Recording features of metamorphic rocks

A **metamorphic rock** is a result of a transformation of a pre-existing **rock**. The original **rock** is subjected to heat and pressure, which cause obvious physical and/or chemical changes.

Types of metamorphism

<u>- Regional extent (over a wide area)</u>

- **- Orogenic metamorphism (T, P, active fluids)**
- **- Ocean floor metamorphism (T)**
- **- Subduction zone metamorphism (HP/LT)**
- **- Burial metamohism (LT/LP)**

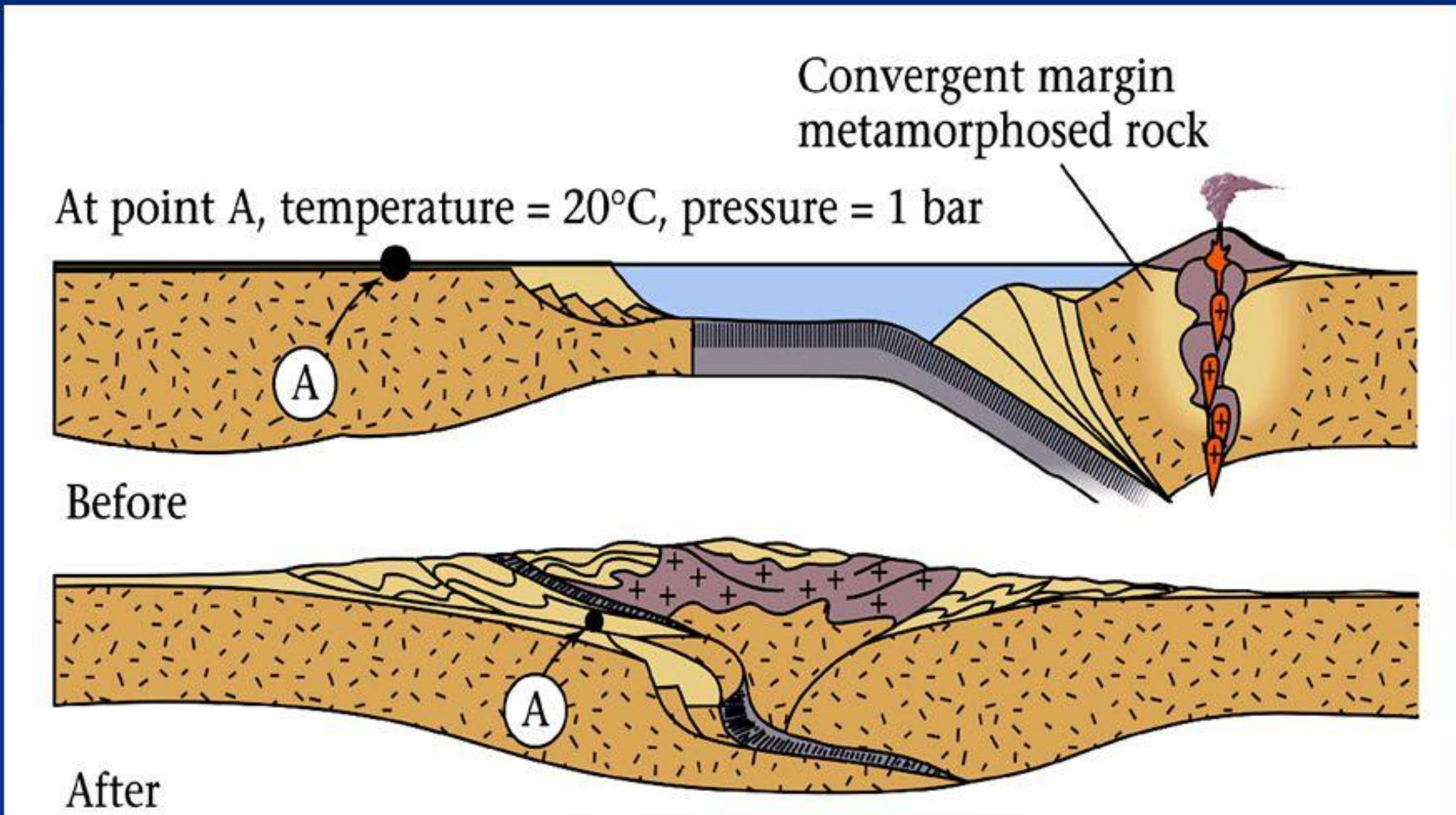
<u>- Local extent (local area)</u>

- **- Contact or thermal metamorphism (T)**
- **- Cataclastic or shear zone metamorphism (P)**
- **- Hydrothermal metamorphism (active fluids)**
- **- Impact or shock metamorphism (extreme P-T)**

Orogenic metamorphism

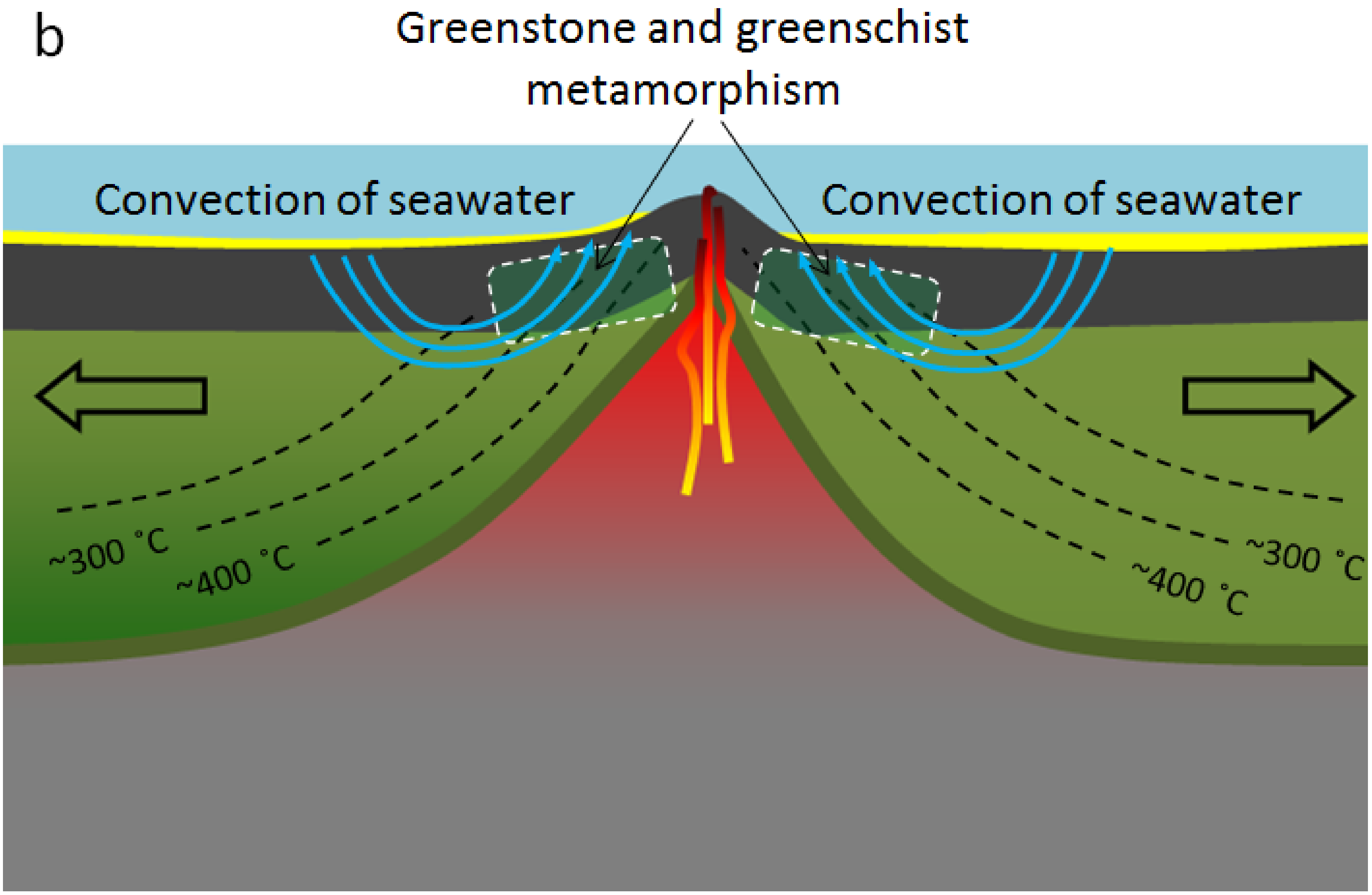
Is the most common type of **metamorphism**. It commonly occurs in island arcs and near continental margins because **orogenic** belts typically form at convergent plates boundaries. Understanding **orogenic metamorphism** leads to the understanding of the thermal, burial and erosion cycle of any **orogeny**.

Orogenic Metamorphism



Ocean floor metamorphism

is a concept that has arisen from recent studies of present oceanic ridges and fracture zones where new crust is being generated, altered, and deformed. Recognition of on-land ophiolite suites as ancient examples of oceanic crust and mantle provide insights into the thermal and dynamothermal regimes that characterize ocean floors.

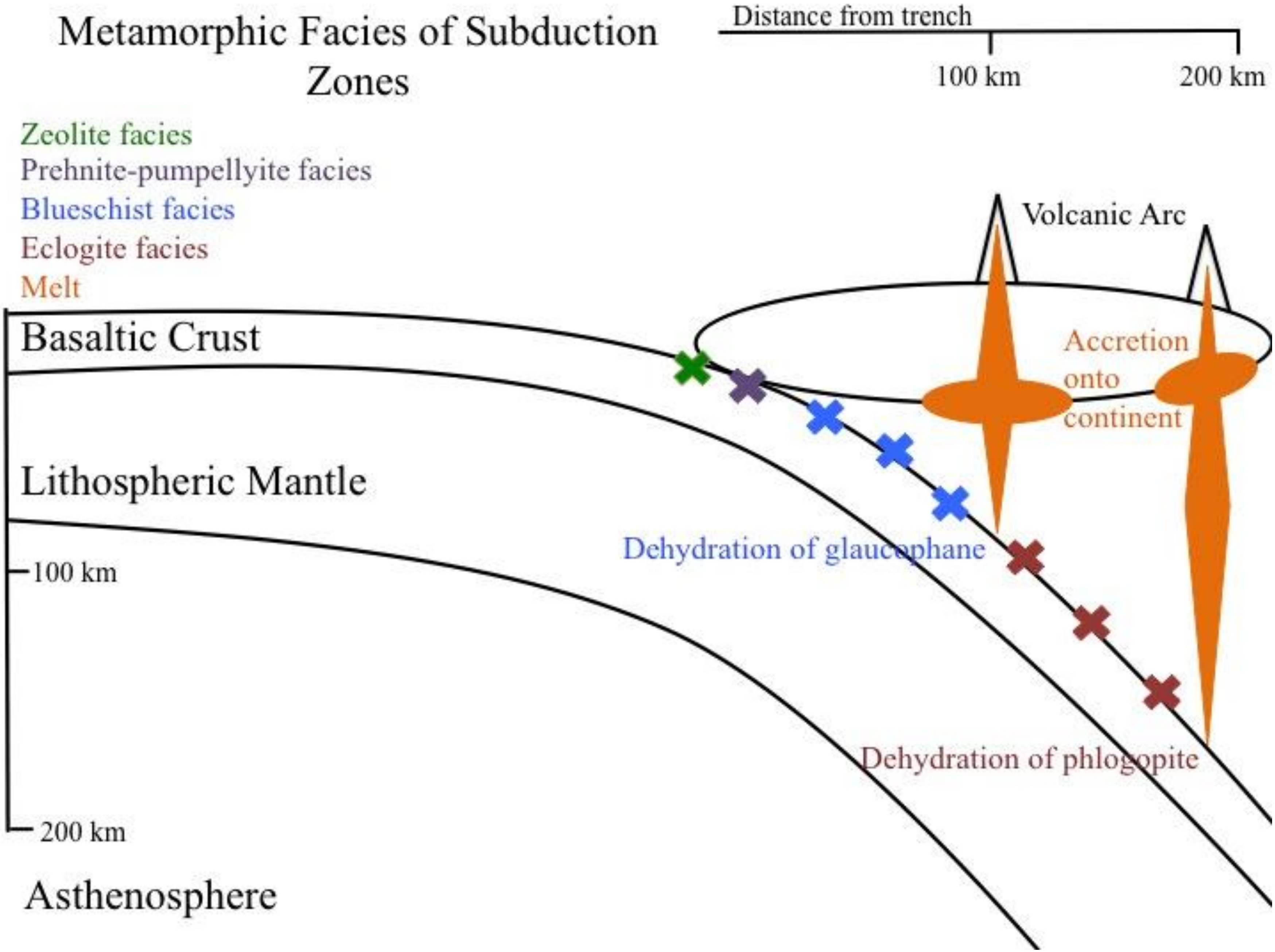


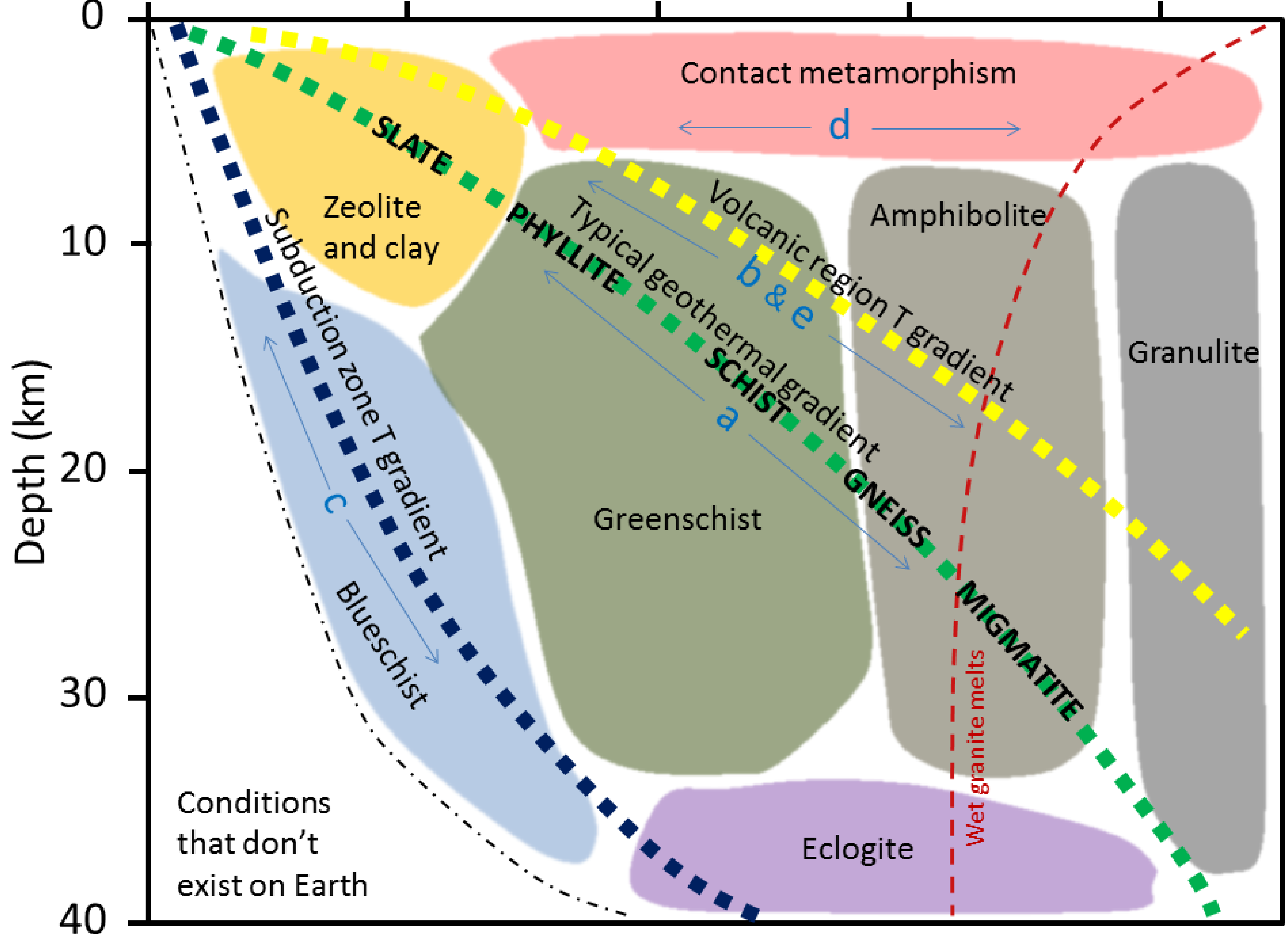
b
Greenstone and greenschist metamorphism
Convection of seawater
Convection of seawater
~300 °C
~400 °C
~300 °C
~400 °C

Subduction zone metamorphism

- Subduction zone metamorphism is characterized by a low temperature, high-ultrahigh pressure metamorphic path through the zeolite, prehnite-pumpellyite, blueschist, and eclogite facies stability zones of subducted oceanic crust

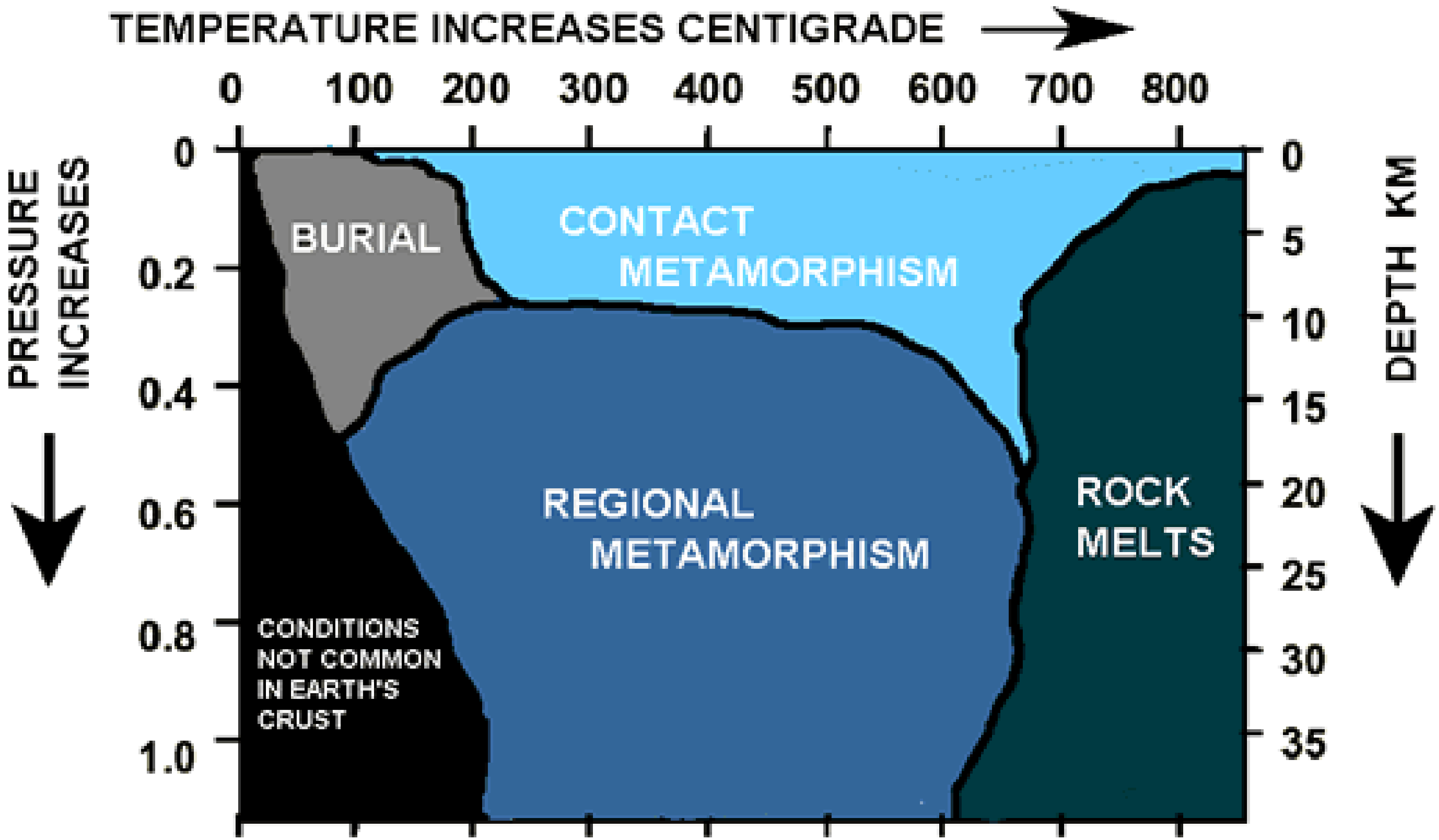
Metamorphic Facies of Subduction Zones




0
10
20
30
40
Depth (km)
Contact metamorphism
d
SLATE
Zeolite
and clay
PHYLLITE
Typical geothermal gradient
Volcanic region T gradient
b & e
Amphibolite
Granulite
SCHIST
a
GNEISS
MIGMATITE
Greenschist
Subduction zone T gradient
c
Blueschist
Wet granite melts
Eclogite
Conditions
that don't
exist on Earth

Burial metamorphism

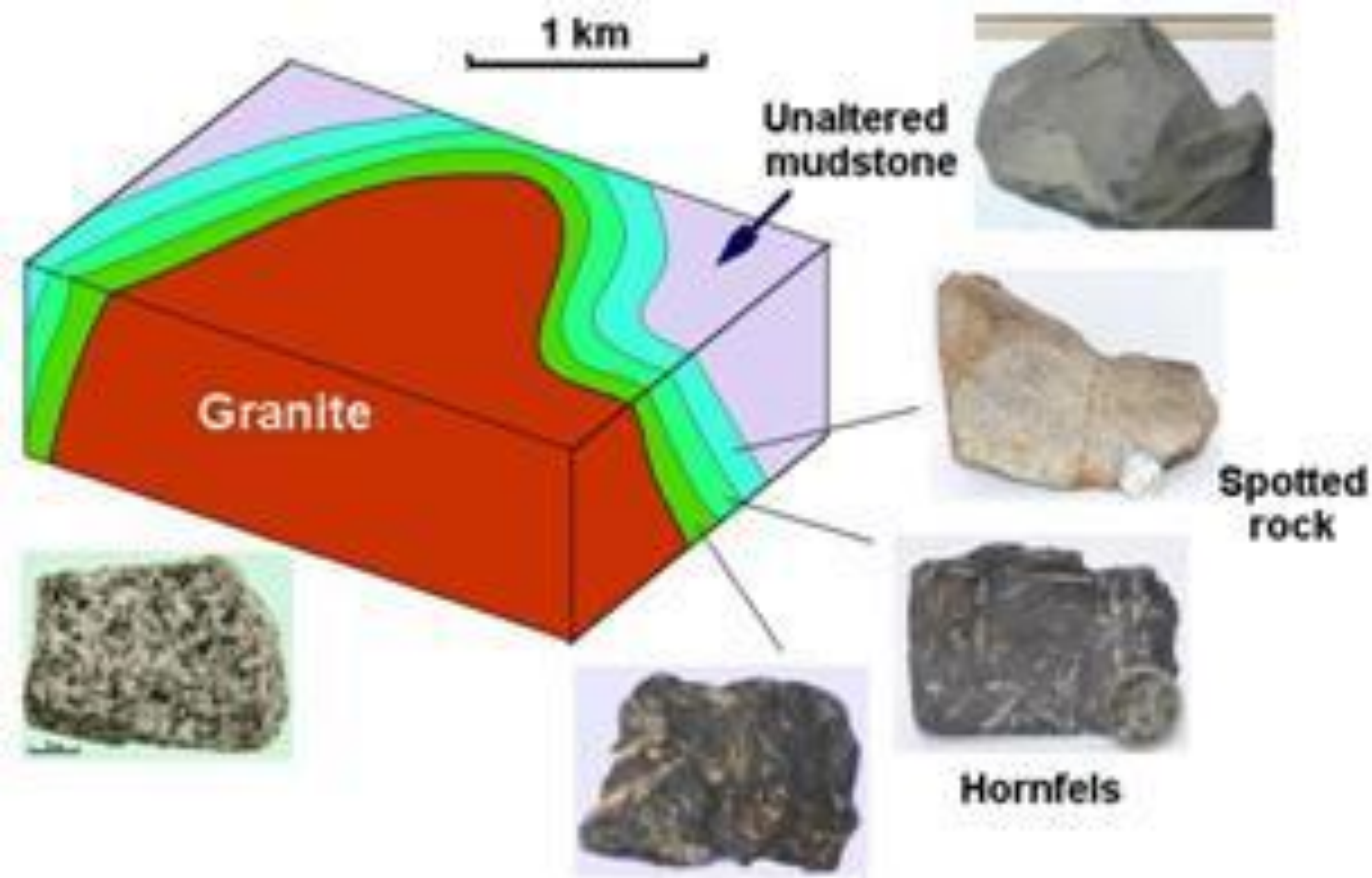
- occurs when sedimentary rocks that had undergone diagenesis are buried even deeper. Diagenesis grades into **burial metamorphism**, a relatively mild type of **metamorphism** resulting from the heat and pressure exerted by overlying sediments and sedimentary rocks.



TEMPERATURE INCREASES CENTIGRADE
0
100
200
300
400
500
600
700
800
PRESSURE INCREASES
0
0.2
0.4
0.6
0.8
1.0
DEPTH KM
0
5
10
15
20
25
30
35
BURIAL
CONTACT METAMORPHISM
REGIONAL METAMORPHISM
ROCK MELTS
CONDITIONS NOT COMMON IN EARTH'S CRUST

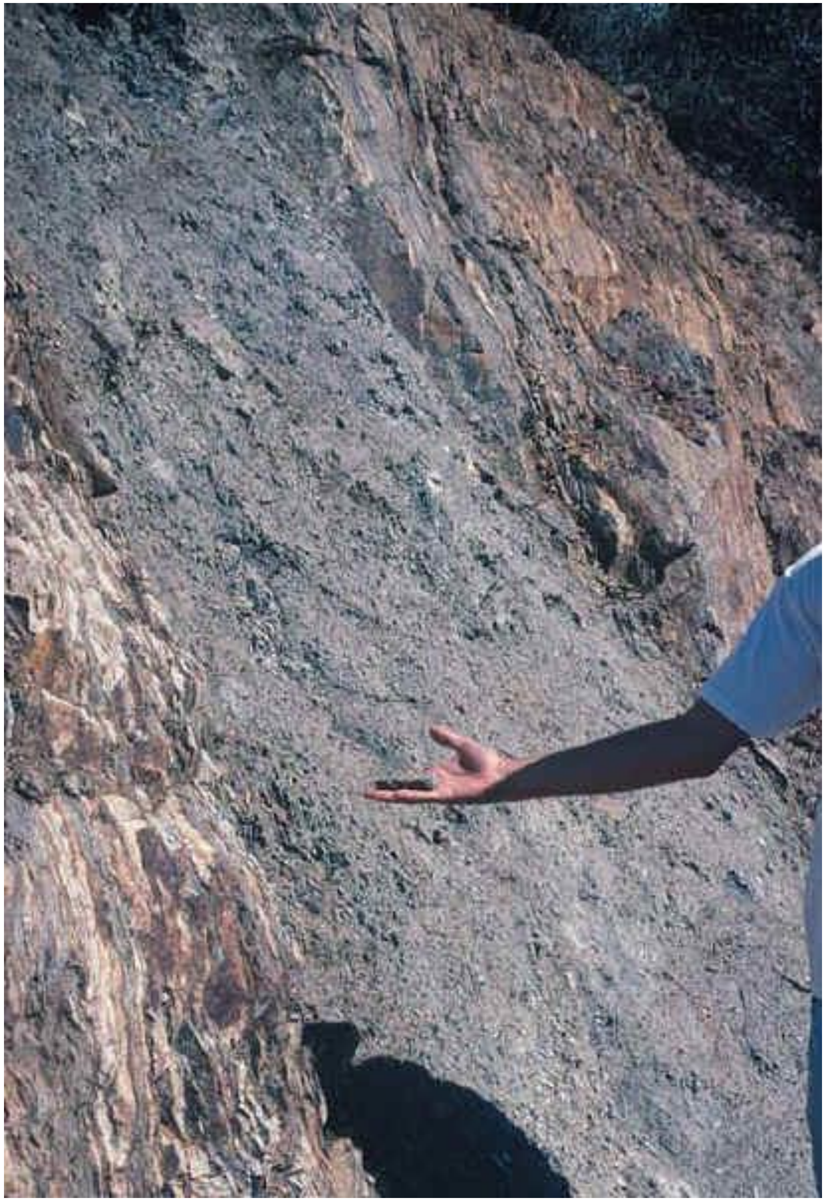
Contact or thermal metamorphism

Is a type of **metamorphism** where rock minerals and texture are changed, mainly by heat, due to **contact** with magma.


1 km
Unaltered
mudstone
Granite
Spotted
rock
Hornfels

Cataclastic or shear zone metamorphism

- Restricted to the vicinity of faults of overthrusts in the upper crust level (brittle deformation

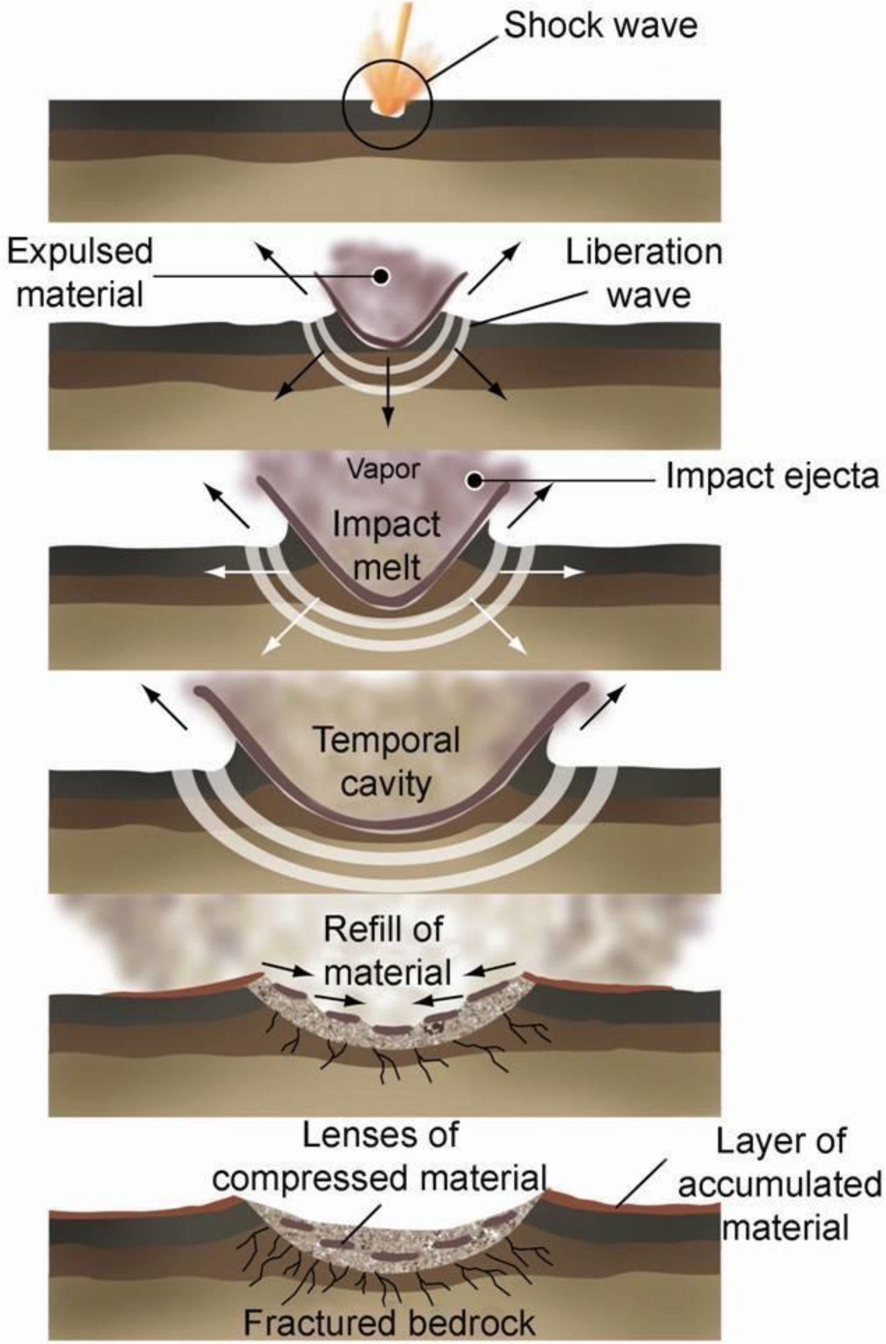


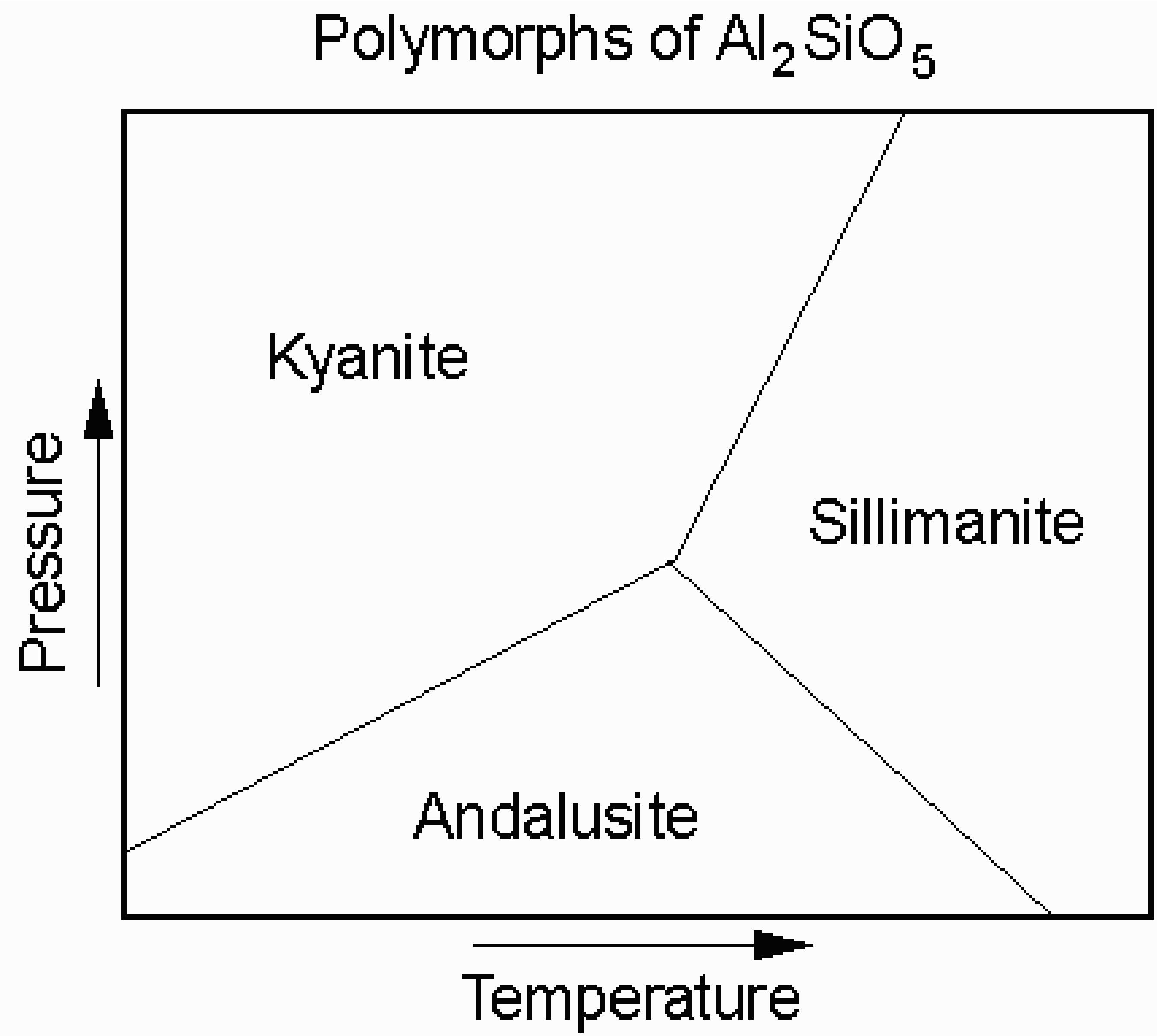
Hydrothermal metamorphism

occurs when hot, chemically active, mineral laden waters interact with a surrounding pre-existing rock (called the country rock).

Impact or shock metamorphism

- occurs when high heat and pressures generated during an **impact** deform the underlying rock layers.


Shock wave
Expulsed material
Liberation wave
Vapor
Impact ejecta
Impact melt
Temporal cavity
Refill of material
Lenses of compressed material
Layer of accumulated material
Fractured bedrock


Polymorphs of Al2SiO5
Kyanite
Sillimanite
Andalusite
Pressure
Temperature

Textures

Careful observation in the field can help build an early understanding of complex rocks, avoid misleading assumptions and help with both sampling and collection of field data.

Banding

- Primary banding, i.e., *cross - lamination*
- Secondary banding

Grain textures

A key observation is whether the rock displays orientated crystals (typical of deformed, regionally metamorphosed rocks), or granular texture. The latter may indicate contact metamorphism caused by a nearby igneous body

Reaction textures

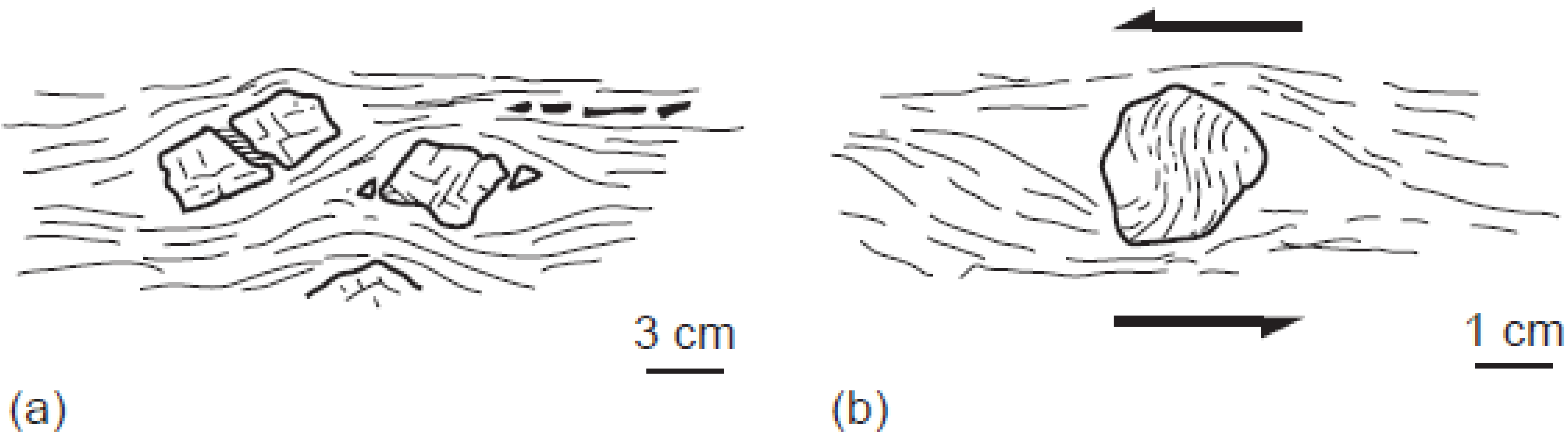
- **Pseudomorphs** are aggregates of new mineral grains that have formed by alteration or replacement of a pre – existing porphyroblast. In many cases, the aggregate retains the form of the original crystal.
- **Coronas** may indicate partial replacement of a mineral by another, or represent a rim of new mineral formed at the interface between two others.

Identifying common metamorphic minerals

Pressure/ temperature conditions	Pelitic (mudstone)	Mafic (basalt)	Felsic (granite)	Ultramafic (peridotite)	Calc-silicate (impure limestone)
LT	Chlorite	Chlorite	Chlorite, epidote	Serpentine	Talc
LP	Andalusite, cordierite No garnet	Pyroxenes, olivine No garnet	Andalusite		
MP/T	Chloritoid, staurolite	Actinolite, epidote, zoisite		Talc (abundant)	Tremolite
HP	Kyanite, talc, rutile No plagioclase	Lawsonite, Na-pyroxene, rutile, glaucophane No plagioclase	Na-pyroxene, kyanite No plagioclase		Zoisite
HT	Sillimanite, spinel, orthopyroxene No muscovite	Clinopyroxene, orthopyroxene	Orthopyroxene, cordierite, sillimanite	Orthopyroxene	Wollastonite, Mg-olivine, Ca-pyroxene, spinel
Wide P and T ranges	Muscovite, biotite, garnet, quartz, plagioclase	Garnet, hornblende, plagioclase, biotite, quartz, titanite	Quartz, biotite, K-feldspar, plagioclase, muscovite	Olivine, chlorite, magnesite	Calcite, dolomite, plagioclase, Ca-garnet, hornblende, chlorite, epidote

Syn-, Pre - kinematic features

- Early porphyroblasts are commonly wrapped by later tectonic foliations. Pre - kinematic grains or clasts may be cracked, bent or even pulled apart



a) Pre - kinematic, broken K - feldspar grains and a boudinaged tourmaline crystal (top right), wrapped by a high - strain foliation. (b) Syn - kinematic garnet with curved inclusion trails, showing inferred shear sense.

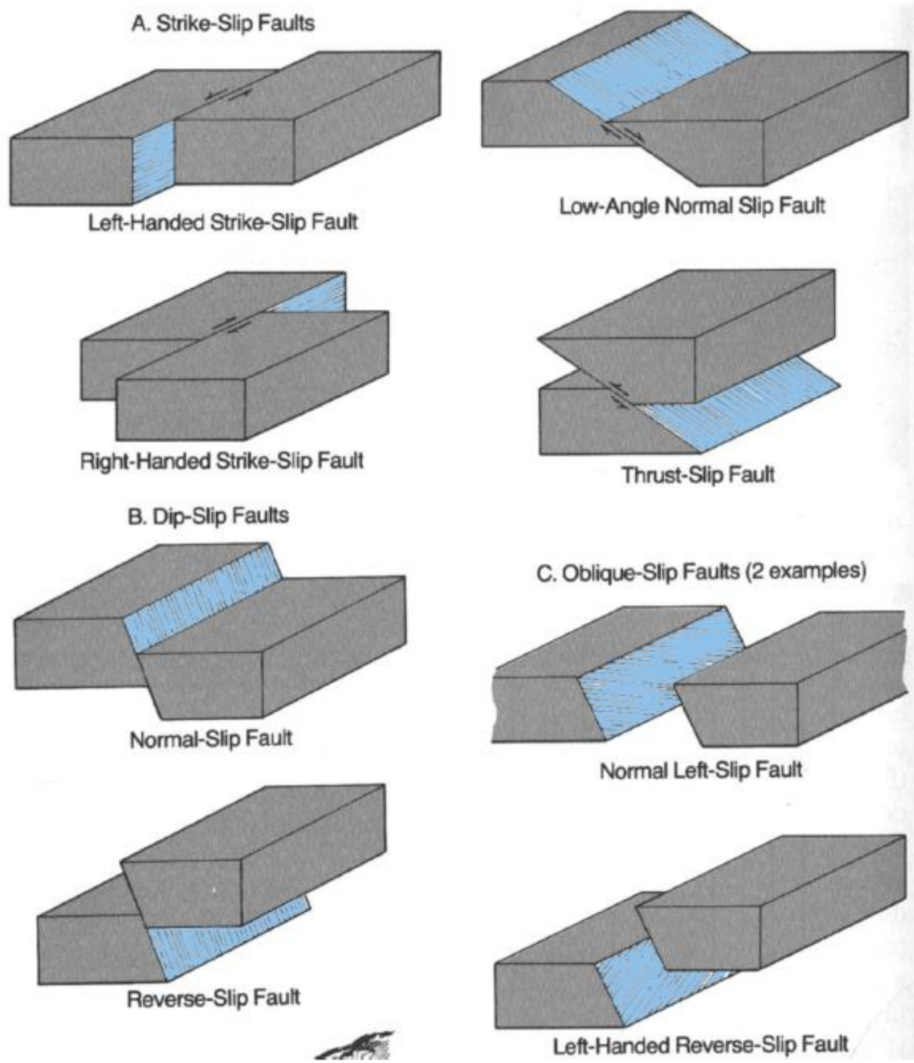
Post- kinematic features

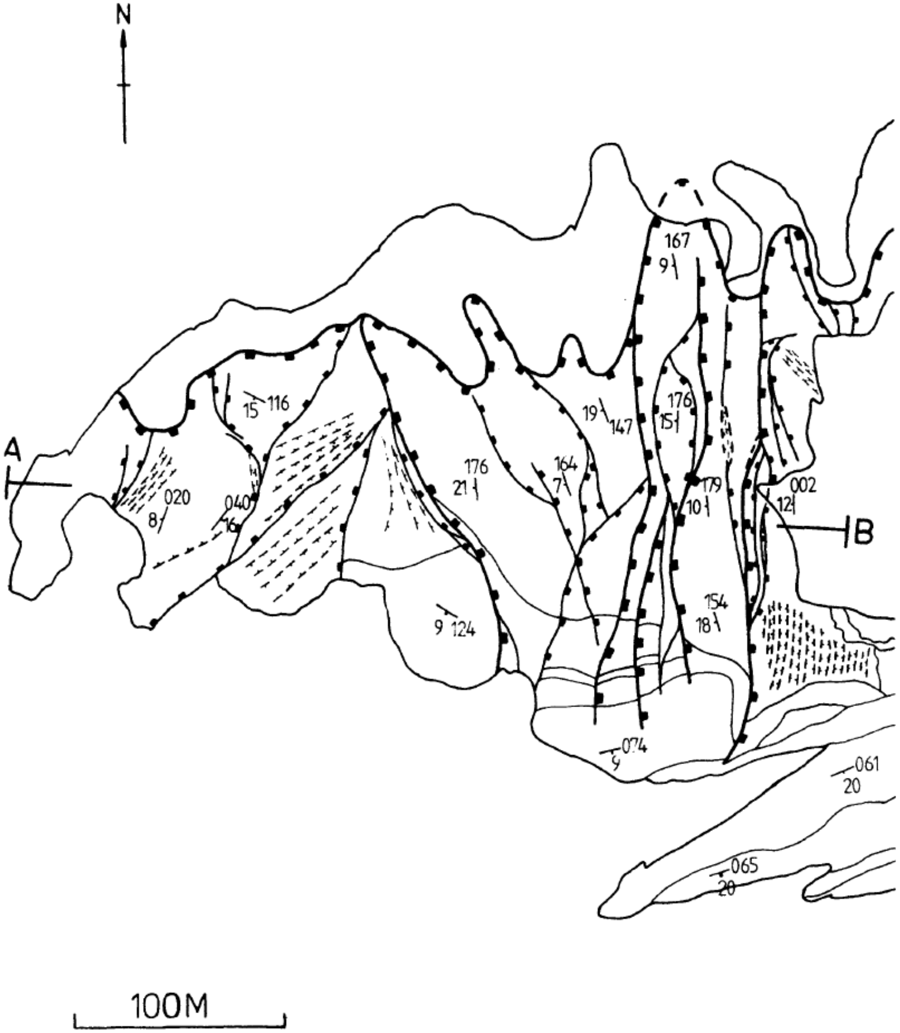
- Post - kinematic features generally show random orientation, indicating static, post - kinematic development.

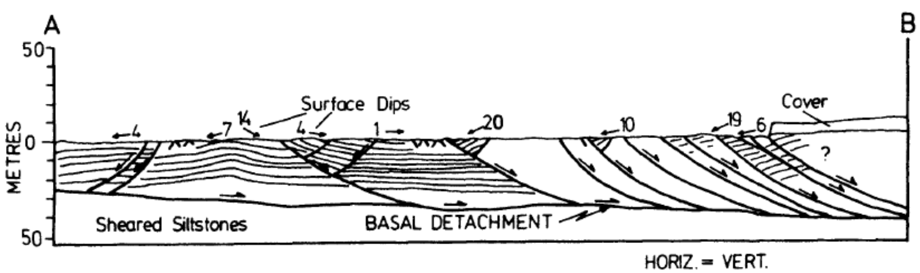
Recording structural information

Brittle structures: Faults, joints and veins

- *Normal faults σ*1 is vertical and σ*2* and σ3*,* are horizontal. The dips of the fault planes are ~ 60°.
- *Wrench or strike-slip faults σ2* is vertical and σ1 and σ3 are horizontal. In this case the fault planes are vertical and the movement direction is horizontal, i.e. strike-slip.
- *Reverse faults σ3* is vertical and σ1 and σ*2* are horizontal. The fault planes dip at approximately 30° to the horizontal.

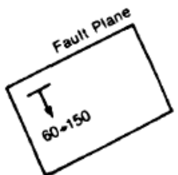
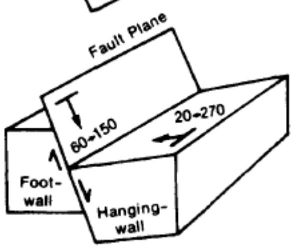
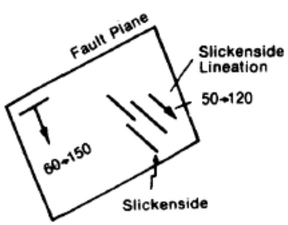

A. Strike-Slip Faults
Left-Handed Strike-Slip Fault
Right-Handed Strike-Slip Fault
B. Dip-Slip Faults
Normal-Slip Fault
Reverse-Slip Fault
Low-Angle Normal Slip Fault
Thrust-Slip Fault
C. Oblique-Slip Faults (2 examples)
Normal Left-Slip Fault
Left-Handed Reverse-Slip Fault

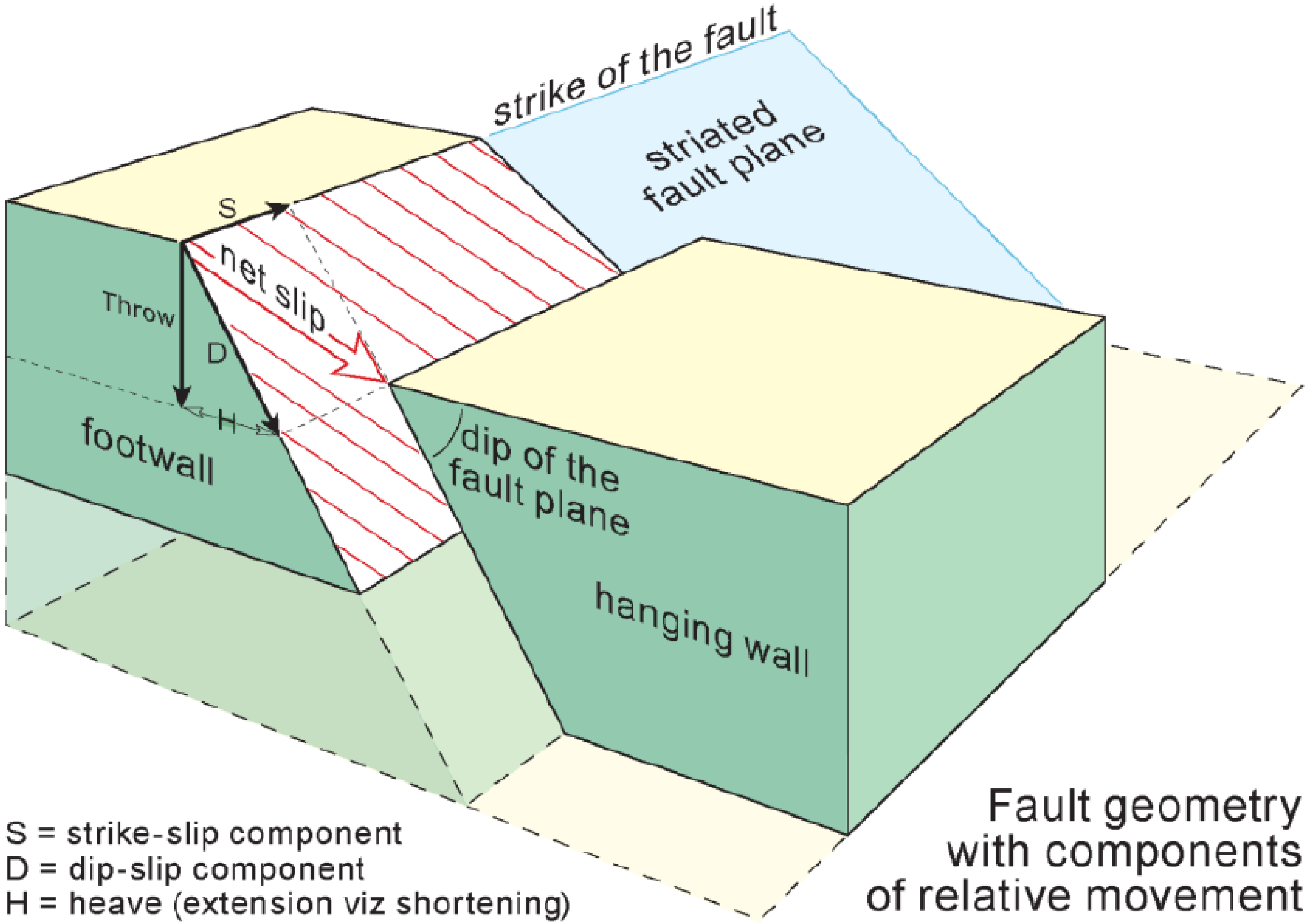


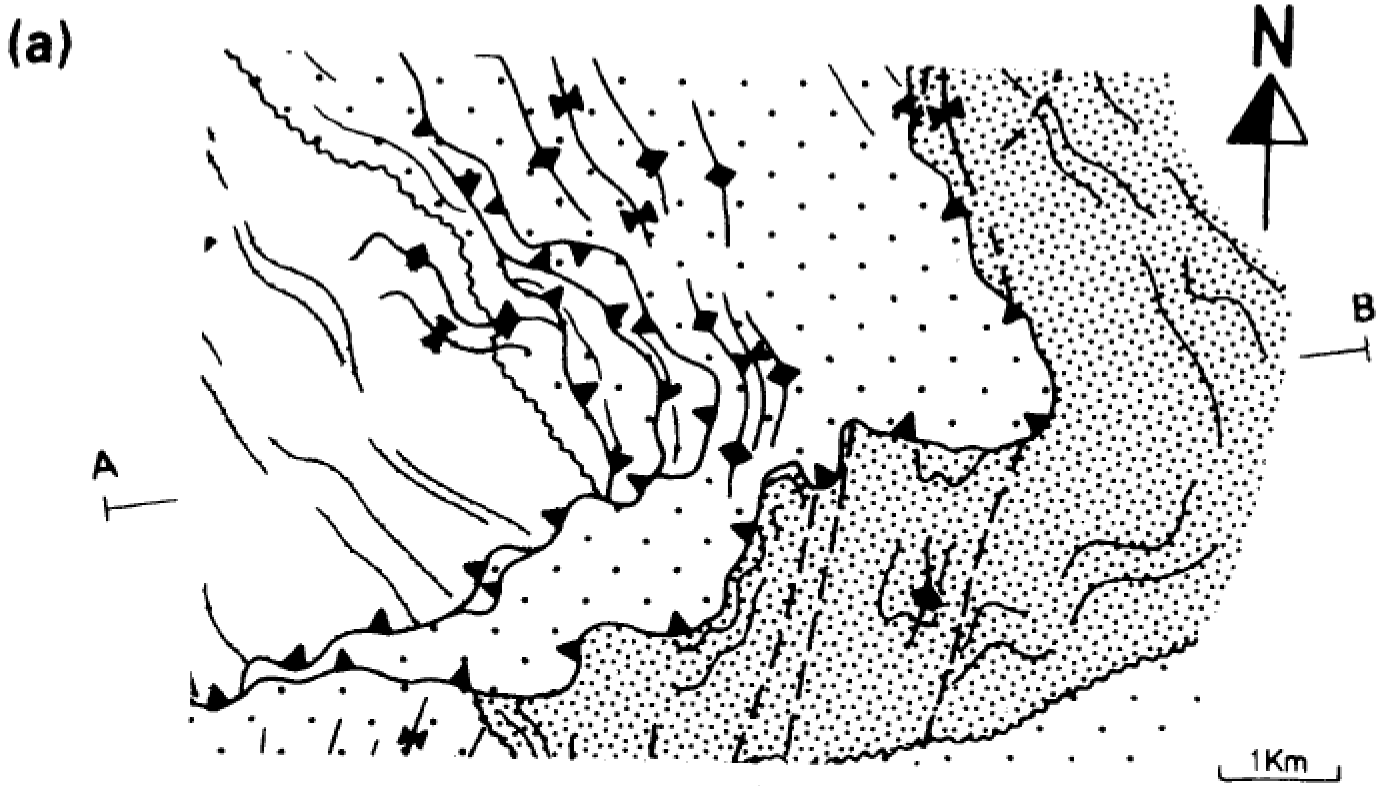


Mapping of normal faults

Table 6.1 Data to be collected from extensional faults.

Structure	*What to Measure*	*What Observations to Record*	*Results of Analysis*
	Orientation of fault plane (dip direction) (Figs. 2.5–2.8).	Nature of fault plane: fault rocks. Curvature of fault plane? Width of fault.	Deformation processes. Listric/planar faulting. (Fig. 6.8)
	Orientation of displaced units on both sides of fault (Figs. 2.5–2.8).	Stratigraphic separation. (Fig. 6.2) Sense of movement. Sense of shear.	Displacement direction. (Fig. 6.6) Minimum slip. Amount of extension.
	Lineations on fault plane: grooving, slickensides, slickolites (Figs. 2.10–2.13; Figs. 5.6 & 6.4).	Nature of lineations on fault plane (fibrous slickensides?). (Table 5.3) Movement sense. (Fig. 5.6)	Movement direction. (Fig. 5.6)
		Relationship to other faults. Cross-cutting relationships. Associated folding. (Fig. 3.13)	Fault sequences. (Fig. 6.8) Kinematic development.
	Orientation data on synthetic structures (Fig. 6.8c): faults and fractures (Figs. 2.5–2.8; 2.11–2.13).	Nature of synthetic structures. Movement directions. (Fig. 5.6)	Fault systems. (Fig. 6.6) Movement patterns. Stress systems. (Fig. 6.1)
	Orientation data on antithetic structures (Fig. 6.8c): faults and fractures (Figs. 2.5–2.8, 2.11–2.13).	Nature of antithetic structures. Movement directions. (Fig.5.6)	Fault systems. (Fig. 6.6) Movement patterns. Stress systems. (Fig. 6.1)


strike of the fault
striated fault plane
S
net slip
Throw
D
H
footwall
dip of the fault plane
hanging wall
S = strike-slip component
D = dip-slip component
H = heave (extension viz shortening)
Fault geometry with components of relative movement



Thrust mapping

Table 6.2 Data to be collected from contractional faults.

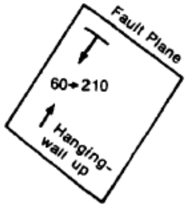
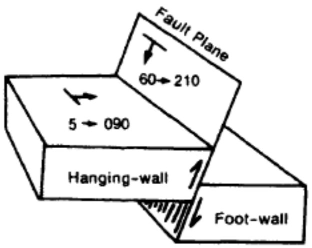
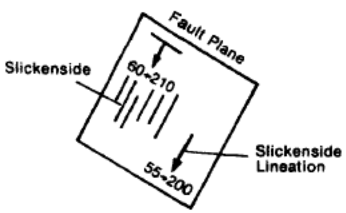
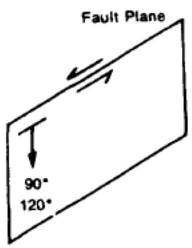
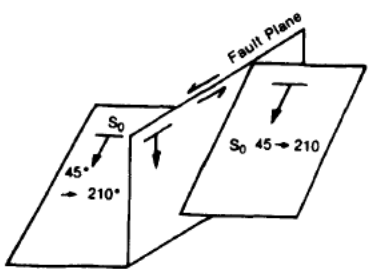
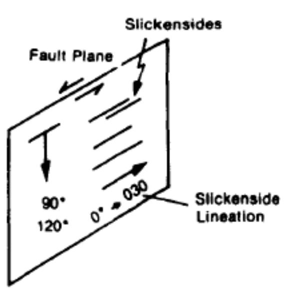
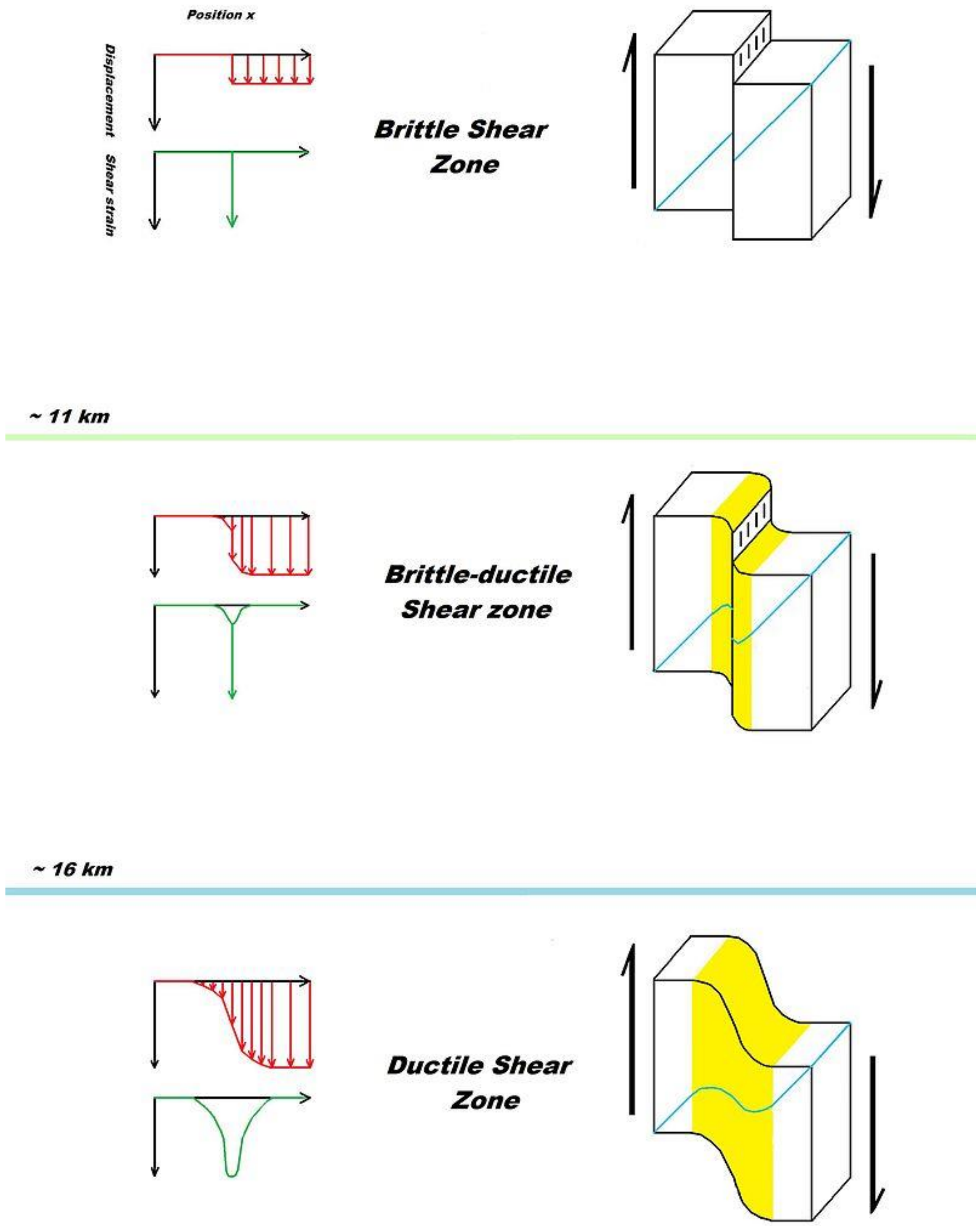
Structure	*What to Measure*	*What Observations to Record*	*Results of Analysis*
	Orientation of fault plane (dip direction) (Figs. 2.5–2.8).	Nature of fault plane: fault rocks. (Fig. 6.18, Table 6.4) Curvature/stepped nature of fault plane? Width of fault zone. (Fig. 6.11)	Deformation processes. Listric/planar/stepped fault. (Fig. 6.11a)
	Orientation of displaced units on both sides of fault (Figs. 2.5–2.8).	Stratigraphic separation/overlap. Sense of movement. Sense of shear.	Displacement direction. (Fig. 5.6) Minimum slip. Amount of contraction.
	Lineations on fault plane: grooving, slickensides, slickolites (Figs. 2.4–2.13, 5.6 and 6.4).	Nature of lineations on fault plane (fibrous slickensides?). (Table 5.3) Movement sense. (Fig. 5.6)	Movement direction. (Fig. 5.6)
		Relationships to other faults. Cross-cutting relationships: Imbricate fan? duplex? out of sequence? Ramps? Associated folding. (Figs. 6.11a and 3.13)	Fault sequences. Kinematic development.
	Orientation data on synthetic structures: faults and fractures (Figs. 2.5–2.8, 2.11–2.13),	Nature of synthetic structures. Movement directions. (Fig. 5.6)	Fault systems. Movement patterns. Stress systems. (Fig. 6.1)
	Orientation data on antithetic structures: faults and fractures (Figs. 2.5–2.8, 2.11–2.13).	Nature of antithetic structures. Movement directions. (Fig. 5.6)	Fault systems. Movement patterns. Stress systems. (Fig. 6.1)

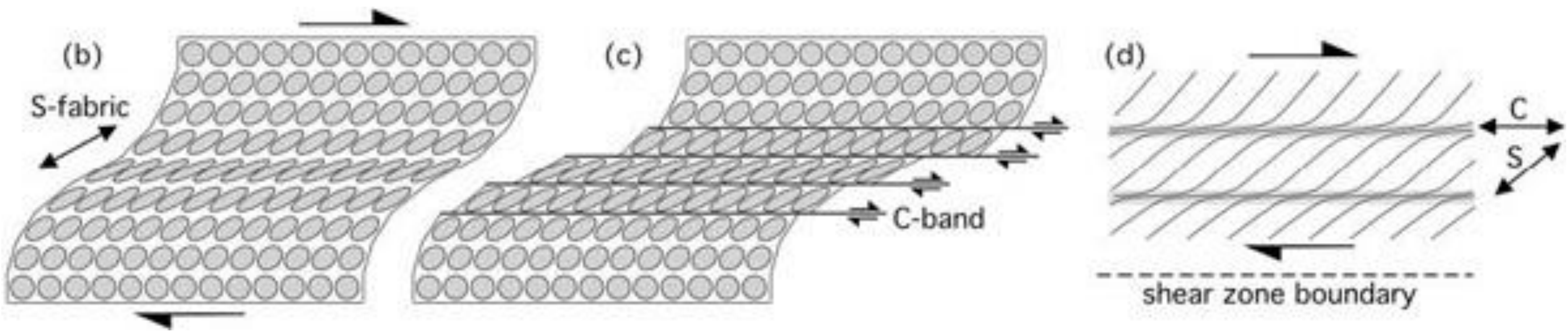
Table 6.3 Data to be collected from wrench faults.

Structure	*What to Measure*	*What Observations to Record*	*Results of Analysis*
	Orientation of fault plane (dip direction) (Figs. 2.5–2.8 and 6.1).	Nature of fault plane fault rocks. (Fig. 6.18 and Table 6.4) Width of fault zone.	Deformation processes.
	Orientation of displaced units on both sides of fault (Figs. 2.5–2.8).	Movement direction. (Fig. 5.6) Sense of shear.	Displacement direction. (Fig. 5.6) Amount of slip/offset.
	Lineations on fault plane: grooving, slickensides, slickolites (Figs. 5.6, 6.4; 2.11–2.13).	Nature of lineations on fault plane (fibrous slickensides?). (Table 5.3) Movement sense. (Fig. 5.6)	Movement direction. (Fig. 5.6)
		Relationships to other faults. Cross-cutting relationships. Associated folding.	Fault sequences. (Figs. 6.16 and 6.19) Kinematic development. (Fig. 6.16a)
	Orientation data on synthetic structures Riedel shears R_1, R_2, P shear (Fig. 6.16a). Second and third order faults Associated folds (Fig. 6.16a).	Nature of synthetic structures. (Fig. 6.16a) Movement directions. (Fig. 5.6)	Fault systems. (Fig. 6.16a) Movement patterns. (Fig. 6.16a) Stress systems. (Fig. 6.16a)


Position x
Displacement
Shear strain
Brittle Shear Zone
~ 11 km
Brittle-ductile Shear zone
~ 16 km
Ductile Shear Zone

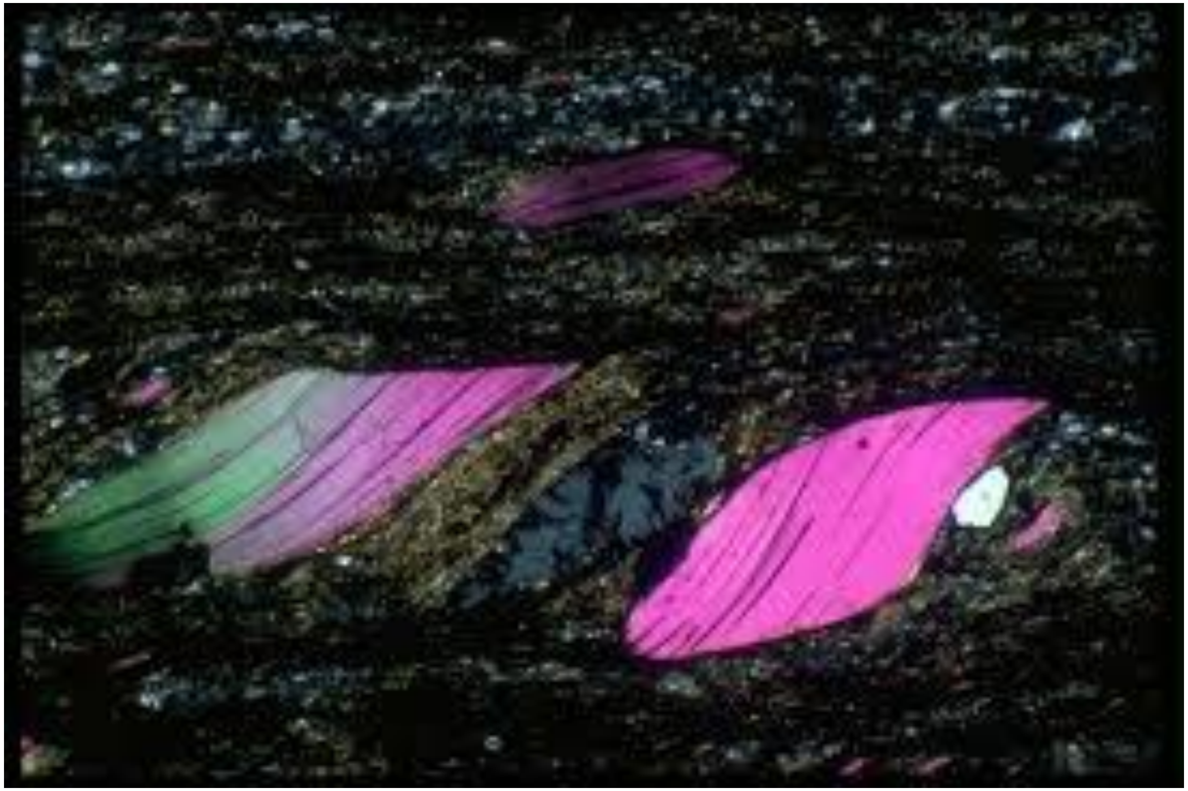
Sense of shear

- S-C fabric
- Shear bands
- Mica fish
- Pressure shadows
- Porphyroclasts (porphyroblasts)
- Veins

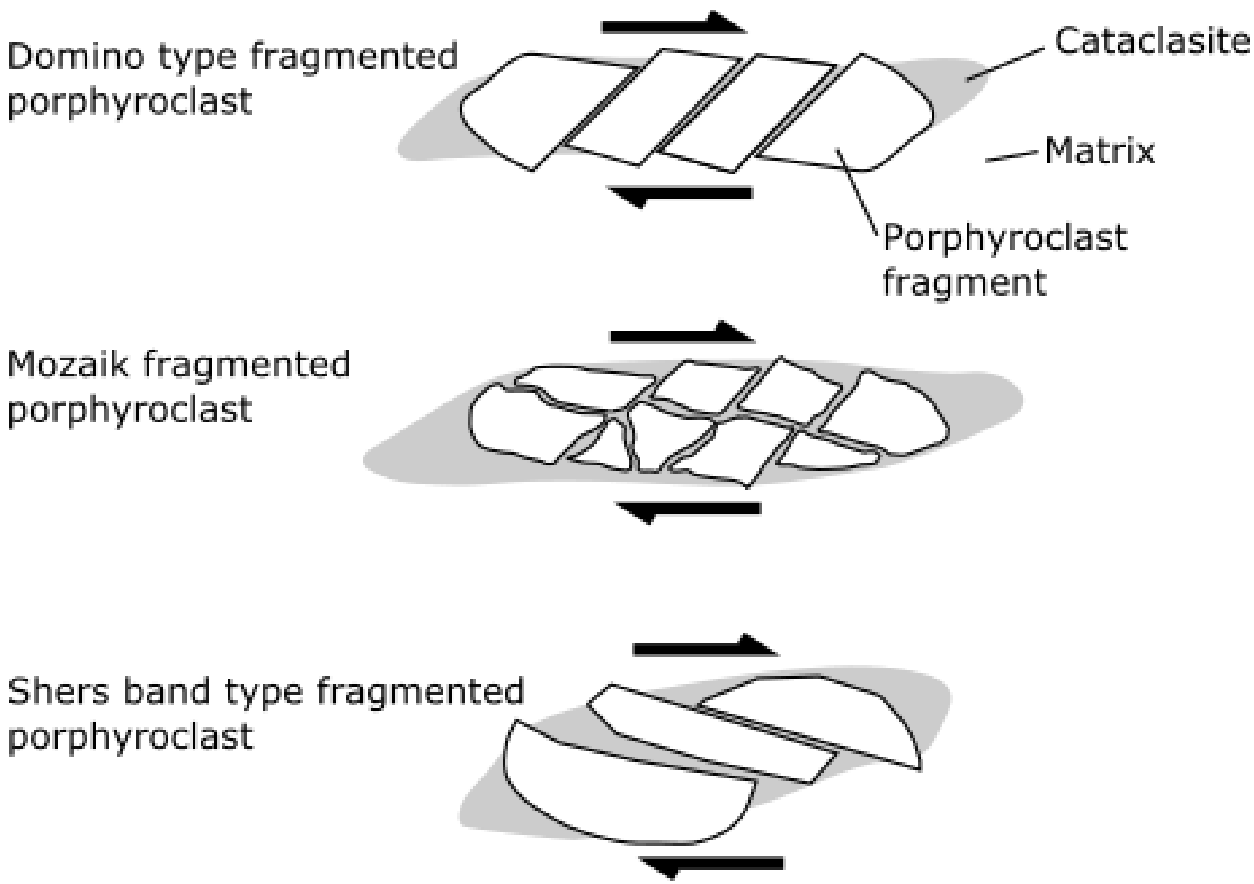


S-C fabric

Mica fish

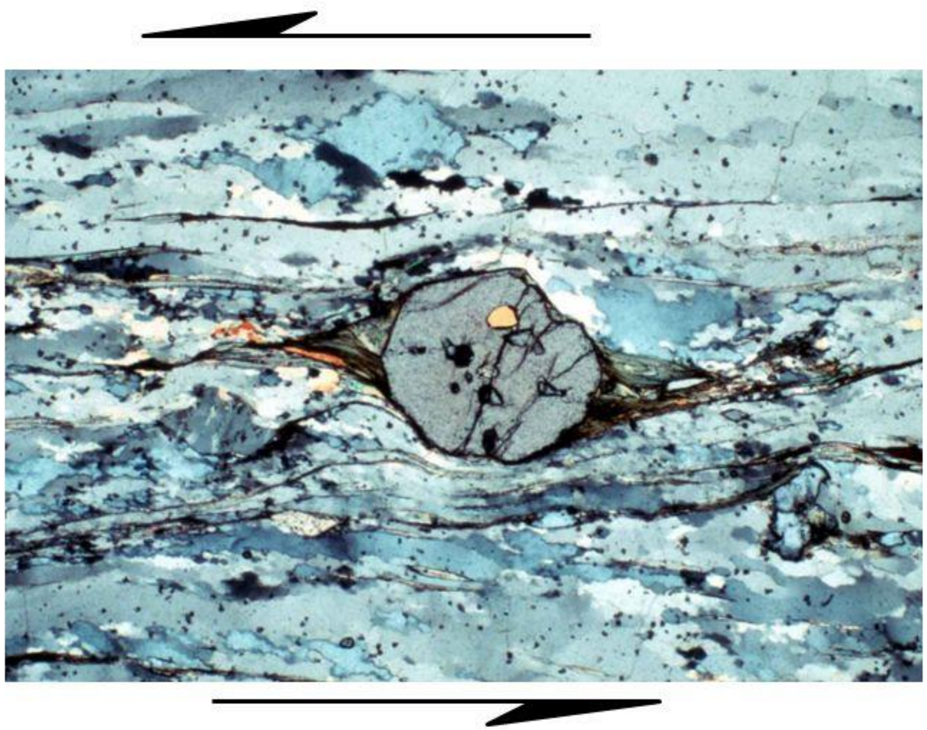


Porphyroclasts

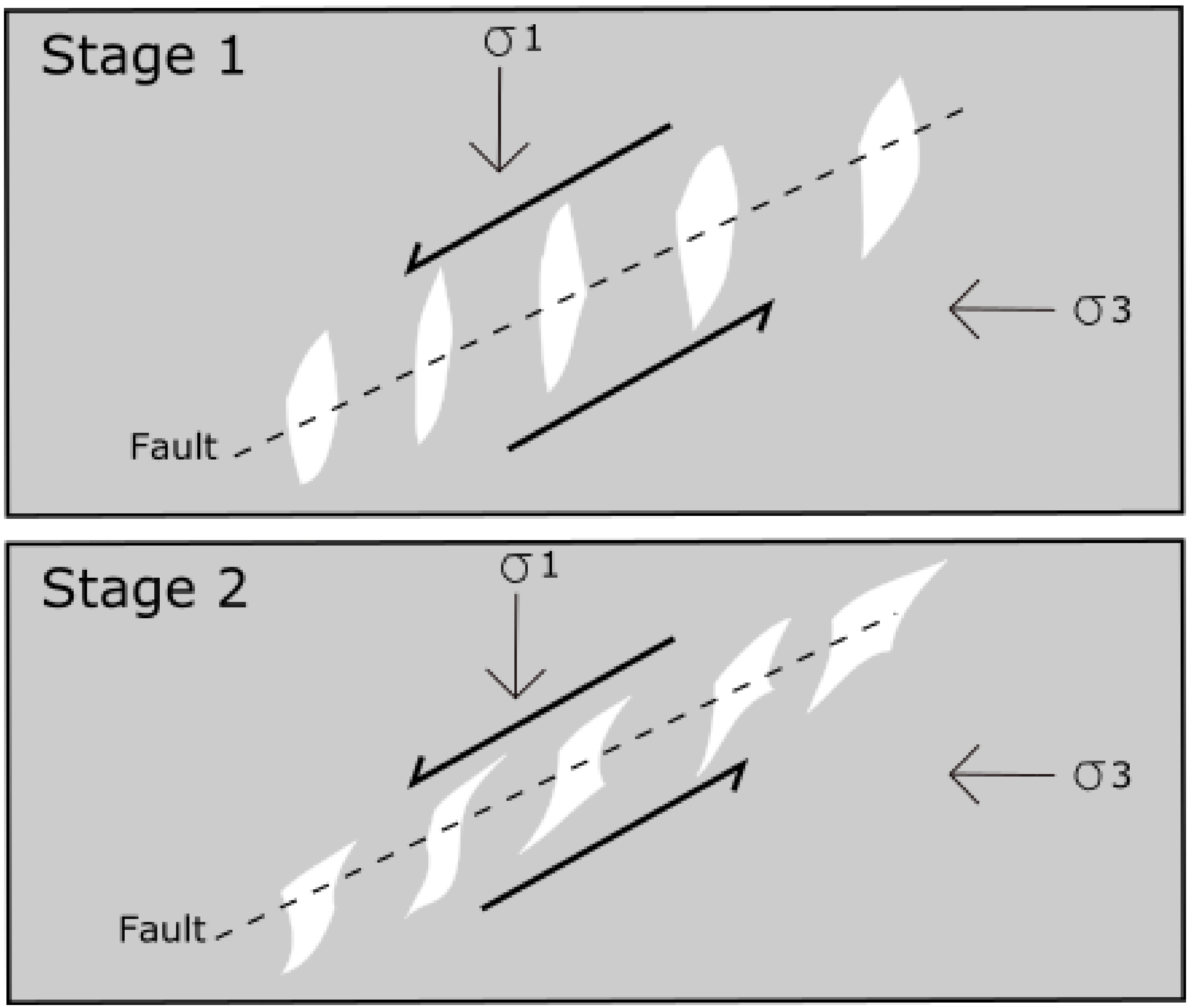


Porphyroblasts

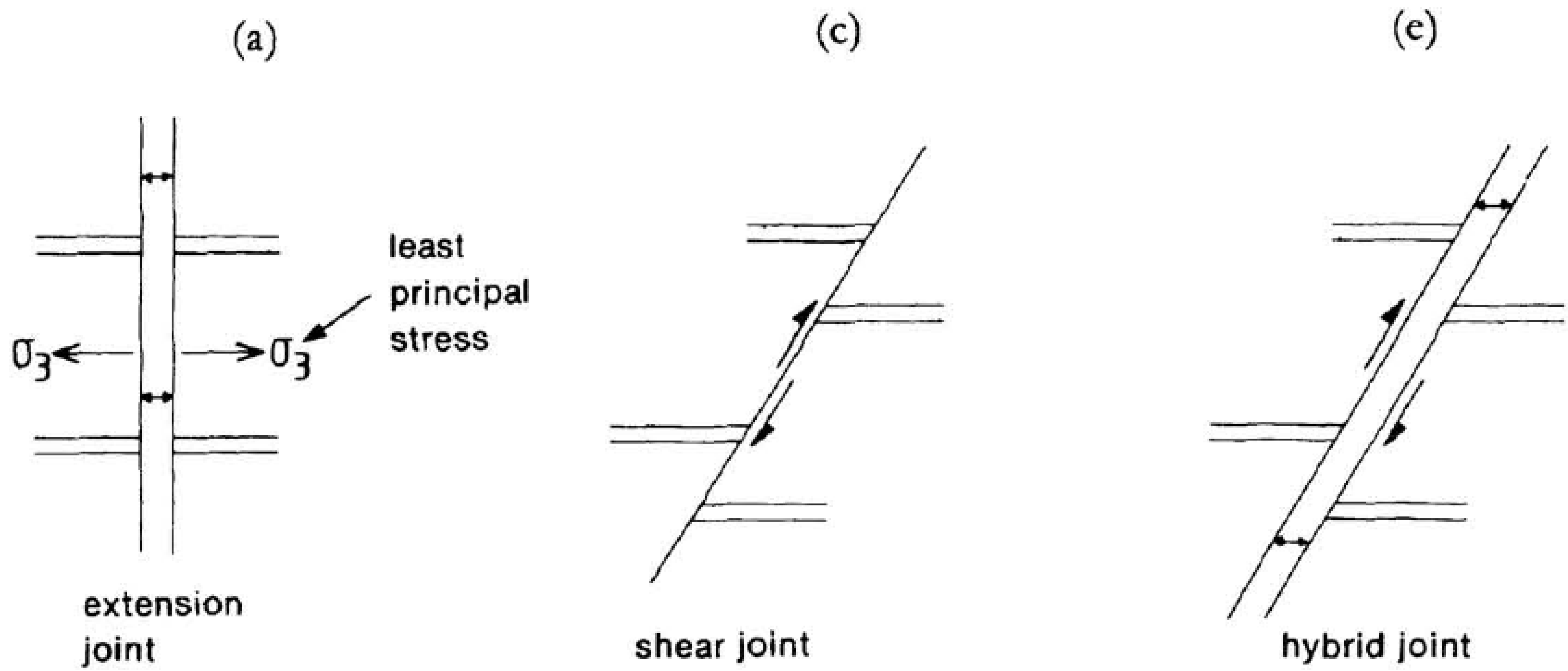
Sense of Shear Indicators



En echelon veins

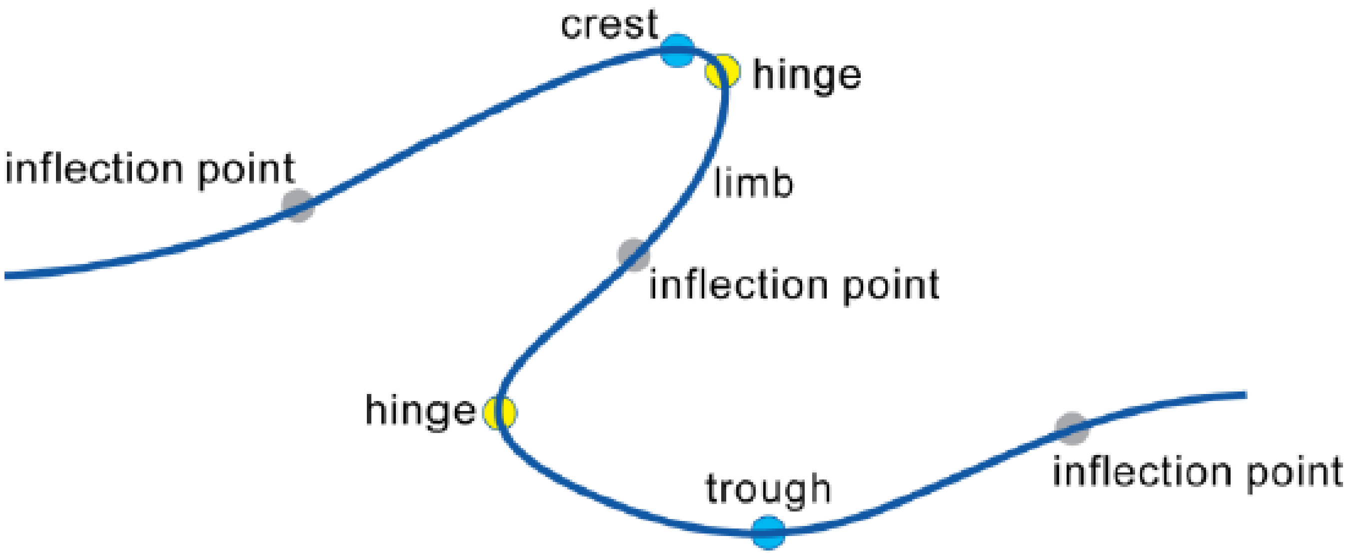


Joints and veins

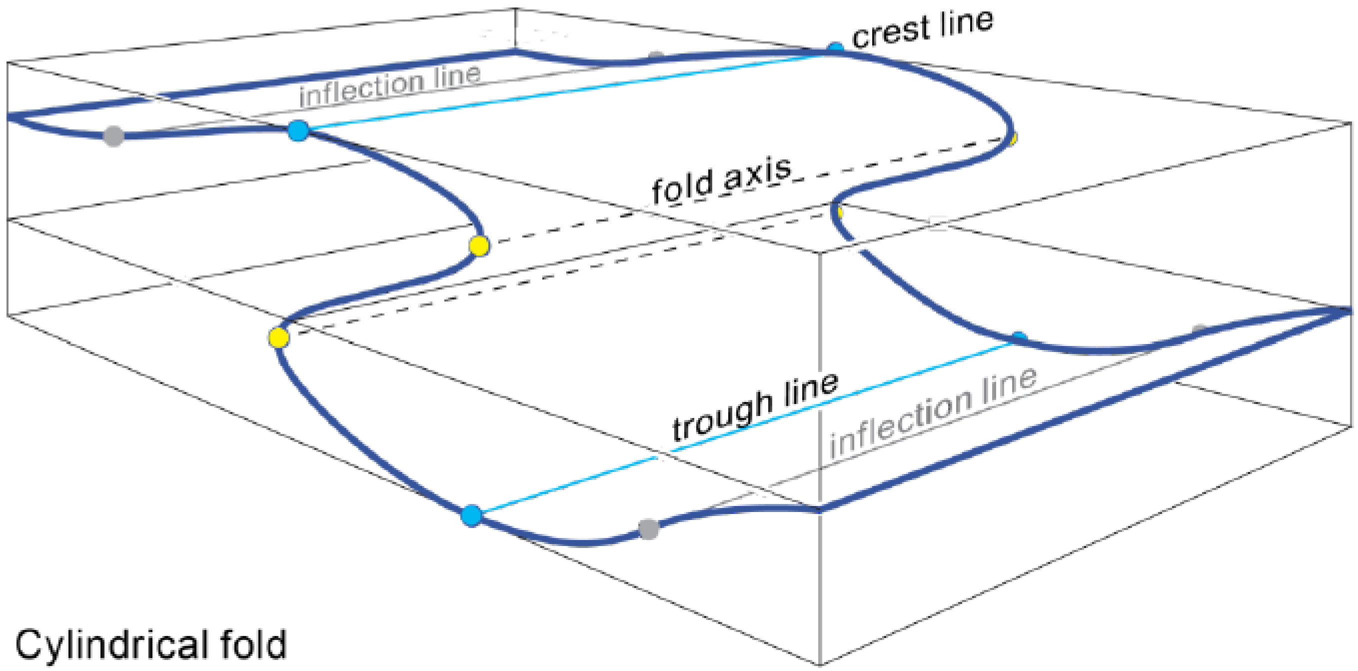


Folds

- The term **fold** is used when one or stacks of originally flat and planar surfaces such as sedimentary beds become bent or curved as a result of plastic (i.e. permanent) and ductile deformation.



Basic terminology on a folded single surface

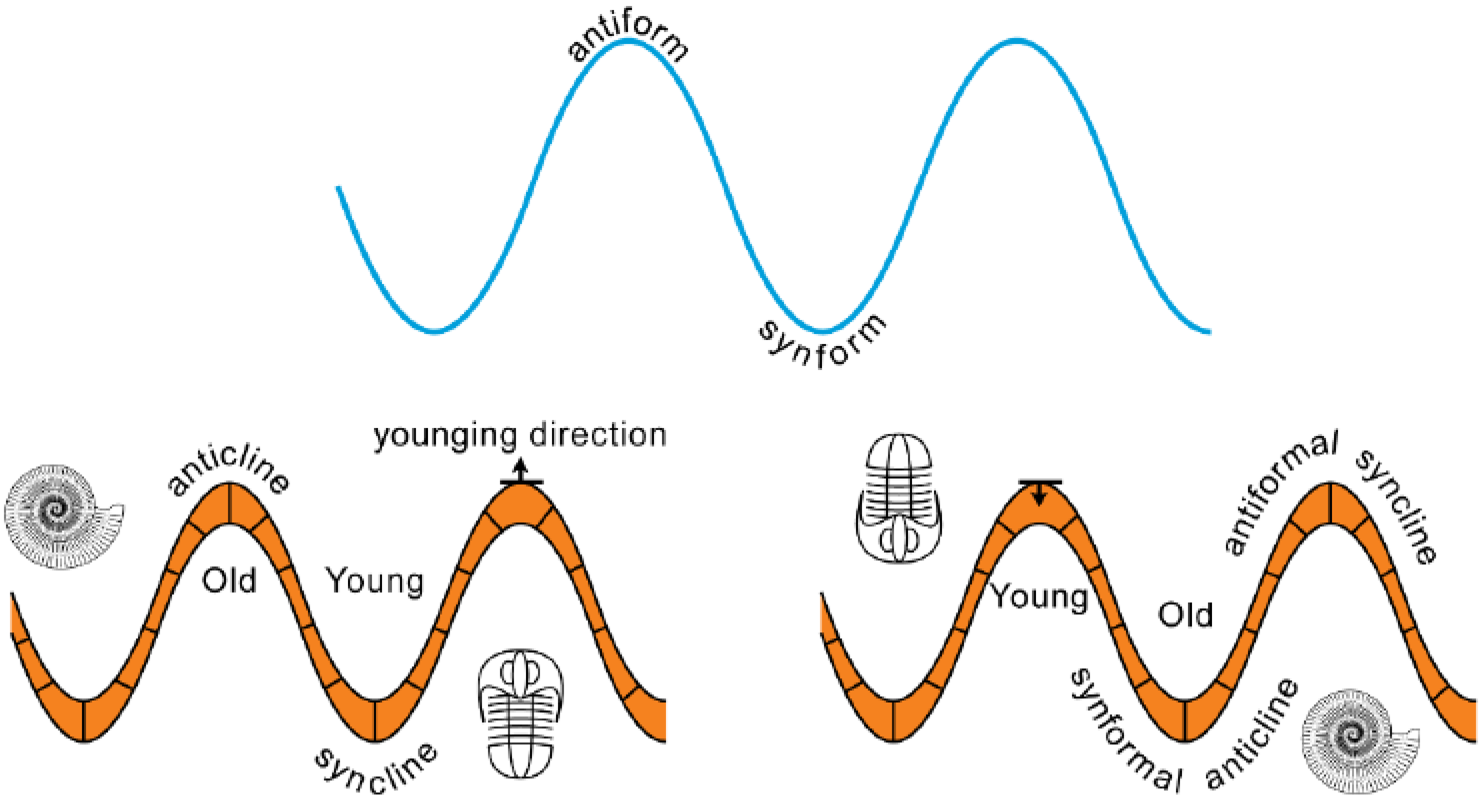


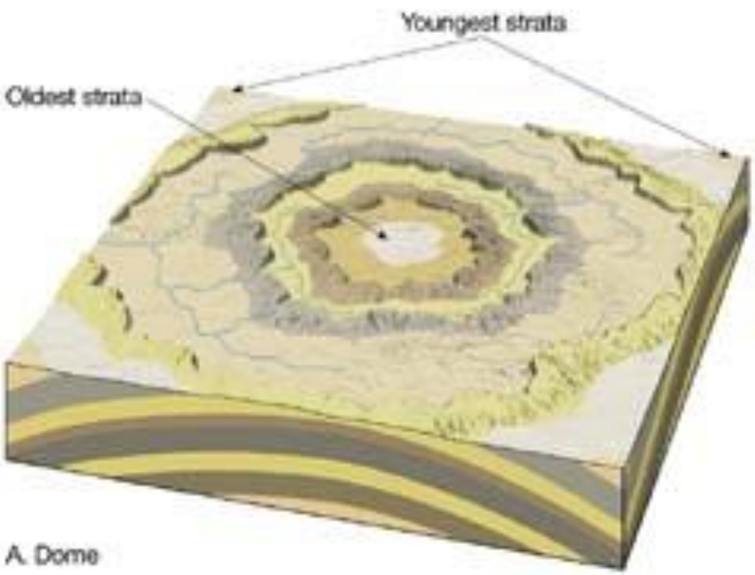
Cylindrical fold

- The point of smallest radius of curvature is called the **hinge.**
- It is flanked by two areas of larger radius of curvature: the **limbs**.
- Connecting the hinge points on a specific folded surface defines the **hinge line** or **fold axis**.
- The **inflection points** are points of zero curvature, where the sense of curvature changes from a convex to a concave line.

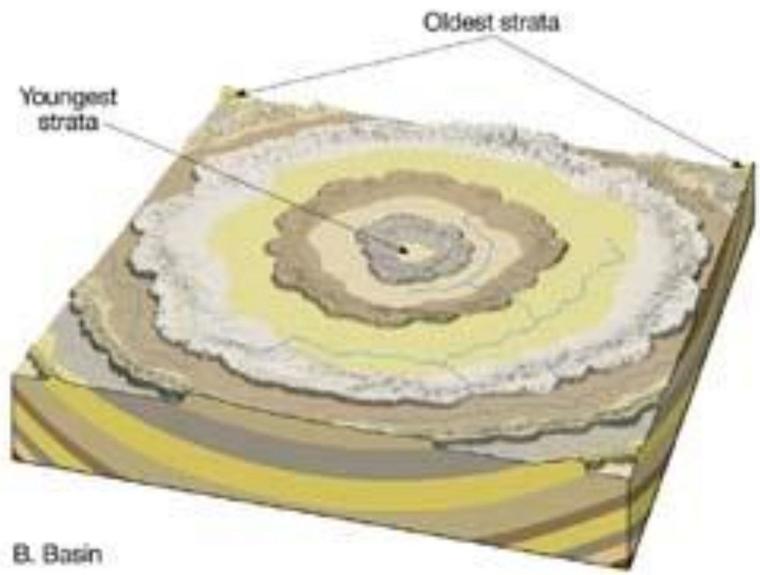
Antiform and synform

- A convex-upward fold is an **antiform**; a convex-downward fold is a **synform**.
- An oval-shaped antiform with no distinct trend of the hinge line, in which layering dips outward from a central point, is termed a **dome**, a synform with no distinct trend of hinge line, i.e. in which layering dips inward toward a central point, is a **basin**.


antiform
synform
anticline
younging direction
Old
Young
syncline
Young
Old
antiformal syncline
synformal anticline



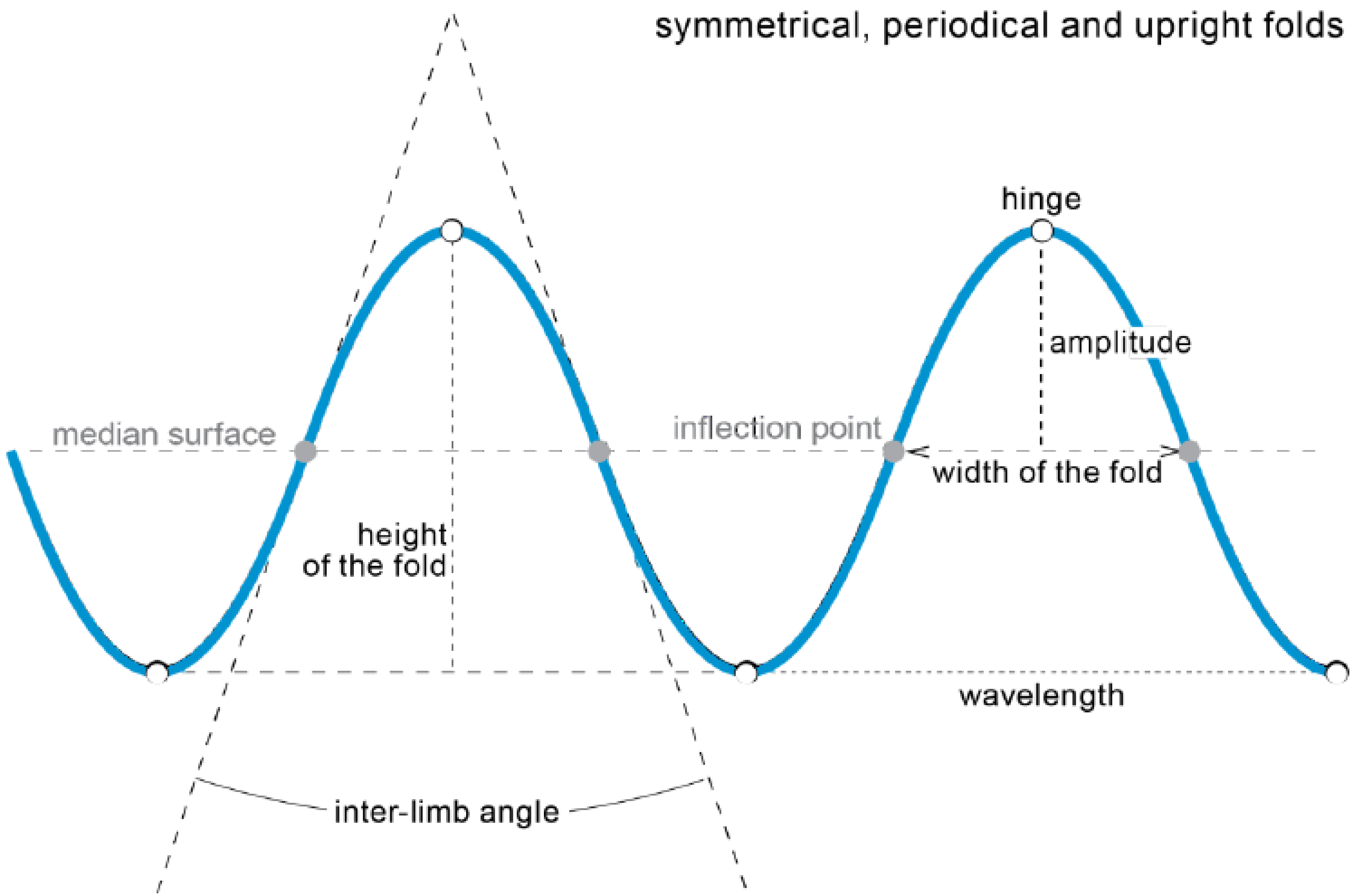
A. Dome



B. Basin

Interlimb angles

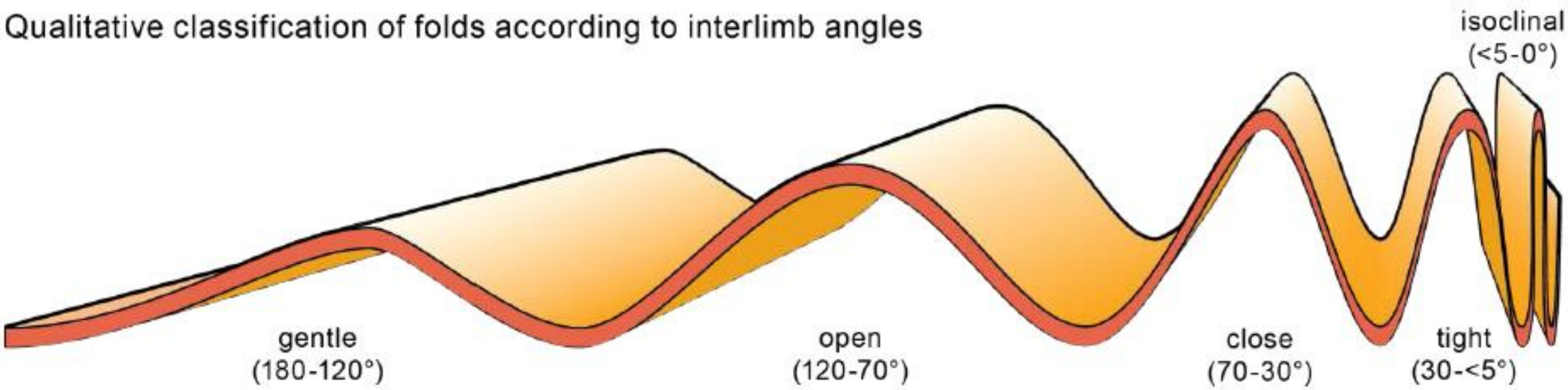
- In profile, the smaller angle made by the limbs of a fold is termed the **inter-limb angle,** a measure of the **tightness of the fold**. It is the angle subtended by the tangents at two adjacent inflection points, which may reflect the intensity of compression.


symmetrical, periodical and upright folds
hinge
amplitude
median surface
inflection point
width of the fold
height
of the fold
wavelength
inter-limb angle

A qualitative classification based on the interlimb angle, separates five tightness classes:

inter-limb angle	tightness class
180 to ca. 120°	Gentle
120 -- 70°	Open
70 -- 30°	Close
less than 30°	Tight
0°, i.e. parallel limbs	Isoclinal
< 0°	Fan

Qualitative classification of folds according to interlimb angles



Fan folds have negative interlimb angles

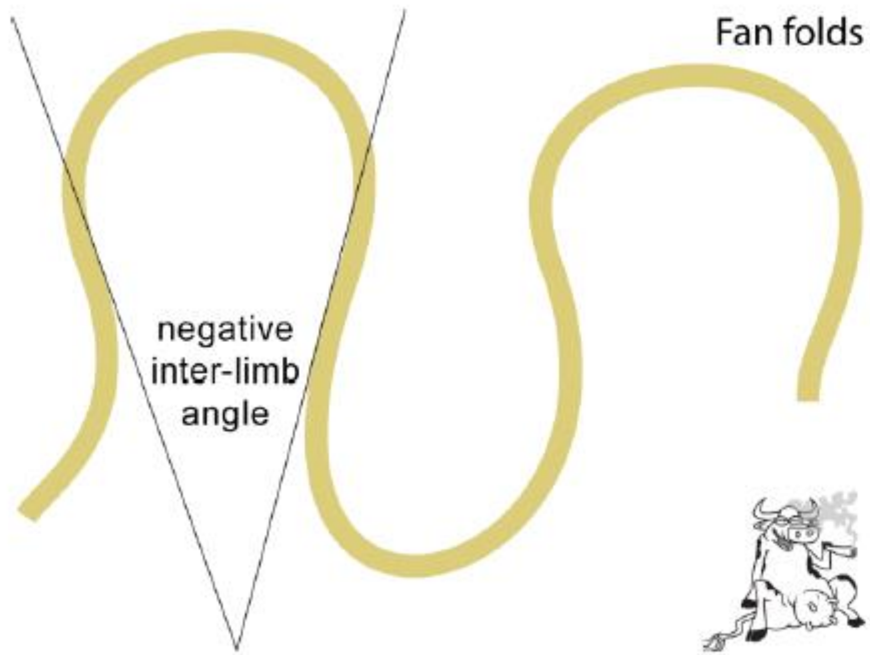
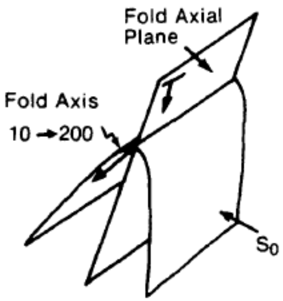
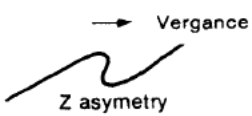
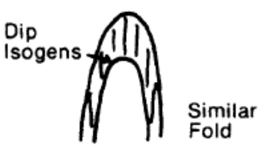
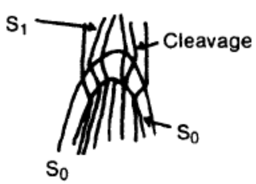
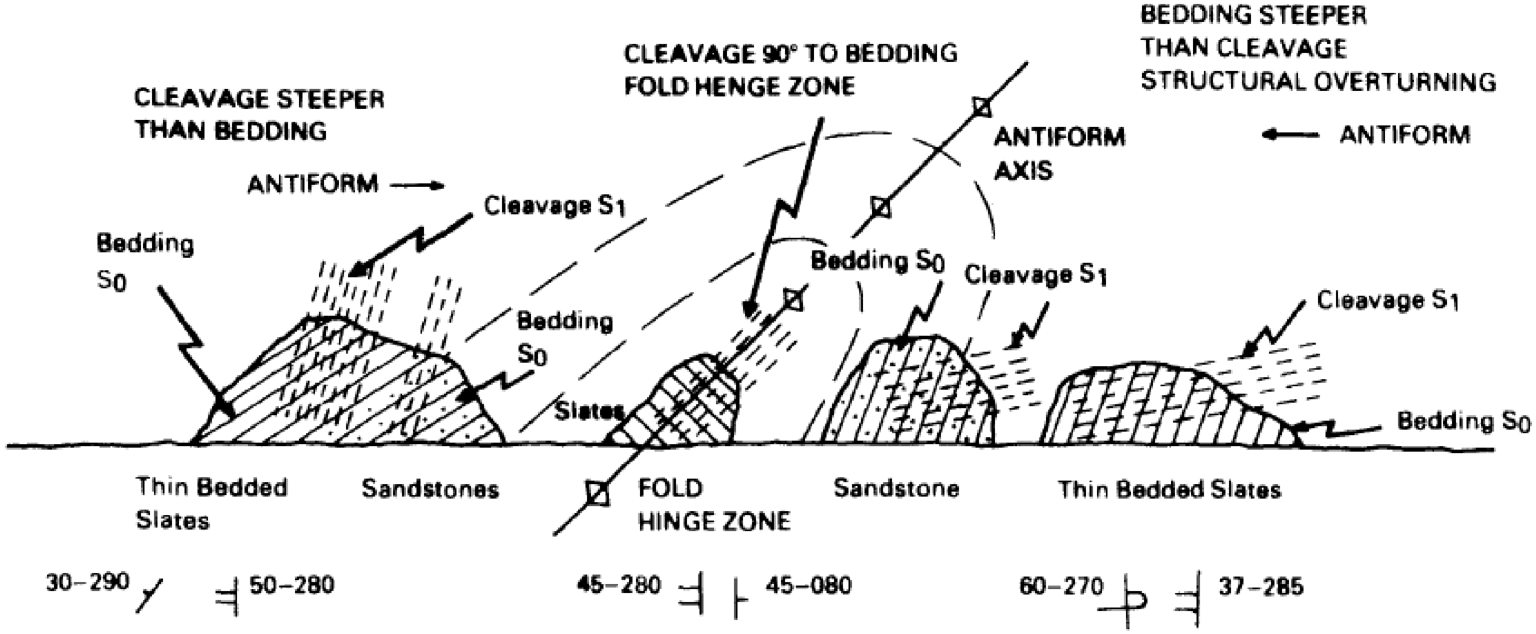
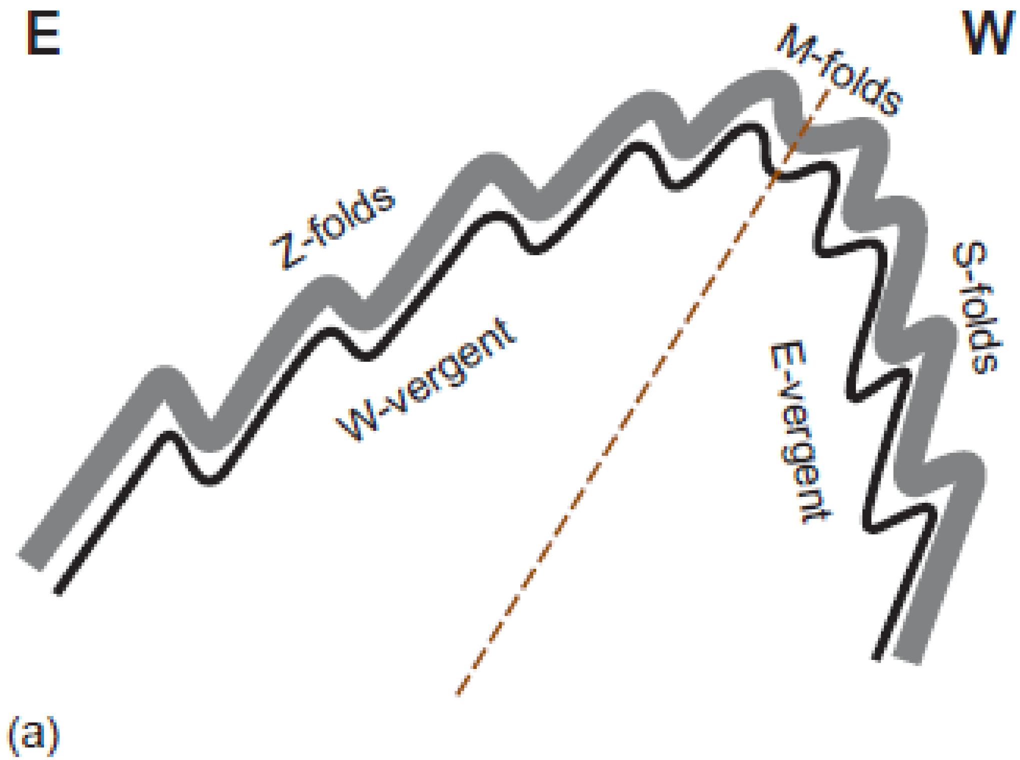


Table 3.4 Data to be collected from observations when mapping folds from a single phase of deformation.

Structure	*What to Measure*	*What Observations to Record*	*Results of Analysis*
	Orientation of fold axial surface (dip direction) (Figs. 2.5–2.8).	Nature of axial surface. Relationships of axial planes in a group of folds.	Orientation of fold structure. (Table 3.2)
	Orientation of fold axis (plunge) (Figs. 2.11–2.13).	Nature of hinge line—straight or curved, Relationships of hinge lines in a group of folds.	
	Vergence (azimuth) (Figs. 3.9 & 3.10).	Vergence and sense of asymmetry. S, Z, M (parasitic folds) facing. (Figs.3.8, 3.5, 3.10)	Vergence boundaries. (Fig. 3.11) Axes of major fold structures. (Fig. 3.8) Tectonic transport direction. (Fig. 3.4)
	Profile section of fold (Figs. 3.2–3.4).	Thickness changes in profile section. Cylindricity. Fold type. (Figs. 3.3, 3.4, 3.5)	Fold classification: 2D or 3D, dip isogons. (Fig. 3.4) Projection of fold down plunge. (Fig. 9.6)
	Cleavage orientations around the fold (Fig. 4.3).	Nature of cleavage. (Fig. 4.1)	Mean cleavage approximates to fold axial plane. (Fig. 4.3b) Deformation mechanisms.

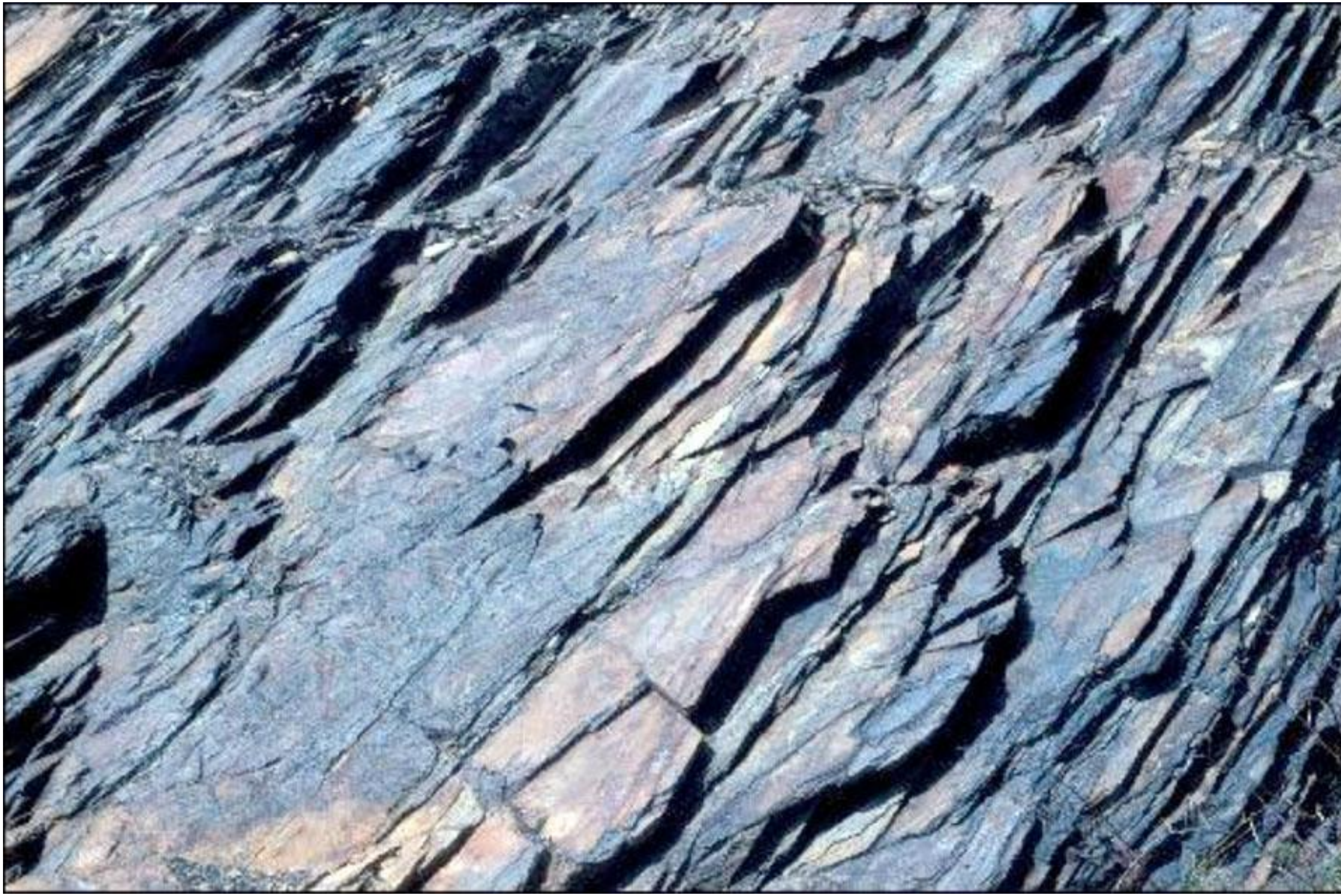

BEDDING STEEPER
THAN CLEAVAGE
STRUCTURAL OVERTURNING
CLEAVAGE 90° TO BEDDING
FOLD HENGE ZONE
CLEAVAGE STEEPER
THAN BEDDING
ANTIFORM
AXIS
ANTIFORM
ANTIFORM
Cleavage S1
Bedding
S0
Bedding S0
Cleavage S1
Cleavage S1
Bedding
S0
Slates
Bedding S0
Thin Bedded
Slates
Sandstones
FOLD
HINGE ZONE
Sandstone
Thin Bedded Slates
30–290
50–280
45–280
45–080
60–270
37–285

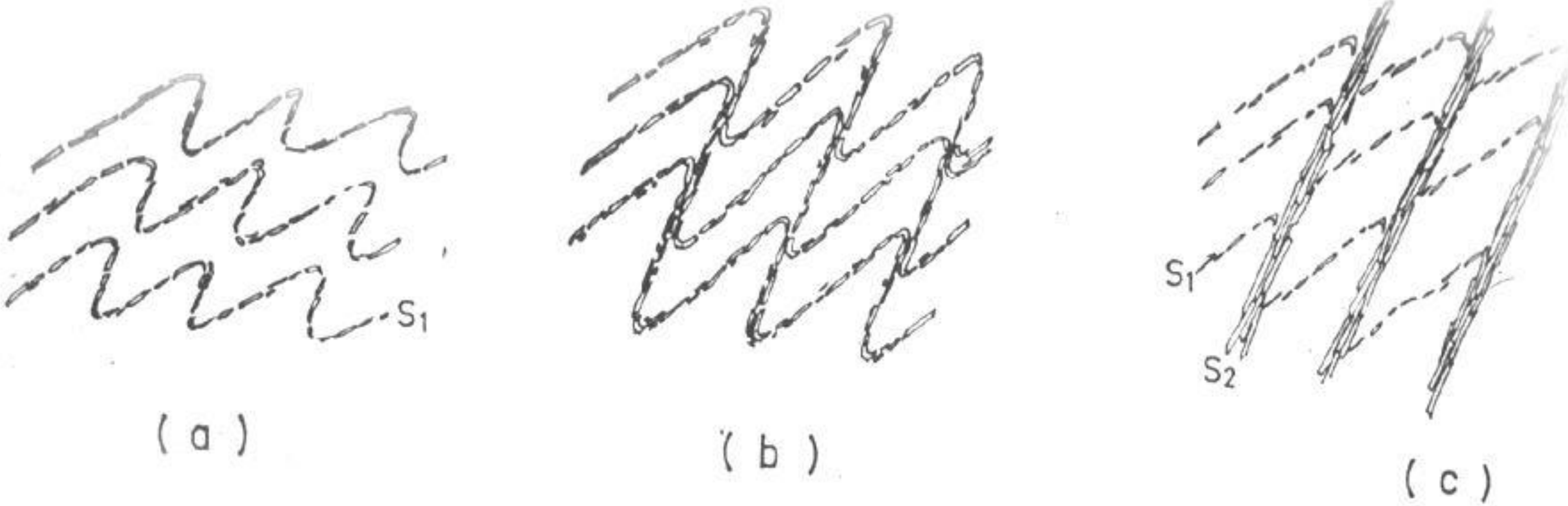


Schematic cross - section showing an example of how fold asymmetry (and vergence) changes across a fold axial plane (red line).

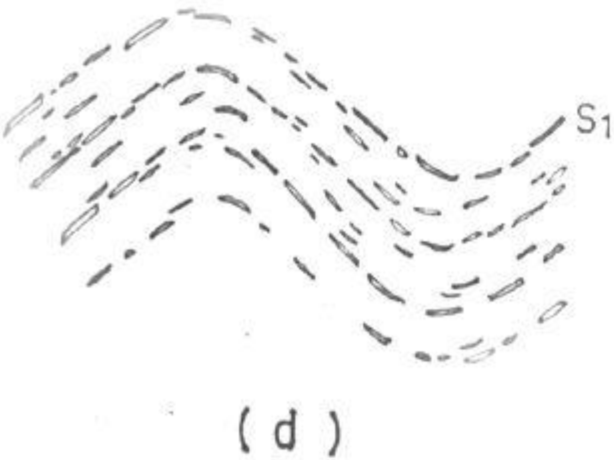
Foliations

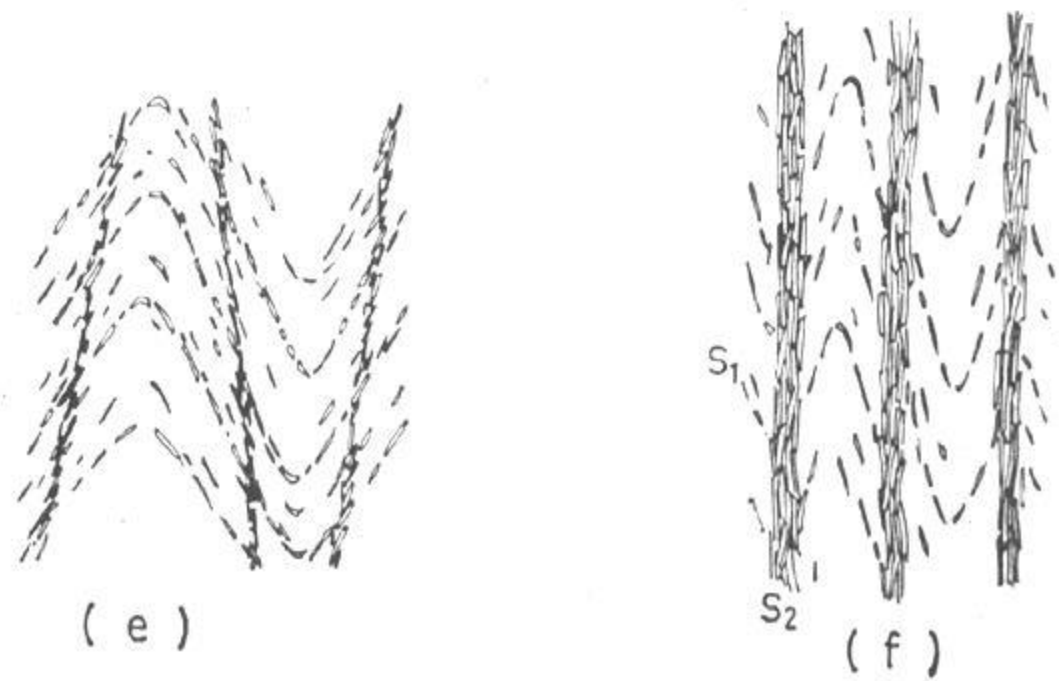
- Foliation is a planar rock fabric.
- ***Slaty cleavage****:* Penetrative foliation occurring in low grade metamorphic rocks.
- ***Crenulation cleavage****:* Foliation produced by microfolding (crenulation folding) *of a pre existing* foliation





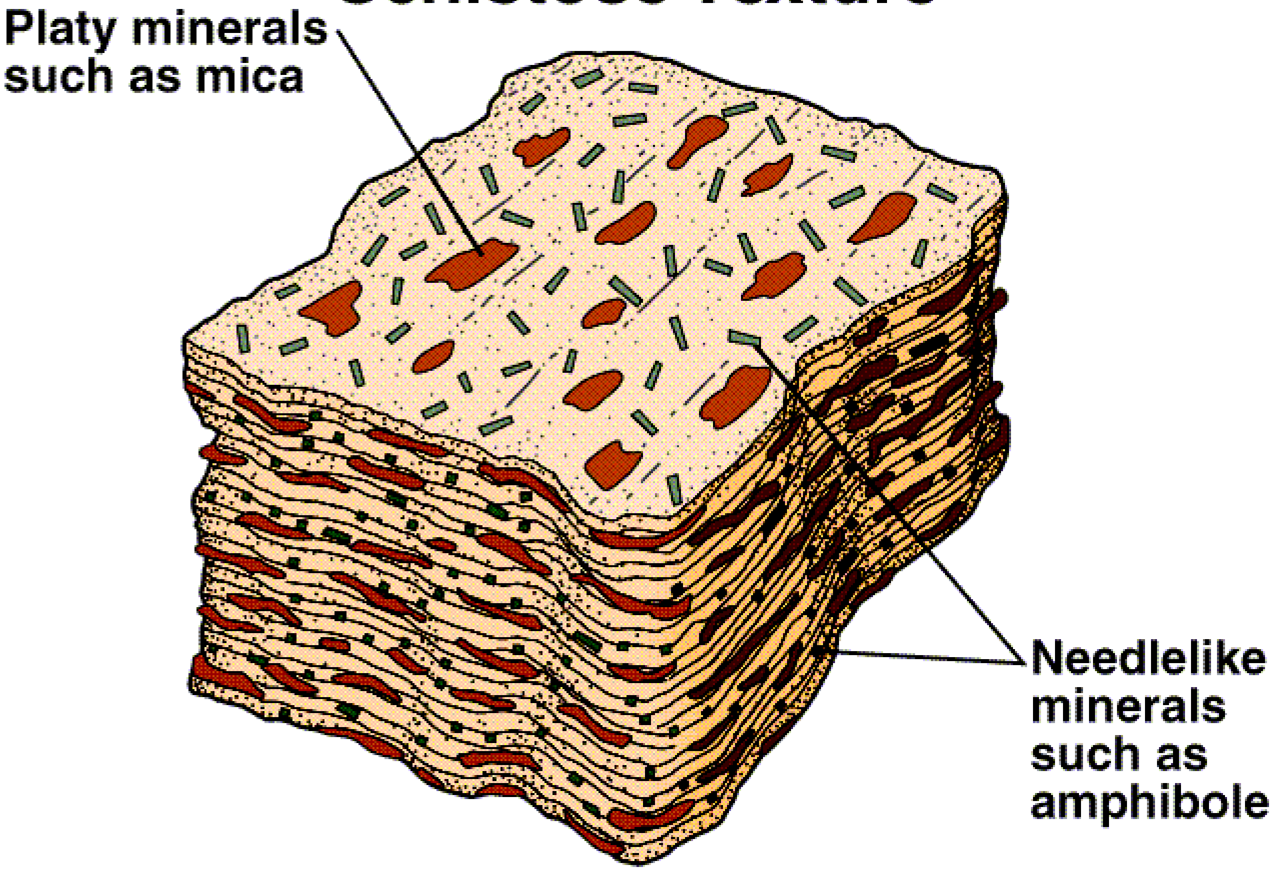
Progressive development (a → c) of a **crenulation cleavage** **for both asymmetric (top) and symmetric (bottom) situations. From Spry (1969)** ***Metamorphic Textures.*** **Pergamon. Oxford.**





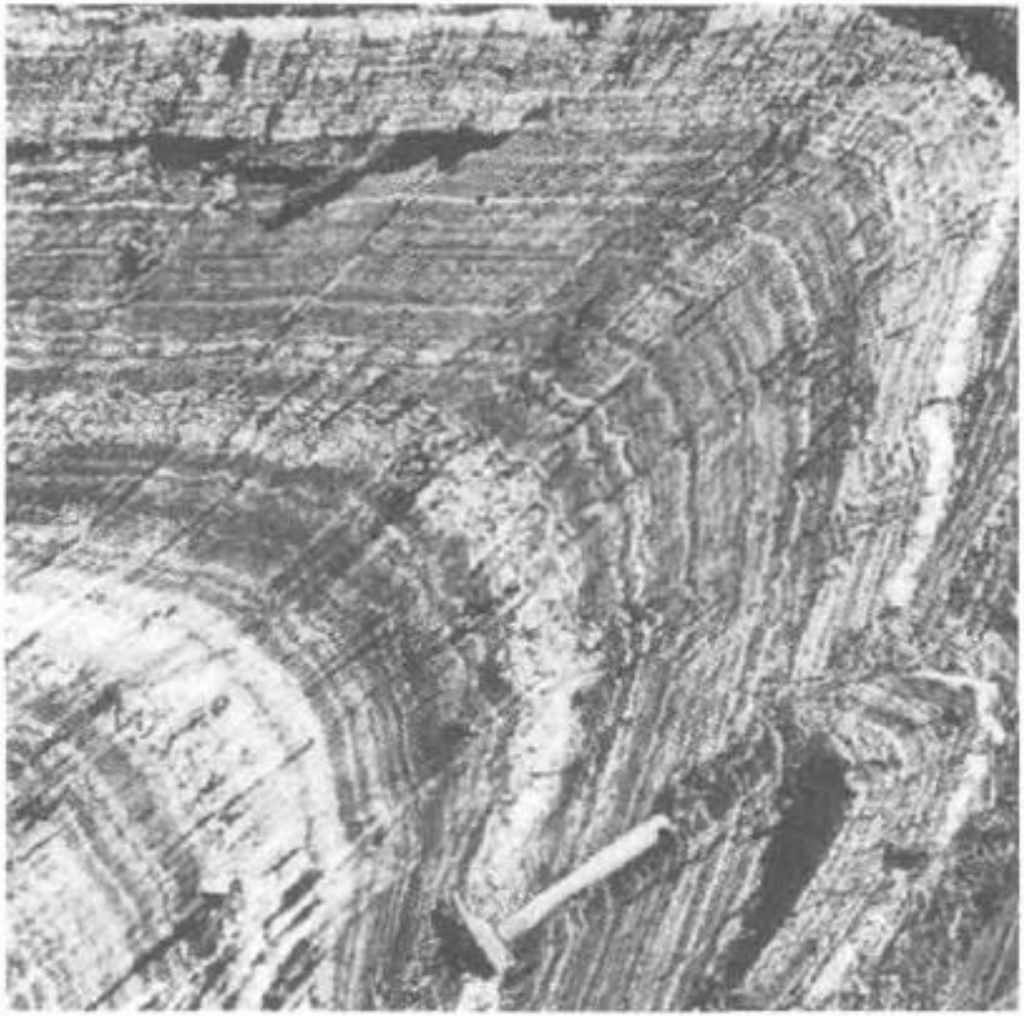
- ***Fracture cleavage**:* A non-penetrative foliation consisting of persistent, closely-spaced fracture.
- ***Schistosity**:* A penetrative/nonpenetrative foliation with visible phyllosilicates and mineral segregation into bands parallel with the foliation.

Schistose Texture



- ***Gneissic foliation****:* A foliation in coarse-grained rocks, consisting of impersistent laminae and segregations of mineral grains
- ***Mylonitic foliation****:* A penetrative foliation developed in zones of high shear strain such as faults and shear zones.

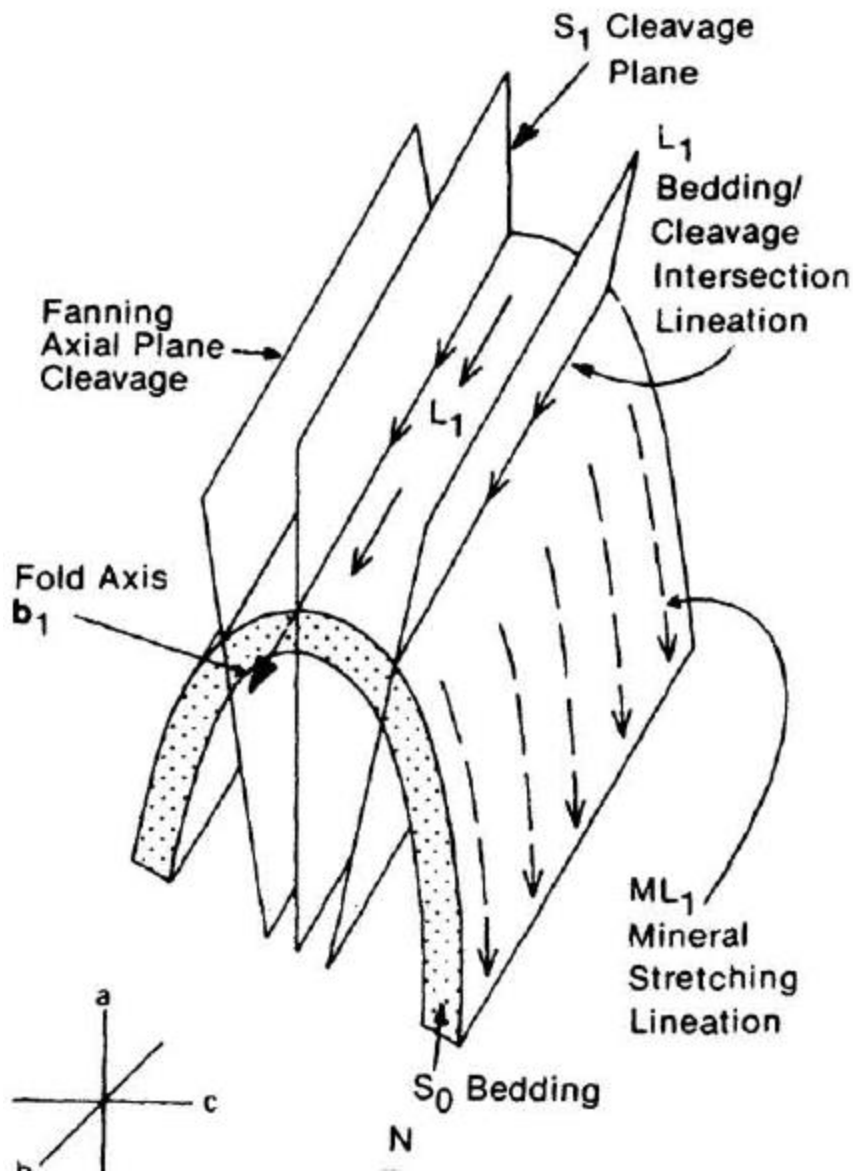
Mylonitic foliation



Axial-planar cleavage in folded siltstones.

Linear structures

- A lineation is a linear rock fabric that may result from the intersection of two planar features, from the alignment of mineral grains, crystals or clasts within the rock, from linear shape fabrics of grains and clasts, or from the parallel alignment of tectonic elements such as minor fold or crenulation axes or slickenside groove features.



S_1 Cleavage Plane
L_1 Bedding/ Cleavage Intersection Lineation
Fanning Axial Plane Cleavage
L_1
Fold Axis b_1
ML_1 Mineral Stretching Lineation
S_0 Bedding
a
c
N

Pencil cleavage lineation