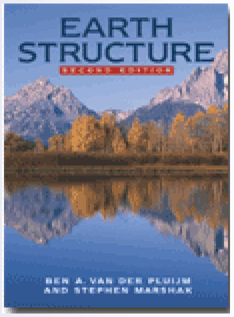
Lecture 12

Rock Fabric: Foliation and Lineation



Earth Structure (2nd Edition), 2004
W.W. Norton & Co, New York
Slide show by Ben van der Pluijm

- Fabric Terminology
- Foliation
  - Cleavage – Disjunctive, Pencil, Slaty, and Crenulation
  - Cleavage and Strain
  - Layering - Phyllite, Schist, and Gneiss
  - Migmatization
  - Mylonite
  - Foliation in Folds and Fault Zones
- Lineation – Form, Surface, and Mineral
- Tectonic Interpretation of Lineation

- **Fabric** of a rock is the geometric arrangement of component features in the rock, seen on a scale large enough to include many samples of each feature.

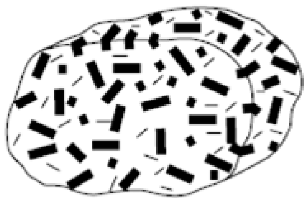
- **Fabric elements** are the component rock features

    - Examples of fabric elements include mineral grains, clasts, compositional layers, fold hinges, and planes of parting.

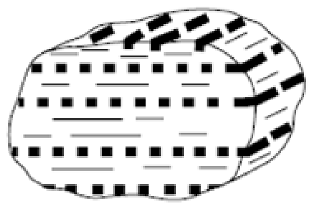
- **Primary fabric** forms during the formation of the rock

- **Tectonic fabric** forms as a consequence of tectonic deformation

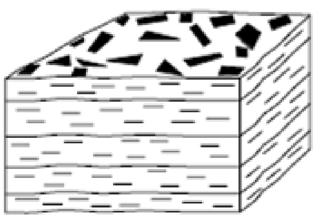
Fabric categories Fig. 11.1



Random - fabric elements (dark, elongate crystals) have long axes that are not parallel to one another.

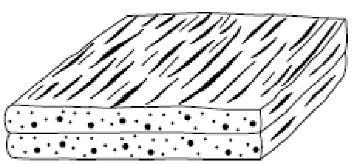


Preferred – Particular elements, such as long axes of elongate crystals are aligned with one another.



Foliation - fabric elements are planar and essentially parallel to one another, creating a 2-dimensional fabric.

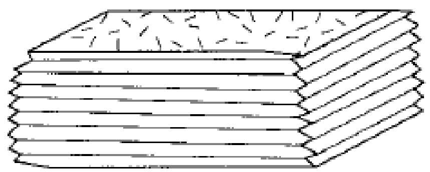
S_0, S_1, S_2 ... multiple planar fabrics ordered by number of relative age



Lineation - fabric elements are linear; in this example, fabric elements are aligned in single planes

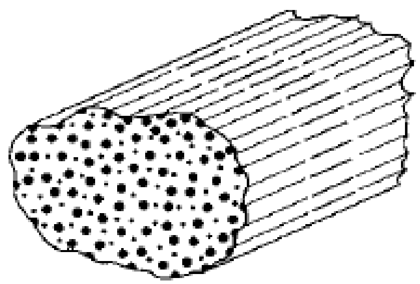
L_0, L_1, L_2 ...

Penetrative fabric; Tectonites Fig. 11.3



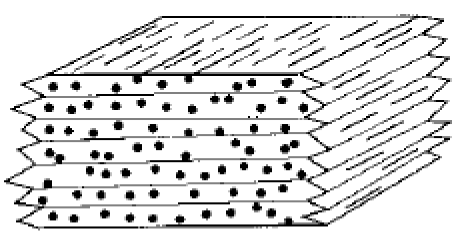
S-tectonite - Dominantly a foliation; rock may tend to split into sheets parallel to the foliation.

- *There is no or only weak lineation*



L-tectonite - Alignment of linear fabric elements creates the dominant fabric, so the rock may split into rod-like shapes.

- *There is no or only weak foliation.*

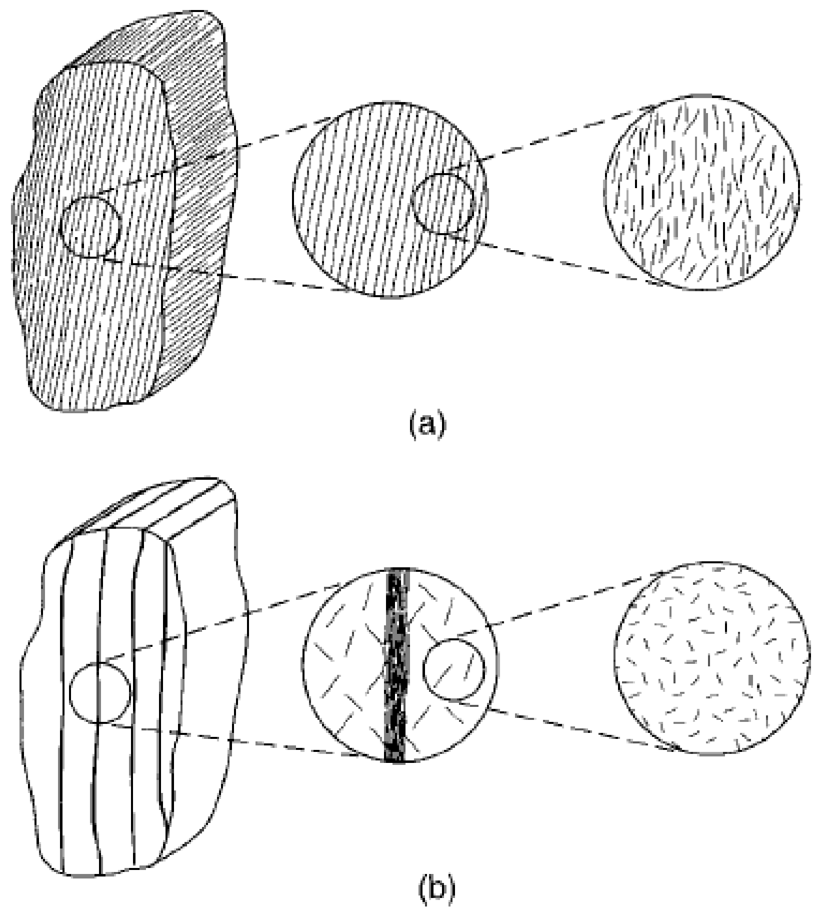


L/S-tectonite - a strong foliation and a strong lineation.

Continuous and spaced fabrics Fig. 11.2

- **Continuous** fabric continues to be visible no matter how small your field of view (at least down to the scale of individual grains).

- **Spaced** fabric has space visible between the fabric elements



Rock cleavage *- a secondary fabric element, formed under low-temperature conditions, that imparts on the rock a tendency to split along planes.*

- Forms subsequent to the origin of the rock.

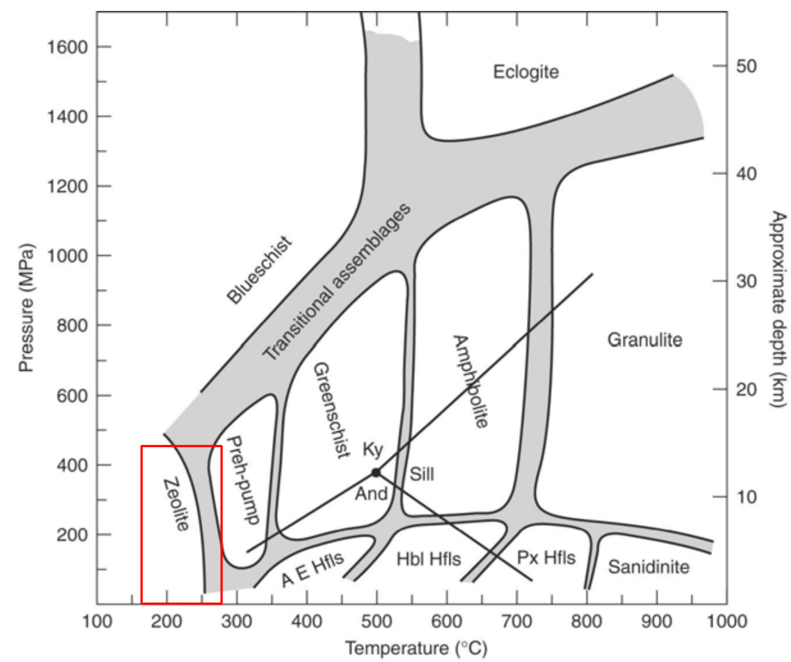
- Cleavage forms as large detrital phyllosilicates *fold and rotate,* fine grains dissolve from *pressure solution, and* new clay *crystallizes* within domains lying perpendicular to the shortening direction.

- Consists of many planes of weakness across which the rock may later break when uplifted and exposed at the surface of the earth, even though cleavage itself forms without loss of cohesion.

- *Microfolding* may occur

- *A closely spaced fracture array is not cleavage*

Metamorphic Facies



- Used for tectonic planar fabrics formed at or below lower greenschist facies conditions (i.e., ≤ 300°C).

- *Not used when referring to the fabric in schist or gneiss*

TABLE 11.2	FOLIATION CLASSIFICATION SCHEME
Spaced cleavage	(a) Disjunctive cleavage (e.g., stylolitic cleavage) (b) Crenulation cleavage
Continuous cleavage	(a) Coarse cleavage (e.g., pencil cleavage) (b) Fine cleavage (e.g., slaty cleavage)
Phyllitic cleavage	Continuous cleavage with a distinctive silky luster in low-grade metamorphic rock (lower greenschist facies)
Schistosity	Mica-rich foliation with a distinctive high sheen in low- to medium-grade metamorphic rock (greenschist facies)
Gneissic layering or gneissosity	Coarse compositional banding in high-grade metamorphic rock (upper amphibolite and granulite facies)

Barrovian sequence

Rock cleavage ii

- *Cleavage development removes soluble grains*.
- In argillaceous (muddy) limestone, calcite is removed, and clay and quartz are progressively concentrated.
- In argillaceous sandstone quartz is preferentially dissolved and clay is concentrated.
- Clay concentrates into ***domains*** containing ***selvages*** where clay plates or laths becomes preferentially oriented and concentrated along with insoluble residues ($\pm$ organics), relict, corroded calcite and quartz grains.
- Field observations suggest that *a rock must contain >10% clay in order for solution or stylolitic cleavage to develop*.
- The distribution of clay in rocks is not uniform.

Rock cleavage iii

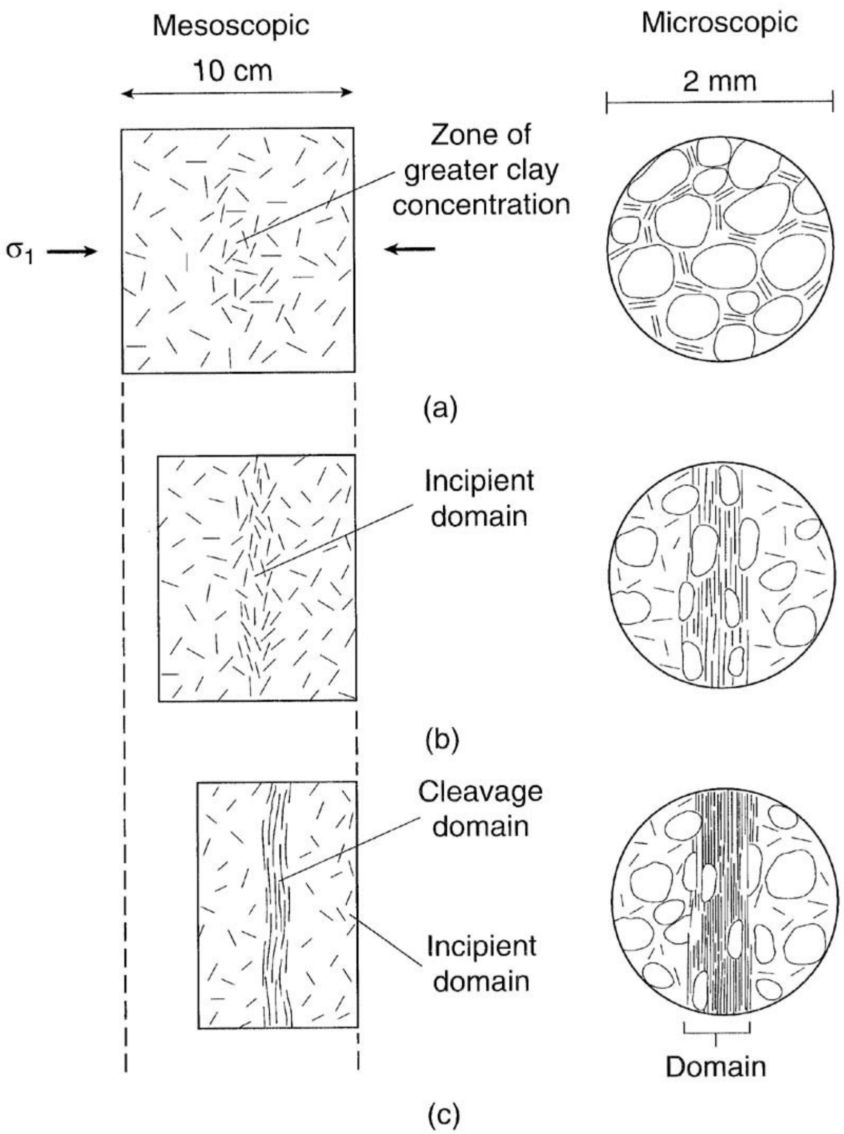
- Pressure solution occurs more rapidly with higher clay concentration (how clay affects pressure solution rates remains enigmatic)
- Hydrated (swelling) clay interlayers may increase ionic diffusion or maybe the charged surfaces of clay grains may act as a chemical catalyst for dissolution.
- As grains of carbonate and quartz are removed from the framework, platy clay grains collapse together like a house of cards.
- Clay concentrates into ***domains*** containing ***selvages*** where clay plates or laths becomes preferentially oriented and concentrated with insoluble residues (± organics), relict, corroded calcite and quartz grains.
- Clay concentration in domains and selvages further enhances the solubility the rock, so there is positive feedback.

Rock cleavage iv

- Domains and selvages thicken along their edges as deformation and pressure solution continue until critical stresses are removed

- As a result, compositional contrast between cleavage domains and microlithons becomes so pronounced that it defines a new stratification in the rock that can nearly or completely obscures the original bedding.

Evolution of spaced cleavage Fig. 11.6

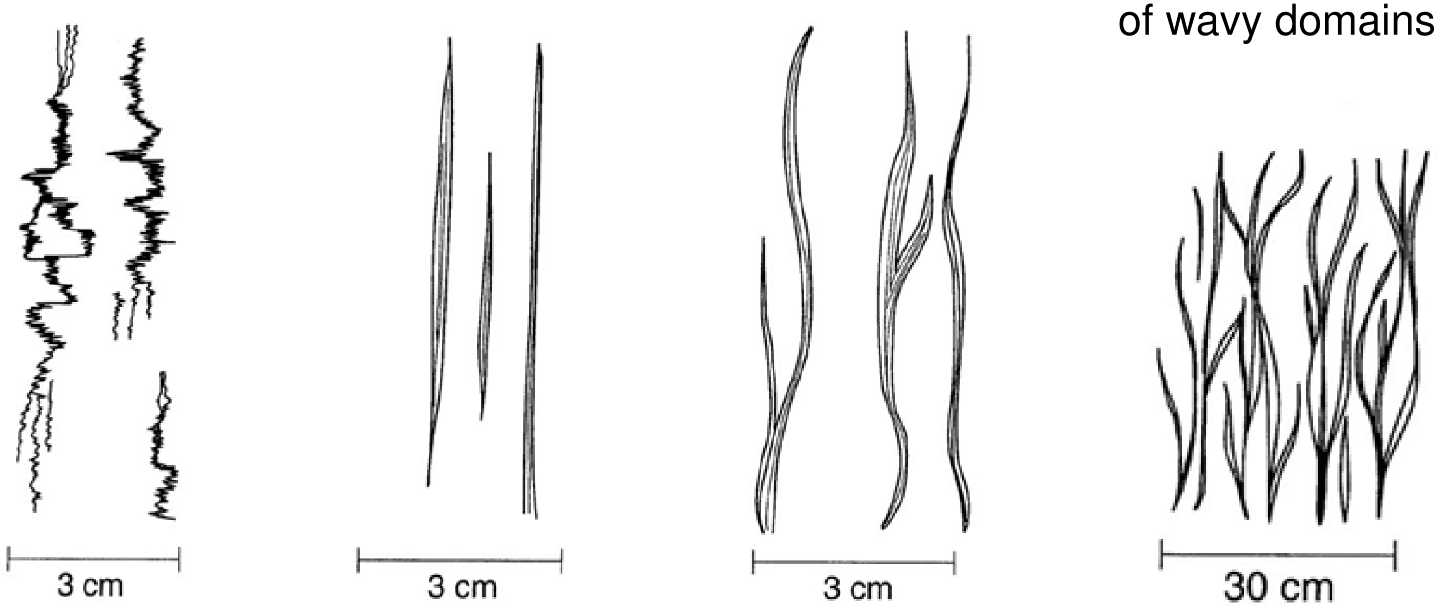


(a) Pre-cleavage fabric of rock have uneven concentrations of clay with random or uneven orientation

(b) Shortening and pressure solution in zones with high clay concentration evolves into incipient cleavage domain with preferential grain dissolution on faces perpendicular to $\sigma 1$, and rotation of clay flakes while flattening

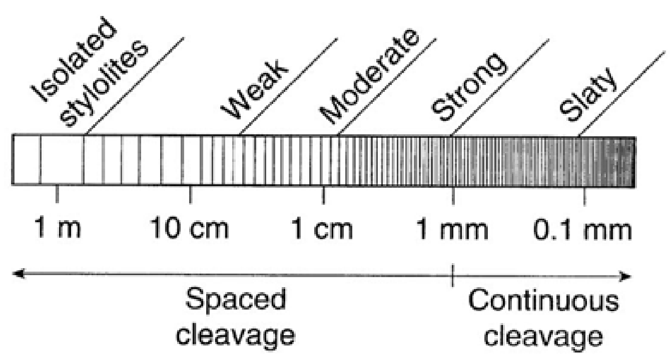
(c) Clearly visible cleavage domain with clay flakes packed tightly together and relicts of soluble mineral grains

Cleavage morphology Fig. 11.7 Domain spacing of spaced cleavage

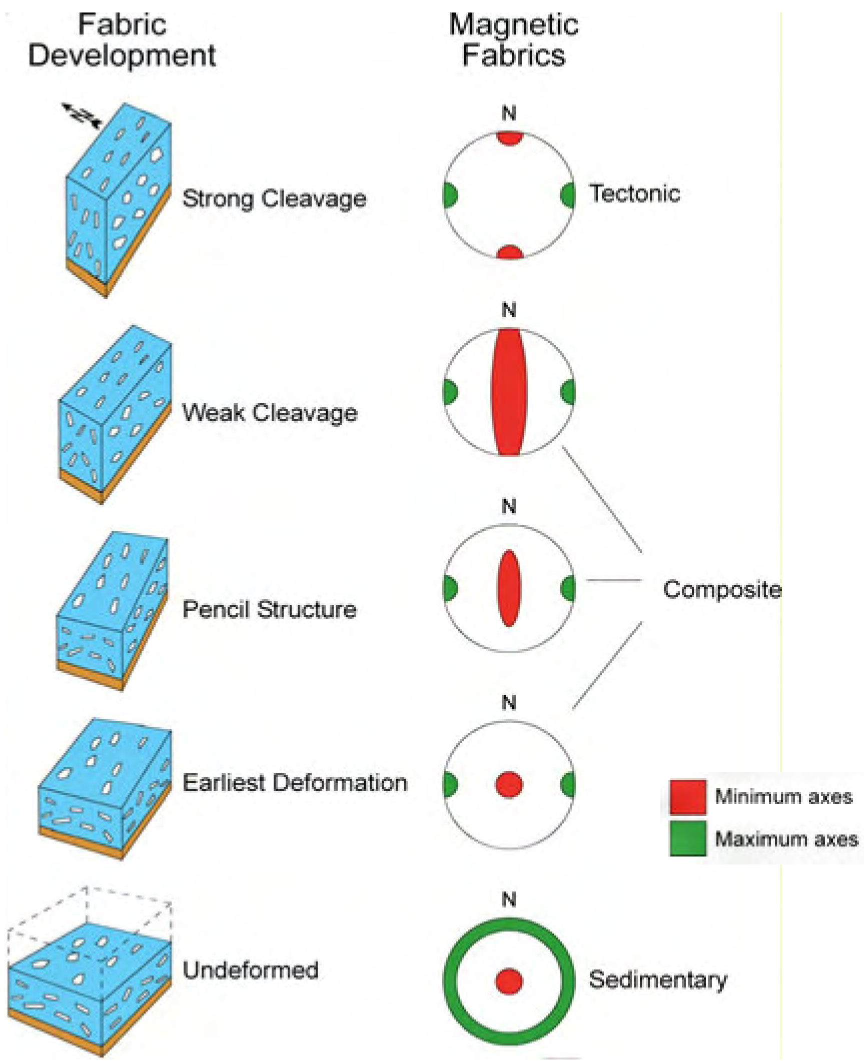


Compaction versus Tectonic stylolites

description of spaced cleavage based on domain spacing



Mica preferred orientation from magnetic susceptibility Fig. 11.29

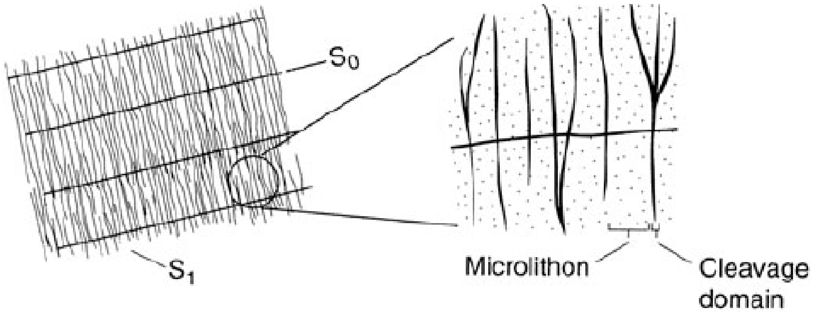


Magnetic fabric becomes more pronounced in progressively cleaved mudrocks

- The degree of foliation development, from compaction fabric to strong cleavage, can be characterized by distributions of a rock's maximum and minimum magnetic-susceptibility axes.

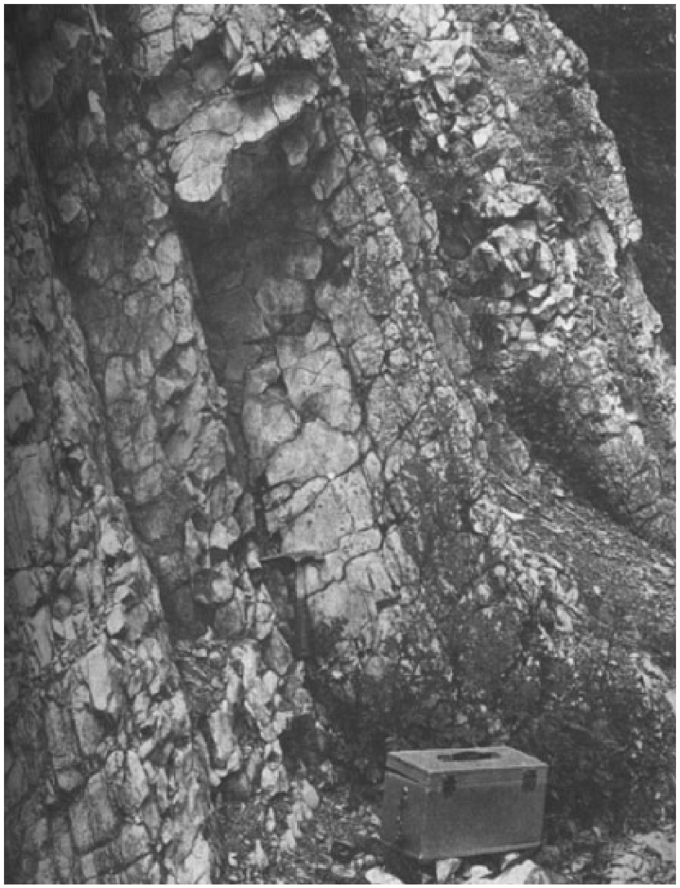
Disjunctive cleavage *is foliation that forms mostly in sedimentary rocks subjected to tectonic differential stress under sub–greenschist facies metamorphic conditions.*

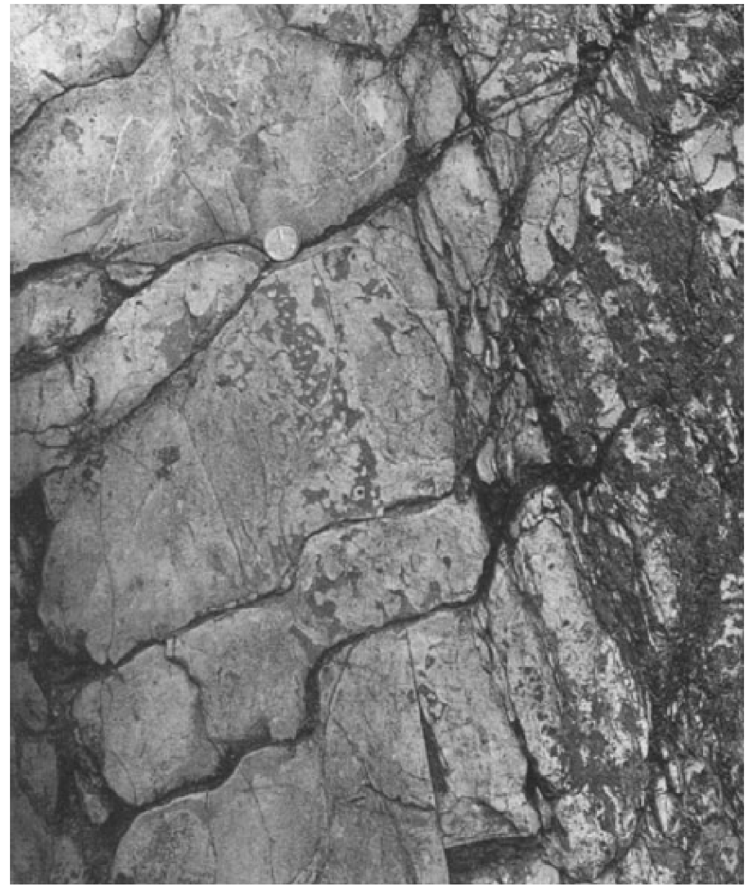
- It is defined by arrays of subparallel fabric elements, called **cleavage domains,** in which the original rock fabric and composition have been markedly changed by the process of pressure solution.
- Domains are separated by **microlithons** in which the original rock fabric and composition are more or less preserved.
- The adjective "disjunctive" implies that the cleavage domains cut across a preexisting foliation in the rock (usually bedding), without affecting the orientation of the preexisting foliation in the microlithons.



Disjunctive cleavage ii

Spaced disjunctive cleavage (or solution cleavage) in limestone from the Harz Mountains of Germany.





The cleavage is marked by the narrow dark bands which cut across the original, lighter-colored argillaceous limestone.

Disjunctive cleavage and Tectonic Stylolites

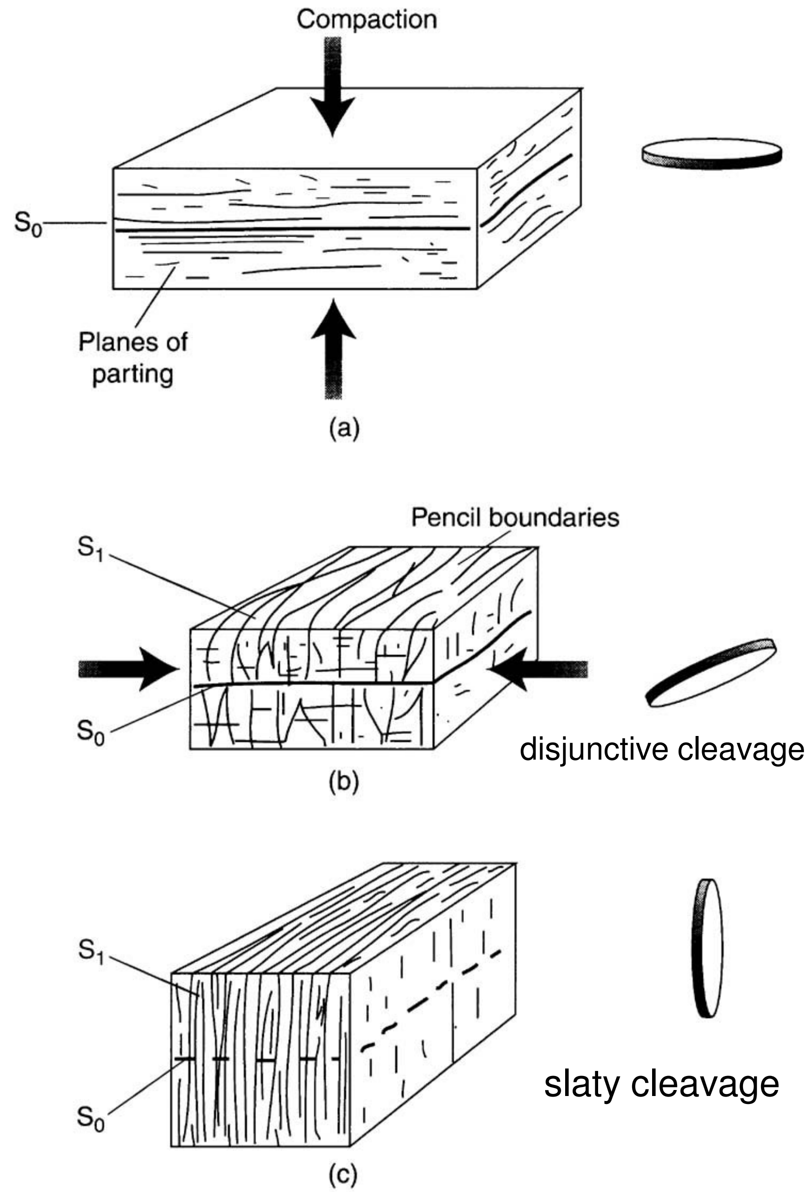
- Because pressure solution *is always involved in the formation of disjunctive cleavage*, terms such as **pressure-solution cleavage** and **stylolitic** cleavage are forms of disjunctive cleavage.

Stylolites (Greek: stylos, pillar; lithos, stone) *are serrated surfaces within a rock mass at which mineral material has been removed by pressure dissolution, in a process that decreases the total volume of rock.*

Pencil cleavage Sec 11.3.3

Illustration of progressive cleavage development from pencil to slaty cleavage

- Compaction during burial of a sedimentary rock produces a weak preferred orientation of clay parallel to bedding and a pancake-shaped strain ellipsoid in the bed plane.
- Shortening parallel to layering creates an incipient tectonic fabric.
- Superposition of this fabric on the primary compaction fabric forms pencil-structured lithons ~5–10 cm long and ~0.5–1 cm wide; the representative strain ellipsoid is now elongate, with the long axis parallel to the pencils.
- Continued tectonic shortening leads to slaty cleavage developed at high angles to bedding.
- The phyllosilicates are now dominantly aligned with the direction of cleavage, and a representative strain ellipsoid is oblate and parallel to cleavage.



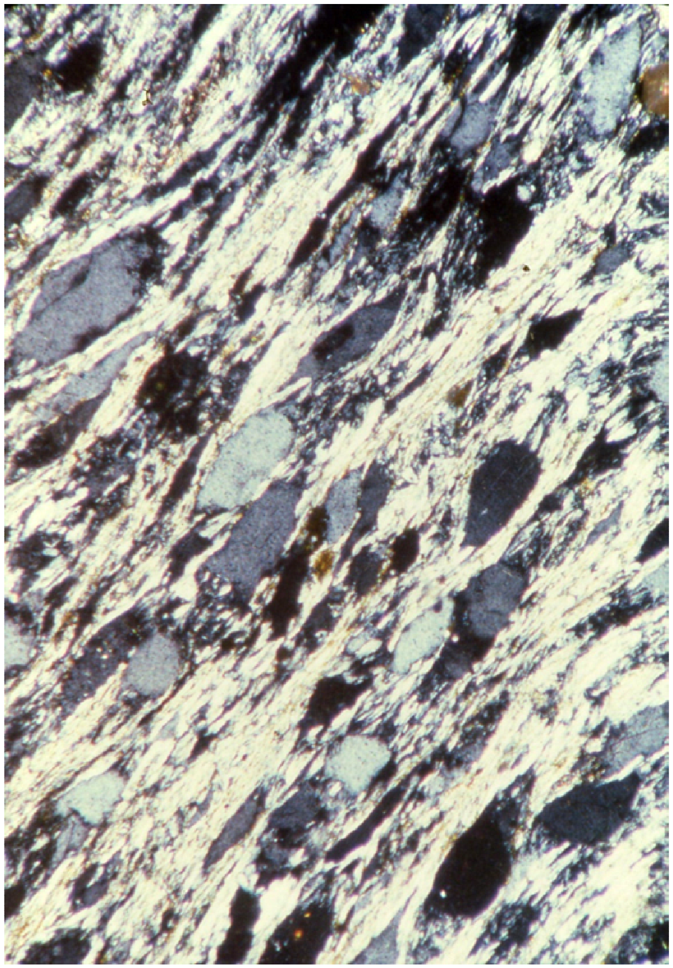
Pencil cleavage Sec 11.3.3

Slaty cleavage forms by the same processes as disjunctive cleavage in argillaceous sandstone or limestone, but results in tightly packed domains with no intervening microlithons and a rock mass with a tectonically induced fabric of preferred orientation.

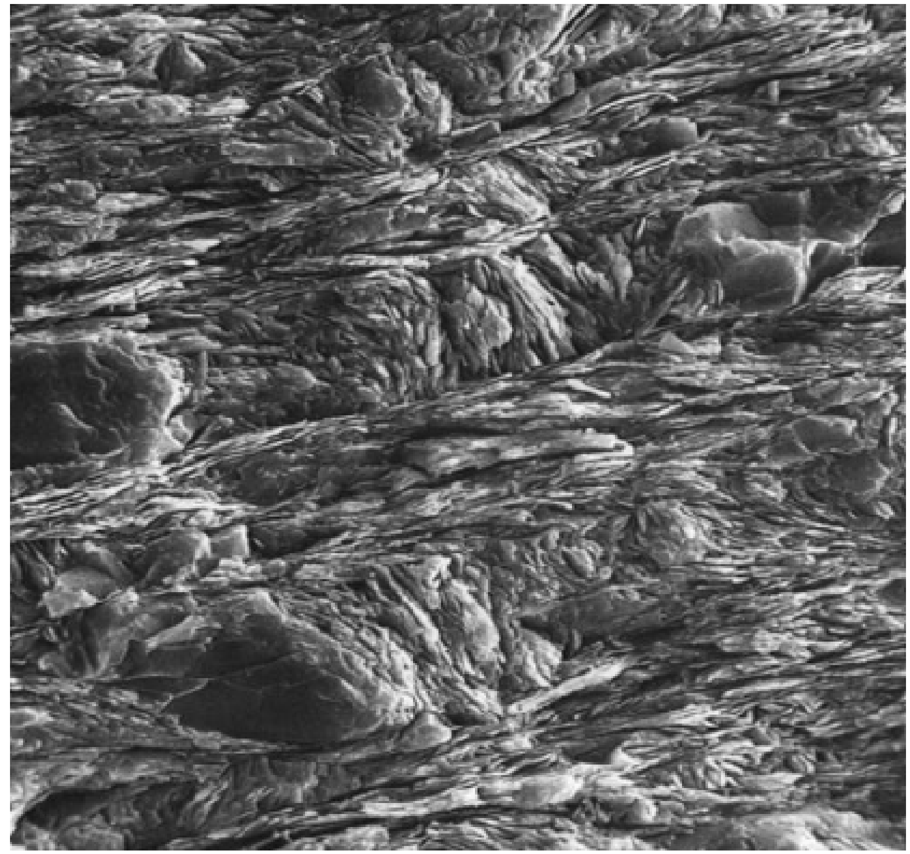
- As shortening perpendicular to cleavage planes accumulates, clay throughout the rock develops a preferred orientation at an angle to the original sedimentary fabric and this orientation dominates over the primary fabric.
- The finite strain ellipsoid for slaty cleavage pancakes parallels to the tectonic fabric.
- Slaty cleavage tends to be smooth and planar and forms under temperature conditions that mark the onset of metamorphism (250°C–350°C).
- ***Slate*** is fine-grained, low-grade metamorphic rock rocks with a highly developed slaty cleavage

Well-developed axial plane slaty cleavage in a__________ syncline from the southern Appalachians, USA

Photomicrographs of slaty cleavage

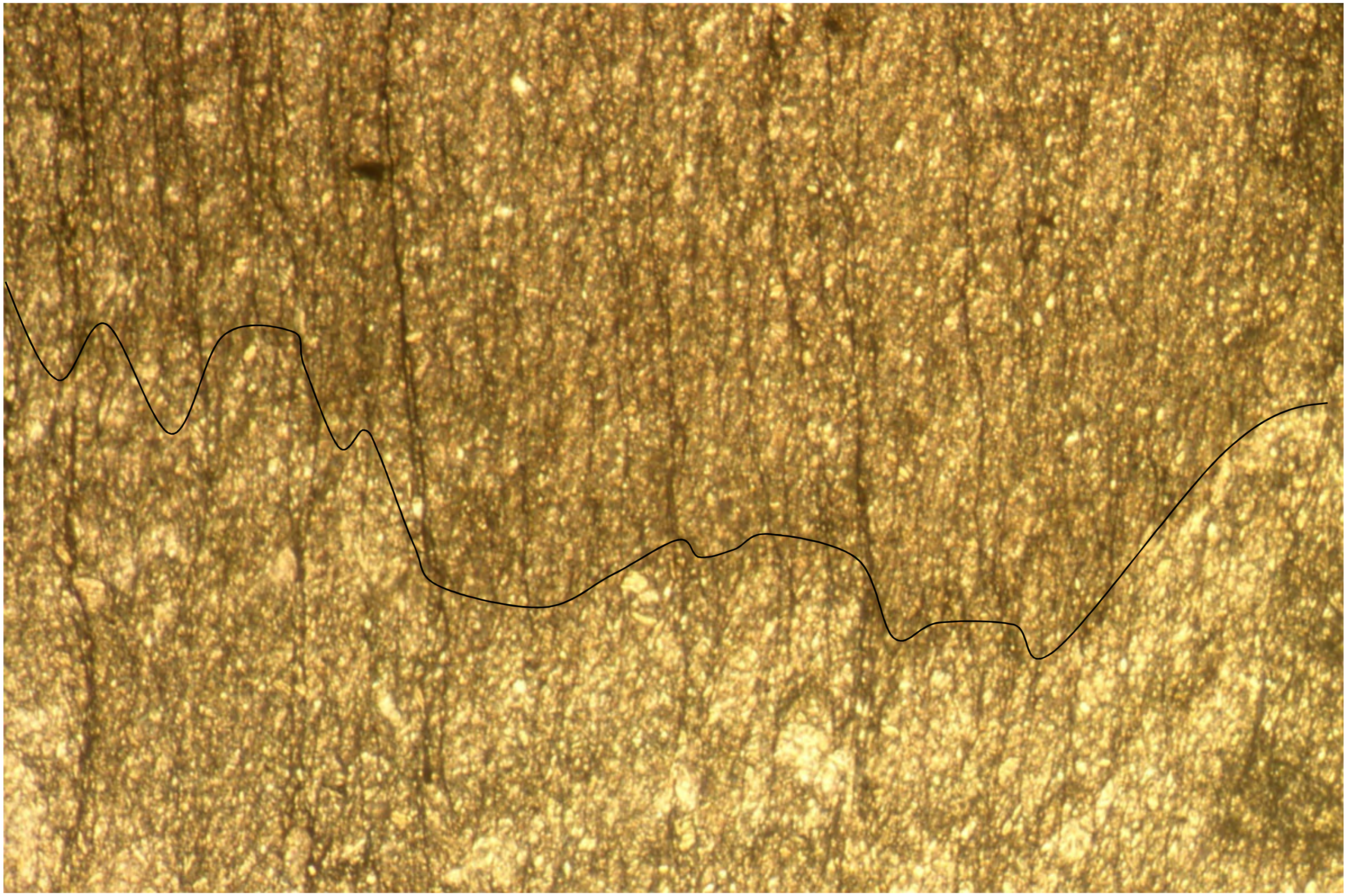


slaty cleavage



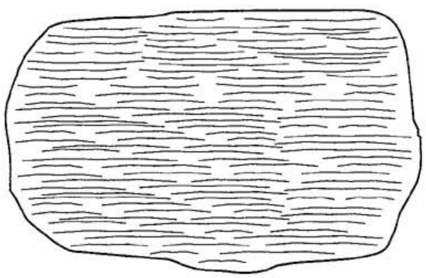
Scanning electron micrograph in slate from Germany. Note the microcrenulation with distinct microlithons having mica parallel to bedding and cleavage domains Width of view is 100 µm.

Photomicrograph of spaced cleavage

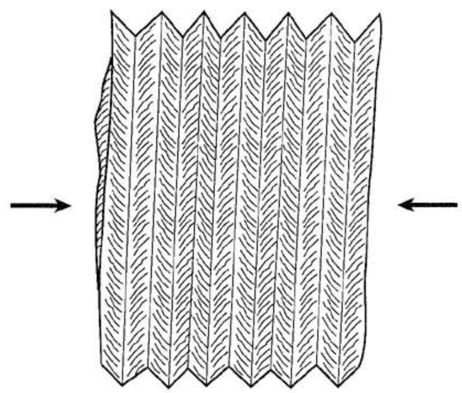


Crenulation cleavage results from closely and evenly spaced foliation that is shortened in a direction at a low angle to it such that crinkles like the baffles in an accordion

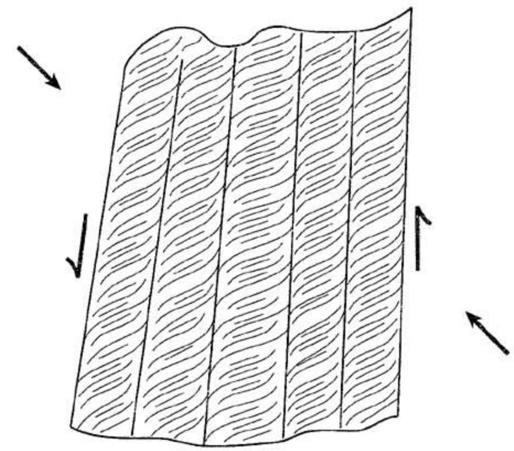
Categories of crenulation cleavage



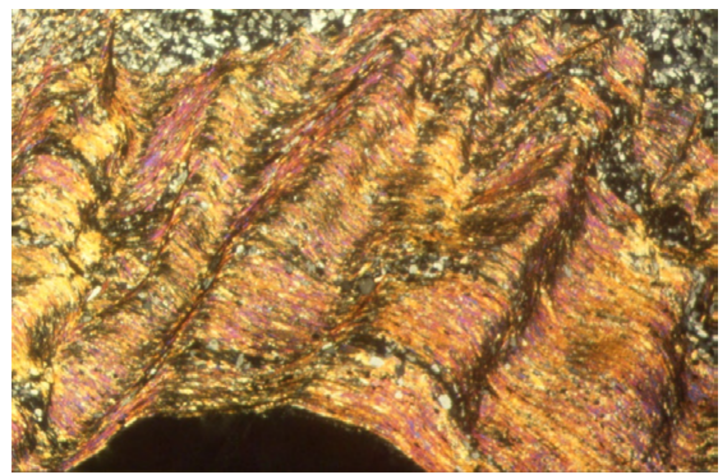
symmetric



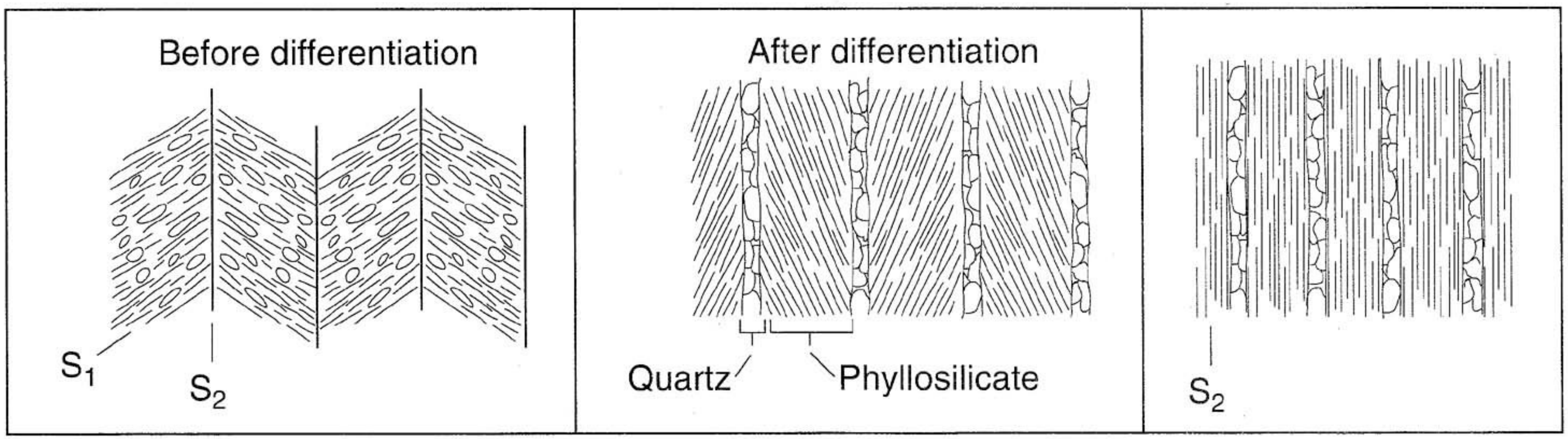
asymmetric



sigmoidal



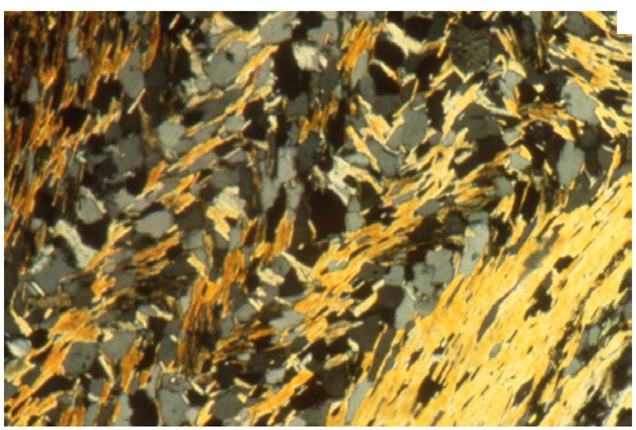
Differentiated crenulation cleavage and Transposition



Fairly homogeneous composition, before migration of quartz

Quartz accumulates in hinges while phyllosilicates concentrate in limbs resulting in compositional banding

Complete transposition of S1 foliation into a new S2 cleavage or schistosity



- **Transposition** occurs when a previous foliation disappears entirely and is replaced entirely by a new foliation that is defined by both the preferred orientation of phyllosilicates and by microcompositional layering from mineralogical differentiation.

Phyllitic Cleavage and Schistosity

- When metamorphic conditions reach the lower greenschist facies, the clay and illite in a pelitic rock react to form white mica3 and chlorite.
- If reaction occurs in an anisotropic stress field, these phyllosilicates grow with a strong preferred orientation.
- Rock that is composed of strongly aligned fine-grained white mica and/or chlorite is called **phyllite** and the foliation that it contains is called **phyllitic cleavage.**

- The mineralogy and fabric of phyllites give the rock a distinctive silky luster.
- Phyllitic cleavage is intermediate between slaty cleavage and schistosity.

Phyllitic Cleavage and Schistosity

- When metamorphic conditions get into the middle greenschist facies, the minerals in a pelitic lithology react to form coarser-grained mica and other minerals.

- When these reactions again take place in an anisotropic stress field, the mica has a strong preferred orientation. The resulting rock is a **schist,** and the foliation it displays is called **schistosity.**

- The specific assemblage of minerals that forms depends not only on the pressure and temperature conditions at which metamorphism.

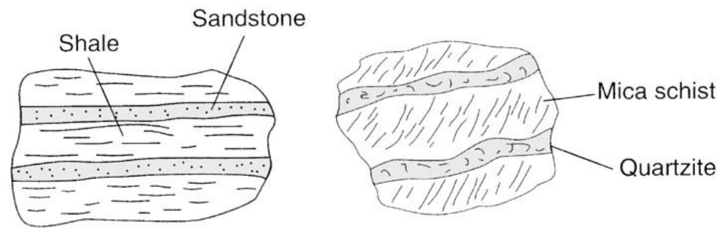
Gneiss

- Foliated **gneiss** is a high-grade metamorphic rock in which the foliation is defined by compositional banding

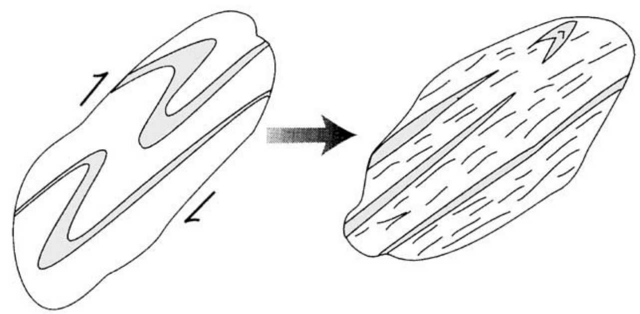
- Commonly, light and dark bands of felsic and mafic mineralogy alternate.

- The light-colored layers are rich in feldspar and quartz, whereas darker layers contain more mafic minerals amphibole/pyroxene and/or biotite.

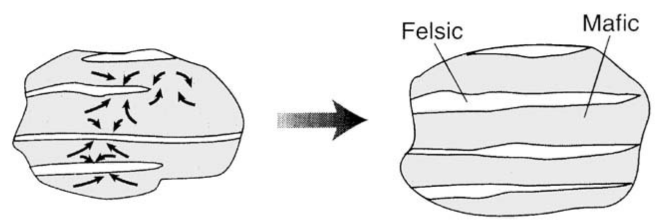
- Color banding in gneiss is called **gneissosity.**



Inheritance from an original lithology

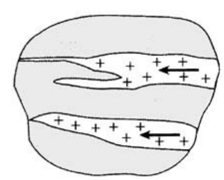


creation of new compositional banding via transposition

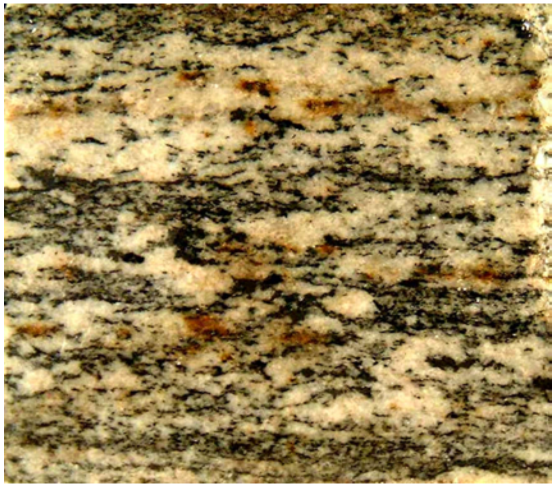


metamorphic differentiation

lit-par-lit intrusion (bed-by-bed)



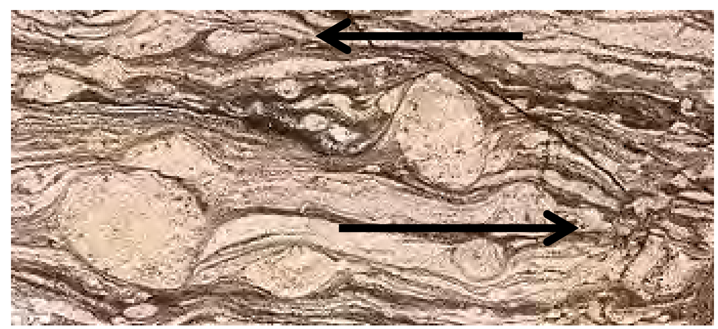
Gneiss ii



Mylonite is ductilely deformed rocks formed by the accumulation of large shear strain, in ductile fault zones.

- Ordinarily a fine-grained, compact rock produced by dynamic recrystallization of the constituent minerals resulting in a reduction of the grain size of the rock and classified as a metamorphic rock.
- There are many different views on it's formation, but it is generally agreed that crystal-plastic deformation must have occurred, and that fracturing and cataclastic flow are secondary processes.
- Mechanical abrasion of grains by milling does not occur, although this was originally thought to be the process that formed mylonites, which were named from the Greek mylos, meaning mill.

Amphibolite mylonite showing a number of (rotated) porphyroclasts: a clear red garnet left in the picture and small white feldspar porphyroclasts throughout.



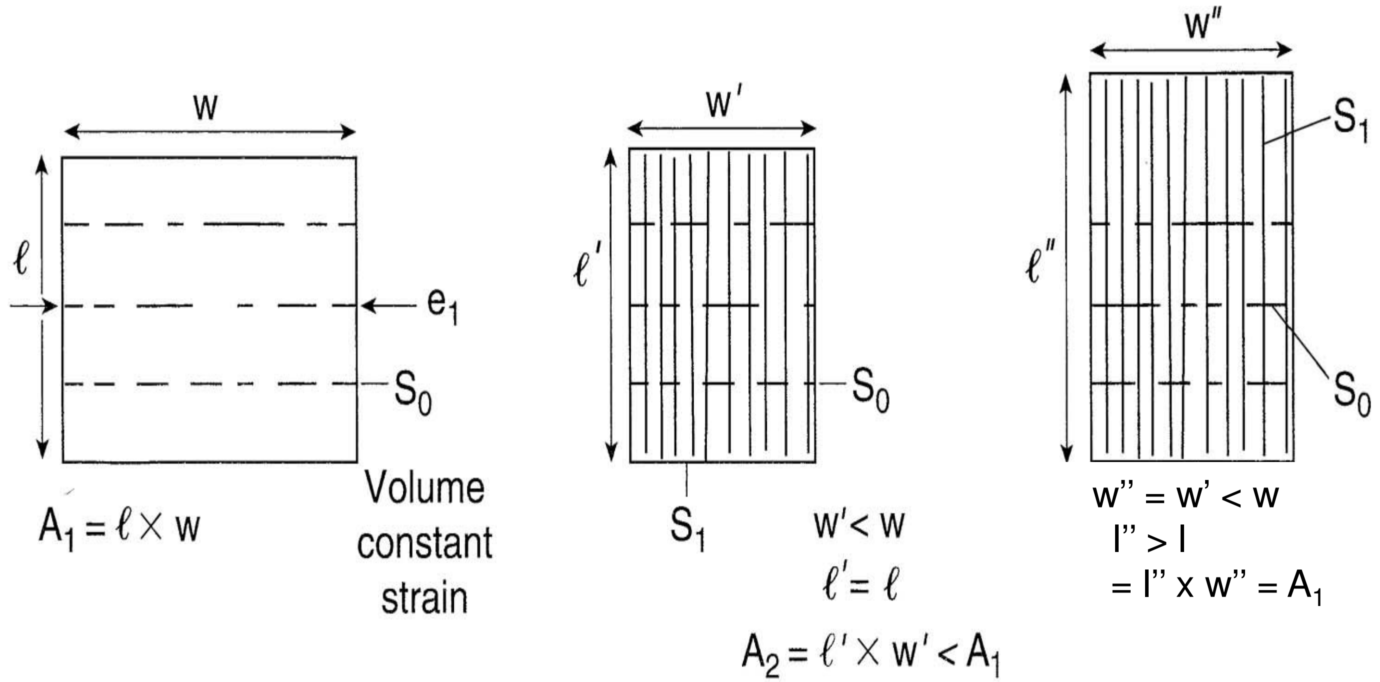
Microscopic view of a mylonite from the Italian Alps showing rotated clasts indicating dextral shear and pressure shadows.

Cleavage and Strain: reduction spots

- Ellipsoidal reduction spots can be used as strain markers if they were formed as spherical regions around a reducing phase prior to deformation

Cleavage and strain: volume change

Is there volume loss from cleavage formation?



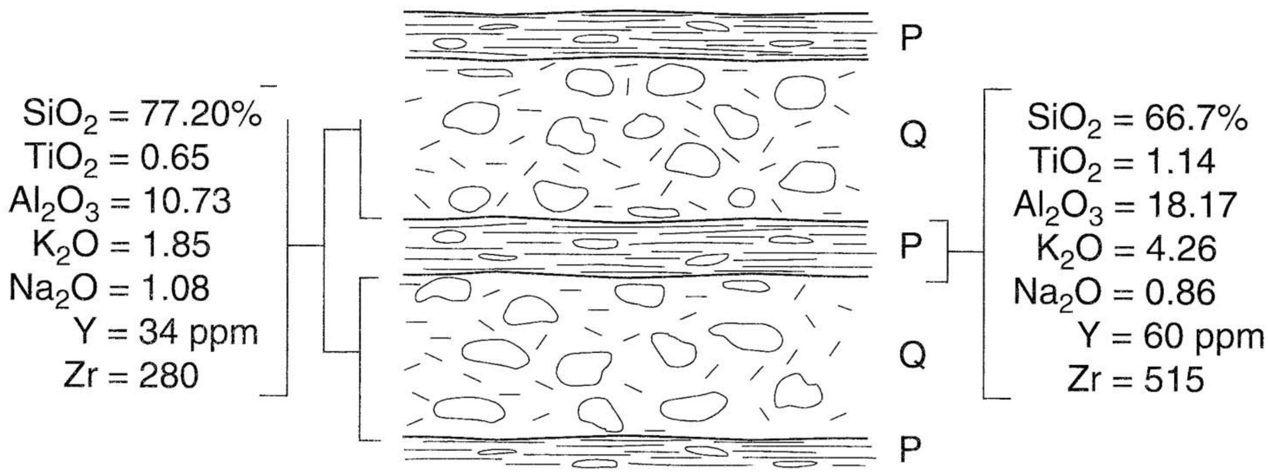
A block of height ℓ and width w is shortened and forms a cleavage.

Volume loss occurs when w′ < w, if $\ell' = \ell$ and we assume no change in the third dimension

Volume constant strain, requires if $\ell'' > \ell'$

Cleavage and strain: volume change

- Volume loss may occur by preferential removal of certain elements.
- If the composition of the microlithons (Q-domains) is assumed to be constant, then the amount of volume loss can be calculated (see equation



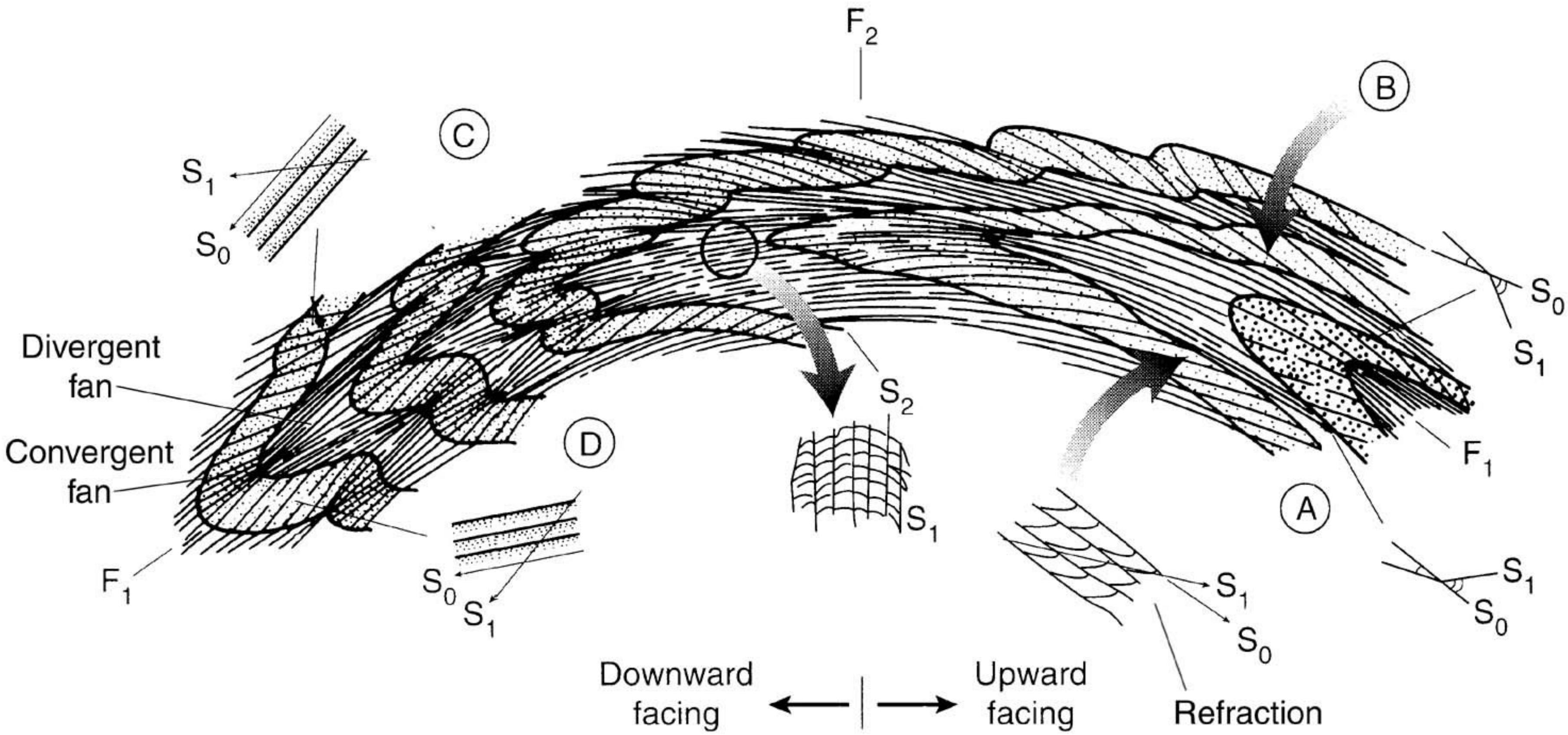
Assume Q-domains are compositionally unmodified.

$$\text{\% volume loss from P-domains} = \frac{(\%\ TiO_2 \text{ in P}) - (\%\ TiO_2 \text{ in Q})}{\%\ TiO_2 \text{ in P}} \times 100$$

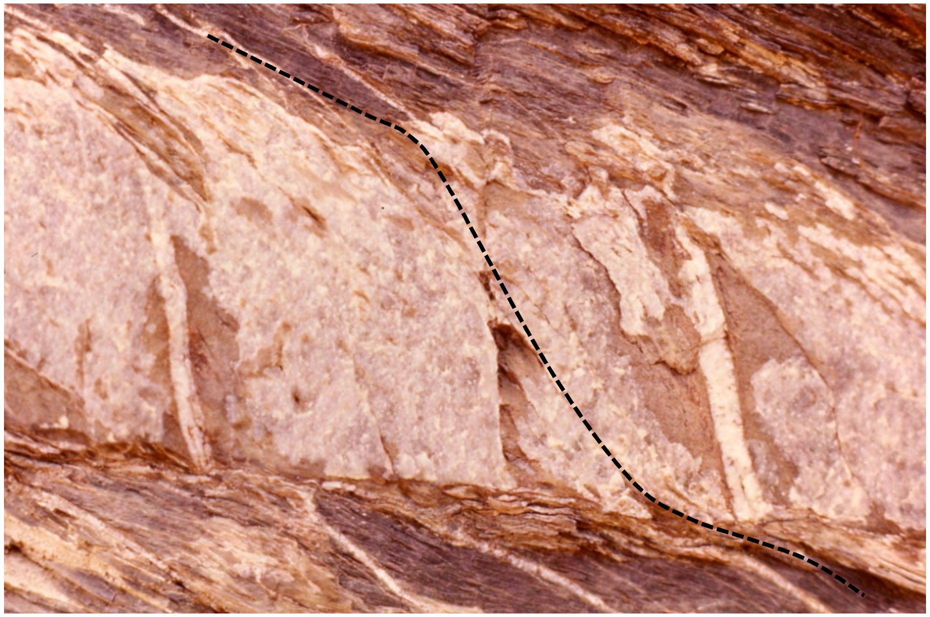
Based on relatively immobile elements TiO2, Y, and Zr, the volume loss calculates at ~45%.

Cleavage, folding, refraction, facing

Cleavage-bedding relationships and cleavage refraction in upright and overturned limbs of upward-facing and downward-facing folds.



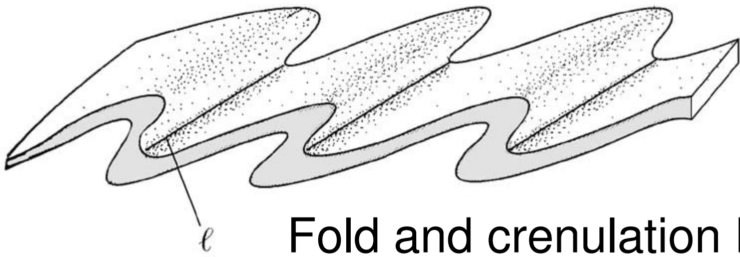
Cleavage Refraction is the change in cleavage attitude that occurs where cleavage domains cross from one lithology into another of different competency, and reflects variation in the local strain field between beds.



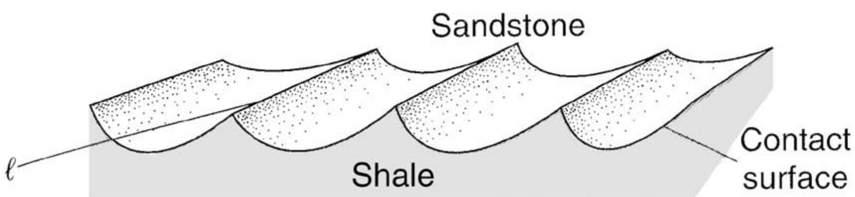
Lineation is any fabric element that can be represented by a line, meaning that one of its dimensions is much longer than the other two.

Lineation can be grouped as form, surface, and mineral

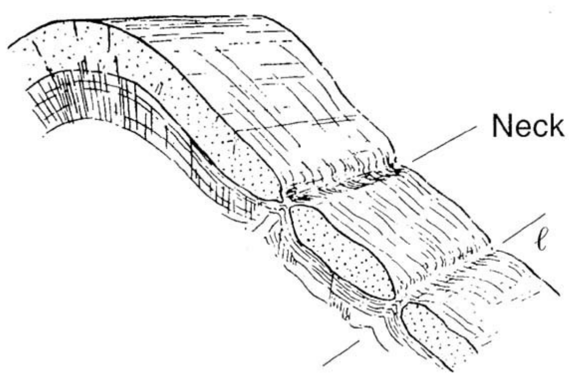
Form lineation



Fold and crenulation hinges



Mullions

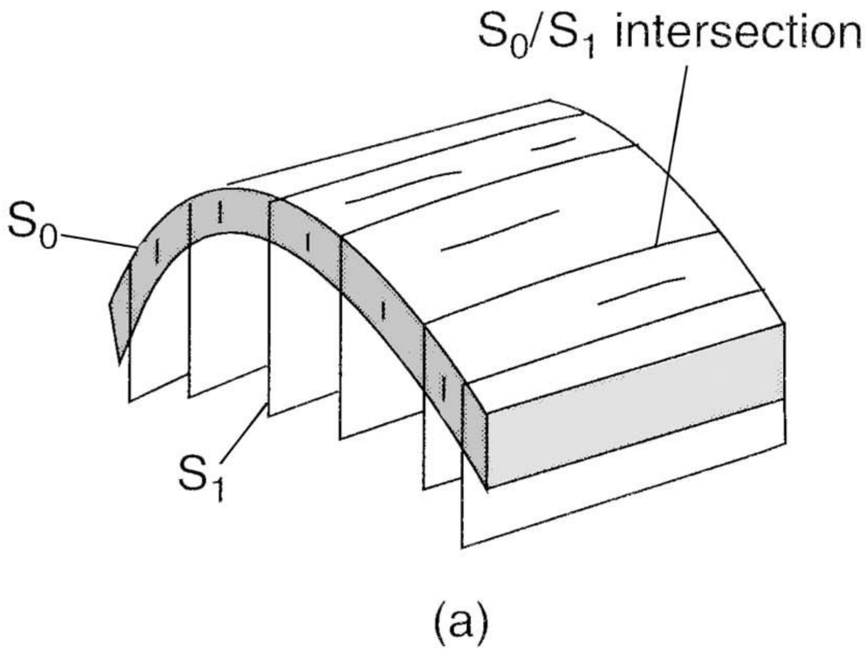


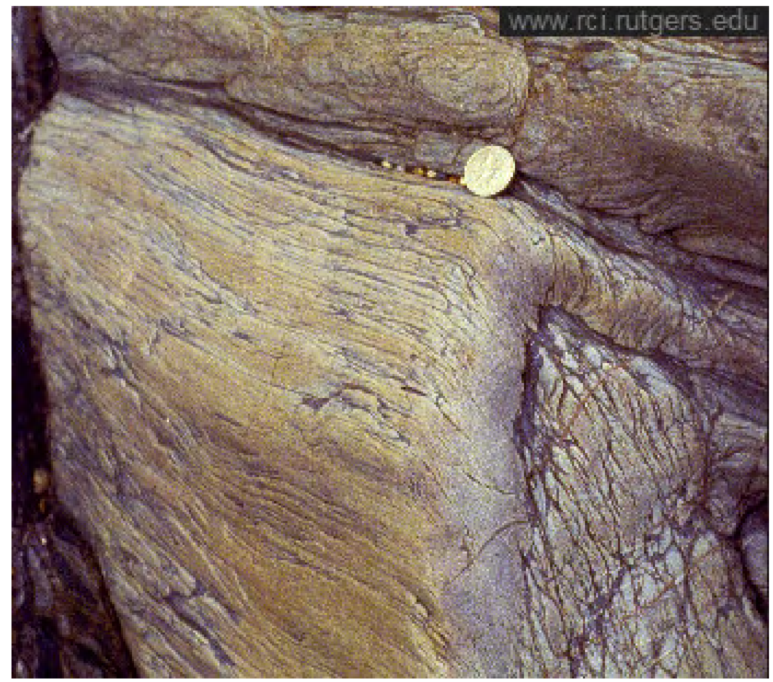
Boudins

Elongated pebbles

Elongate pebbles (arrows) in a stretched conglomerate (Narragansett, Rhode Island, USA)

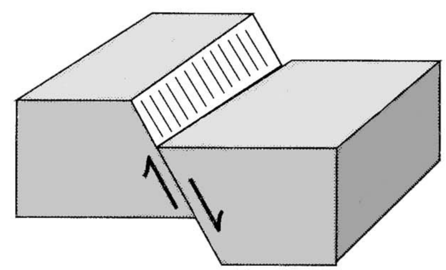
Bedding-cleavage intersection lineation





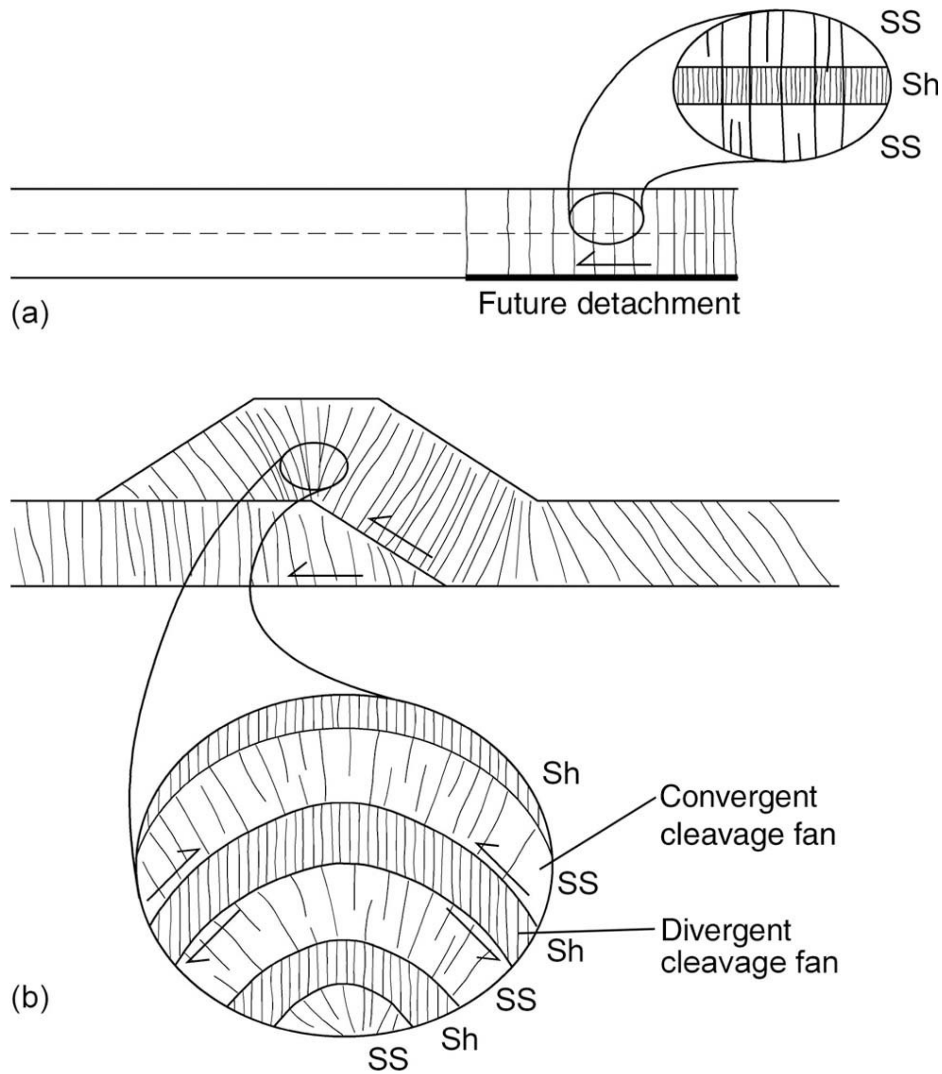
Intersection lineation of bedding (S0) and (axial plane) cleavage (S1) in a fold

Surface and mineral lineation



Evolution of cleavage in a foreland fold-thrust belt.

- Cleavage forms normal to bedding but variously spaced in different lithologies
- After formation of a ramp anticline regional shear has caused cleavage to be inclined with respect to bedding.
- In the fold itself, cleavage refracts as it passes from lithology to lithology.
- Cleavage in the shale beds is axial planar with respect to the folds, but fans around the folds in the sandstone layers.



Transected cleavage can form in transpressional environments where they are strain components of both pure and simple shear

- Cross-cutting cleavage cuts obliquely across the fold axial plane

- It may stem from cleavage superimposed on preexisting folds, or local complexities in the strain field.

- For example, rotation of a thrust sheet during folding may cause fold hinges to become oblique to the regional shortening direction.