Principles of structural geology and tectonic analysis

Strain

- In response to stress, rocks undergo transformations that are decomposed in 3 operations:
  - Rotation
  - Translation
  - Deformation which corresponds to a change in form
- Strain is a change in shape or internal configuration of a body

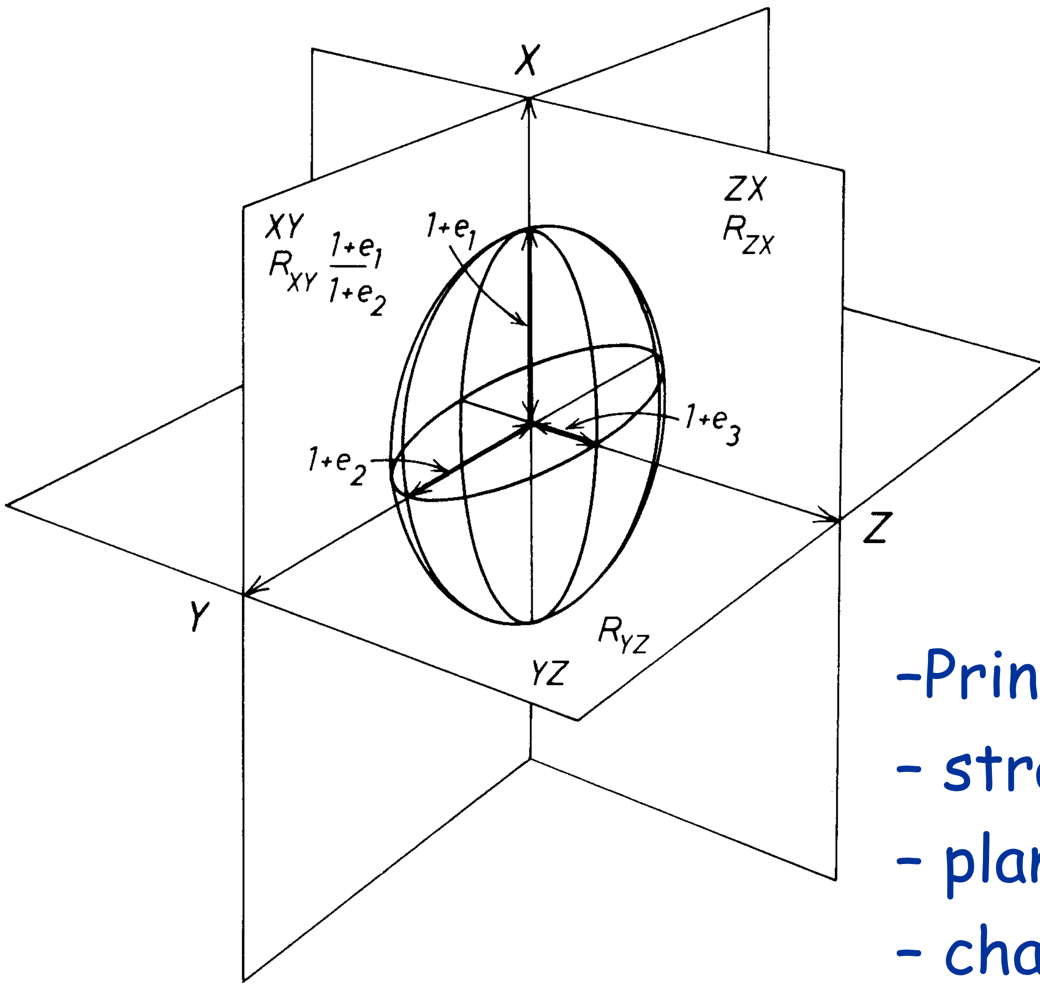
Strain

- Strain is marked by
  - Transformation of an initial circle/sphere into an ellipse/ellipsoid
    - The axis of deformation
  - Movement of particules defined by an instantaneous velocity vector, defining flow lines and finally trajectories
    - The kinematic notion, a function of time

Stress and strain

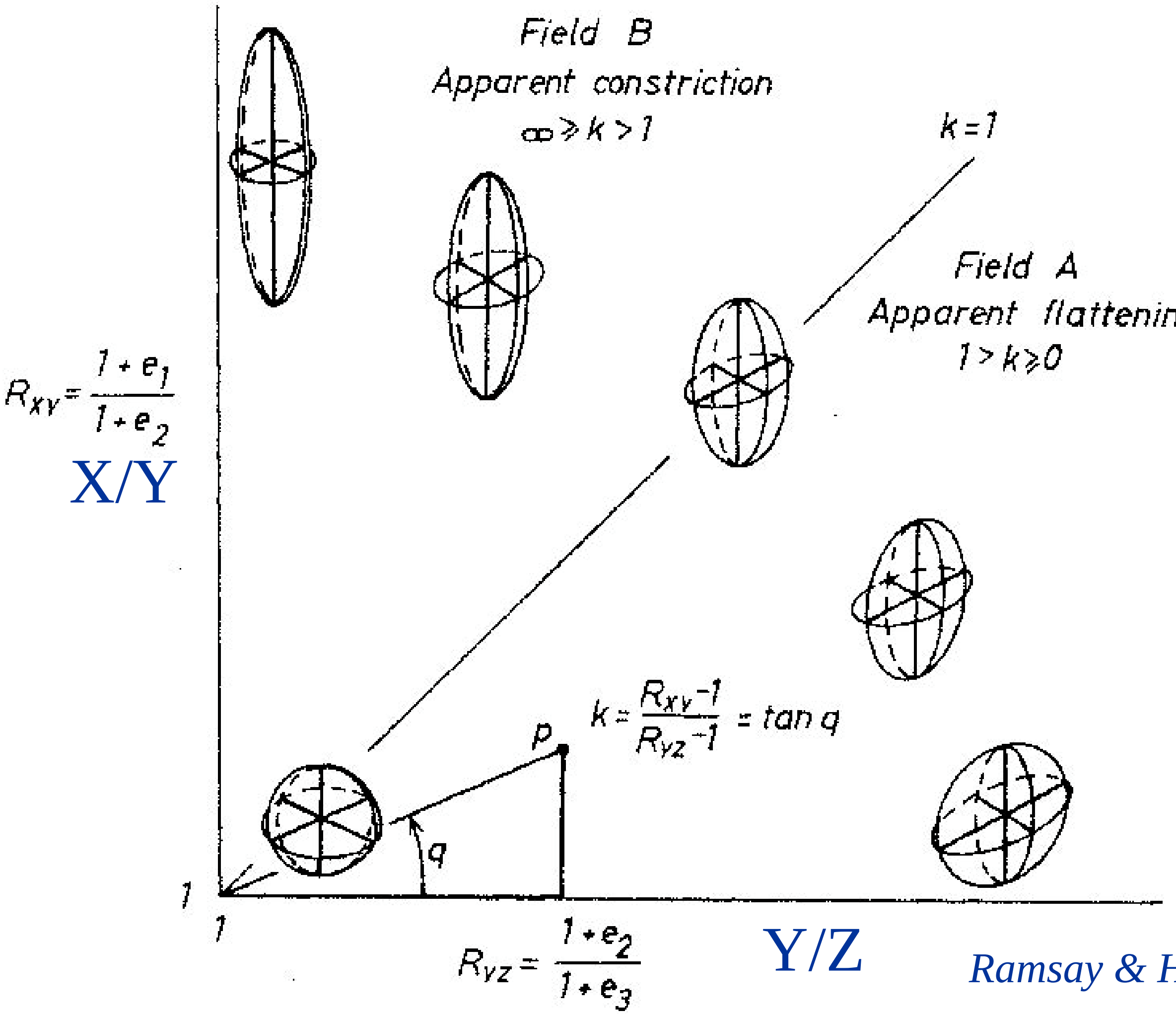
- Rheology is the study of the relationships between stress imposed on a body and resulting strains or strain rates
- Competence is a general term to describe the ease with which a material can deform
- In response to a stress, strain may be
  - Reversible, elastic deformation
  - Brittle, failure of a stressed body, at a certain state, the solid rocks lose their internal cohesion
  - Permanent, ductile flow without brittle deformation

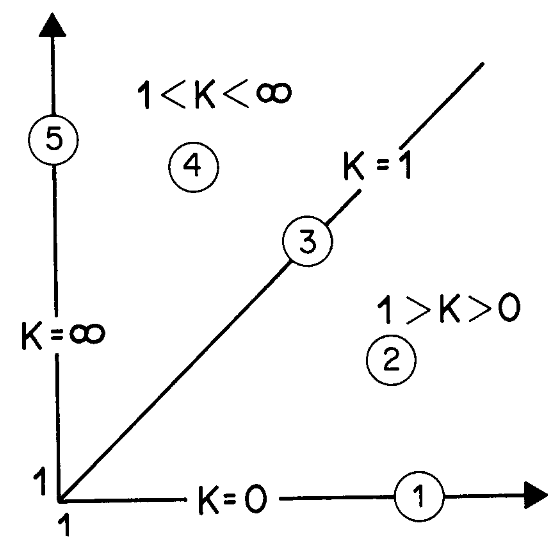
3 axis of deformation, a finite strain ellipsoid



- Principal
- strain directions, X, Y, Z
- planes XY, YZ, ZX
- changes in length e1, e2, e3
- ratios Rxy, Ryz, Rzx

The Flinn graph for representing the shape of any ellipsoid





Ramsay & Huber, Academic Press Lim., 1983

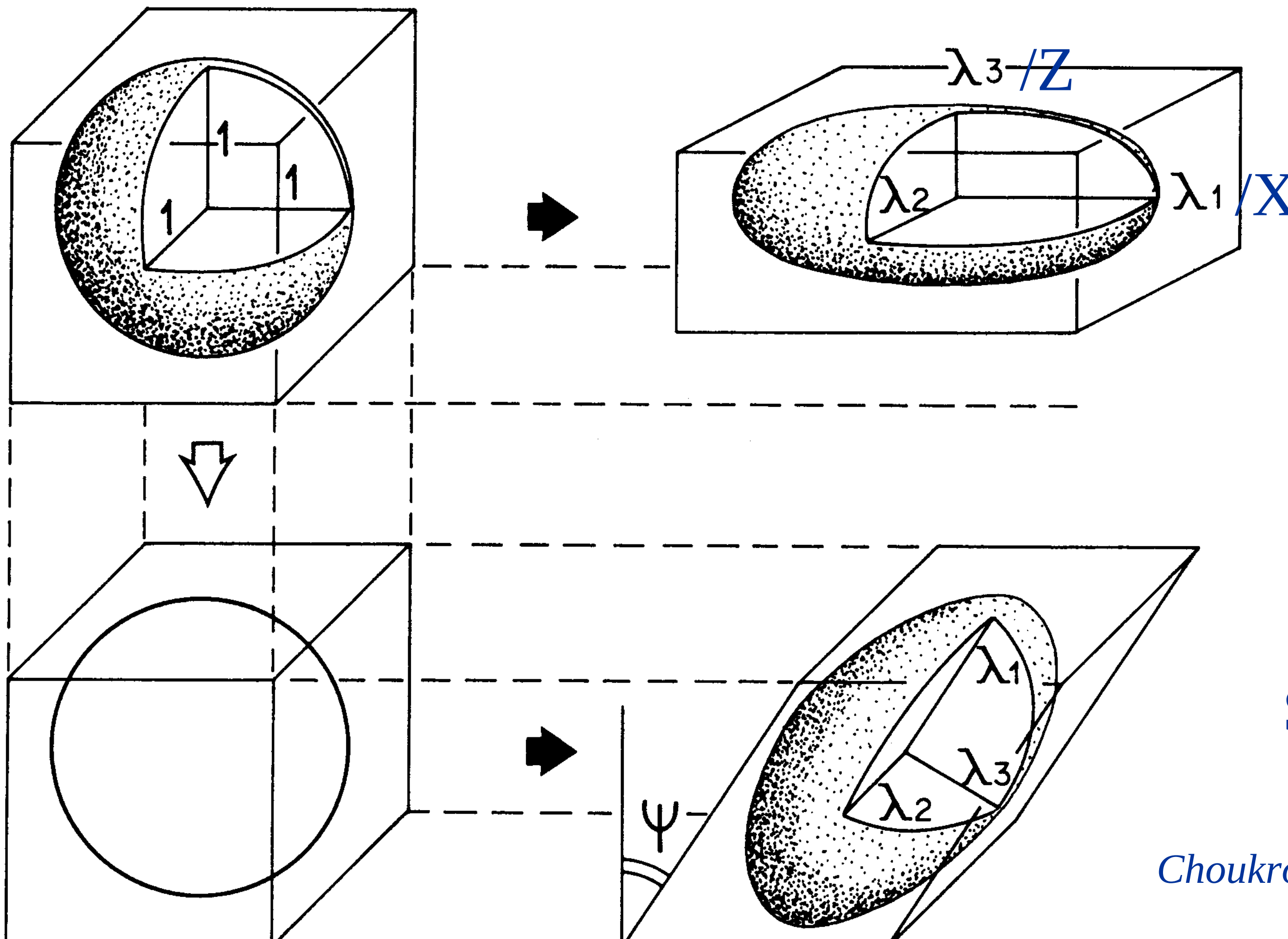
Strain regimes

- Deformation in rocks occurs under 2 strain regimes:
  - Pure shear
  - Simple shear
- Under combination of pure and simple shear

Simple shear

- A displacement which transforms an initial square in a parallelogram where the displacement vectors are all oriented parallel to one set of the opposite sides of the square and parallelogram. The vector direction is know as the shear direction.

Transformation of a sphere in an ellispoid, 2 strain regimes

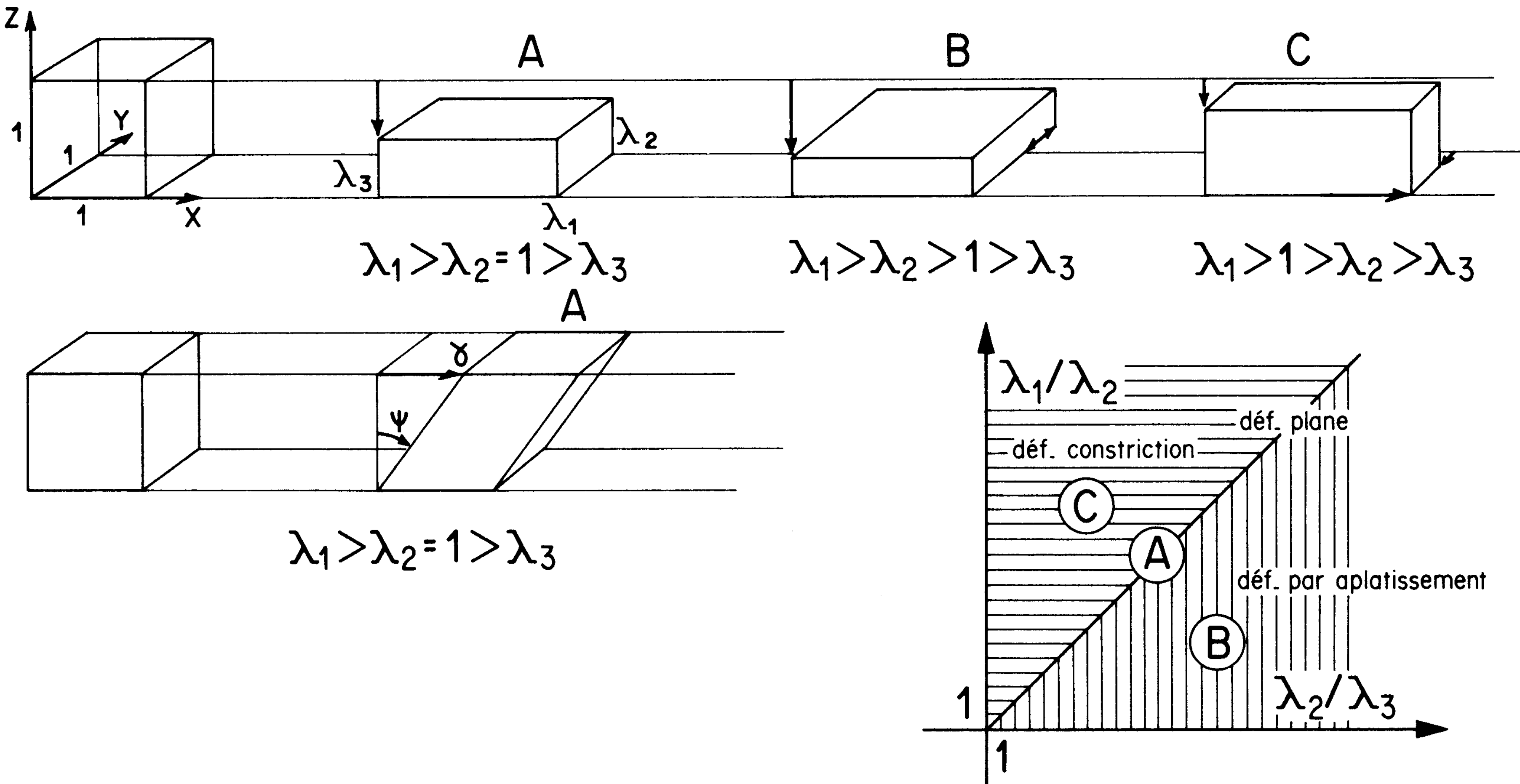


Choukroune, Masson, 1995

2 end-members

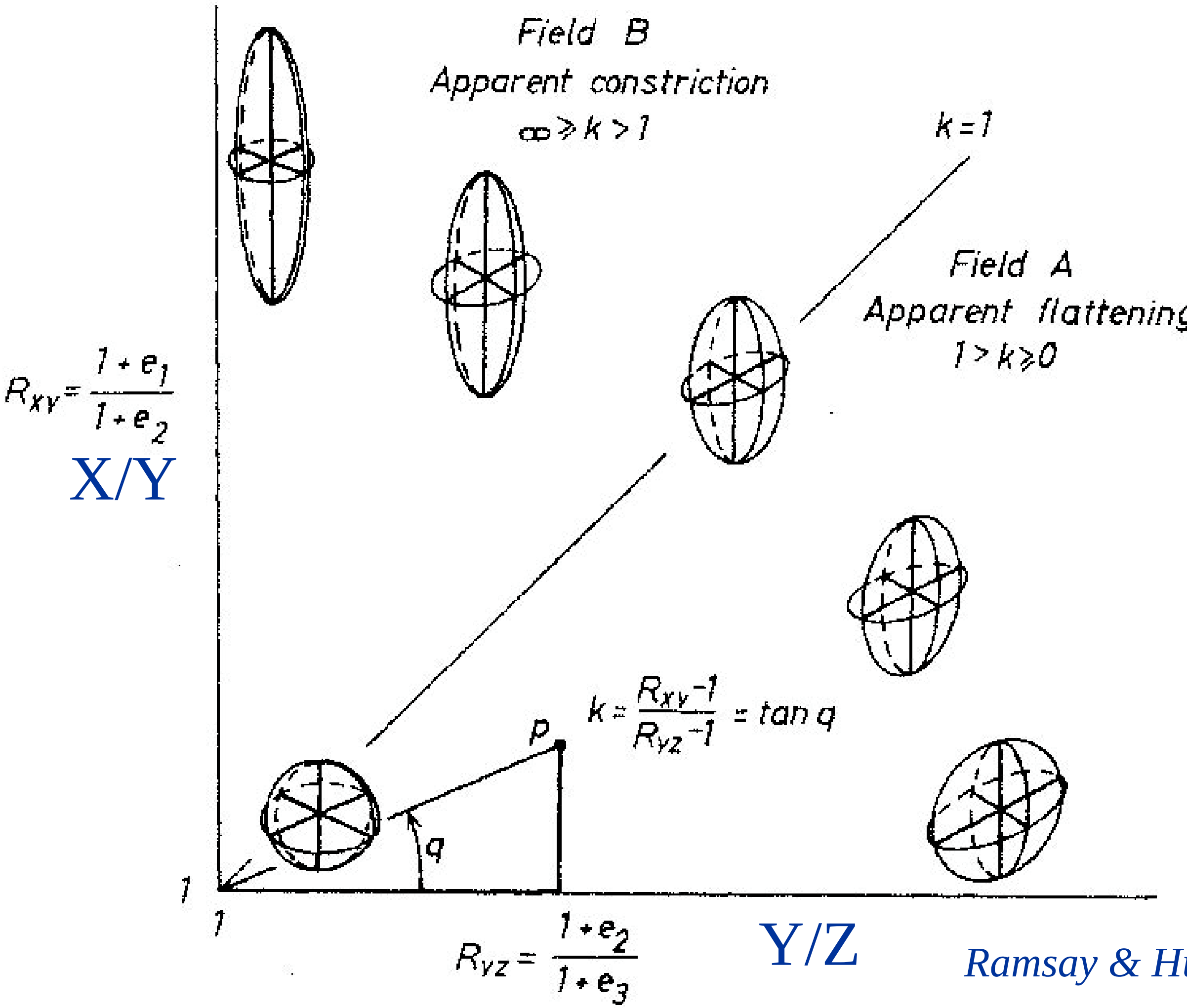
Pure shear	**Simple shear**
Axis of deformation remains parallel (coaxial and non rotational)	Axis of deformation rotate (non coaxial and rotational)
Flow lines tends to become perpendicular to the Z shortening axis	Flow lines are parallel to the shear direction during the deformation
Deformation >> Displacement	Deformation << Displacement

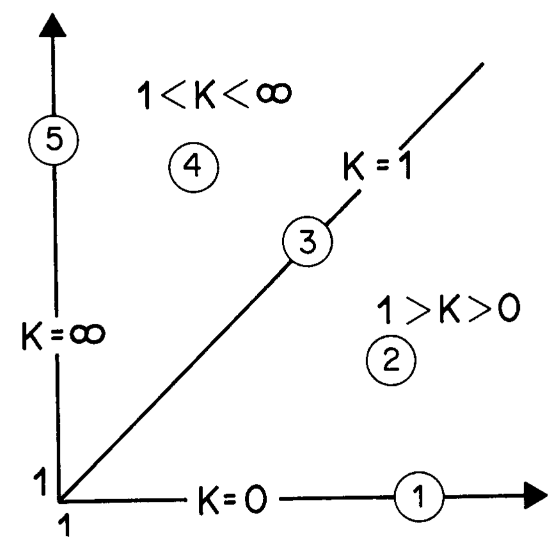
Finite strain ellipsoid and strain regimes



Choukroune, Masson, 1995

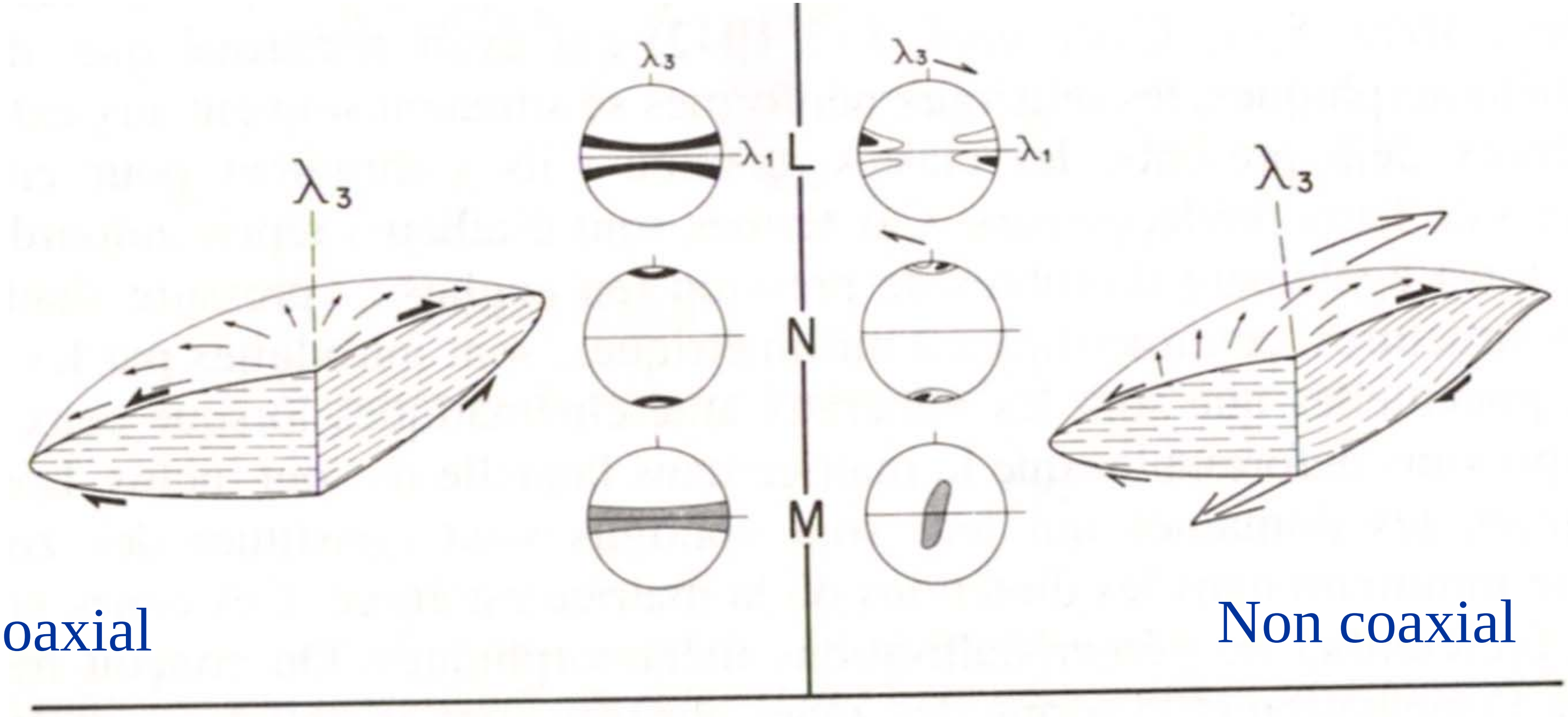
The Flinn graph for representing the shape of any ellipsoid





Ramsay & Huber, Academic Press Lim., 1983

Change in geometry from coaxial to non coaxial regimes



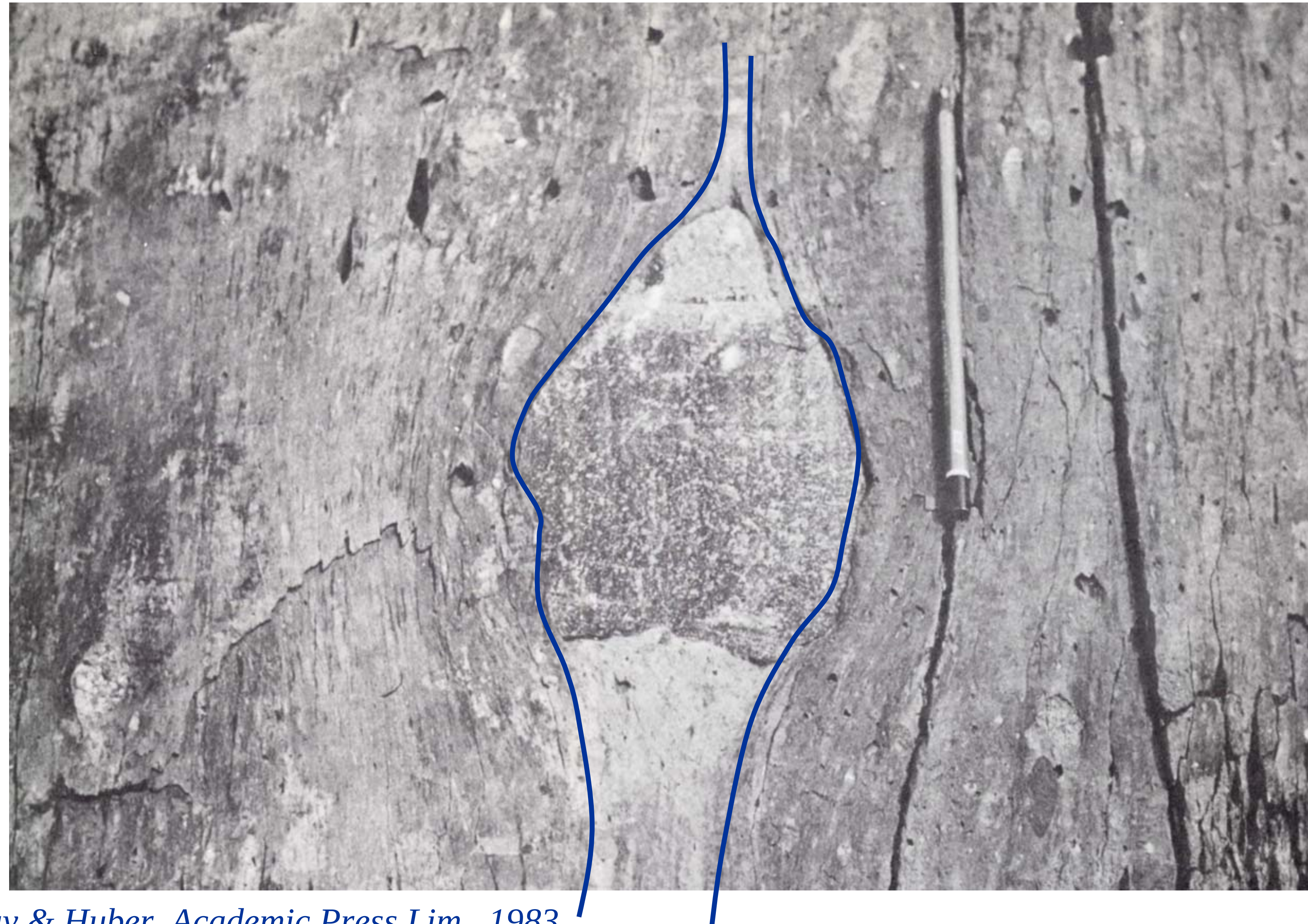
Coaxial

Non coaxial

Markers of the finite strain ellipsoid

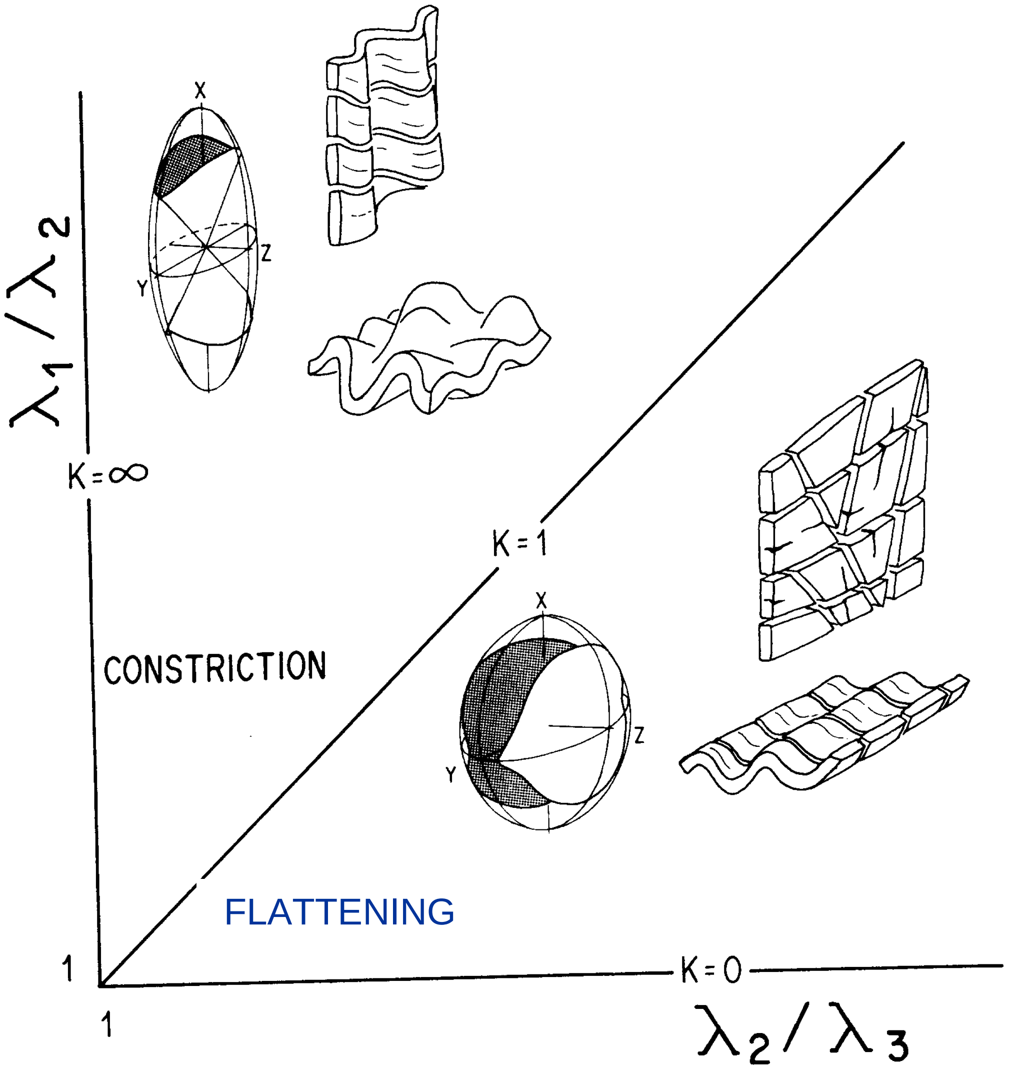
- Fold and boudinage structures
  - Boudinage is a structure produced during he extension of competent layers enclosed in an incompetent matrix

Deflection of cleavage around a competent fragment of quartzite in an argilite



Ramsay & Huber, Academic Press Lim., 1983

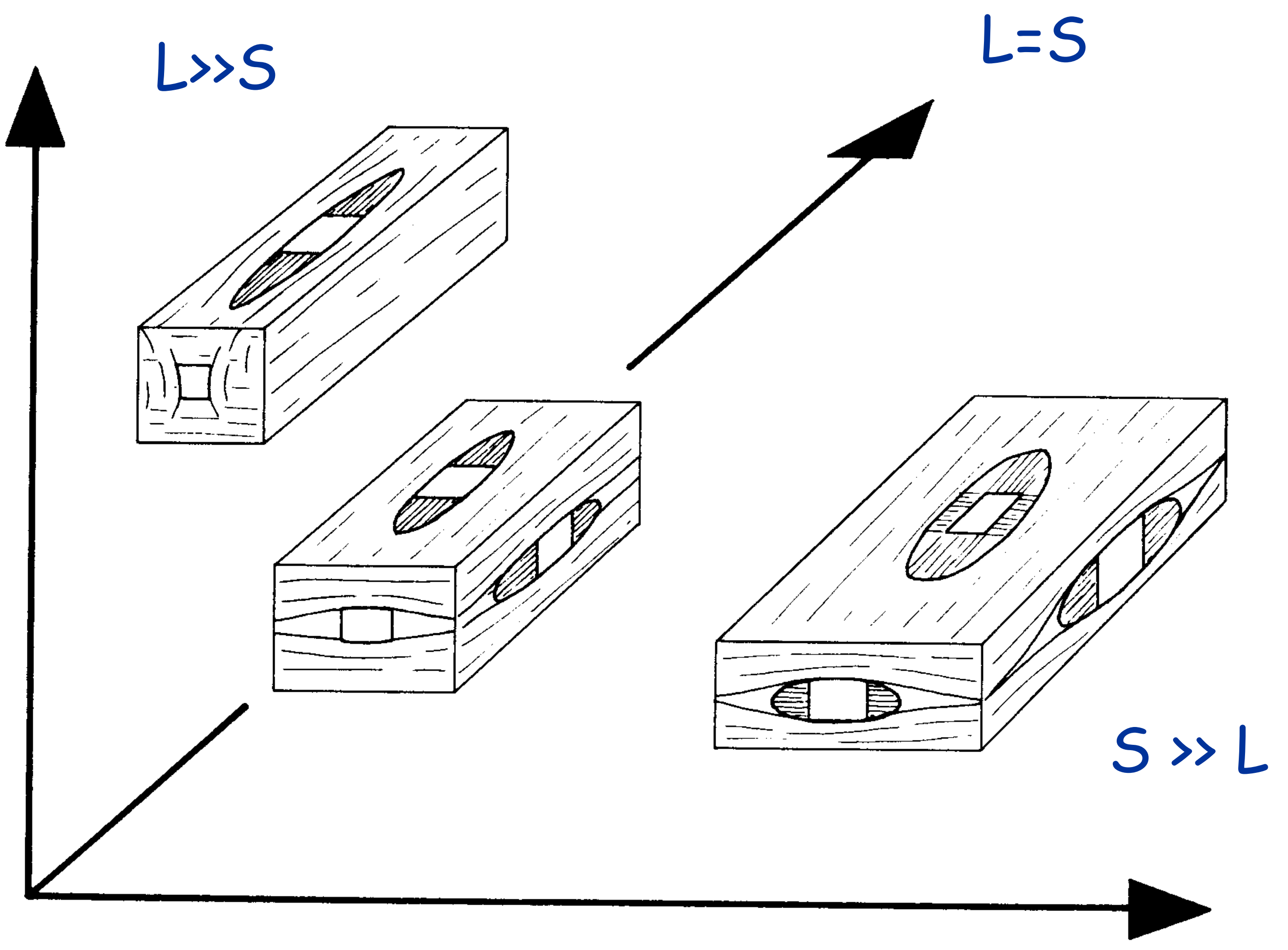
Folding and boudinage in a Flinn graph



Markers of the finite strain ellipsoid

- Deformation of pre-tectonic objects
  - pebble, phenocryst, oolithe, redox spot, fossil..
- Mineral fabric and pressure shadows
  - Fabric is the geometric and spatial relationships between the crystal components making a rock, i.e. preferred orientation of grain shapes and crystallographic axis, the grain size…
  - Pressure shadow is a region of low strain protected from deformation by a rigid or competent object in a rock of lower competence

Pressure shadows in a Flinn graph

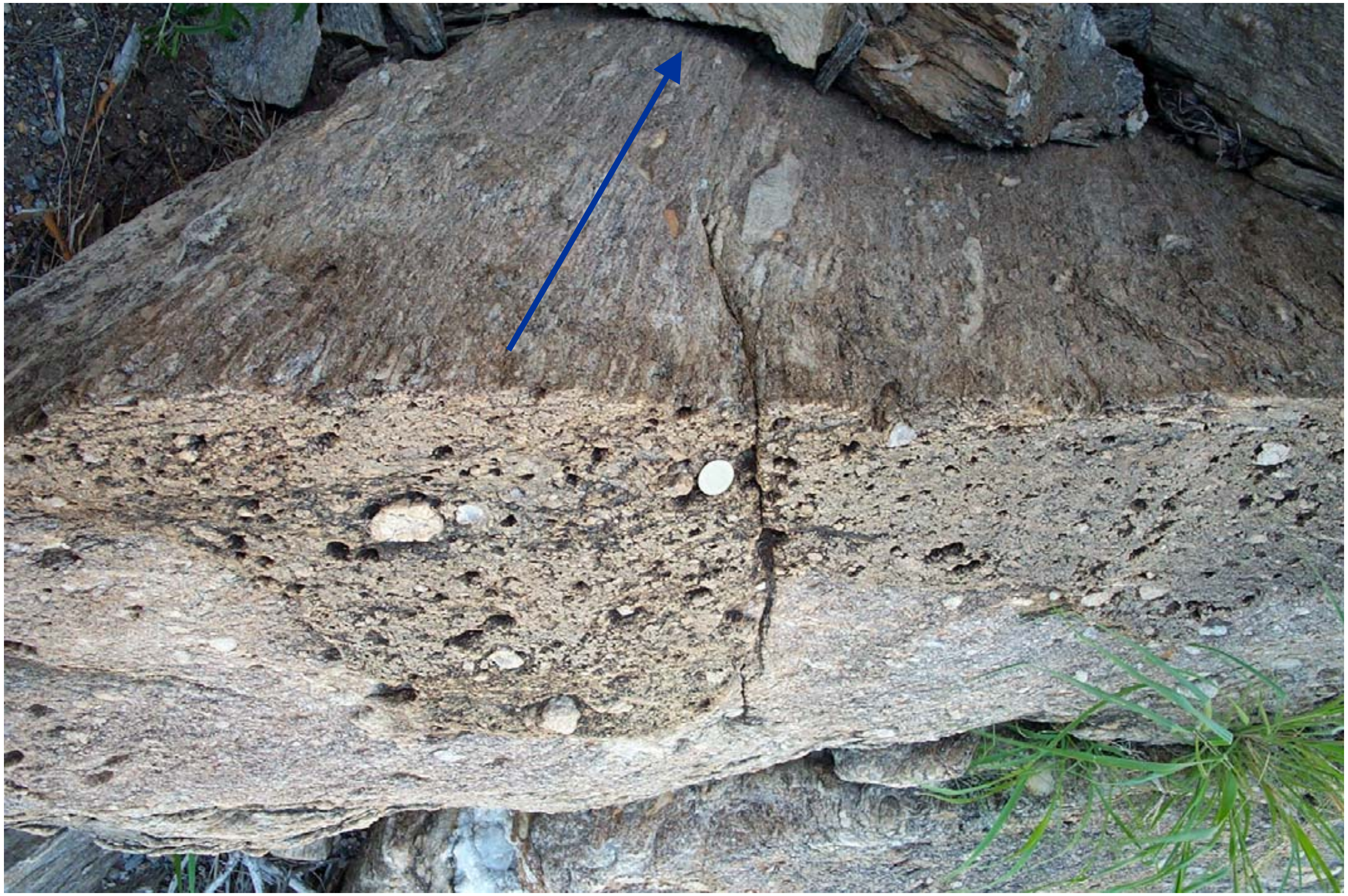


A linear type fabric: L>>S from the Hakos mountains

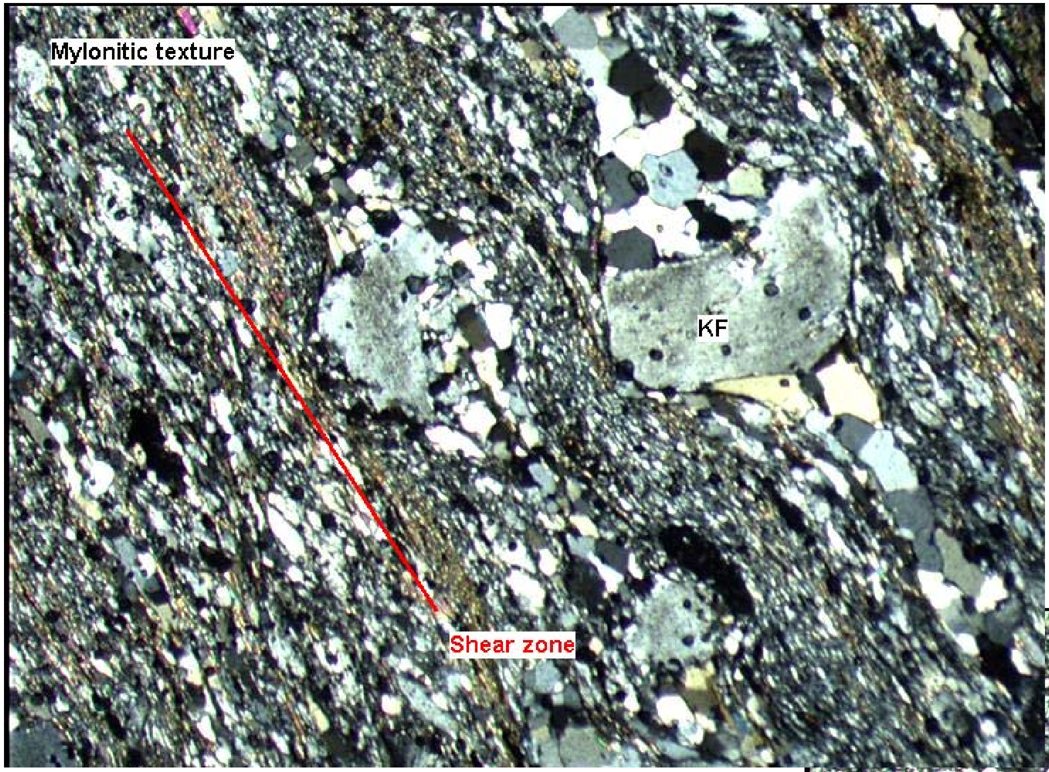
A granitic orthogneiss

A linear type fabric: L>>S from the Hakos mountains

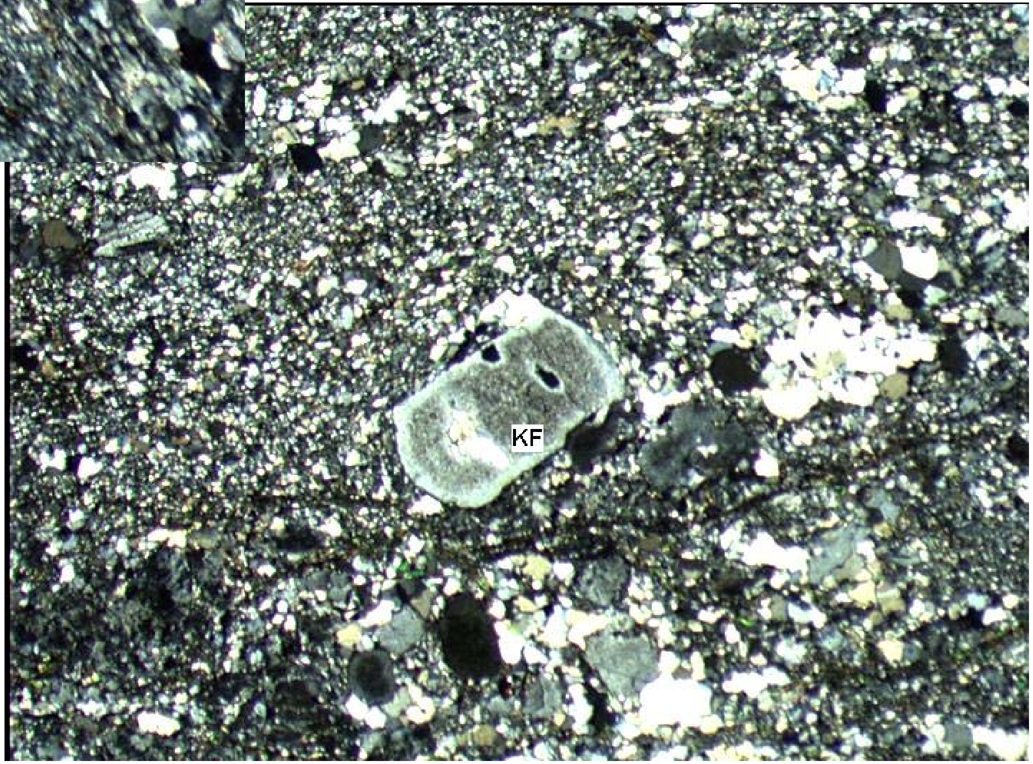
A metaconglomerate



Sheared Gamsberg granite



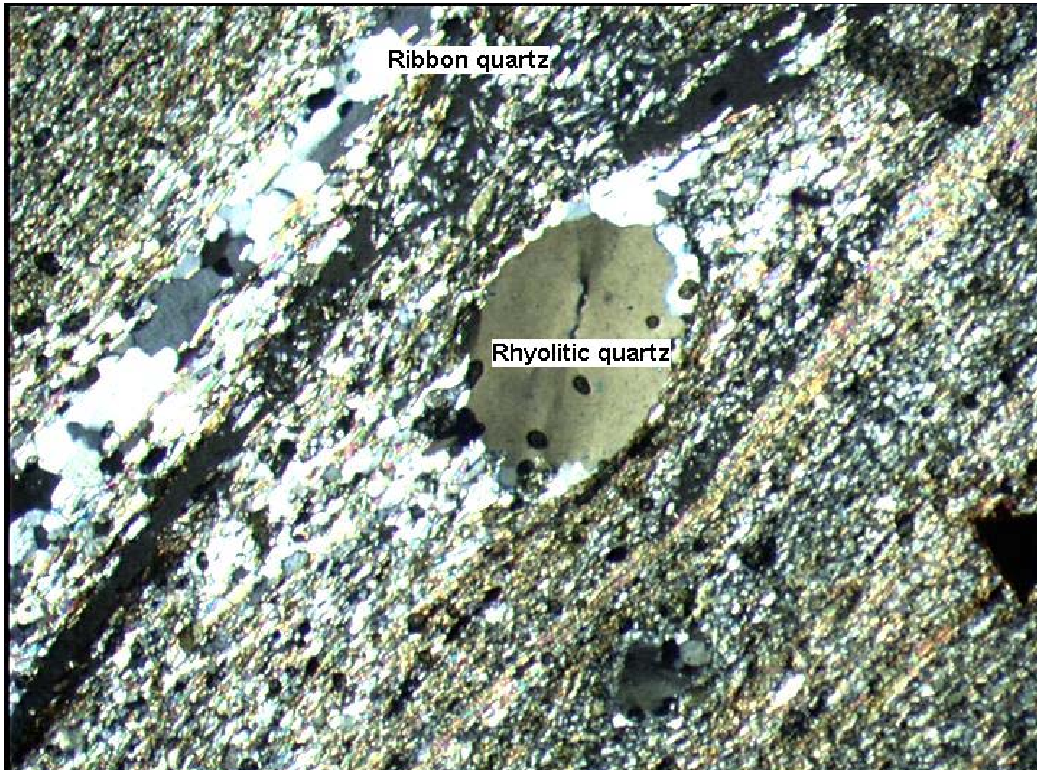
XZ plane



1 single rock!

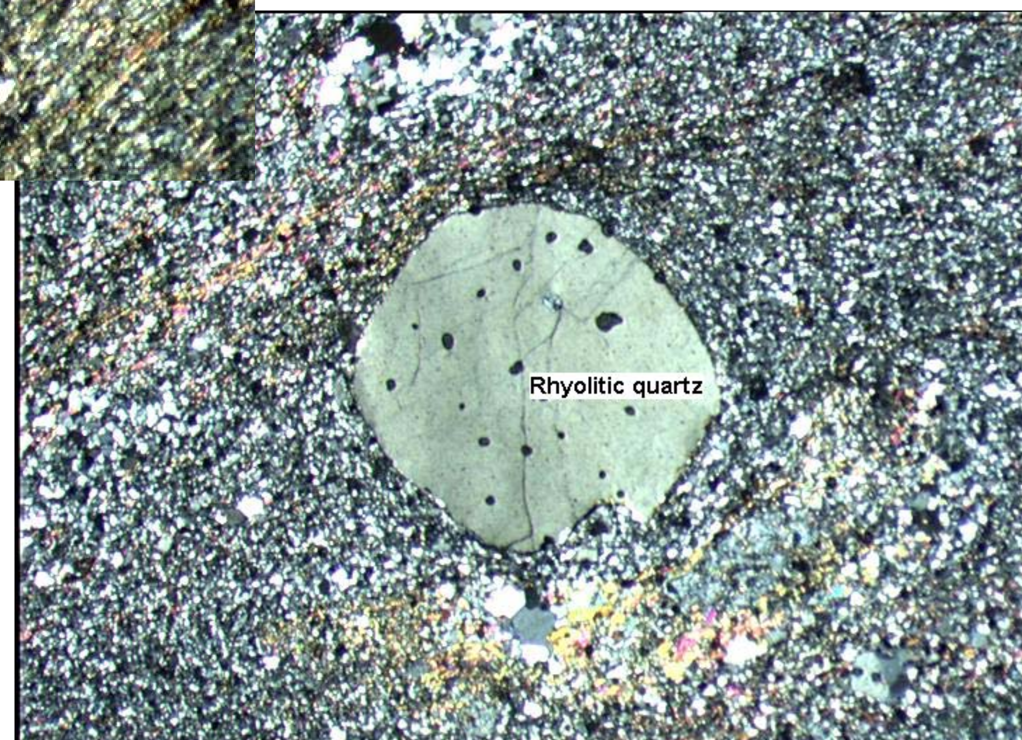
YZ plane

Sheared rhyolite



XZ plane

1 single rock !



YZ plane

Partitioning and time...

- Homogeneous vs non homogeneous deformation
  - The definition of zones of homogeneous deformation
  - The notion of bulk strain, an average strain in a heterogeneously deformed material
- Finite strain vs incremental deformation, notion of progressive deformation
  - Increment from one stage to the next
  - Rate of change along the main strain axis and of rotation defines the principal strain rates and the vorticity
  - Definition of the strain regime by identification and analysis of the markers of incremental deformation

Pure shear and development of structural elements

- Crenulation and mechanical rotation
- Pressure-solution, a deformation process whereby material under stress goes into solution at a localized point in a material, this material is transported by flow or diffusion
- Recrystallisation
- Transposition

Pure shear and development of folds , axial plane cleavage...

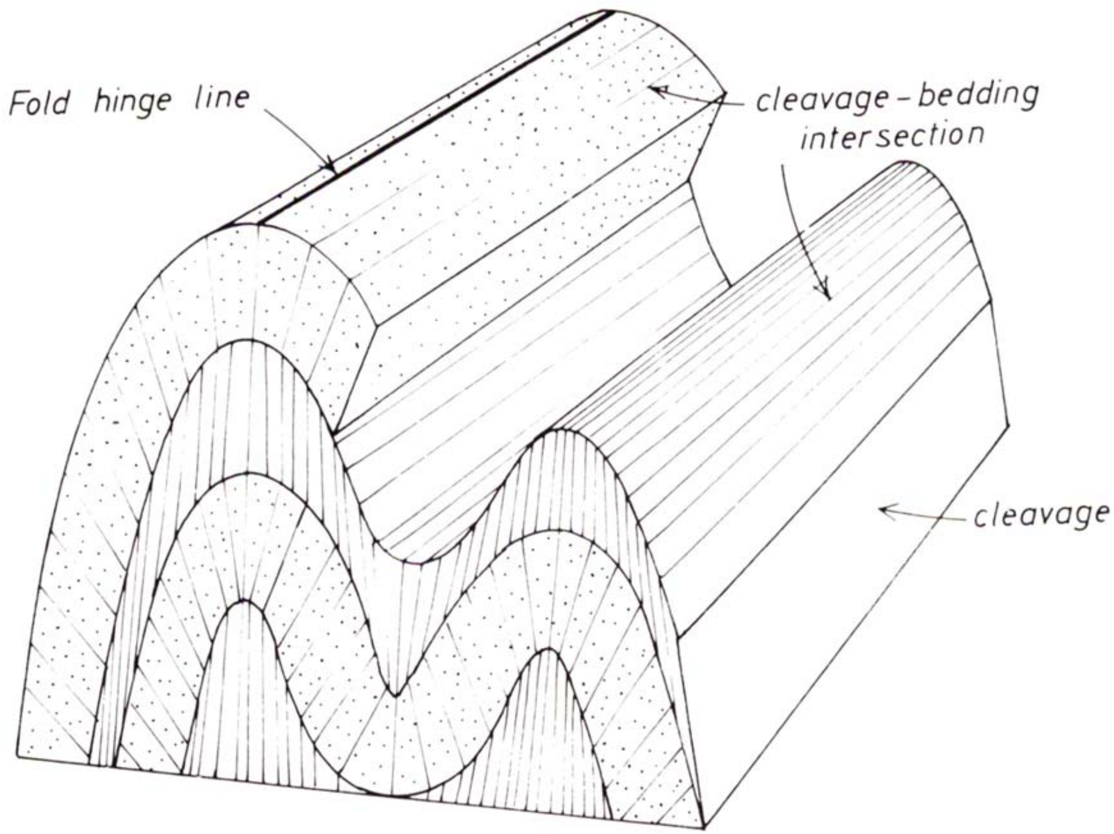


Figure 10.21. *Geometric form of cleavage fans and cleavage–bedding intersection lineations in folded rocks. The most competent layers are stippled, the least competent layers unstippled. In simply folded rocks the cleavage–bedding intersection lineation is parallel to the fold hinge lines.*

Pure shear and development of folds, axial plane cleavage...

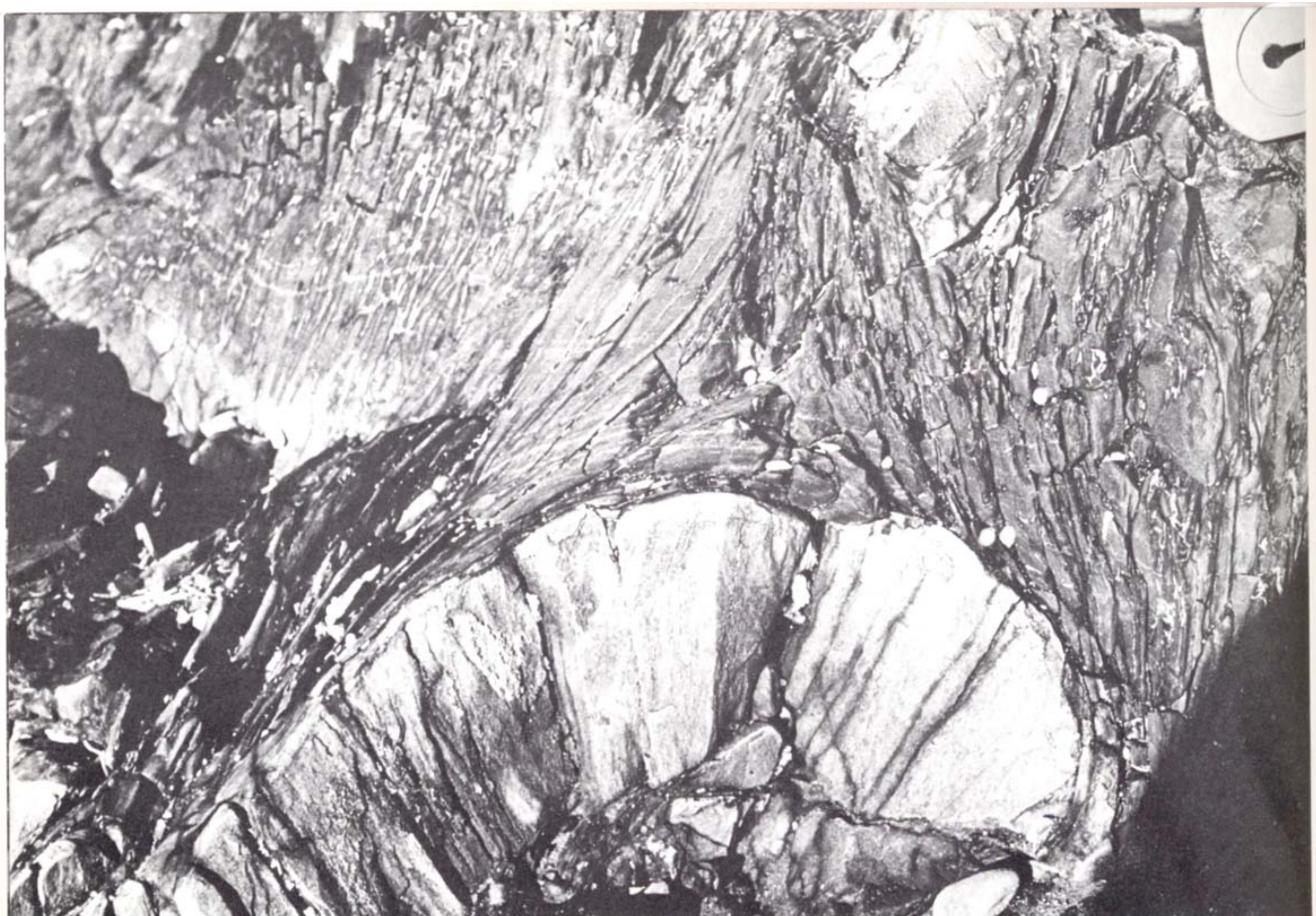
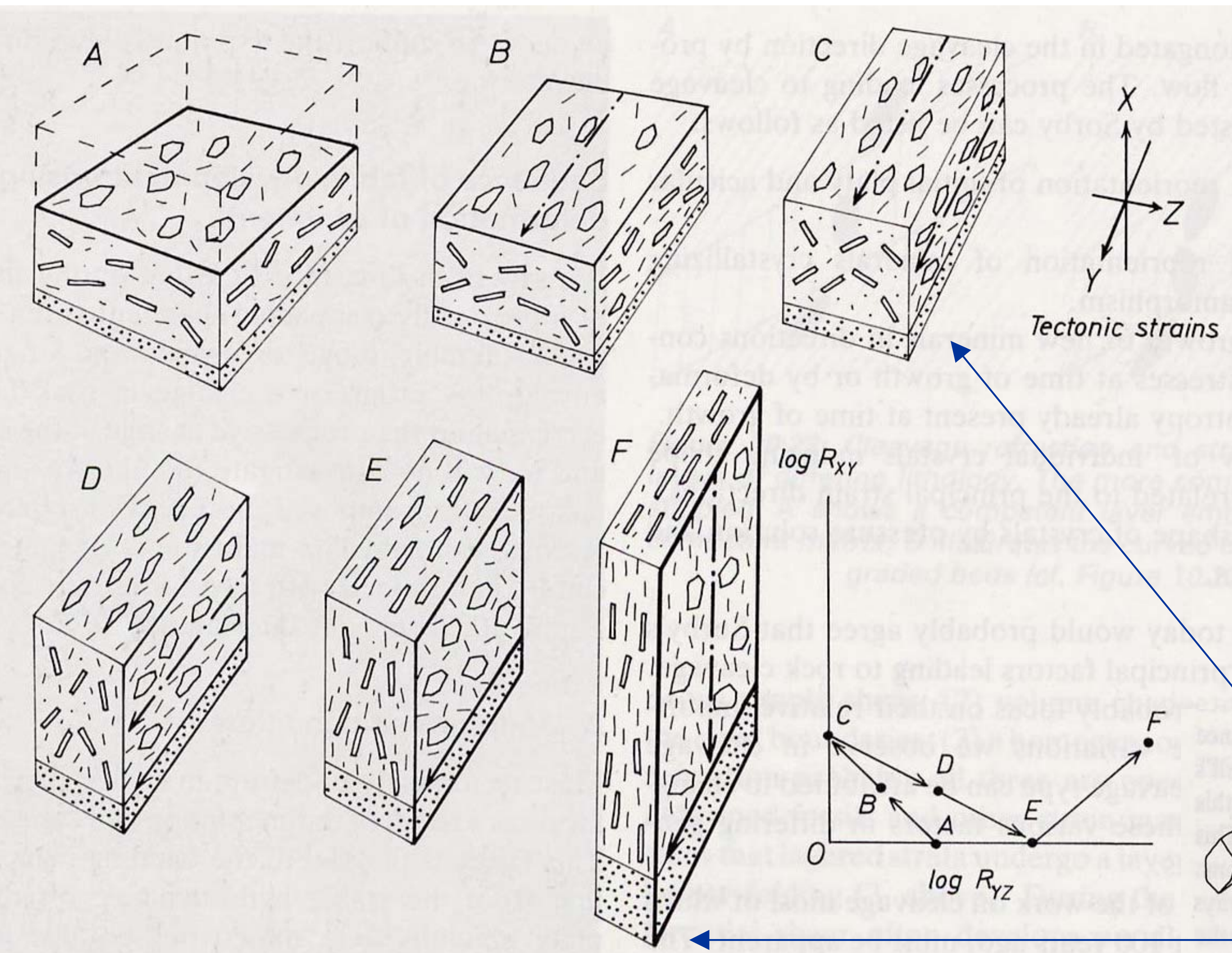


Figure 10.18. *Cleavage fans in folded Ordovician sediments, Rhosneigr, North Wales.*

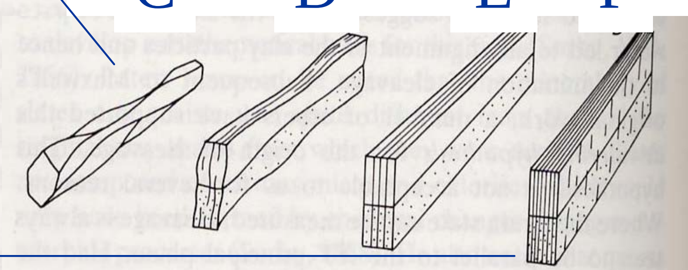
Progressive stages in fabric development of a shale



- Initial compacted
- Ealiest deformation
- Pencil structure
- Embryonnic deformation plane
- deformation plane
- deformation plane with stretching lineation

Type of linear fabric

C D E F

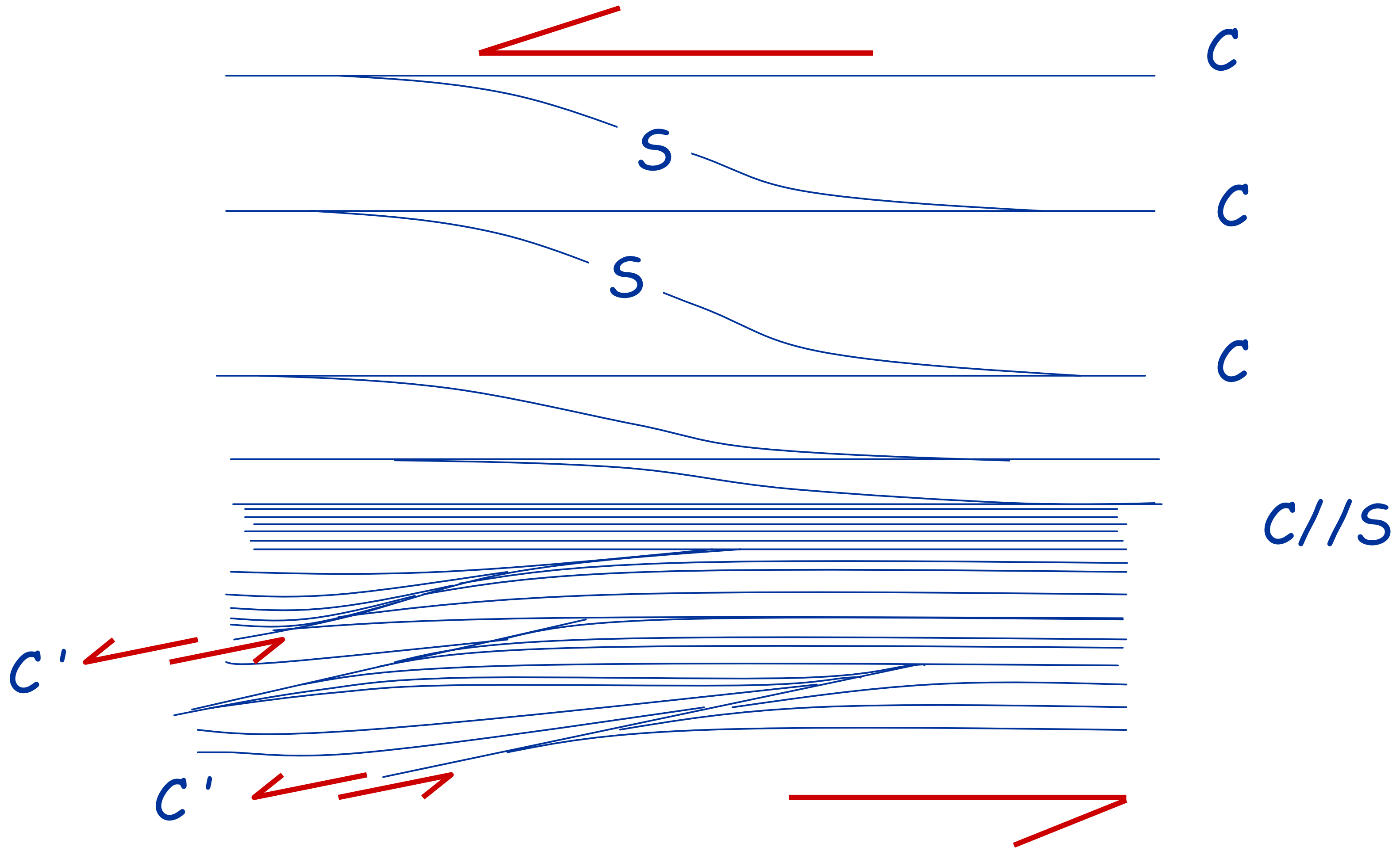


Simple shear and development of shear zone

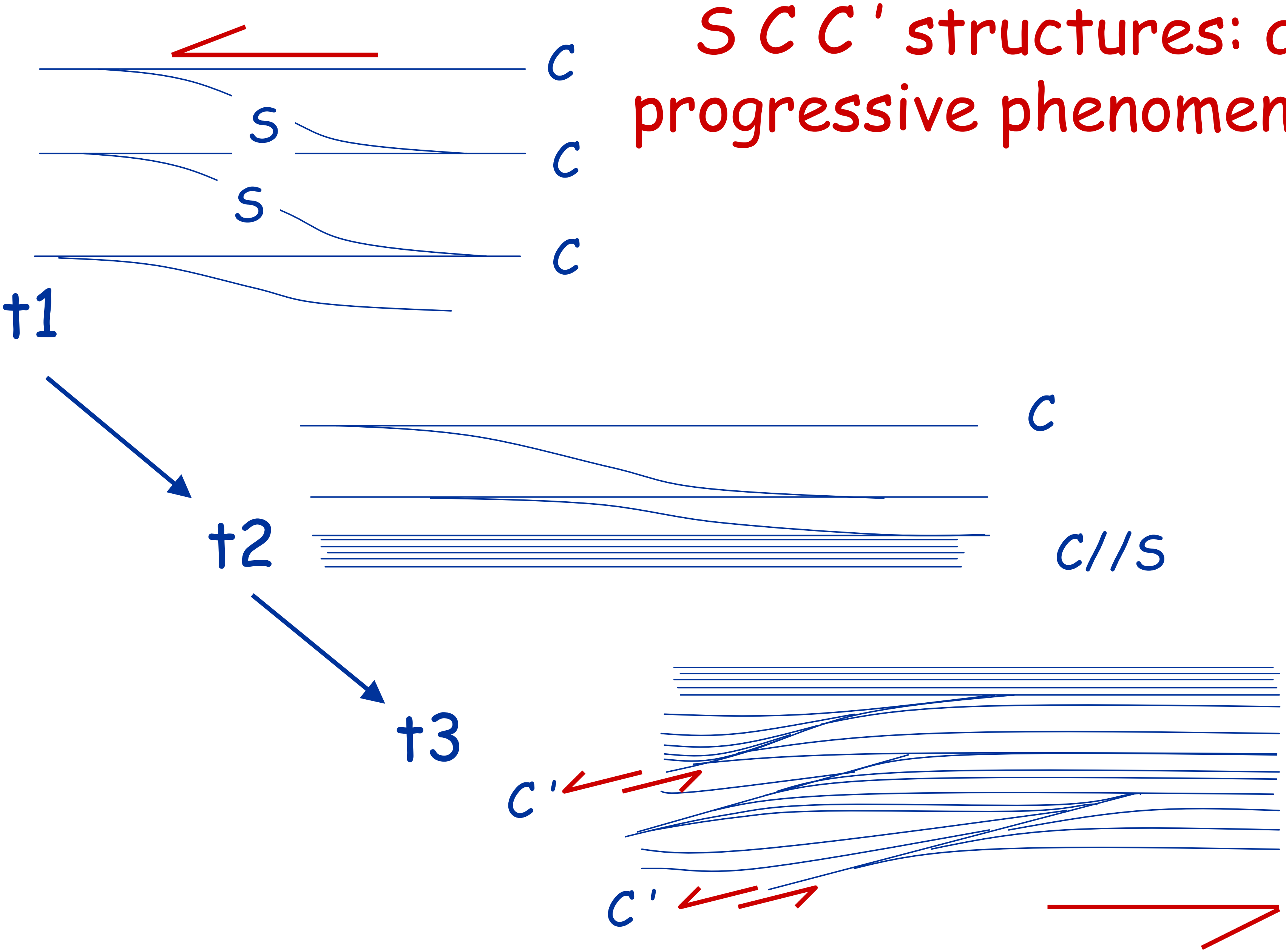
- A shear zone is a zone with sub-parallel walls in which high deformations are localized
- Effects of non coaxial deformation
- Plane strain ellipsoid
- Markers of rotational deformation
  - Coexistence of deformation and displacement planes, S/C/C' structures
  - Assymetric pressure shadows and mineral fabric
  - Folding

S C C ' structures

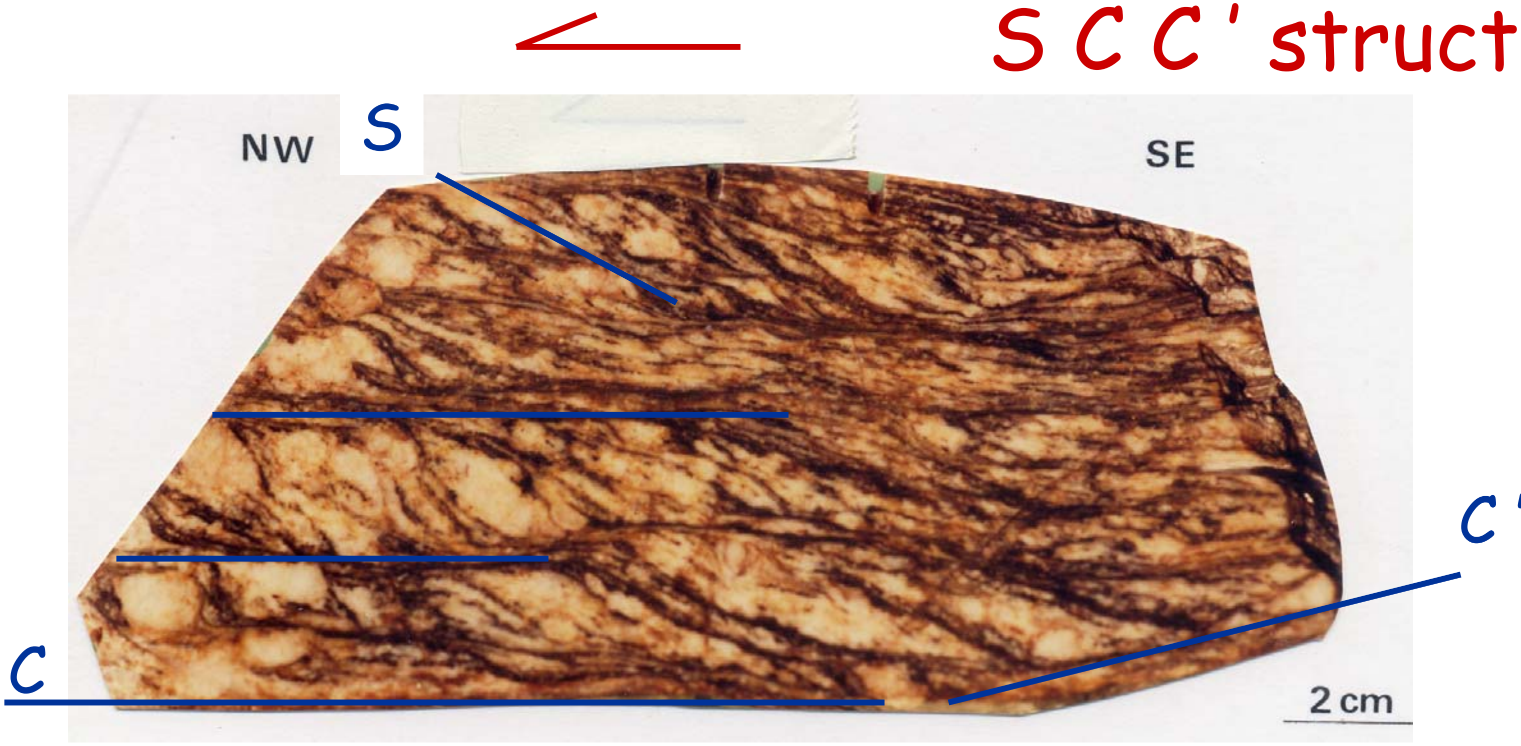
- The S plane: the deformation plane, with no displacement
- The C and C ' planes: the displacement planes with high deformation (mylonitisation)

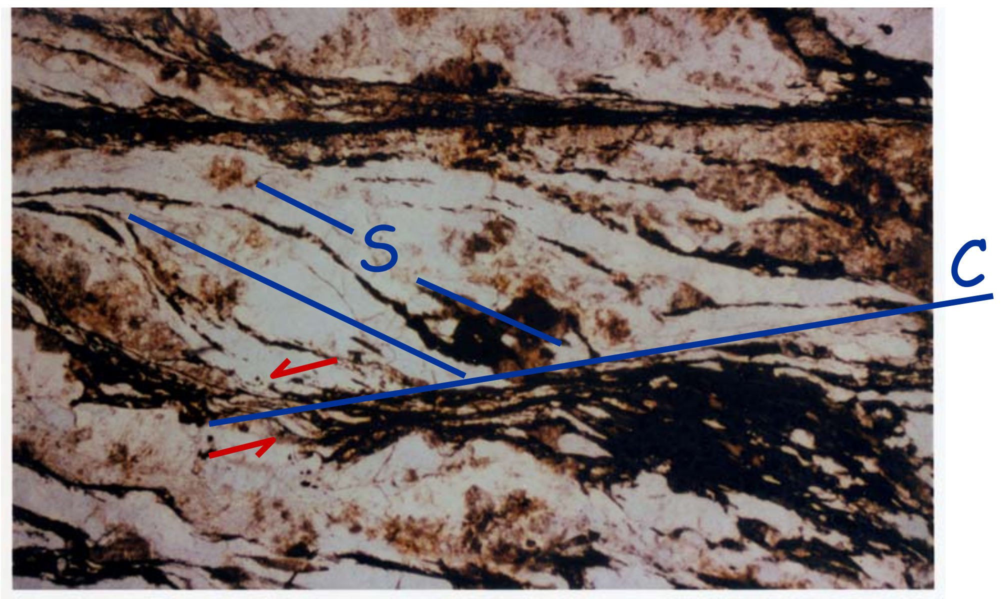


S C C ' structures: a progressive phenomenon

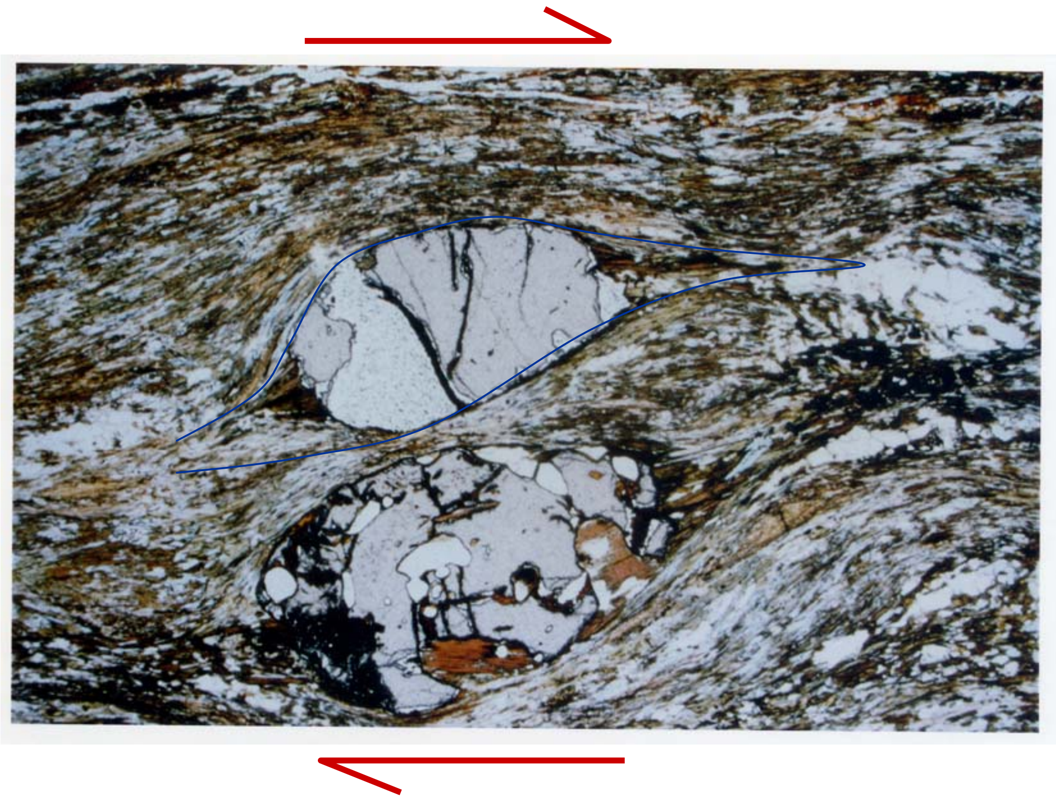


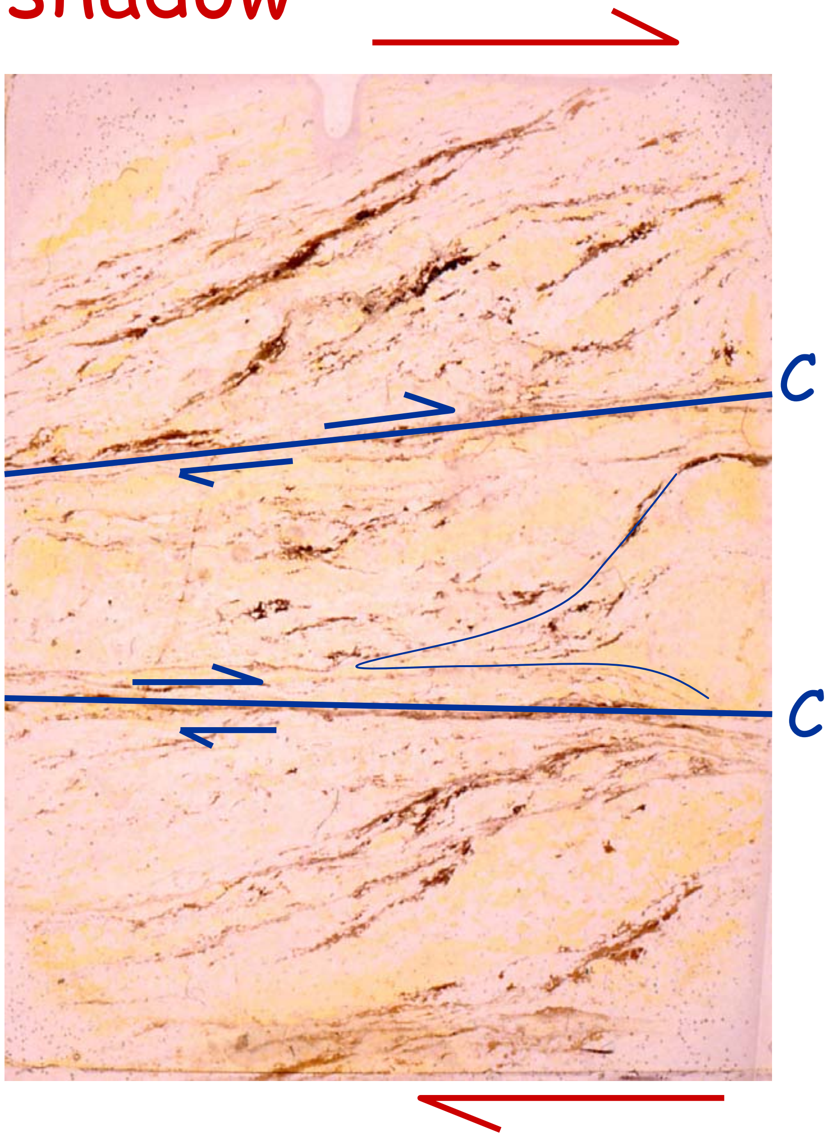
S C C' structures





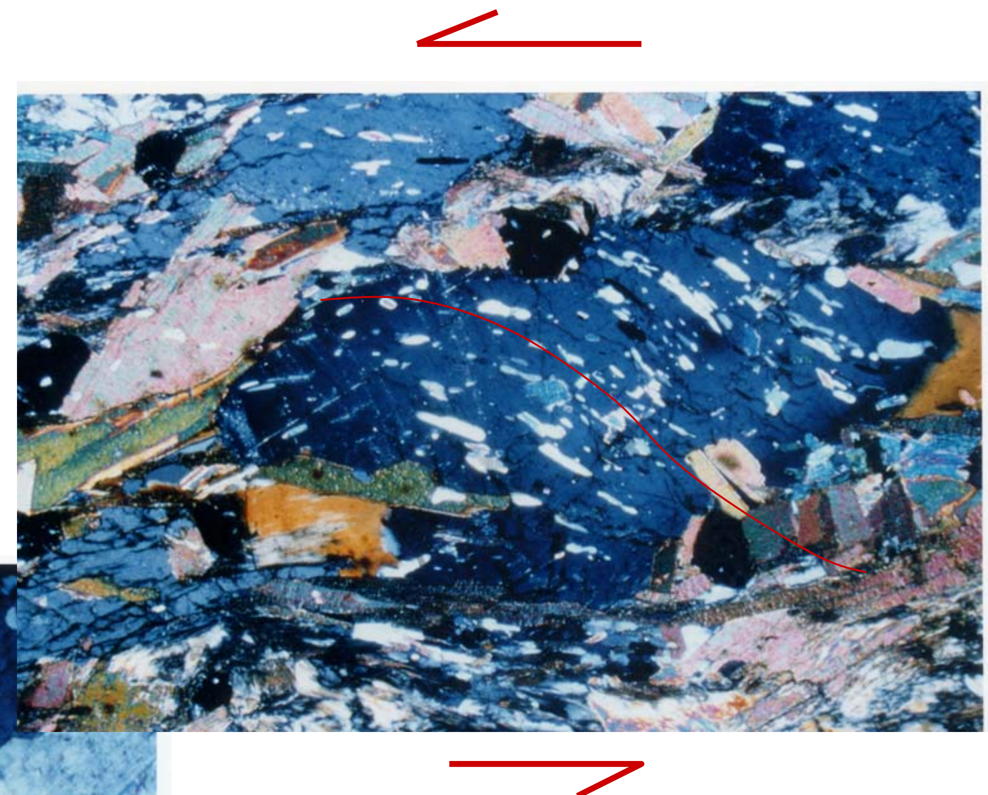
Assymetric pressure shadow

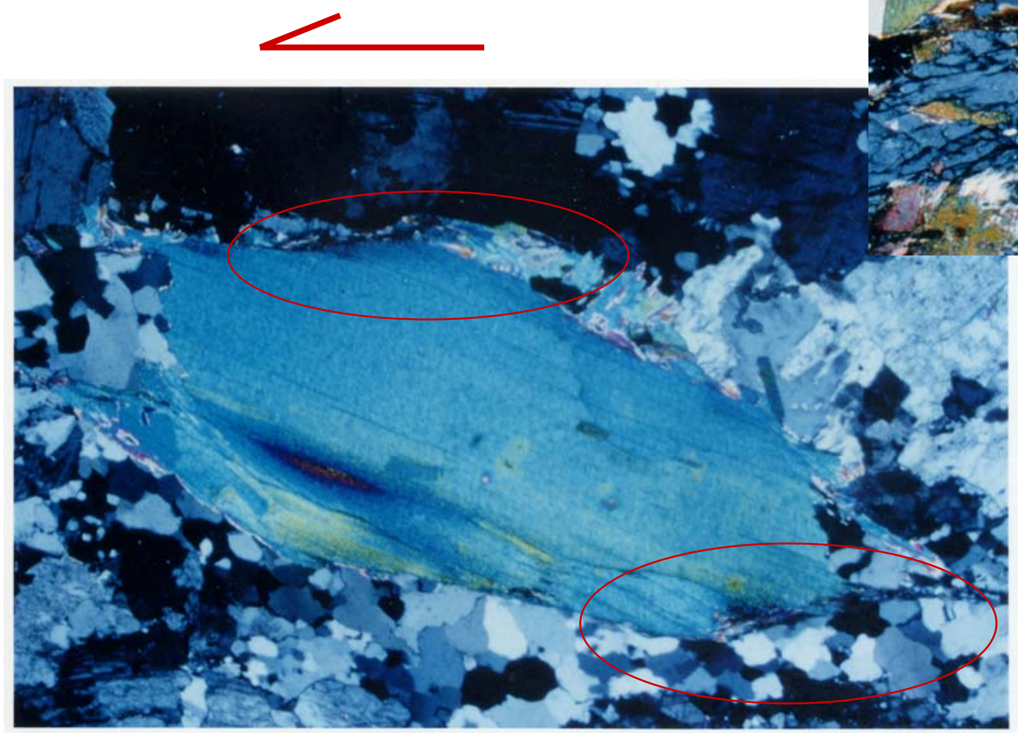




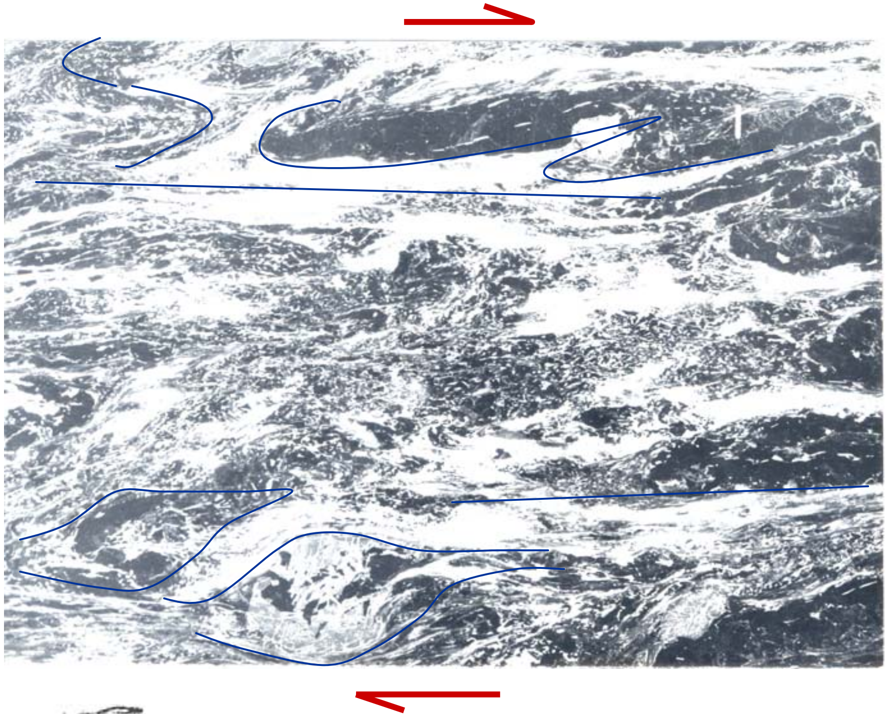
Assymetric pressure shadow

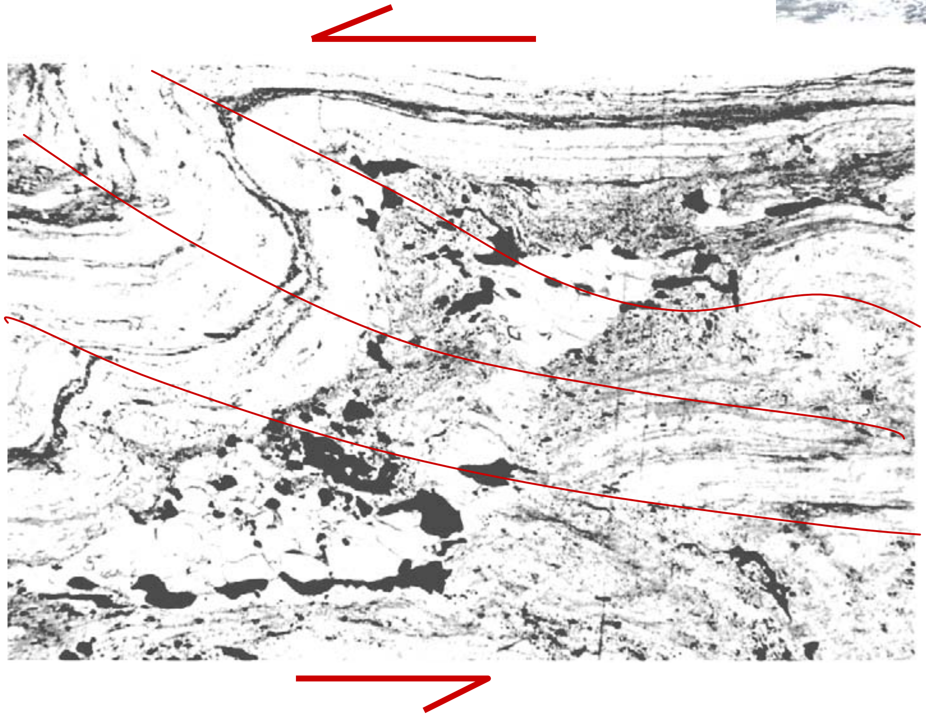
Cleavage bending and helicitic inclusions



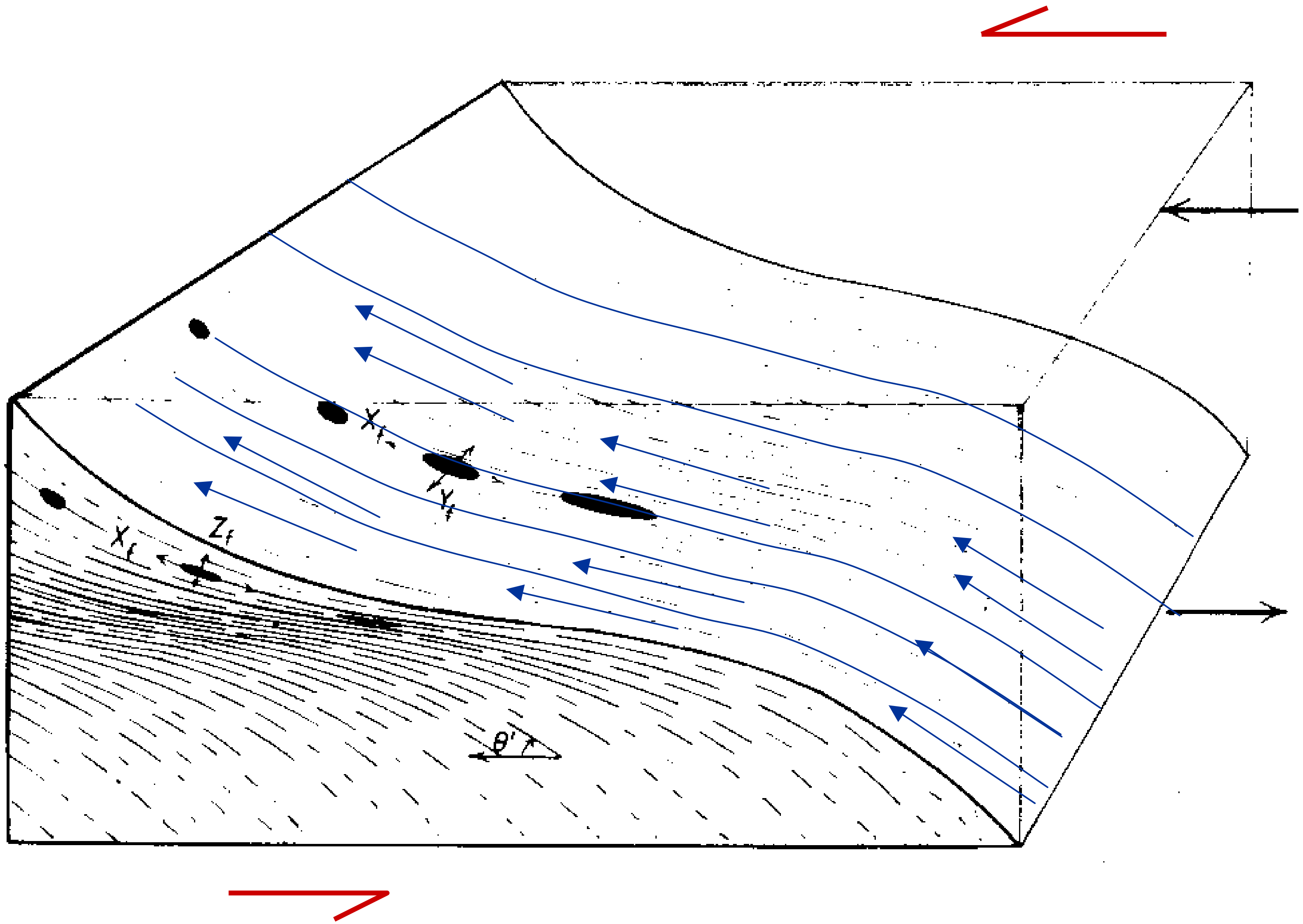


Assymetric folds and pressure shadows

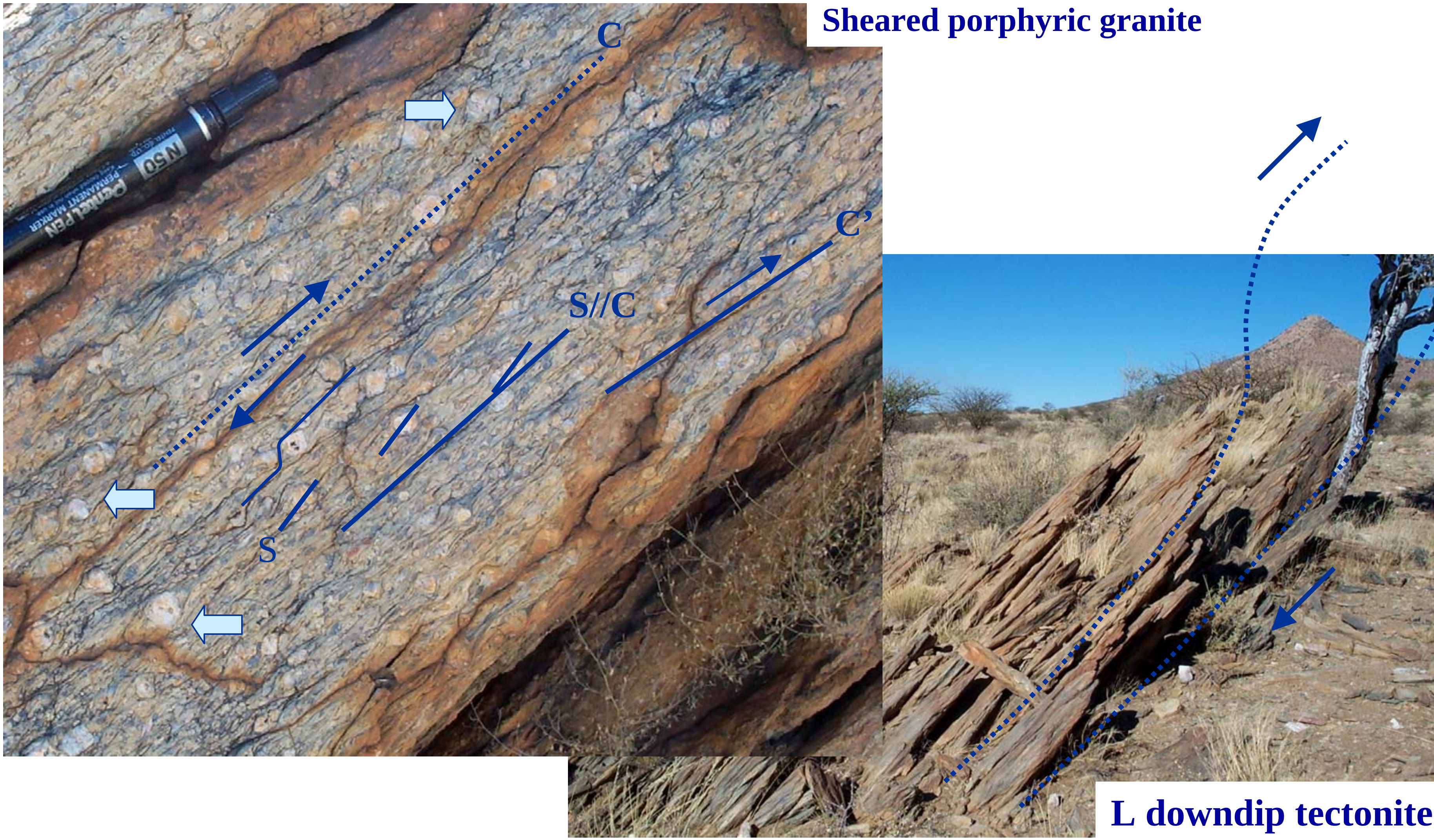




Fabric in a ductile simple shear zone



A reverse shear zone within the basement inlier of the Damara foreland



Sheared porphyric granite

L downdip tectonite

Development of non cylindrical folds during non coaxial deformation

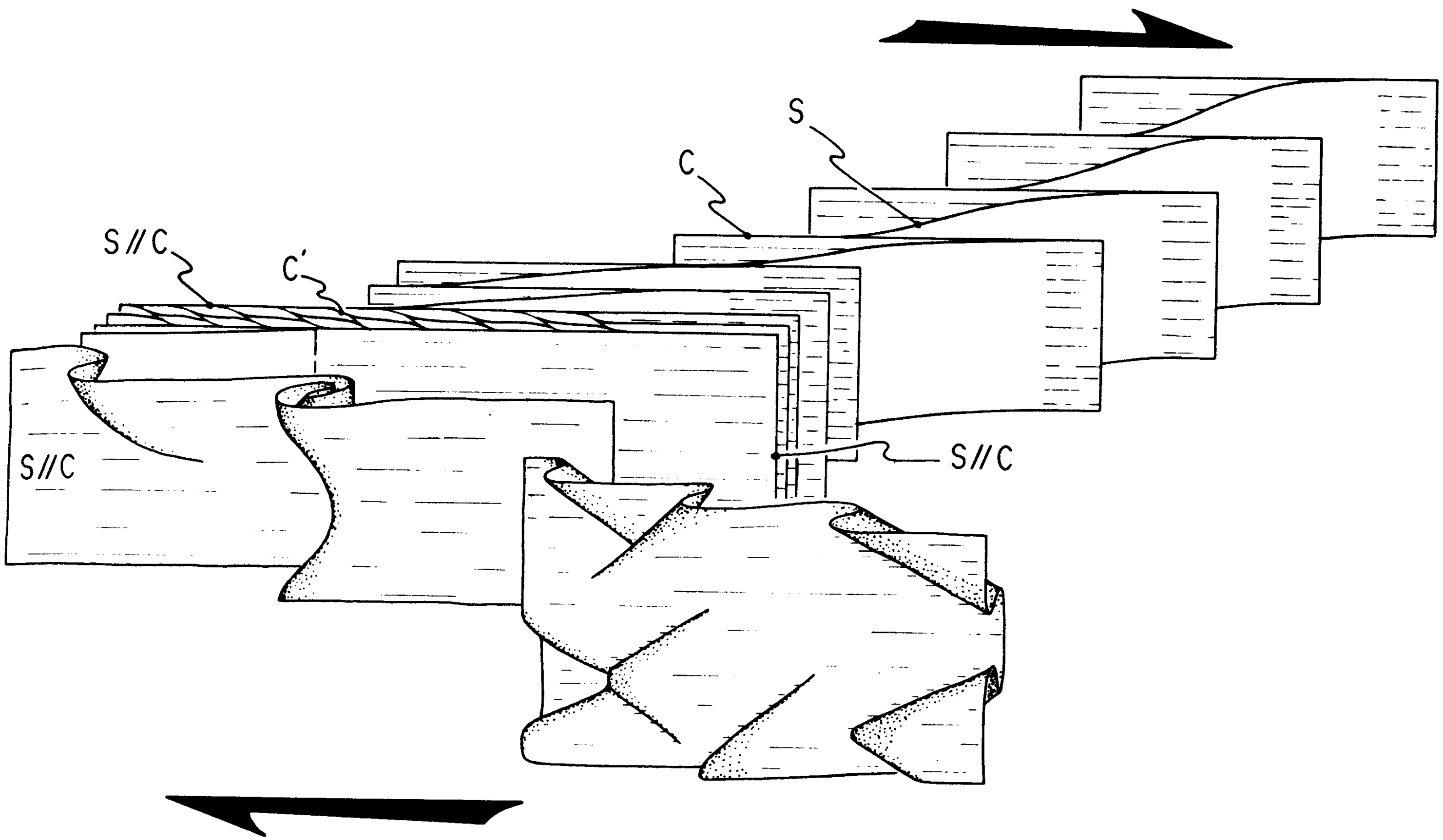


Fig. 147 – *Schéma montrant l'évolution de la déformation dans la bordure sud du massif granitique impliqué dans le ciaillement sud-armoricain. C'est une séquence de mylonitisation avec les structures C/S.*

Development of non cylindrical folds during non coaxial deformation

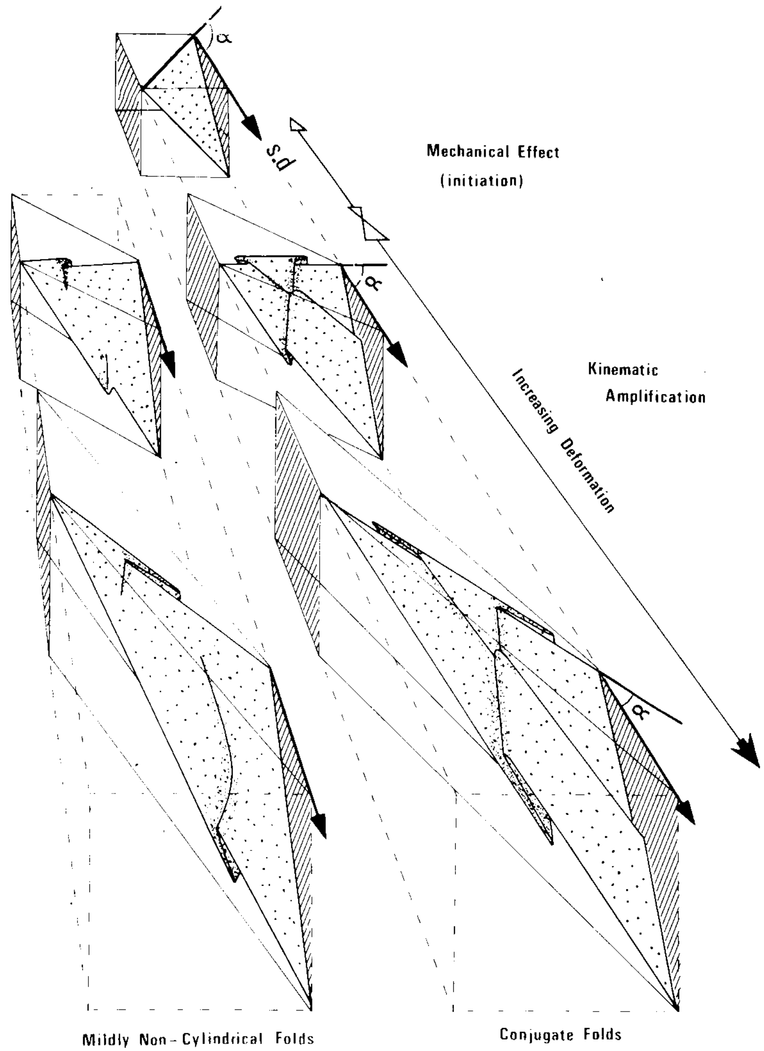


Fig. 6. Purely geometrical model for the development of the two types of fold during progressive simple shear (plane with diagonal shading is the shear plane). If the surface to be folded makes an initial angle (α) of more than 90° with the shear direction (s.d), conjugate fold sets develop (right). If the initial angle (α) is less than 90°, only one set develops (left).

Development of non cylindrical folds during non coaxial deformation

Progressive developement of sheath folds

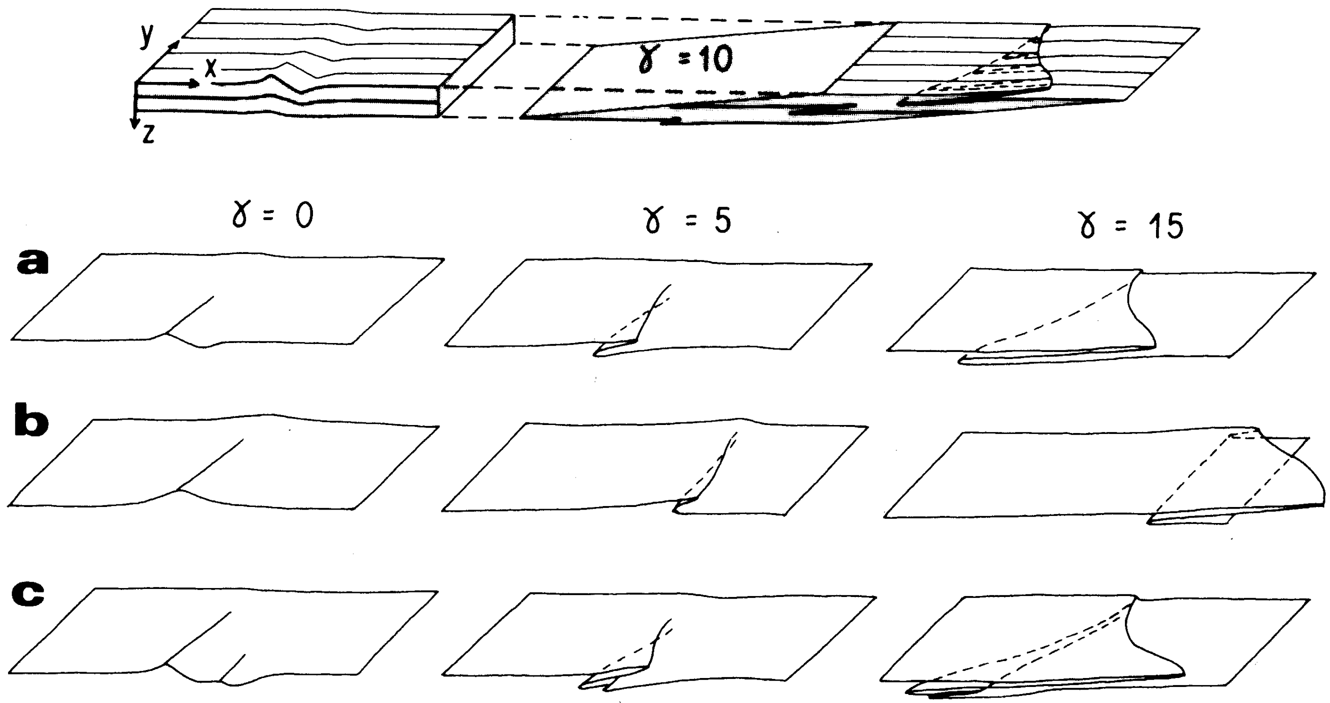
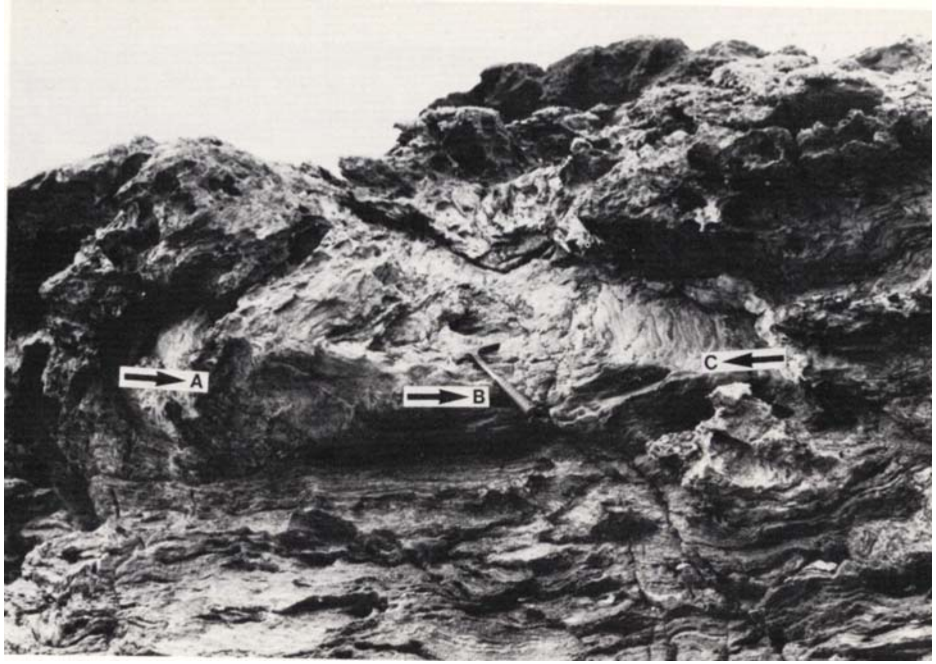


Fig. 2. Model 1: theoretical results. Noncylindrical initial deflections of various shapes (a, b & c) have been deformed in simple shear (top: x = shear direction, xy = shearing plane). Folds become asymmetric at moderate shear strains ($\gamma = 5$) and strongly noncylindrical at high shear strains ($\gamma = 15$).

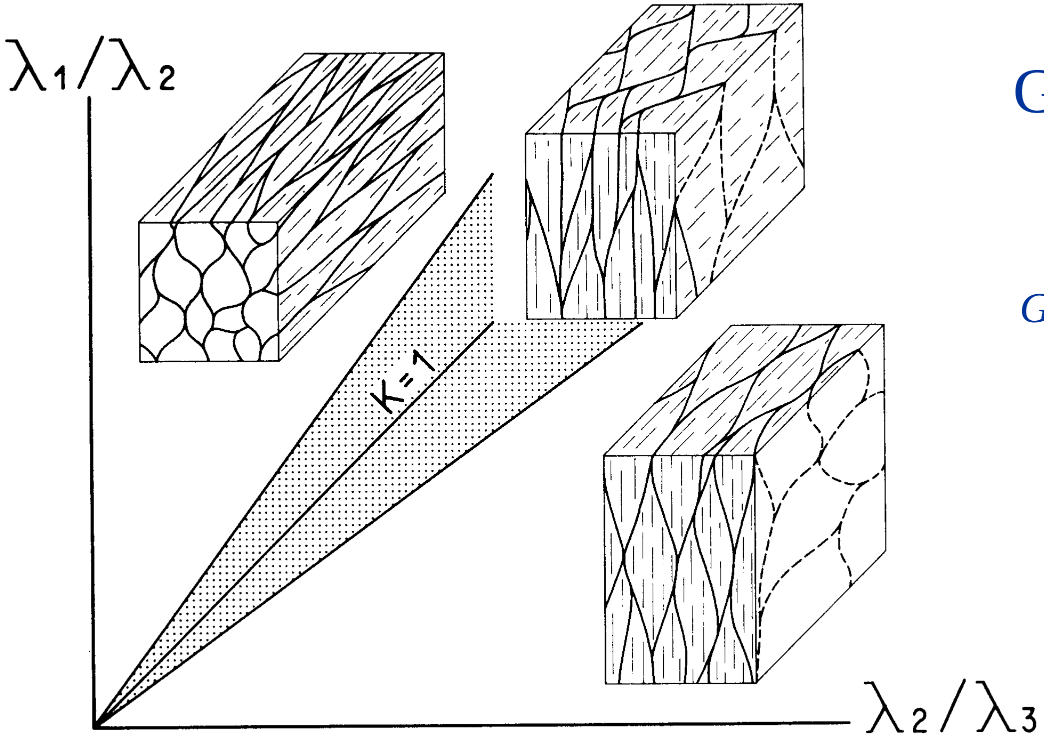
Sheath folds from the Ile de Groix



Sheath folds from the base of a thrust nappe from the Variscan belt of France

Sheath folds from the base of a thrust nappe from the Hakos mountains

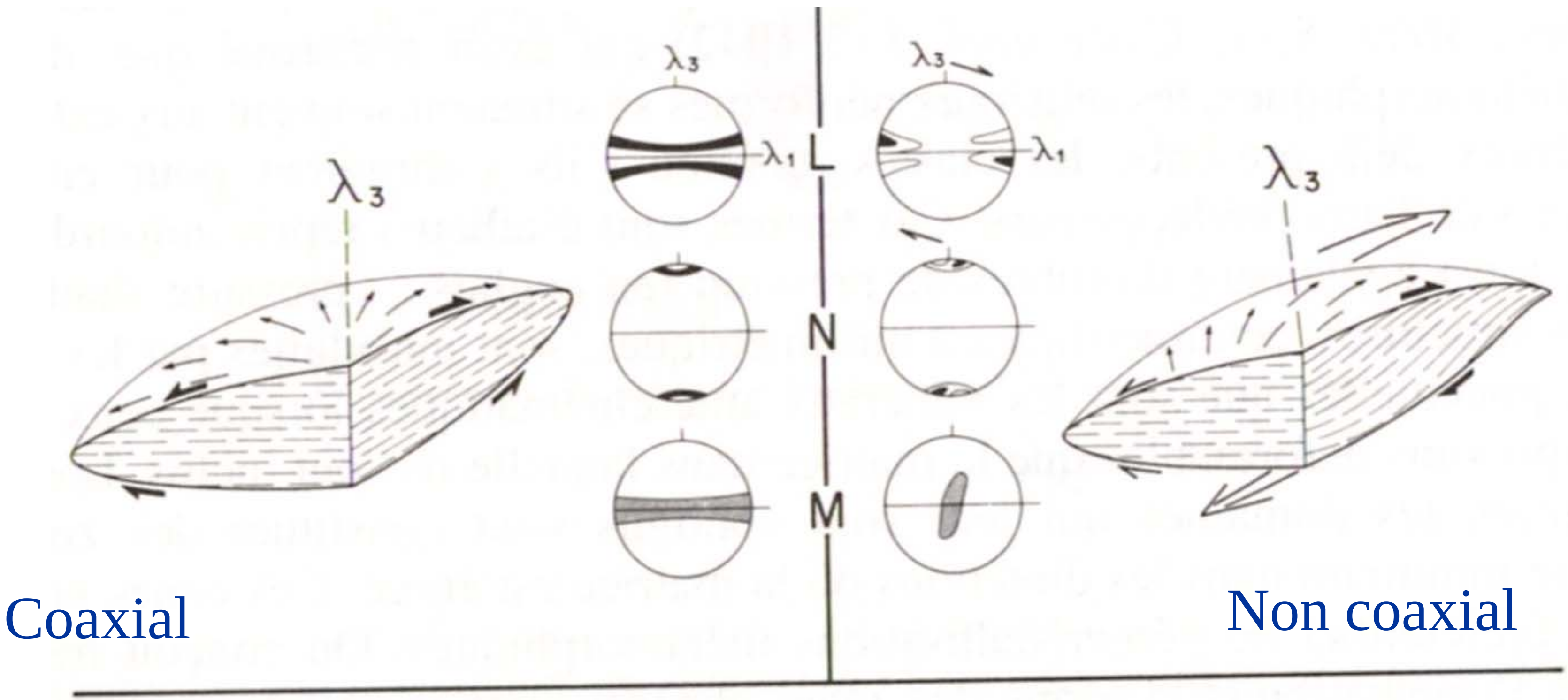
Shear zones and shear zones…



Geometry of the shear zones developed in flattening or constriction field

Gapais et al., Journ. Struct. Geol, 7, 1987

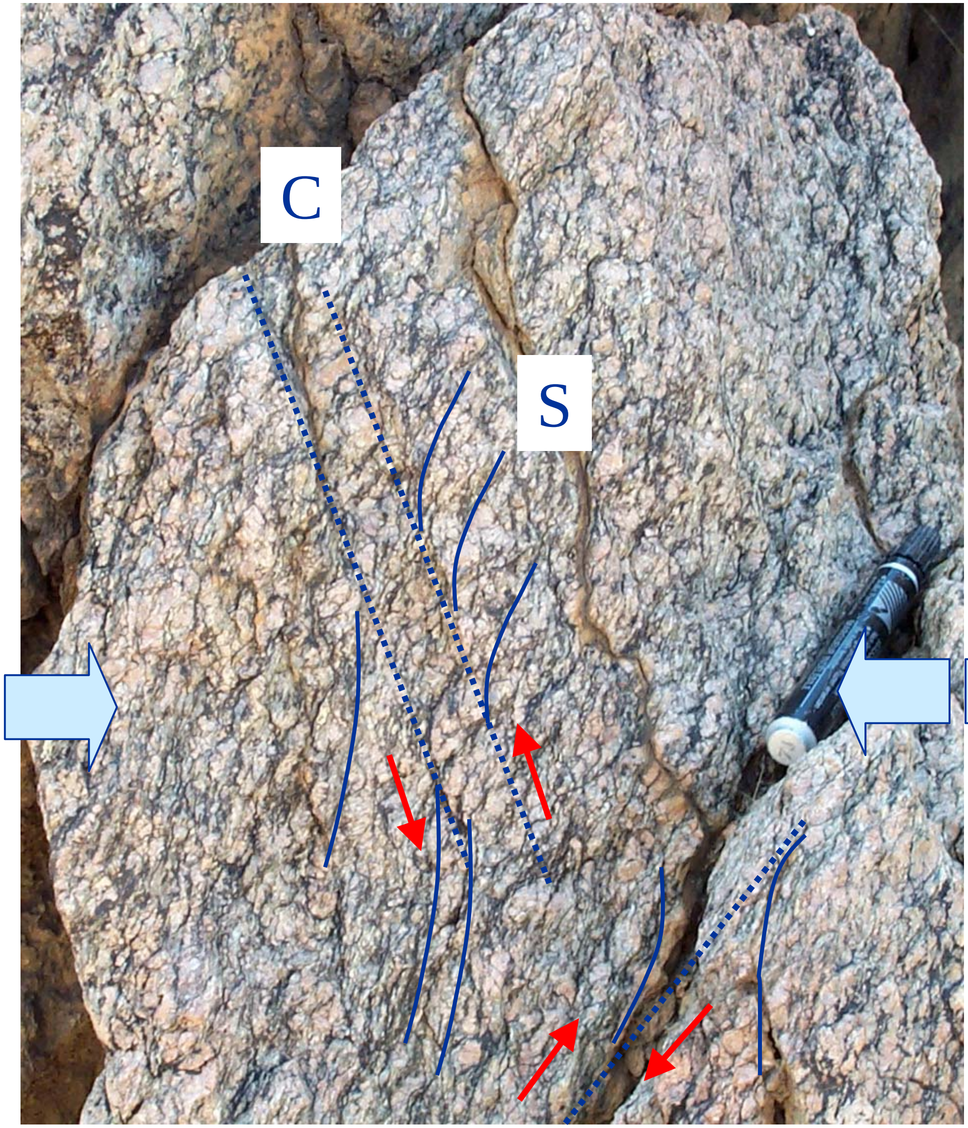
Change in geometry from coaxial to non coaxial regimes

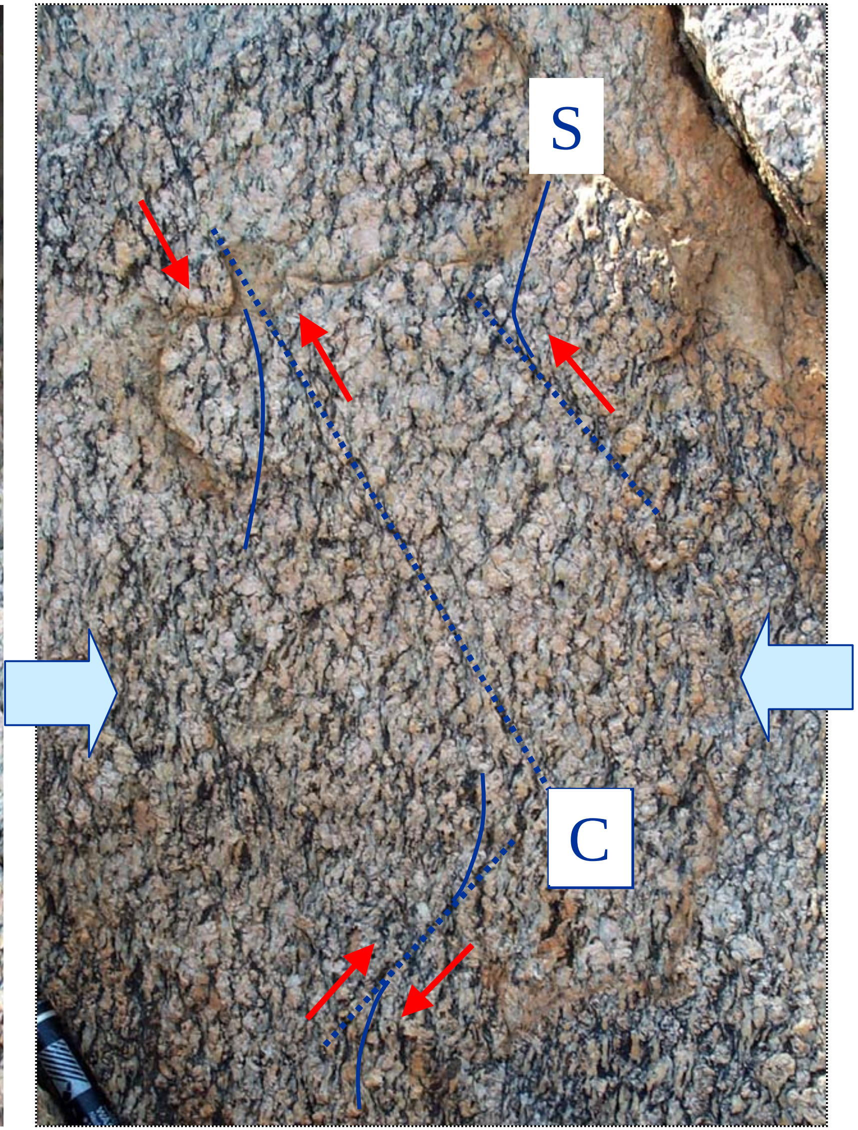


Conjugate shear zones: a coaxial regime

NNW

SSE





vs a non coaxial regime...