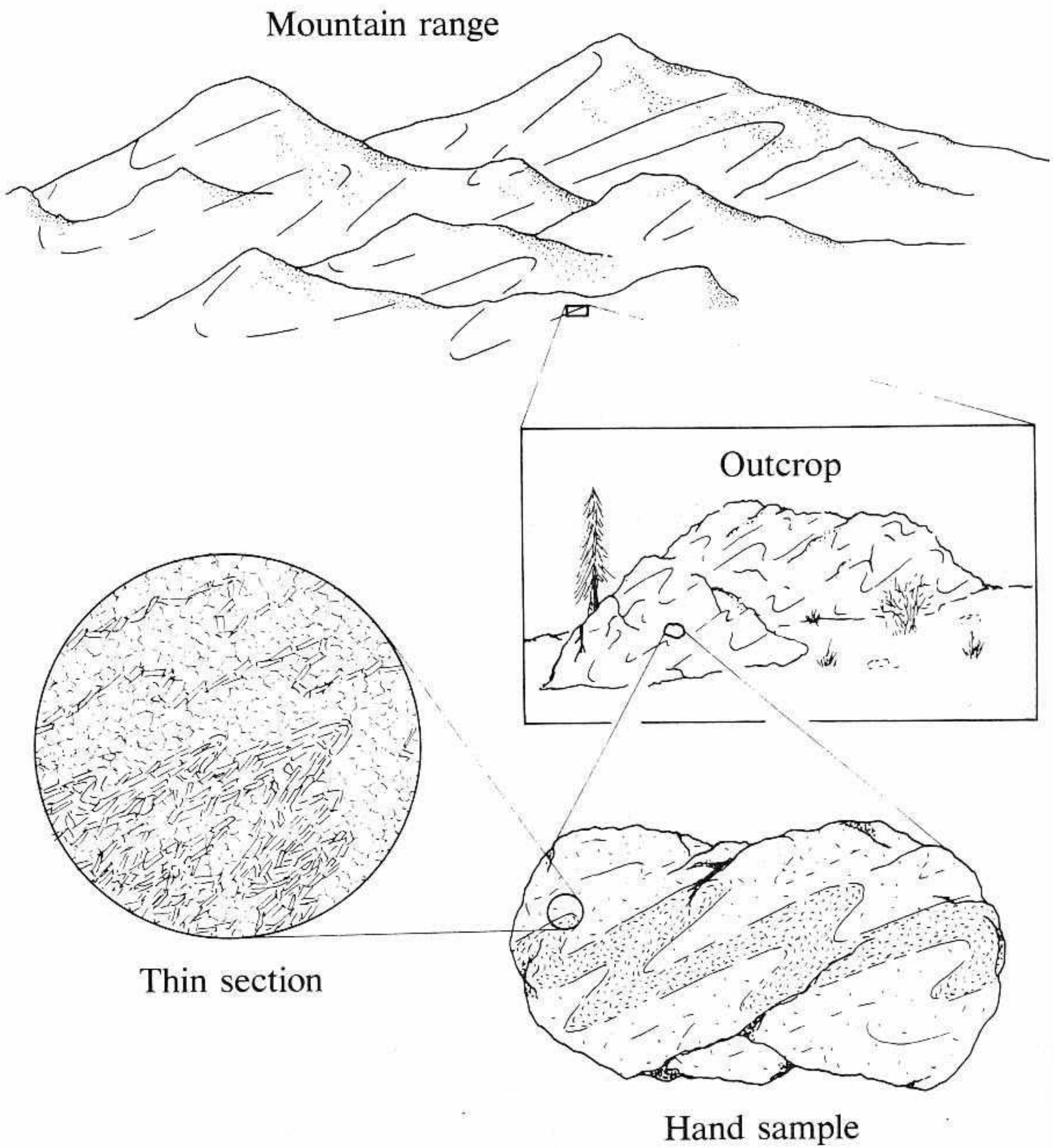
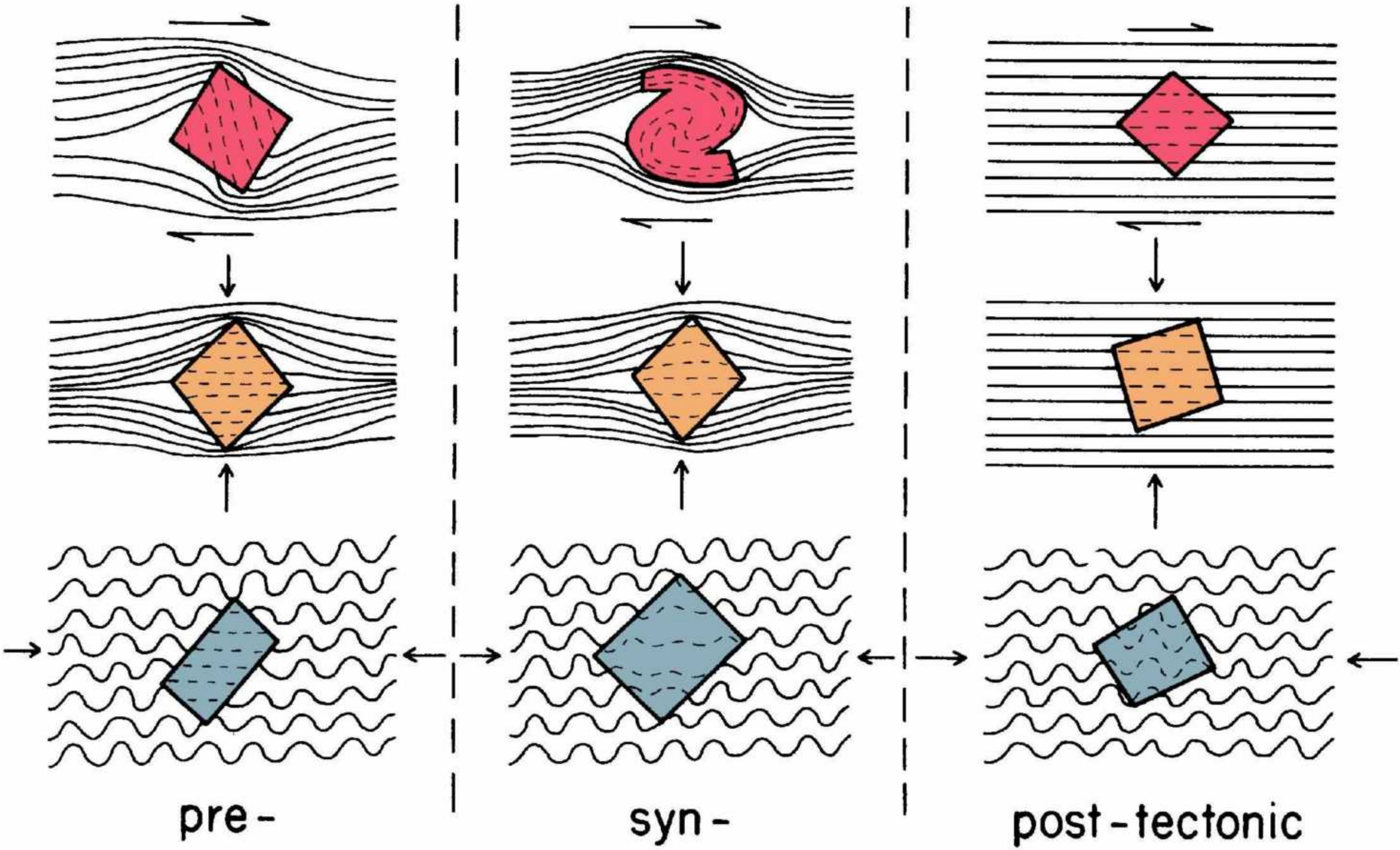


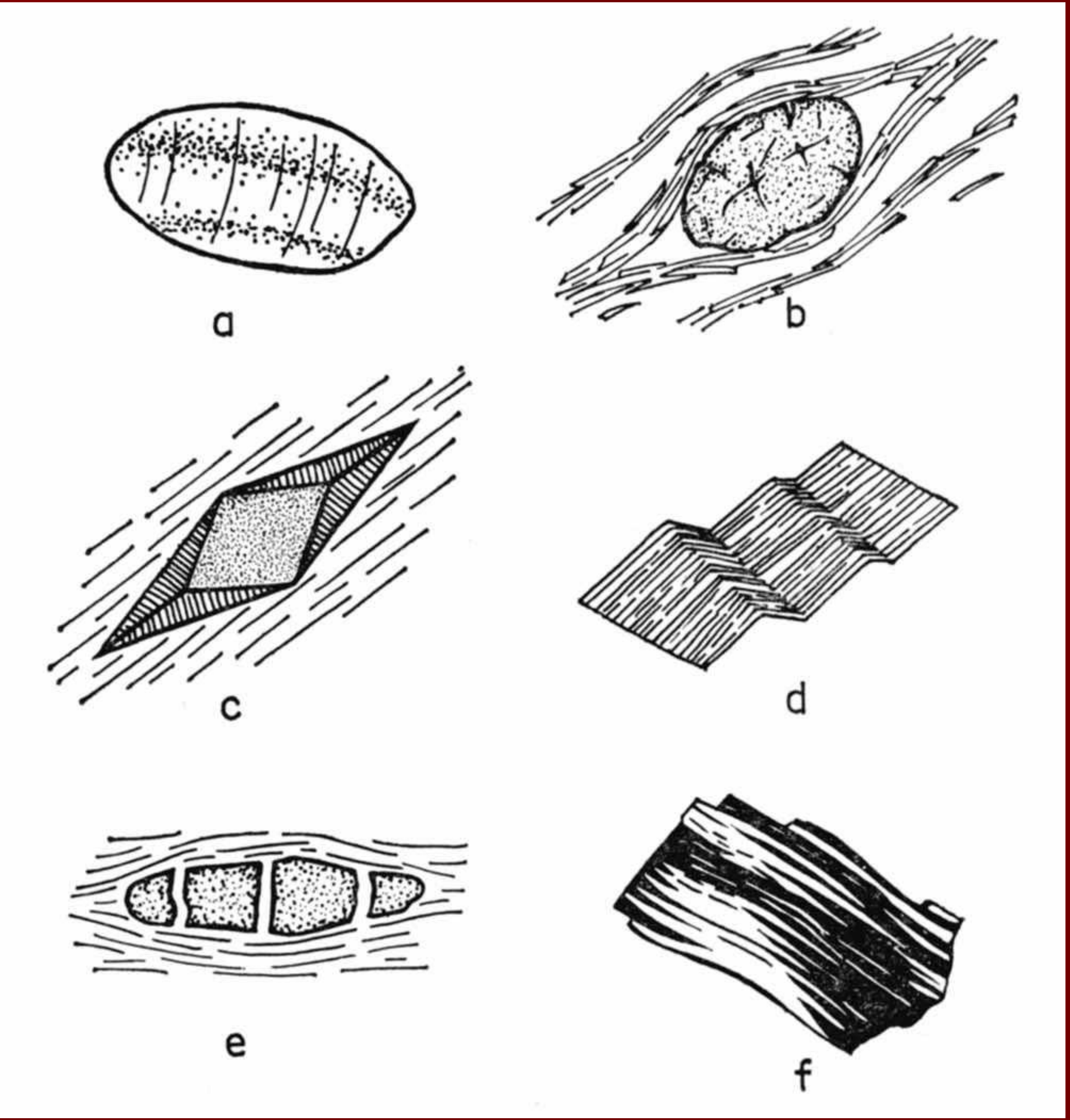
Diagram showing that structural and fabric elements are generally consistent in style and orientation at all scales.



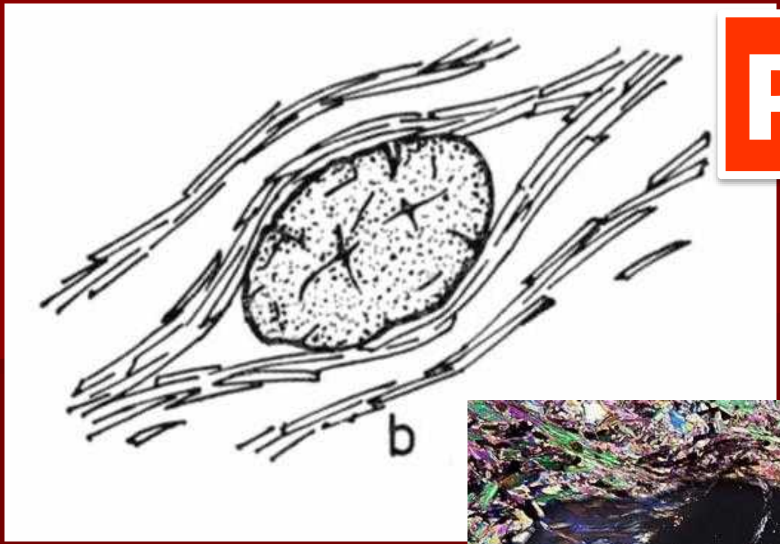
S_i characteristics of clearly pre-, syn-, and post-kinematic crystals as proposed by Zwart (1962). a. Progressively flattened S_i from core to rim. b. Progressively more intense folding of S_i from core to rim. c. Spiraled S_i due to rotation of the matrix or the porphyroblast during growth. After Zwart (1962) *Geol. Rundschau*, 52, 38-65.

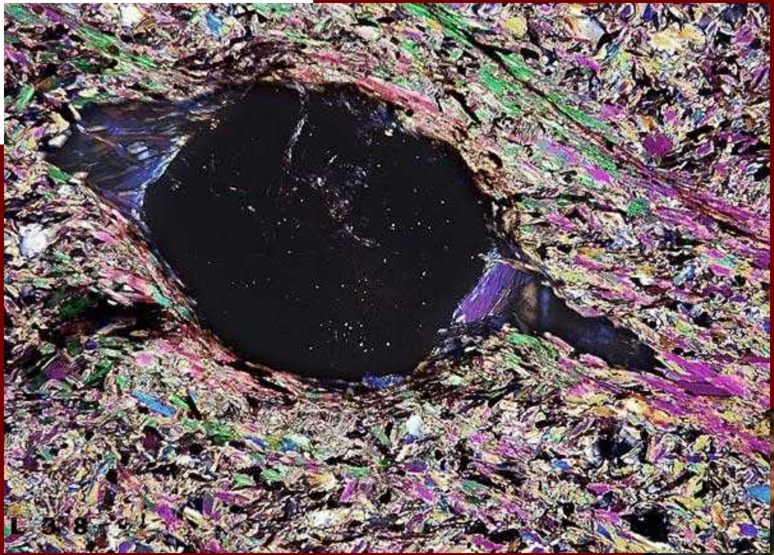
Pre-kinematic crystals

a. Bent crystal with undulose extinction
b. Foliation wrapped around a porphyroblast
c. Pressure shadow or fringe
d. Kink bands or folds
e. Microboudinage
f. Deformation twins



Pressure Shadows

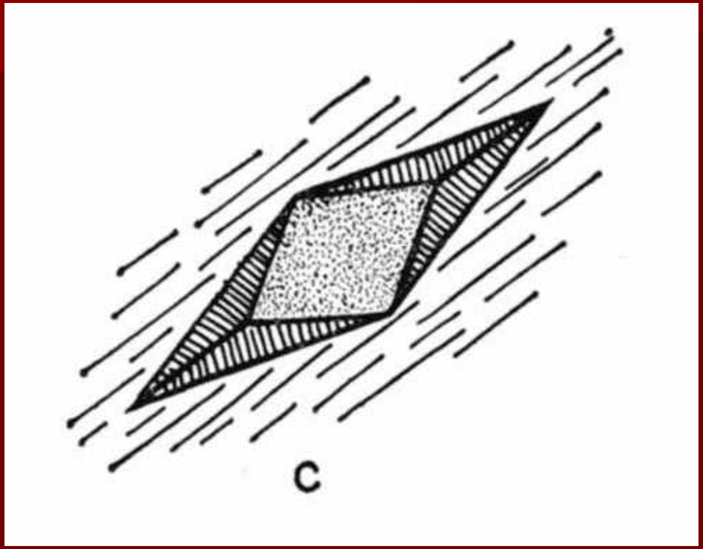


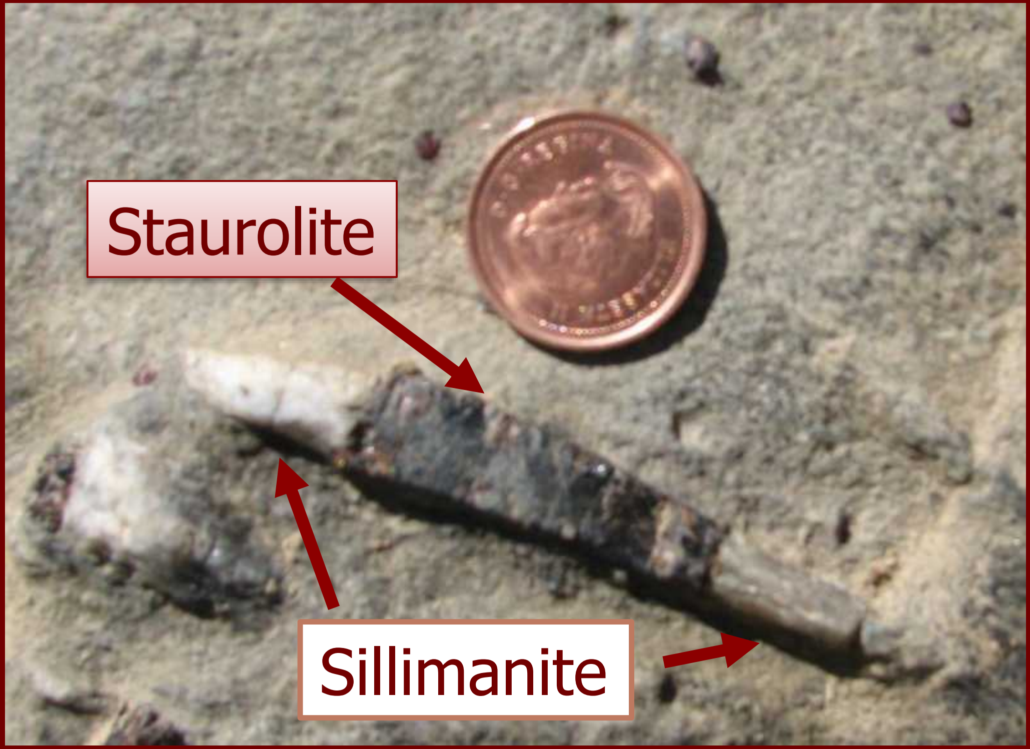


Chlorite in shadow around garnet

Quartz in shadow around staurolite

Pressure Fringes

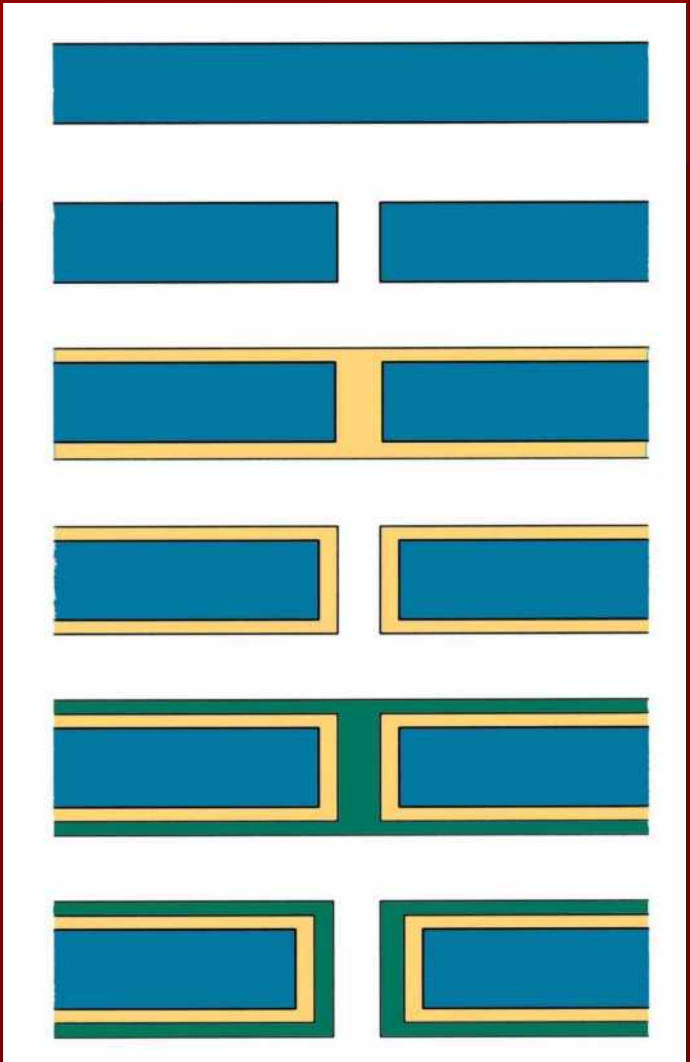


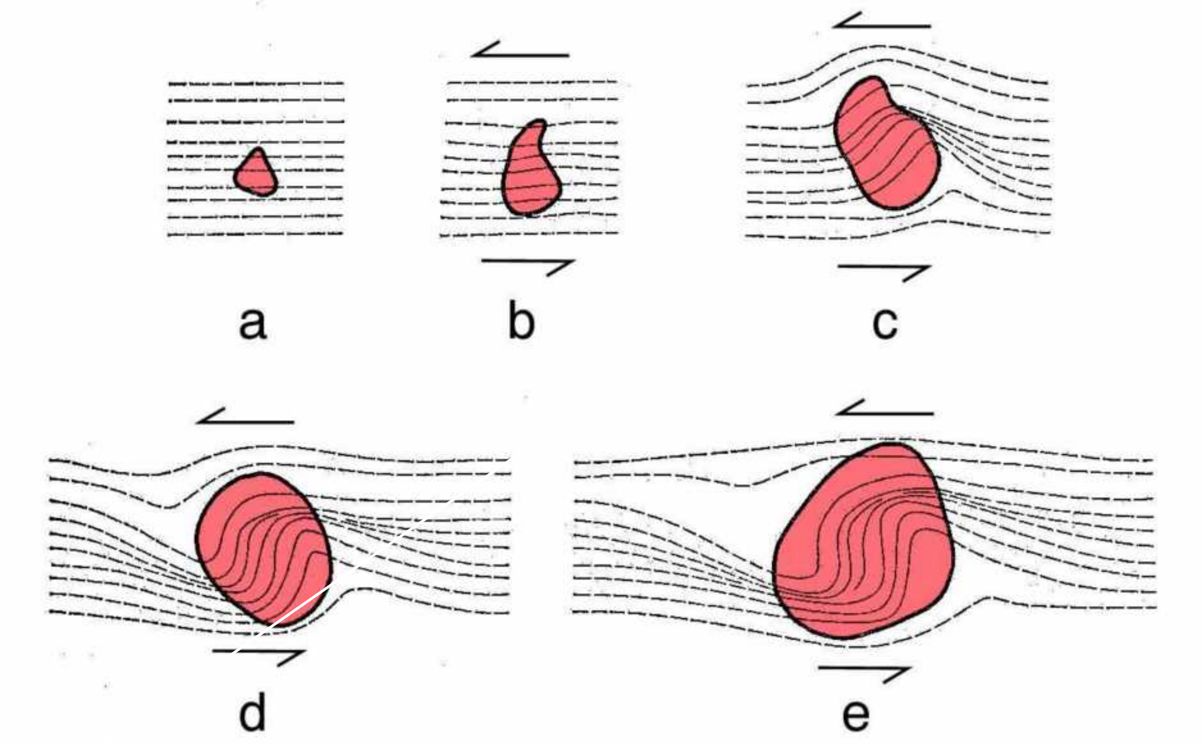


Syn-kinematic crystals

Paracrystalline microboudinage

Spiral Porphyroblast





Traditional interpretation of spiral S_i train in which a porphyroblast is rotated by shear as it grows.

Syn-crystallization micro-boudinage. Syn-kinematic crystal growth can be demonstrated by the color zoning that grows and progressively fills the gap between the separating fragments.

Syn-kinematic crystals

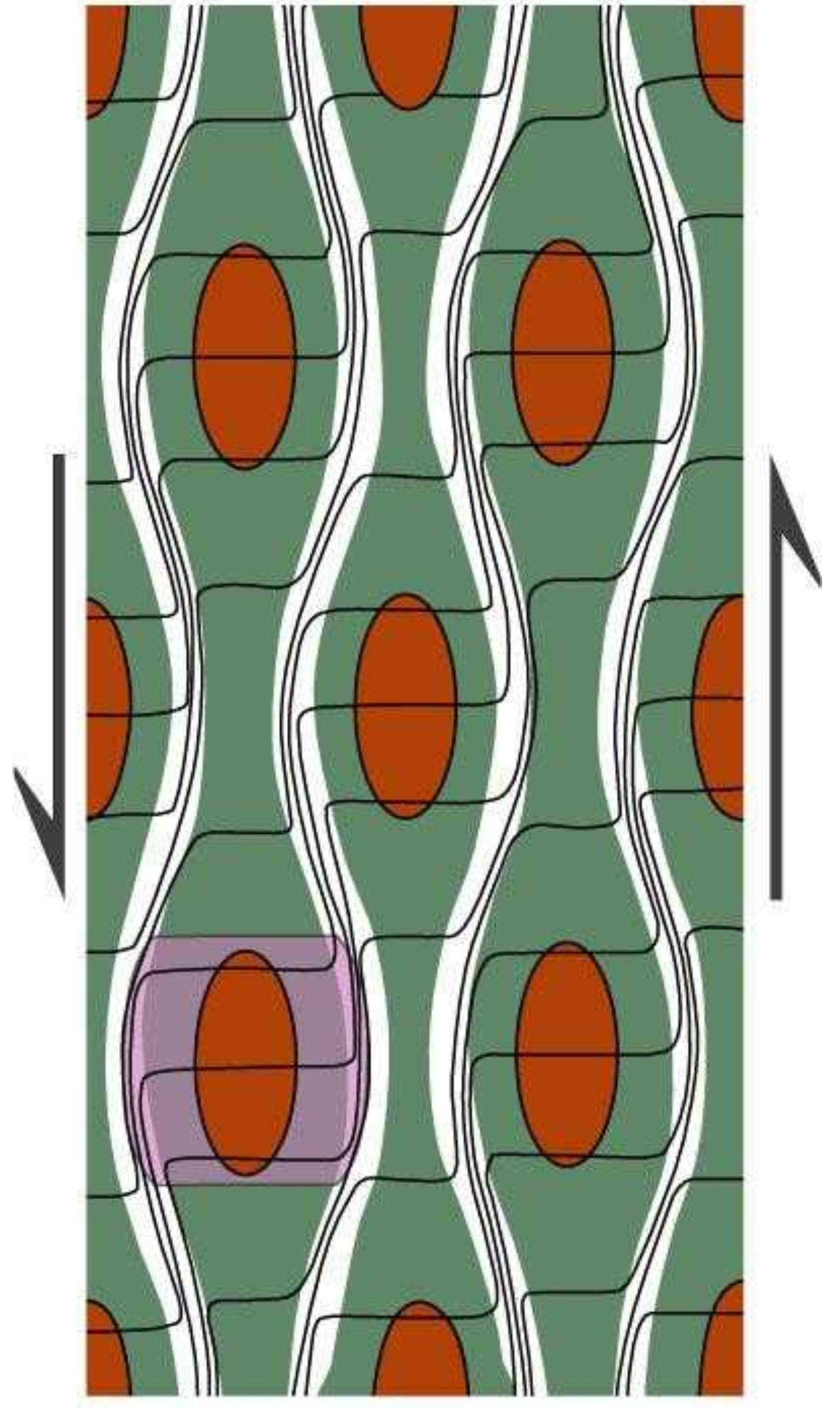
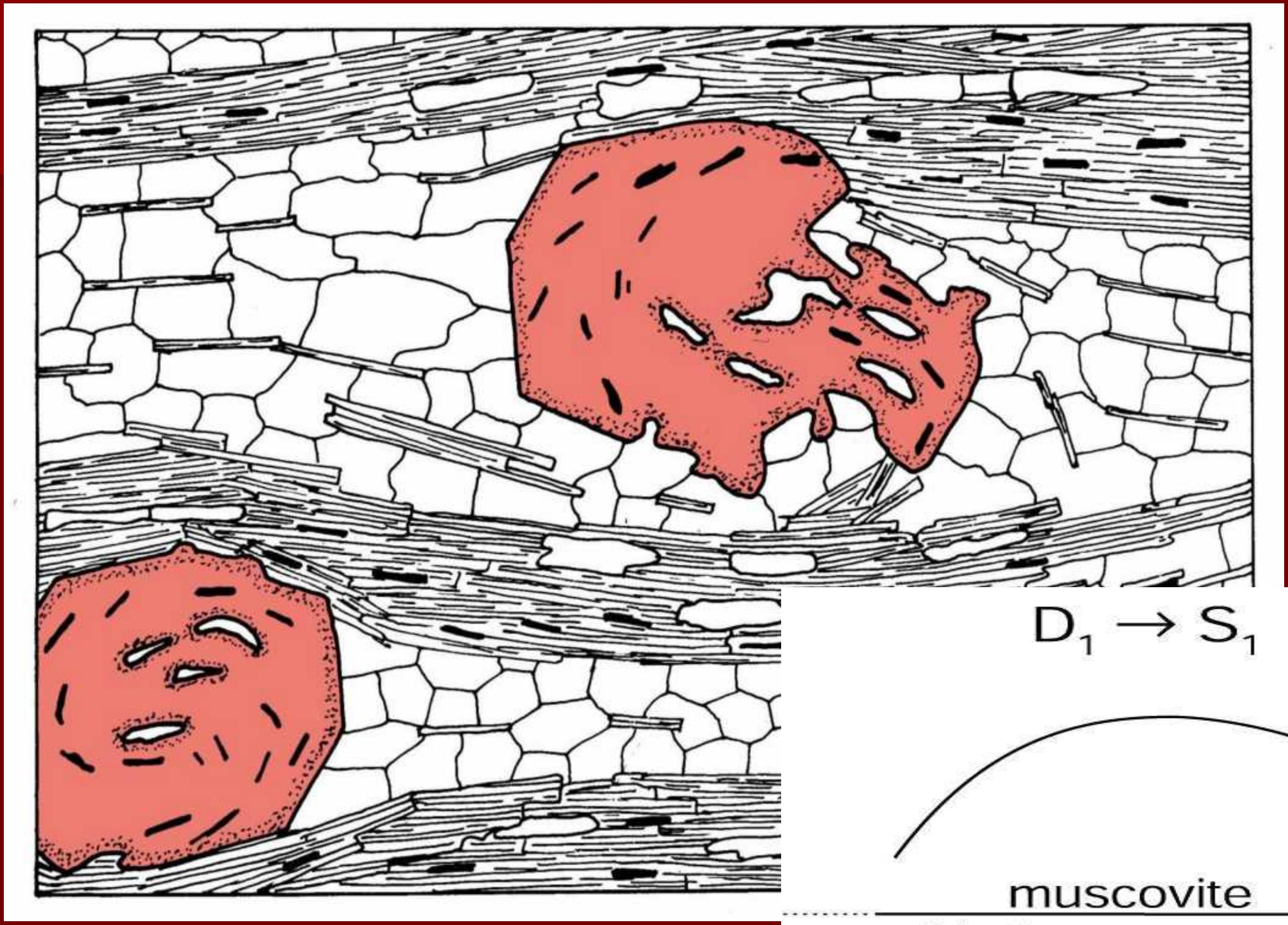


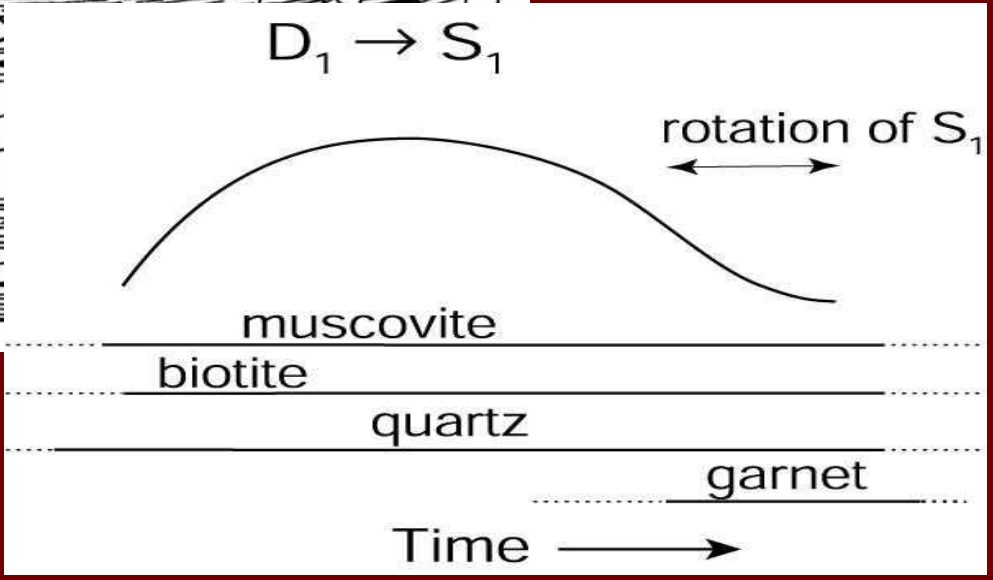
Figure 23.40. Non-uniform distribution of shear strain as proposed by Bell *et al*. (1986) *J. Metam. Geol.*, 4, 37-67. Blank areas represent high shear strain and colored areas are low-strain. Lines represent initially horizontal inert markers (S_1). Note example of porphyroblast growing preferentially in low-strain regions.

Syn-kinematic crystals

Spiral S_i trails in garnet

Syn-tectonic Texture





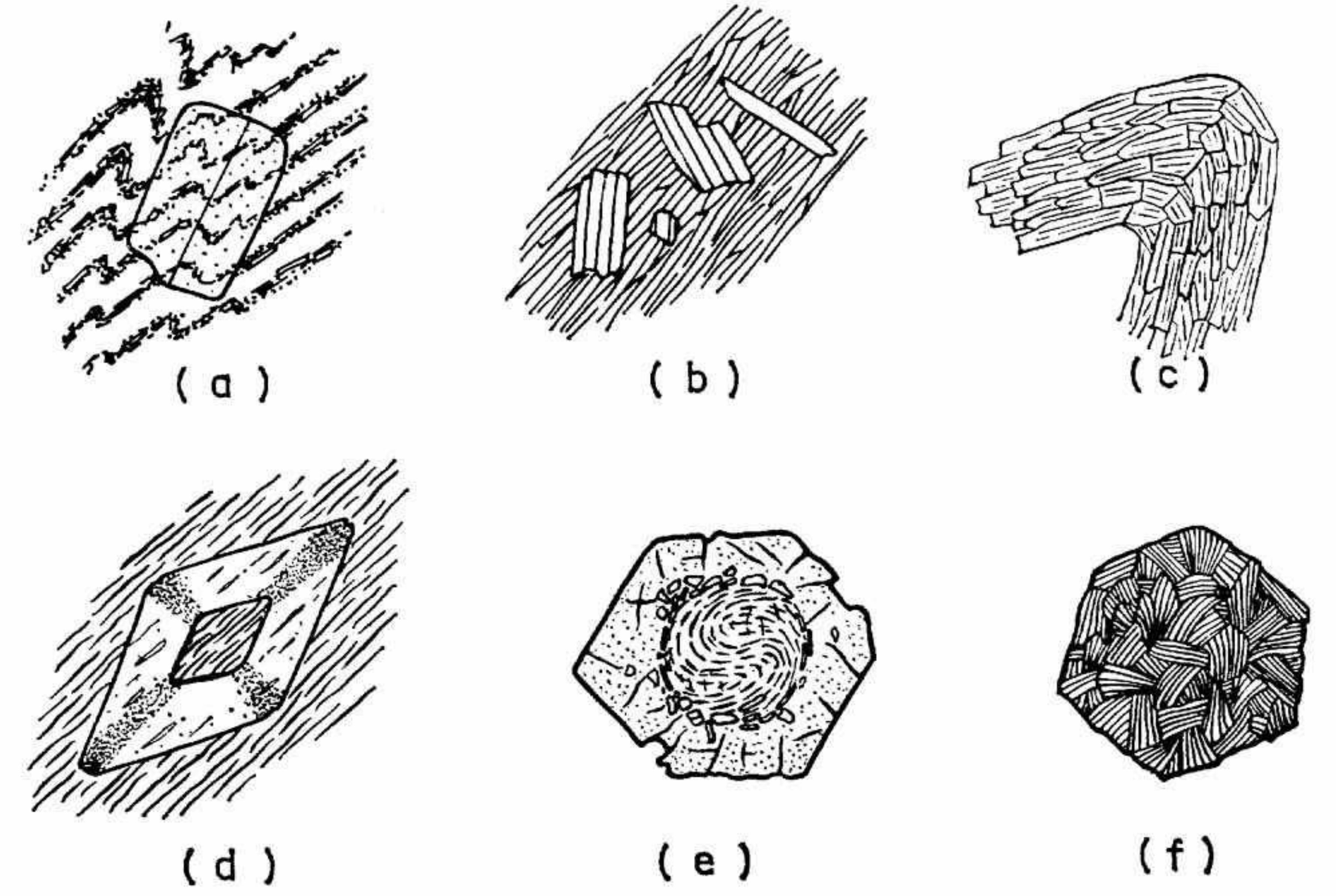
Snowball Garnet with Pressure Shadows

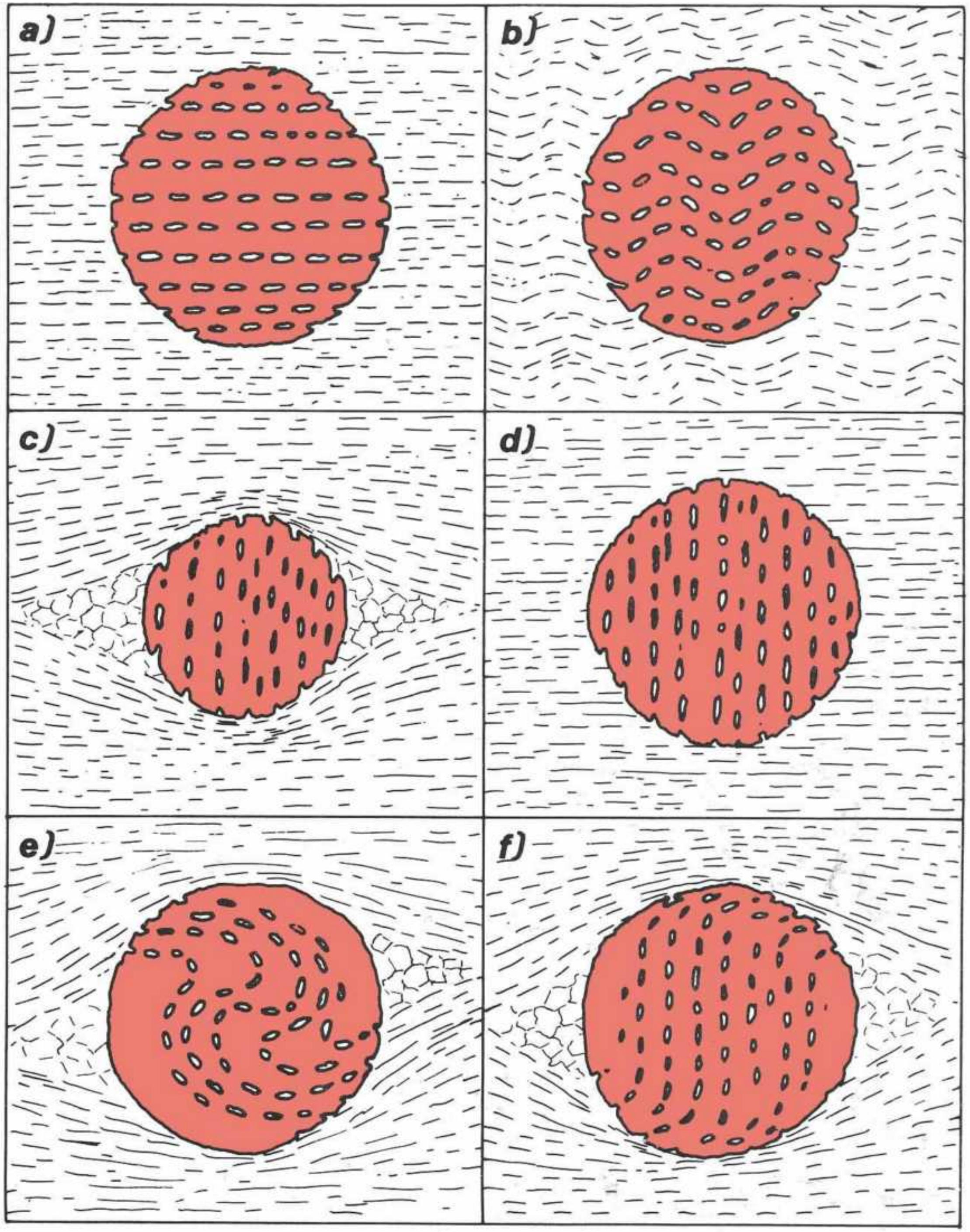
Syn-kinematic crystals

"Snowball garnet" with highly rotated spiral S_i.

Post-kinematic crystals

a. Helicitic folds b. Randomly oriented crystals c. Polygonal arcs d. Chiastolite e. Late, inclusion-free rim on a poikiloblast (?) f. Random aggregate pseudomorph





Post-kinematic: S_i is identical to and continuous with S_e

Pre-kinematic: Porphyroblasts are post-S_2. S_i is inherited from an earlier deformation. S_e is compressed about the porphyroblast in (c) and a pressure shadow develops.

Syn-kinematic: Rotational porphyroblasts in which S_i is continuous with S_e suggesting that deformation did not outlast porphyroblast growth.

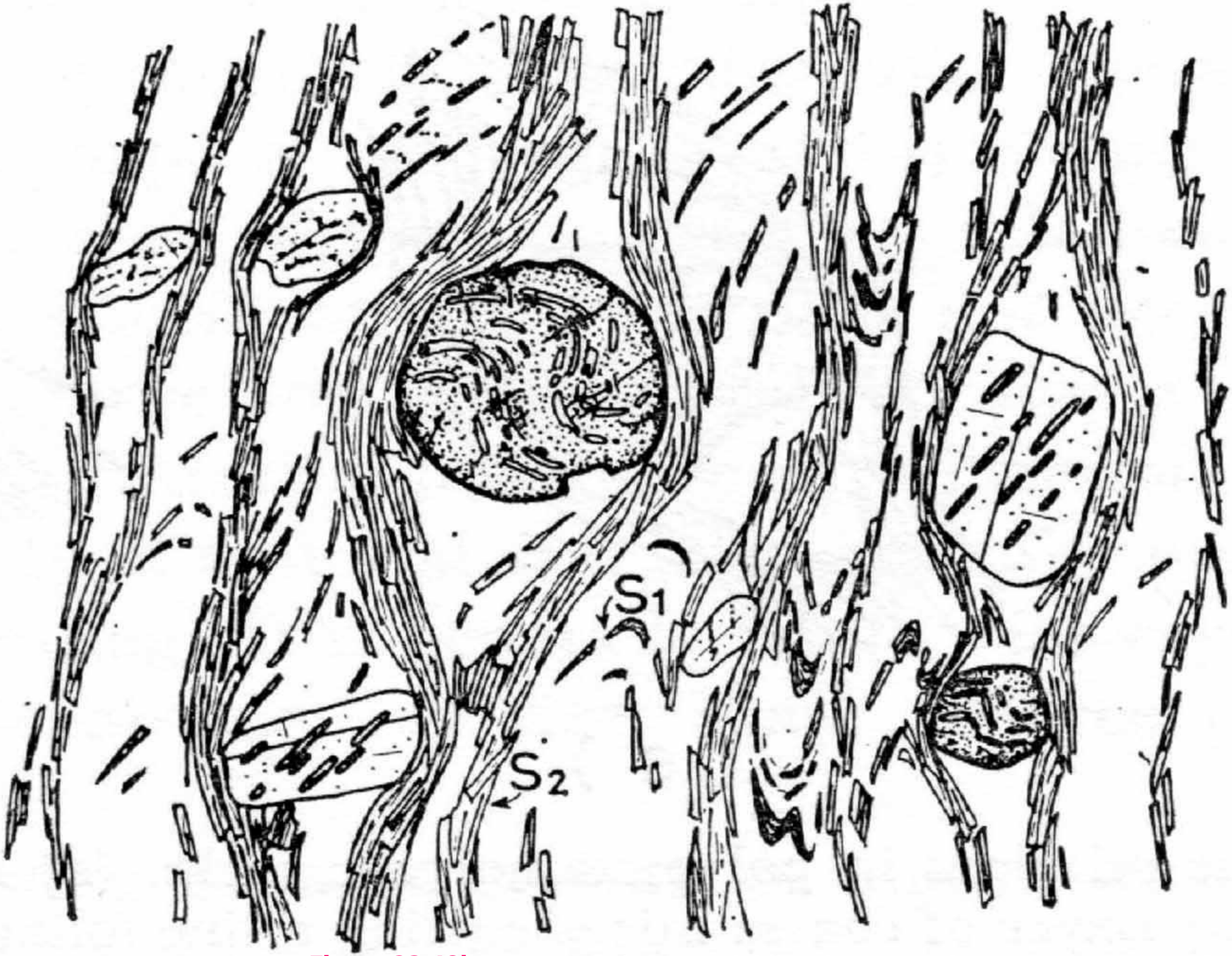
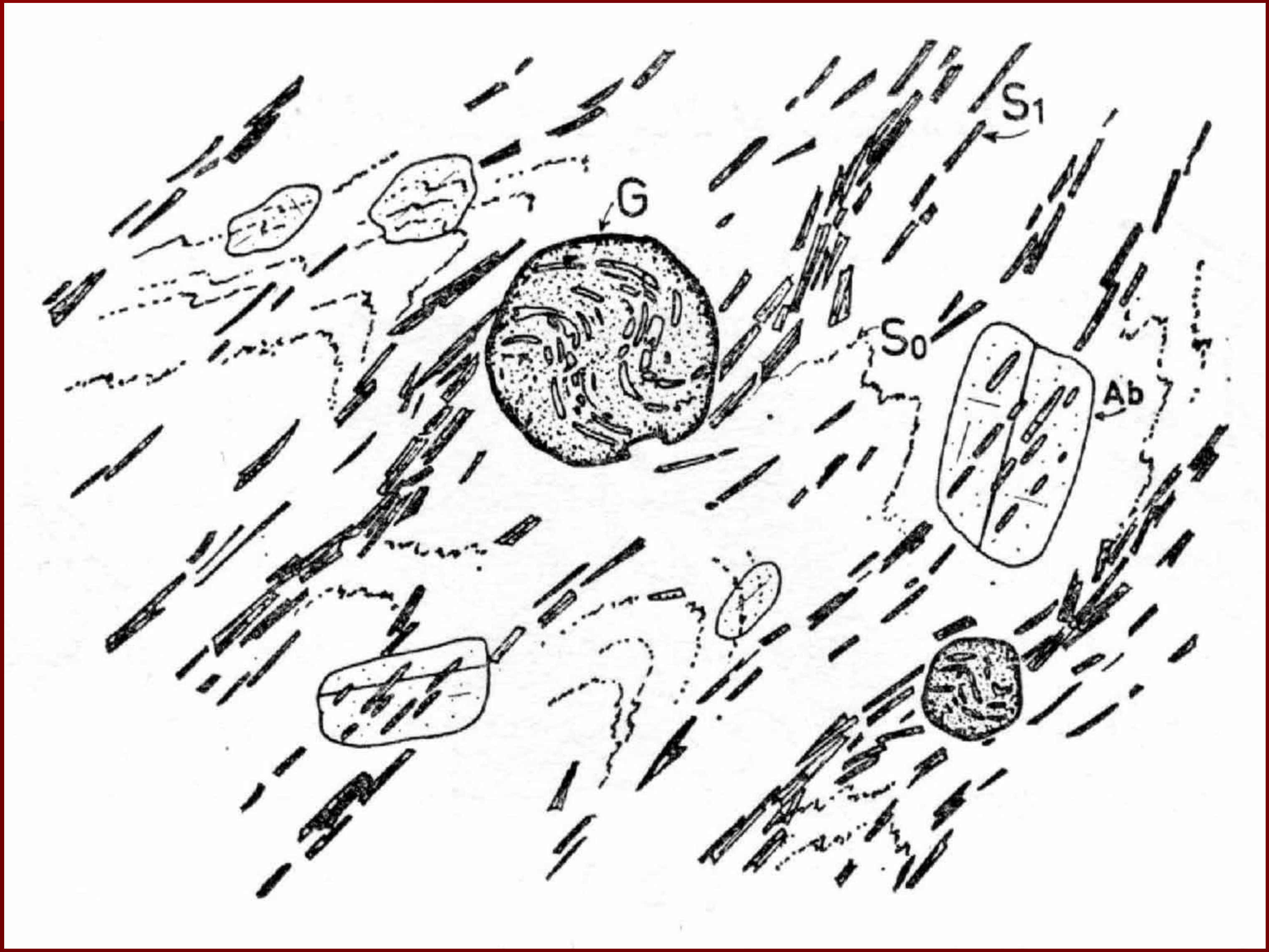
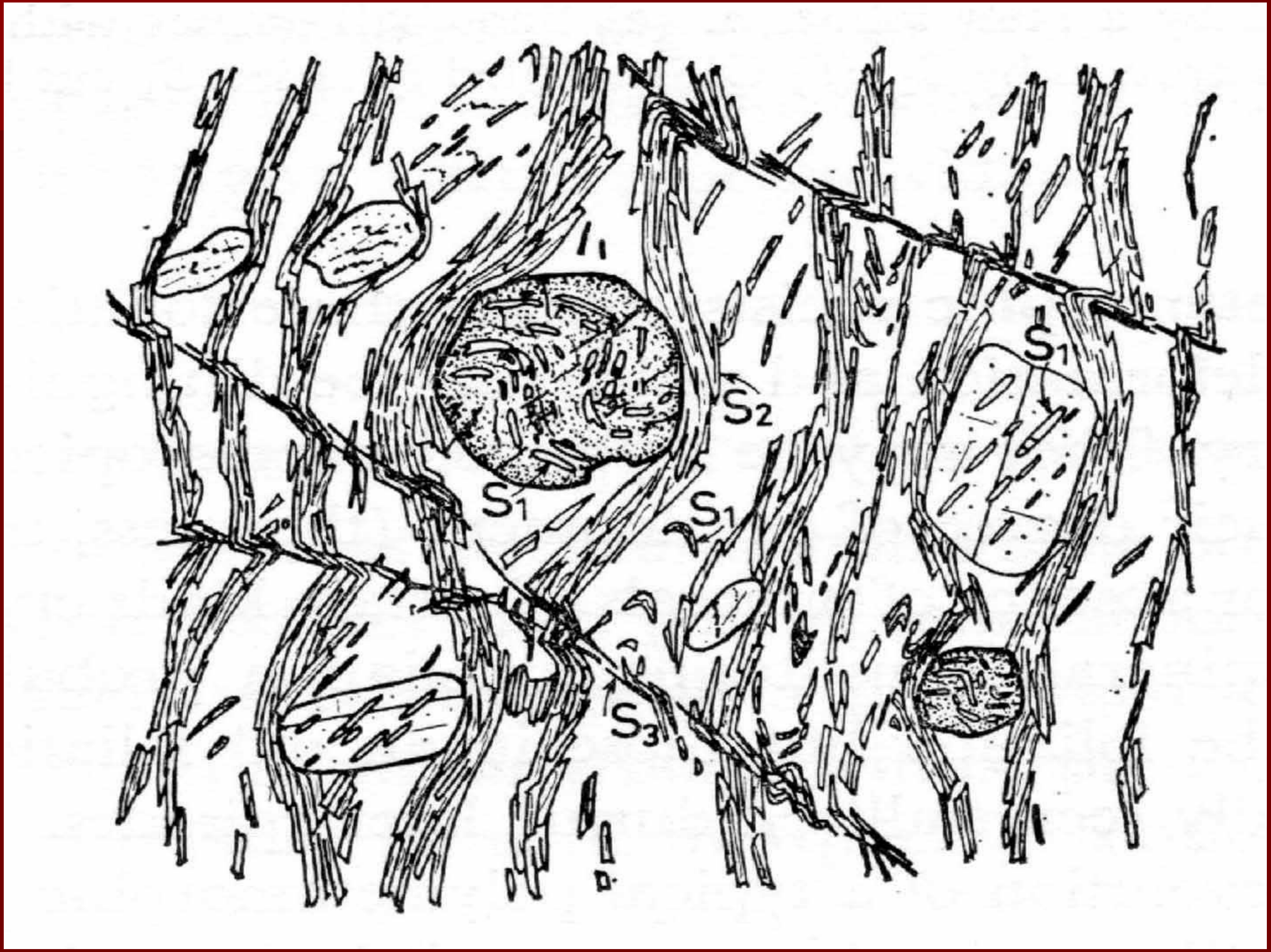


Figure 23.48b.

Stages in Polymetamorphism (S_0, S_1)



Stages in Polymetamorphism (S_3)

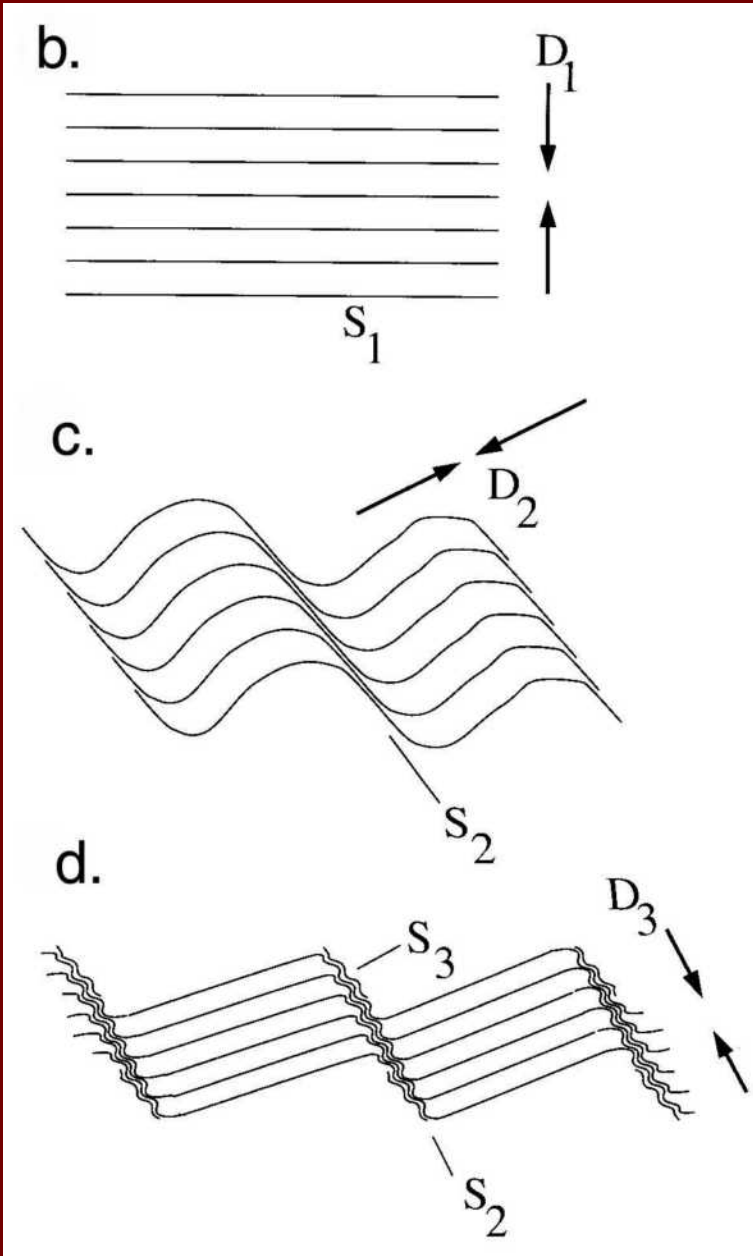


Analysis of Deformed Rocks

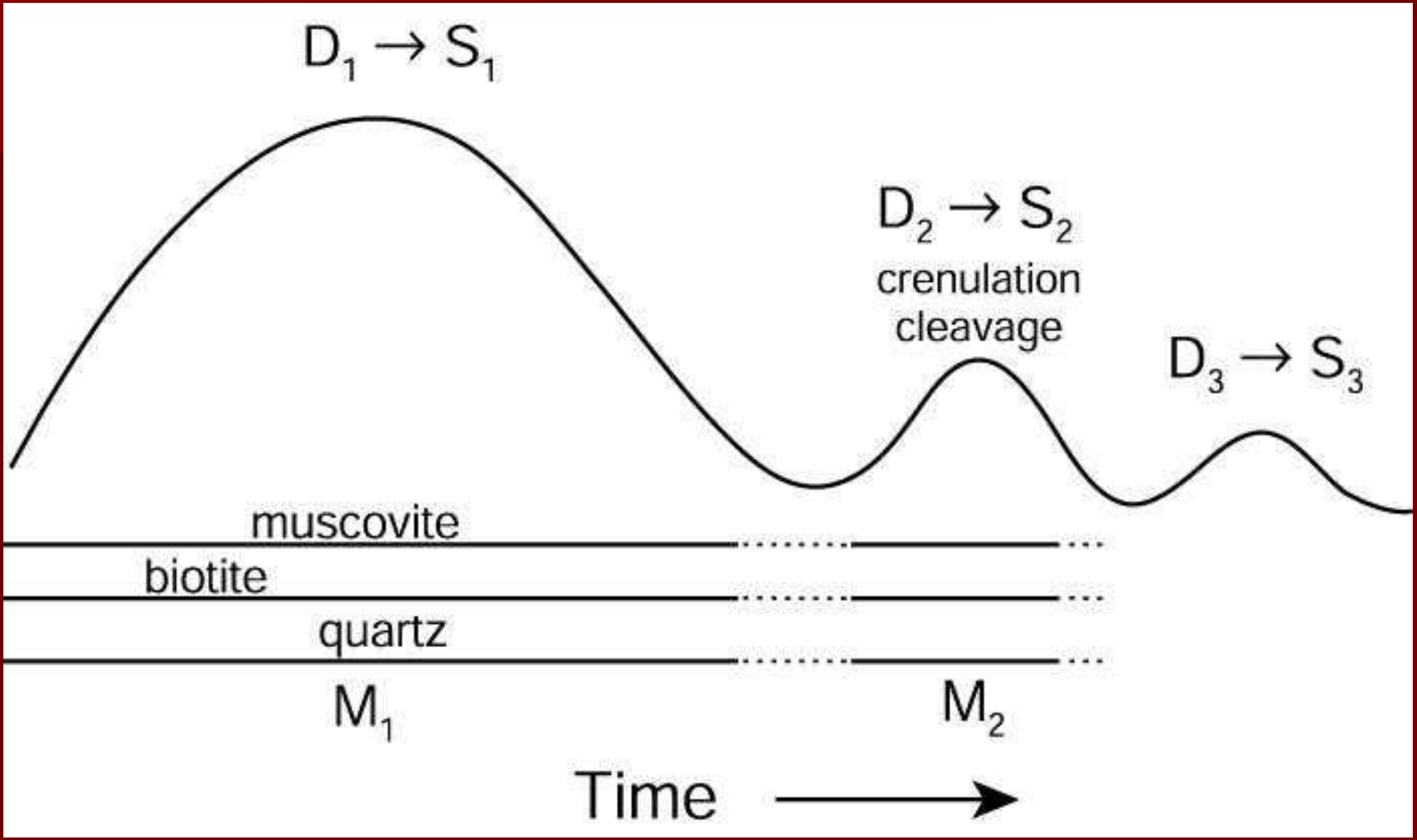
- Deformational events: D_1 D_2 D_3 …
- Metamorphic events: M_1 M_2 M_3 …
- Foliations: S_o S_1 S_2 S_3 …
- Lineations: L_o L_1 L_2 L_3 …
- Plot on a metamorphism-deformation-time plot showing the crystallization of each mineral

Analysis of Deformed Rocks

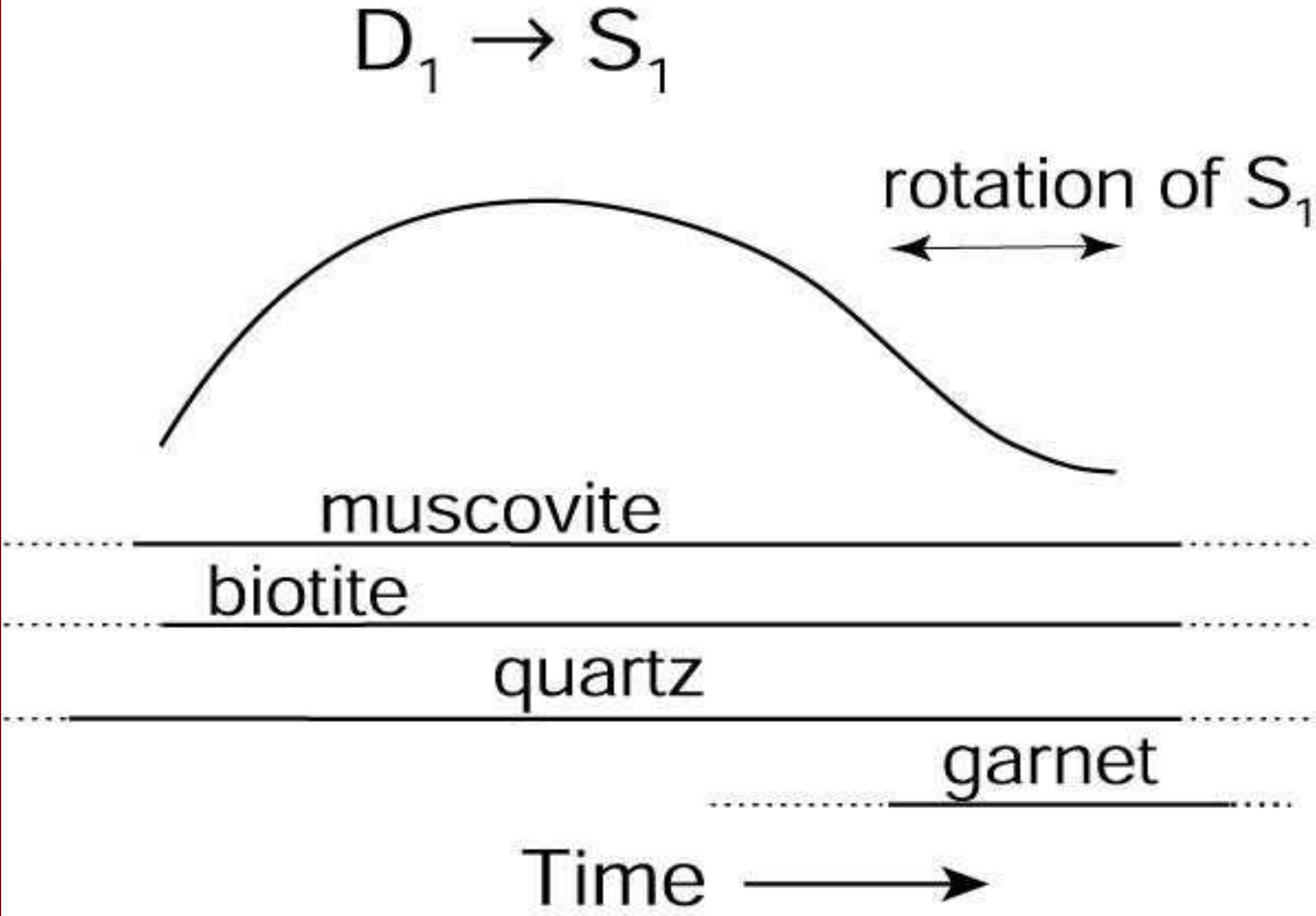
Asymmetric crenulations cleavage (S_2) developed over S_1 cleavage. S_2 is folded, as can be seen in the dark sub-vertical S_2 bands.



Analysis of Deformed Rocks

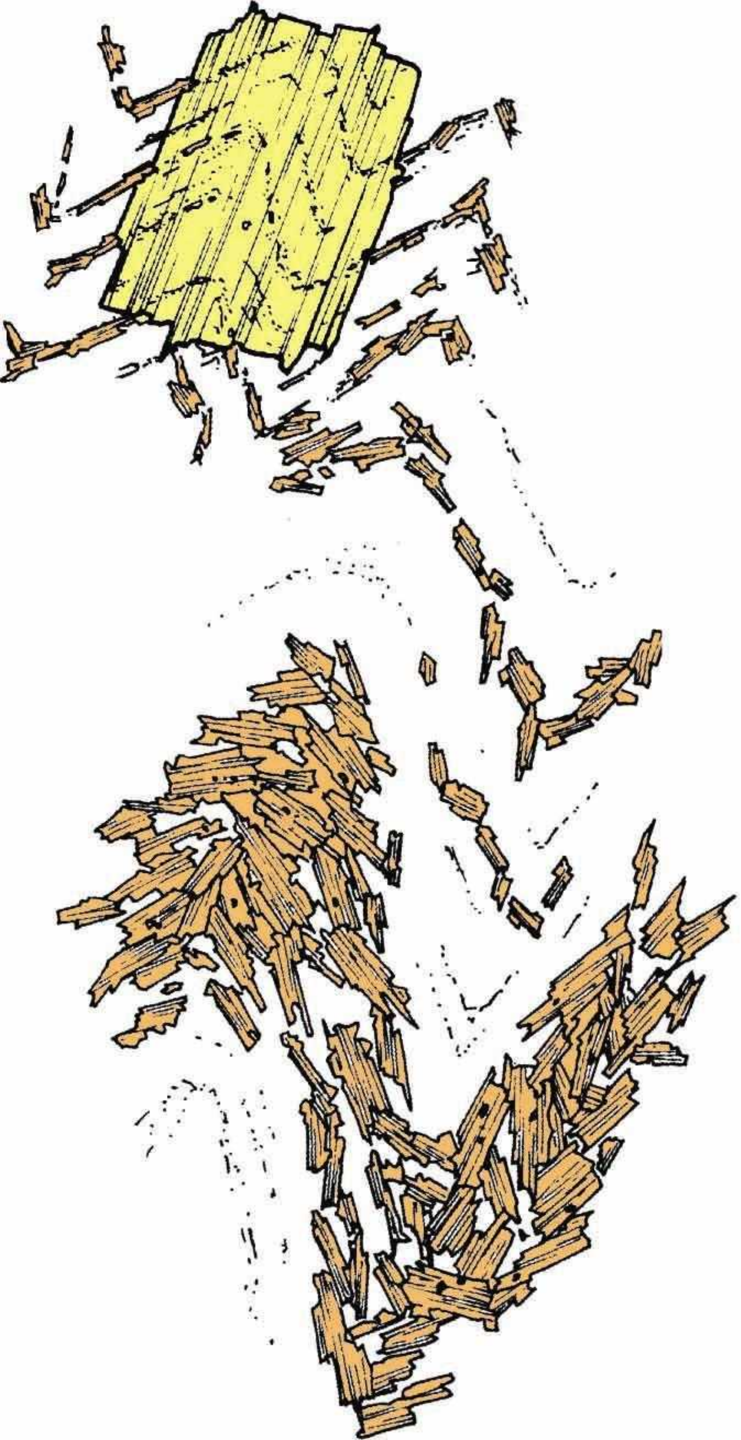


Graphical analysis of the relationships between deformation (D), metamorphism (M),

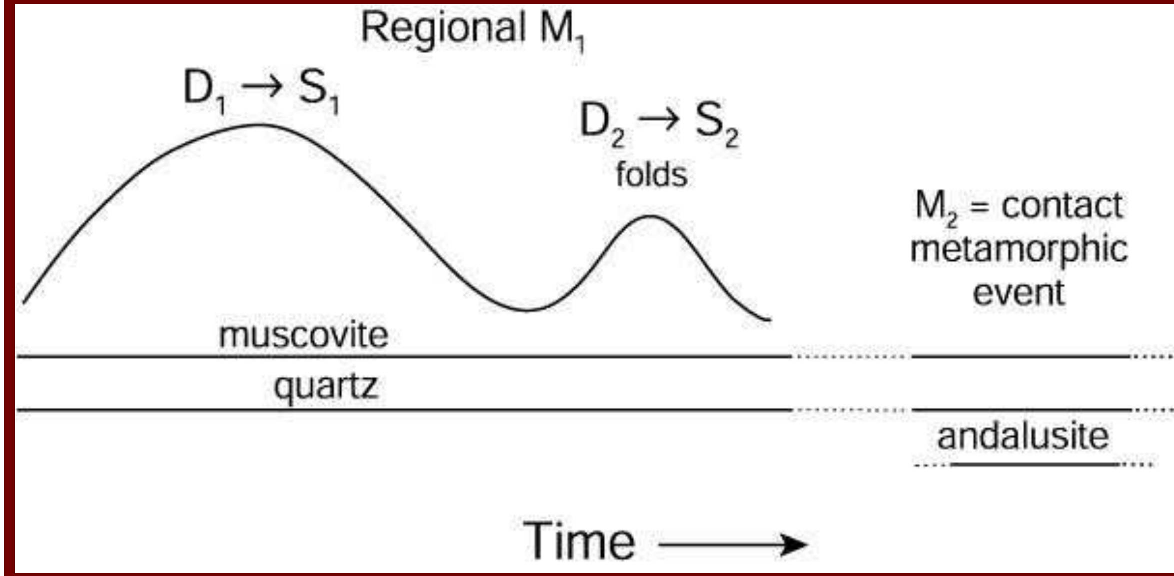


$D_1 \rightarrow S_1$
rotation of S_1
muscovite
biotite
quartz
garnet
Time

Figure 23.45.



Textures in a hypothetical andalusite porphyryoblast-mica schist.



Graphical analysis of the relationships between deformation (D), metamorphism (M), mineral growth