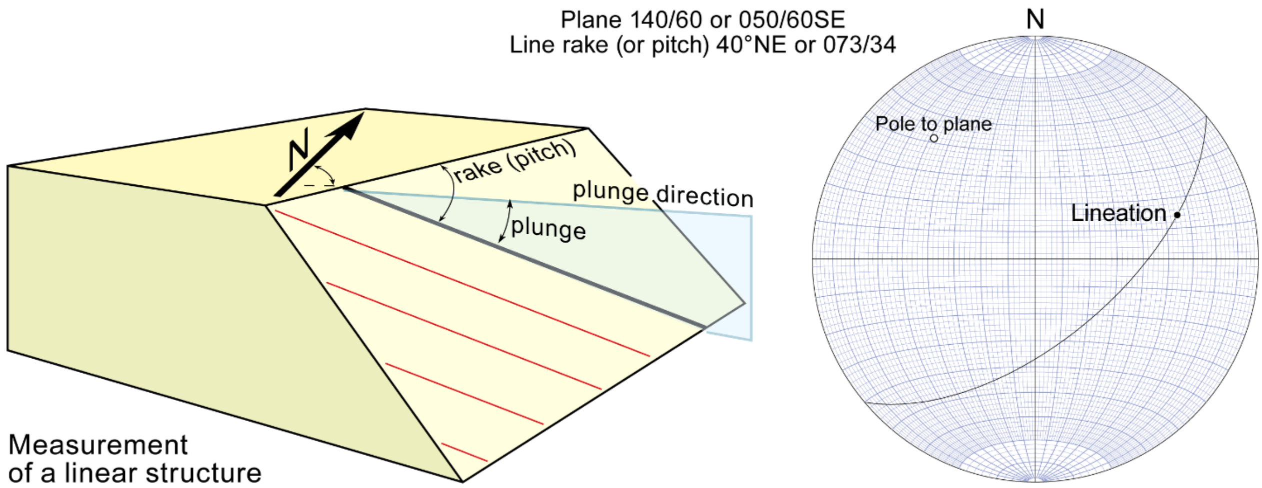
LINEAR STRUCTURAL ELEMENTS

Lineation is a general term to describe any repeated, commonly penetrative and parallel alignment of linear elements within a rock (to envision lineation, imagine packages of spaghetti). A lineation may be a primary igneous or sedimentary fabric element, such as an array of elongate K-feldspar porphyroblasts, inclusions or pebbles oriented with their long dimensions mutually parallel, or flute casts. The primary alignment of markers is correlated with the direction of flow of magma or paleocurrent and form **flow lines**. Structural geology is particularly concerned with lineations produced by deformation.
Lineations due to ductile deformation lay on foliation planes and are, therefore, as penetrative as foliations. A single deformation may produce several sets of lineations with different orientations within a given foliation plane.
Lineations are referred to as L-elements of the rock fabric. Where L-lines of different generations are present in the same fabric, they are given numerical suffixes according to relative age: L_0 is the primary line and L_1, L_2, L_n are secondary lineations in order of determined superposition.
Lineated rocks without an identifiable foliation are known, particularly in gneisses, as **L-tectonites** (or **pencil tectonites**). Lineation is one of the most significant fabric elements and it should be included in all complete structure maps.

Description

Orientation

The attitude of a linear structure is described by its **trend**, which is the compass direction of the lineation projected on a horizontal plane, and its **plunge**. The plunge is the angle made by the linear structure with the horizontal, in the vertical plane parallel to its trend. The **rake** (or **pitch**) is the angle between a line lying in a plane with the horizontal strike of the same plane. Therefore, it is an angle not measured in a vertical or horizontal plane but in the plane that contains the linear structure. This angle is often used to measure slickenside striations on a fault plane.



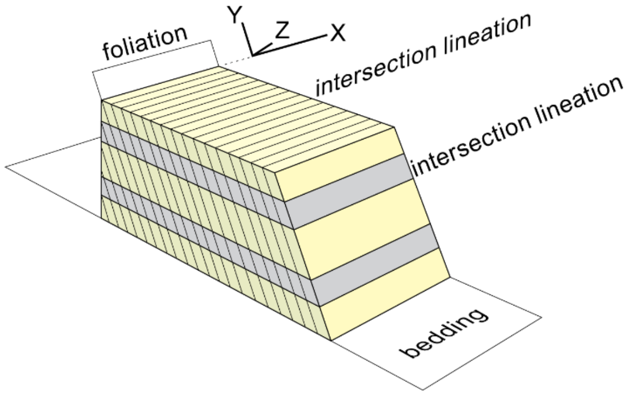
Non-penetrative lineation

Slickensides are rock surfaces naturally polished by motion on faults. They often display **striae**, which are linear structures due to frictional sliding on the fault surfaces. Slickenside striae (**slickenlines**) are confined to these surfaces; therefore, they are not a penetrative fabric element.
Ridges and grooves or **striations** are parallel linear channels made by shear abrasion of one fault wall on the other. They indicate the direction of the fault slip vector.

Slickenside striae and fibers may be found on bedding surfaces involved in **flexural slip folding**. They indicate that successive layers have slipped over one another as the folds tightened. These lineations usually make a large angle with the fold axis and consistently show that the upper beds move upward towards the anticline axes.
When a rock splits along a C-surface of a C-S structure (see lecture on foliation), the surface is striated in a ridge-and-groove morphology parallel to the shear direction whereas S-surfaces carry a stretching lineation as described below.

Intersection lineations

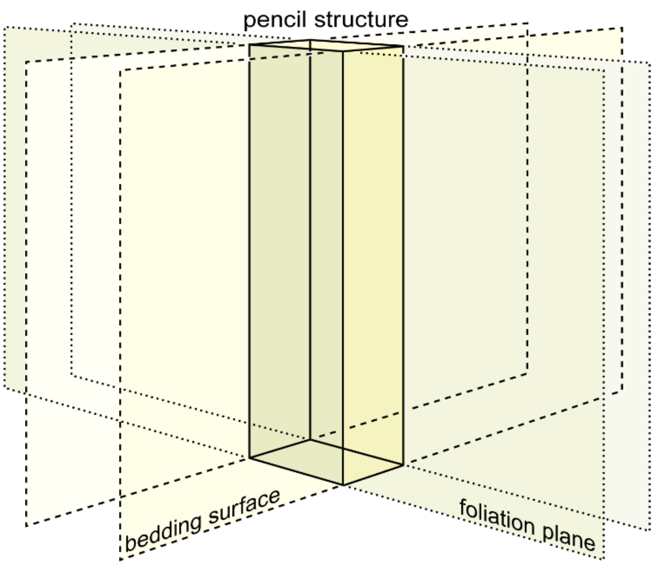
Since any two planar surfaces intersect in a line, most rocks folded with concomitant development of an axial plane foliation display the **intersection lineation** between bedding and the axial plane foliation. The trace of bedding on an intersecting foliation plane commonly appears as color stripes generally parallel to local fold axes (hence it is sometimes called **striping lineation** to avoid using a genetic term).



Two non-parallel foliations can also produce an intersection lineation; for example, the intersection of a crenulation cleavage and the earlier foliation. The more planar surfaces there are in an exposure, the more potential intersections there will be.

> Attention: The linear trace of any plane on a random joint surface has no significance in structural analysis; a lineation must be measured on and only on the foliation plane of the same deformation episode. Intersection lineation, however, may also be measured on the bedding plane.

When the fissility of both a foliation and bedding (or yet another foliation) is prominent, the rock tends to break up along elongate fragments sub-parallel to the local fold hinges. The resulting geometry, with rectangular or prismatic cross-sections, is a **pencil structure**.



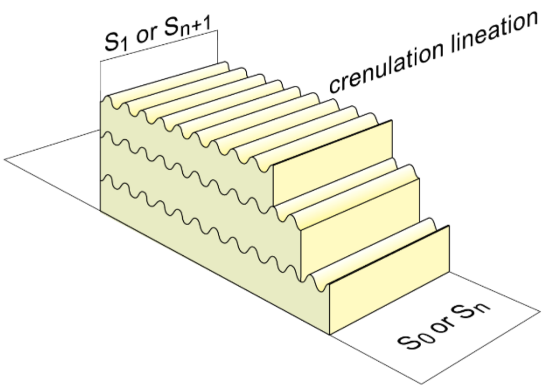
Intersection lineations and pencil structures are often utilized to determine the orientation of the unexposed, related fold axes.

Axes of folds as lineations

Hinges of cylindrical folds are linear structures.

Crenulation lineation

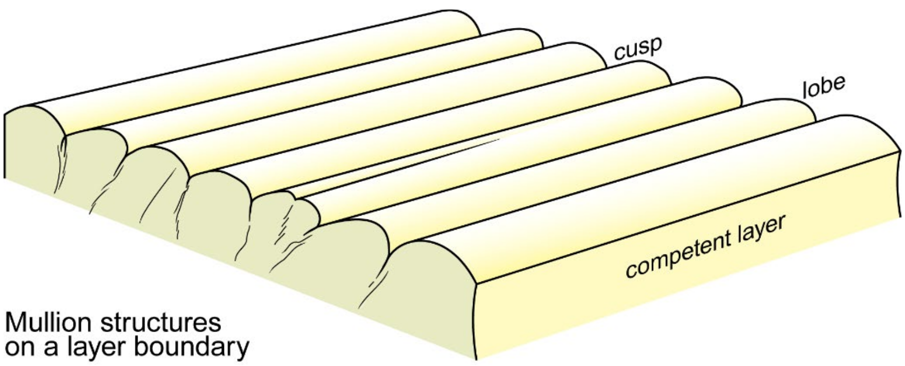
Small scale rippling of an earlier foliation (and occasionally bedding) produces an obvious linear array parallel to the closely spaced and regular wrinkle hinges. The **crenulation lineation** is the fabric element parallel to the tightly spaced hinges. Many schists exhibit this type of lineation. It generally is a good indication of superposed deformation. Two or more sets of crenulation lineation may intersect one another, sometimes in a conjugate manner, forming all sorts of small-scale interference patterns.



Rolling of some minerals during deformation may produce a wrinkling of an existing part of the foliation. If carried out far enough, this may produce some kind of chevron folds parallel to the rotation axis of the minerals, the resulting crumples trending across the general direction of flow.

Mullions

Mullions are coarse corrugation of the bedding surface between a competent and an incompetent layer. The term stems from the old French "*moinel*", designing the vertical columns in tall windows of Gothic architecture. Mullions form at any size in the original rock material as opposed to segregated or introduced material. Their ribbed or grooved appearance is often due to broad, smoothly curved convex surfaces of the competent layer rather regularly separated by narrow, sharp, inward-closing hinges. These long, convex and cuspate structures are remarkably cylindrical and surface features are very persistent along the length of the mullions. Characteristically, micas coat mullions, but polished or longitudinally striated surfaces have been described.



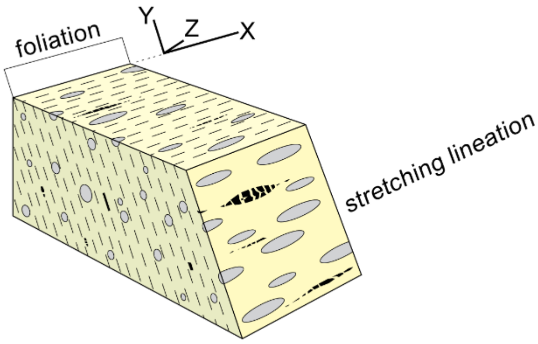
Mullions generally represent the intersection between bedding and a spaced foliation in the competent layer.

Rods

Rod is a morphological term for elongate, cylindrical and monomineralic bodies of segregated mineral (quartz, calcite, pyrite, etc.) in metamorphic rocks of all grades. Rods may have any profile outline, from elliptical to irregular, dismembered rounded structures. Rods are generally parallel to local fold axes and often are isolated fold hinges detached from their limbs.

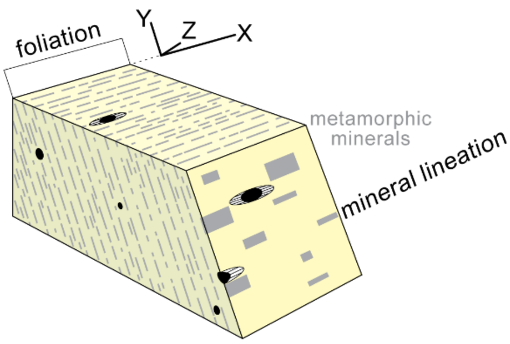
Stretching lineations

The parallel alignment of individual grains, aggregates or fragments of any size that have been elongated and/or rotated during deformation is an important type of lineation. Ellipsoidal ooids and spherulites must have been deformed since they generally are originally almost spherical and their long axes define the **stretching** (**extension** or **elongation**) **lineation**. Deformed pebbles or boulders also define such lineations. Elongated grains or grain aggregates define a **preferred shape orientation**.



Mineral lineations

Metamorphic minerals often grow with a preferred crystallographic and dimensional orientation, i.e. with their long axes in parallel alignment-The long axes of individual, elongate crystals (for example amphibole crystals, sillimanite needles) or mineral aggregates aligned and sub-parallel within a foliation plane delineated **mineral lineations**. They are a penetrative element of the rock fabric, commonly coincident with other types of lineation, and serve to reinforce them. Mineral lineations may be parallel or inclined to the axes of related folds. They indicate a stretching direction if the involved minerals are segmented along the lineation. They also can define the intersection between foliation planes and rotation axes of rotating minerals.



"**Pressure shadow**" or "**pressure fringe**" structures comprise spindle-shaped aggregates of new grains crystallized on opposed sides of a host porphyroblast or competent, clastic objects. The new grains form when material dissolved by pressure solution is re-precipitated, occasionally as fibers, in the regions sheltered from strain on either side of the rigid grains. The fibers generate tails filling openings in the extending direction between grain and matrix, during deformation. The central grain and the tails produce an elongate structure contained in the foliation; this structure and the fiber crystals thus define a lineation. Circular fringes with radial fibers on the foliation, however, characterize pure shear without stretching direction (pan-cake finite strain ellipsoid). Similarly, the oriented growth of mineral fibers in tensions gashes and veins indicates the local extension direction and may record incremental strain directions.

Strain significance of lineations

Lineations are genetically related to the foliation planes on which they occur, particularly where both are shaped by mineral orientations. Therefore, the planar and linear fabrics are both together aspects of the same three-dimensional geometry, which is related to the shape of the finite strain ellipsoid or, more important still, to the history of incremental strains.

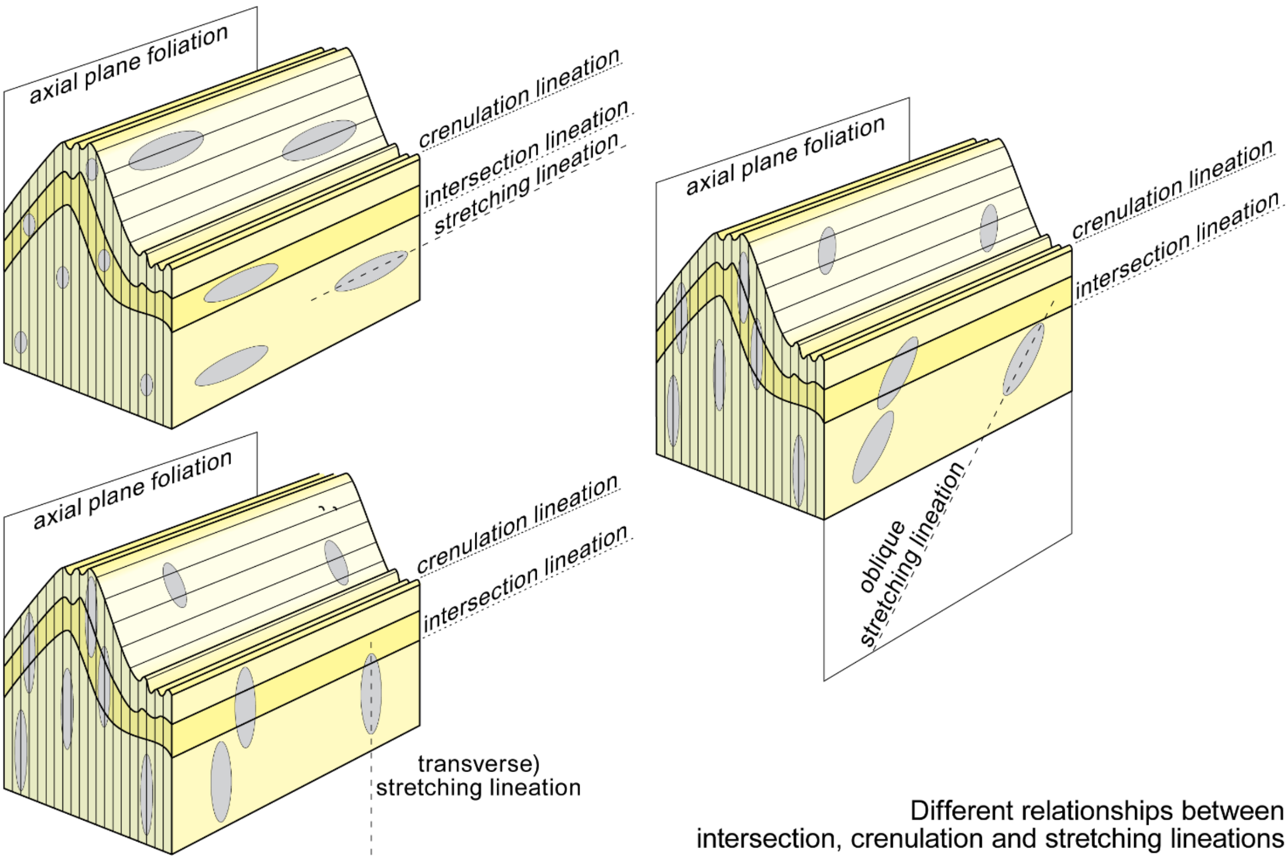
Finite strain measurements in rocks containing strain markers such as fossils, ooliths or vesicles, show that the mineral lineation, if one developed on the foliation, generally coincides with the maximum elongation axis X of the finite strain ellipsoid. Consequently, many mineral lineations are often equated with stretching lineations.

The situation is more complex for pebbles whose mechanical properties differ from that of the matrix. Under these conditions, the shape of an initially spherical pebble only represents the strain of that pebble and not the strain of the rock as a whole. Furthermore, the pebble has not only changed its shape but, in general, has rotated within the matrix. The theory relating the rotation of elongate bodies to strain is complex. If the strain history is coaxial, elongate pebbles tend to be parallel to X. If the strain history is non-coaxial, pebbles may align in the flow planes, perpendicular to the direction of flow (close to the Y-axis of finite strain). This could occur for some non-equant mineral grains as well.

In some complex cases such as transpressive or transtensive zones, the stretching lineation lies at the intersection of the foliation and the XZ plane of the finite strain ellipsoid, the orientation depending on the rates of development and recovery of the fabric with respect to the imposed strain rate.

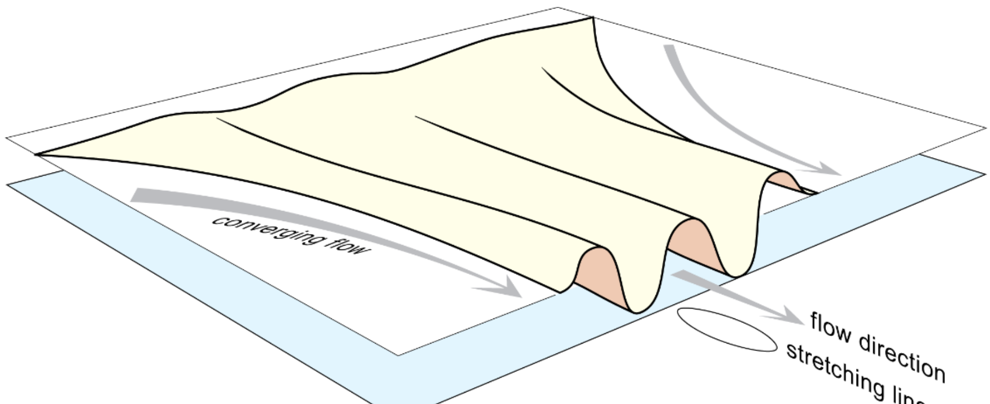
Relationship between lineations and fold axes

The intersection of bedding and axial plane foliation is parallel to the fold axis. Other linear structures may or may not be parallel to the fold axis. Many examples report mineral and stretching lineations oblique or even orthogonal to the associated fold axes.



Different relationships between intersection, crenulation and stretching lineations

Mineral lineations and aligned stretched objects parallel to fold hinges indicate that the fold axes are parallel to the X-axis of the finite strain ellipsoid. In effect, there may be extension parallel to the fold hinge in the culmination of doubly plunging folds or the outer arcs of arcuate fold belts. However, experiments show that folding generates little (generally <15%) extension parallel to the fold axis even for extreme shortening. Another explanation is that mineral lineations parallel to fold axes are a mimetic growth phenomenon controlled by a pre-existing anisotropy such as the intersection lineation.
Stretching lineations are often inclined to the related fold axes; at an angle close to 90°, they are **transverse lineations**. In highly deformed rocks, stretching may be parallel to the fold axes. In high shear strain, the parallelism of the mineral – stretching lineation and fold axes has several interpretations. One is that fold axes formed at an angle to the stretching direction and have been rotated into approximate parallelism with that direction. Theoretically, they can only be truly parallel where the strain is infinite but the discrepancy can be too small to appreciate. This mechanism has been proposed for mylonites where strain is assumed to be simple shear. Thus, the lineation would be parallel to the direction of large relative movements. The alternative is that fold axes formed directly parallel to the stretching direction in a constrictive (convergent) flow.



Development of folds
parallel to the stretching lineation in a constriction flow

Origin of penetrative lineations

Several mechanisms are invoked to explain the development of lineations. Like for the formation of foliations, they include preferential growth, passive and active rotation and deformation of grains.

Directional mineral growth

Lineations defined by the parallel linear orientation of elongate mineral grains and **fibers** are attributed to oriented growth (they show **growth anisotropy**) in response to local deviatoric stress. Minerals may then assume a statistical lattice orientation. Mineral lineations are commonly parallel to other types of lineation and reinforce them.
Pressure shadow and pressure fringe structures are growth features developed on opposite sides of clasts, in parts of the rock where the mean stress is low due to a shielding effect of the relatively rigid object in the weaker, deforming matrix.
Rods formed by segregation of quartz are often related to oriented growth.
Crystal growth may reproduce a pre-existing lineation and is then referred to as **mimetic crystallization**.

Passive rotation and fragmentation

A mineral lineation may also be due to rotation towards and into a favored, stable attitude during deformation. Rotation may be accompanied by the crumbling of large grains and grain aggregates. Strings of fragments produce a lineation along the movement direction. This process is identified in ductile mylonites as well as in cataclasites (in the latter, one talks of **cataclastic lineation**).
Some rods form by the segmentation and rotation of quartz veins into the flow direction.

Dimensional elongation

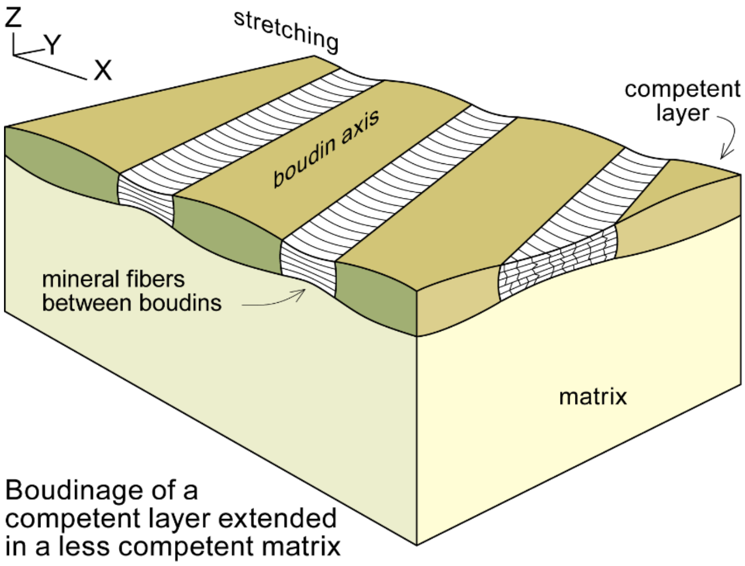
Ductile deformation and pressure solution may be responsible for dimensional elongation. For example, initially spherical ooids generally have the same mechanical properties as the rock matrix; if there are ellipsoidal, their shape is that of the strain ellipsoid for the rock whether the deformation involved is ductile or due to solution-redeposition processes. The fact that pebbles do not only change in shape but also rotate to produce a dimensional elongation has already been discussed. In general, the interpretation of lineations becomes difficult where some body rotation is involved. Plastic or diffusion deformation of grains and mineral aggregates contributing to a lineation often develops a **crystallographic preferred orientation**.

Boudinage structures

The geological **boudins** (blood sausage in French) are side-by-side segments of a layer or object sandwiched in a less competent (i.e more deformable) matrix**. Boudinage** describes the process of stretching, necking and eventually segmentation and separation of these segments; this is produced in general by extension parallel to the bedding plane and failure of the competent, boudinaged layer during the ductile flow of the less competent host. Objects such as fossils, pebbles, and minerals can also be boudinaged (**linear streaking of minerals**).

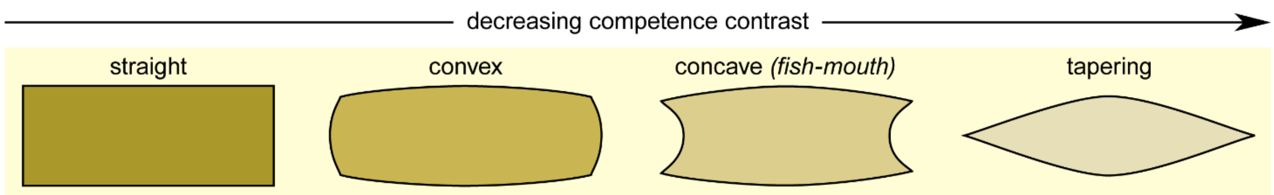
Description

Boudinage ranges from micro- to macroscopic scales; typically, a strong layer or dike is broken up at regular intervals into a series of elongate and aligned blocks whose profiles, seen orthogonal to the long axis of boudins, are the basis for the classification of boudinage structures.



Boudinage of a competent layer extended in a less competent matrix

Boudin profiles are variable, symmetrical or asymmetrical. Long faces, usually layer boundaries of the boudins, can be concave (bone-shaped boudins), convex (barrel-shaped boudins) or parallel to each other (blocky boudins). These shapes reflect ductility contrasts between layer and matrix. Large contrasts produce boudins with sharp edges, and small contrasts produce rounded boudins.



Description of boudins extremities

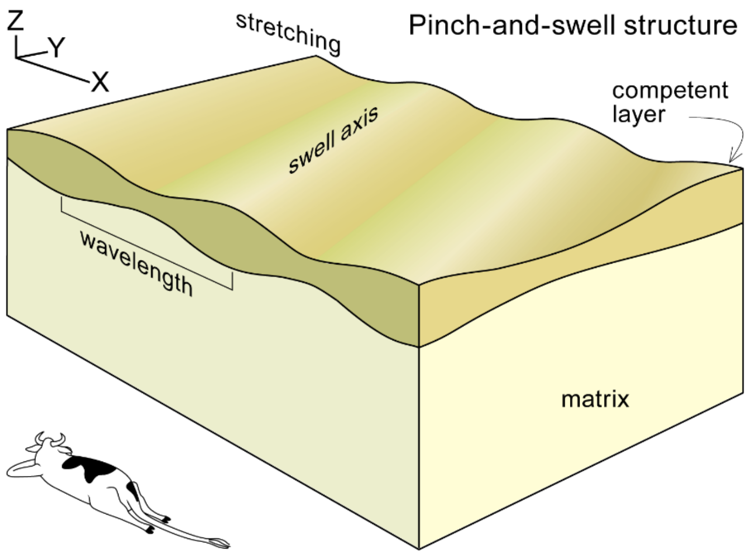
Boudins with a blocky geometry

Boudins with rectangular, barrel, rhomboidal and lozenge shapes are common in low-grade rocks. They are usually separated by an extensional gap (**pull-apart structure**), which is commonly mineralized. The zone of separation is referred to as a **scar**.

Boudins with a wavy geometry

At higher grades, and in unconsolidated rocks, the competent layers have generally not broken through; narrow thinned **necks** separate and alternate with relatively thicker swells. The resulting wavy structure is called **pinch-and-swell**.

After separation, the disconnected layer segments display lens- or pillow-shaped forms. Extreme stretching reduces necks to the very thin and long selvage of the layer connecting variably shaped swells. Boudin profiles range from terminating at a point (tapering, lenticular boudins), or having convex (sausage boudins), straight (blocky boudins) and concave to extremely concave (fish-mouth) extremities.



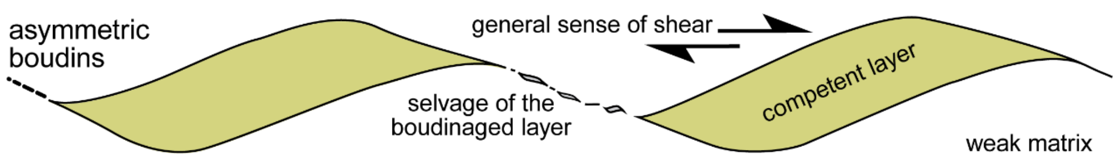
Pinch-and-swell and pull-apart structures may be combined at any level since they depend on the ductility contrast between the strong bed and its matrix.

Foliation boudinage

Structures similar to boudins and pinch-and-swells may occur in homogeneous, strongly foliated rocks with no apparent lithological contrast between the segmented rock and the host rock. The generally long, lens-shaped boudins are separated by fractures, which are often filled with vein material. The ruptured foliation planes are commonly bent (pinched) next to the separating fracture. The whole is described as **foliation boudinage**. At variance with boudinage of stiff layers, foliation boudinage is rarely sequential and periodical.

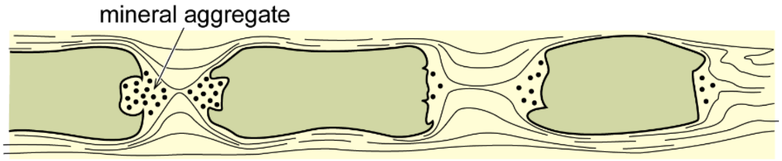
Asymmetric boudins

Asymmetric boudins are common in medium to high-grade metamorphic rocks. Such boudins have often lozenge shapes pinched and stretched at diagonally opposed corners; this shape is frequently used as a sense of shear indicator, consistent with the pinched corners.



Inter-boudin zone

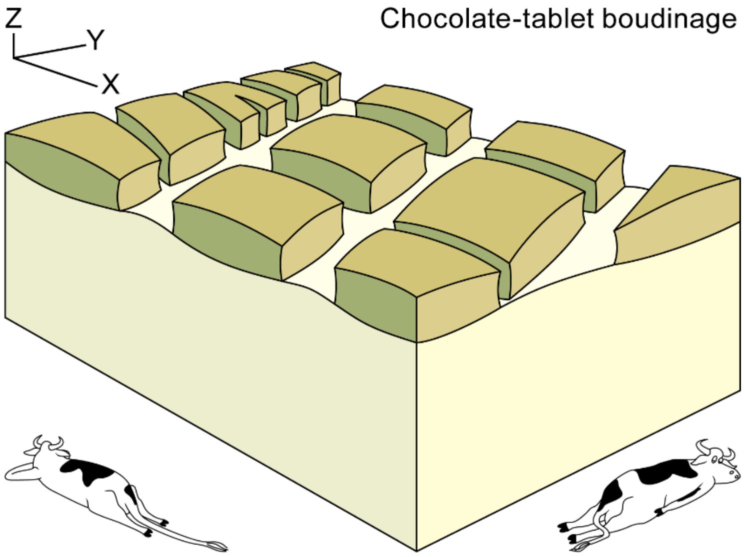
Boudins are separated by the material that originally lay on either side of the segmented layer or by mineral aggregates that have grown in situ while individual boudins moved apart. The surrounding ductile layers that flow in the space between boudins form **scar folds** (or **neck folds,** also called **flanking structures**). Quartz, micas and carbonate and, in high-grade rocks, pegmatite and leucosome veins represent material transfer into scar zones.



Scar folds in matrix and mineral filling between boudins

Relationship to other structures

Boudins are commonly linear and separated by a single set of tension fractures; their long axes are often parallel to the axes of related folds. However, a layer-parallel extension may take place in two or more directions (effect of pure shear component across the segmented layer). Segmentation and opening of extension gaps in two directions produce nearly equidimensional rather than elongate boudins. **Chocolate-tablet boudinage** describes the three-dimensional, blocky fragmentation of layers.



Boudins (like mullions) tend to be long and are commonly restricted to certain layers. Thus at the outcrop scale, they are a non-penetrative feature.

A boudin axis can be measured like a fold axis. The neckline connects points of minimum layer-thickness. The length of a boudin is measured parallel to the boudin axis. The width and the thickness are dimensions orthogonal to this axis.

Origin

Boudinage is easily reproduced in the laboratory on rock analogs. Boudinage results from heterogeneous, layer-parallel extension and disruption of a relatively hard layer or object surrounded by a more ductile matrix.

A simple conceptual and physical model consists of a three-layer package with a stiff, competent medial layer. In such a sequence, the rate at which the various layers can deform in a ductile manner varies. The package is compressed normal to layering, causing outward squeezing of ductile matrix layers, which can deform faster than the stiff layer. Interface friction and outward flow of the top and bottom layers cause extensional stresses in the stiff layer. If the strain rate in the sequence as a whole

exceeds the rate at which the stiff layer can behave in a ductile manner, then it splits when its tensional strength is exceeded. Sequential sideways extension and rupture result with progressive compression perpendicular to layering.
The range of boudin profiles is a function of the rheological contrast between layer and matrix, layer dimensions, and stress and strain states. Layer viscosity and stress state control the mode of deformation (brittle extension or flow). With large viscosity differences, the competent layer has a brittle behavior and tensile failure occurs by the formation of discrete extension fractures. If the viscosity difference is small, the layers thin locally in a ductile manner (necking) before eventual fracturing. Necking is typical of stiff layers with non-linear rheology (i.e. non-Newtonian).
A similar system compressed parallel to layering, with extension permitted also parallel to layering produces buckling with boudins approximately normal to fold hinges, which can be boudinaged. Numerical modeling agrees with this laboratory observation.

Strain estimate from boudinage

Boudinage is conventionally discussed in terms of strain fields defined by values of the two principal elongations λ_1 and λ_2 (X- and Y-axes of finite strain ellipsoid), as measured in the plane of layering.

- In the strain field $\lambda_1 > 1 > \lambda_2$, there is no area of principal extension and one of principal contraction, producing folding in one direction and boudins (or cross-jointing) orthogonal to fold axes. Partings are accepted to be perpendicular to λ_1, but initial obliquity cannot be excluded.
- In the strain field $\lambda_1 > \lambda_2 > 1$, all directions within the plane of layering have extended, producing chocolate-tablet boudinage or lens-shaped phacoidal structures. Many necks will be aligned approximately perpendicular to λ_1, although no uniform orientation is ordinarily present. On the field boundary $\lambda_2 = 1$, one set of boudins will form preferentially with long axes orthogonal to λ_1.
- The linear separation measured parallel to the matrix stretching lineation between boudins indicates the minimum amount of matrix extension.

Summary

Many lineations are strain indicators, fundamentally parallel to the maximum finite extension direction.
A convenient subdivision of lineations can be made in the following groups:
- lineations indicating the direction of movement along a surface (e.g. slicken side striations) or a movement zone (stretching in shear zones).
- axes of parallel crenulations or small-scale folds and intersection of sets of planes that have no specific relationship to either axis of finite strain and bulk movement directions.

> Attention: Linear structures can be utilized to determine the orientation of the fold axis or the movement direction only if their geometrical relations with the folds can be established from the observations on critical outcrops.

The separation between boudins is indicative of matrix strain. The presence of elongate boudins indicates that an extension direction was parallel to the boudinaged layer and perpendicular (in reality at a high angle) to the length of the boudins during at least part of the deformation. Chocolate block-type boudinage indicates that two or more directions within the boudinaged layer were directions of extension for at least part of their history.

An understanding of the origin of the various types of lineation may provide some insight concerning the movement history of an area. For a long time, lineations were used more or less indiscriminately as indicators of "**direction of tectonic transport**". This term is synonymous with the direction that one rock mass had been displaced relative to another, which is a reasonable assumption for high shear strain as seen in major thrust or detachment systems. On a rock specimen, however, the stretching direction is fundamentally the direction of maximum finite extension. But, provided that they belong to the same tectonic event, a bedding/cleavage intersection, mullions and rods, and a crenulation lineation will be parallel to the major folds with which they are associated to, which may have no specific geometric relationship to the regional bulk **flow direction**.

Recommended literature

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