MICRO STRUCTURES, UNIT-4

A **joint** is a break of natural origin in which there is no measurable movement parallel or perpendicular to the surface (plane) of the fracture.

JOINTS

Most rocks are broken by Relatively smooth fractures known as joints.

They are very closely spaced with a spacing of inches or fractions of inches

In British coal field they thought that the rocks joining along the fracture just as the bricks are put together in the wall.


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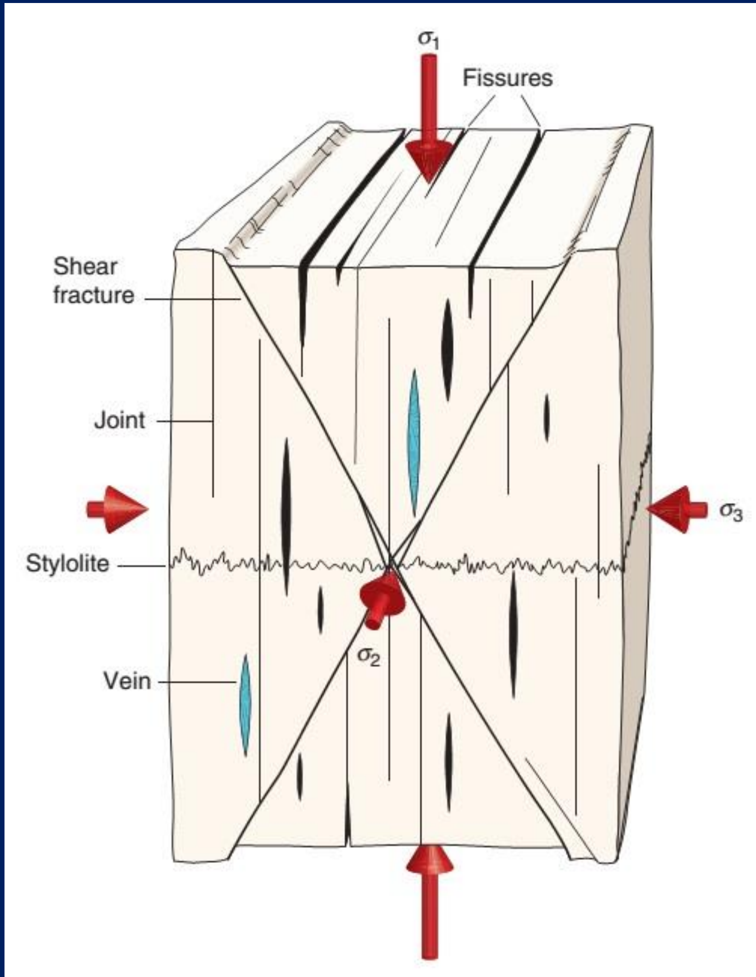
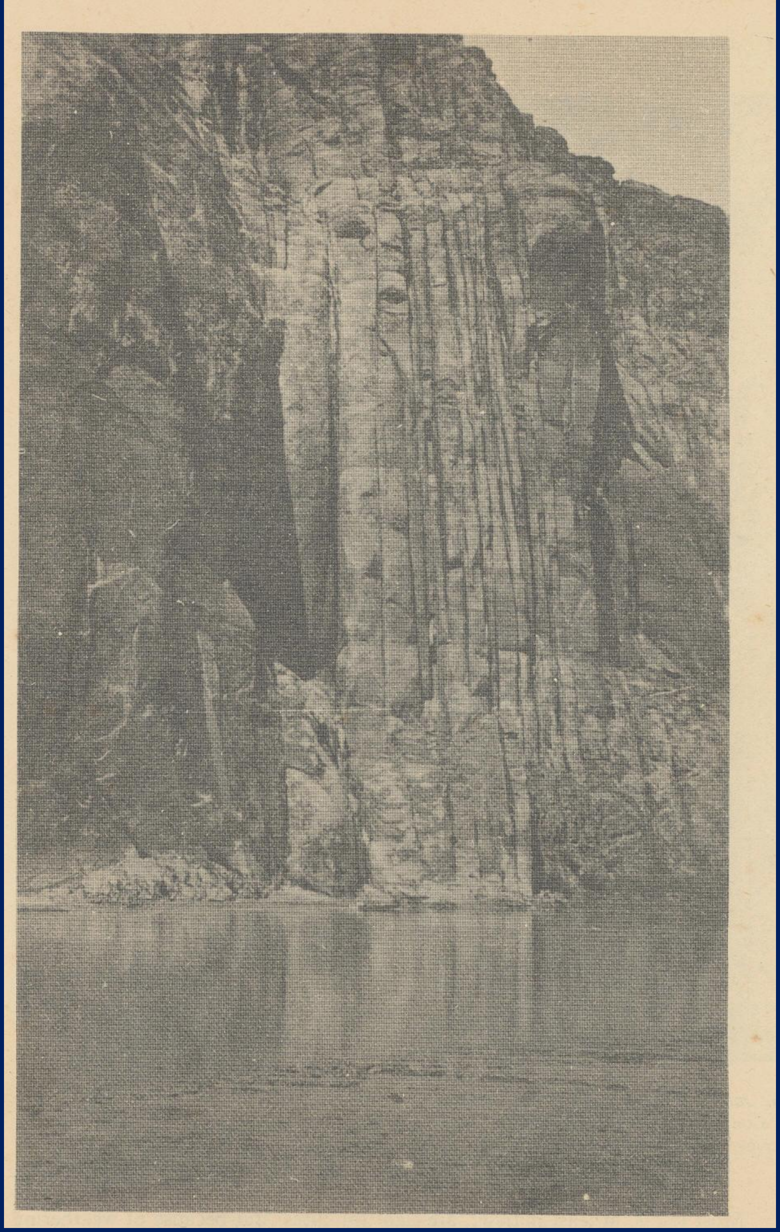
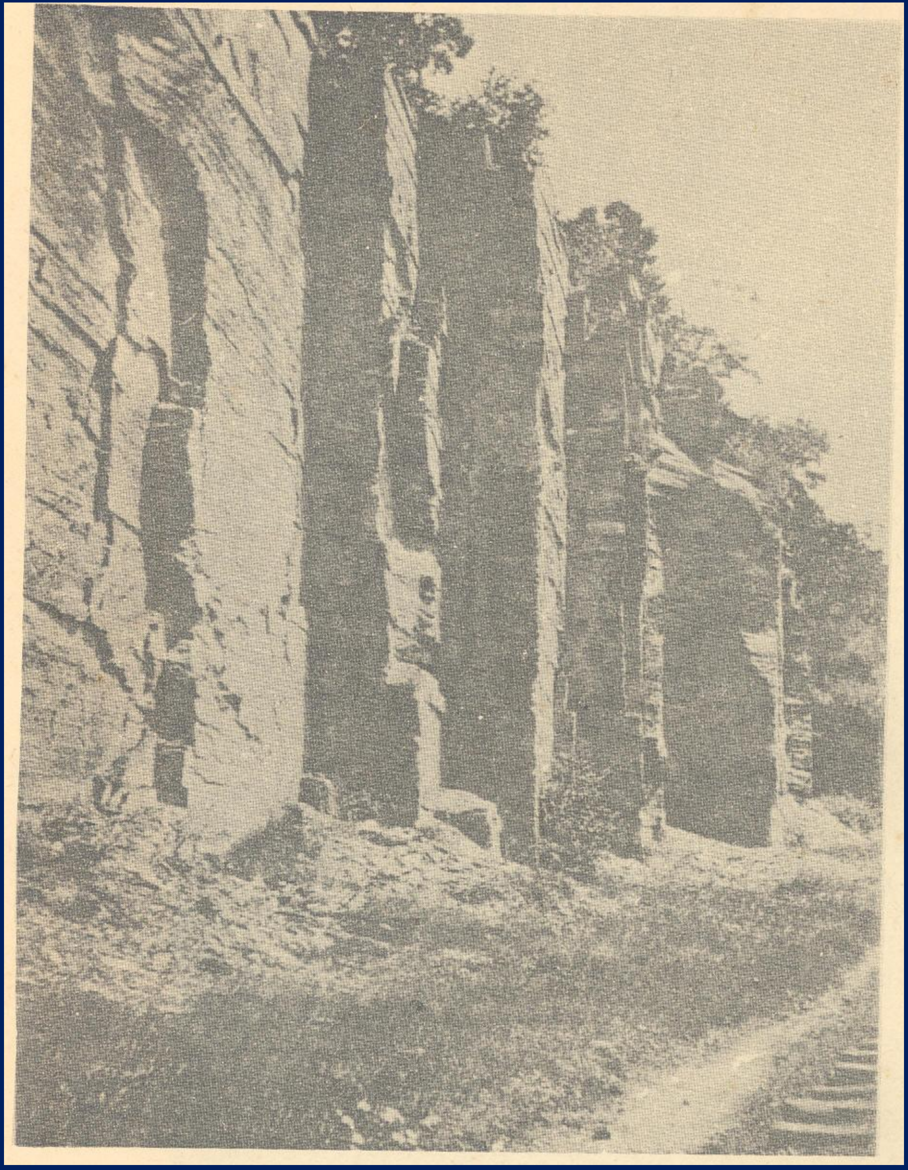


σ_1
Fissures
Shear fracture
Joint
σ_3
Stylolite
σ_2
Vein





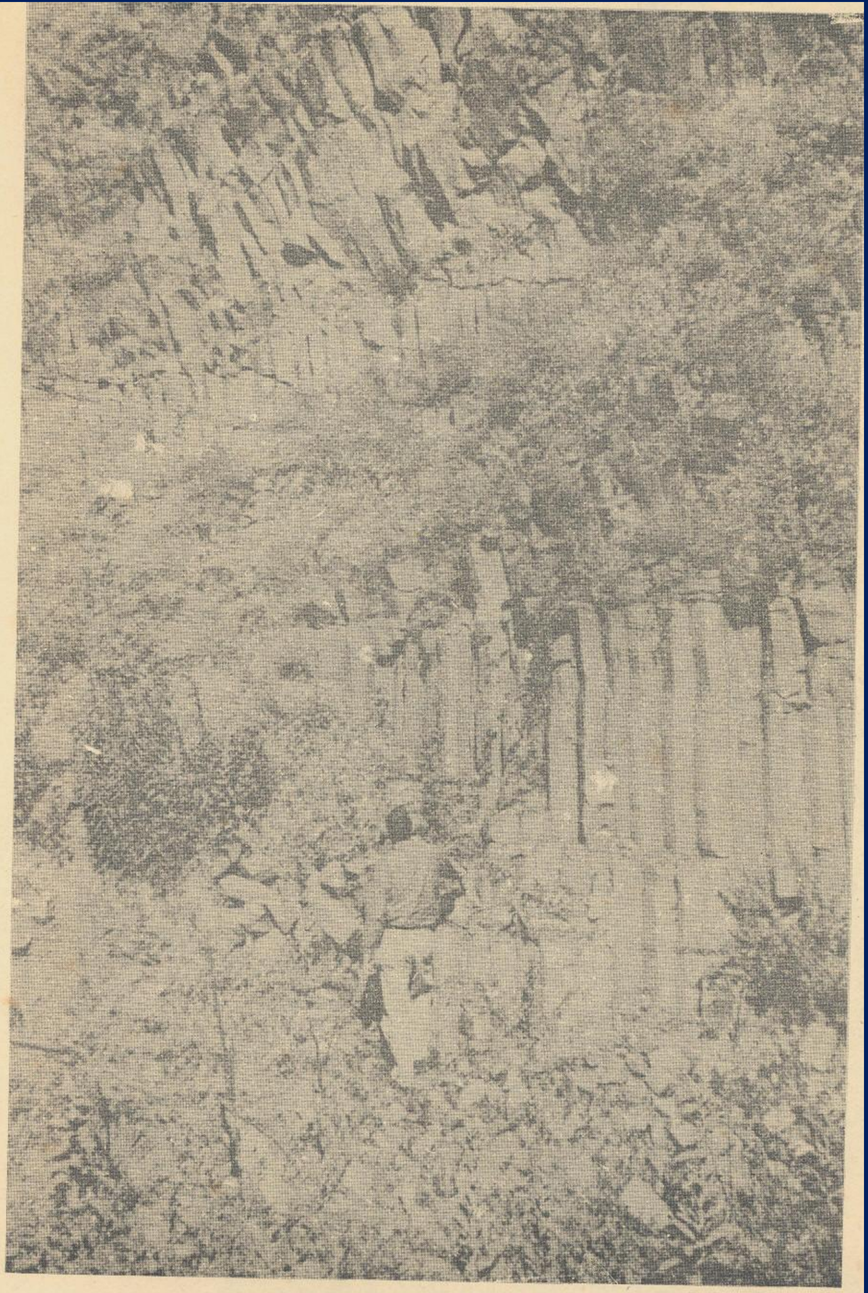


Plate 17. *A columnar jointing.* Columbia River Basalt near Race Creek, Riggins Quadrangle, Idaho. Photo: W. B. Hamilton, U. S. Geological Survey.

DIMENTIONS/ CHARACTERS

Lengths: few feet to hundreds of feet
Intervals: feet to tens of feet.

- No relative movements
- If movement is perpendicular to the joint plane the joint is open fissure.
- Generally they are very tight but due to weathering it gets opened up.
- In general they are smooth planes.

USEFULLNESS:

- In quarry operations
- Engineering projects
- In High way project
- Ground water prospecting
- To determine the forces acted in the region.

ATTITUDE:

- Horizontal, vertical and inclined
- It has got the strike and dip.

CLASSIFICATION:

- Geometrical
- Genetic

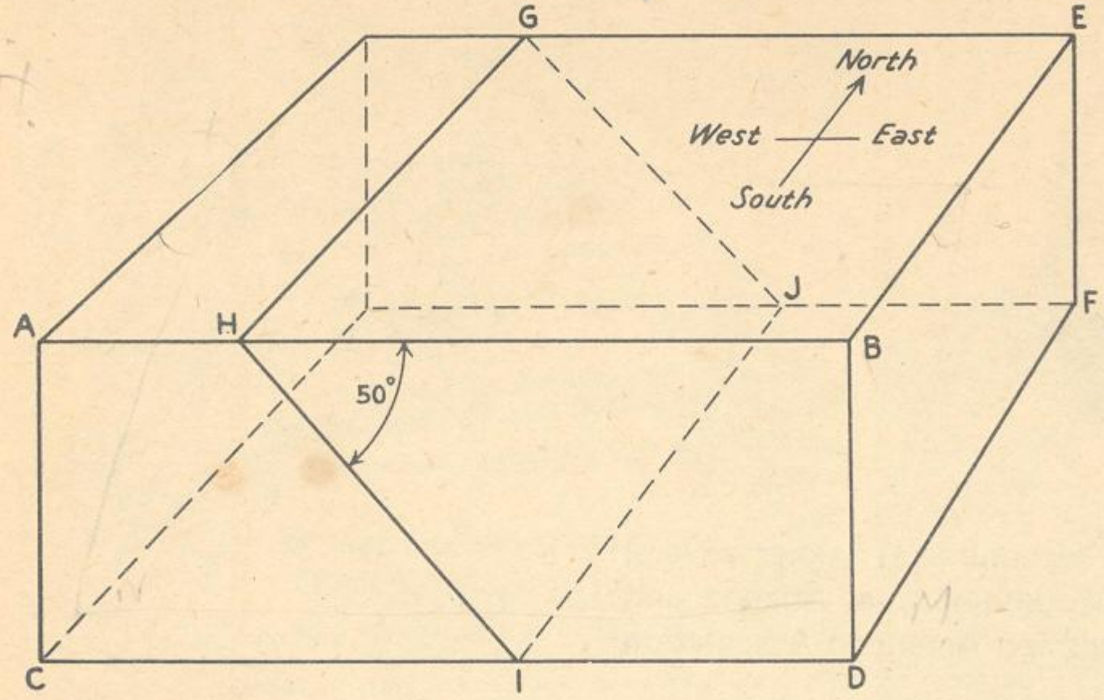


Fig. 7-2. Attitude of joints. Plane *ABCD* represents a vertical joint that strikes east-west; plane *BDEF* represents a vertical joint that strikes north-south; plane *GHIJ* represents a joint that strikes north-south and dips 50° east.

Geometrical classification

On the basis of their attitude to the bedding or similar structures.

- **Strike joint**
- **Dip joint**
- **Oblique / diagonal joint**
- **Bedding joint**

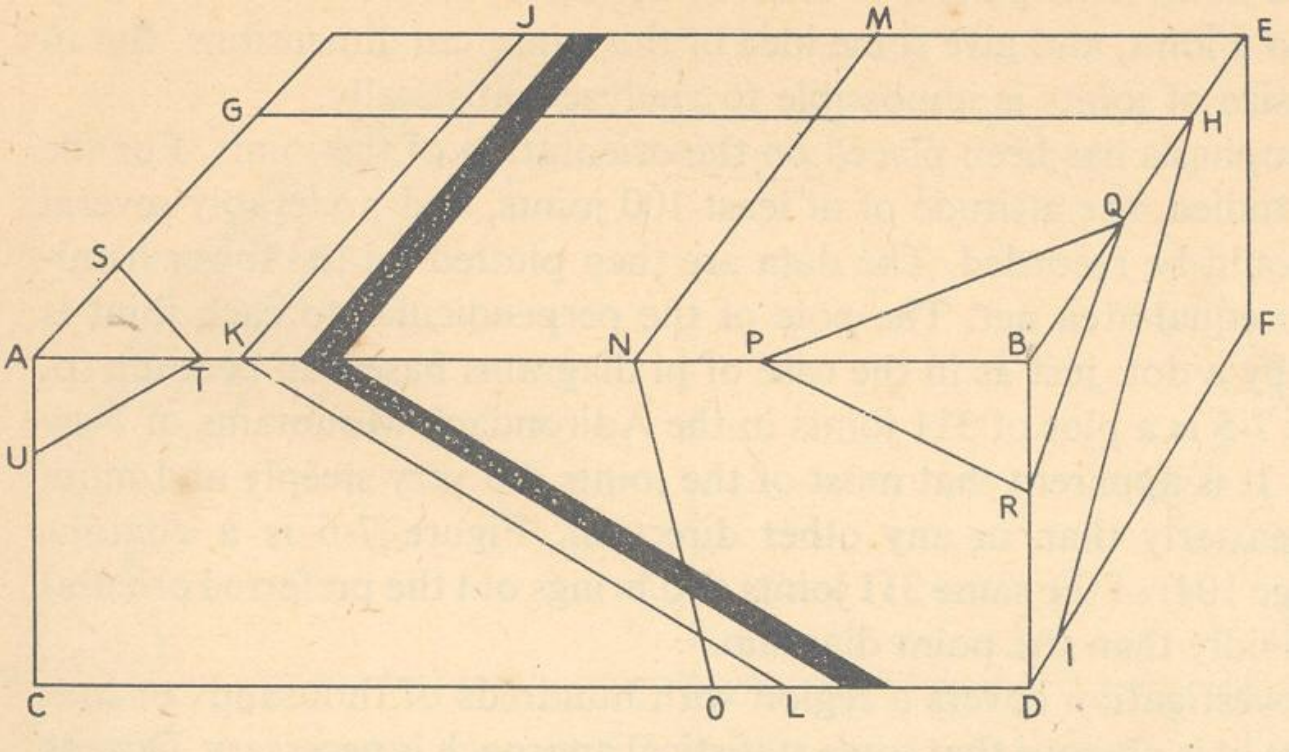


Fig. 7-4. Geometrical classification of joints. Heavy black layer is a bed. *ABCD* and *GHI* are dip joints; *BDEF* and *MNO* are strike joints. *JKL* is a bedding joint. *PQR* and *STU* are diagonal joints.

Geometrical classification Conti……….

On the basis of its numbers / quantities

- **Joint sets (Parallel joints)**
- **Joint system (two or more with different orientation)**

(in some cases with one orientation but varying dips eg. N-S/30,50,80 degree)

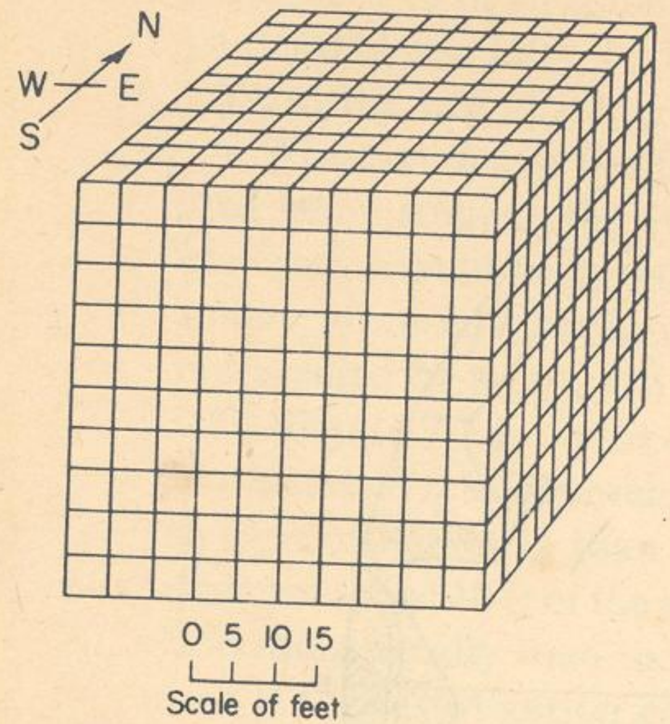


Fig. 7-7. Block with three sets of joints. Demonstrates importance of attitude of surface on which sets are seen.

GENESIS OF JOINTS:

The causes may be several

- **Tectonic stress** – Causing fracturing essentially contemporaneous with the tectonic activity
- **Residual stress** -- Due to events that happened long before the fracturing.
- **Contraction** -- due to shrinkage because of cooling or desiccation.
- **Surfacial movements** – such as downhill movements of rocks or mountain glaciers.

TYPES OF JOINTS:

i) Tectonic

- Extension joints
- Release Joints
- Shear joints

ii) Residual stress:

- Sheeting joints
- Exfoliation joints

iii) Contraction:

- Columnar joints
- Mud cracks

iv) Surfacial movements :

- Landslide and related cracks

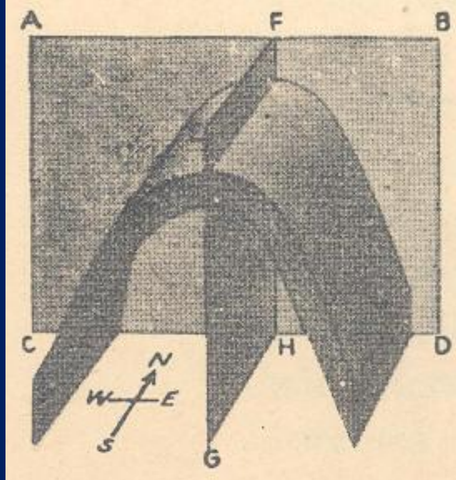


Fig. 7-25. Fold with vertical dip joint and vertical strike joint. *ABCD*, vertical dip joint. *EFGH*, vertical strike joint.

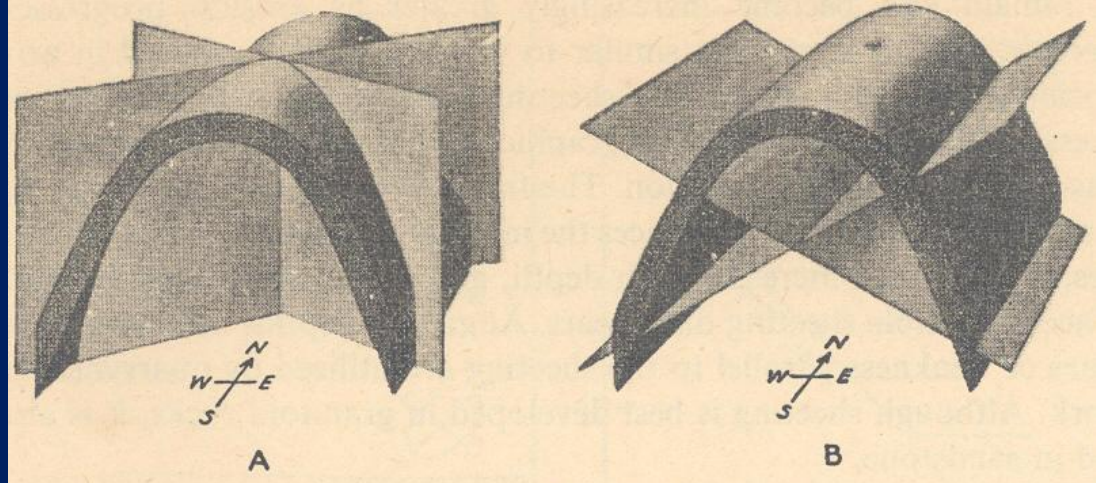


Fig. 7-26. Folds with conjugate joint systems. (A) Fold with vertical diagonal joints. (B) Fold with strike joints dipping about 30°.

Form perpendicular to the minimum stress, and parallel to the maximum stress.

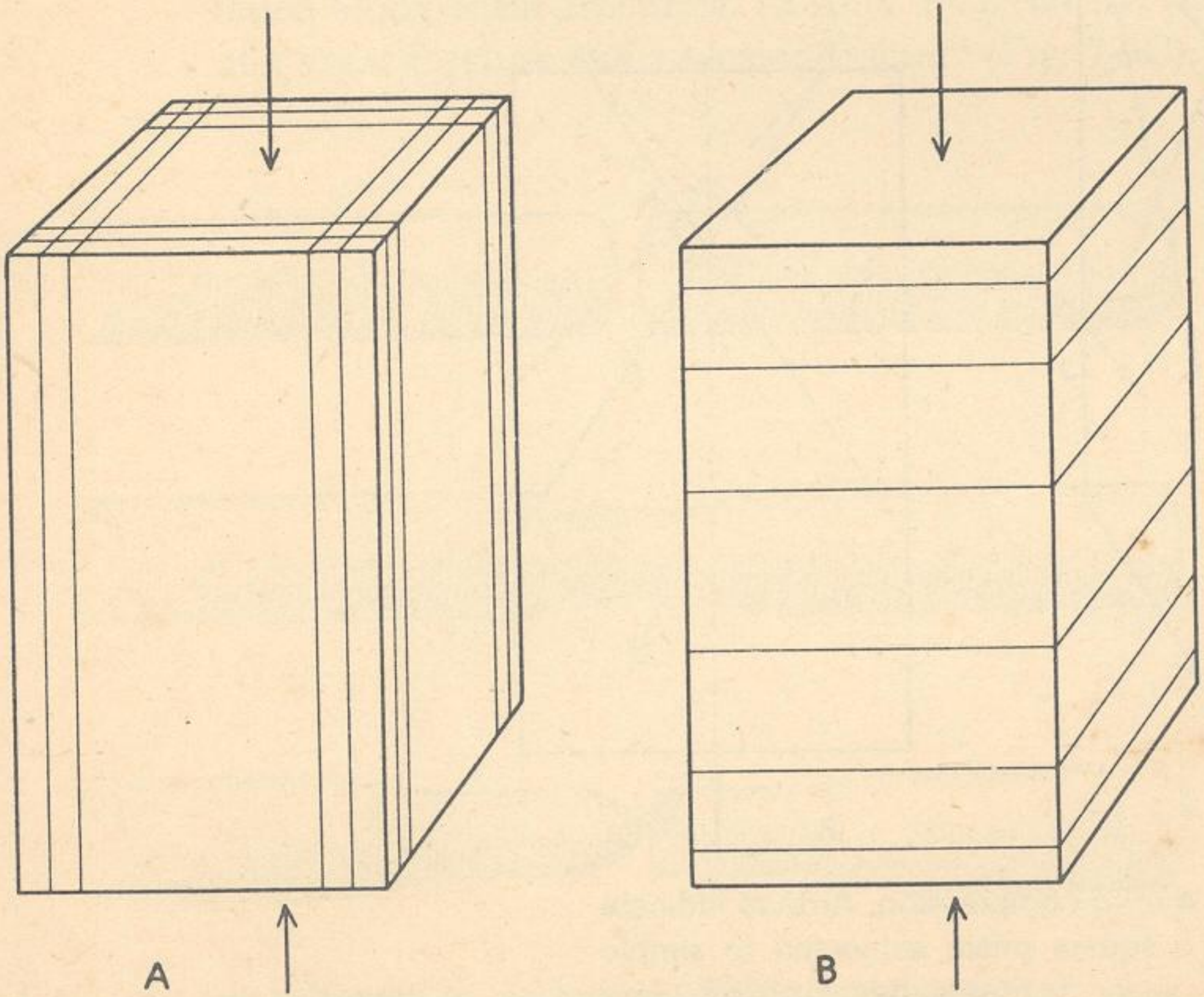


Fig. 7-11. Extension fractures and release fractures due to compression. Arrows indicate compressive force. (A) Extension fractures form parallel to sides of the prism. (B) Release fractures form parallel to top of prism.

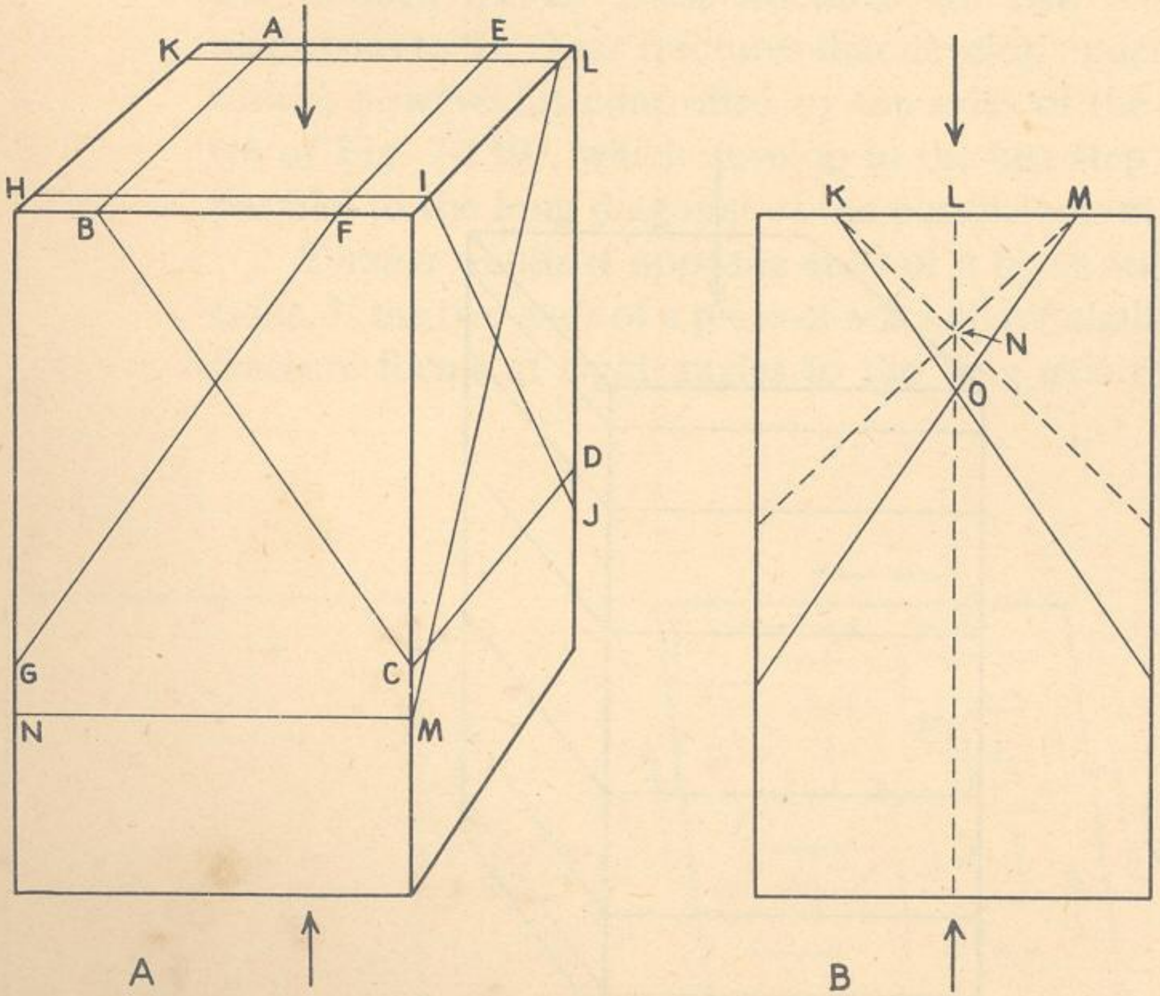


Fig. 7-10. Shear fractures due to compression. Arrows indicate compressive force. (A) In a square prism subjected to simple compression, four sets of shear fractures develop; they are parallel to the planes *ABCD, EFG, HIJ,* and *KLMN*. (B) *KN* and *MN* represent planes of maximum shearing stress deduced mathematically; *KO* and *MO* represent approximate position of shear fractures that form in experiments.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PRINCIPLES OF FAILURE BY RUPTURE:

Factors:

- The nature of the deformation preceding the rupture
- The physical conditions at the time of rupture
- The stresses necessary to cause rupture
- The orientation of the fractures relative to the causative stresses.

Conditions:

- Under atmospheric pressure and room temperature the rocks are brittle and fail by rupture at the elastic limit.

- Under high confining pressure and high temperature most rocks undergo plastic deformation above the elastic limit.

Rupture Classification

Tension fracture – **results from the stresses that tend to pull the specimen.**

Shear fracture – **results from stresses that tend to slide one part of the specimen past the adjacent part.**

Tension fracture:

Rupture depends upon the brittleness of the material.

- **Brittle substance** – single fracture perpendicular to the tension
- **Ductile substance** – rupture may be preceded by necking finally conical fracture develops (Shear fracture)

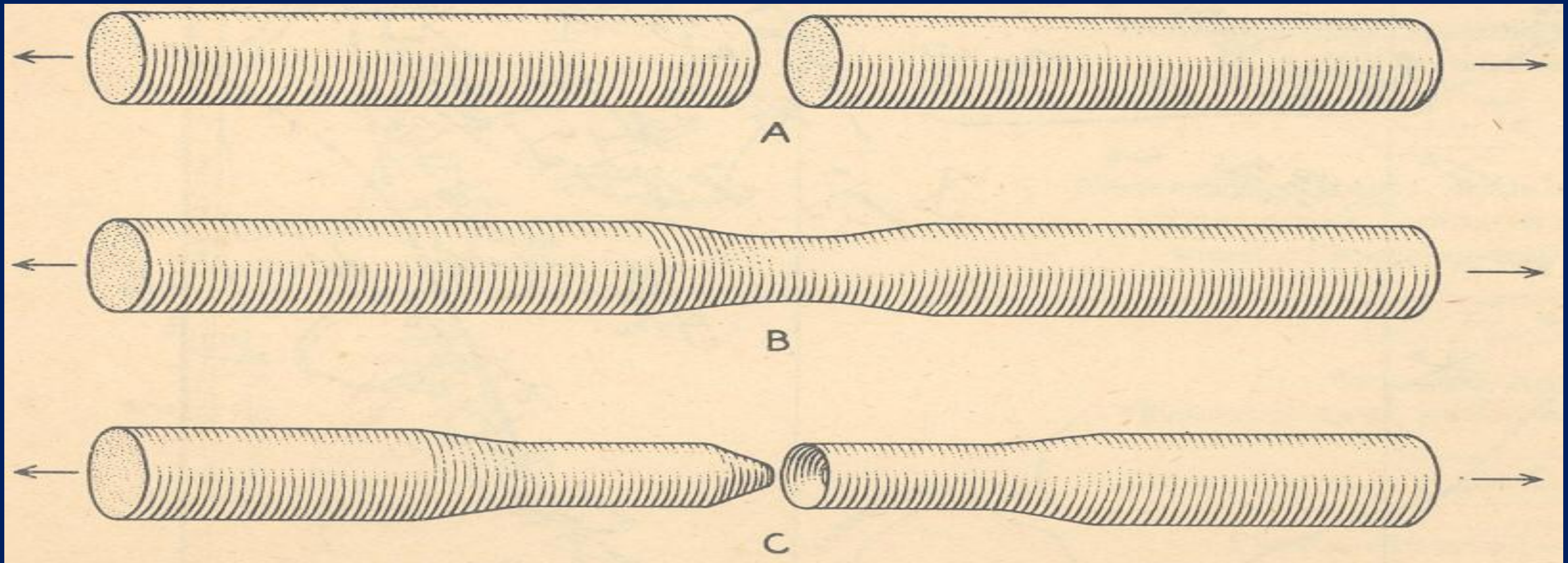


Fig. 7-9. Rod subjected to tension. (A) Brittle material, with a tension fracture at right angles to the axis of the rod. (B) Ductile material that has "necked," but not ruptured. (C) Ductile material that has ruptured; the conical surface is a shear fracture; the blunt end of the cone is a tension fracture.

By compressive force:

Tension / extension fracture ---- develop along the compressive force and perpendicular to tensional force.

Release fracture --- develop perpendicular to compressive force. It is also one type of extension / tension fracture (but not a active tension)

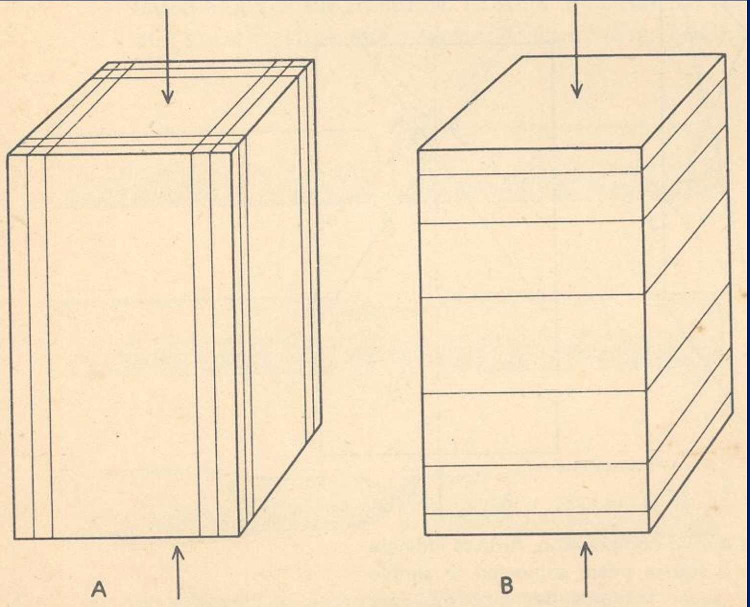


Fig. 7-11. Extension fractures and release fractures due to compression. Arrows indicate compressive force. (A) Extension fractures form parallel to sides of the prism. (B) Release fractures form parallel to top of prism.

By Couple force:

Tension fracture – first developed parallel to short diagonal of the parallelogram.
Vertical shear fracture – parallel to top and side of the parallelogram
Thrust fracture --- along long diagonal of the parallelogram.

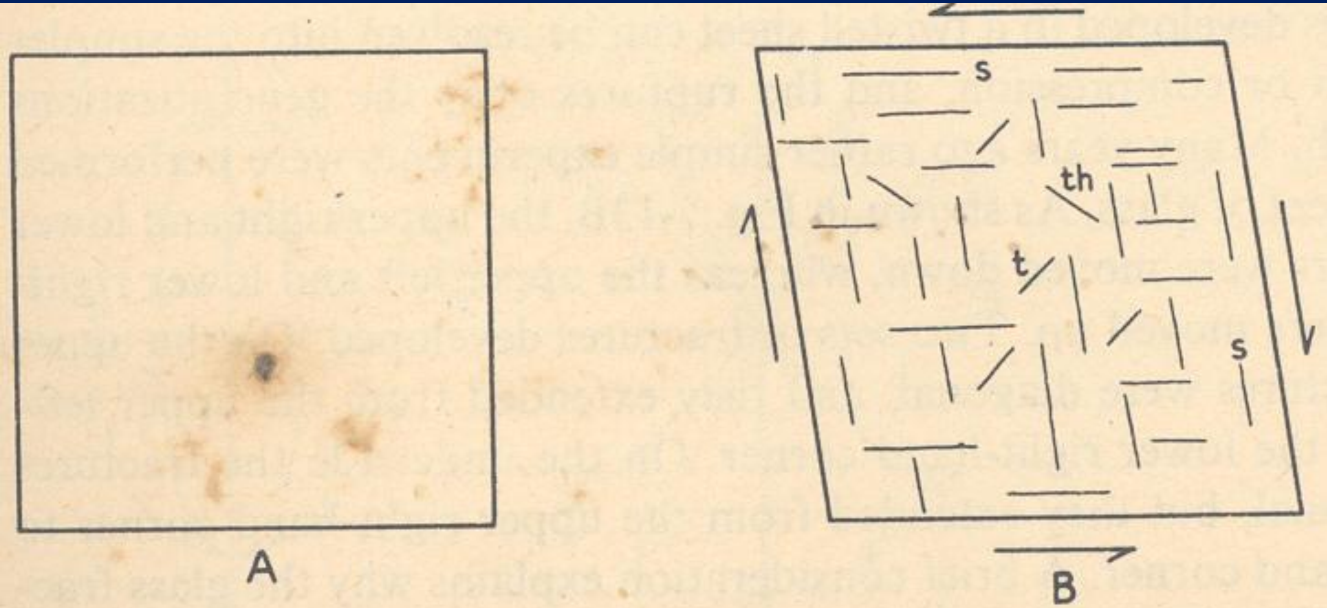


Fig. 7-12. Ruptures due to a couple. (A) Square frame that is covered by a sheet of rubber, on which there is a layer of paraffin. (B) Fractures that develop because of a couple: *t*, tension fractures (perpendicular to plane of paper); *s*, shear fractures (perpendicular to plane of paper); *th*, thrust faults (inclined to plane of paper).

Due to rotation:

Torsion results if the two ends of the object is rotated / twisted in two opposite direction

Helical fracture is the result

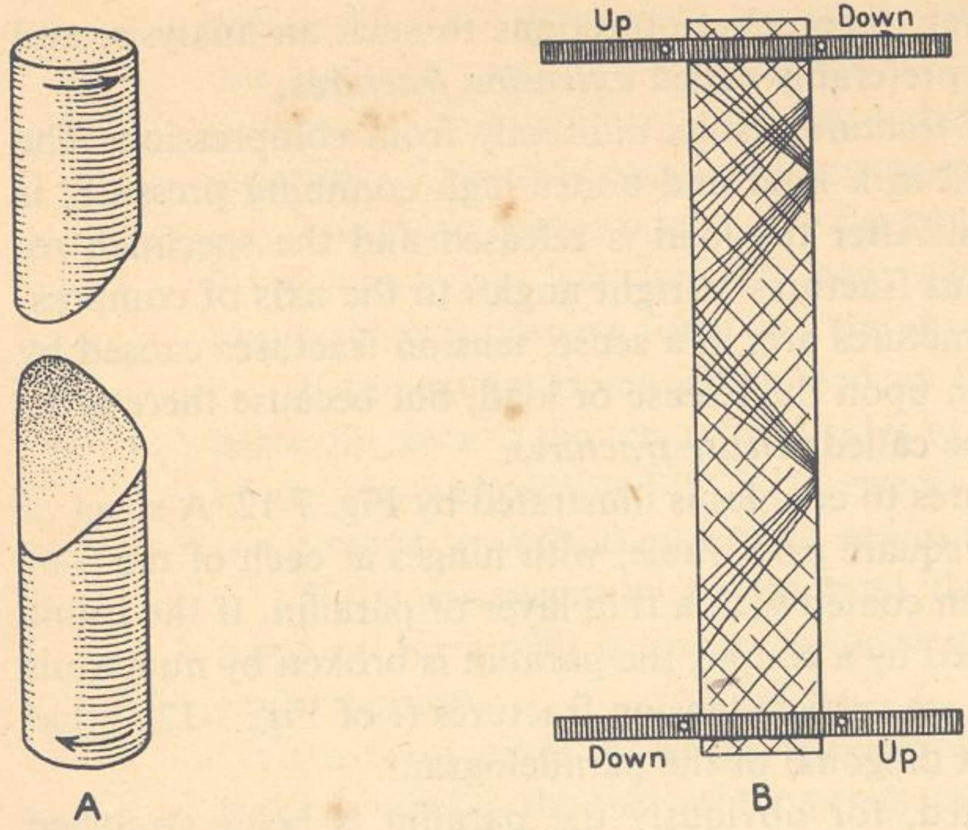


Fig. 7-13. Rupture due to torsion. (A) Helical fracture due to twisting of a piece of blackboard chalk. (B) Tension fractures on a piece of glass. Fractures that extend from upper left-hand to lower right-hand corner are on upper side of sheet of glass; those that extend from upper right-hand to lower left-hand corner are on underside of the sheet of glass.

RELATIONSHIP OF RUPTURE TO STRESS

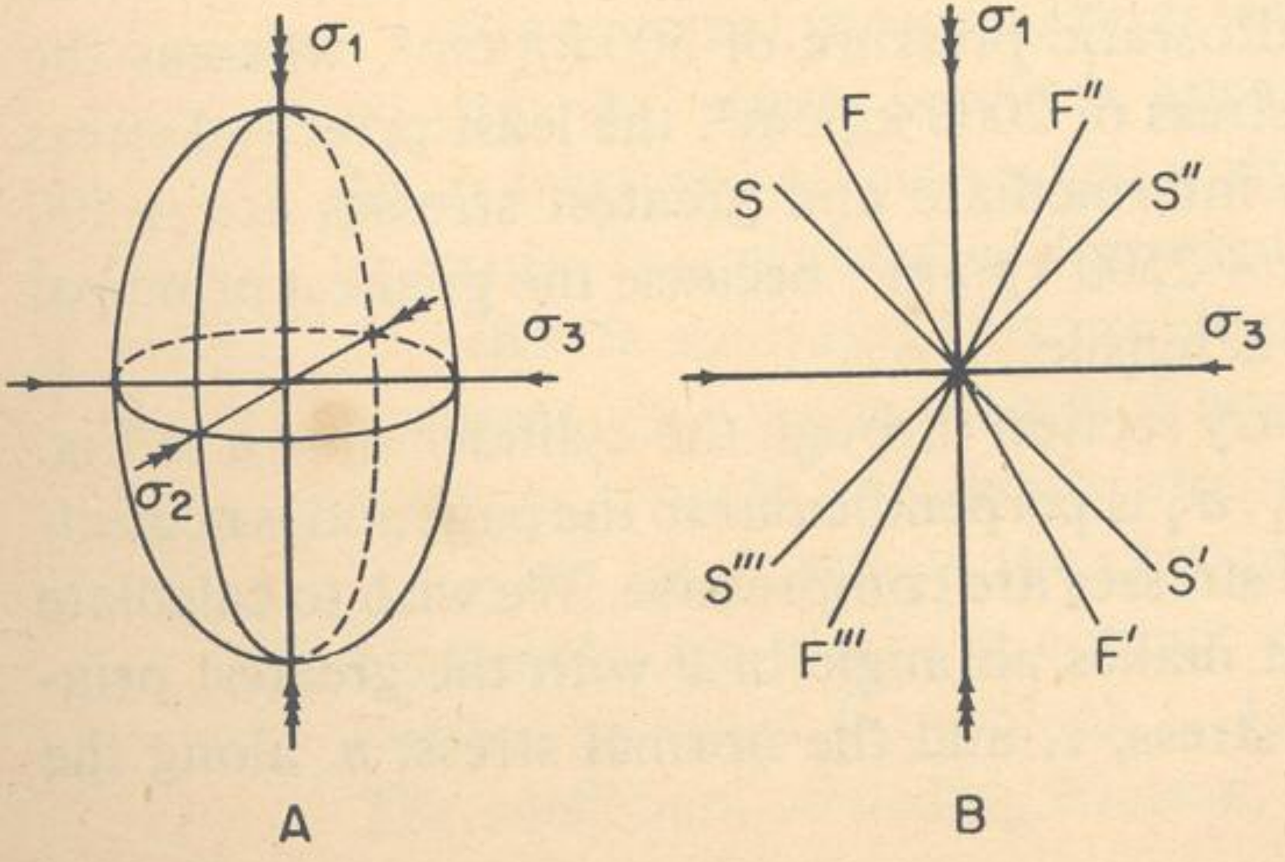


Fig. 7-14. Stress ellipsoid and rupture. (A) Stress ellipsoid. (B) Planes of maximum shearing stress (*SS'* and *S''S'''*) and planes of rupture (*FF'* and *F''F'''*).

RELATIONSHIP OF RUPTURE TO STRAIN

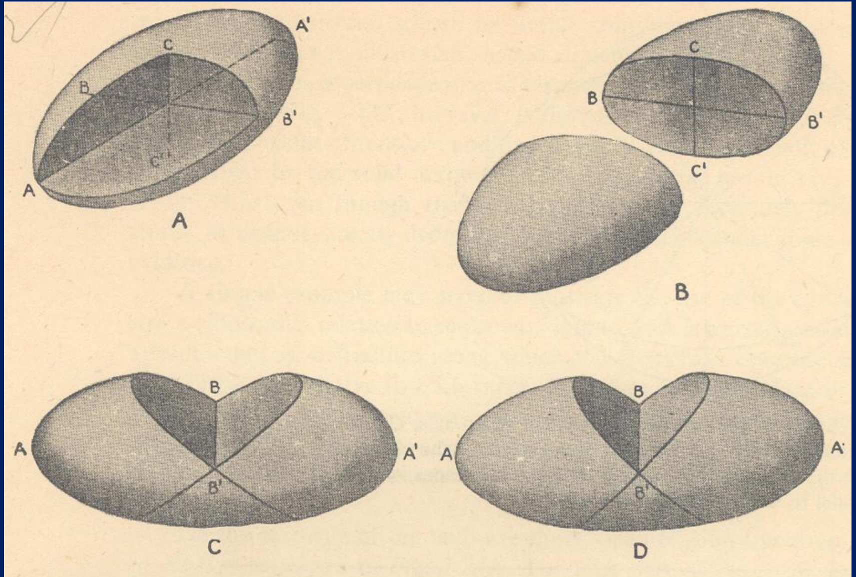


Fig. 7-21. Strain ellipsoid. (A) *AA'* is the greatest strain axis, *BB'* is the intermediate strain axis, and *CC'* is the least strain axis. (B) Tension fractures form perpendicular to the greatest strain axis. (C) Every ellipsoid has two circular sections that intersect at the intermediate axis *BB'*. Acute angle between circular sections is bisected by *AA'*. (D) Obtuse angle between shear fractures is bisected by *AA'*.

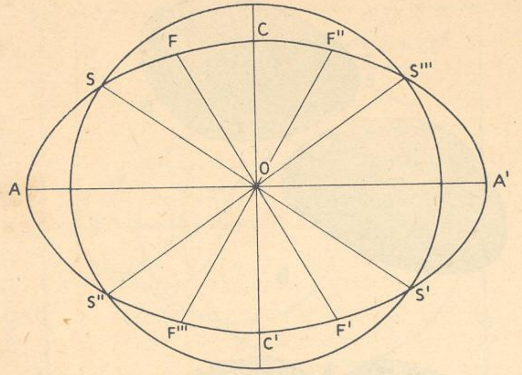


Fig. 7-22. Strain ellipse. *AA'* is the greatest strain axis. *CC'* is the least strain axis. *SS'* and *S''S'''* are the traces of the circular sections of the ellipsoid. *FF'* and *F''F'''* are the traces of the planes parallel to which shear fractures form.

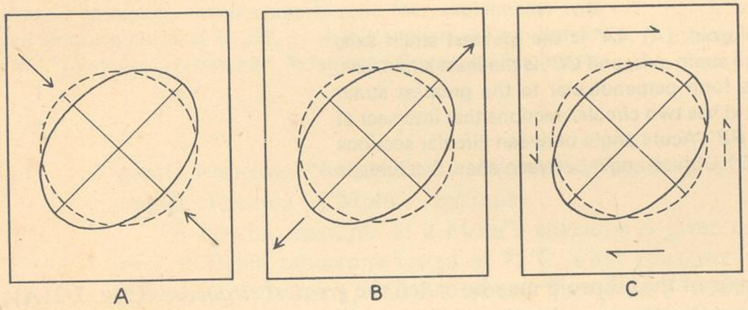


Fig. 7-23. Deformation of circle into an ellipse. (A) Compression. (B) Tension. (C) Couple.

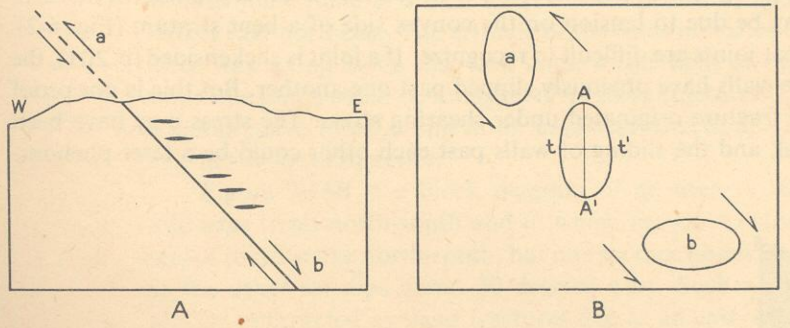


Fig. 7-24. Use of strain ellipse in a structural problem. (A) Cross section; heavy diagonal line is a fault. The problem is to decide whether movement has been of type represented by arrows at *a* or by arrows at *b*. Small gashes are open tension cracks. (B) The tension cracks of diagram A are represented by *tt'*; therefore the greatest strain axis lies in direction *AA'*, which is the long axis of the strain ellipse. The movement represented by the arrows at *a* would give such an orientation of the strain ellipse; the movement represented by the arrows at *b* would not.

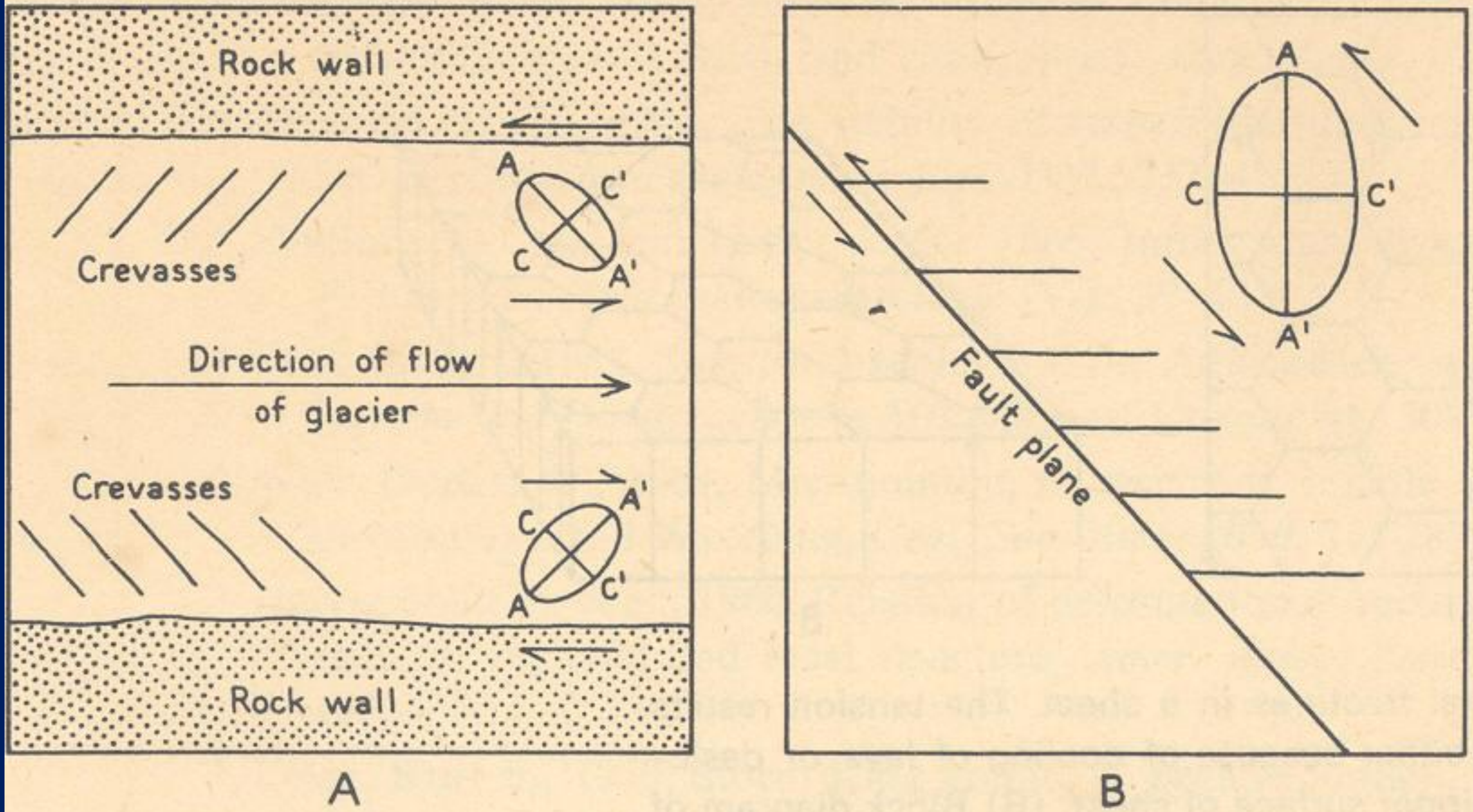


Fig. 7-27. Tension fractures. (A) Crevasses along side of glacier. Couples caused by friction are shown by smaller arrows. Ellipses represent orientation of strain ellipsoid. (B) Cross section to show feather joints, which are represented by horizontal lines to right of fault plane. Arrows near fault show relative movement along it. Orientation of ellipse resulting from this movement shown in upper right-hand corner.

CLEVAGE, FOLIATION & LINEATION

Foliation:

“It is the property of rocks whereby they break along approximately parallel surface”

Primary: **inherited from the time of their formation.**

- Bedding fissility – Parallel to stratification caused by the platy & elongated grains in sedimentary rocks
- Primary foliation --- Caused due to rock flowage in igneous rocks.

Secondary: **Due to metamorphism in metamorphic rocks.**

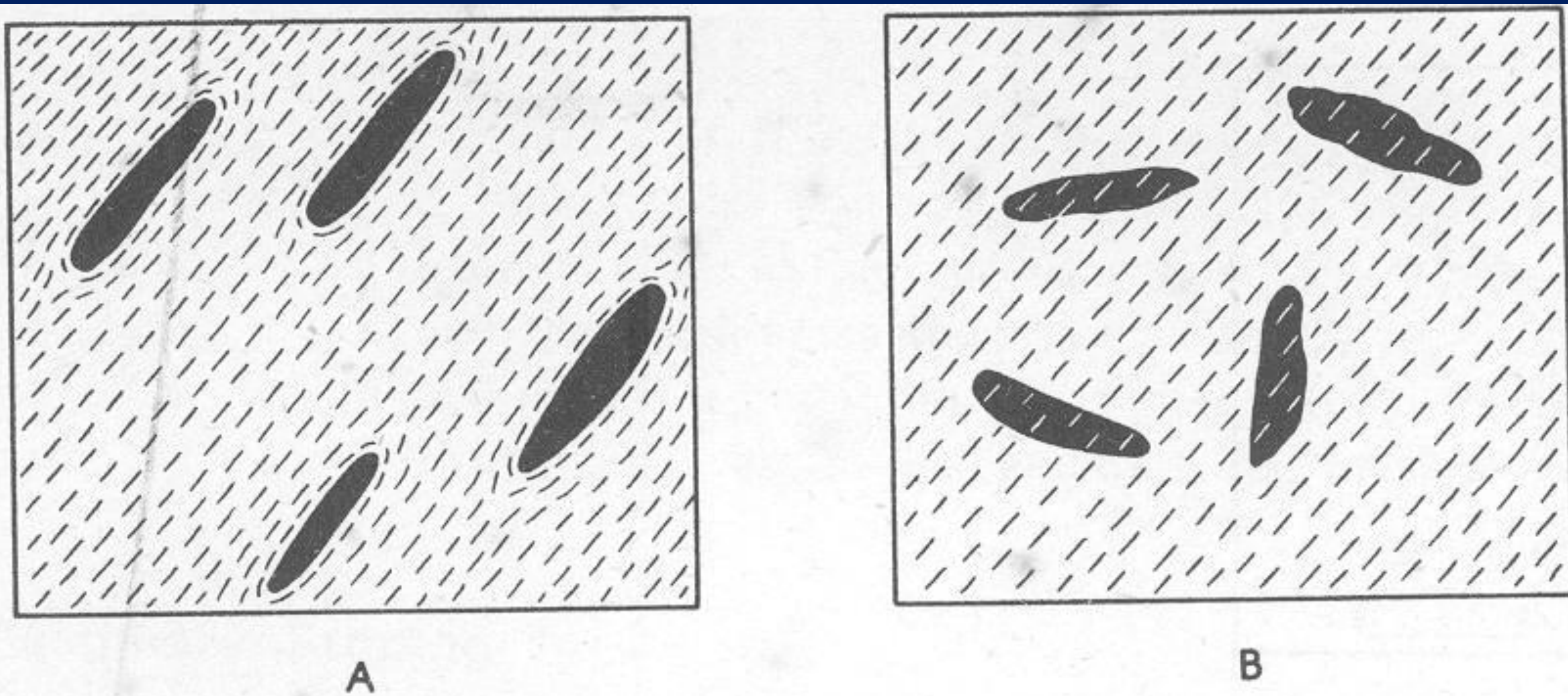


Fig. 17-9. Relation of inclusions to foliation. Solid black represents platy inclusions; black and white short dashes represent foliation due to platy minerals. (A) Platy inclusions parallel to primary foliation. (B) Platy inclusions, diversely oriented, cut by a secondary foliation.

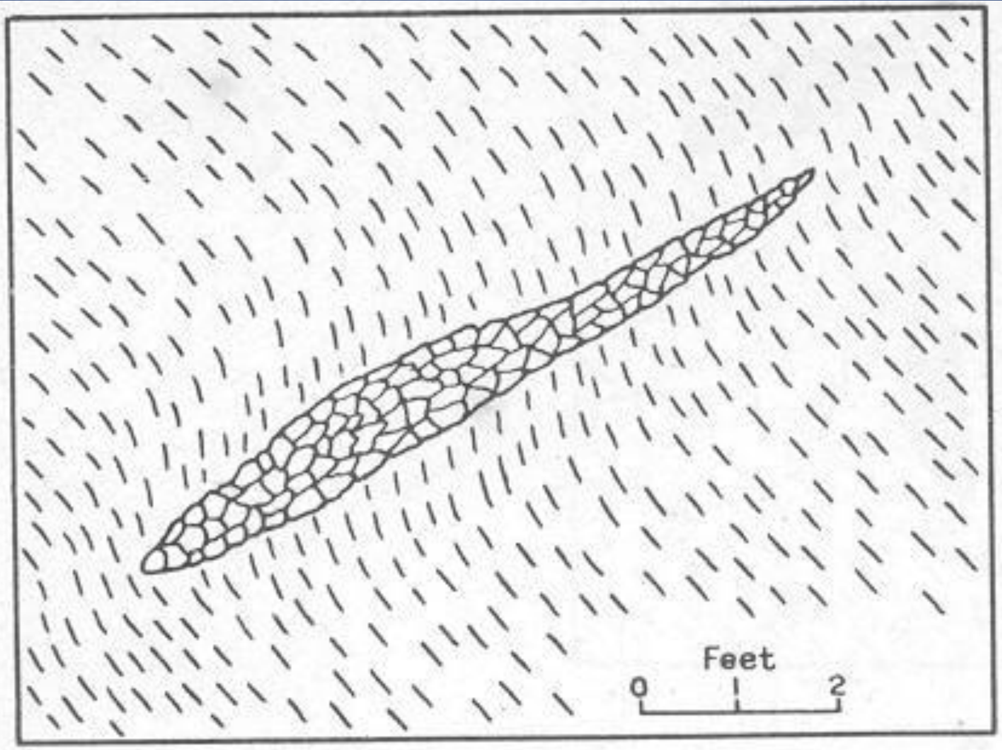


Fig. 17-10. Shear filled with pegmatite. Short dashes represent primary platy flow structure that is a primary foliation. Granular pattern is pegmatite or coarse granite.

Cleavage:

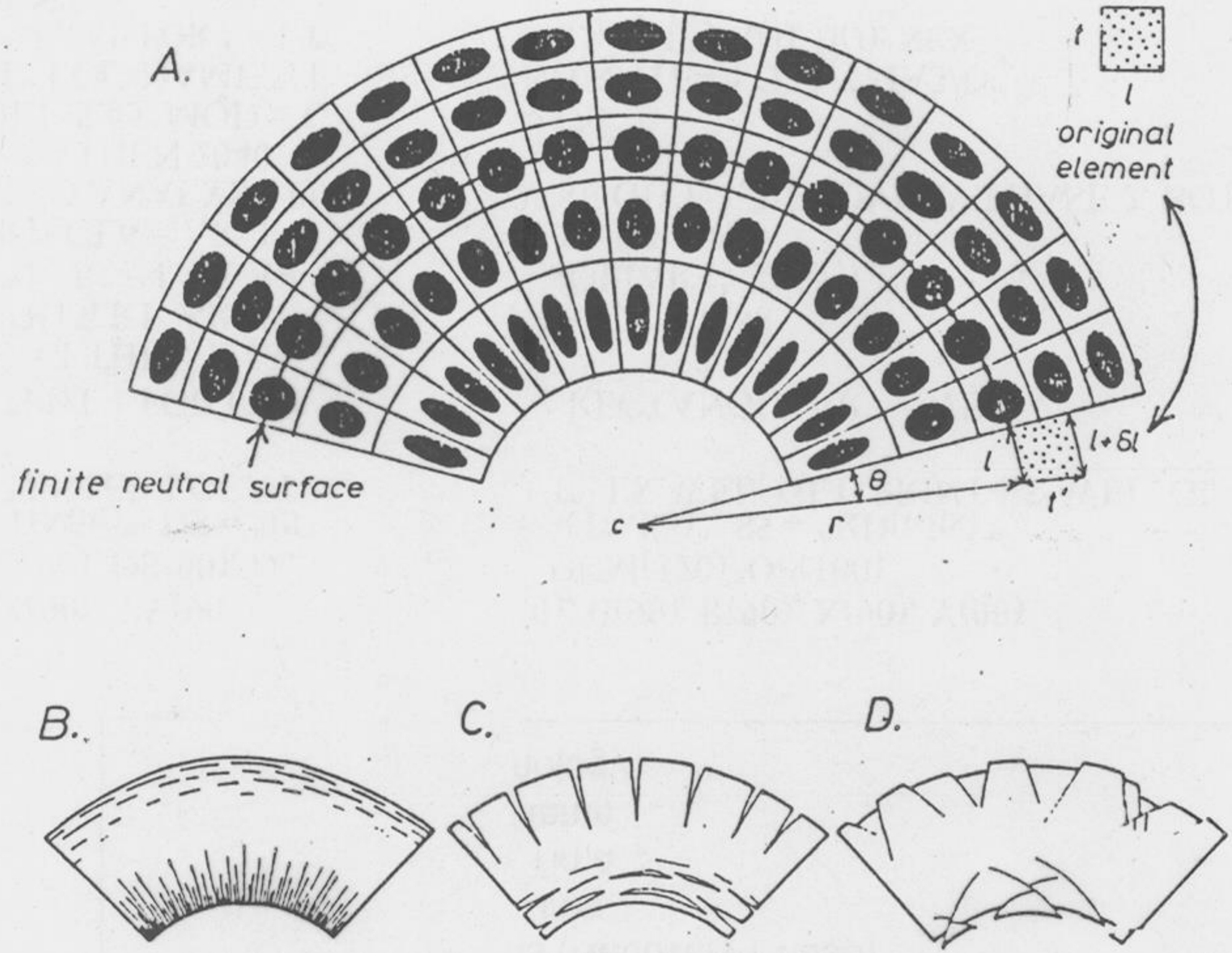
- Also called as rock cleavage – it is the property of the rocks where by they break along parallel surfaces (eg. Slate)

- In general they are oblique / inclined to primary bedding, some time they are parallel to bedding as well.

Schistosity:

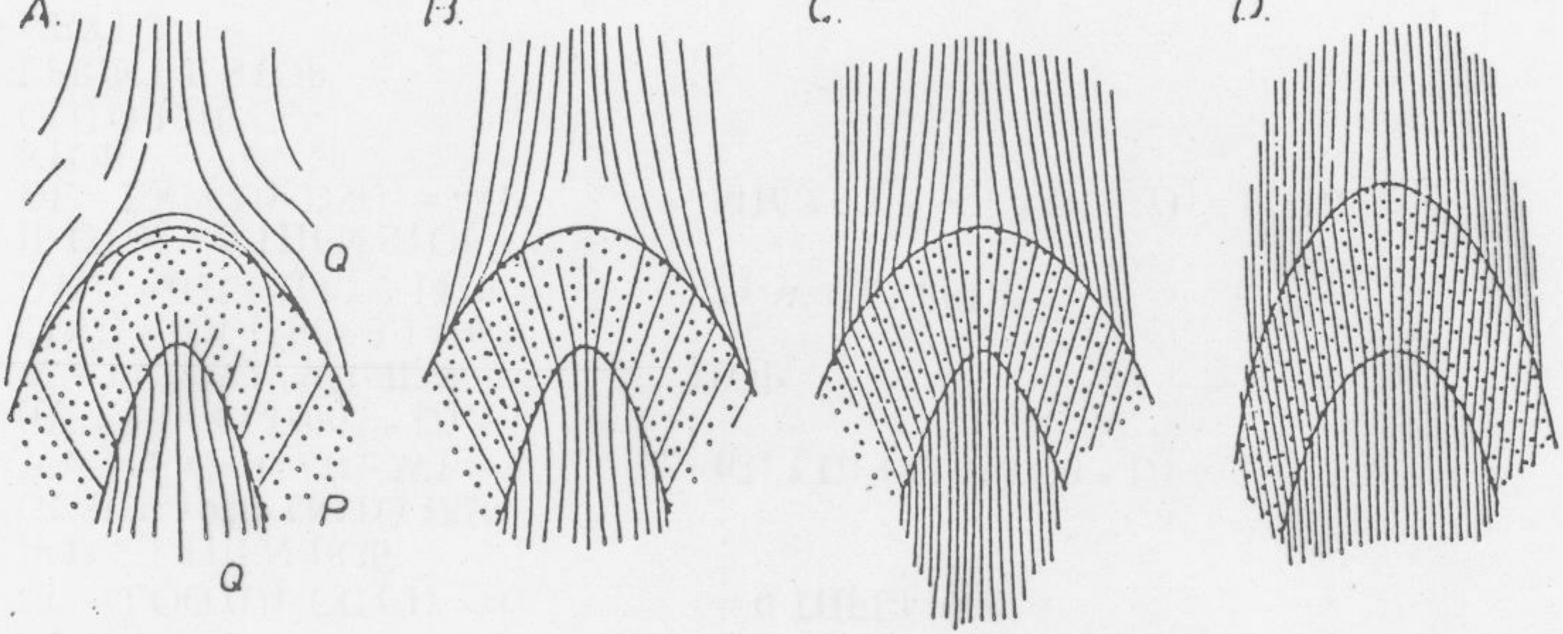
Variety of rock cleavage found in sufficiently recrystallised rocks (eg. Schists)

Structural development of rock strain



A: *The geometrical features of a fold formed under conditions of pure tangential longitudinal strain. Structural development of rock strain:* B, *cleavage;* C, *extension fissures;* D, *conjugate shear faults.*

Cleavage formation



Cleavage patterns in folds with no (A), some (B) and strong (C) initial layer parallel shortening. D shows the modified fold and cleavage geometry arising from a homogeneous strain with shortening normal to the fold axial surface. Rock P is more competent than rock Q.

TYPES OF CLEVAGES / SCHISTOSITIES:

- Slaty cleavage or schistosity
- Fracture cleavage
- Shear cleavage
- Slip cleavage
- Bedding cleavage
- Axial plane cleavage.

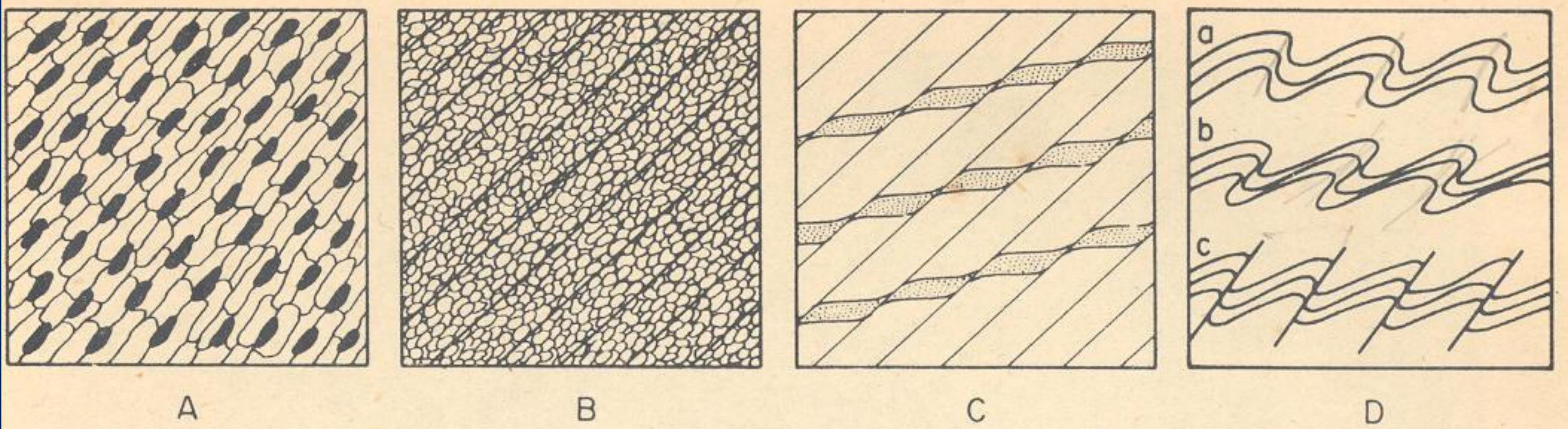


Fig. 18-2. Kinds of cleavage. (A) Slaty cleavage or schistosity. (B) Fracture cleavage. (C) Shear cleavage. (D) Slip cleavage.

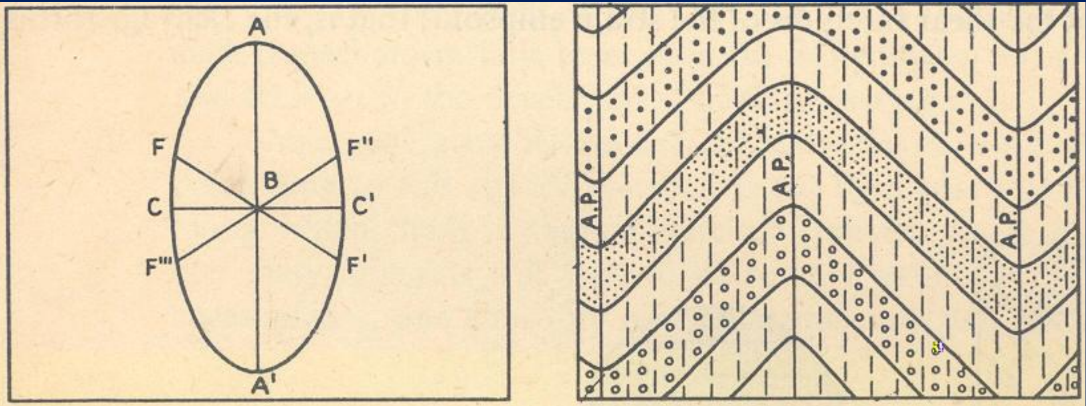


Fig. 18-5. Relation of cleavage to strain ellipsoid. Flow cleavage forms at right angles to the least strain axis (*CC'*) of the strain ellipsoid; it includes the greatest strain axis (*AA'*) and the intermediate strain axis (*B*), which is perpendicular to the plane of the paper. Fracture cleavage develops essentially parallel to the planes represented by *FF'* and *F''F'''*.

Plate 39. *Axial plane cleavage in syncline.* Old quarry No. 2, Slatington, Lehigh County, Pennsylvania. Photo: E. B. Hardin, U. S. Geological Survey.

Slaty cleavage or schistosity:

Slaty cleavage

Parallel arrangement of

- **Platy minerals of mica and chlorite**
- **Ellipsoidal minerals such as quartz and feldspar**
- **Elongate minerals like hornblende, actinolite, tremolite**

Their long axis lie in perpendicular direction to the force.

Rock can be split into an indefinite number of thin sheets.

- **Slaty cleavage in less metamorphosed rocks**
- **Schistosity in more metamorphosed rocks**

Schistosity is called as "**Continuous cleavage"**

- **Cleavage is the result of rock flowage**
- **Rock is shortened perpendicular ti cleavage and lengthened parallel to the cleavage**
- **Rotation of flaky and needle minerals parallel to the cleavage surface**
- **Greater the deformation more is the rotation**
- **Flatening and as well as crystalisation alon the cleavage.**

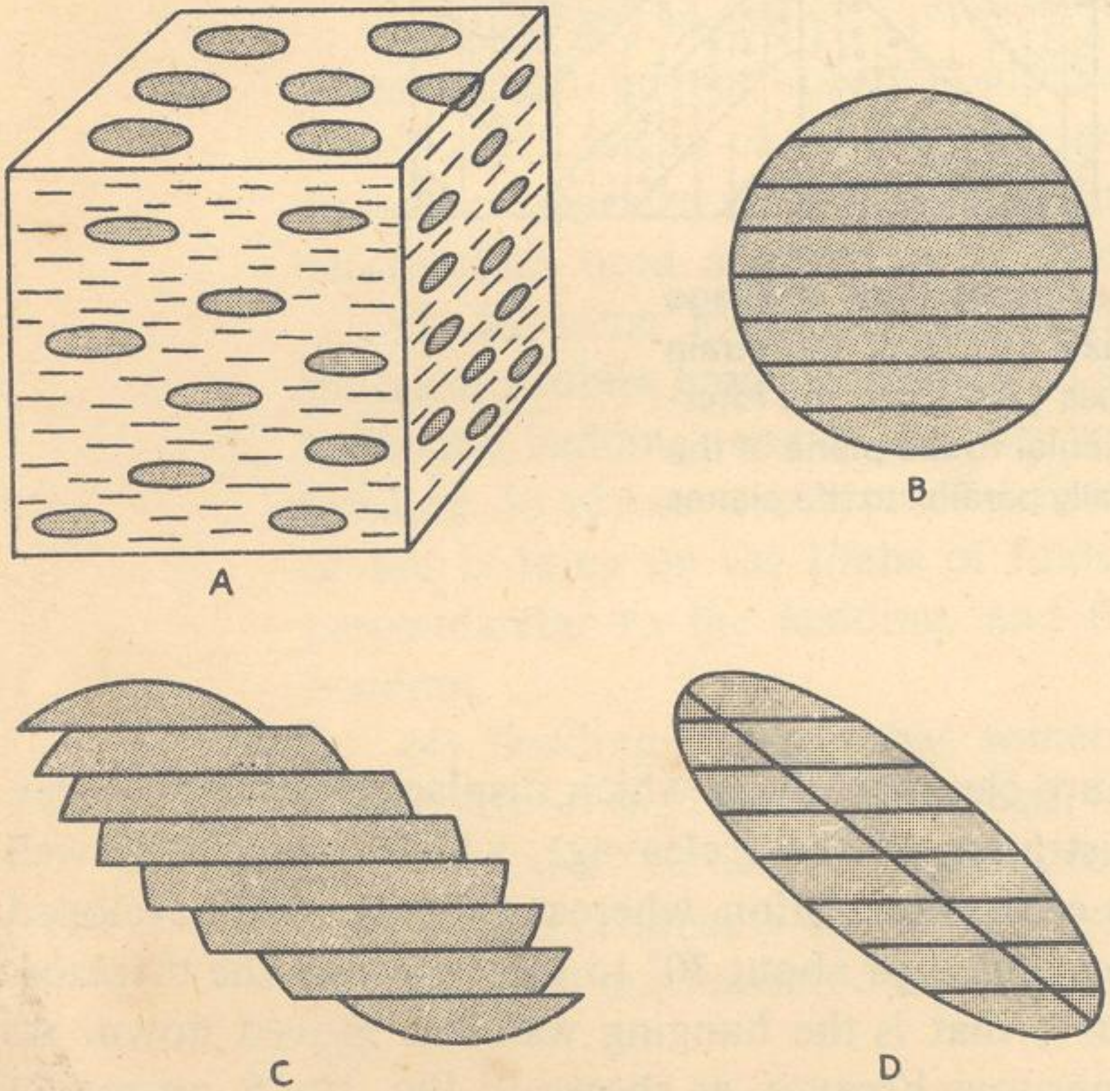


Fig. 18-4. Evidence against shear theory for origin of cleavage. (A) Characteristics of slaty cleavage; short dashes are platy minerals, stippled areas are ellipsoidal grains. (B) Circle cut by shear planes. (C) Circle sheared to jagged ellipse. (D) Same as (C), but with shear planes so close that ellipse is smooth.

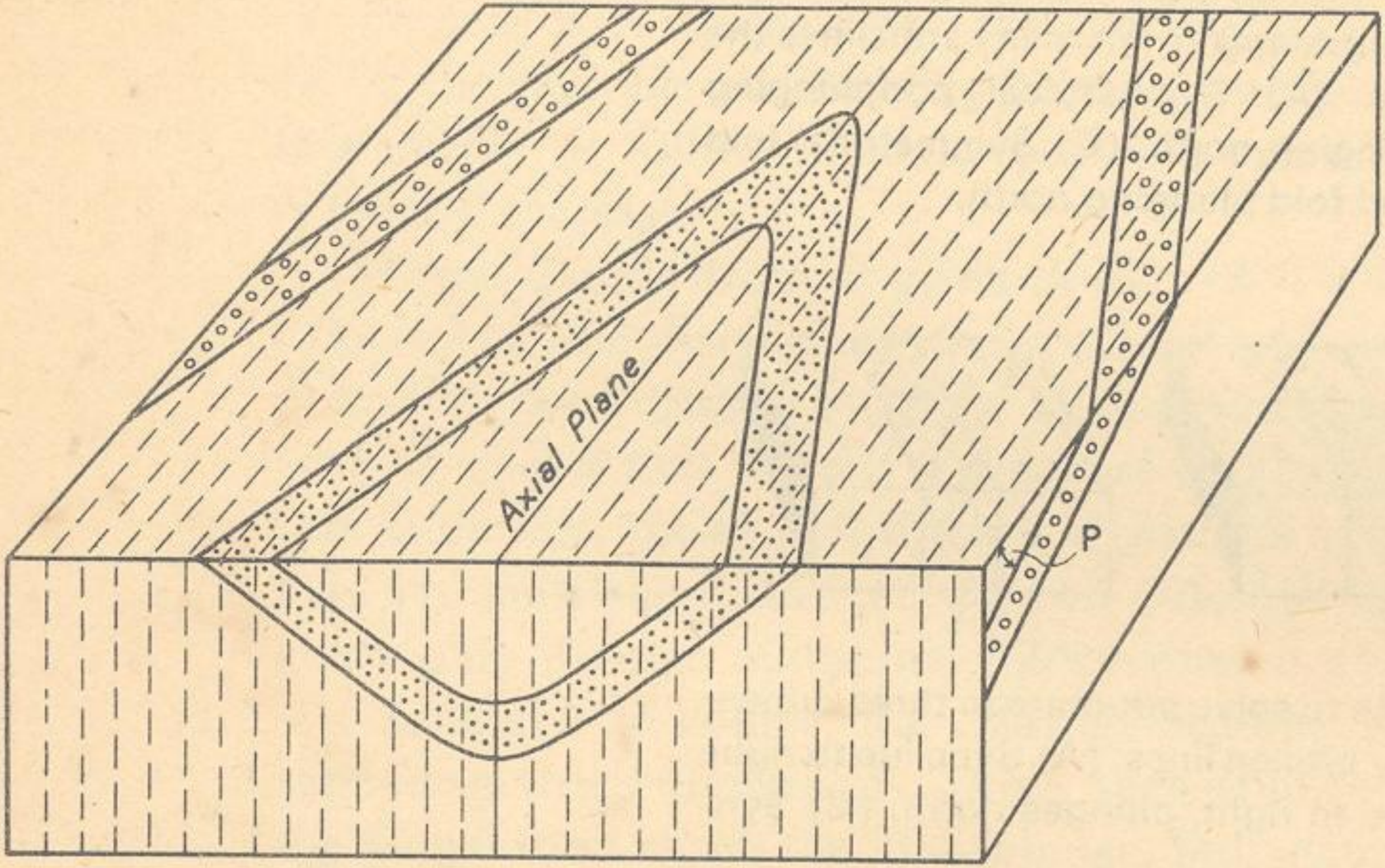


Fig. 18-10. Three-dimensional representation of slaty cleavage. Cleavage represented by broken lines. Value of plunge of fold is equal to *P*, which is measured on the cleavage; it is the angle between the trace of the bedding and a horizontal line.

Fracture cleavage:

- Closely spaced cleavage
- Minerals in the rocks are not parallel to the cleavage
- Spacing is few millimeter to centimeter
- If spacing exceeds few centimeters , it is called Joint
- It is also called as "Spaced Cleavage"
- It is the Phenomenon of shearing
- Cleavage is inclined to the greatest principle stress axis with 30 degree.

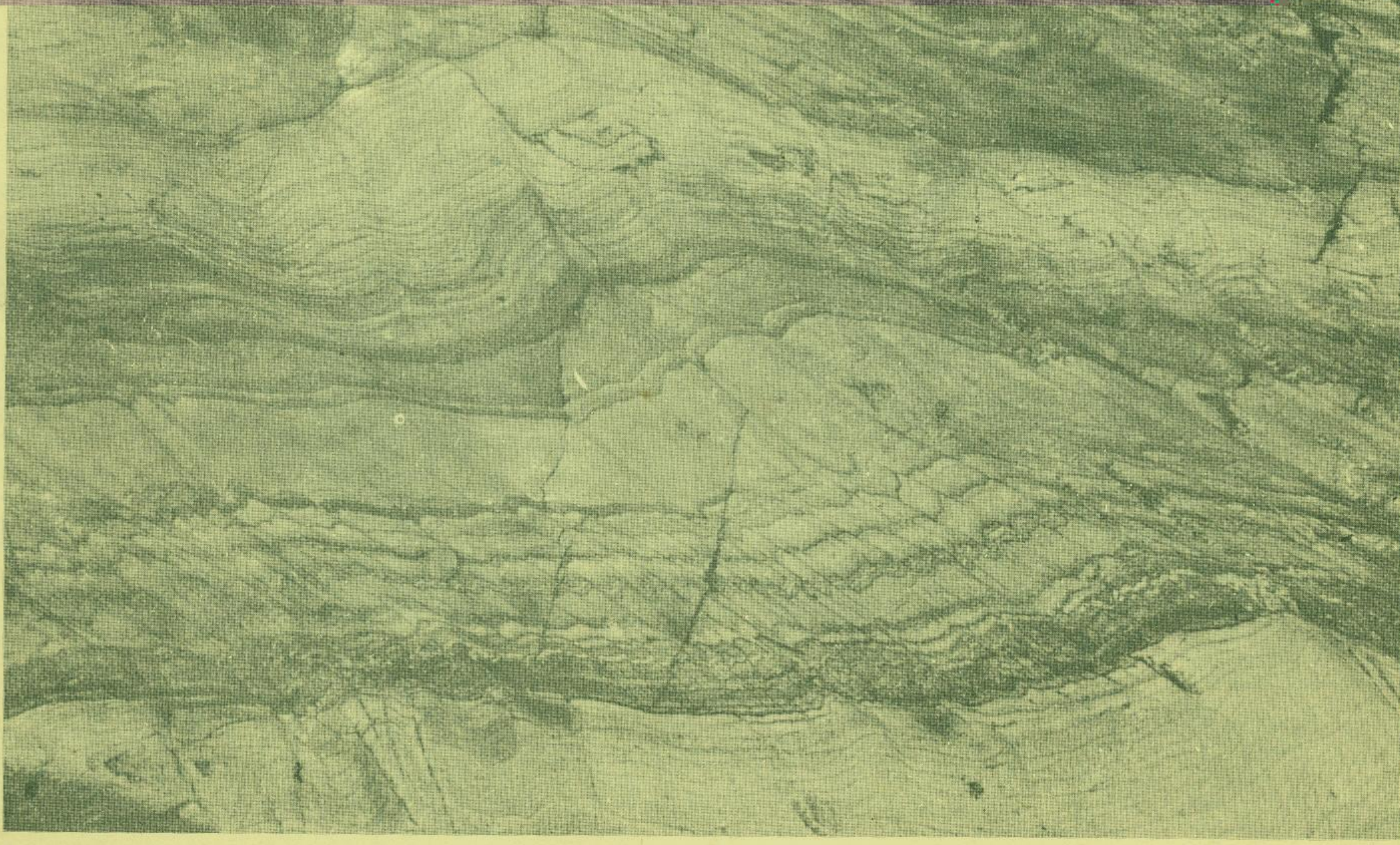


Plate 36. *Fracture cleavage.* Locally is a shear cleavage. Blue Canyon Formation, south bank of South Yuba River, 3½ miles east of Washington. Nevada County, California. Photo: L. D. Clark, U. S. Geological Survey.

Shear cleavage:

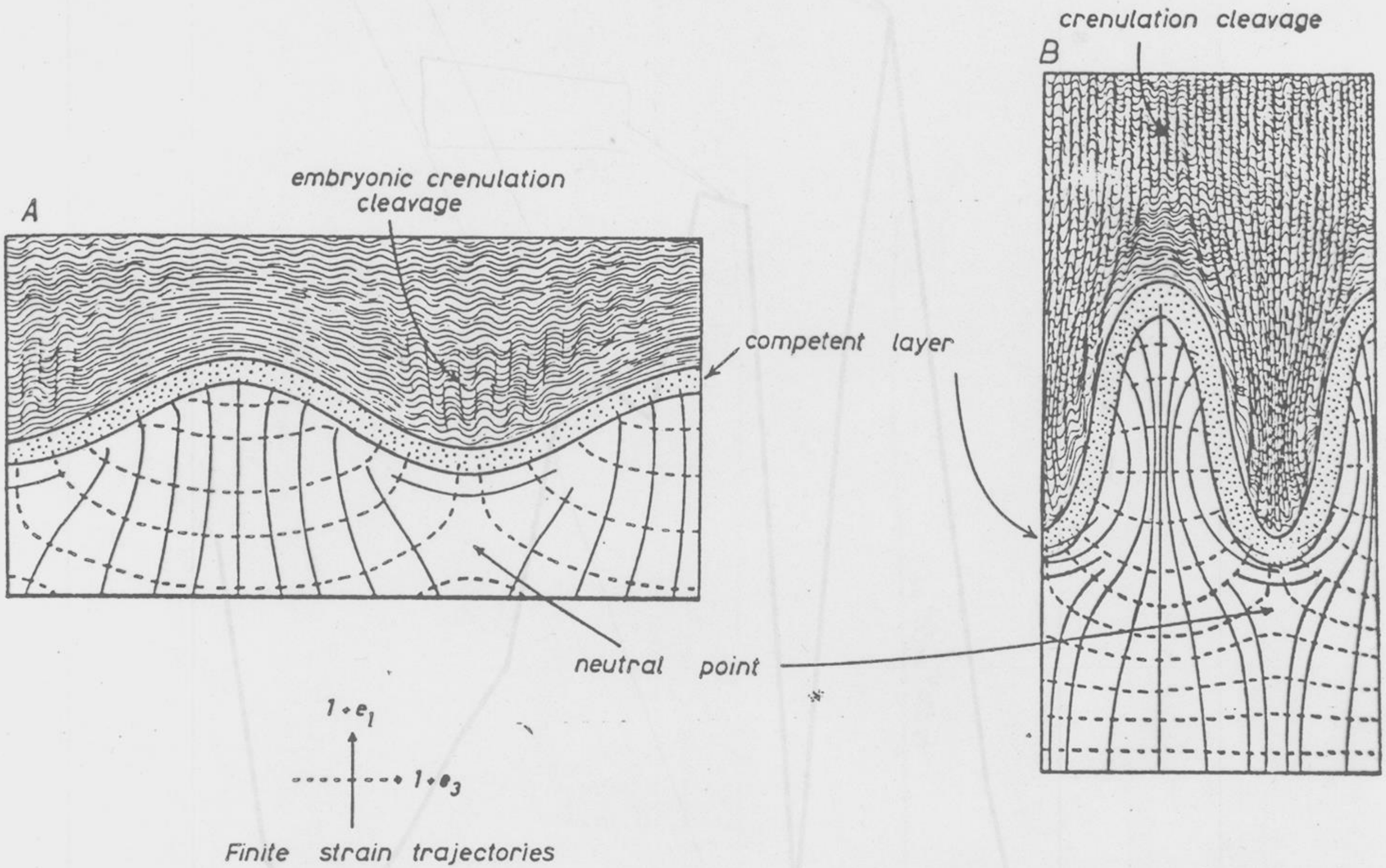
It is a fracture cleavage as well along which there has been displacement.

Minor drag develop near to cleavage.

Slip cleavage:

- Also called as strain-slip cleavage or crenulation cleavage
- Cleavage associated with small crinkles
- Shorter limb having maximum thinning and it is the plane of weakness.
- Earlier formed schistosity only thrown into crinckles.
- Crinckles developed due the force perpendicular to the plane normal to the schistosity.
- Assymetrical crinckle due to couple force acting parallel to schistosity.
- Mica flakes are rotated to this weak plane pof the axial plane of crinkles.
- Displacement takes place along this cleavage.

Cleavage formation



Scheme of development of symmetric and asymmetric crenulation cleavage in a material with a strong initial fabric as a result of buckling of a competent layer.

Bedding cleavage:

- Cleavage or schistosity is parallel to the bedding may be due to
- In Isoclinal folding – Cleavage parallel to the bedding in the limbs
- Mimetic recrystalisation – schistosity parallel to the hinge of the fold
- Rock flowage parallel to the bedding – Pebble flattening due to layer stretching, shortening takes place perpendicular to bedding and flow cleavage develop parallel to bedding – **bedding cleavage**

CLEAVAGE BANDING:

In a Sand stone and Shale intercalate layer – due to high degree of deformation squeezing of plastic shale into the inclined planes of cleavage that give rise to once again an intercalation appearance but along the cleavage orientation

Some time during the deformation and metamorphism the metamorphic fluids come and occupy the cleavage which finally look like banding.

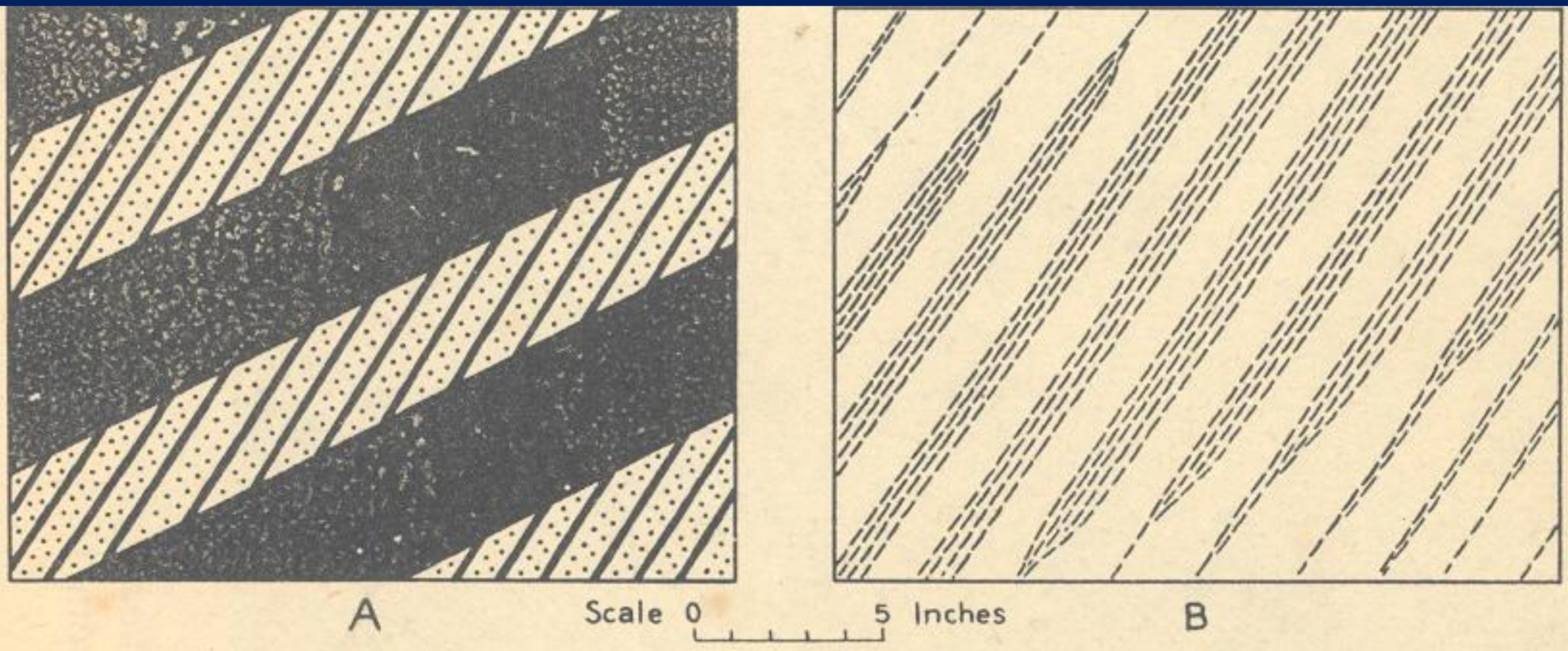


Fig. 18-3. Cleavage banding and segregation banding. (A) Cleavage banding. Solid black represents shale; dots represent sandstone. Bedding dips 25 degrees to left; cleavage dips 60 degrees to left. The more plastic shale has been injected along cleavage in the sandstone to produce a rhythmic alternation of shale and sandstone that simulates bedding. (B). Segregation banding. Short dashes represent bands rich in dark minerals. White areas are rich in light mineral. Bedding dips 25 degrees to the left.

METAMORPHIC BANDING

Due to very high grade metamorphism the dark and light colour minerals segregate together and give rise banding appearance which is called metamorphic or segregation banding.

Stratigraphy establishment:

- Clevage vertical – right side up - axial plane vertical and parallel
- Cleavage dips in the same direction of bedding dip – right side up – synclinal axis is in the same direction of bed dip
- If the bedding is vertical - right side up – synclinal axis is in the opposite direction to that of cleavage dip
- If the cleavage is gentler than the bedding dip – upside down – over turned limb – synclinal axis is in the opposite direction to that of cleavage

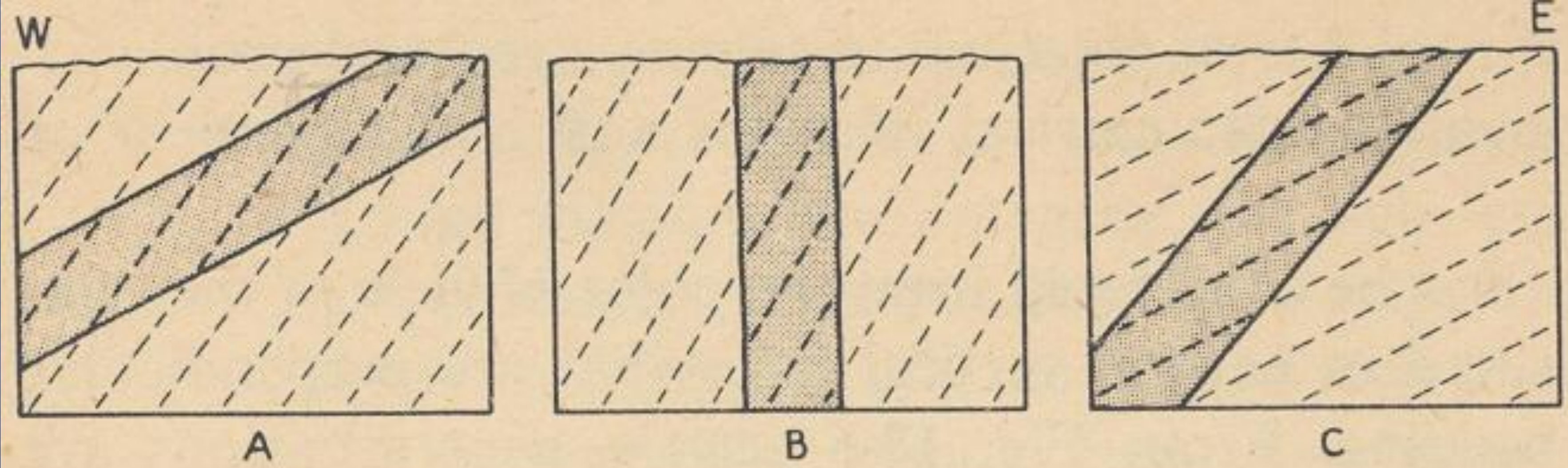


Fig. 18-7. Use of slaty cleavage to solve structure in two dimensions. Cleavage represented by broken lines. (A) Syncline is to left. (B) Syncline is to right. (C) Syncline is to right.

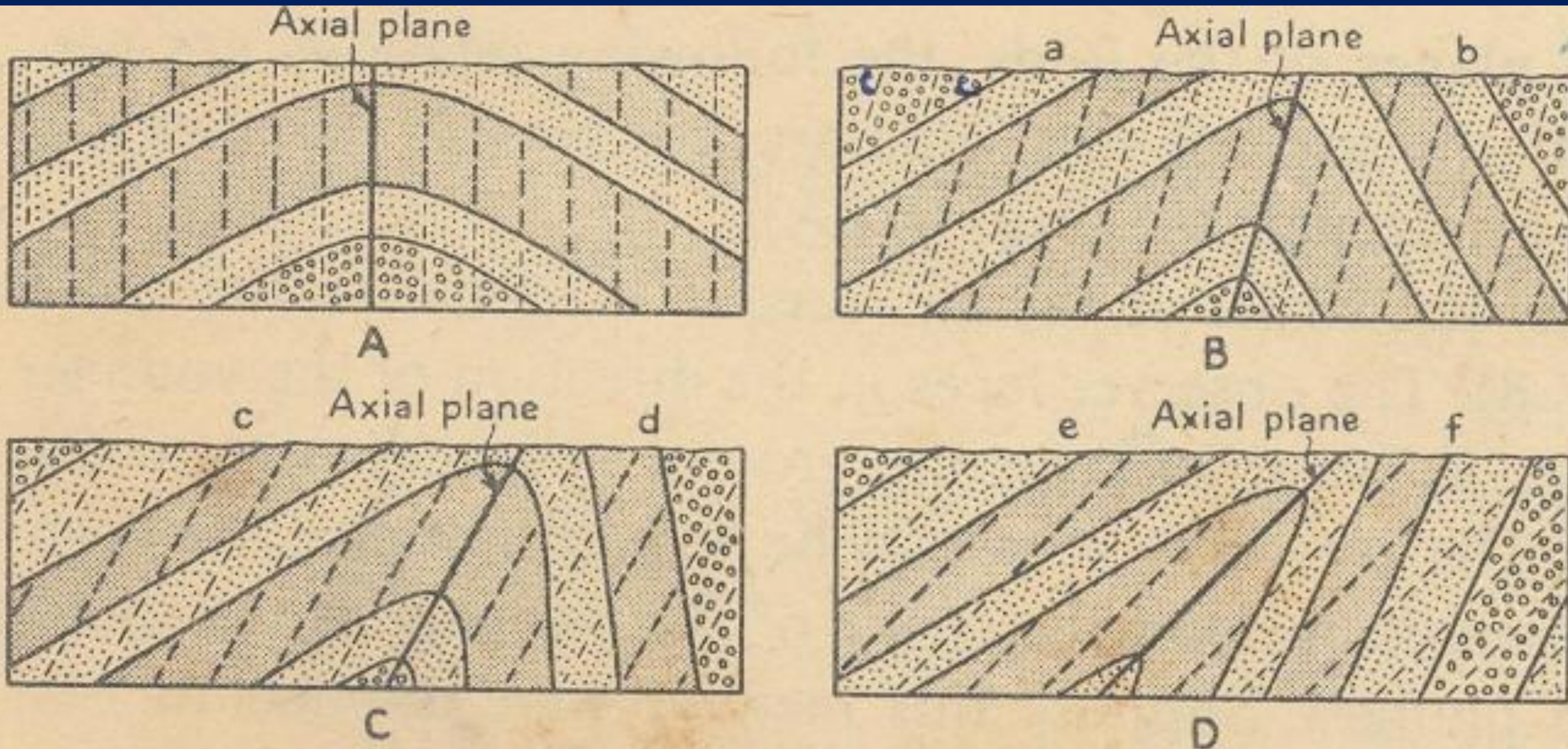


Fig. 18-6. Relation of slaty cleavage to folds in two dimensions. Cleavage represented by broken lines. Smaller letters are referred to in text. Rigorous parallelism of cleavage to axial plane is diagrammatic. (A) Symmetrical fold. (B) Asymmetrical fold. (C) Asymmetrical fold with one steep limb. (D). Overturned fold.

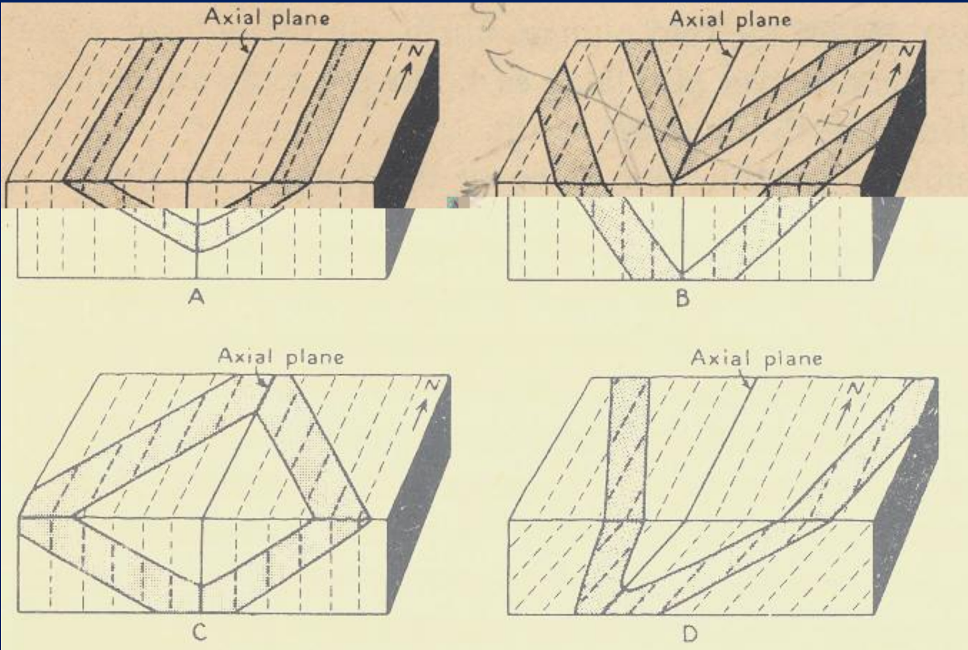


Fig. 18-8. Relation of slaty cleavage to folds in three dimensions. Cleavage represented by broken lines. Rigorous parallelism of cleavage to axial plane is diagrammatic; in many anticlines the cleavage diverges downward. (A) Symmetrical nonplunging fold. (B) Symmetrical fold plunging north. (C) Symmetrical fold plunging south. (D) Overturned fold plunging north.

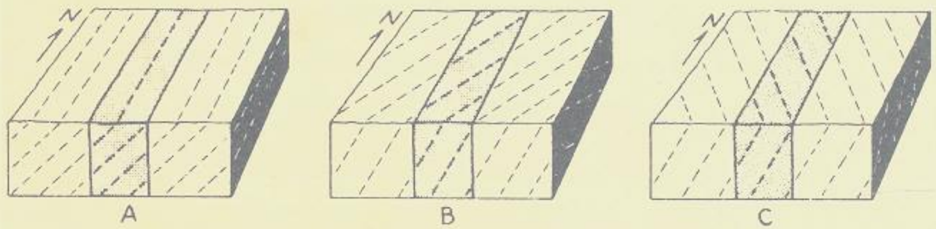


Fig. 18-9. Use of slaty cleavage to solve structure in three dimensions. Cleavage represented by broken lines. (A) Syncline to right, does not plunge. (B) Syncline to right, plunges north. (C) Syncline to right, plunges south.

LINEATION

Lineation:

It is **the result of the parallelism of some directorial property in the rock such as the long axis of Hornblende crystals. Platy minerals or spherical grains may be strung out in lines to produce lineation.**

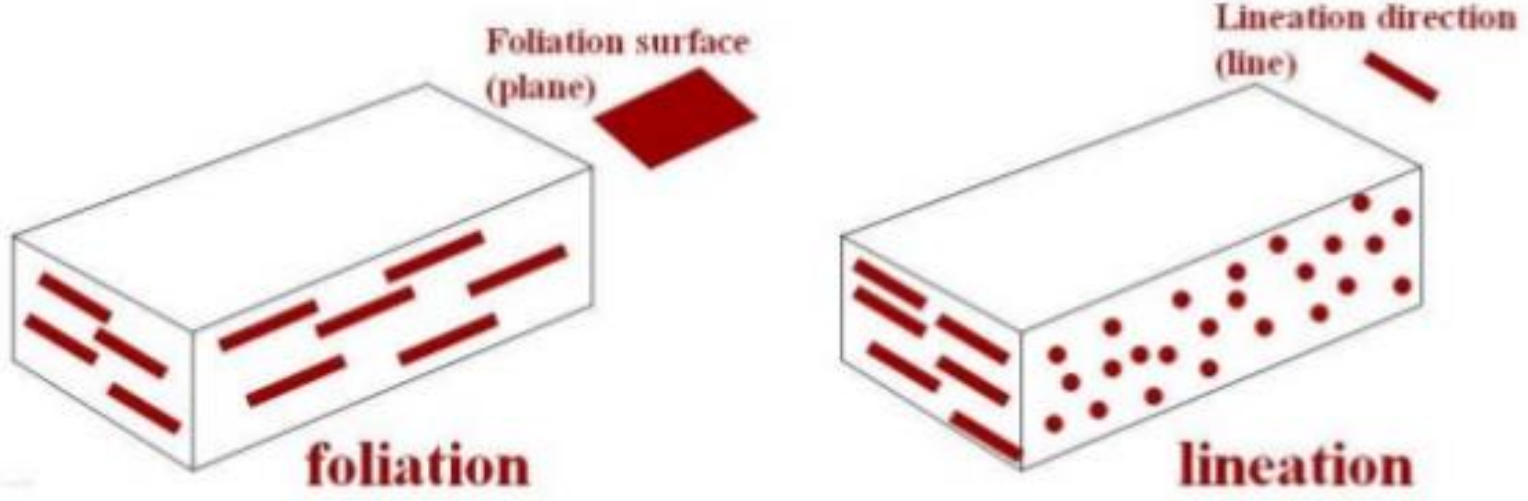
Foliation Vs Lineation

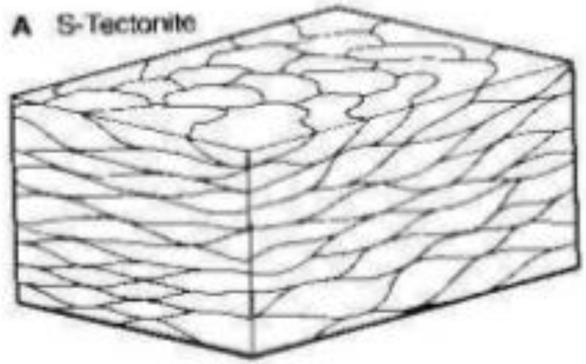
Foliation: planar features (disk, sheet shapes)

Viewed at the sides, one sees lines on all sides.

Lineation: linear features (cigar shapes)

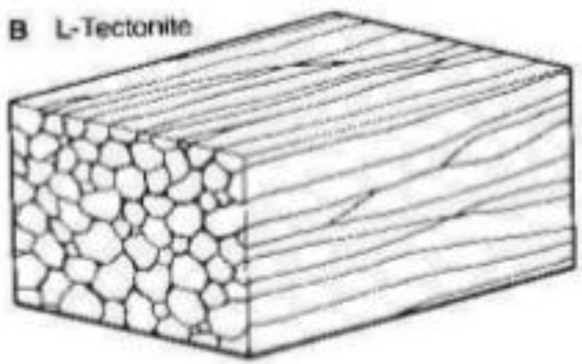
Viewed at the sides, one sees dots on at least one of the surfaces.



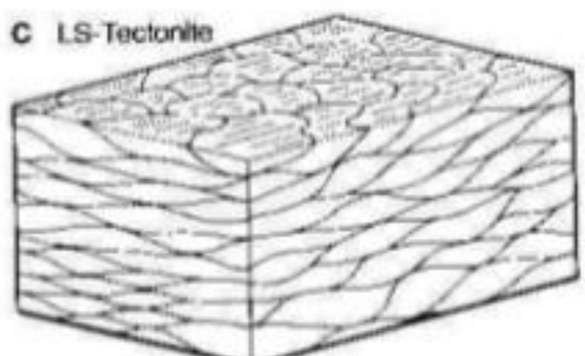


Tectonites: Rocks that are pervaded by foliation and or lineation- flowed in solid state

Schistosity (foliation) only due to flattening- no lineation.



L: Lineation only, due to unidirectional stretching or constriction.



LS: Foliation and Lineation, related to non coaxial strain- shearing.

Lineation Types:

Primary → Igneous Rock
→ Sedimentary Rocks

Secondary - Metamorphic Rocks

- It may occur with or without foliation
- A rock without cleavage or schistosity may possess lineation
- Commonly this secondary lineation is associated with foliation and lies in the plane of foliation

Kinds of Lineation

- Pebble lineation
- Intersection lineation
- Slickenside
- Bundinage or sausage
- Mullion structures

Fold axes are commonly considered to be the lineation

The attitude of the fold axis is often the reference to which other lineations are Compared

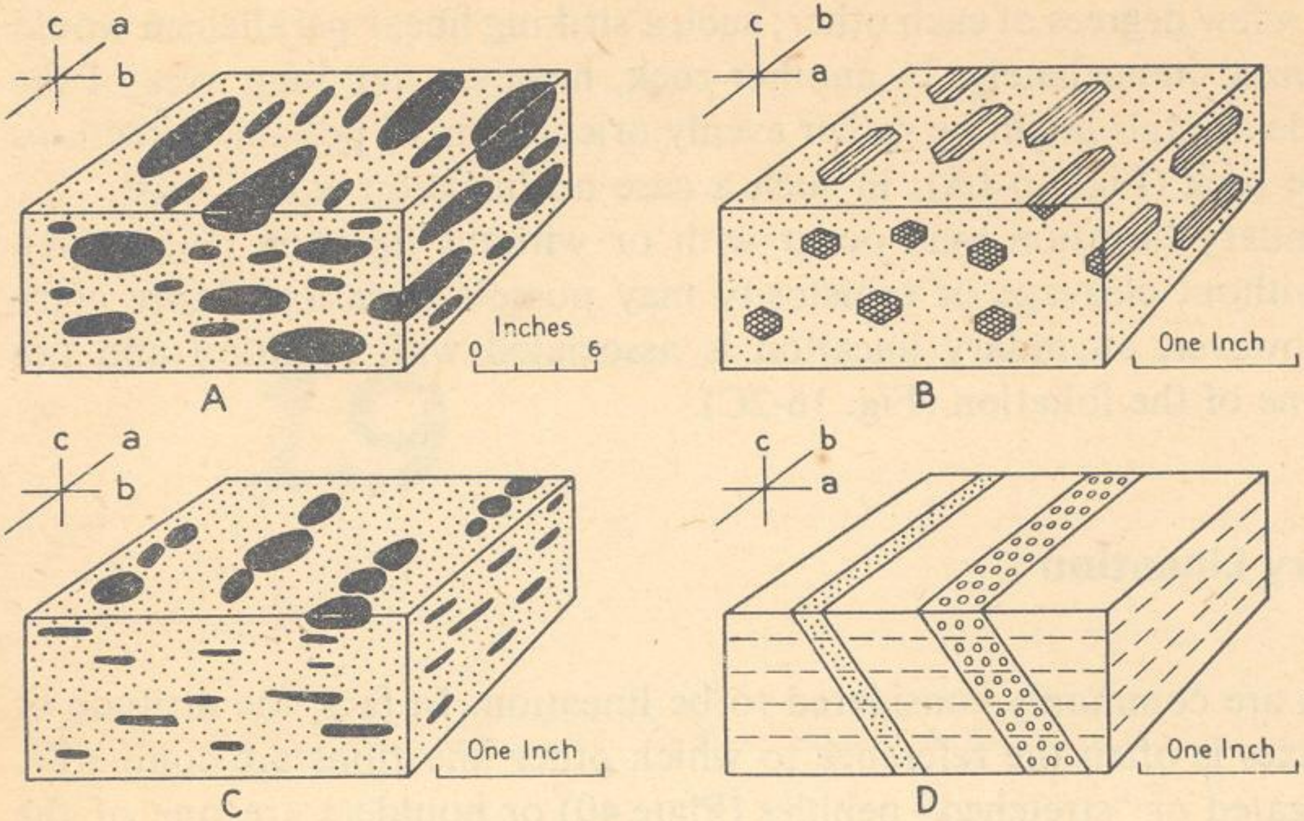


Fig. 19-1. Lineation. (A) Elongated pebbles are shown in solid black. Each pebble is an irregular ellipsoid, the longest axis of which is parallel to *a*, the shortest axis is parallel to *c*, and the intermediate axis is parallel to *b*. (B) Elongate crystals of hornblende, the long axes of which are parallel to *b* in the diagram. (C) Lineation caused by circular plates of mica, shown in solid black, strung out like beads on a string. (D) Cleavage is represented by top of block and by planes shown by broken lines. Bedding is shown by dots and open circles. Trace of bedding on cleavage gives a lineation.

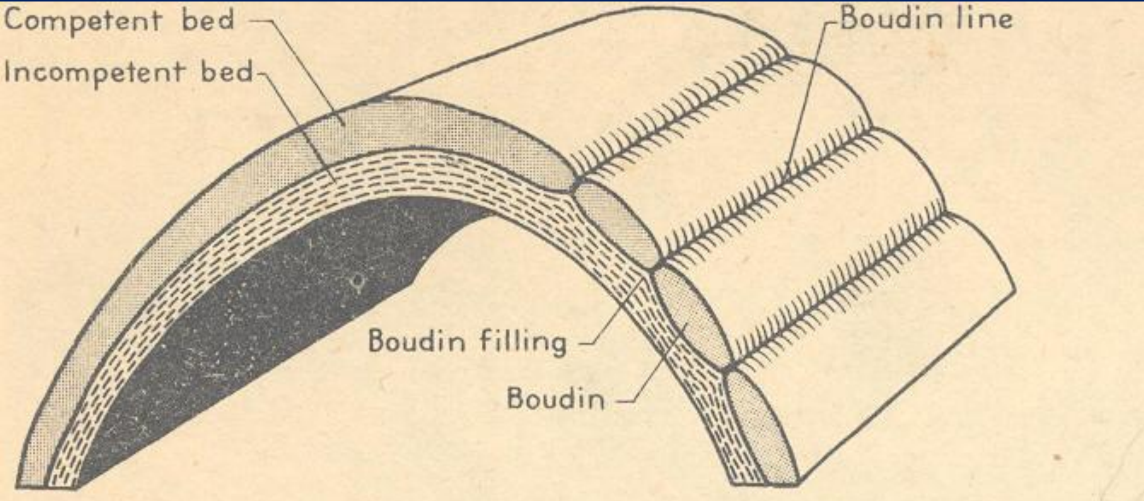


Fig. 19-2. Boudinage. In this case the boudin line is parallel to fold axis, but this is not necessarily true.

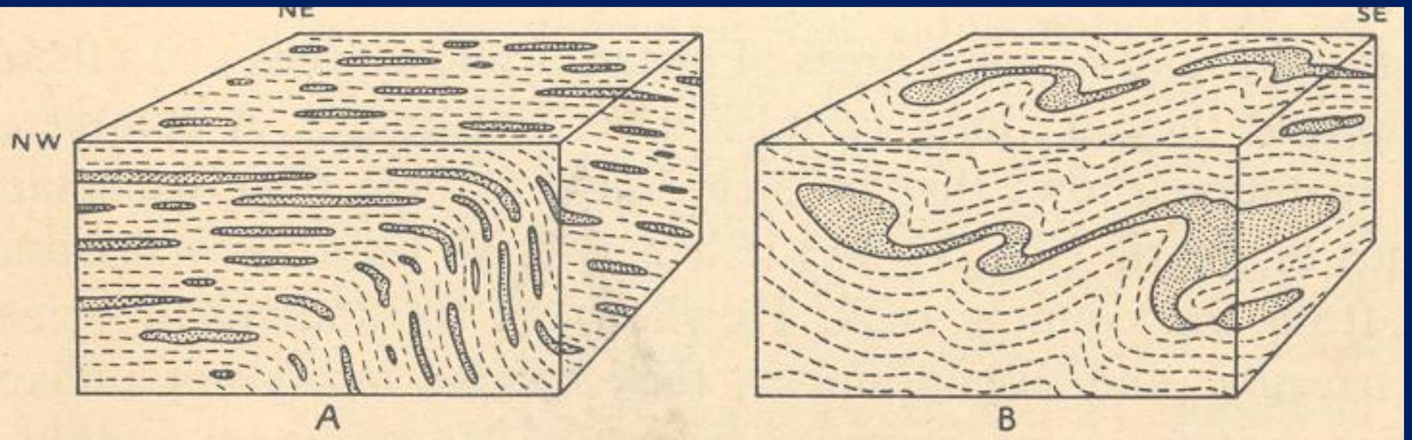


Fig. 19-3. Quartz rods. Quartz shown by dots, bedding by broken lines. (A) Quartz lenses parallel to bedding. (B) More irregular quartz lenses parallel to bedding. (Based on diagrams by G. Wilson.[7])

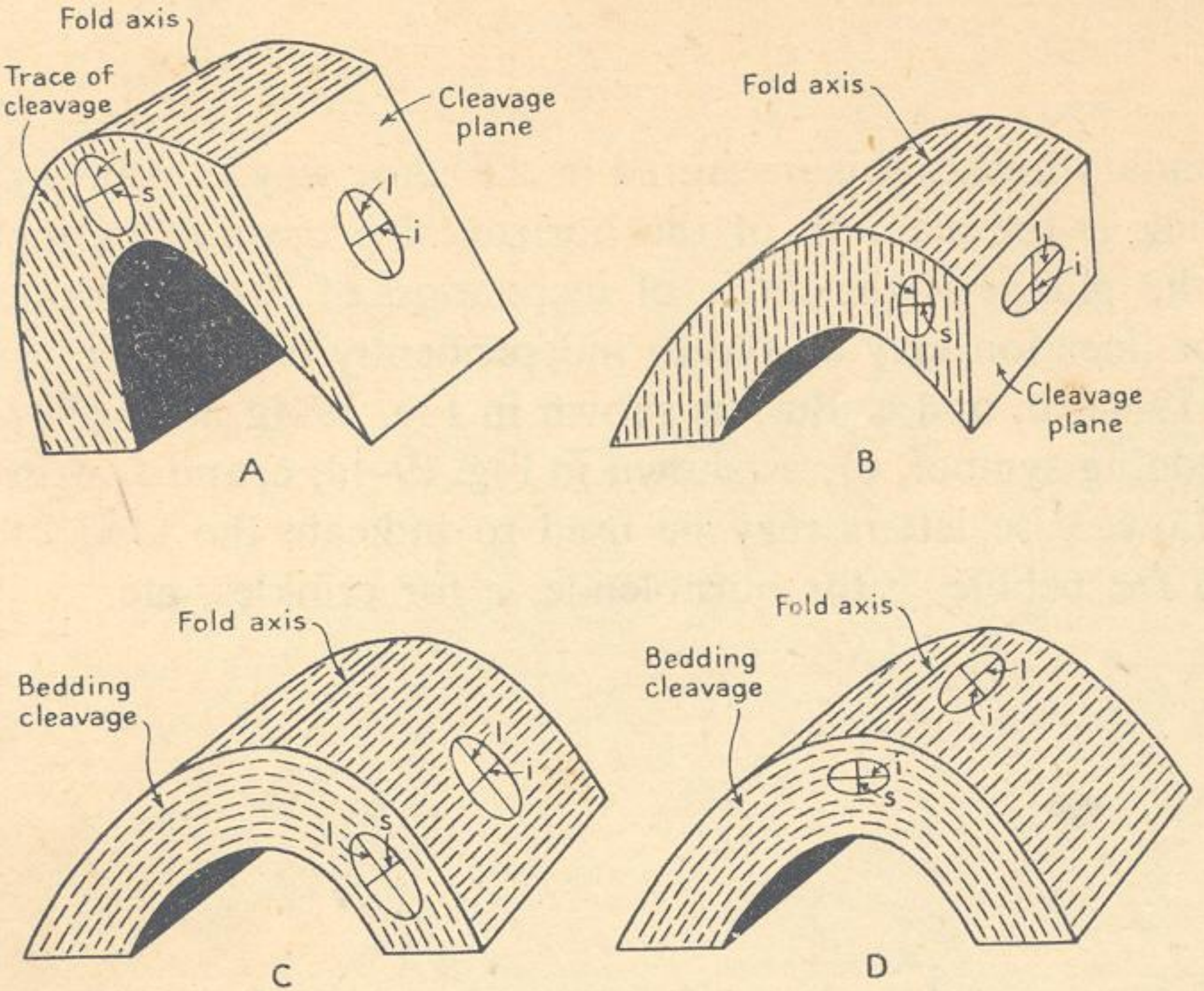


Fig. 19-5. Various orientations of long axes of deformed spheres. (A) In axial plane cleavage and perpendicular to fold axis. (B). In axial plane cleavage and parallel to fold axis. (C) In bedding plane cleavage and perpendicular to fold axis. (D) In bedding plane cleavage and parallel to fold axes.

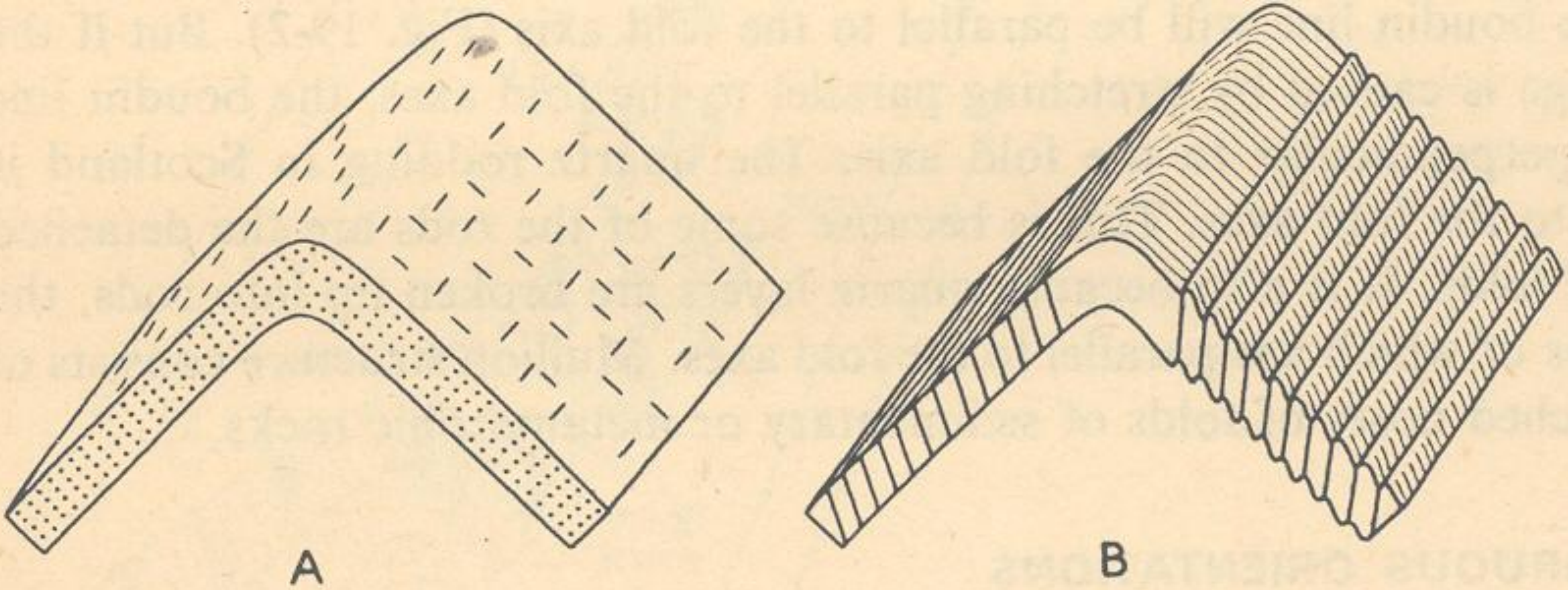


Fig. 19-6. Different kinds of lineation on folds. (A) Two lineations, one parallel to axis of fold and other at right angles. (B) Left-hand limb shows lineation due to intersection of fracture cleavage with bedding. Right-hand limb shows lineation due to intersection of shear cleavage with bedding; displacement on the cleavage causes either tiny faults or small crinkles.

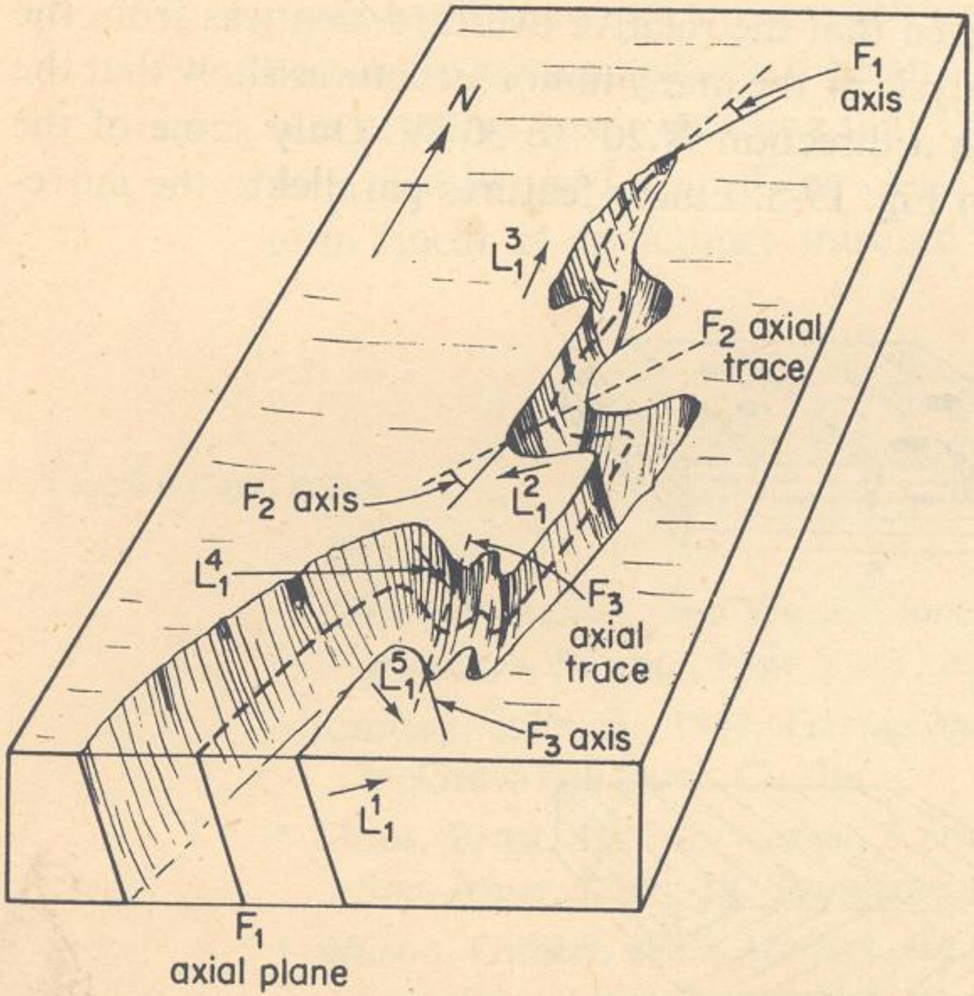


Fig. 19-7. Orientation of original lineation changed by succeeding stages of folding. Three stages of folding, F_1, F_2, F_3. In first stage of folding the axial plane of an isoclinal anticline dips steeply east and plunges 15° north. Lineation, L_1^1, forms parallel to fold axes at this time. But this lineation is reoriented to positions such as L_1^2 and L_1^3 by a second folding, and to such positions as L_1^4 and L_1^5 by a third stage of folding.

Mineral lineation

- Mineral lineation can be defined by the preferred dimensional orientation of inequant grains or by elongate mineral aggregates

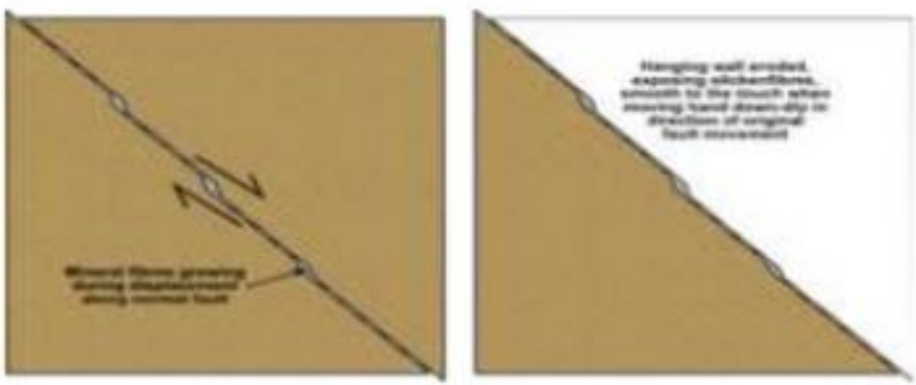
Hornblende lineation in orthogeiness

Slickenside striae

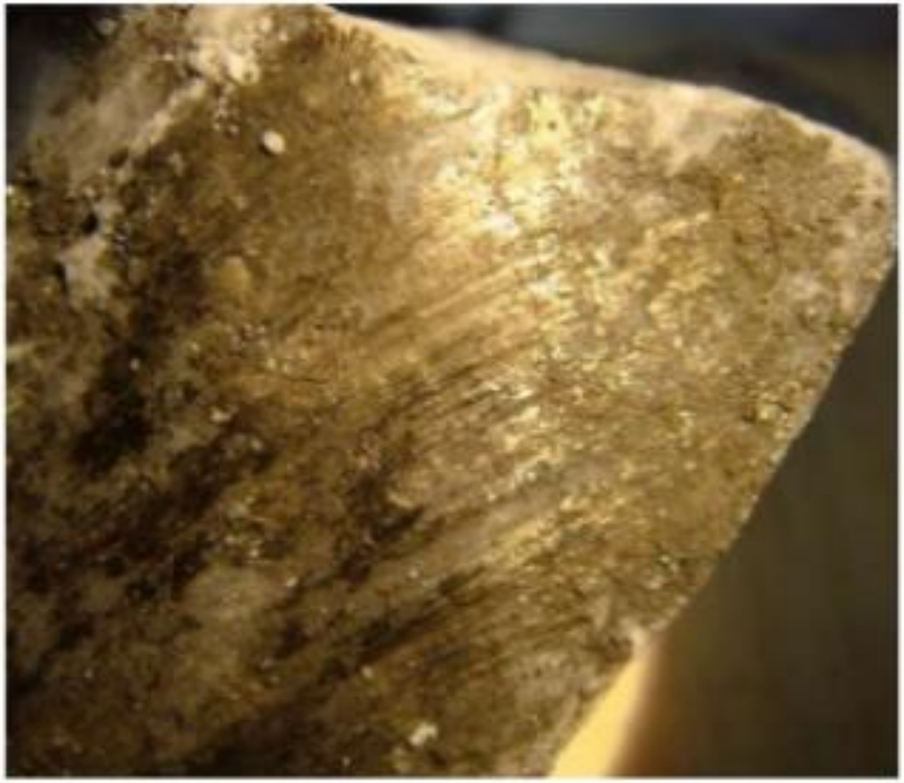
- Slickenside striae are common linear structure in many rocks but they are not generally a penetrative features and therefore not a fabric element.
- a **slickenside** is a smoothly polished surface caused by frictional movement between rocks along the two sides of a fault. This surface is normally striated in the direction of movement. The plane may be coated by mineral fibres that grew during the fault movement, known as *slickenfibres*, which also show the direction of displacement.
- How slickenside is form

  and show sense of

  movement on a fault

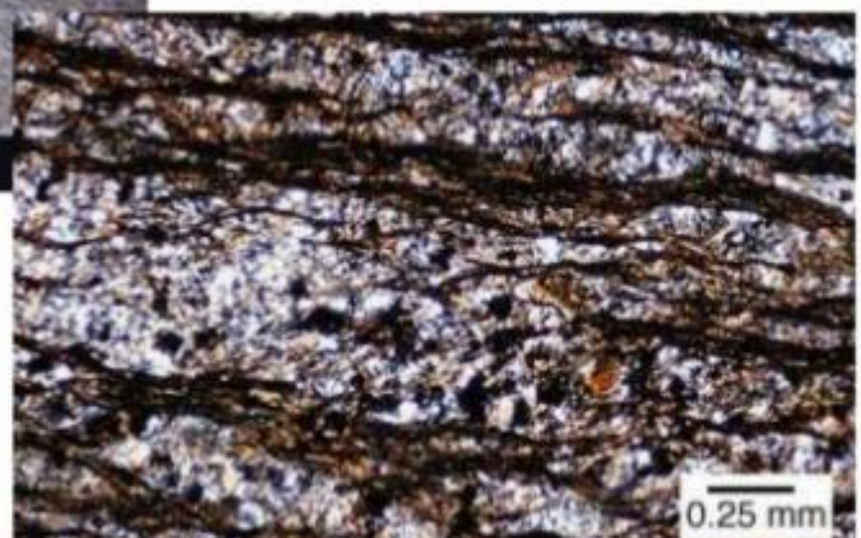



1 cm



Crenulations

- Crenulation lineation: Intersection between fold hinges and foliation



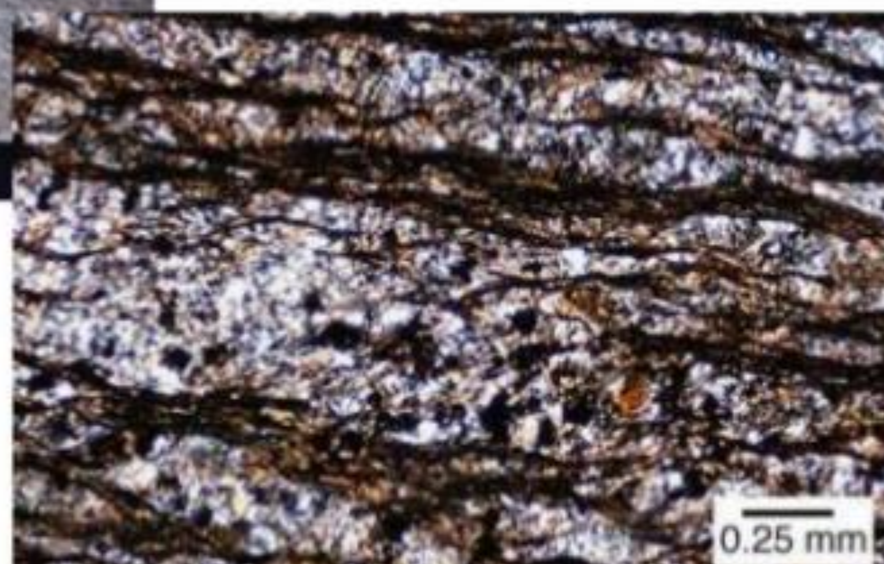
Intersection

- Intersection of two planar features- an "apparent" lineation in that there is no fabric that is linear.

- e.g., intersection between cleavage and planar surface

Crenulations

- Crenulation lineation: Intersection between fold hinges and foliation



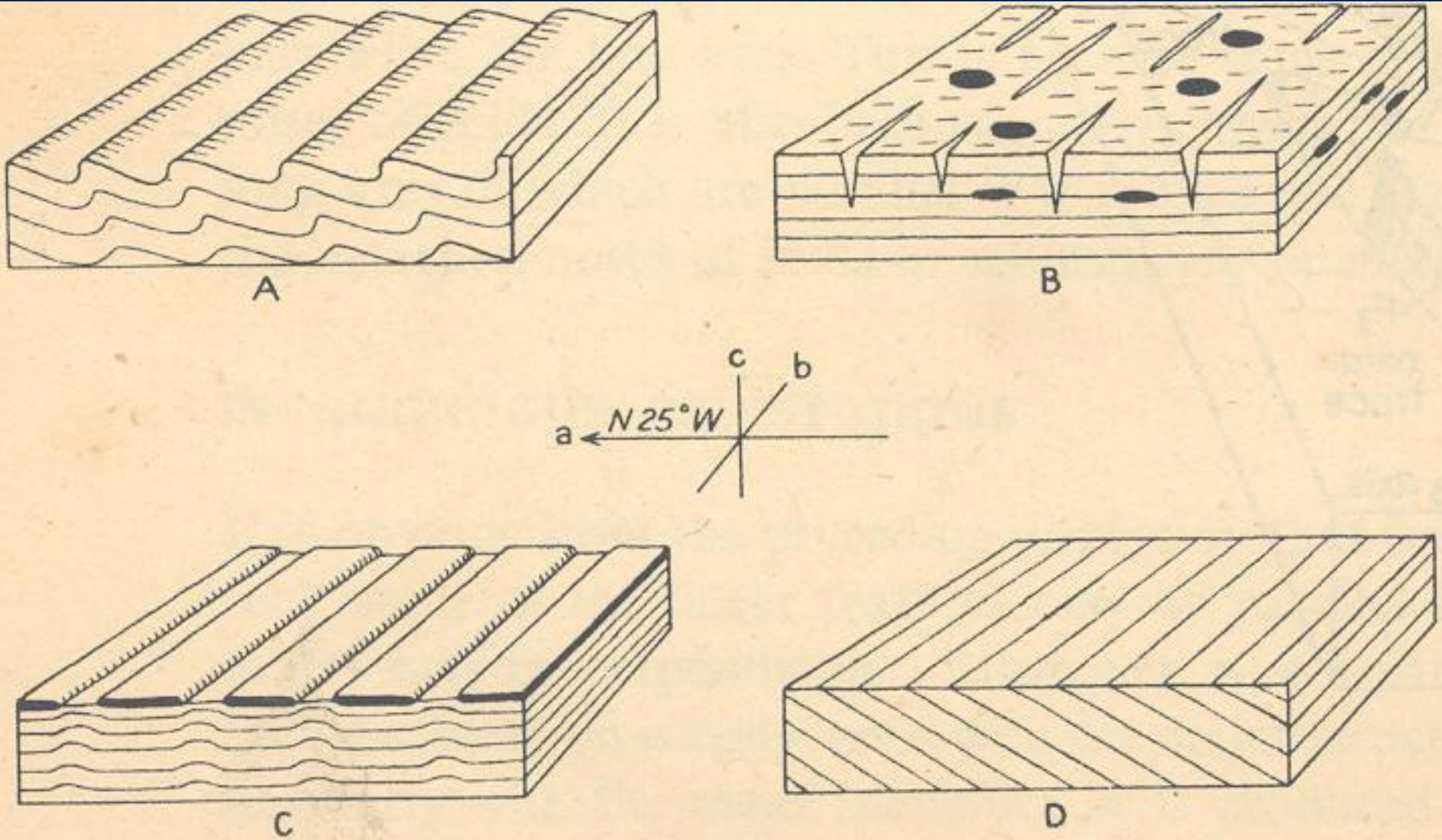


Fig. 19-8. Relation of minor structures to overthrusting in Tintagel area, North Cornwall, England. (A) Drag folds. (B) slickensides shown by short lines on top of block; deformed pillows and amygdules shown in solid black; tension cracks shown by open gashes. (C) Boudinage. (D) Fracture cleavage. (After Gilbert Wilson.[7])

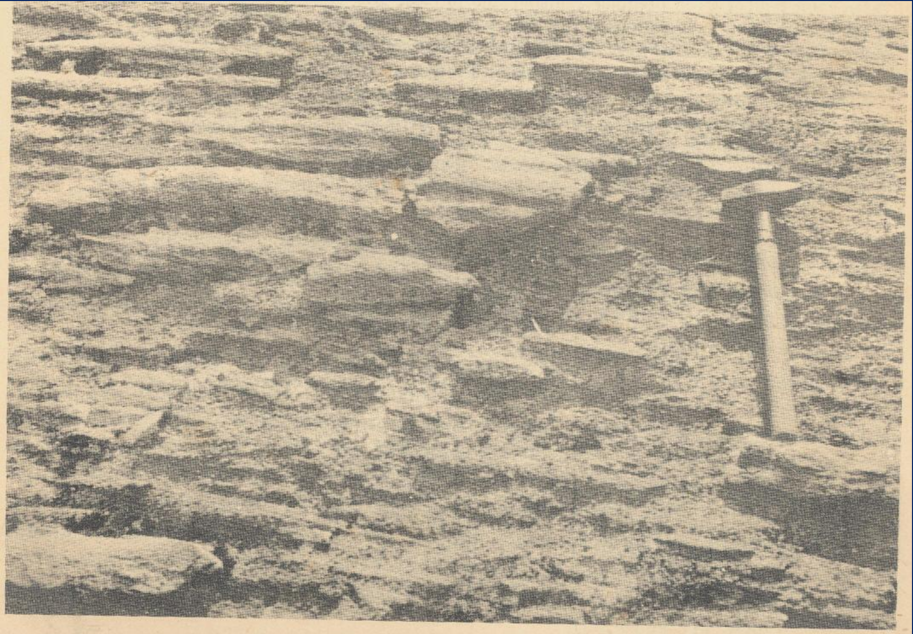


Plate 40. *Stretched conglomerate.* Actually a garnet amphibolite derived from an agglomerate, a clastic rock of volcanic origin, Lower Paleozoic. Överuman (lake), Swedish Lapland. Photo: J. Haller.

Plate 41. *Boudinage.* Light-colored dolomite interstratified with dark shaly limestone. Boudin in center is about 400 feet across. Limestone-dolomite series of Precambrian Eleanore Bay Group. Kejser Franz Joseph Fjord, East Greenland. Photo: Lauge Koch Expedition.

Conformity structures related to Igneous Intrusion

Igneous intrusion due to mobility and forcible injection into the higher level due to squeezing.

<u>**Intrusion**</u>

Batholiths
Stocks
Tongues and apophyses

Surface Character

- Doming up of the surrounding rock
- Encircling nature of foliation
- Mostly discordant relation to the surrounding rock
- Local Conformity
- Fragments of surrounding rocks into the intruded bodies as softs and Xenoliths
- Tongues and Apophyses of intrusive body with surround country rock
- Radial & Concentric fractures / faults.
- Drag effect (anticline and syncline)

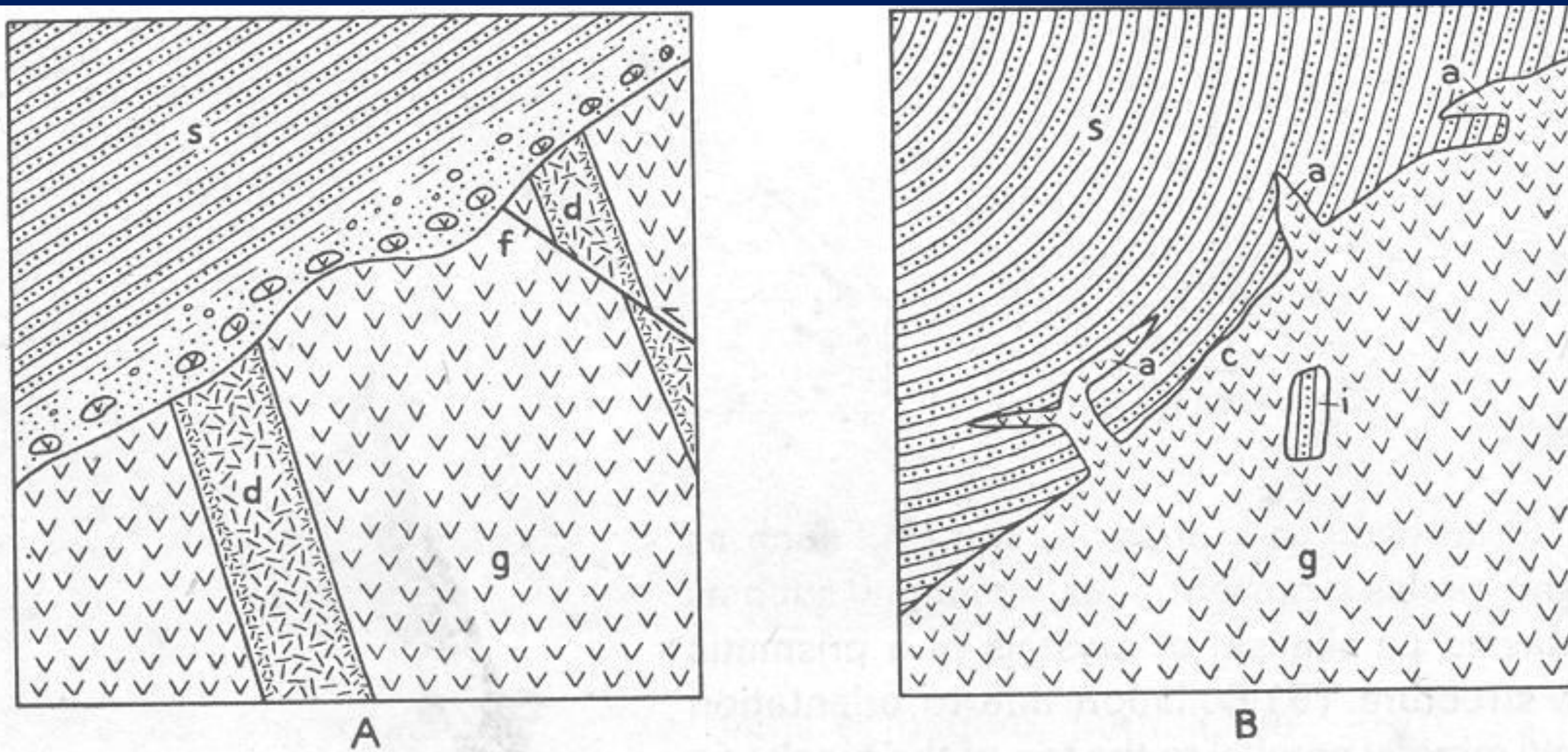


Fig. 16-3. Relative age of pluton and adjacent rocks. *s*, sandstone and shale ; *g*, granite ; *d*, dike of diorite ; *f*, fault ; *i*, inclusion ; *a*, apophyses ; *c*, chilled contact of granite. (A) Unconformity. (B) Intrusive contact.

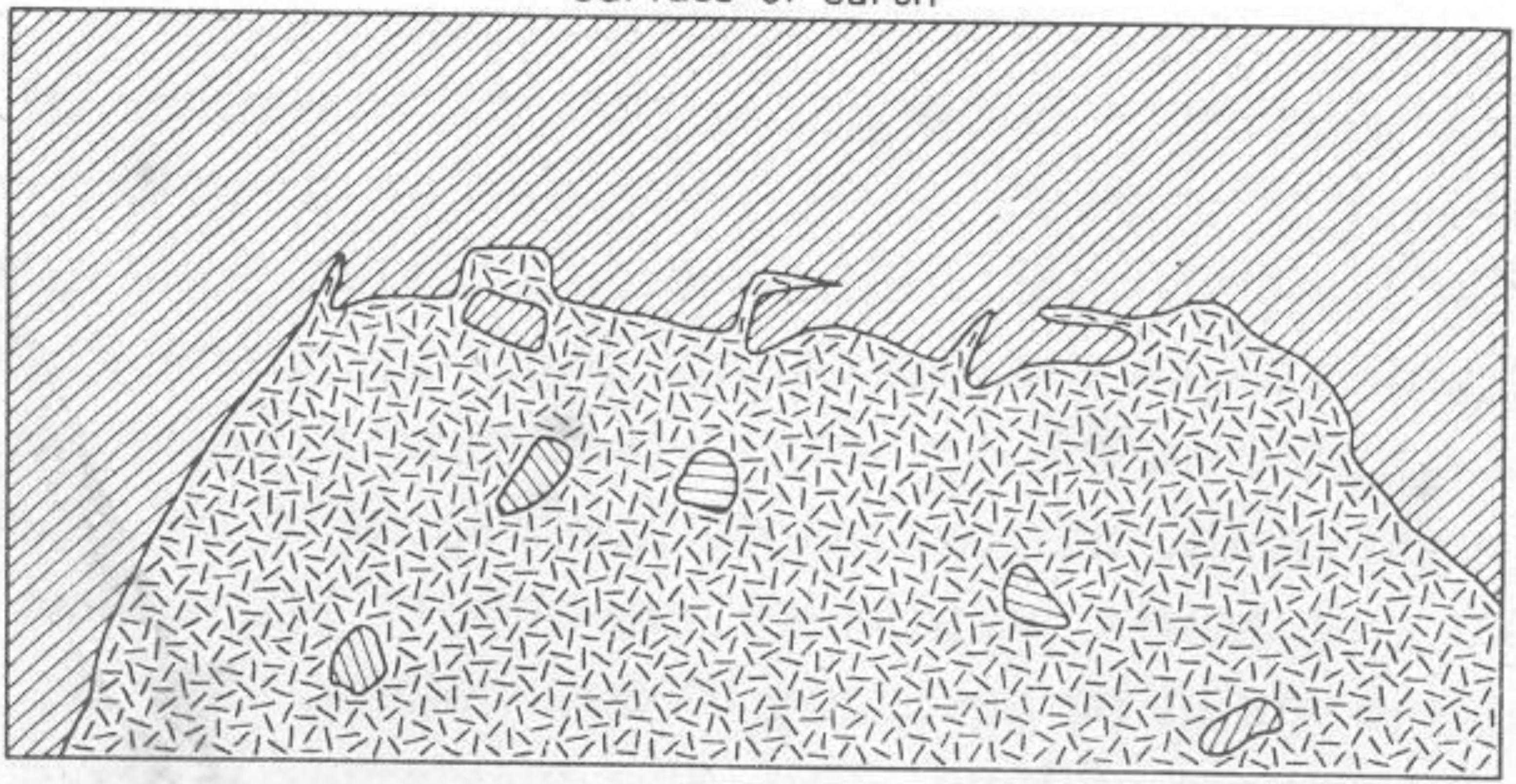


Fig. 17-12. Magmatic stoping. Diagonal lines are older rocks. Diversely oriented dashes are plutonic rock.

Sills - Parallel structures
Dyke - Discordant
Laccoliths - Doming up of the upper layer
Bysmoliths - roof was uplifted along a arcuate / circular fault.
Lopoliths - Intruded into structural bearing
Phacoliths - Intruded into structural Domes.

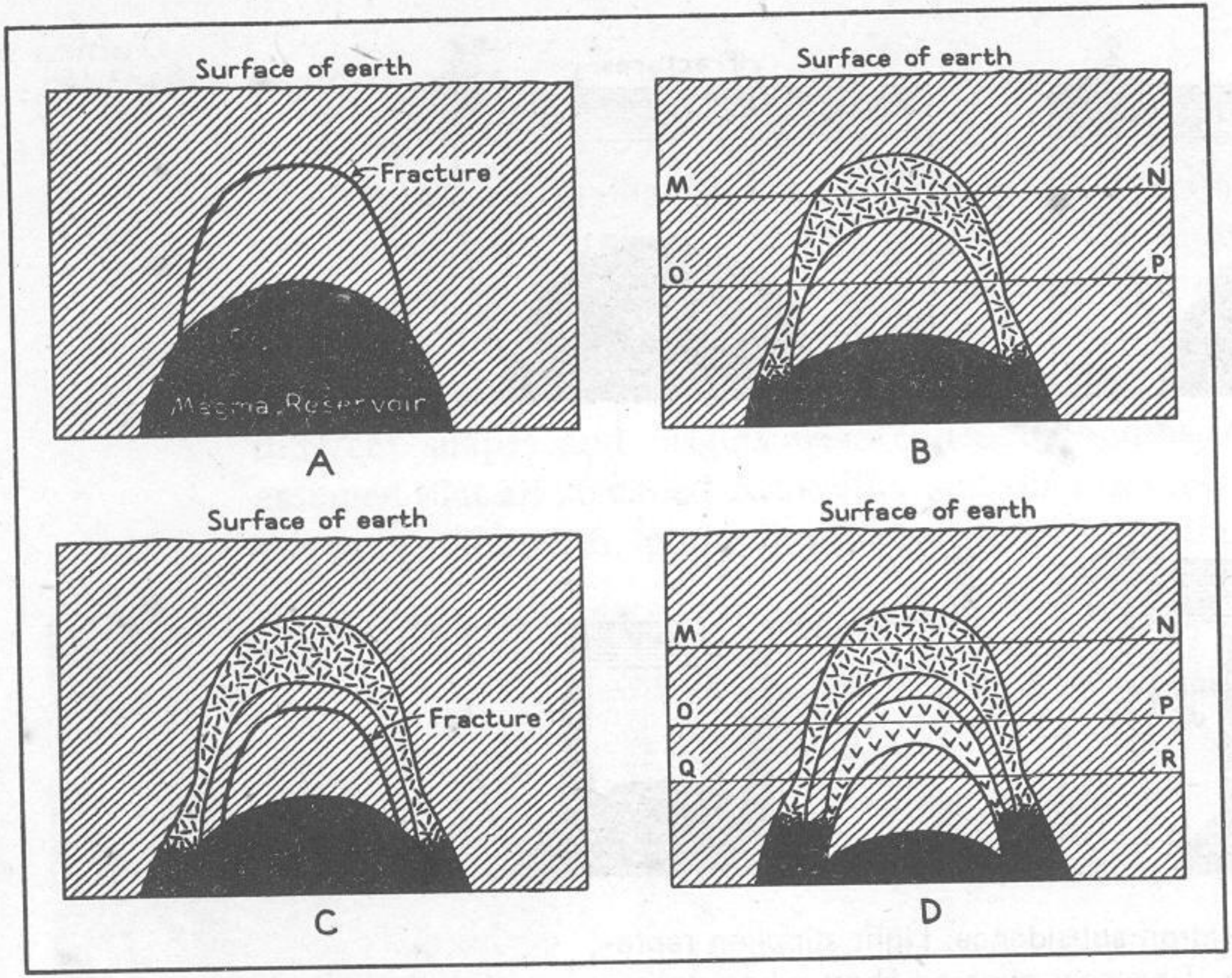


Fig. 16-33. Underground cauldron subsidence. Diagonal lining represents older country rock; diversely oriented short dashes represent one intrusion; checks represent a second intrusion. (A), (B), (C), and (D) represent successive stages of intrusion. *MN*, *OP*, and *QR* are a few of the many levels to which erosion may cut.

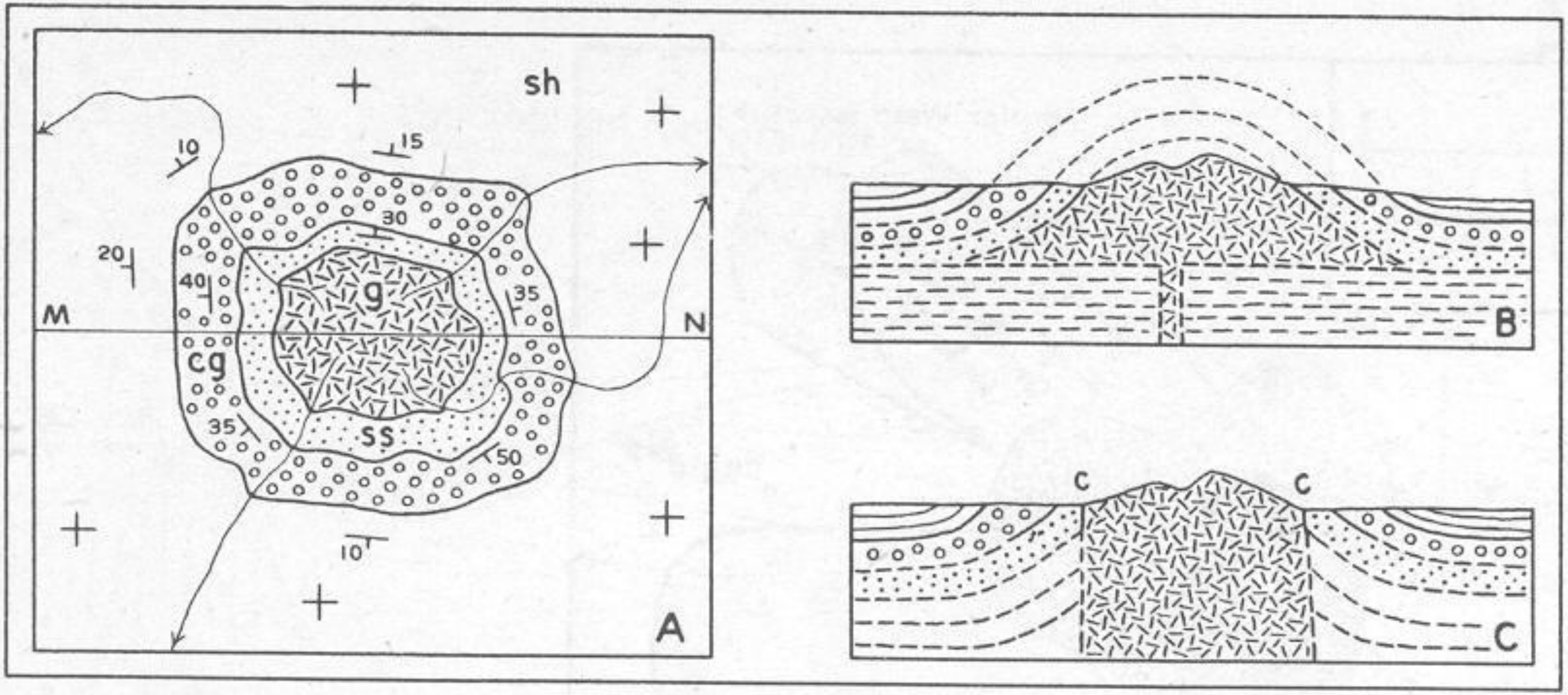


Fig. 16-14. Intrusive rock in the center of domed-up sediments: *g*, granite porphyry; *ss*, sandstone; *cg*, conglomerate; *sh*, shale; *c*, contact of intrusive. The granite porphyry intrudes the sandstone. (A) Geological map. (B) Interpreted as a laccolith. (C) Interpreted as a "bottomless" stock.

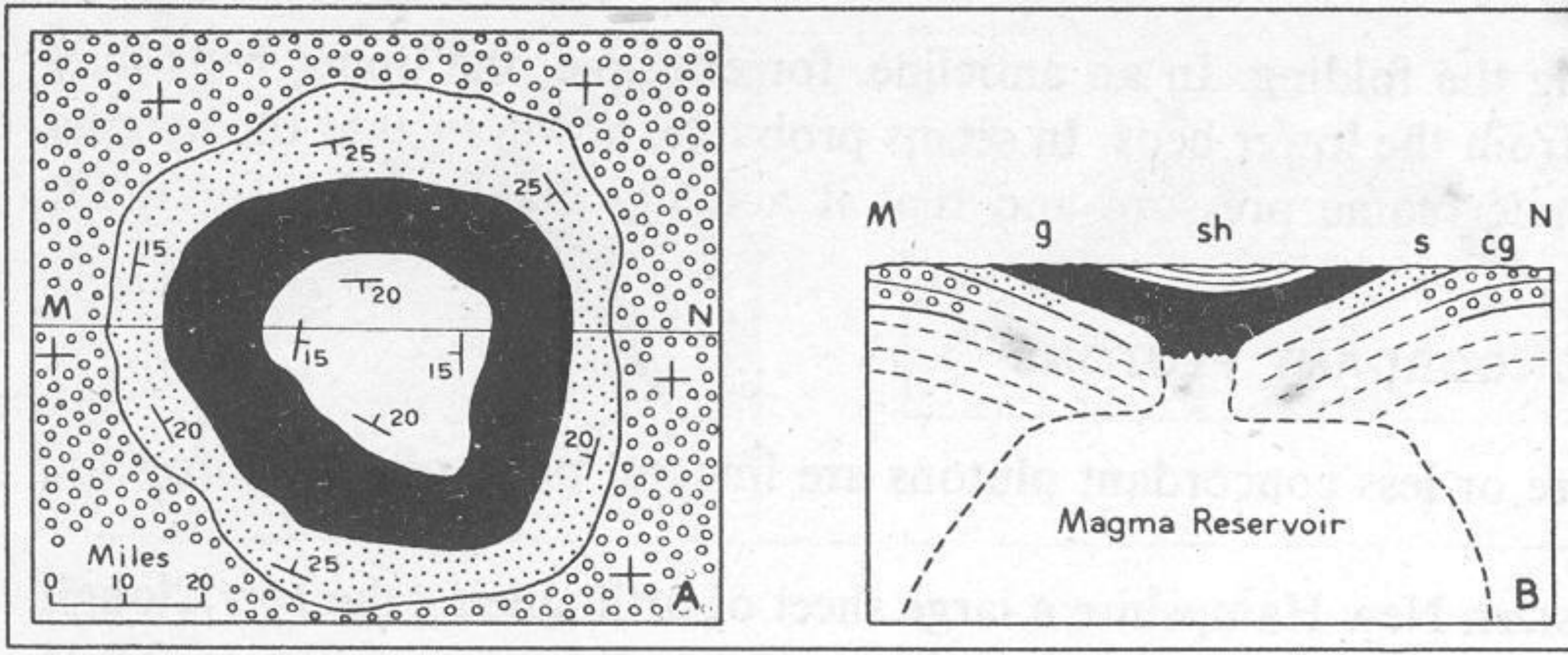


Fig. 16-18. Lopolith : *cg*, conglomerate ; *s*, sandstone ; *sh*, shale ; *g*, gabbro of lopolith. Usual dip-strike symbols ; +, flat strata. (A) Geological map. (B) Structure section.

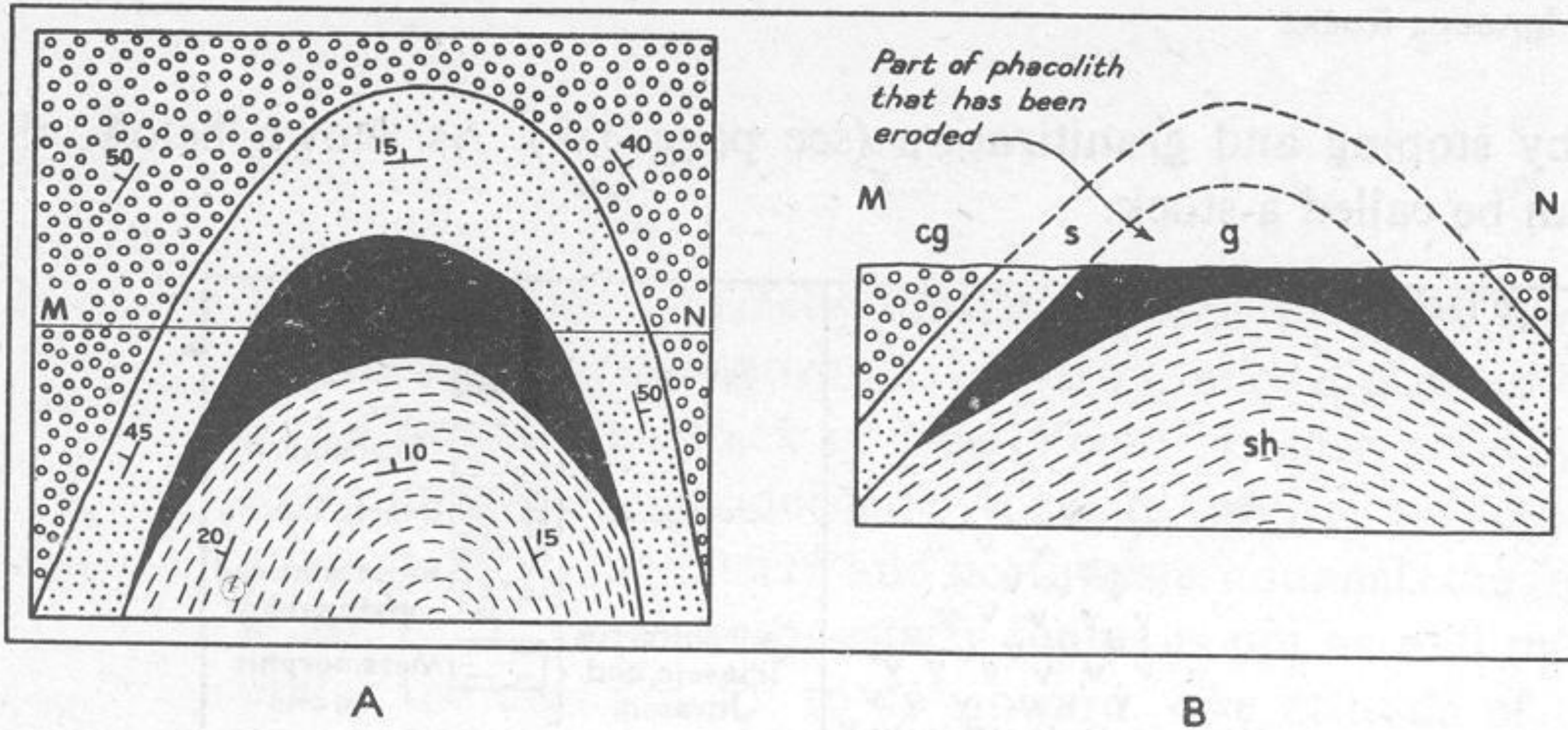


Fig. 16-21. Phacolith : *sh*, shale ; *s*, sandstone ; *cg*, conglomerate ; *g*, granite. (A) Map of granite phacolith in a northerly-plunging anticline. (B) Cross section of the same phacolith.

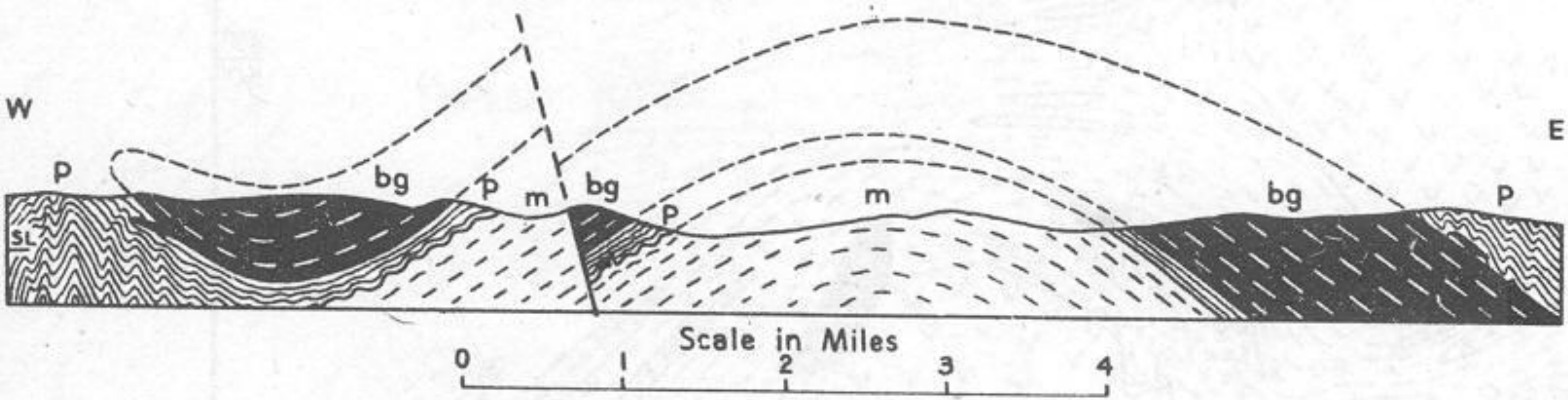


Fig. 16-22. Large concordant pluton, Mascoma quadrangle, New Hampshire. *P*, Paleozoic schists; *m*, granitic rocks of Mascoma group; *bg*, Bethlehem gneiss, which forms a large concordant pluton. (After C. A. Chapman.[14])

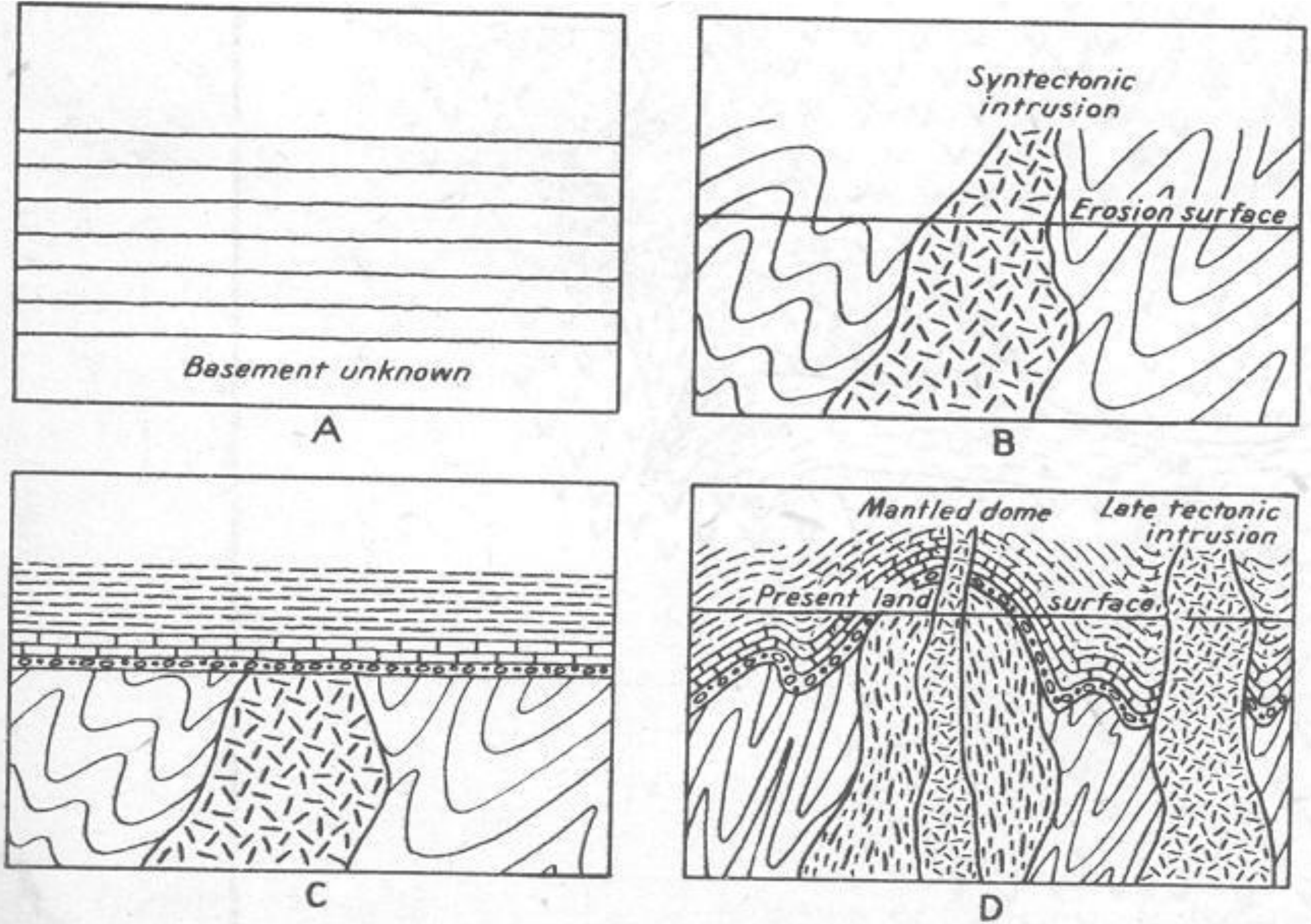


Fig. 16-23. Origin of mantled gneiss domes. (A) First sedimentation. (B) First orogeny. (C) Second sedimentation. (D) Second orogeny. (After P. Eskola.[15])

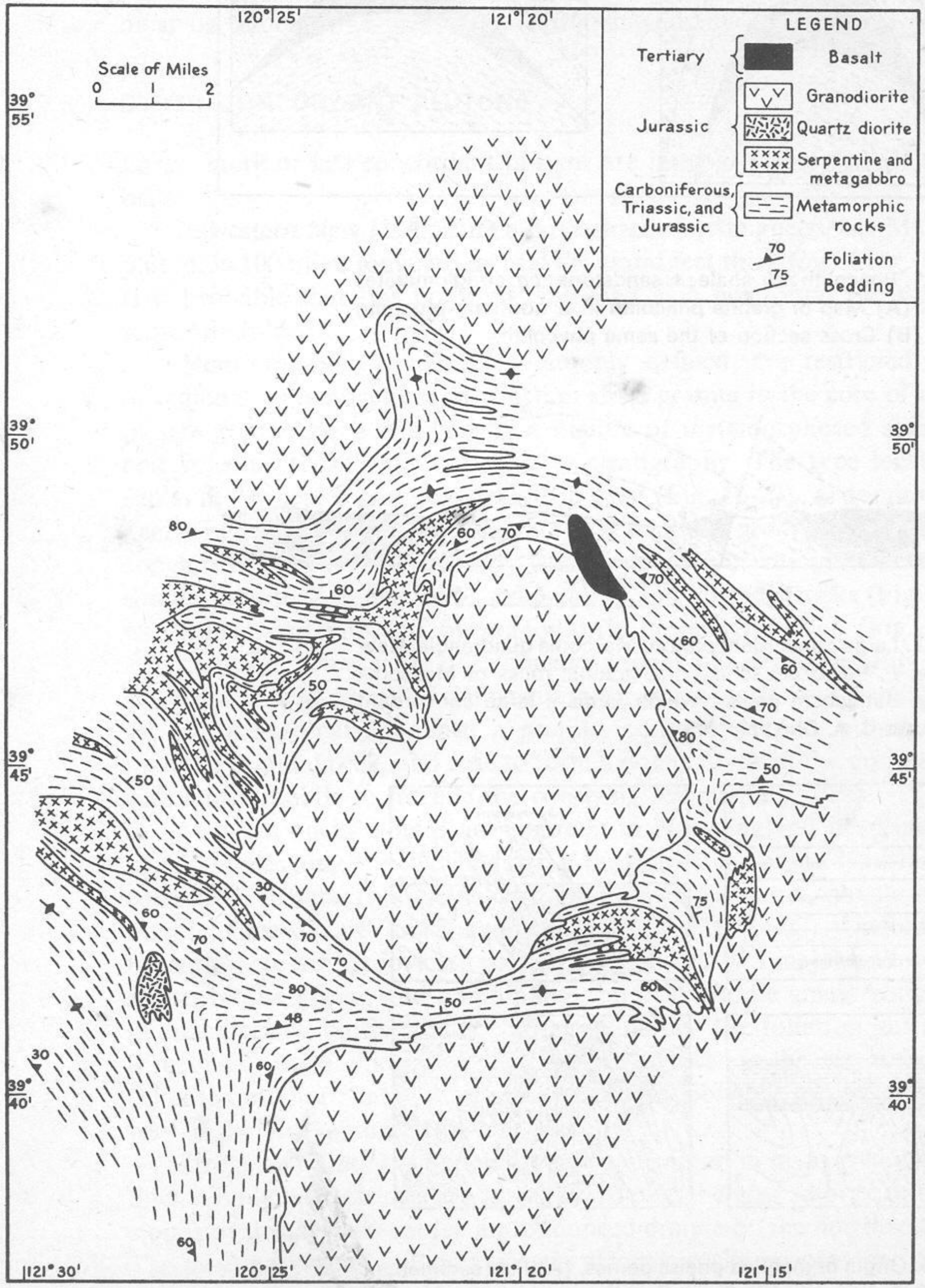


Fig. 16-24. Irregular cylindrical intrusion, composed of granodiorite. Geological map of Merrimac area, California. (After A. Hietanen.[18])

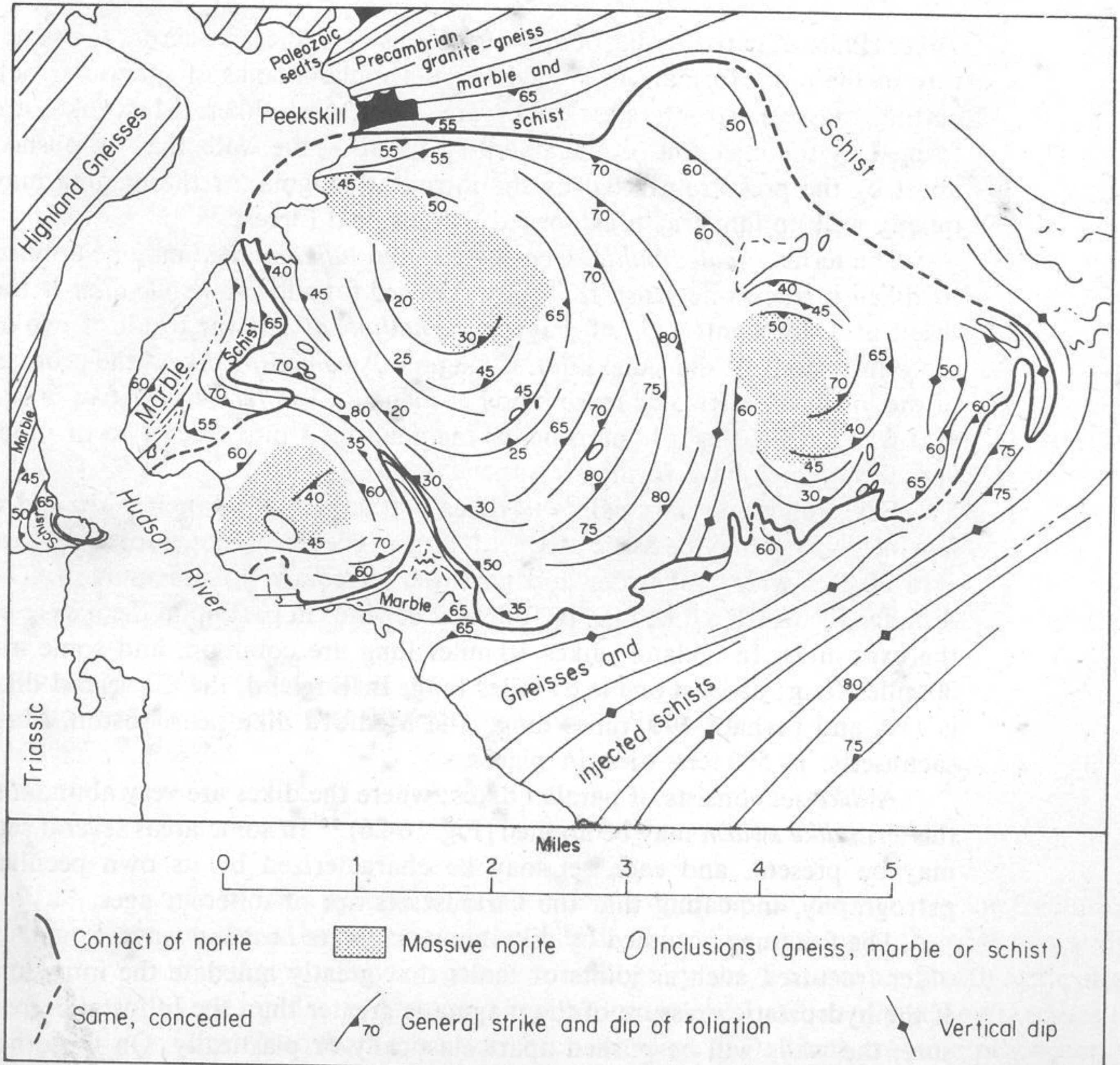


Fig. 16-25. Funnel structure shown by foliation in norite, Cortlandt complex, New York. (After Balk and Shand.[19])

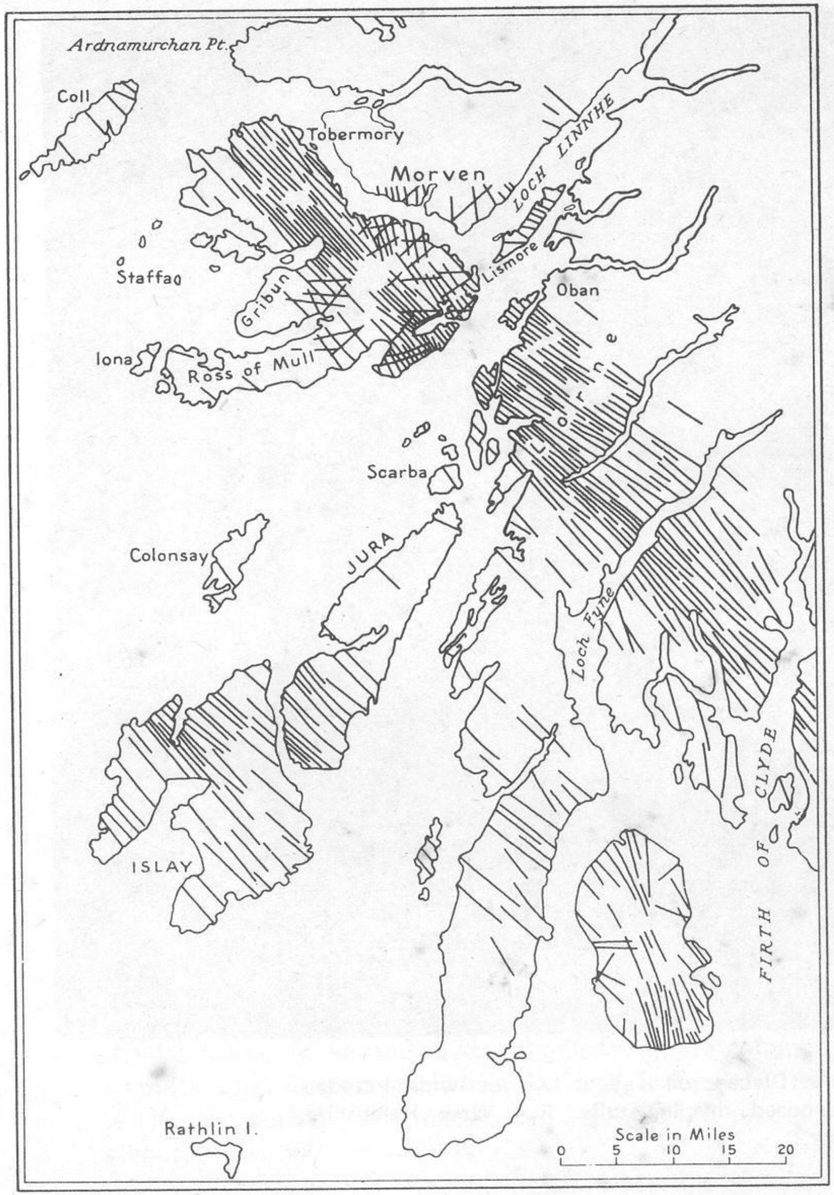


Fig. 16-26. Dike swarm. Tertiary dikes of the Southwest Highlands of Scotland. The map is diagrammatic in the sense that: (a) each line represents 10 to 15 dikes; (b) each dike is only a few feet wide, and not as wide as the scale implies; and (c) individual dikes canot be traced for the long distances that the map implies. (After J. E. Richey,[23] with permission of the Controller of Her Britannic Majesty's Stationery Office.)

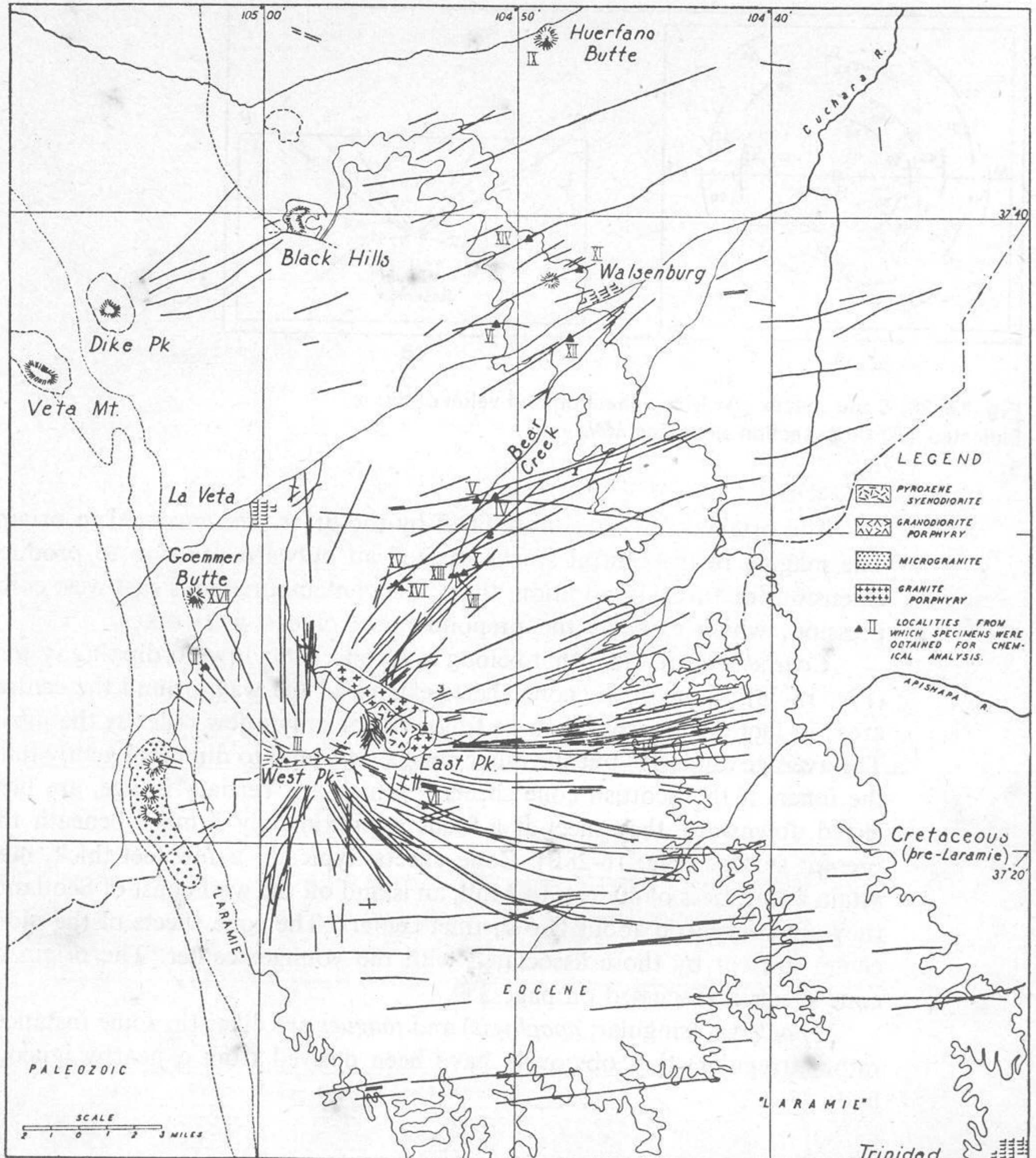


Fig. 16-27. Radiating dikes around Spanish Peaks, Colorado. (After Knopf.[21])

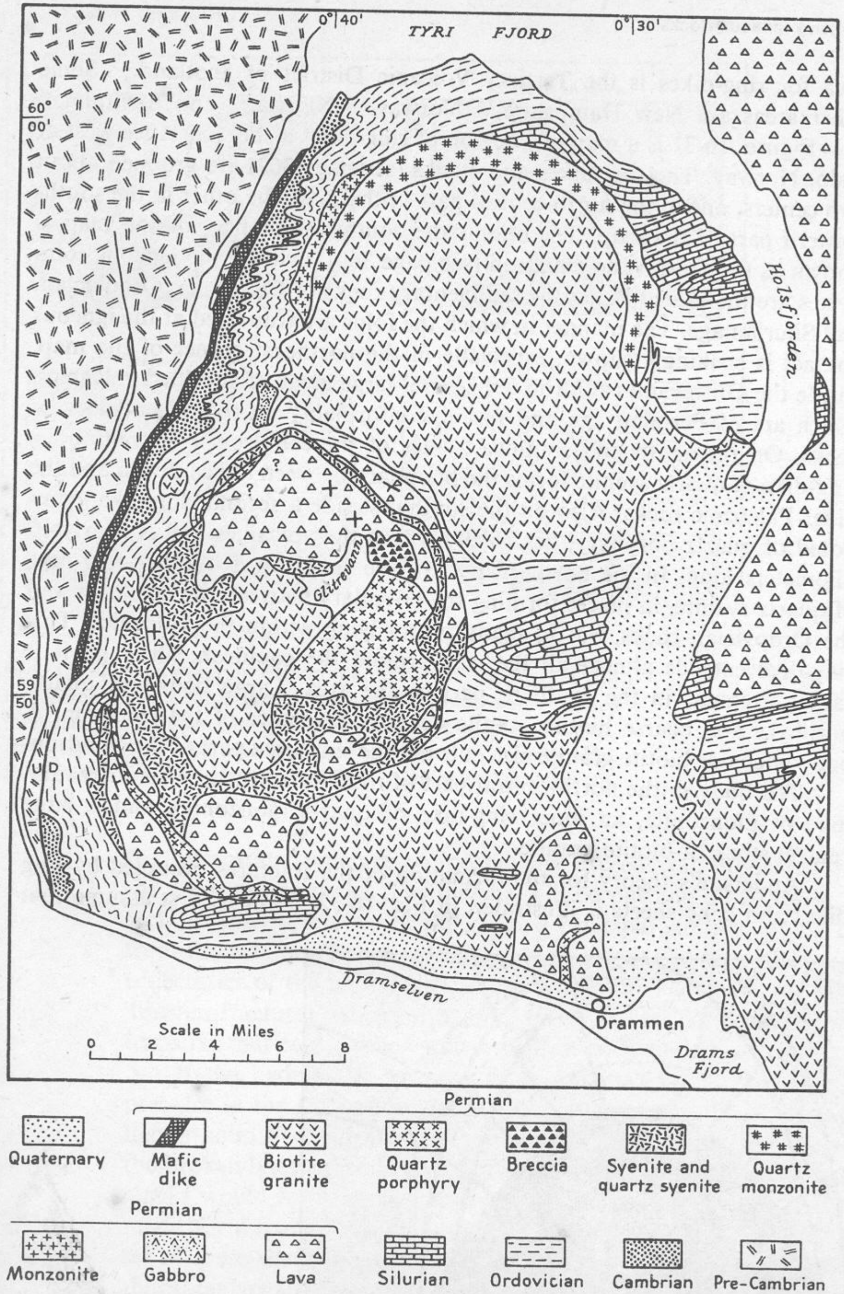


Fig. 16-31. Ring-dikes and stocks. Oslo region, Norway. Longitude is measured west from Oslo. Dip-strike symbols show attitude of volcanic rocks. *D*, downthrown side of gravity fault. (Based on maps by W. C. Brögger, J. Scheltig, and C. Oftedahl.[26])

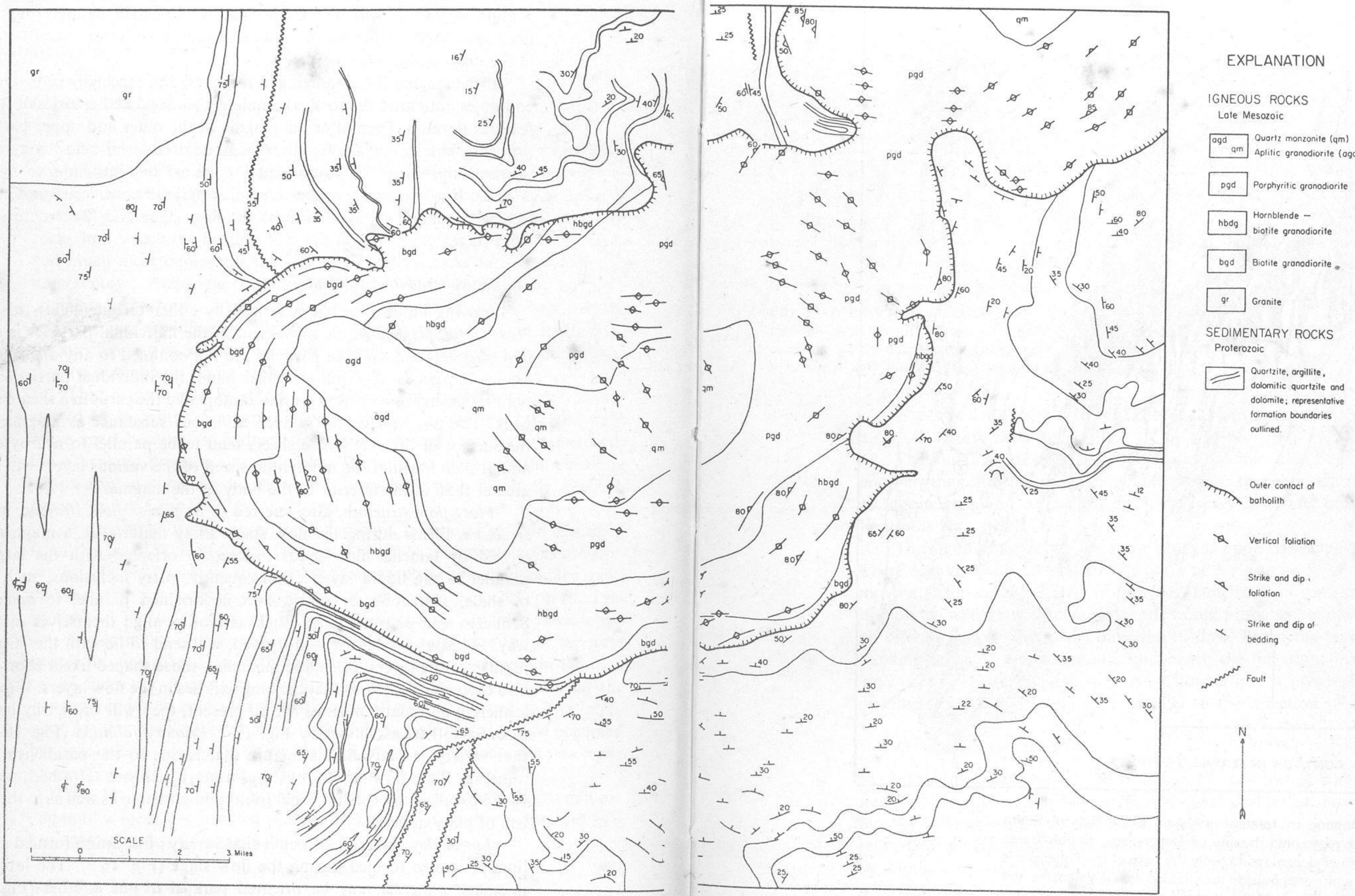


Fig. 17-5. Forceful injection. Mesozonal batholith of Mesozoic age. White creek batholith, British Columbia. (After Buddington.[4])

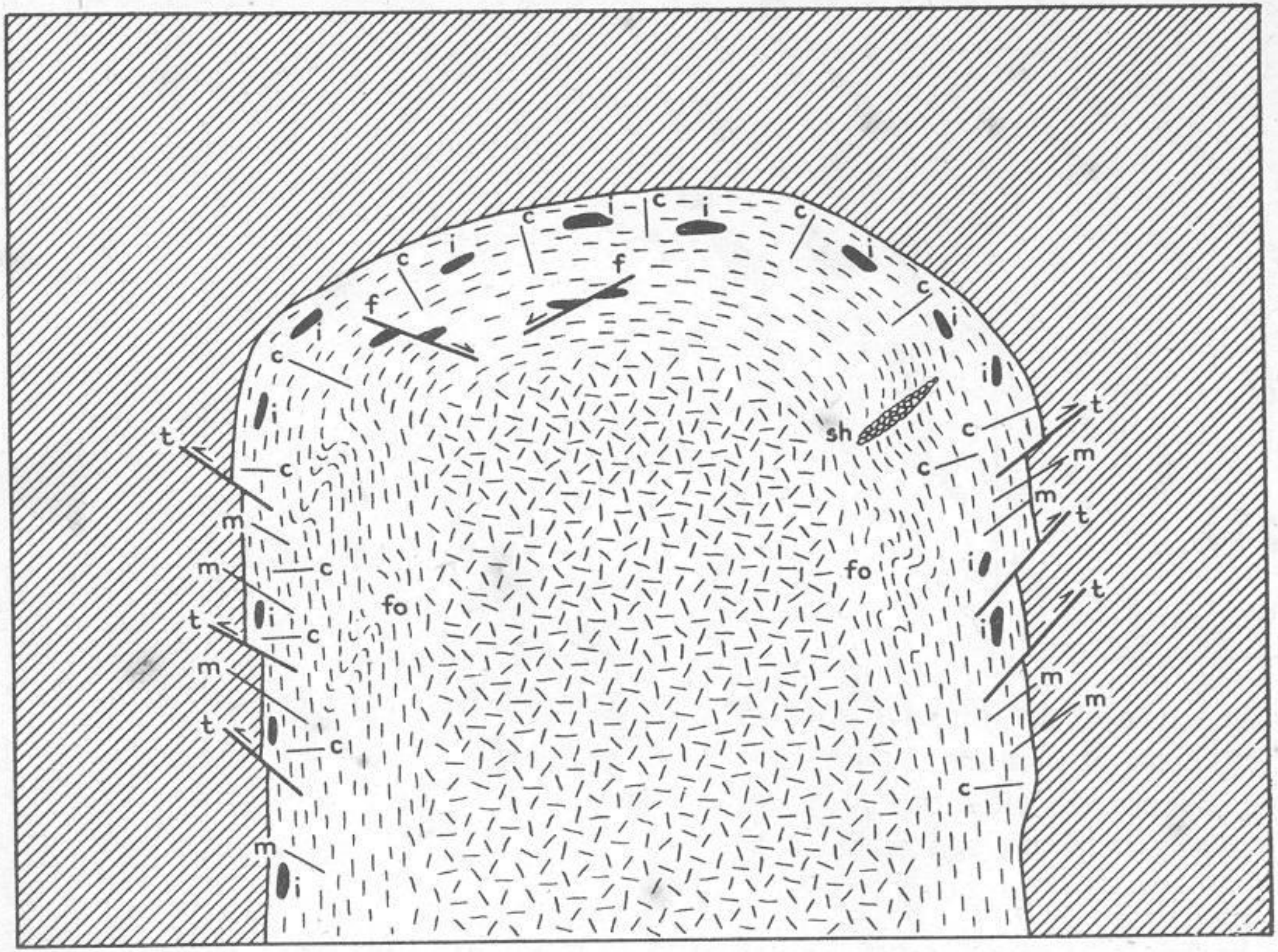


Fig. 17-8. Cross section of a hypothetical pluton. Section is parallel to strike of the linear flow structure. Short dashes are platy minerals; *i*, inclusion; *fo*, flexure; *sh*, shear filled with pegmatite or coarse granite; *c*, cross joint; *m*, marginal fissure; *t*, marginal thrust; *f*, flat-lying normal fault.

DIAPIRS

- A diapir or piecement structure results from the upward intrusion of a more light material into/through overlying strata.
- As ancient seas evaporated they left salt deposits that were buried by sediment.
- The salt deposits were less dense than overlying rock the buoyant mass of salt ballooned upward, intruding into the overlying rocks through weak spots, the intruding "salt bubble" is called a salt diaper.

DIAPIRS

- The flow may be produced by gravitational forces (heavy rocks causing underlying lighter rocks to rise), tectonic forces (mobile rocks being squeezed through less mobile rocks by lateral stress), or a combination of both. Diapirs may take the shape of domes, waves, mushrooms, teardrops, or dikes

Diapir - Structure
Diapiric - Force
Diapirism - Process

All derived from Greek work – "DIAPERIGN" – Meaning "To Pierce through"

- **Concept was originally confined to injection of Sedimentary strata**
- **The rocks commonly involved are evaporites (rock salt, gypsum, anhydrite) Shale and Serpentine**
- **Concept gradually expended to include all type of piercement including Magmatic Injection**

Salt Diapir - Due to density contrast and Buoyancy

Igneous Diapir - Mostly due to emplacement by horizontal forces

Origin

- Intrusion of solid halite into surrounding sediments
- Difference in density between salt and the overlying sediments
- Rock salt has got uniform density (2.2 g/cm2) invariable of its depth (but changes with amount of anhydrite and temperate)
- But sediments (average density 1.9 to 2.2 g/cm2 upto 2000 feet)
- But below 2000 feet sediment change its density progressively to a value of 2.46 at 20,000 feet.
- Under this unstable gravitational condition of density variation at depth below a 2000 feet or so the salt tends to more upward (similar to lighter fluid moves upward through heavier fluid)
- This movements initiated where there is a minor anticlinal flexure exist on top of the original salt bed.

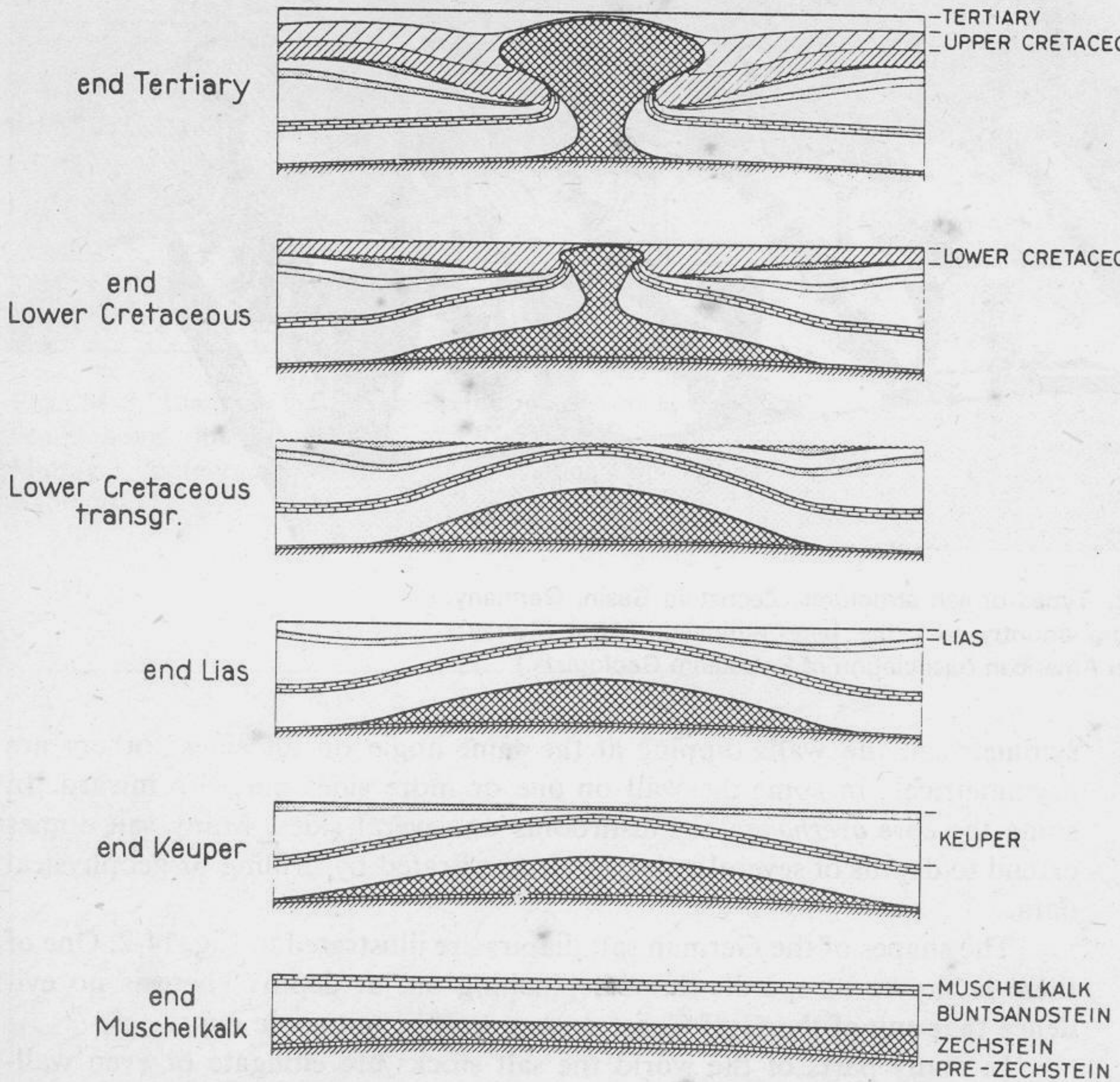


Fig. 14-1. Hypothetical development of a salt stock in northwest Germany. (After Sannemann;[3] permission American Association of Petroleum Geologists.)

Salt Dome / Evaporite Diapir

Chiefly consist of Halite (sometime anhydrite and gypsum)

Shape

- **Circular or elongate in plan with one to few miles**
- **Walls dips steeply outward**
- **Top may be flat or domical**
- **Some are symmetrical with well dipping at same angle**
- **Some walls may dip inward and some are over hanging or mushrooms**

Internal Structures

- Vertical walls
- Ceilings show isoclinal, attenuated, refolded, faulted folds with vertical plunge
- All the above folds are due to flowage
- Salt moved upward as lobes and spins a series of differential movements so the complex flow folds are develops.

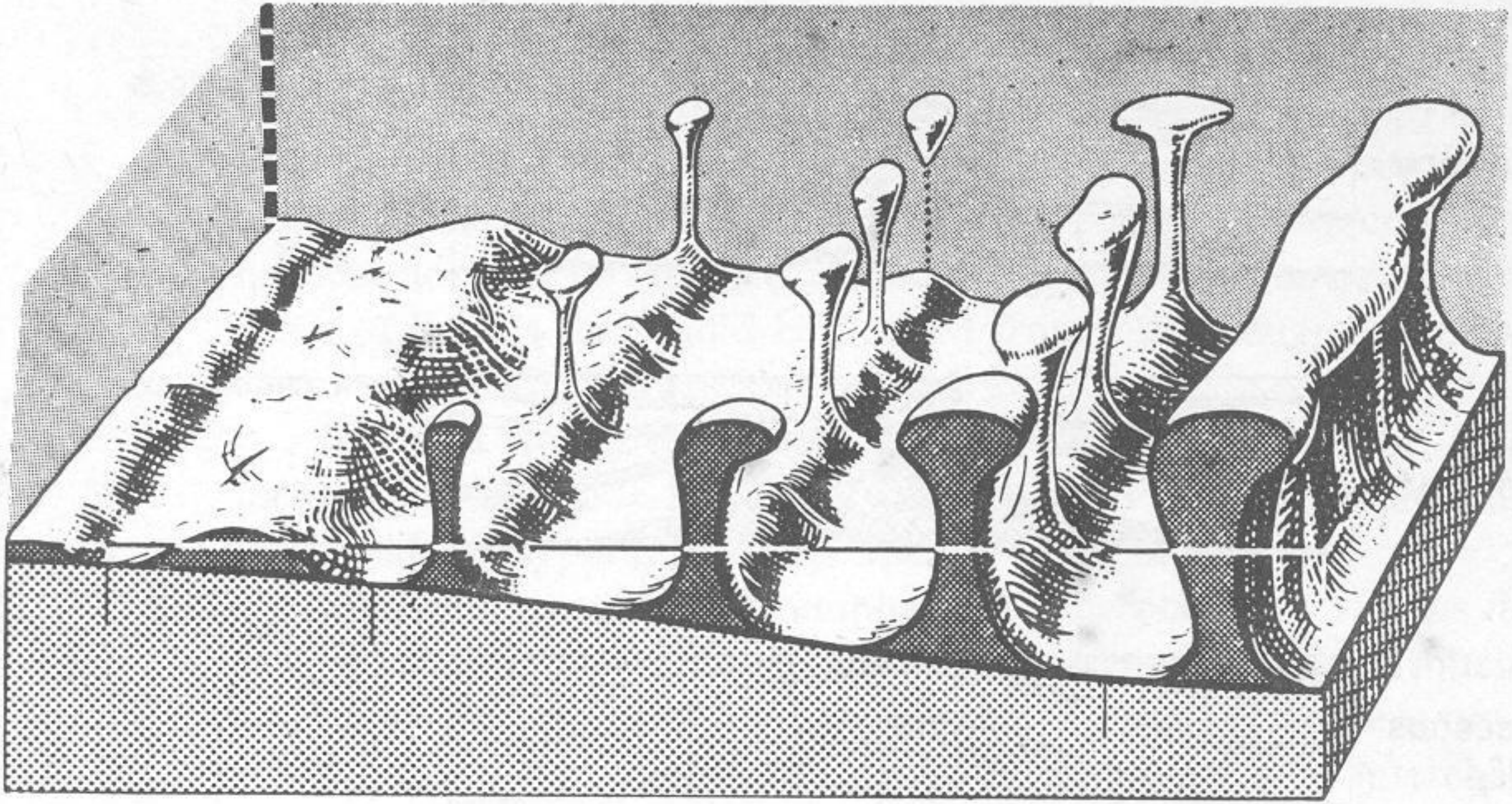


Fig. 14-2. Types of salt structures, Zechstein Basin, Germany. Surrounding country rock has been removed. (After Murray;[1] permission American Association of Petroleum Geologists.)

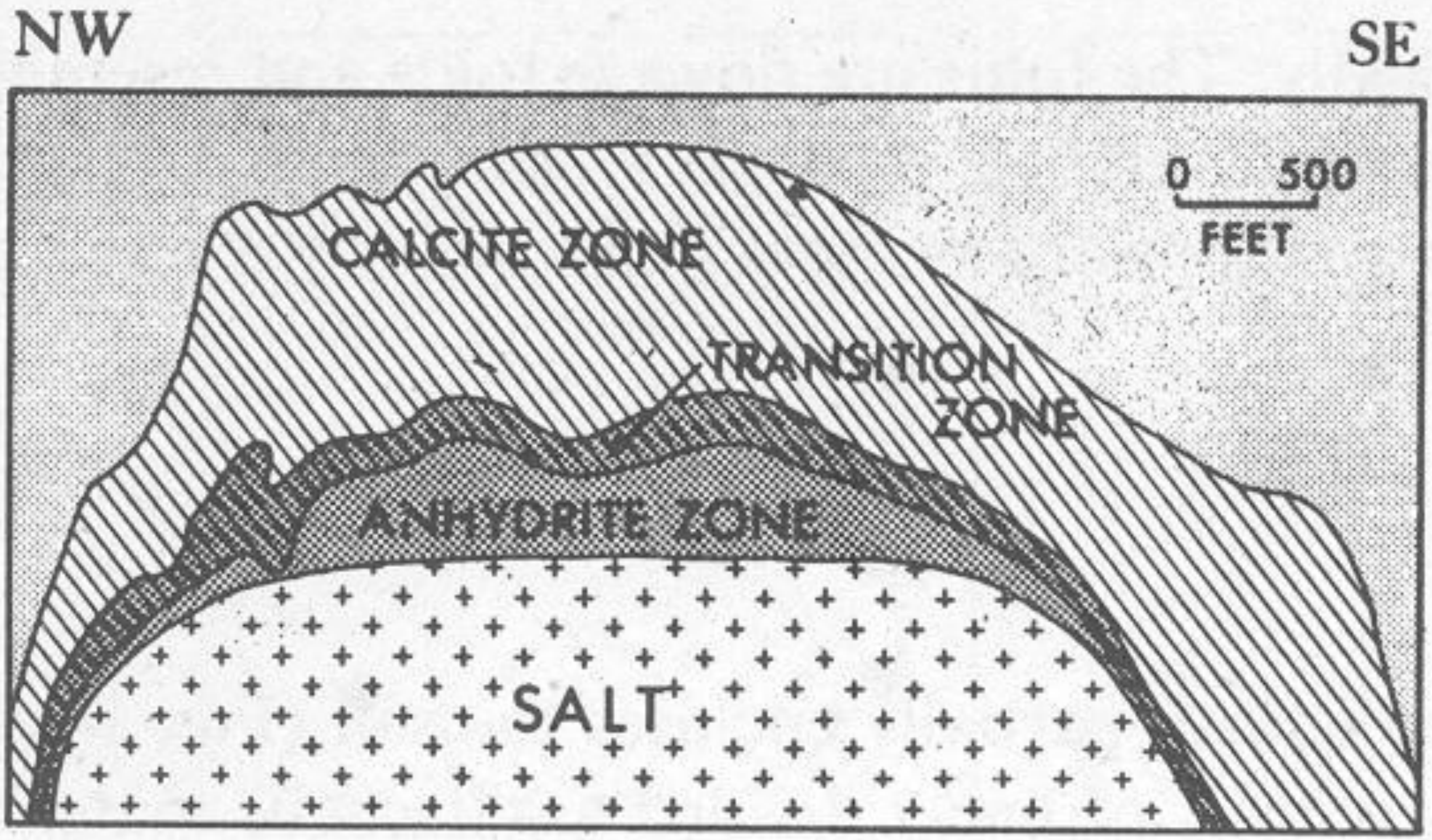


Fig. 14-3. Diagrammatic cross section of cap rock, Jefferson Island dome, Iberia and Vermilion Parishes, Louisiana. (After Murray;[1] permission American Association of Petroleum Geologists.)

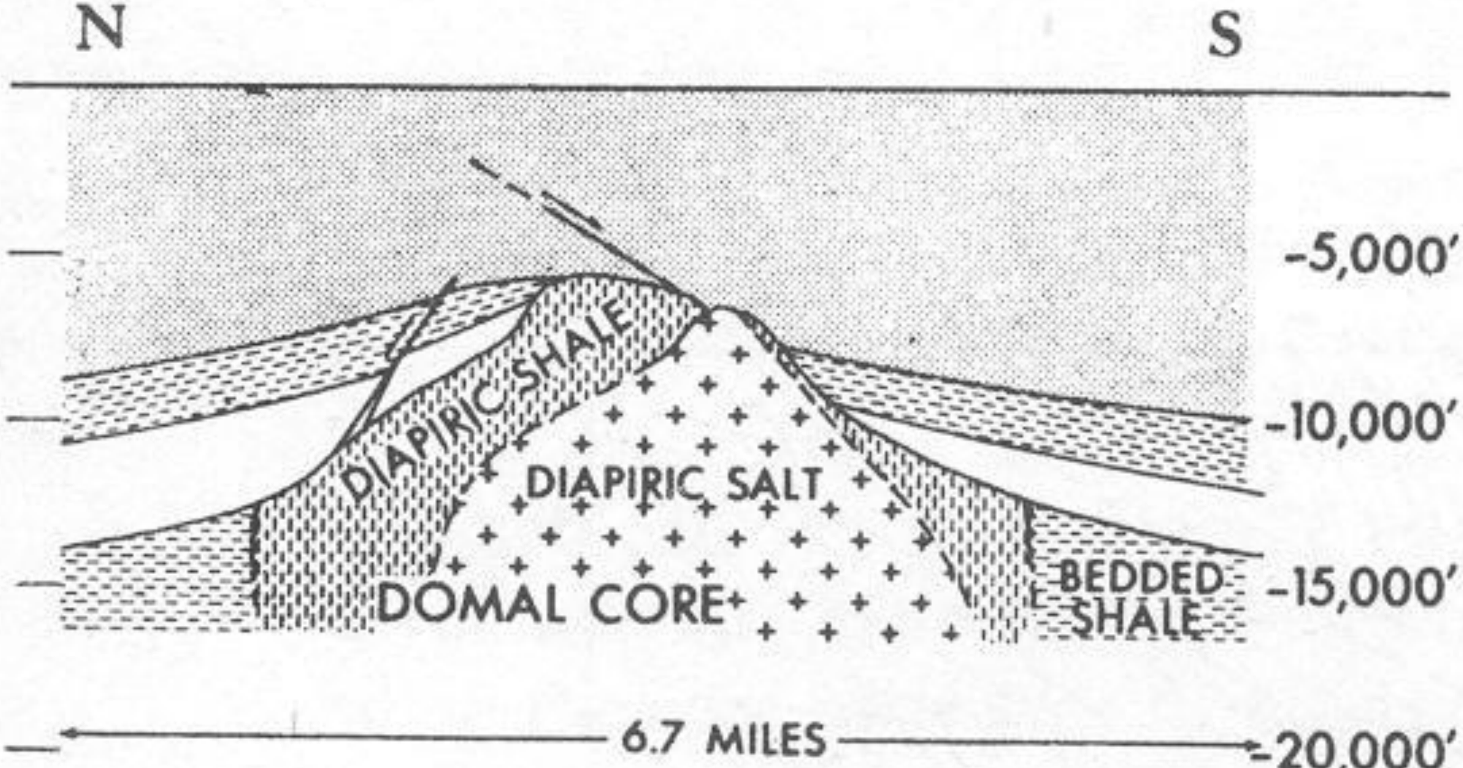


Fig. 14-5. Diapiric shale associated with a salt dome. North-south cross section of Valentine dome, Louisiana. (After Murray;[1] permission American Association of Petroleum Geologists.)

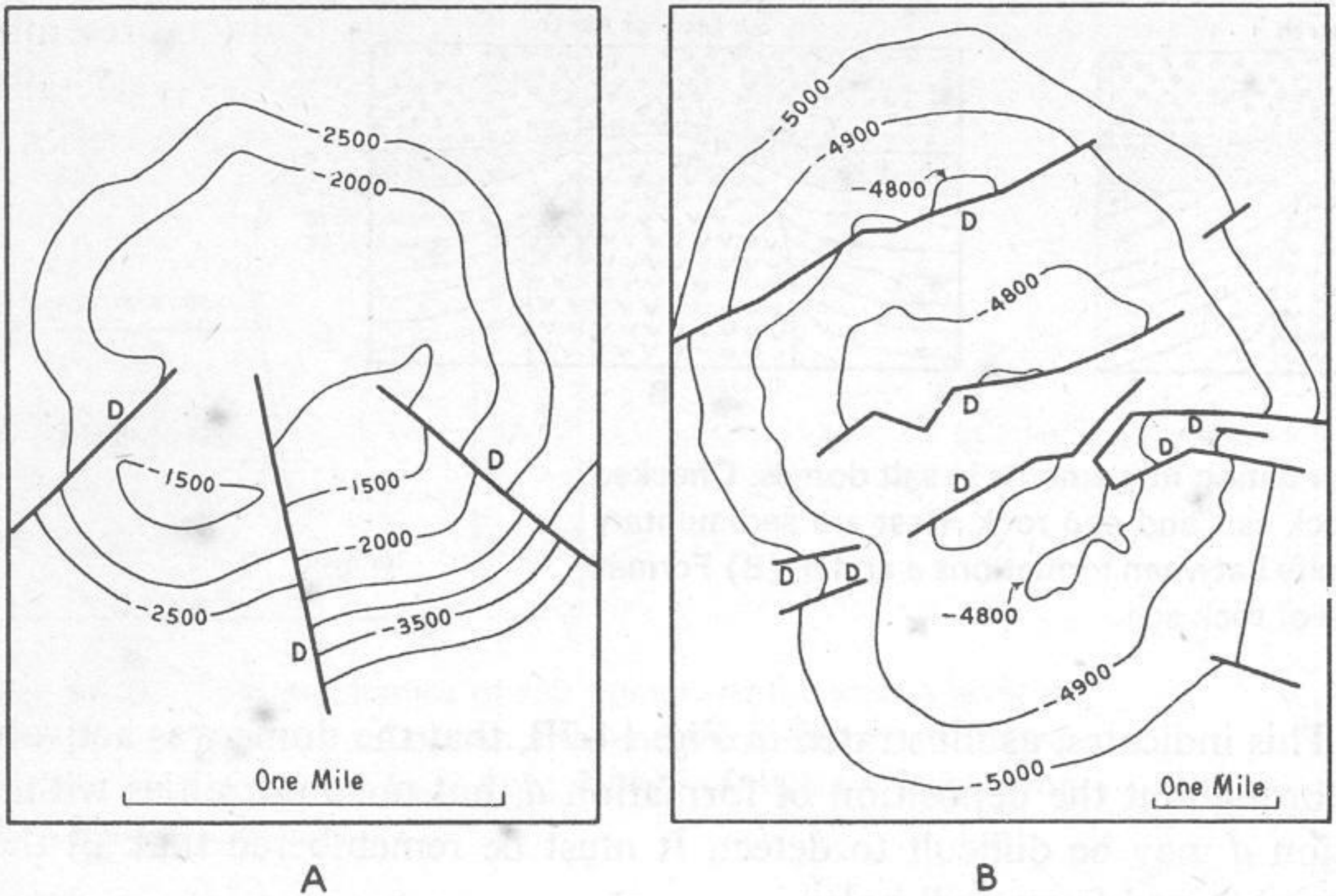


Fig. 14-6. Faulting on salt domes. Heavy black lines are faults; *D* is the downthrown side. (A) Clay Creek salt dome, Texas; structure contours on top of cap rock; contour interval 500 feet. (After W. B. Ferguson and J. W. Minton.) (B) Conroe oil field, Texas; structure contours on top of main Conroe sand; contour interval 100 feet. (After F. W. Michaux, Jr., and E. O. Buck. Data from *Bulletin American Association Petroleum Geologists.*)

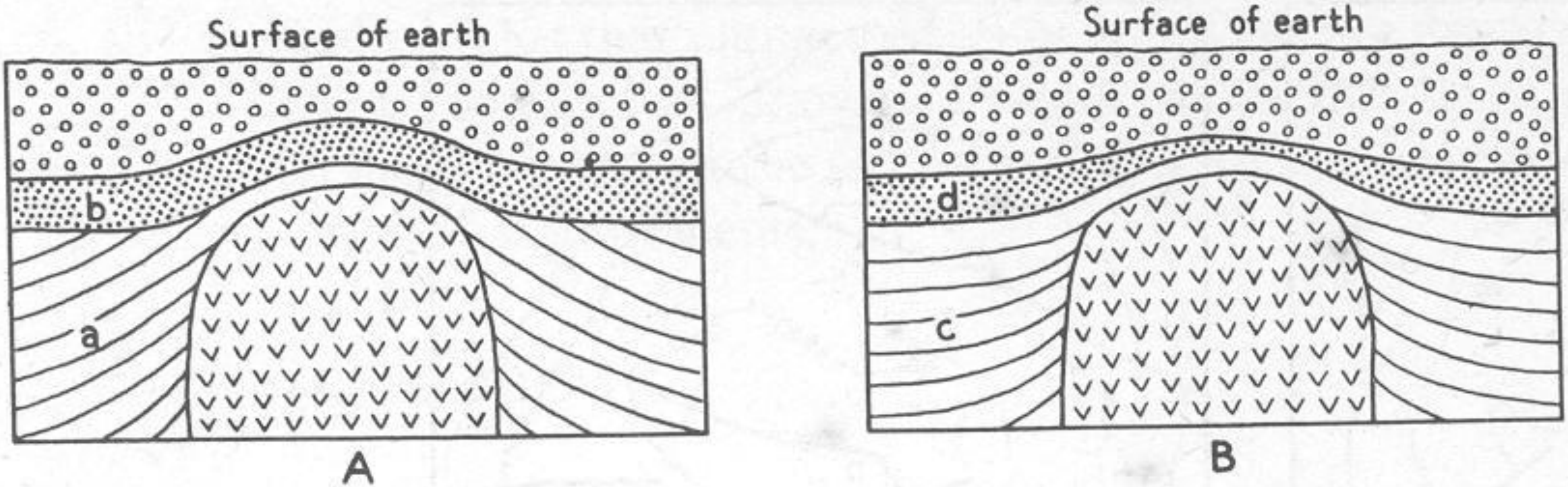


Fig. 14-7. Criteria for dating movements in salt domes. Checked area is the core of rock salt and cap rock. Rest are sedimentary rocks. (A) Unconformity between formations *a* and *b*. (B) Formation *d* thins over core of rock salt.

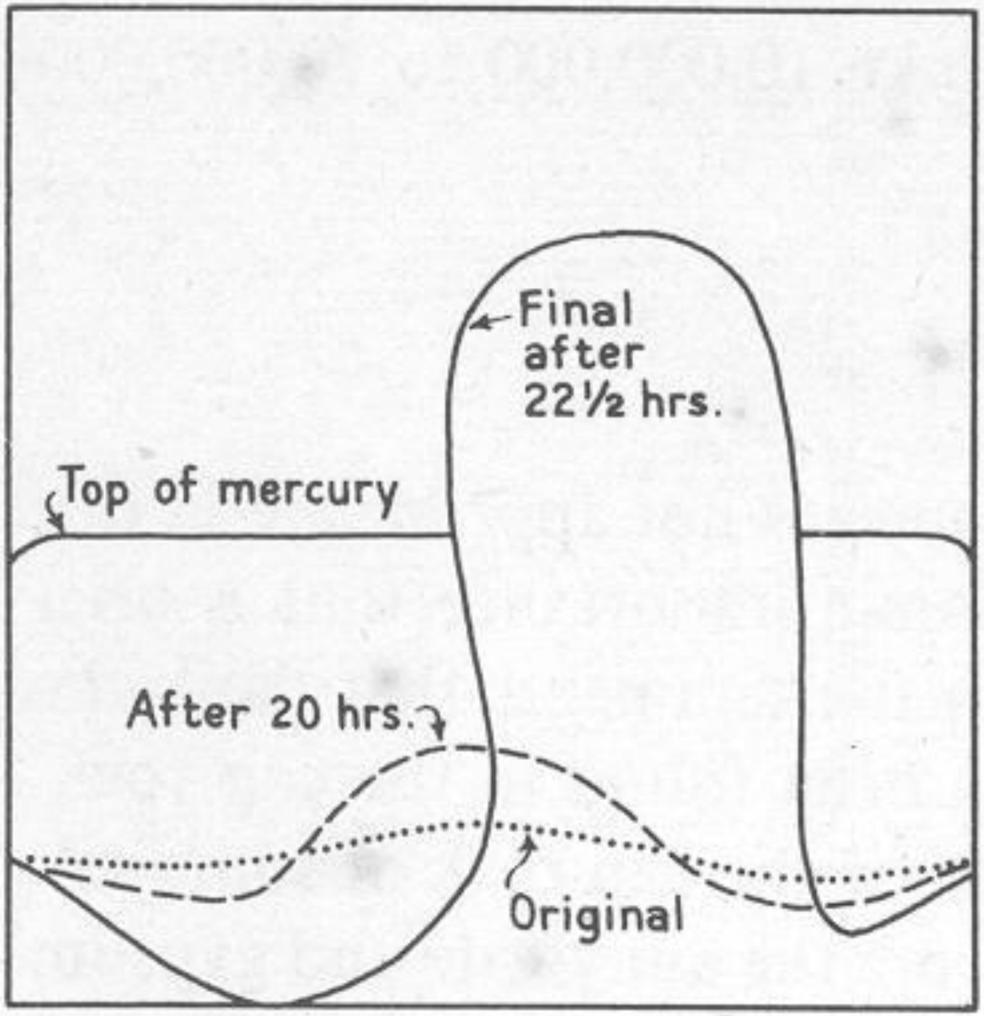


Fig. 14-8. Fluid mechanics of salt domes. At the start a layer of paraffin lies beneath the dotted line, and the mercury lies above. (After L. L. Nettleton.[8] Data from *Bulletin American Association Petroleum Geologists.*)

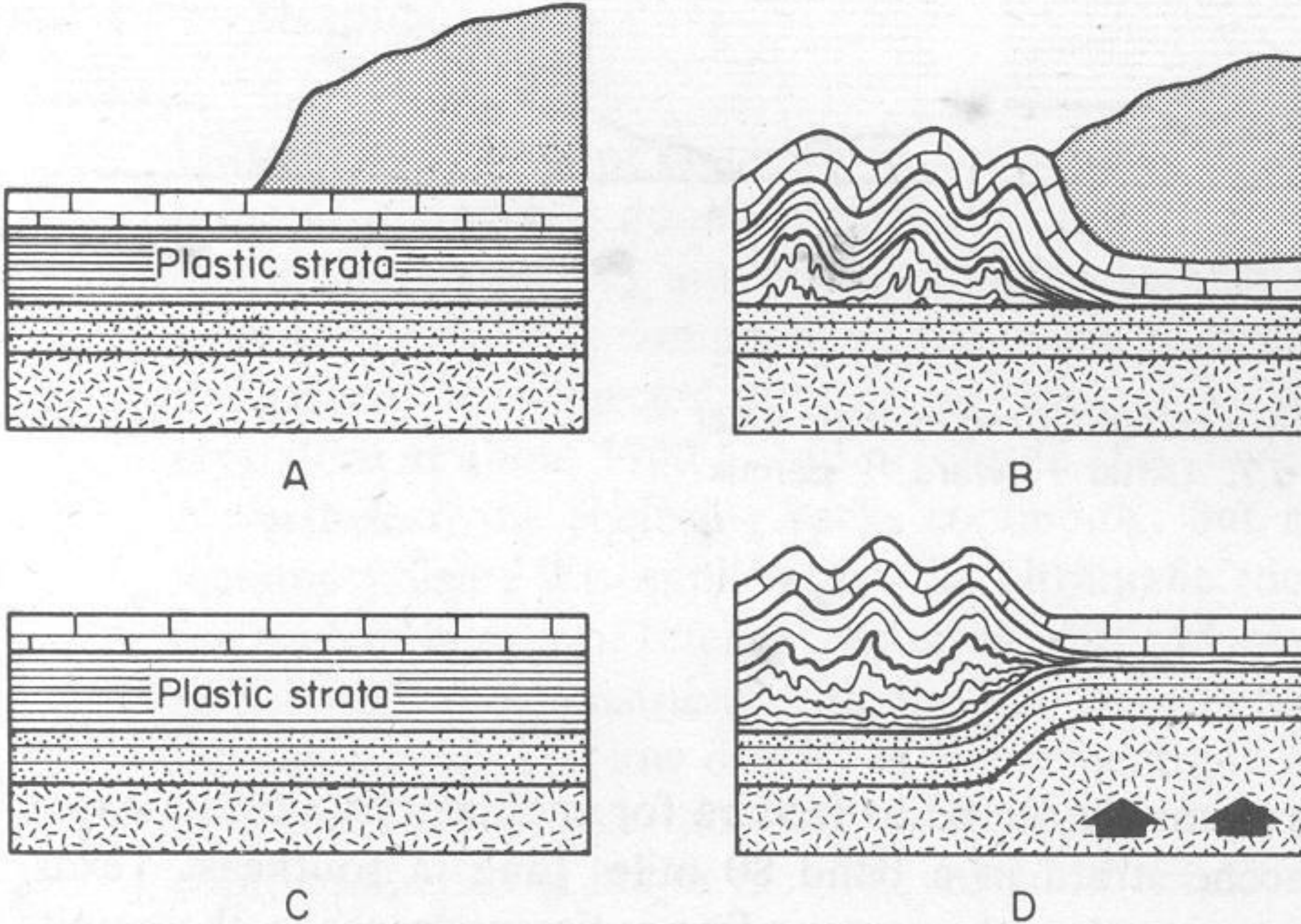


Fig. 14-11. Injection folding. (After Beloussov.)

SHEAR ZONE

- **Shear zone is** a zone composed of rocks that are more highly strained than rocks adjacent to the zone.
- The **intensity** which rock can be deformed in shear zones is astonishing (e.g. granites that seems schist).
- Shear zone can be **formed under three main conditions:**

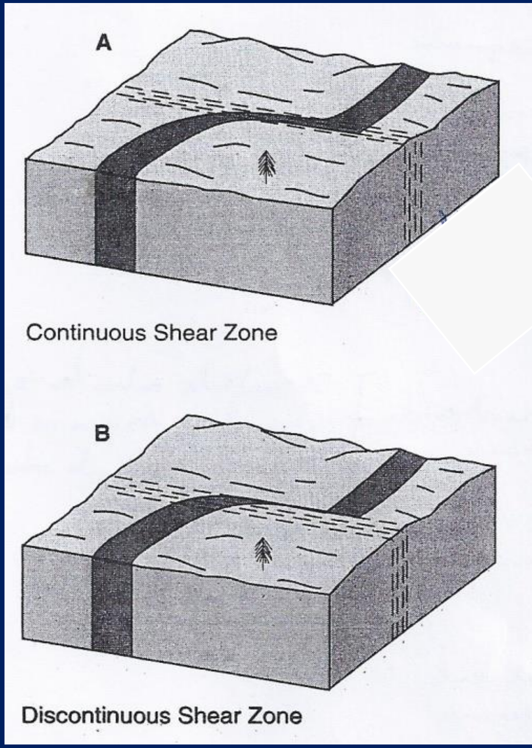

Fault in brittle conditions.Vadiello (Huesca).

- **Brittle conditions:** Generates a fault zone.
- **Ductile conditions:** (deformation + metamorphism) Foliation, lineations, folds….
- **Intermediate conditions.**

- Shear zones provide a detailed record of the history of deformation and permit us to determine the amount of strain, and the sense and amount of displacement.

- The distribution of strain in shear zones it´s mainly heterogeneous.
- There are a spatial gradient in the amount of strain. The strain is higher in the center of the zone.
- There are two types of shear zones in order to their continuity:

  - **Continuous:** Gradual increase of strain, within break, ductile conditions.
  - **Discontinuous:** Abruptt increase of strain, sharp physical breaks, brittle conditions.



- The scale of length and displacement can be very different magnitude (mm-km).

- Usually shear zones are much longer than thicker.
- Whether a shear zone appears continuous or discontinuous depends on the scale at which we observe the structures too.

Types of shear zones

We can subdivide shear zones in four mainly types, based on the characteristic type of deformation of each one:

1. A **brittle shear zone** contains fractures and other features formed by brittle deformation.

2. A **ductile shear zone** displays structures that have been formed shearing by ductile flow.

3. **Semibrittle shear zones** involves mechanisms such as pressure solution and cataclastic flow.

4. The last one, **brittle-ductile shear zones**, shows evidence for both brittle and ductile deformation.

Brittle shear zones

- Brittle shear zones form in the upper part of the crust, where the brittle deformation dominates.
- Shear zones formed in this conditions are characterized by closely spaced faults, numerous joints and shear fractures.
- These zones of intensely fractured and crushed rocks associated with faults vary in thickness from less than a mm to a km or more.
- The wall rocks outside a brittle shear zone may be unaffected by the faulting, or may show a zone of drag folding flanking the zone.

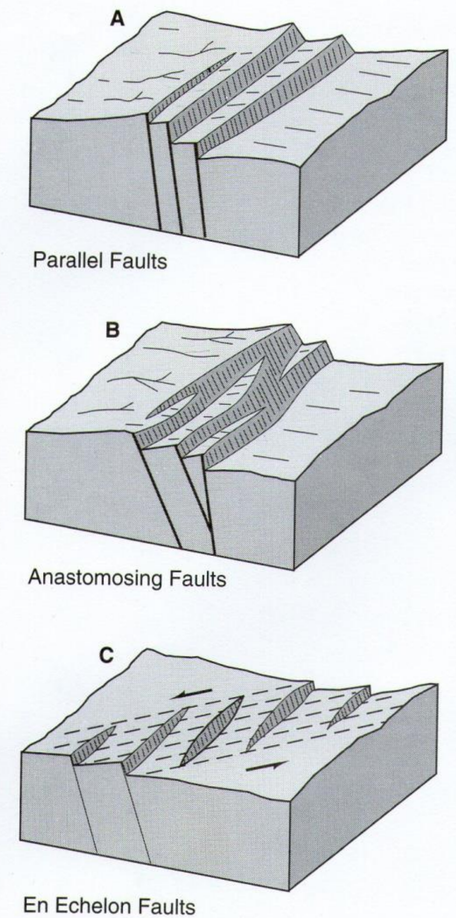


Figure 9.19 Sets of brittle shear zones (faults and fault zones): (*A*) parallel, (*B*) anastomosing, and (*C*) en echelon.

Ductile shear zones

- Ductile shear zones are formed by shearing under ductile conditions, in this case it produces at the middle-lower part of the crust. Accordingly, we generally see ductile shear zones with rocks we would expect to find in the middle crust and deeper like gneiss, schist, marble, migmatite, pegmatite…
- The principal feature of a ductile shear zone is that it doesn't display any physical break. Instead, differential translation of rock bodies is achieved entirely by ductile flow.
- Some rock types that form in ductile shear zones are different from the normal metamorphic rocks. Such rocks are called tectonites (we must indicate the type of rock, e.g., marble tectonite).

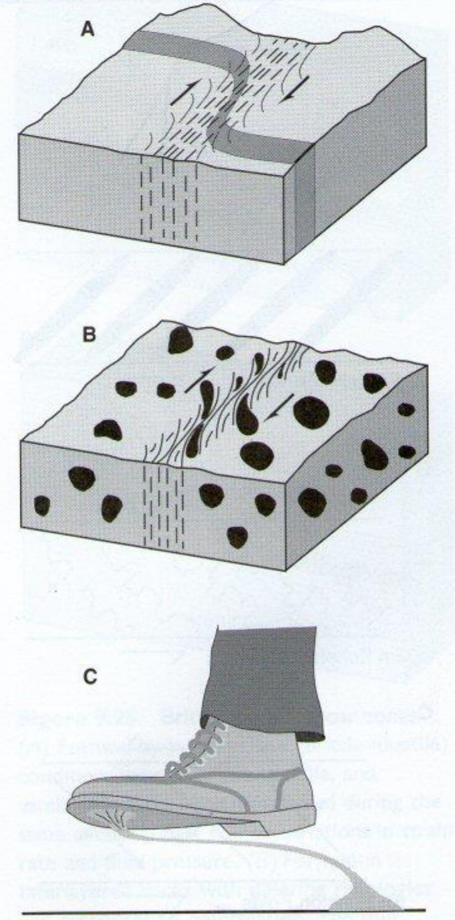


Figure 9.21 Ductile shear zones: (*A*) marker offset by continuous, dextral shear zone, (*B*) shear zone cutting plutonic rocks with inclusions and isotropic initial fabric (compare with Figure 9.6*A*), and (*C*) sinistral shear of chewing gum.

Semibrittle shear zones

- These zones are dominated by brittle deformation mechanisms but contain some ductile aspects as well.

- Shear zones defined by *en echelon* folds can be either semibrittle or ductile, depending of the conditions under which they form. Many zones of en echelon folds are associated with faults and are probably best classified as semibrittle shear zones. The faults are brittle features, but the folding may occur by ductile mechanisms, such as pressure solution, without loss of cohesion of the rocks.

*Note: the term "**en echelon**" refers to closely-spaced, parallel or subparallel minor structural features in rock that are oblique to the overall structural trend.*

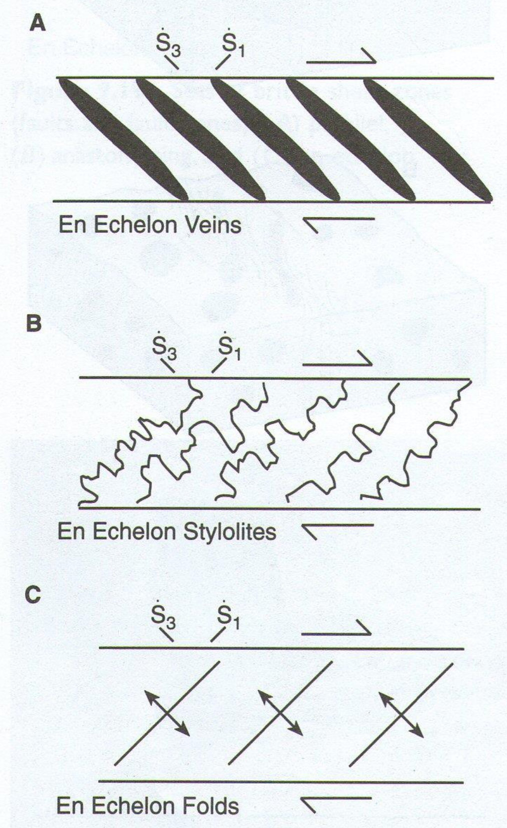


Figure 9.23 Semibrittle shear zones: (*A*) en echelon extension veins, (*B*) en echelon stylolites, and (*C*) en echelon folds. $\dot{S}_1$ is the axis of maximum instantaneous stretching, and $\dot{S}_3$ is the axis of maximum instantaneous shortening.

Brittle-Ductile shear zones

- Brittle-ductile shear zones contain evidence of deformation by both brittle and ductile mechanisms.
- Brittle-ductile shear zones can be formed when:

1. the physical conditions permit brittle and ductile deformation to occur at the same time
2. different parts of a rock have different mechanical properties
3. a shear zone strains harden
4. physical conditions change systematically during deformations
5. a shear zone is reactivated under physical conditions different from those in which the shear zone originally formed.

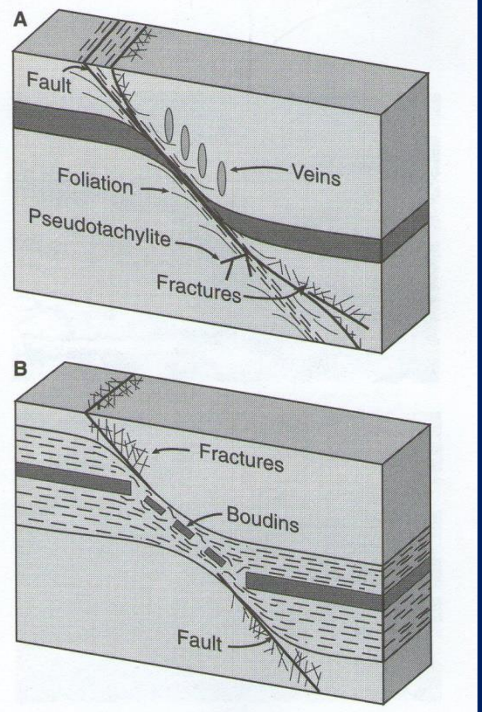


Figure 9.25 Brittle–ductile shear zones. (*A*) Formed by intermediate (brittle–ductile) conditions, where brittle, ductile, and semibrittle deformation occurred during the same event, in part due to variations in strain rate and fluid pressure. (*B*) Formed in interlayered rocks with differing rheologies and responses to deformation. The thin, middle gray layer was relatively rigid and formed boudins because it is enveloped in a less competent and more foliated unit that deformed ductilely. The top and bottom layers were more competent and deformed by faulting and fracturing.

3.Determining sense of shear

- One of the main goals in studying shear zones is to determine the **sense of shear** (the direction one side of a shear zone is displaced laterally relative to the other side).
- **Shear-sense indicators** are those features that show the sense of shear for a deformation.

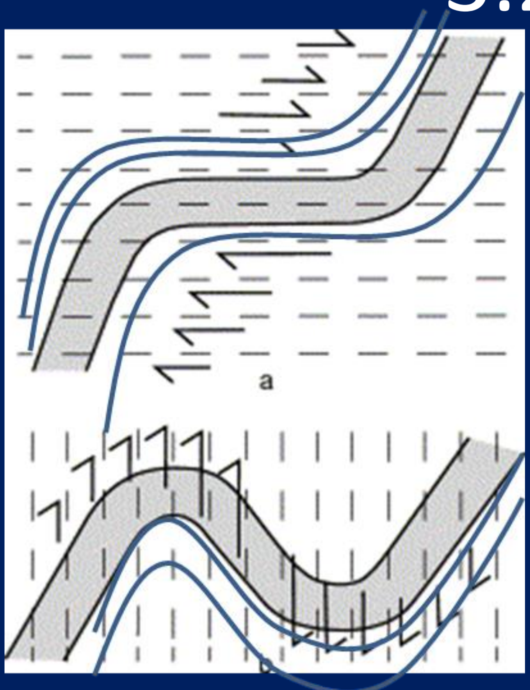
Shear-sense indicators:

- Offset Markers.
- Foliation Patterns.
- Shear Bands, S-C Fabrics, Oblique Micorscopic Foliation.
- Mica Fish.
- Inclusions.
- Pressure Shadows.
- Porphyroclasts and Porphyroblasts.
- Foliation Fish.
- Fractured and Offset Grains.
- Veins.
- Folds.

3.1. Offset Markers

- We can determine both the amount and sense of displacement if we realize the similar-appearing features on opposite side of the shear zone were originally continuous.

3.2. Foliation Patterns

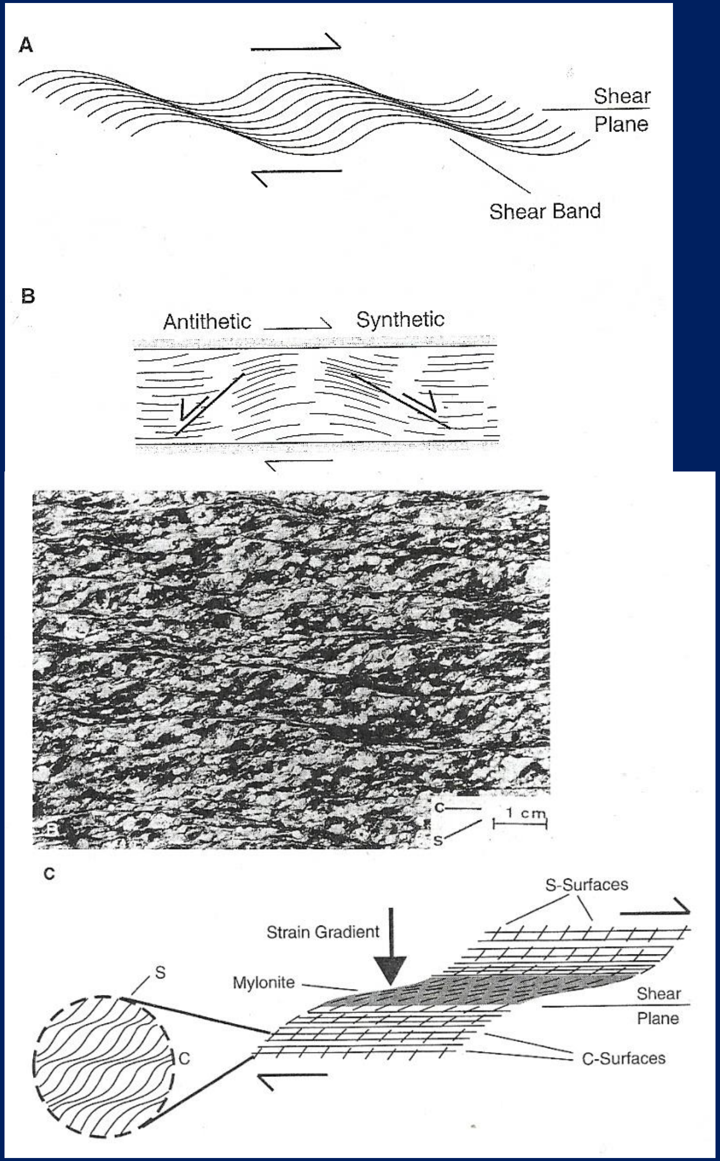


- Systematic variations in the orientation of foliation are common in ductile shear zones and provide one of the most useful shear-sense indicators.
- Foliation will be rotated towards parellelism with the shear zones where the rocks are more strongly deformed, and the strain is higher.

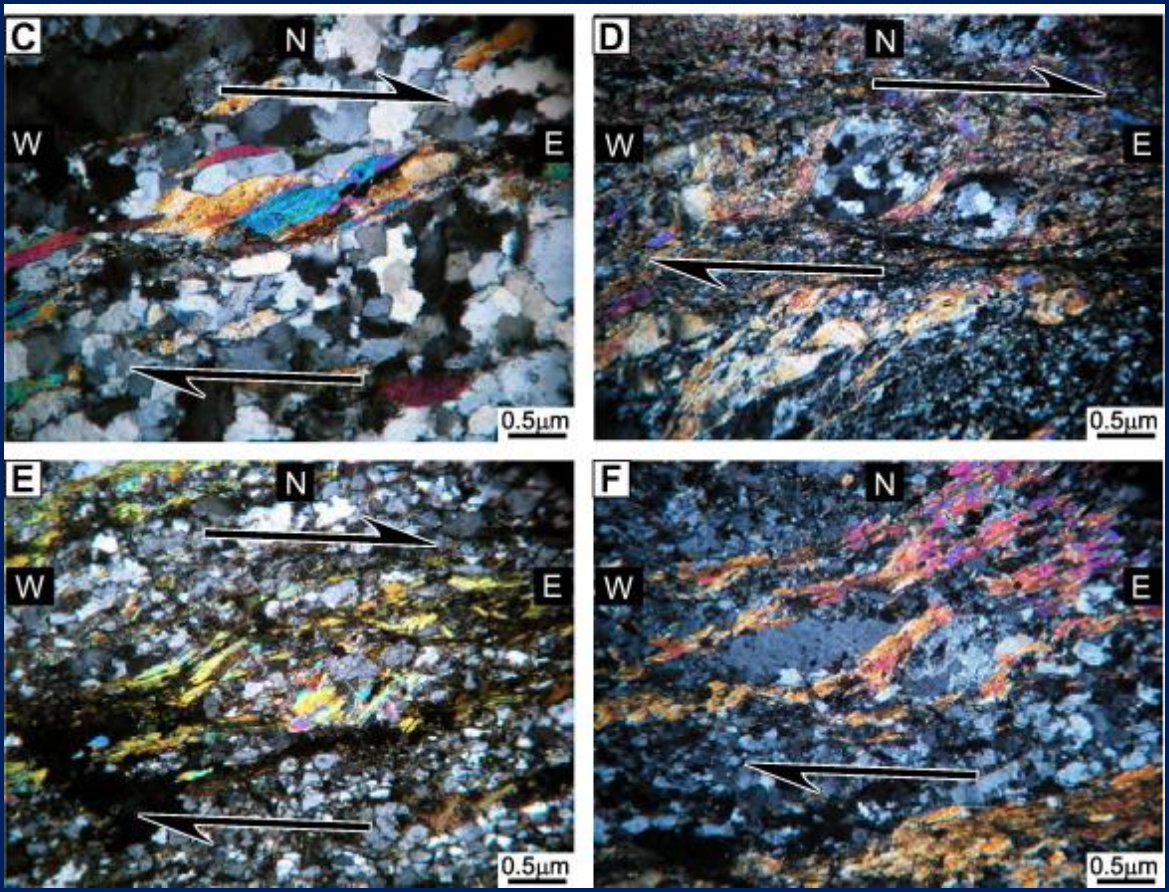
3.3. Shear Bands, S-C Fabrics, and Oblique Microscopic Foliation.

- **Shear bands** are thin zones of very high shear strain within the main shear zone. A shear band is synthetic if it is inclined in the same direction as the overall sense of shear, and antithetic if it is inclined in the opposite direction.

- **S-C fabrics.** They consist of two sets of planes: foliation planes (S-surfaces) and shear bands (C-surfaces). The clearest examples are in mylonitic granitic and gneissic rock.

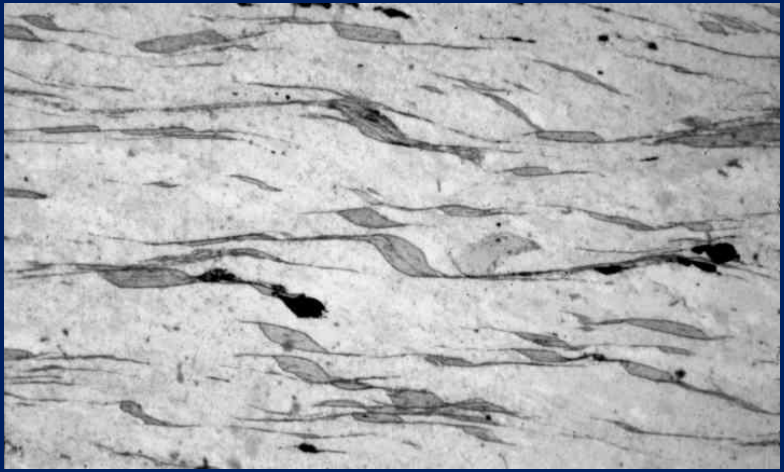


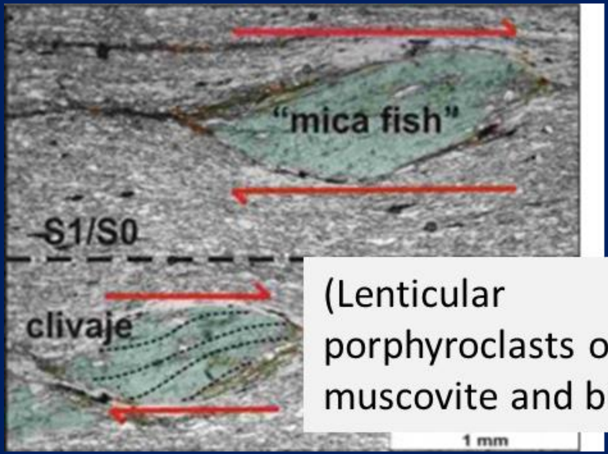
- The **oblique microscopic foliation** is defined by aligned subgrains oblique to the long axis of larger individual grains and ribbons. The oblique foliation leans over in the direction of shear relative to the main foliation defined by the larger grains.



3.4. Mica Fish

- They are commonly aligned with S-surfaces in S-C fabrics, and lean over in the sense of shear.

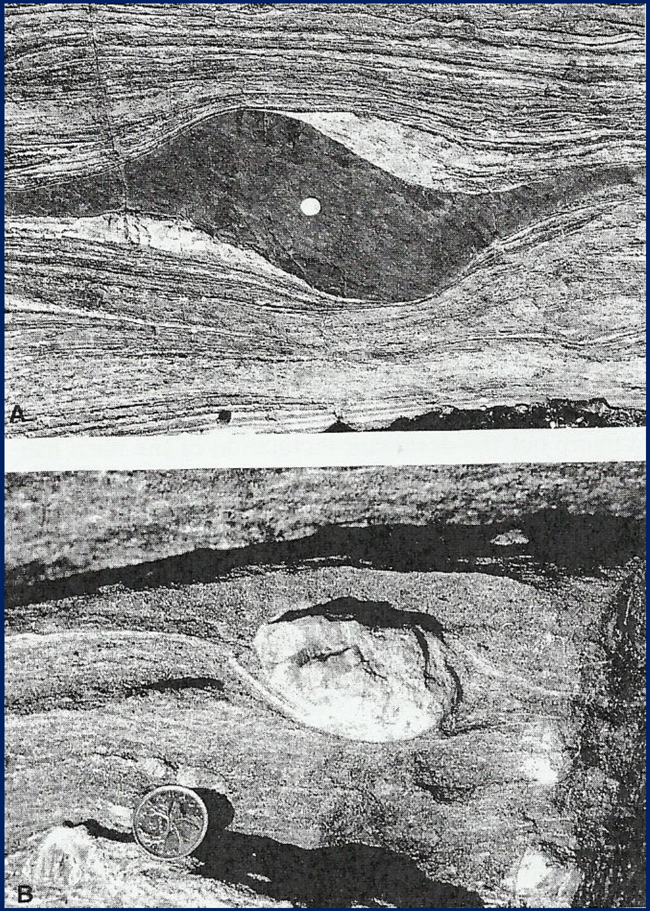




(Lenticular porphyroclasts of muscovite and biotite.)

3.5. Inclusions

- Inclusions provide sense-of-shear information by the way they rotate, deform, recrystallize, and interact with their matrix.

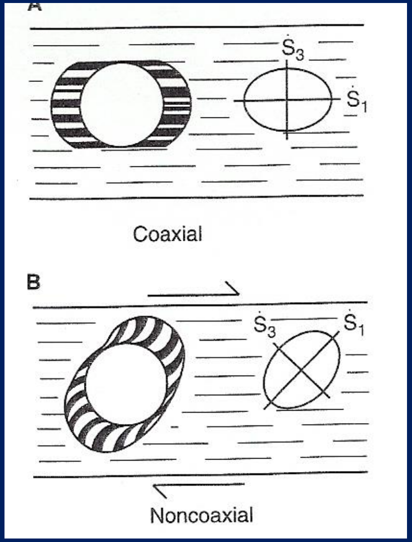


3.6. Pressure Shadows

- When inclusions are strong compared to the matrix, they help shielding the matrix on the flanks of the inclusion from strain. These shielded areas (**pressure shadows**) are composed of less deformed matrix or of minerals that grew or recrystallized during deformation.

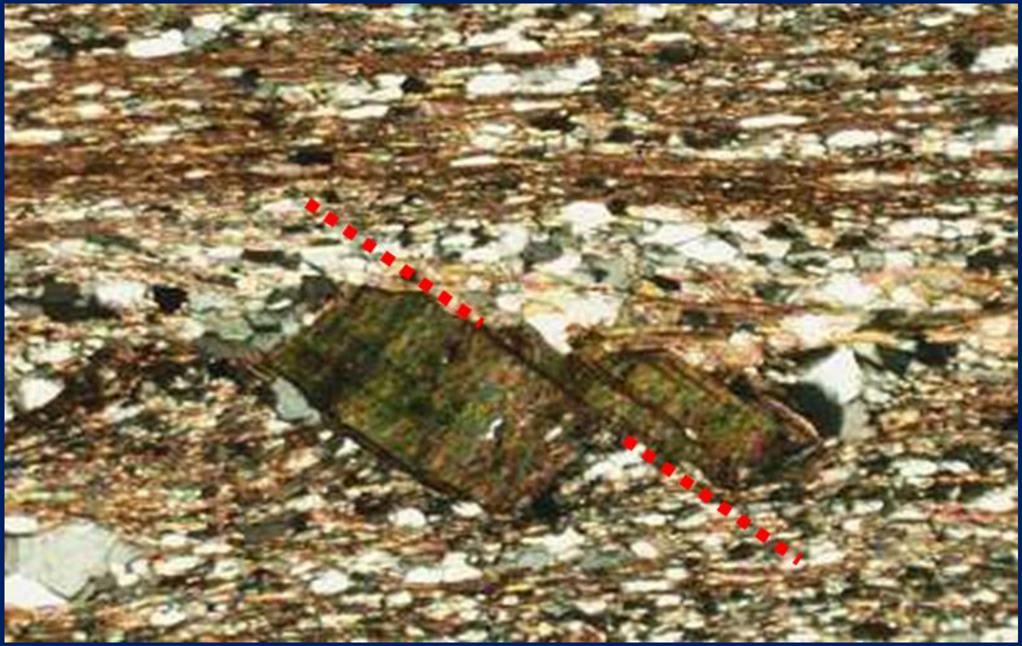
3.7. Porphyroclasts and Porphyroblasts

- Rigid grains of one mineral within a more strongly deformed matrix having a different mineralogy. Knowing the shape due to noncoaxial deformation, we can define the sense of shear.



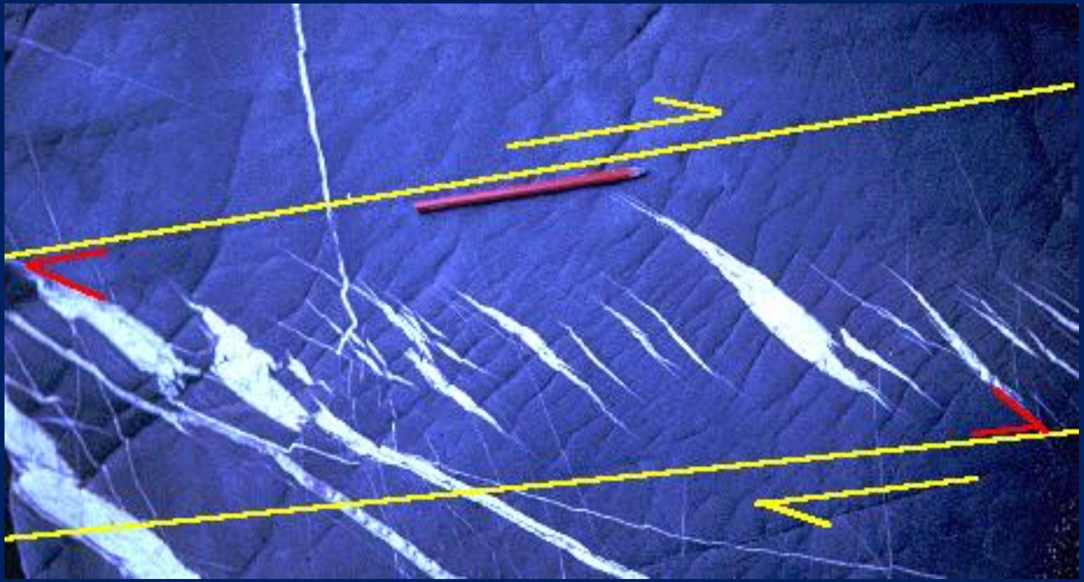
3.8. Fractured and Offset Grains

- Porphyroclasts and other rigid inclusions may accommodate deformation by becoming sliced up by small-scale or grain-scale faults.
- The sense of displacement on such faults can be a shear-sense indicator, but not a totally reliable one.



3.9. Veins

- Most shear zone-related veins contain quartz and calcite. These minerals are deposited from the fluids that filled the opened fractures.
- Most veins form “perpendicular” to the axis of maximum extension, because this is the direction in which tension fractures form.



SHEAR ZONE

Shear zones are defined as planar or curvi planar zones of higher deformation which are long relative to their width (5:1) which are surrounded by rocks showing lower state of finite strain.

SHEAR ZONE: zone of highly strained rocks

A fault zone is a shear zone formed in the brittle regime

Can also have a purely ductile shear zone

Or even a zone with a mixture of brittle and ductile deformation- due to composition (feldspar or qtz) or strain rate (silly putty analogy)

Types of Shear zone.

Ductile Shear - Deformation state varies continuously from wall to wall across the zone.

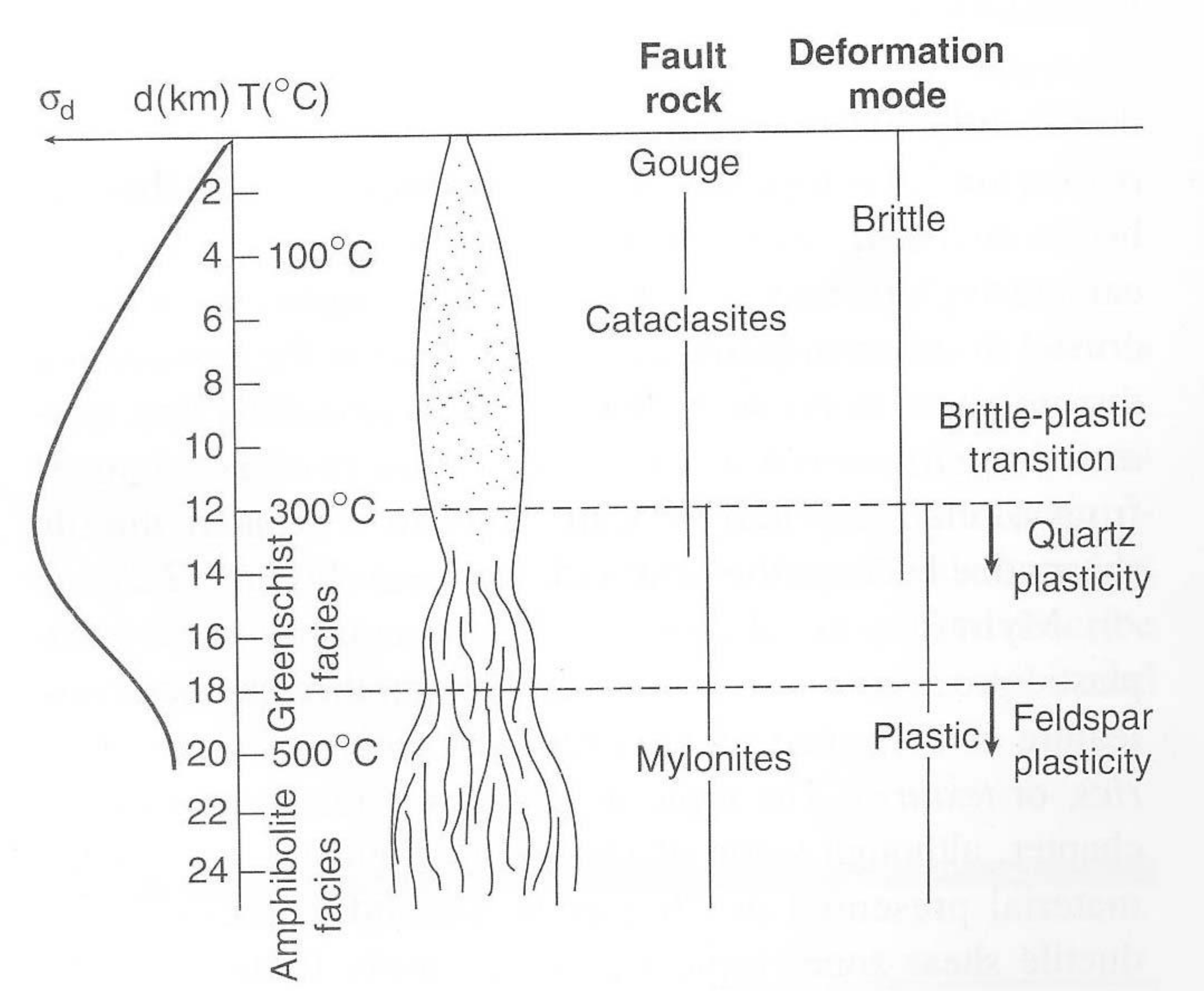
Brittle Shear - Walls are separated by a clearly defined discontinuity of fracture surface – (eg. Fault).

Brittle–ductile Shear - Where the tangential (wall parallel) movement along the Zone is associated with both ductile shearing and brittle fault.

In many regions the Ductile and Brittle - Ductile shear zones may be the deep level counterparts and brittle shear zones and faults seen at high level in the crust.

Recognition of Shear Zone

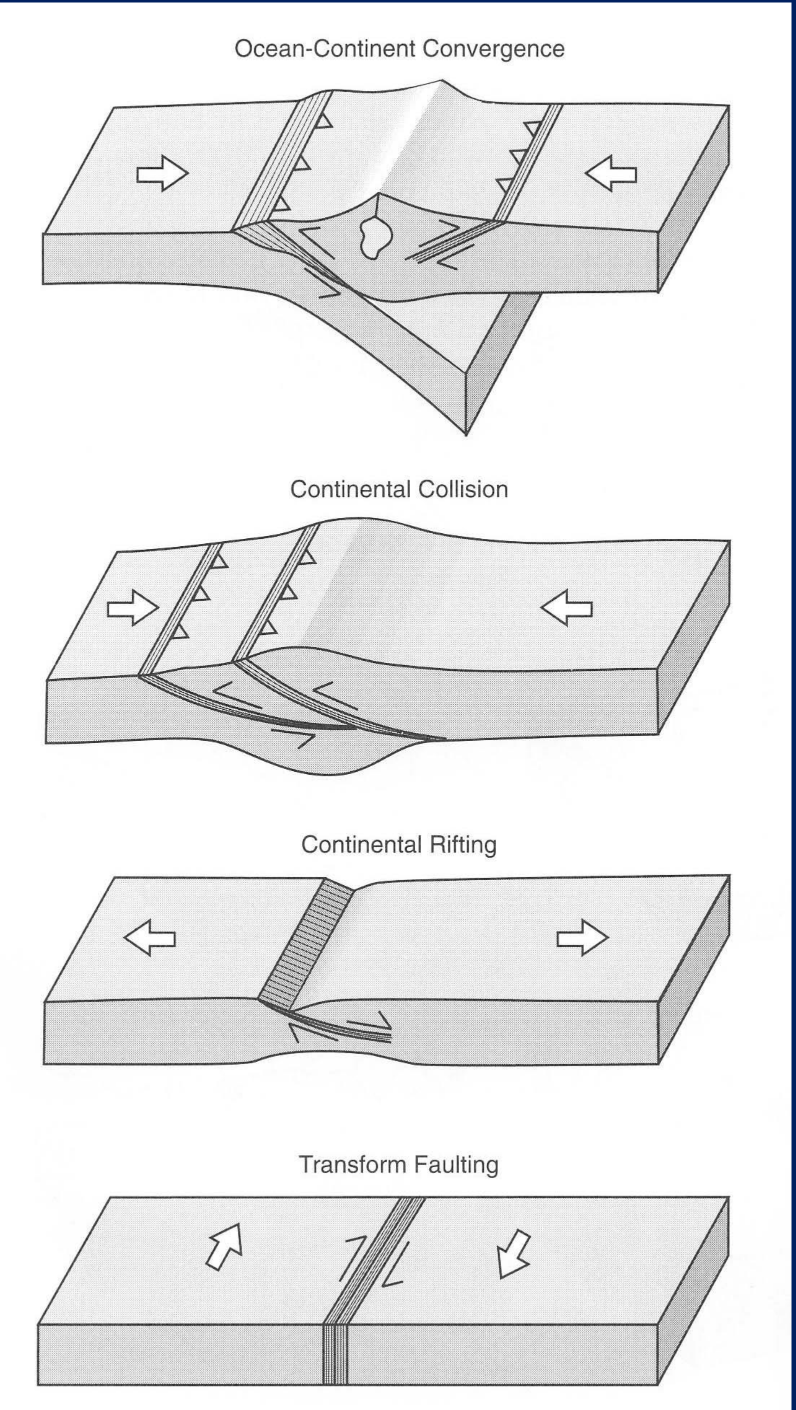
- An unusually regular layering of constant thickness.
- A straight linear shapes fabric in the plane of the layering
- Presence of isoclinal and sheeth folds in the layering with fold axes sub parallel to the lineation.



Fault rock
Deformation mode
σd
d(km) T(°C)
Gouge
Brittle
2
4
100°C
6
Cataclasites
8
10
Brittle-plastic transition
12
300°C
Quartz plasticity
14
Greenschist facies
16
18
Feldspar plasticity
Plastic
20
500°C
Mylonites
22
Amphibolite facies
24

Shear zones form in the deeper crust of all structural systems: thrust, strike-slip and normal

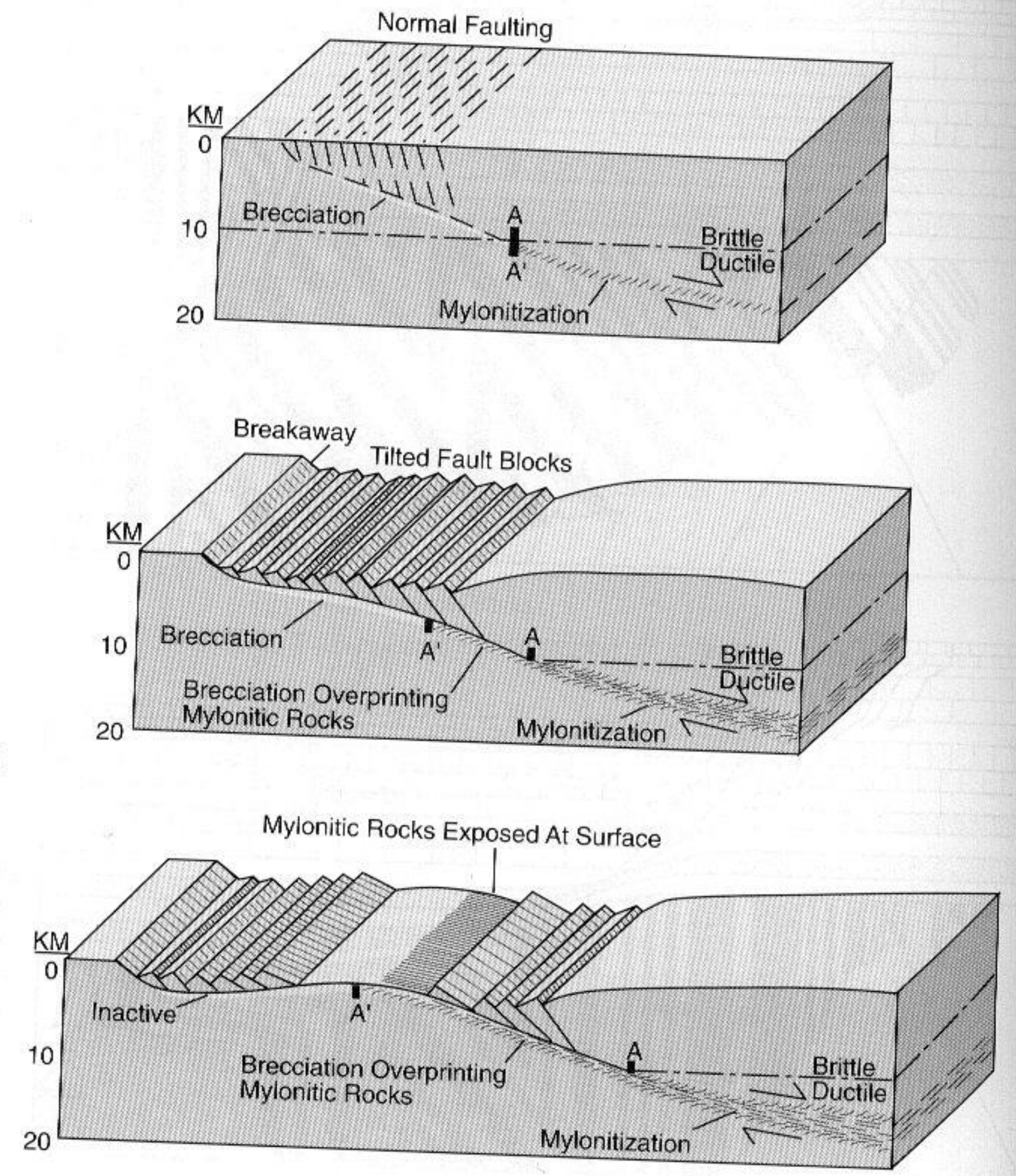
But how are they brought to the surface?



"Tectonic Exhumation"

Removal of overburden by normal faulting.

Erosion plays a role, but is not required!

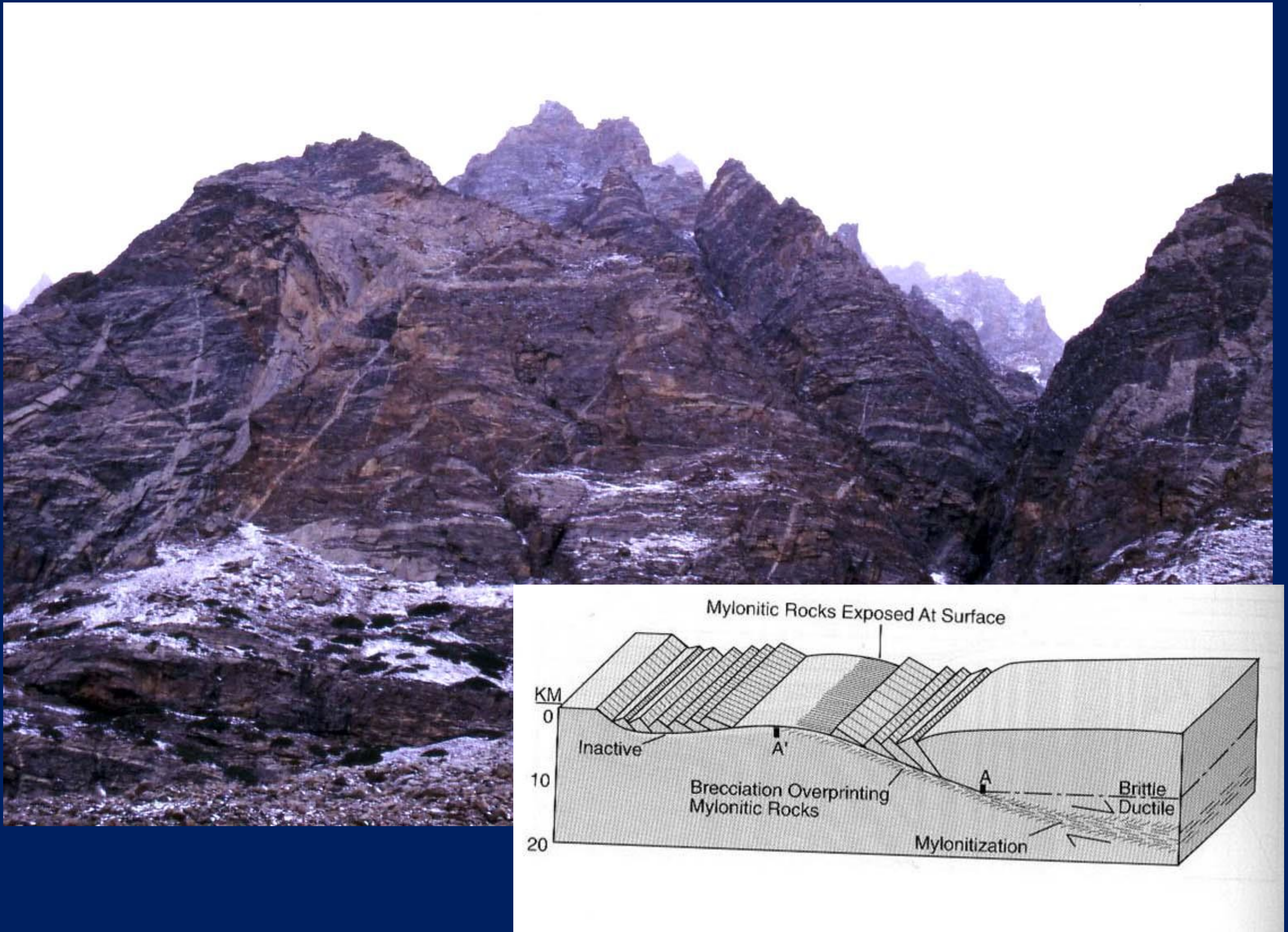


A ledge of fault breccia below the detachment

thick zone of mylonitic rocks below the detachment

Ahh, sweet mylonites! What is sense of shear?

Even deeper- a less deformed "injection complex"



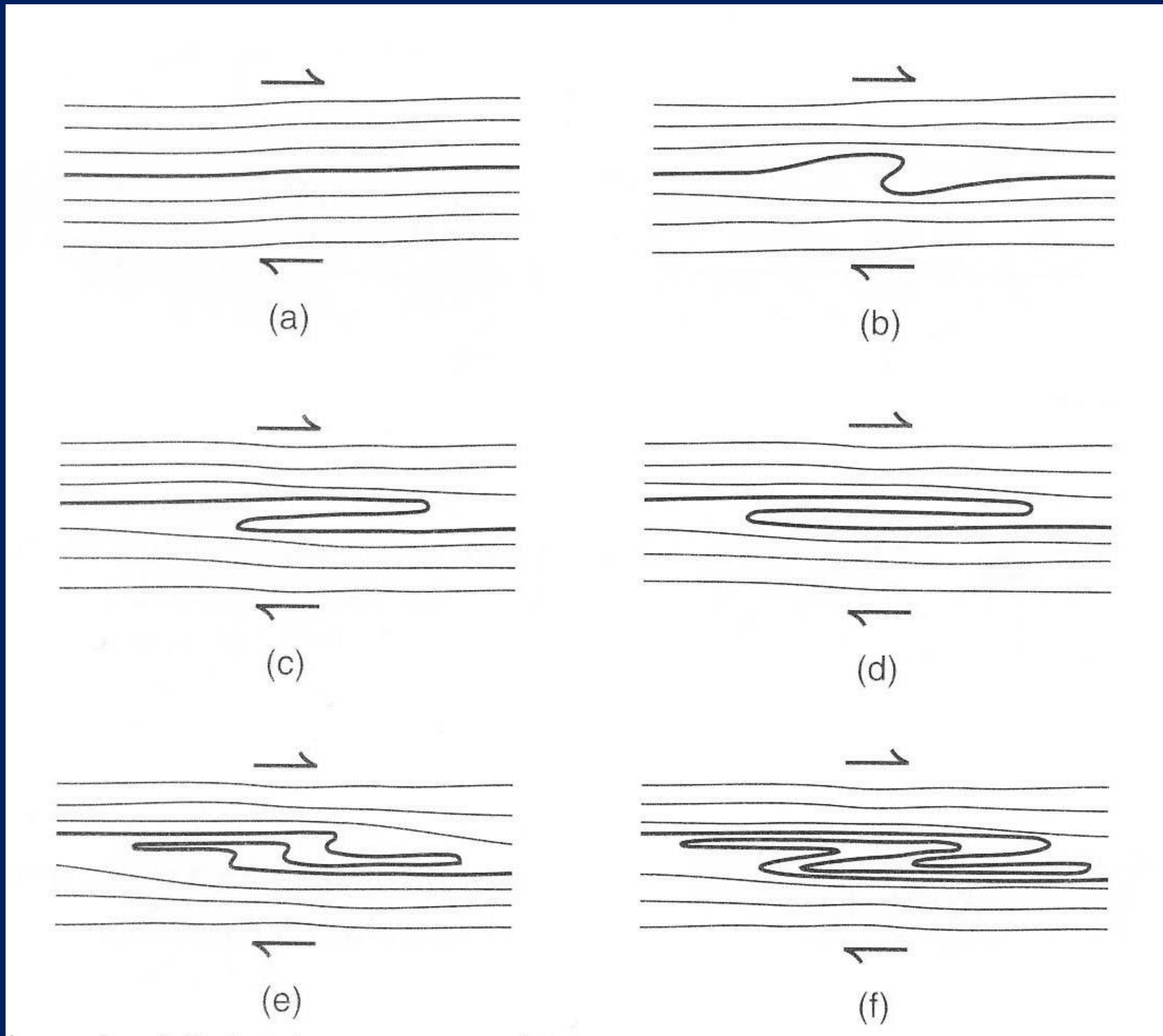
Undeformed granite in core

Mylonite

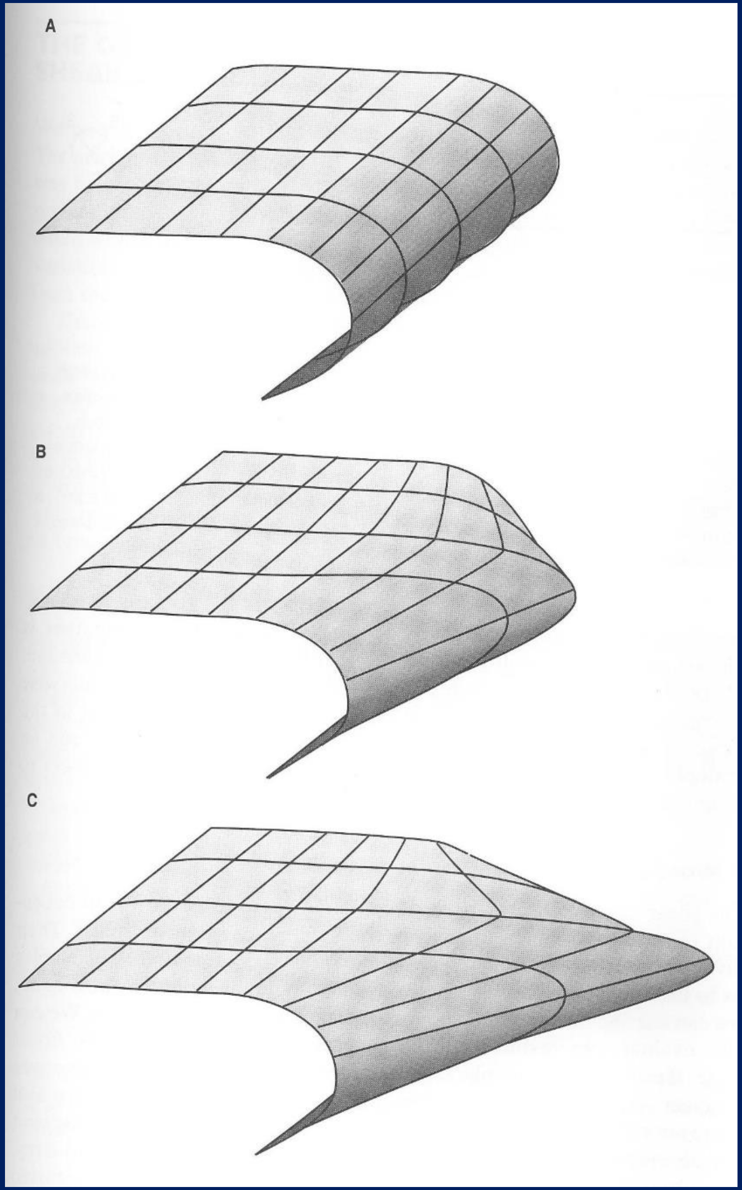
Shear sense indicators in shear zones

Example of a small ductile shear zone

Folds, transposition, and ambiguous sense of shear



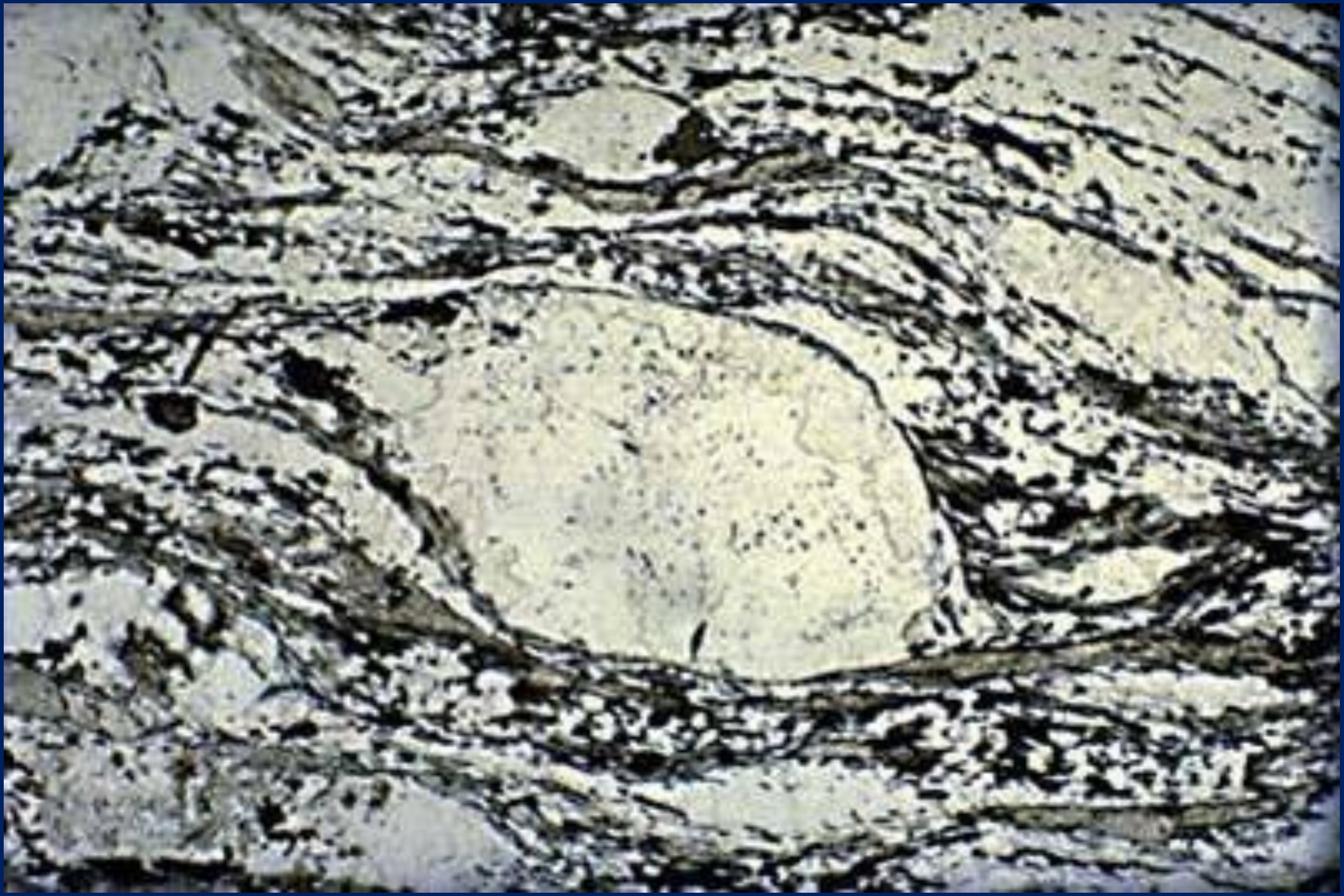
sheath folds (tongues that point in direction of shear)



Cross section of a sheath fold

Mylonites are EXCELLENT! What is sense of shear?

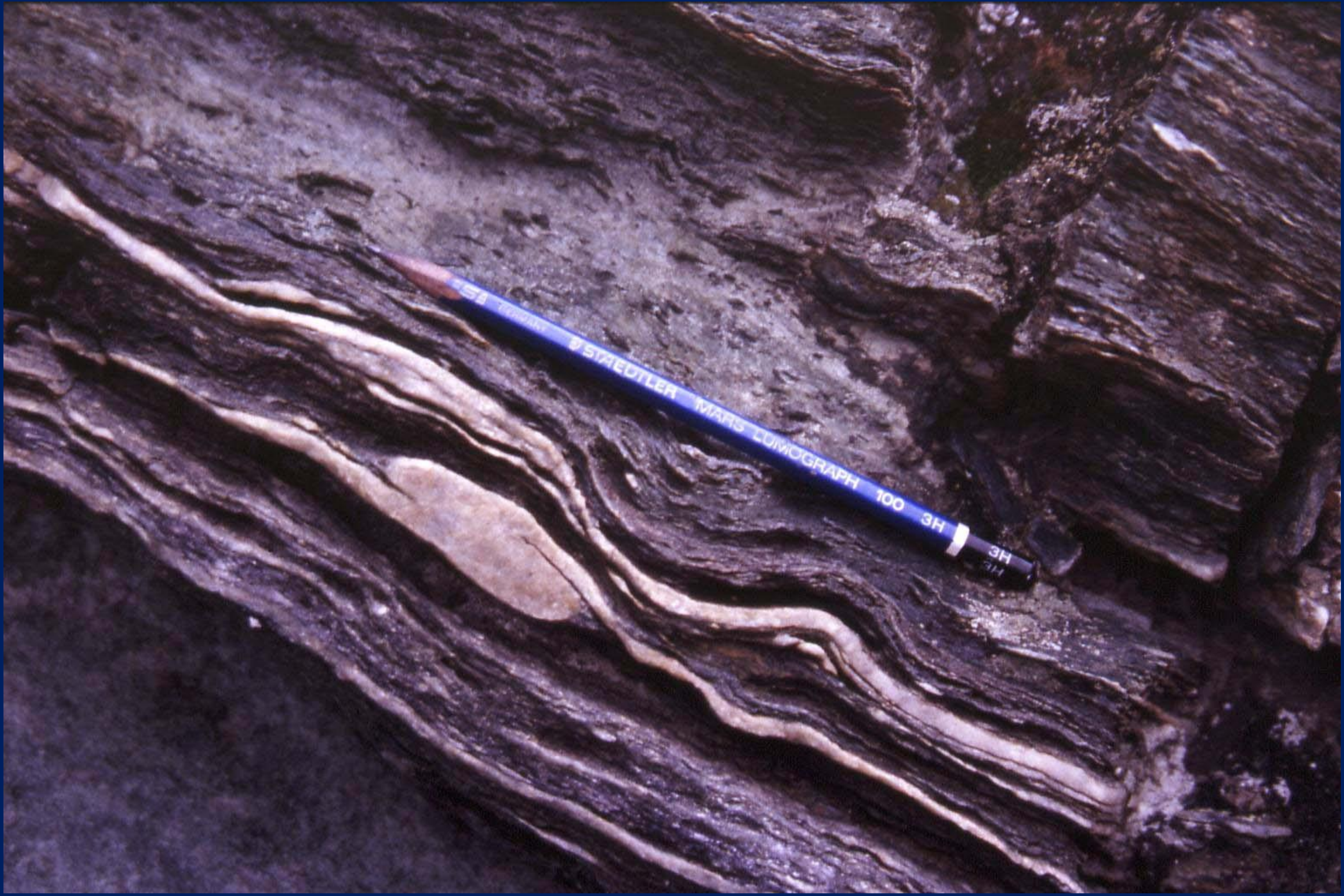
Sigma structure- wings step up in direction of shear



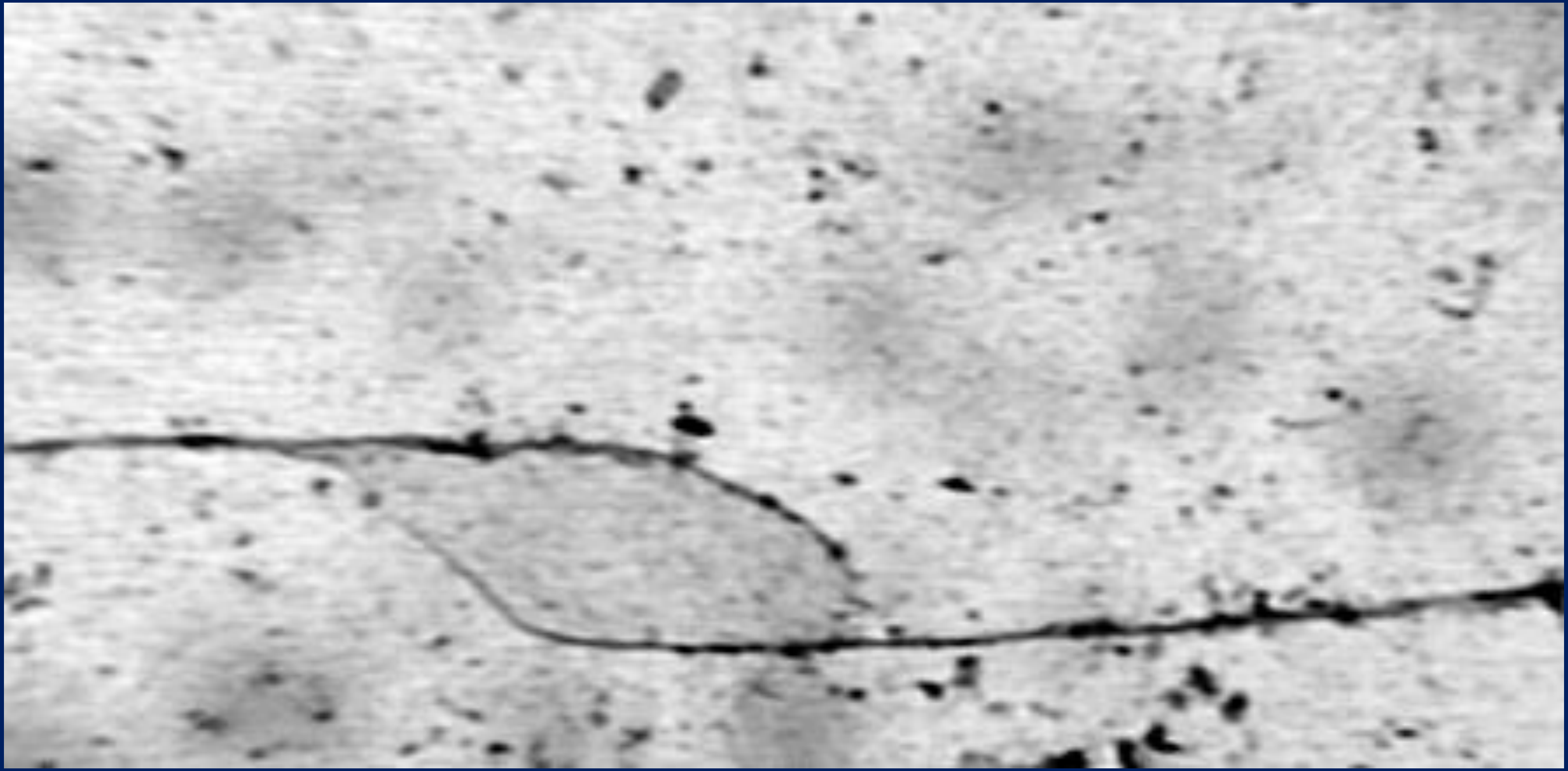
Delta structure: porphyroclast rotates faster than wings

Delta structure: porphyroclast rotates faster than wings

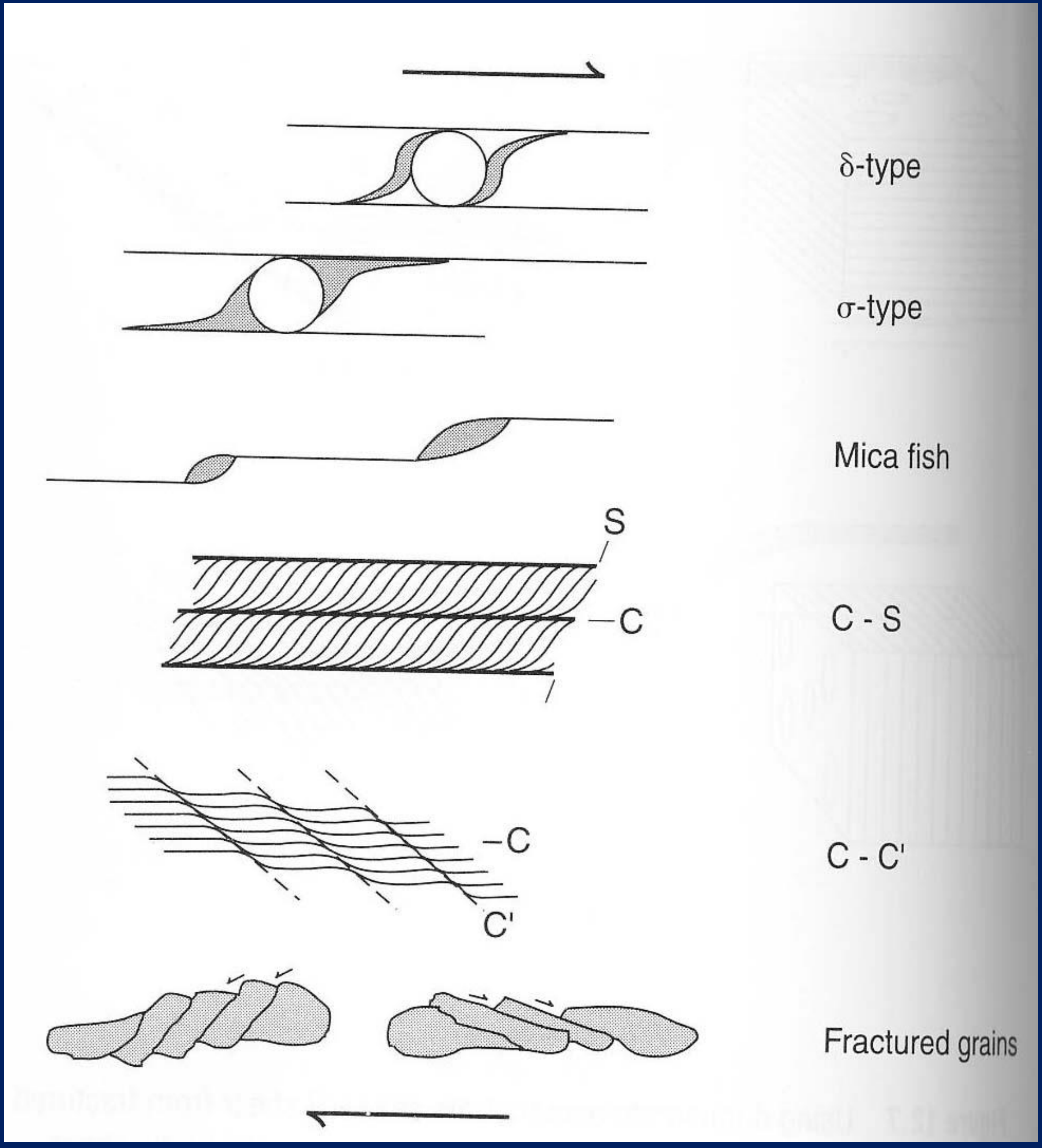
A delta + sigma structure- what is sense of shear?



Mica-fish fabrics. Typical for sheared rocks with muscovite and/or biotite. A special form of S-C fabric. Again wings/tails step up in direction of shear



Summary of shear fabrics



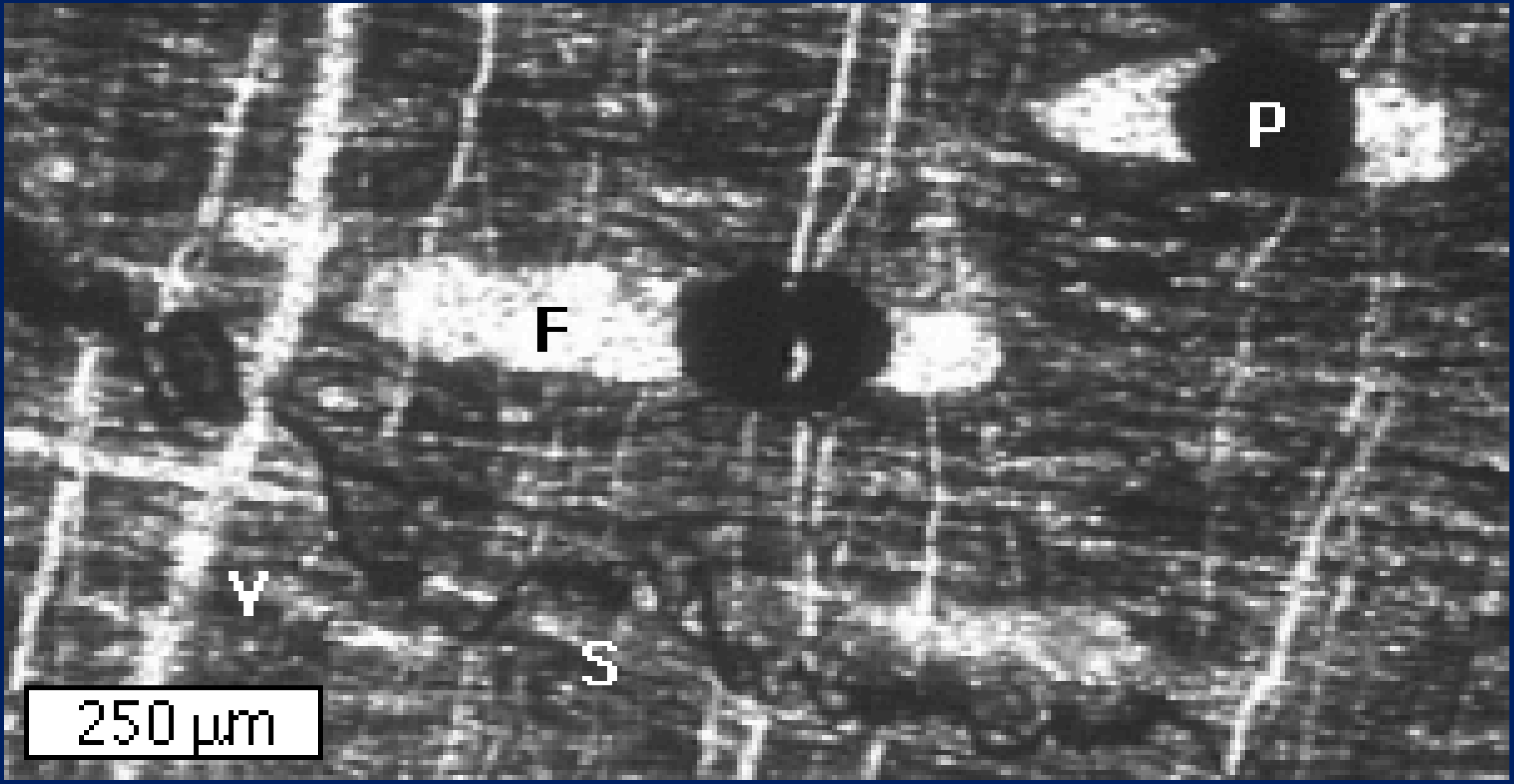
So far, we have talked about shear fabrics related to noncoaxial deformation (simple shear).

Some "shear" zones are not due to simple shear, but rather coaxial deformation (pure shear)

What do some of these structures look like?

symmetric boudins due to flattening/stretching

Symmetric pressure shadows due to flattening (pure shear) strain



SENSE OF SHEAR

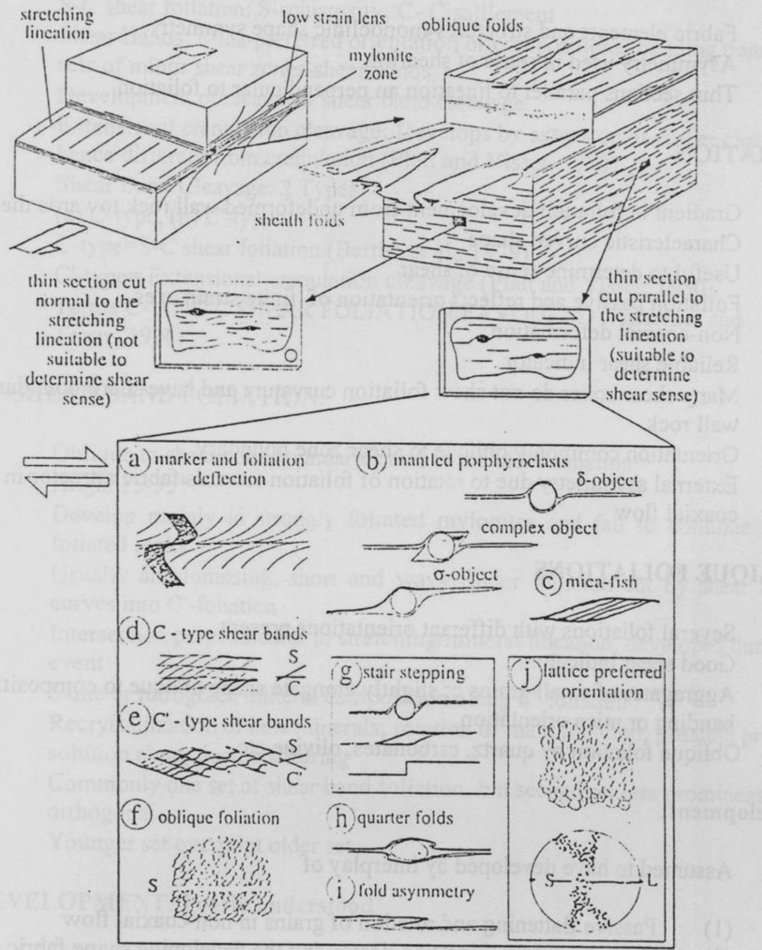


Figure 4: Geometry of a ductile shear zone and various shear criteria used for deciphering sense of displacement.

Shear Zone rocks

"MYLONITE"

In the very coarse grained rock (Granite or Quartzite) the coarse grains are strained and drastic grain reduction takes place mainly through recrystallisation (large grains / Porphyroclasts / Residual mega crysts surrounded by fine grained matrix.)

Protomylonite	-	Mylonite Orthomylonite	-	Ultramylonite
50:50	-	50 – 90 % Matrix	-	10 : 90 Matrix

The process of grain refinement is often associated with extreme stretching along newly formed foliation.

Fabric – foliation and lineation

S – C Fabric S = Schistosity; C = Cisaillement

CATACLASTITE:

Grain refinement is by the cataclastic process
Deformation is by sliding and rotation of grains

Protocataclastite –	Cataclastite –	Ultracataclastite
50 : 50	50 – 90 % Matrix	10 : 90 Matrix

Both Mylonite and Cataclastite are the product of Cohesive shear zone.

Non – Cohesive rocks (Fault Breccia & Gouge)

Mainly produced by crushing on the fault surface

Fault breccia – large grains in a pulverized groundmass.
Gouge – Extremely fine rock flour (fully pulverized material)

Remote Sensing and GIS Based Mapping Techniques Of Igneous intrusion and Diapir:

- Surface manifestation of such domes need through understanding and mapping

- Doming up character need to be established by

  Circular or arcuate trend lines and drainage

  Radiating drainages (Centrifugal)

  Radiating fractures / faults

  Central core represented by igneous / salt

  Circular or elongate shape

  Contrasting tonal variation

  Contrasting vegitational variation

  Steep dip

Pseudotachylite :

- Developed from local melting due to frictional heating
- Angular rock fragments in a glassy matrix
- Matrix might have undergone various degree of re – crystallization but does not show any preferred orientation of recrystallised grains
- Psudotachylite is considered important because it is assumed that they are the indicators of ancient earth quake at depth (Sibson 1975)
- But association of psudotrachylite and mylonite puts a ? to the above inference.

Psudotrachylite – fault indicator (brittle faults)

Mylonite -- Shear zone indicator (Show plastic process)

Unconformity and structural relation

An unconformity is a break in the stratigraphic sequence, it records major time gap and it is caused by erosion and non-deposition.

Recognition of an unconformity is of considerable importance in structural geology.

Types of Unconformity:

1. Angular Unconformity
2. non-conformity
3. disconformity
4. paraconformity

Angular Unconformity:

Flat lying, undeformed or weakly deformed sediments of a younger age overlie an older group of rocks such as schists and gneisses

Non-conformity:

It is a erosional unconformity above massive plutonic rocks

Disconformity:

The beds above and below are parallel. New sedimentary rocks are laid above the older eroded or non eroded sedimentary rocks

Paraconformity:

Limestone strata may lie disconformably on the other limestone strata without any clastic zone between the two sets

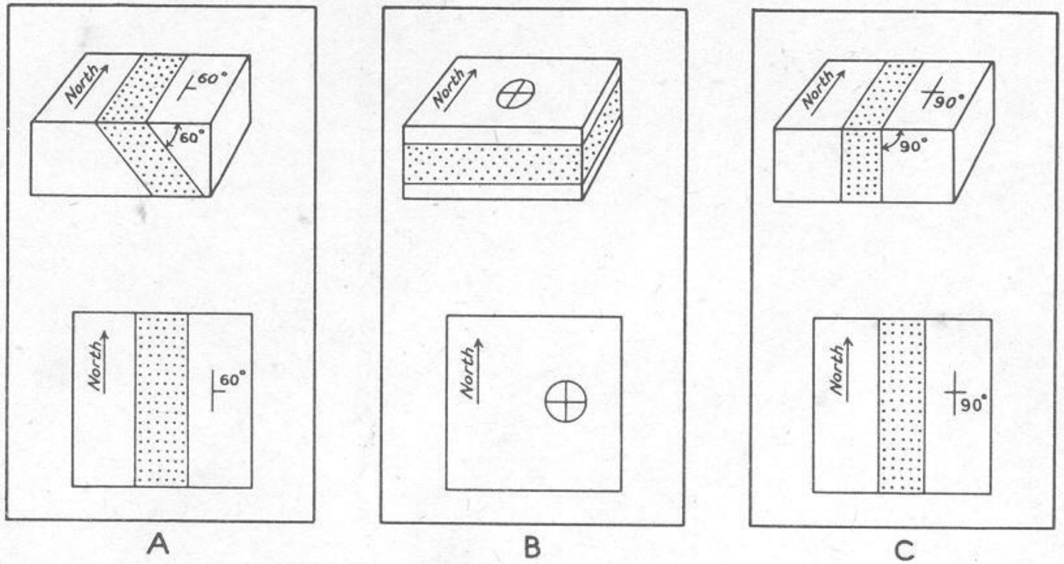


Fig. 3-1. Dip-strike symbols used for inclined, horizontal, and vertical strata. Block diagram above, map below. (A) Inclined strata. (B) Horizontal strata. (C) Vertical strata. The position of the 90° may be used to indicate the top side of the bed (see page 81).

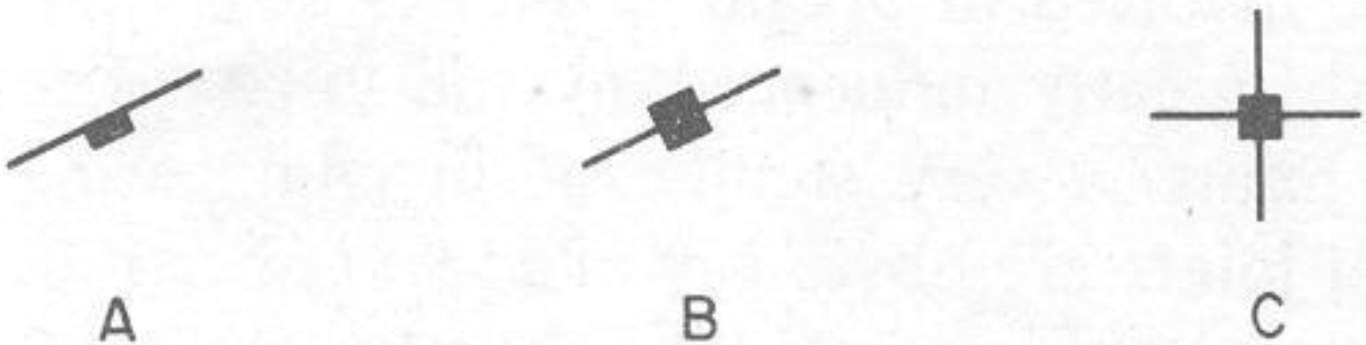


Fig. 7-3. Map symbols for joints. (A) Strike and dip of inclined joint. (B) Strike of vertical joint. (C) Horizontal joint.

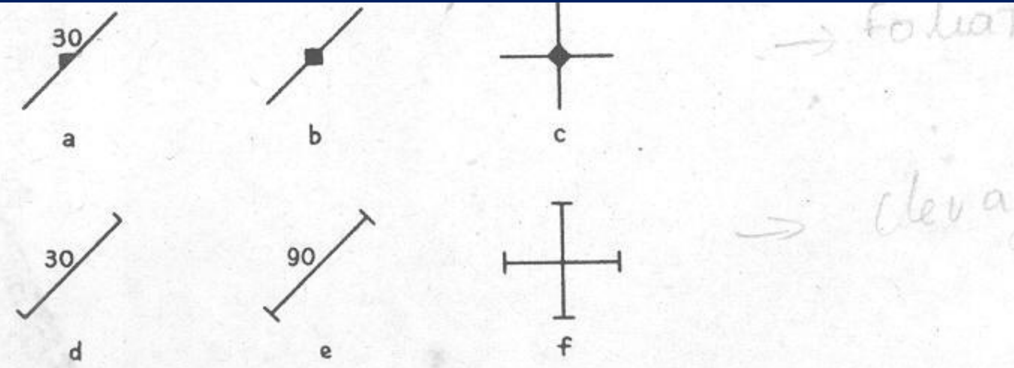


Fig. 18-1. Symbols for foliation. Upper line shows symbols for foliation in general. Lower line shows symbols for cleavage. (a) Strike and dip of foliation. (b) Strike of vertical foliation. (c) Horizontal foliation. (d) Strike and dip of cleavage. (e) Strike of vertical cleavage. (f) Horizontal cleavage.

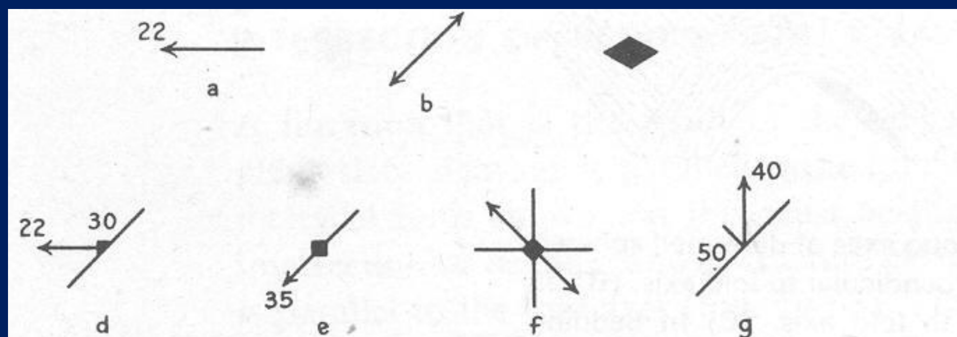


Fig. 19-4. Map symbols for lineation. (a) Lineation plunging 22°W. (b) Horizontal lineation striking NE. (c) Vertical lineation. (d) Foliation striking N. 45°E., dipping 30° NW.; lineation plunging 22°W. (e) Vertical foliation striking N.45°E., lineation plunging 35°SW. (f) Horizontal foliation, with horizontal lineation striking N.45°W. (g) Bedding striking N.45°E., dipping 50°NW.; lineation plunging 40°N.

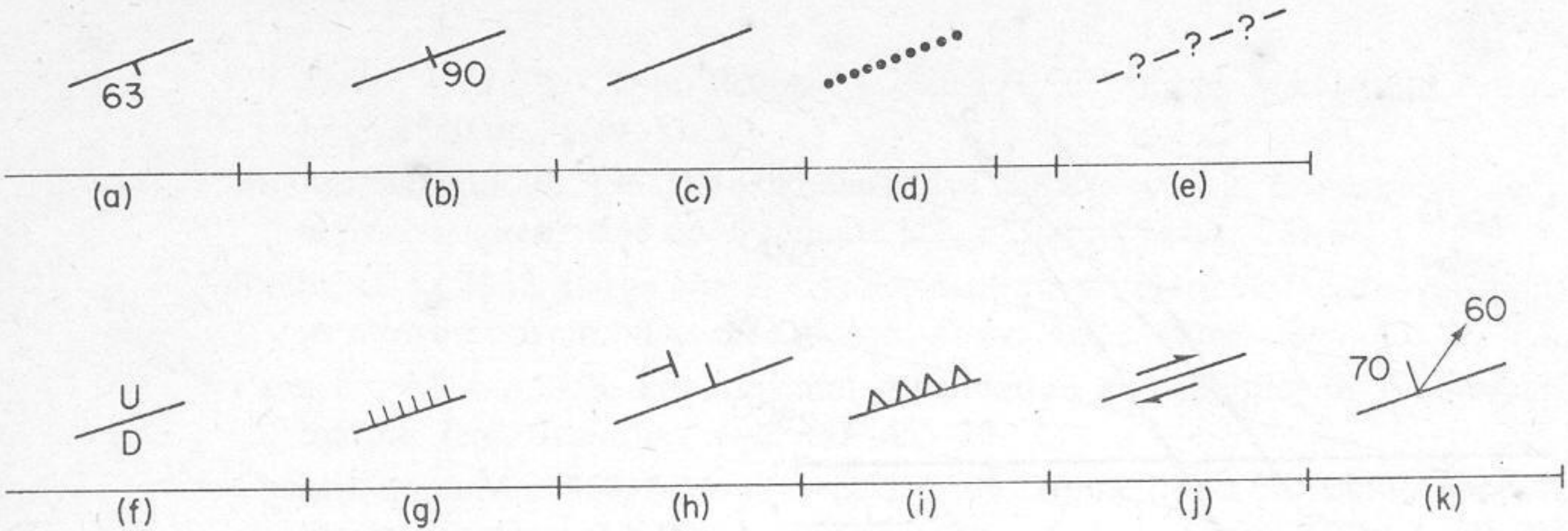


Fig. 9-12. Map symbols for faults. (a) Fault, showing strike and dip. (b) Strike of vertical fault. (c) Strike of fault, dip uncertain. (d) Concealed fault, i.e., fault overlain by younger beds not affected by fault. (e) Possible fault. (f) Normal fault; *U* on upthrown block, *D* on downthrown block. (g) Normal fault, hachure on downthrown block. (h) Thrust; *T* on upthrown block. (i) Thrust, sawteeth on upthrown block. (j) Strike-slip fault, showing relative movement. (k) Fault with dip, also shows bearing and plunge of slickensides.