THE MAPPING OF GEOLOGICAL STRUCTURES

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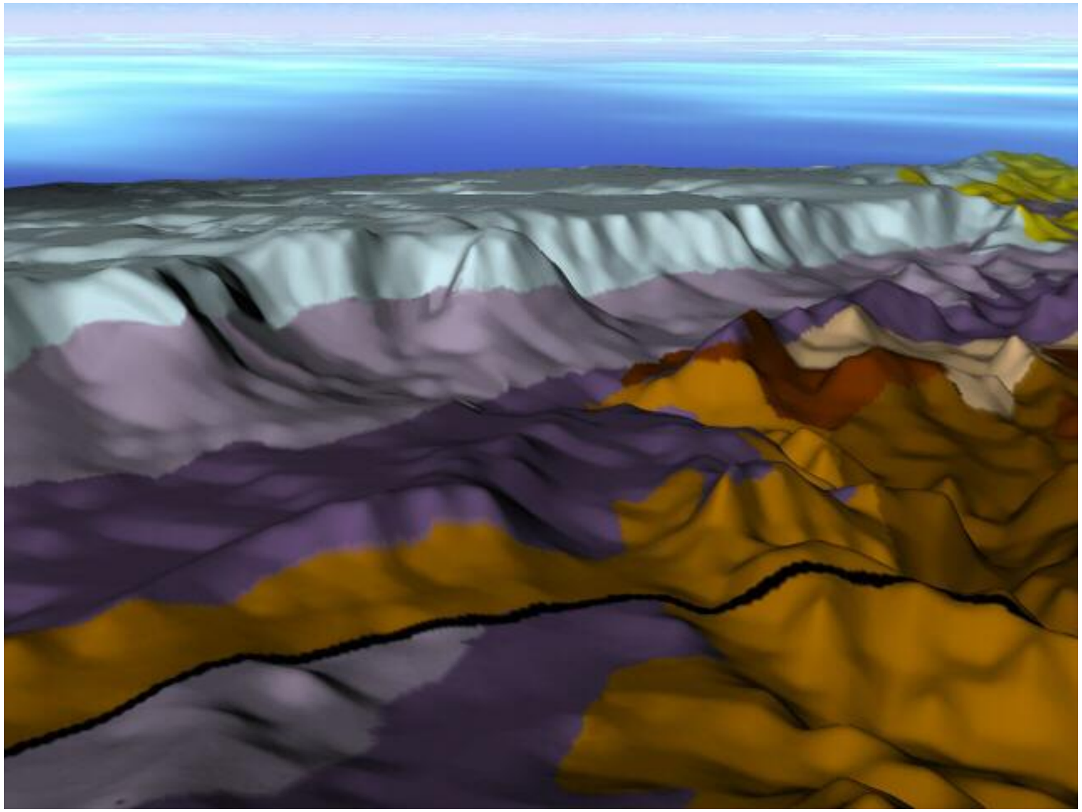
CZECH REPUBLIC
DEVELOPMENT COOPERATION



Content:

1. Part

Introduction to structural geology

Fabrics and structures of rocks

Mapping techniques of field structural research

2. Part

Field course of structural mapping

3. Part

Tectonic evolution of the Main Ethiopian Rift (MER)

Structural data processing and interpretation

STRUCTURAL GEOLOGY

Structural geology is the three-dimenstional study of processes and products of deformation of sedimentary, magmatic and metamorphic rocks.

The main goal of **structural geology** is to use tectonic measurements of rock anisotropy to uncover information about the history of rock deformation and understanding the regional stress field.

Structural geology is also important for **engeneering geology**, which is concerned with the physical and mechanical properties of natural rocks.

Fabrics and structures of rocks (brittle, brittle-ductile and ductile) such as e. g. faults, joints, folds and foliations are internal weaknesses of rocks which may affect the stability of underground depositories.

METHODS OF STRUCTURAL RESEARCH

Field structural mapping and microstructural analyses

Desctiption of structures and textures including analyses of their temporal and space relationships

Application of analytical methods in structural geology

Verification of field-structures using by analytical methods

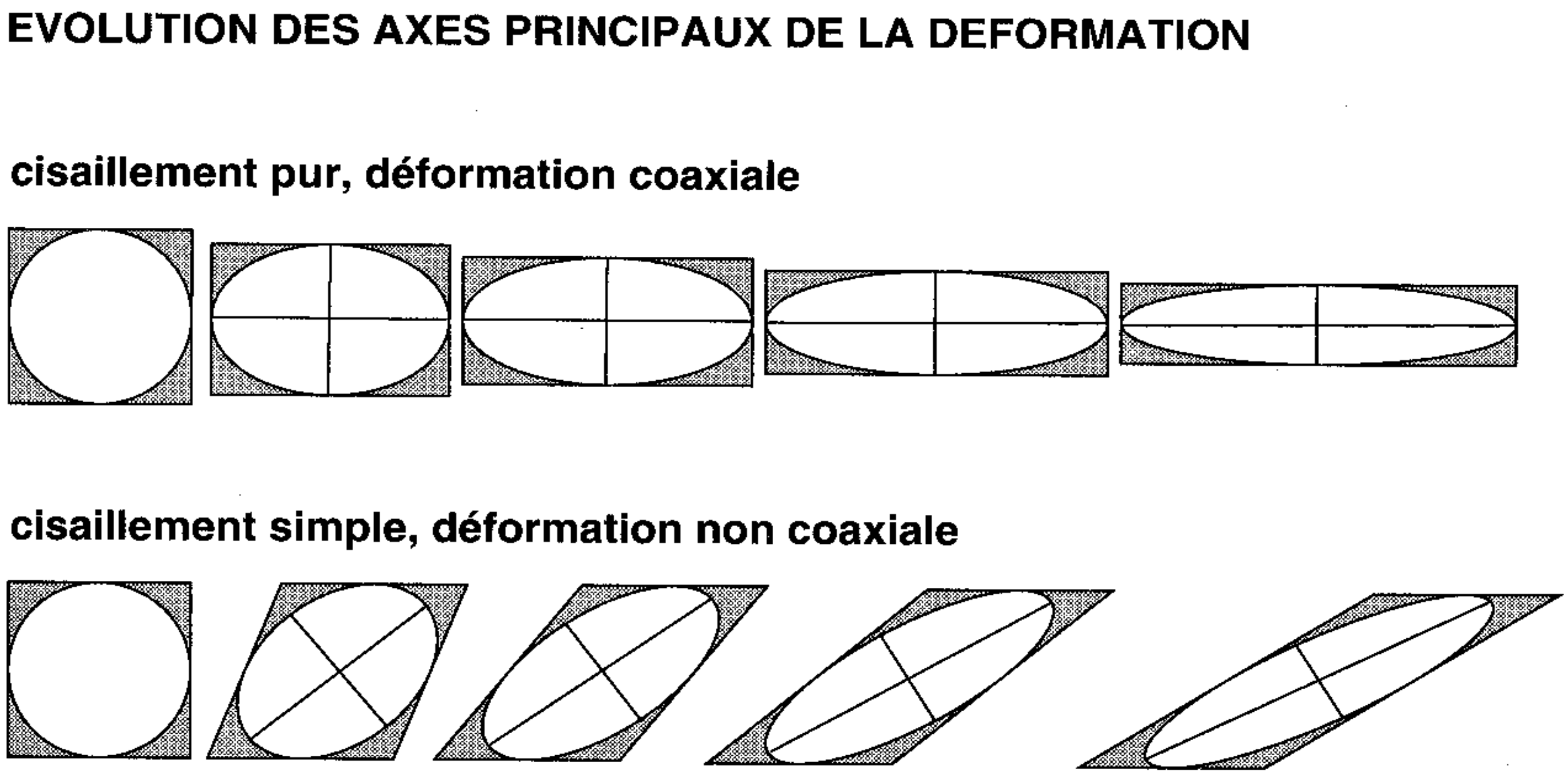
Geophysical methods such as gravity or seismic modelling

Remote sensing and image interpretation

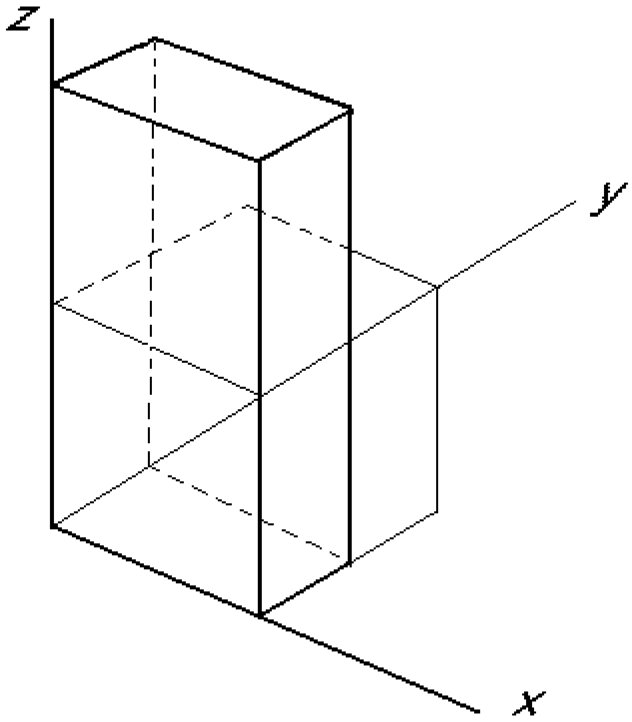
Processing of synthetic structural map and 3D sross-sections

DEFORMATION:

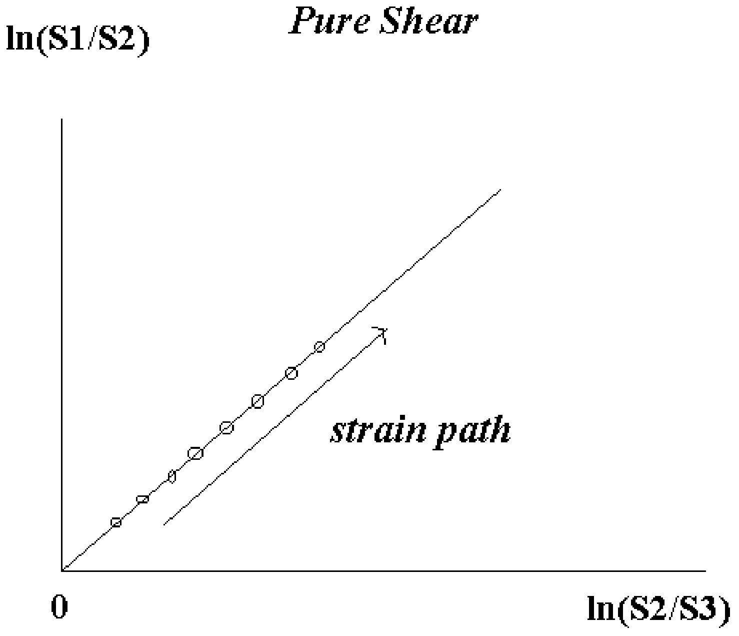
Modification of shape and original structures of rock as the efect of regional stress-field



Pure Shear

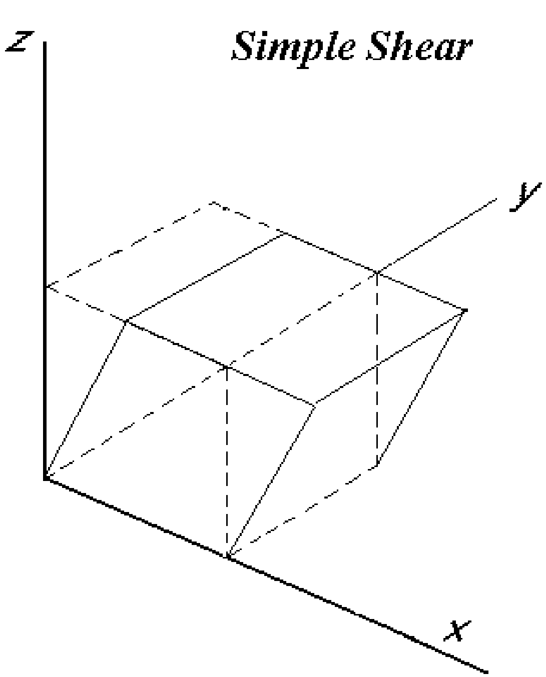


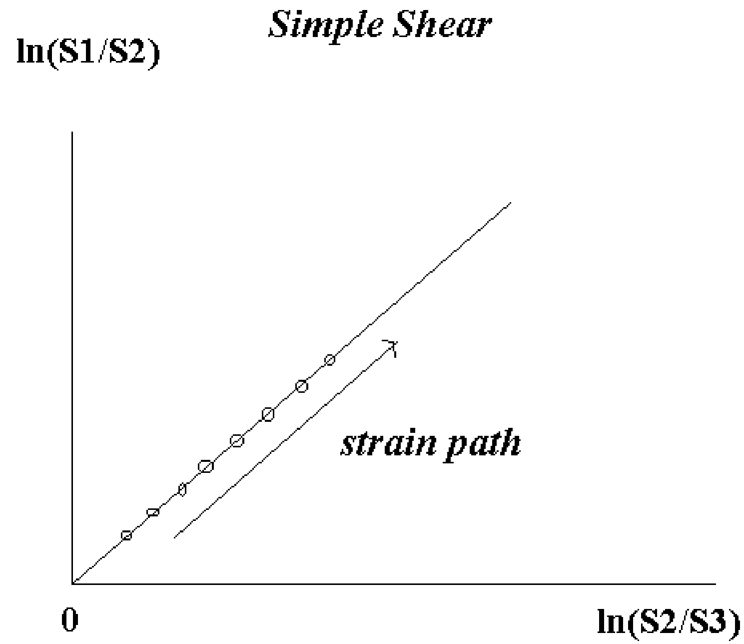
$$\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1/a & 0 \\ 0 & 0 & a \end{vmatrix}$$



Angles and sizes (sides) of deformed object remain unchanged

Simple Shear

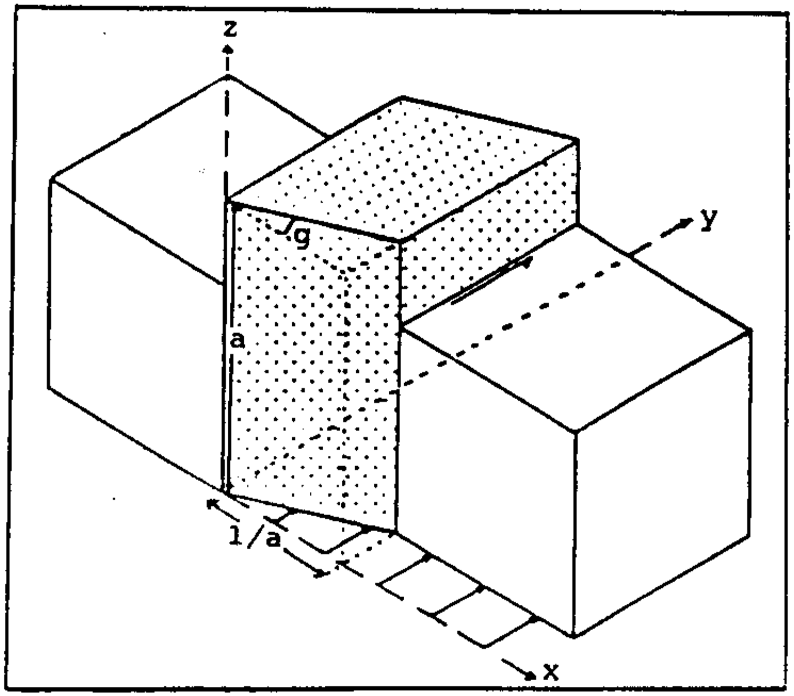


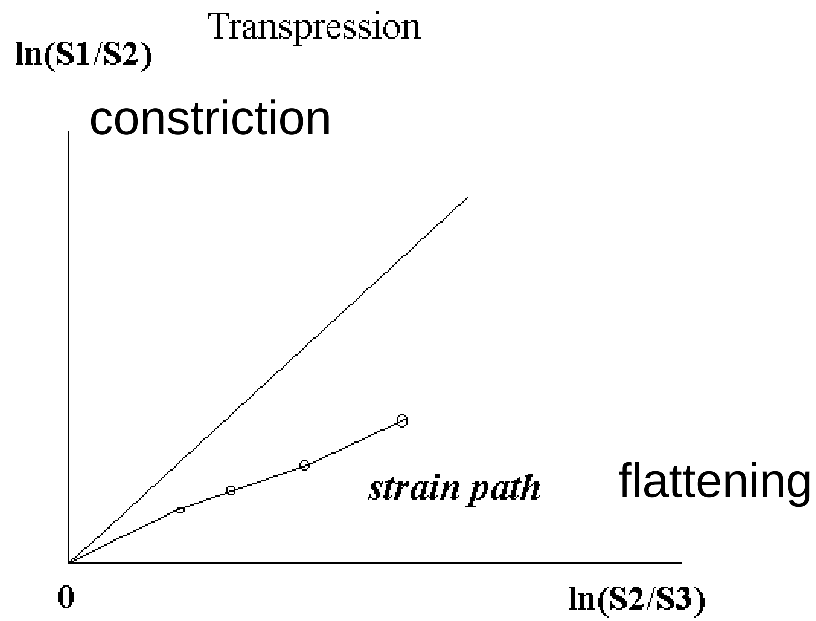


$$\begin{matrix} 1 & 0 & \gamma \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}$$

Angles between the sides of the original object changes

Transpression



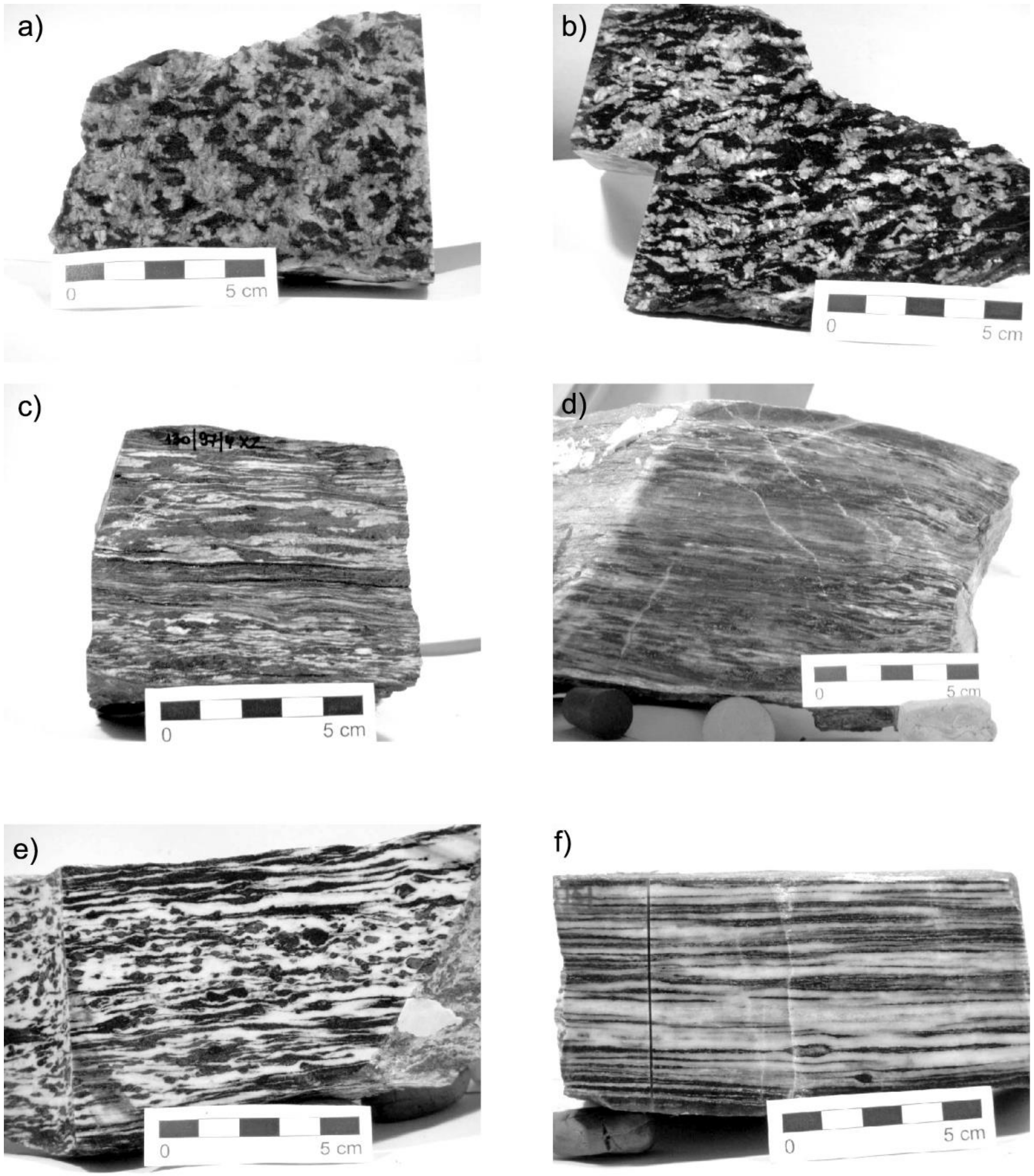


$$\begin{vmatrix} 1/a & g(a-1)\ln a & 0 \\ 0 & 1 & 0 \\ 0 & 0 & a \end{vmatrix}$$

Simple shear and pure shear act simultaneously

Transtension

Mezoscopic evidence of regional strain-field



Mezoscopic structural observation provides basic information about

type,

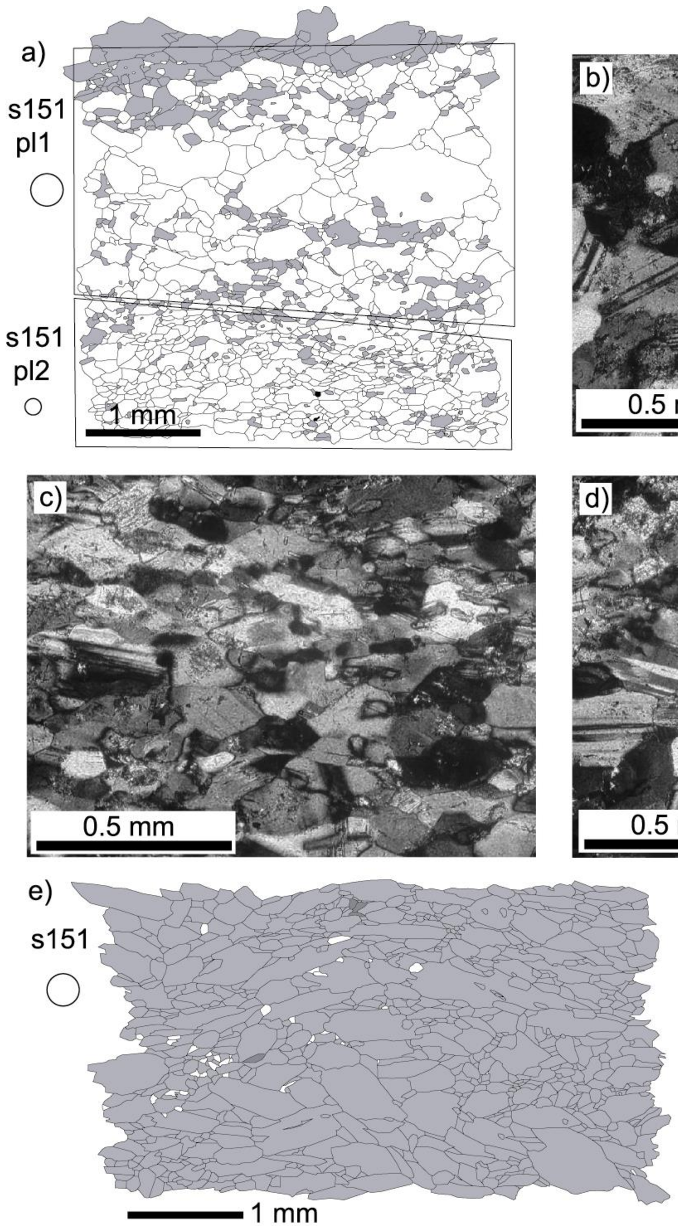
character,

orientation,

relationships

of the fabrics or structures.

Micro-scale evidence of regional strain-field



Size
Distribution
Internal structures
Preferred orientation
Mineral composition

Micro-scale observation brings additional information about evolution of rocks

Strain-rate

Mechanisms of deformation

PT condition of deformation

DEFORMATIONAL STRUCTURES:

A. **Non-tectonic structures** **originate** close to the Earth´s surface, most likely due to **gravitational forces**

B. **Tectonic structures** **are related with** regional stress-field as the response to geodynamic (tectonic) processes

NON-TECTONIC STRUCTURES

Folds as a result of mud-flow

TECTONIC STRUCTURES:

Primary structures

Primary structures are related with the origin of rocks

Sedimentary bedding
Preferred orientation of minerals in magmatic rocks

Secondary (superimposed) structures

Their origin is related according to regional stress-field

Superimposed metamorphic foliation
Cleavage

Tectonic structures

On the basis of different strain regimes we can distinguish several deformational stages:

Compression **Tension** **Shearing**

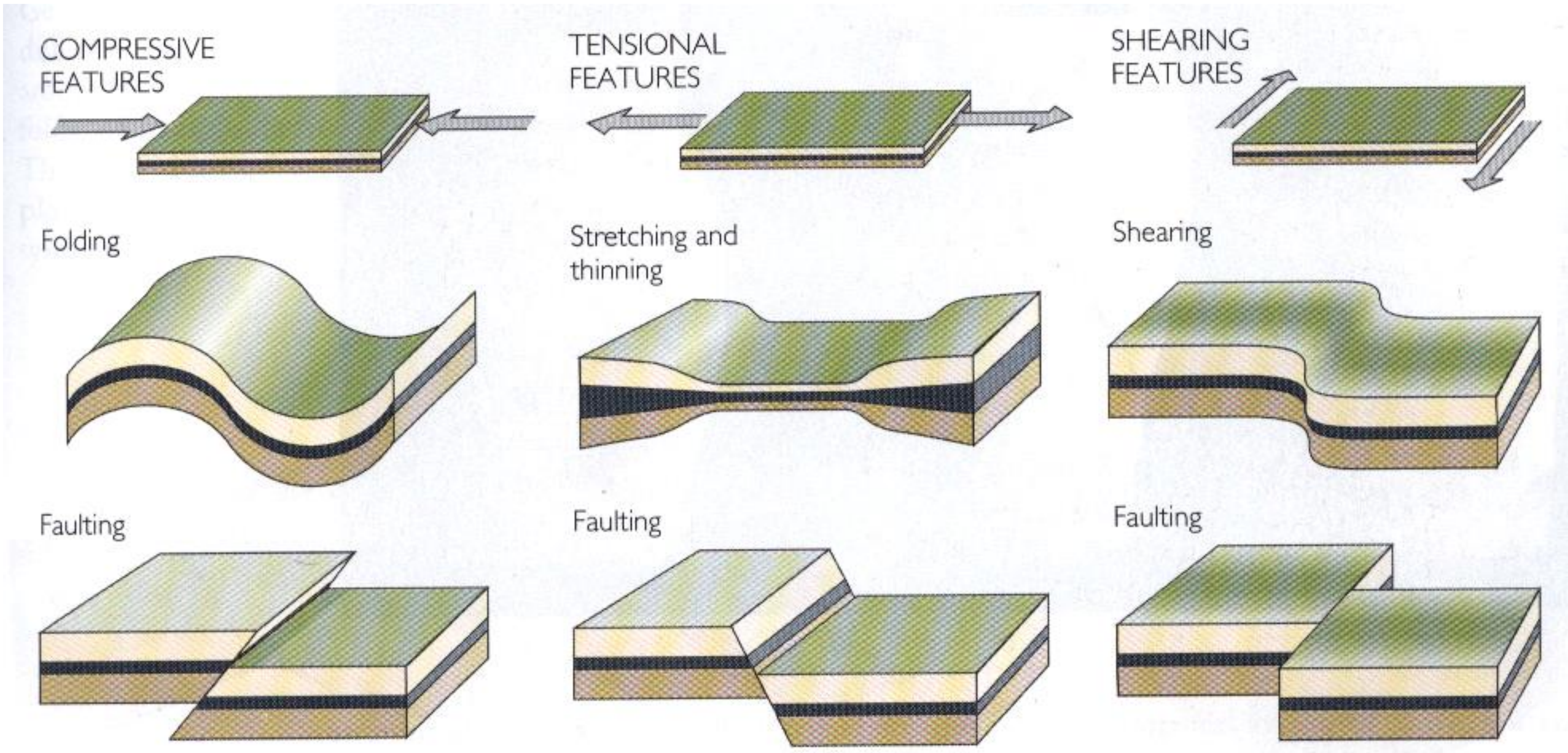
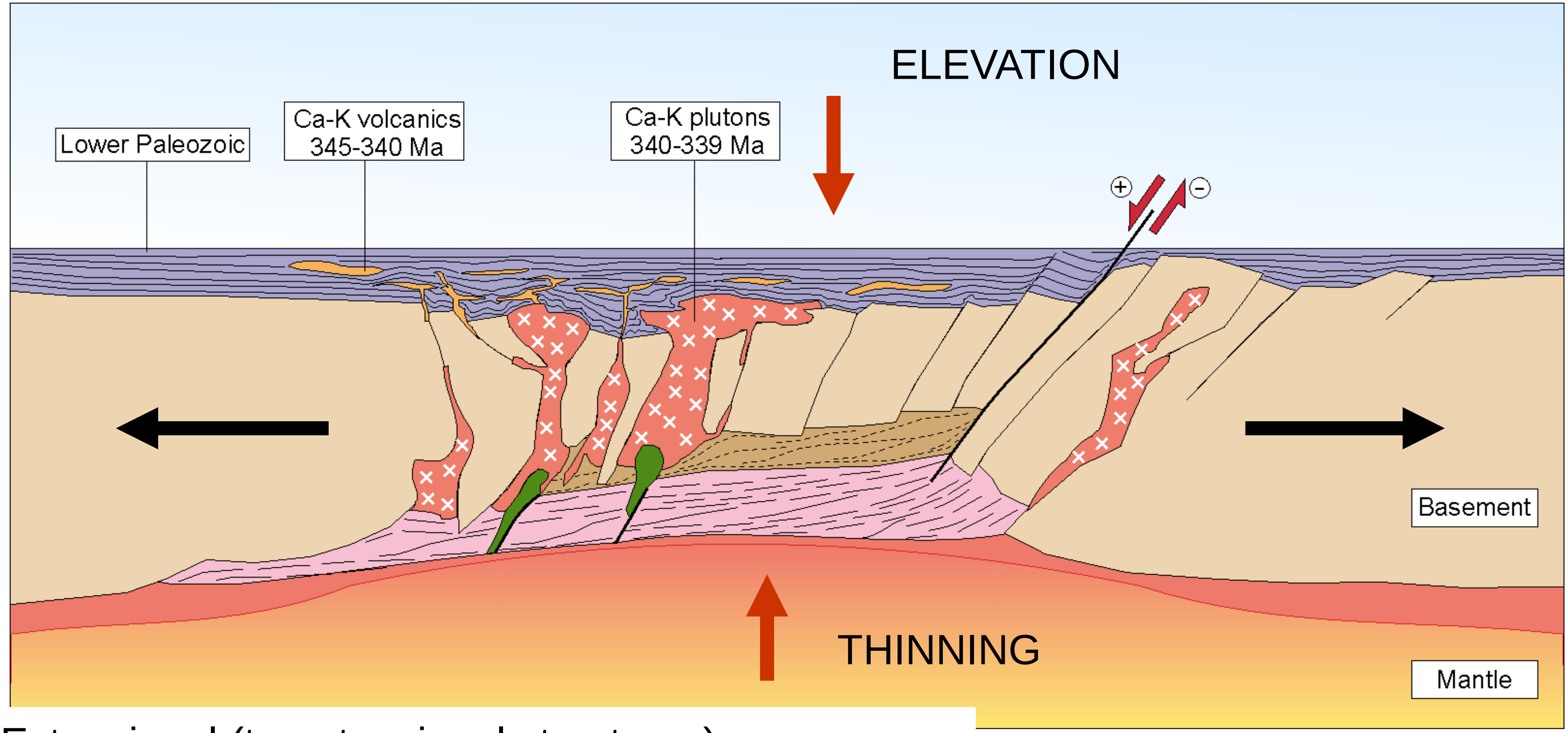


FIGURE 10.6 Rocks are deformed by folding or by faulting when they are subjected to different kinds of tectonic forces. Geologists see the pattern of deformation in the field and infer the nature of the forces that caused it.

EXTENSIONAL REGIME - Rifting

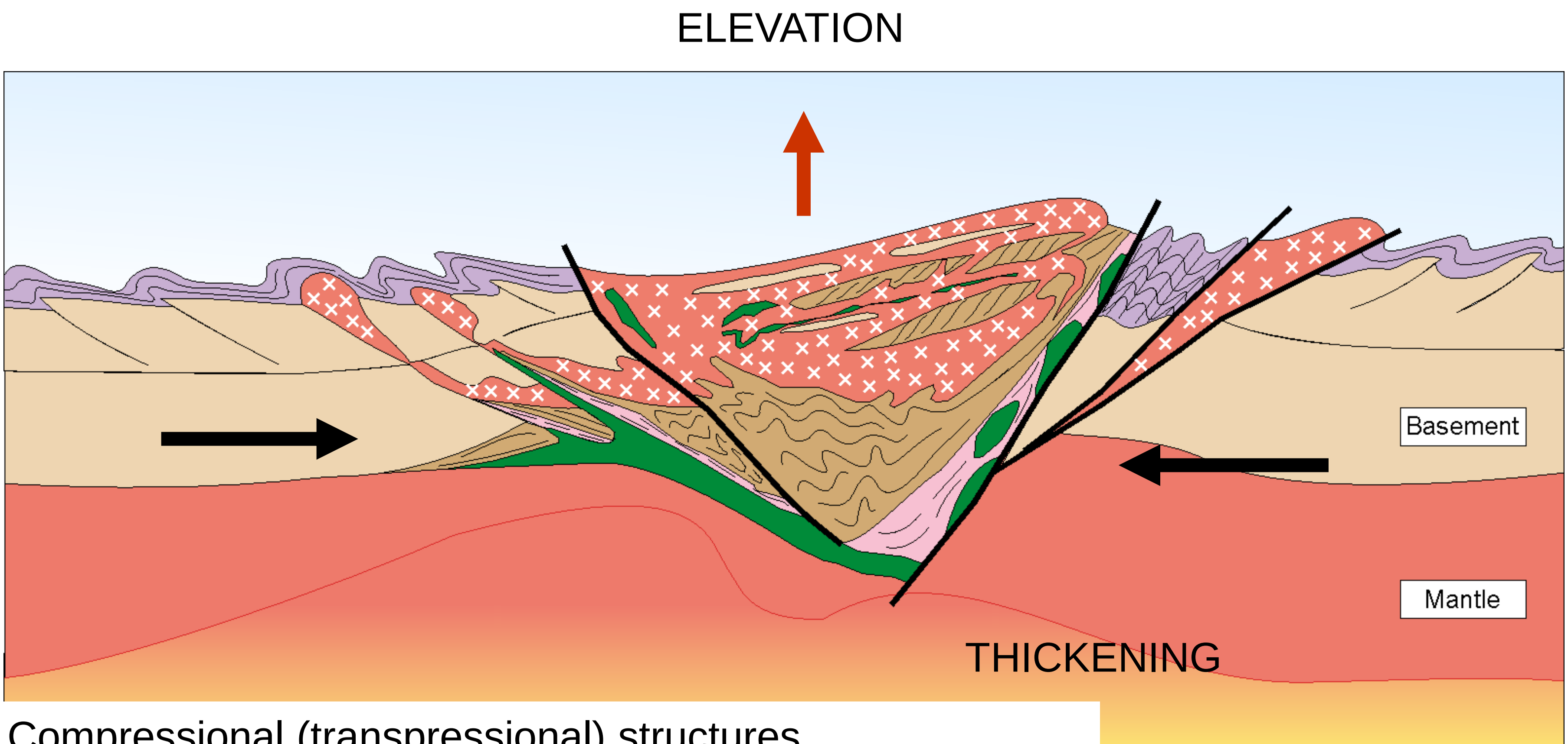
Tectonic model of development of Variscan root



Extensional (transtensional structures)
Increasing heat-flow and related HT metamorphism
Magma orgin and ascent and emplacement
Crustal thinning and reduction of topography

COMPRESSIVE REGIME - Collision

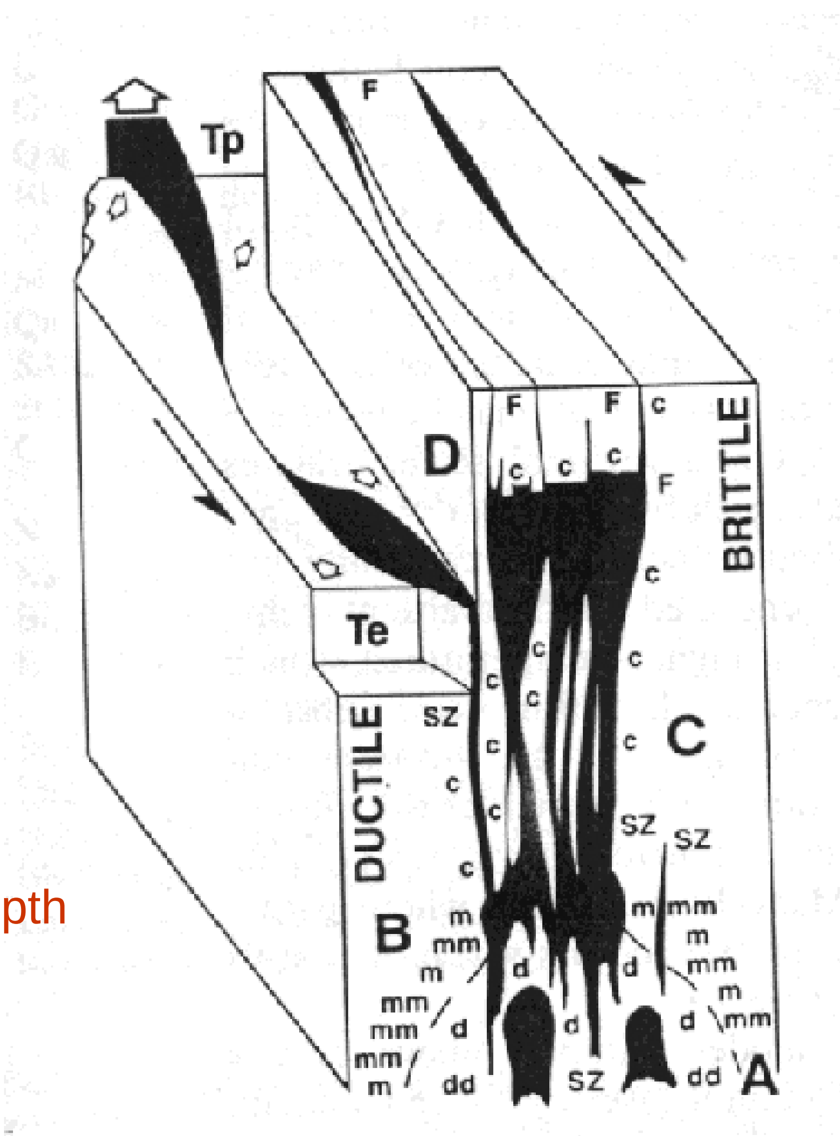
Tectonic model of development of Variscan root

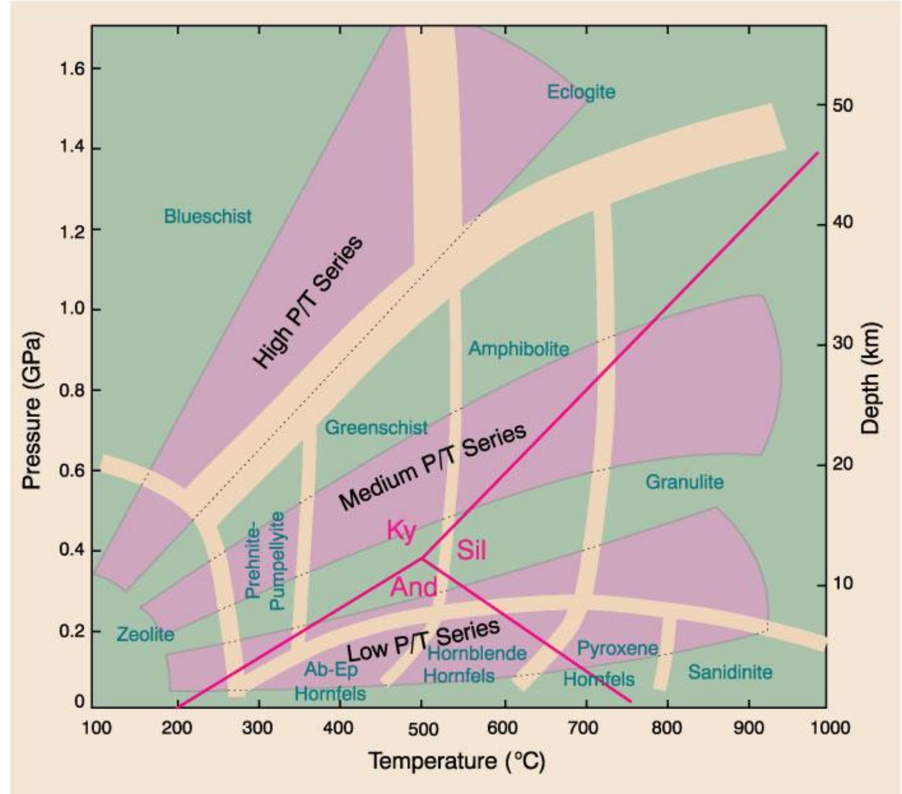


Compressional (transpressional) structures
Prograde metamorphism
Magma ascent and emplacement driven by tectonic forces
Thickening of the orogenic root systém
Growth of the topography

The origin of tectonic structures with respect to rheology

depth





Brittle structures

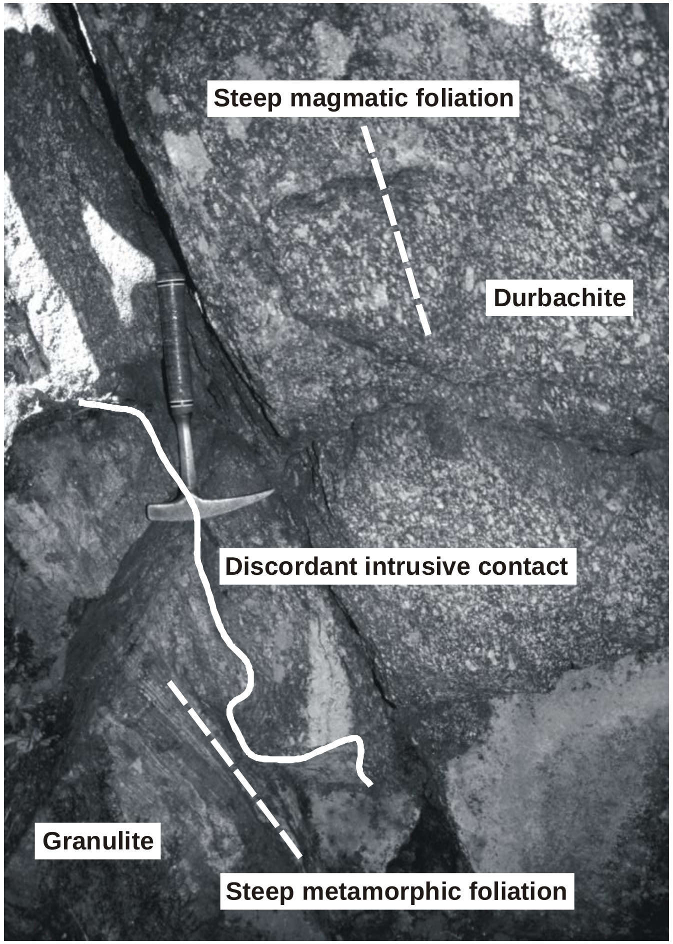
Brittle-ductile structures

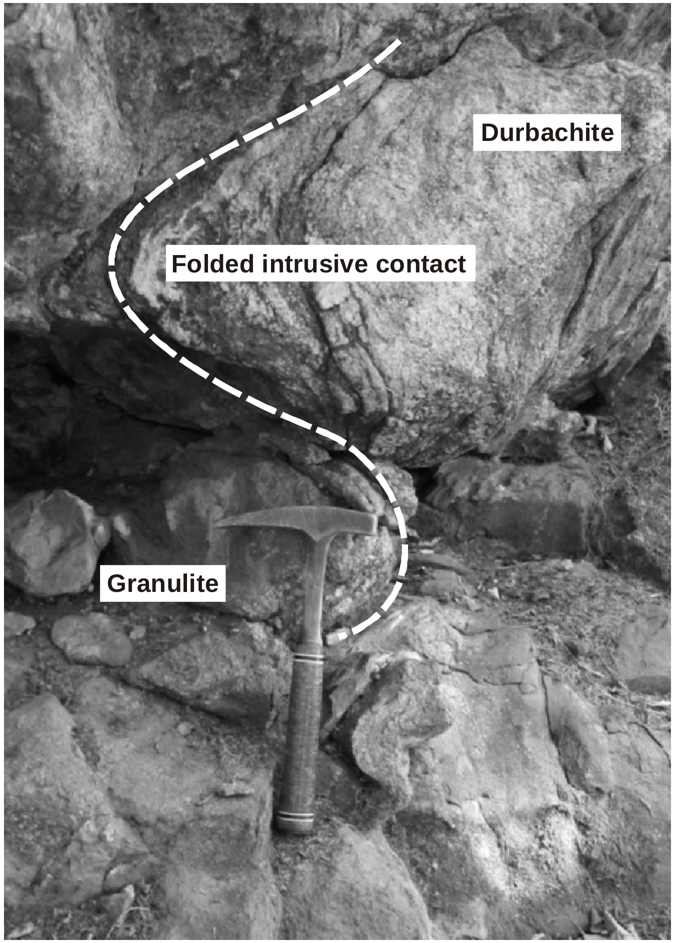
Ductile structures

Ductile structures

Deformational structures as the result of regional geodynamic evolution of rocks emplacement processes at higher depth (more than 15 km)

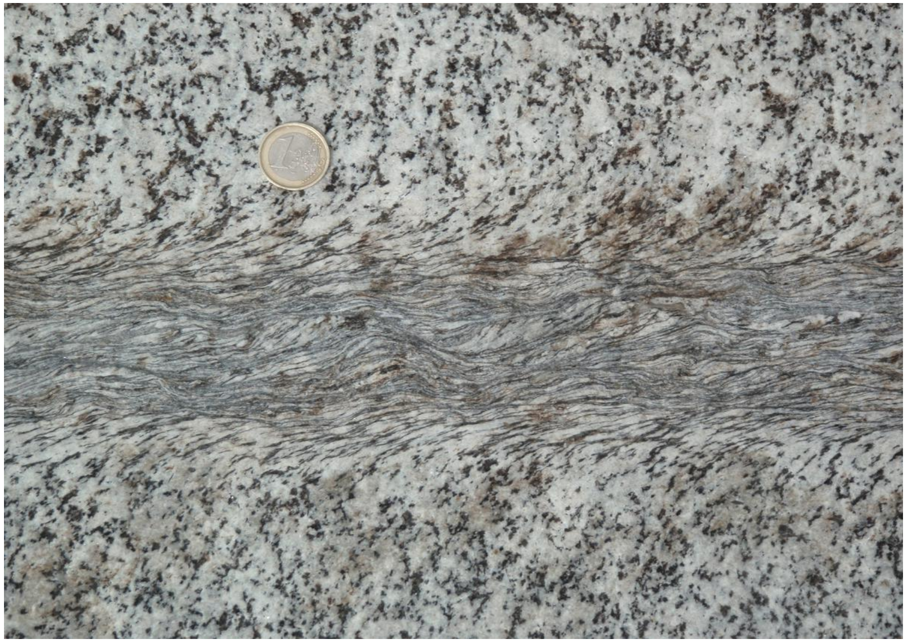
Folded intrusive contact of and magmatic fabric defined by space orientation of K-feldspars



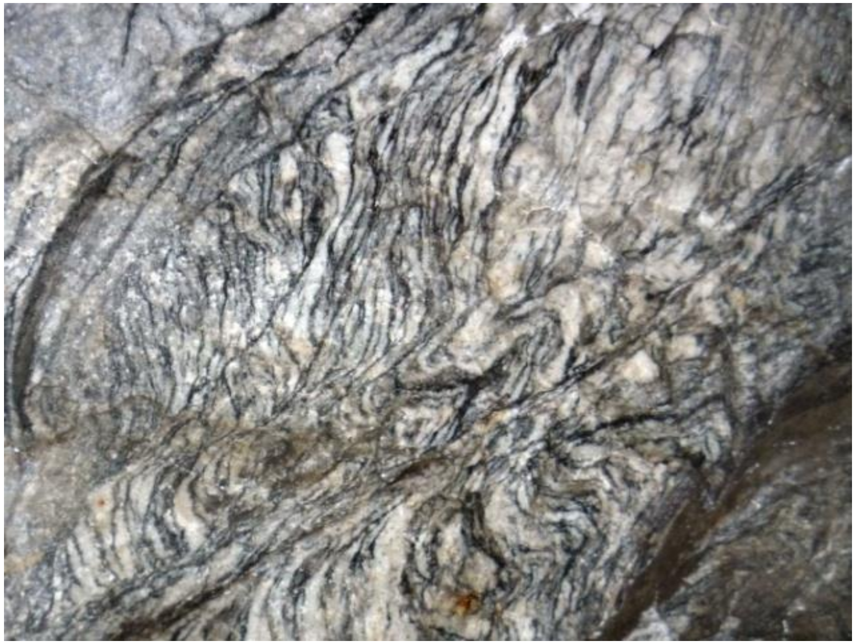


Brittle-ductile structures

Localized planar fabrics of later stages of deformation, often accompanied with retrograde metamorphism and partial recrystallization of rocks (15-10 km in depth)



Shear zone with an evidence right-lateral kinematics (tonalite)



Low-temperature shear structures reflecting thrusting kinematics (migmatite)

Brittle structures

Extensional joints

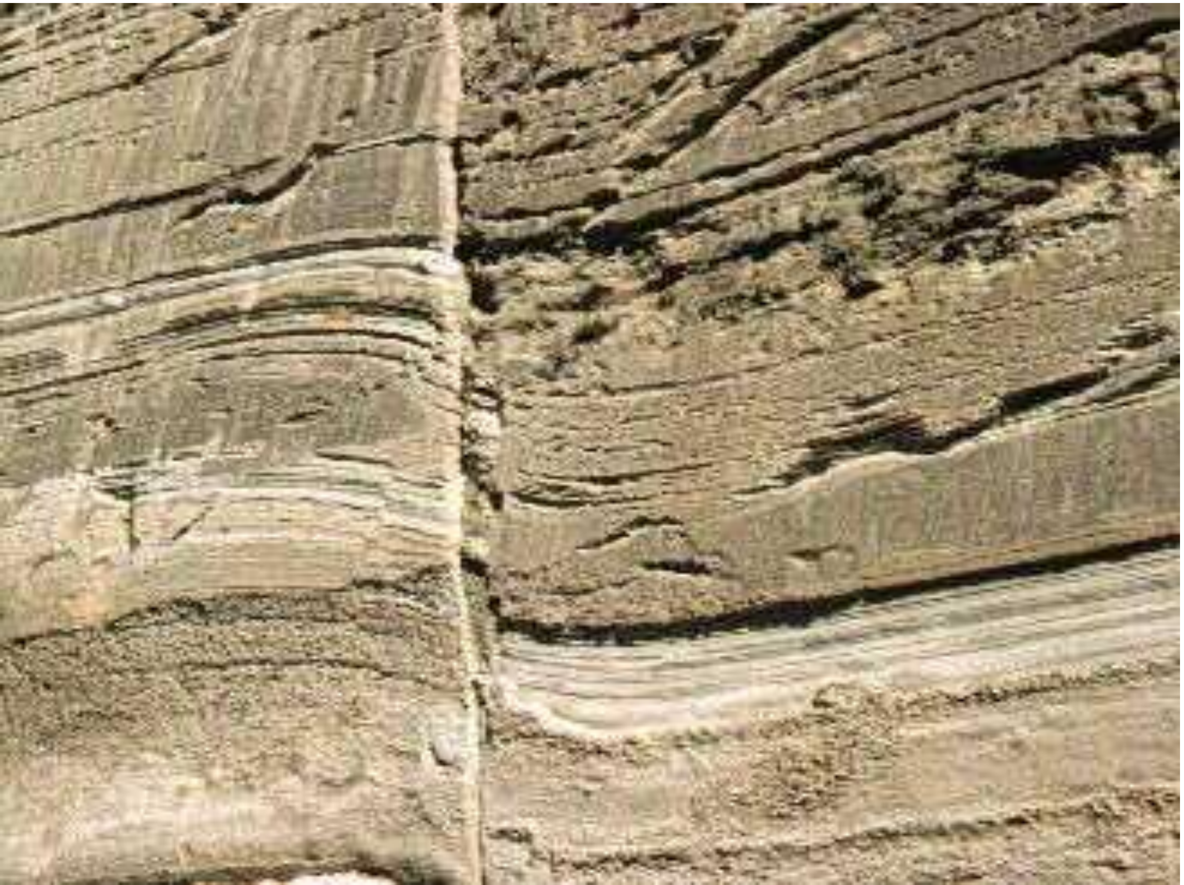
Faults and joints

Results of deformation in brittle enviroment

Fault plane with kinematic indicators

Primary fabrics in sedimentary rocks

Sedimentary bedding
Primary accumulation planar structure in sedimentary rocks defined by bedding lithology, grain-size, grain-shape and grain-fabrics



Sedimentary structures, composition and character of material gives us information about:

Composition of source material

Processes and conditions of sedimentary deposition

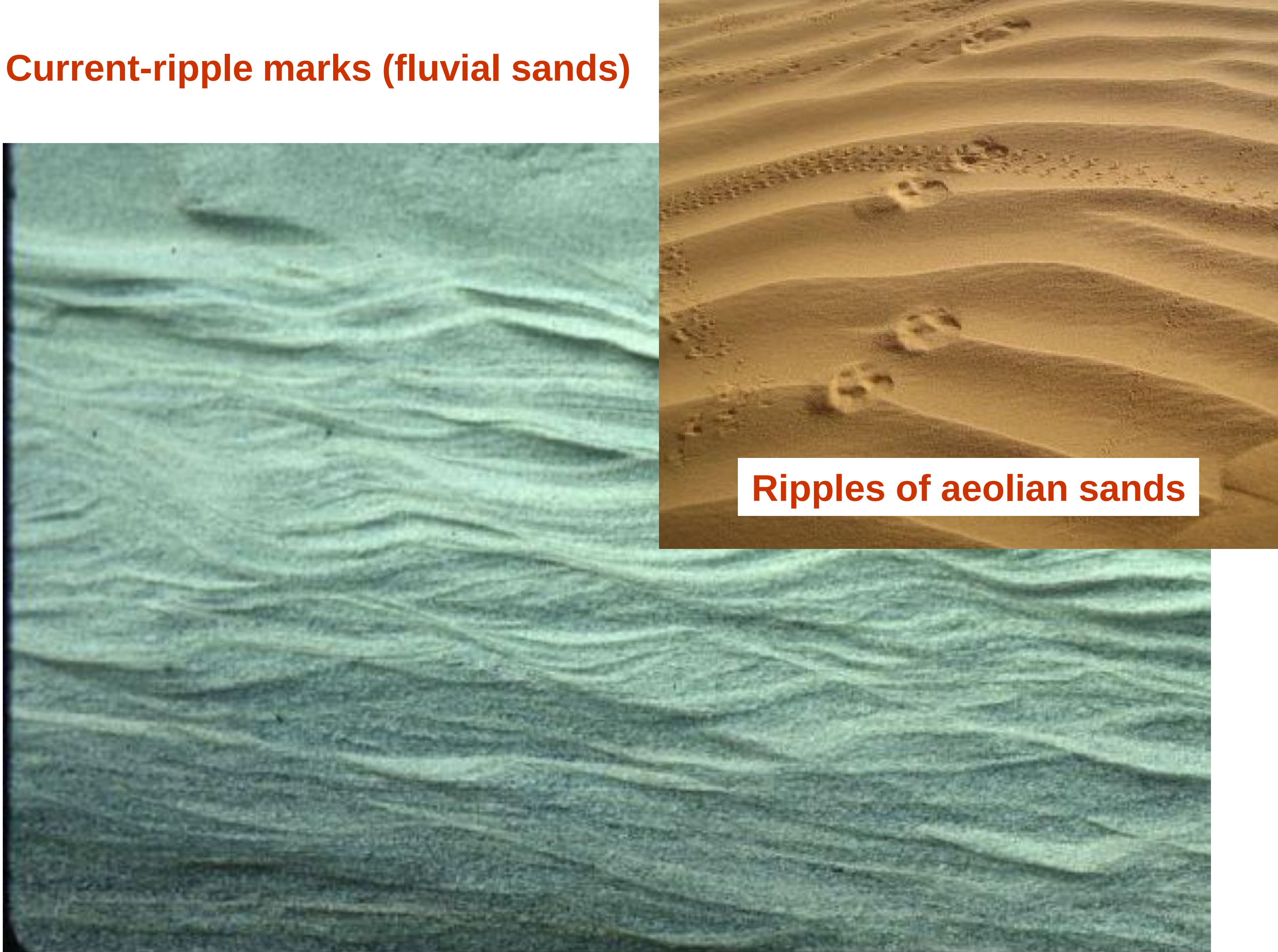
Rate of sedimentation and tectonic evolution of sedimentary basins

Subhorizontal sedimentary bedding (beach sands)

Normal graded bedding
Coarse grains at the base passing upwards into finer grain sizes

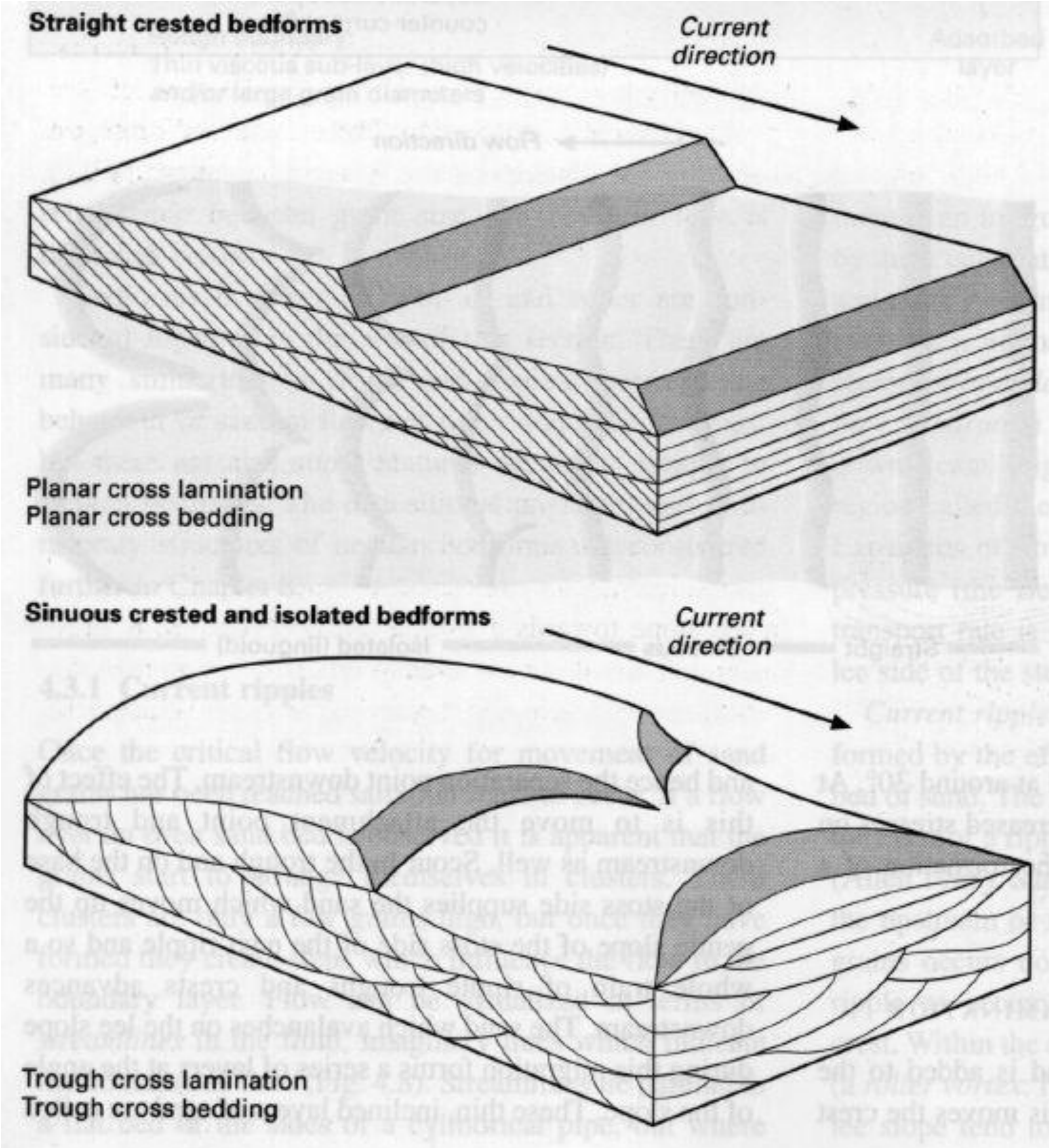
Matrix supported debris-flow deposits (no structure apparent)

Current-ripple marks (fluvial sands)



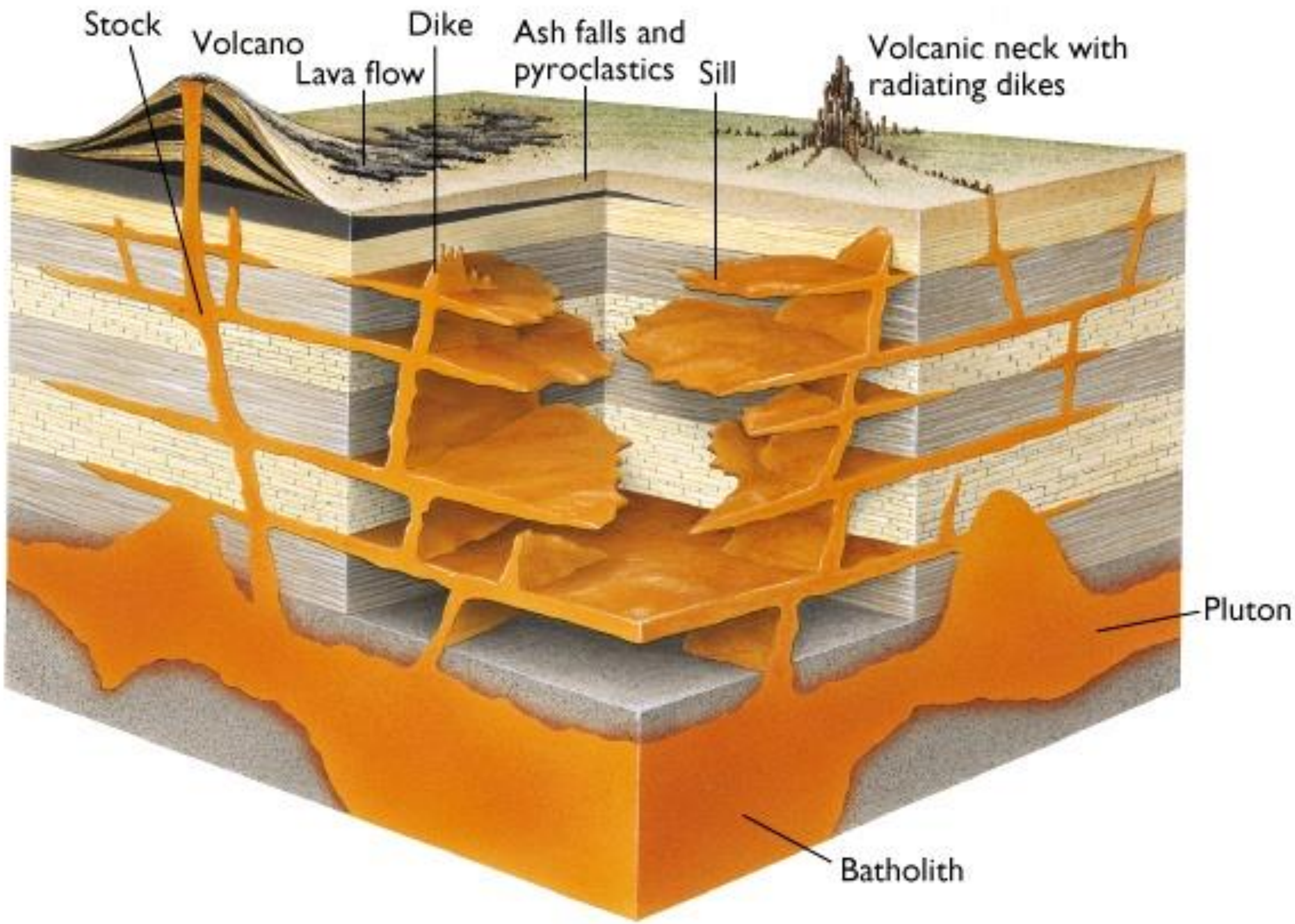
Ripples of aeolian sands

Types of cross-bedding



Fabrics and structures of magmatic rocks

Types and shapes of magmatic bodies



Extrusive

Intrusive

Planar and tabular bodies:

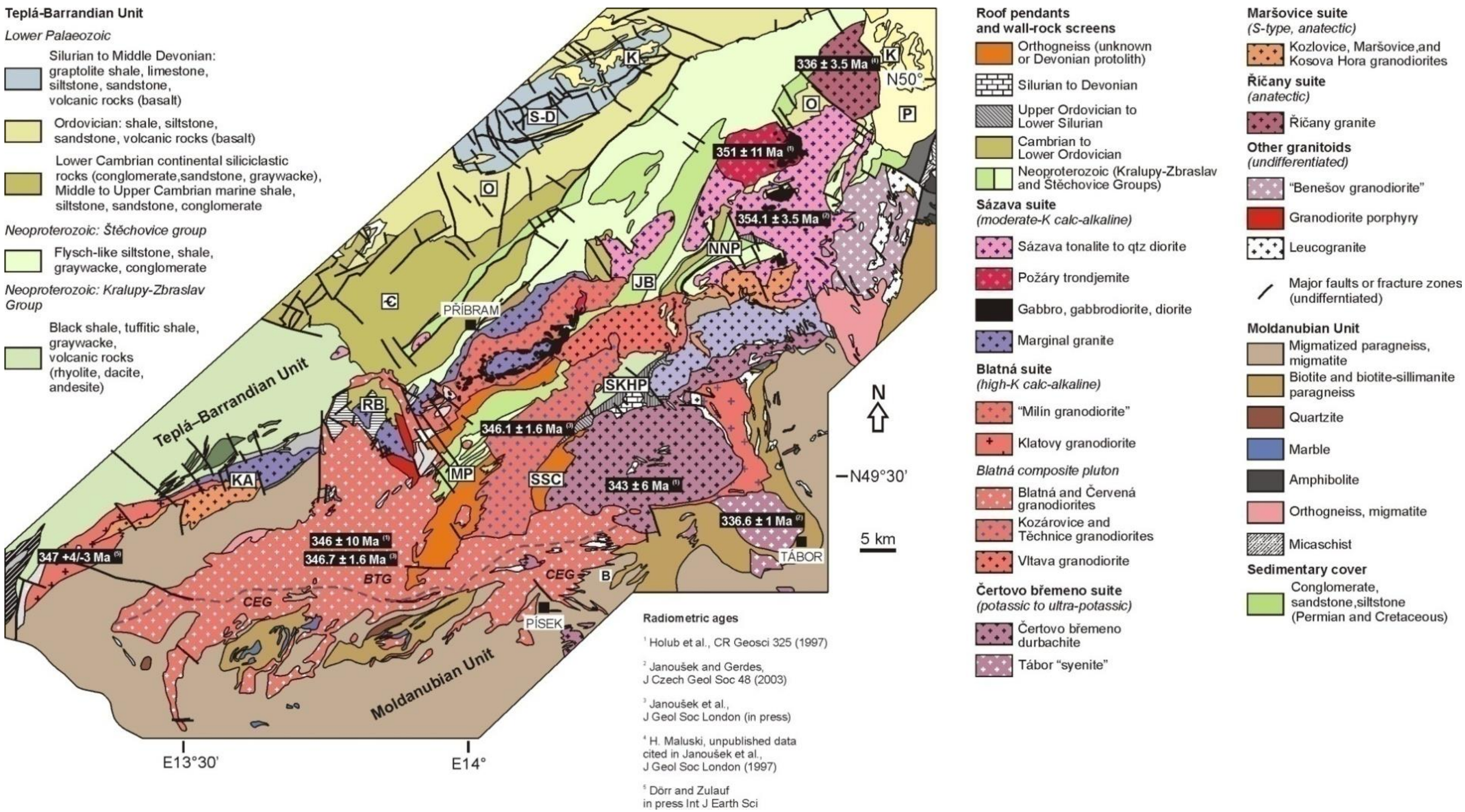
Dikes, tabular plutons, lacolites

Eliptical and irregular boides:

stock > 10 km^2 > pluton > 100 km^2 > batholith

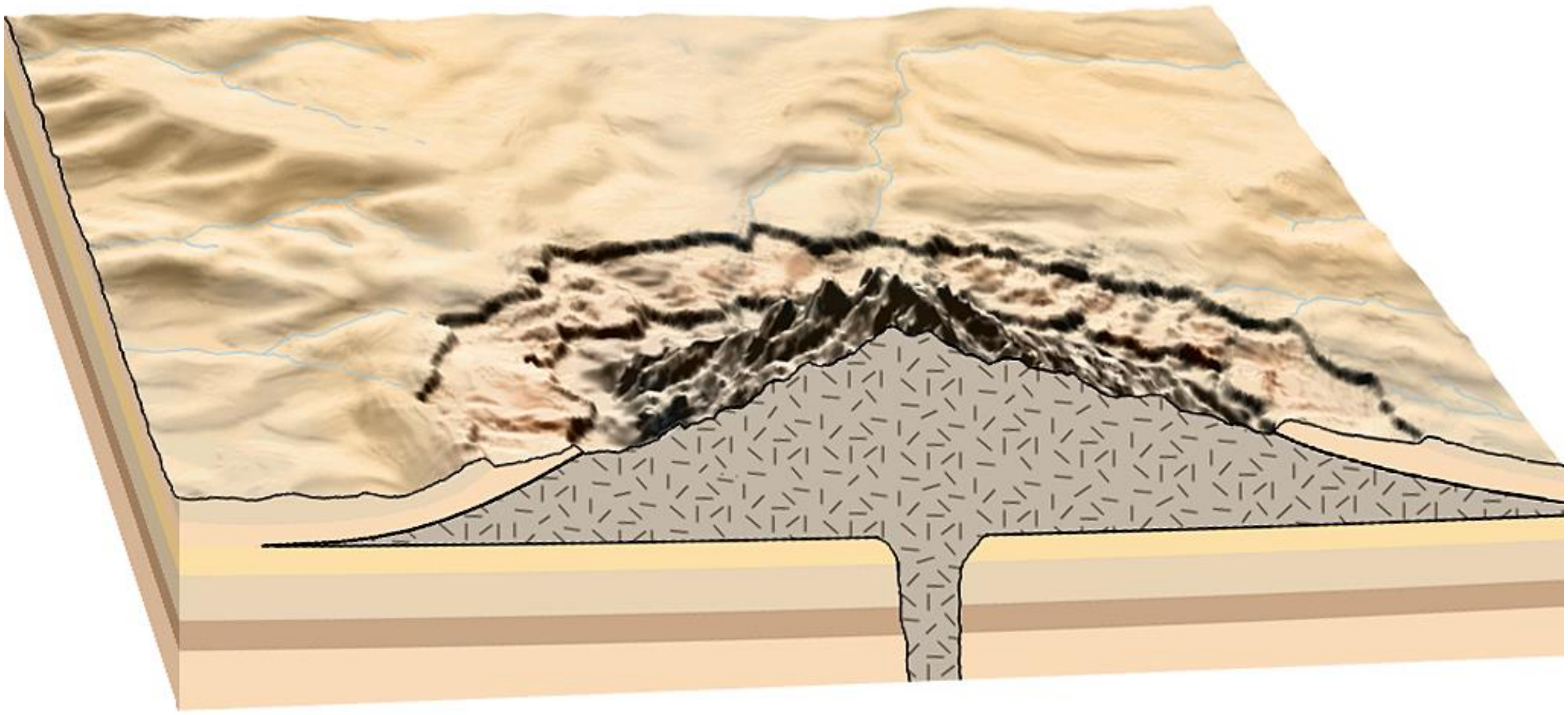
Pluton / Batholith

Batholith is a magmatic body compound of several plutons



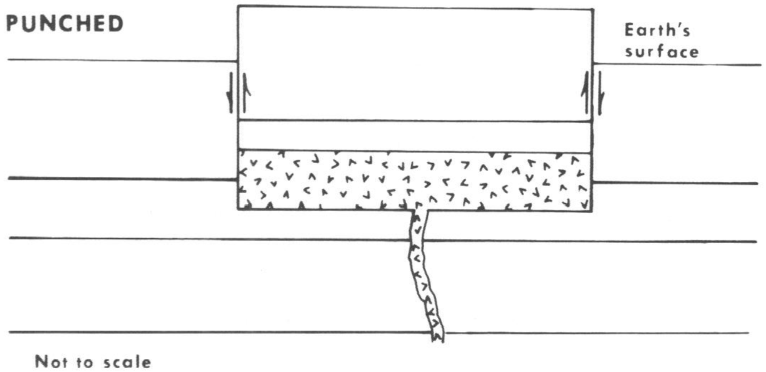
Lacolite

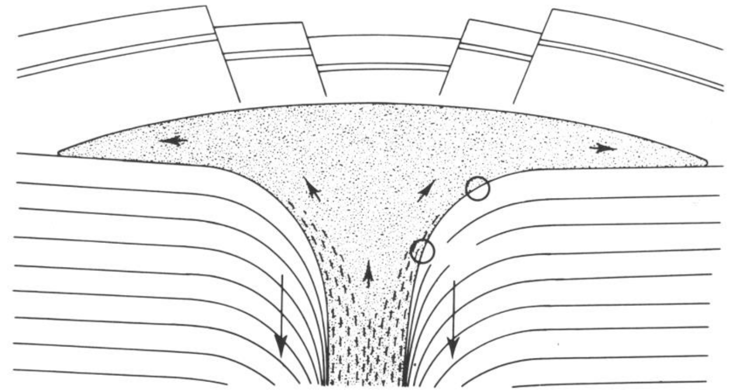
Tabular body concaved upward with rigid base

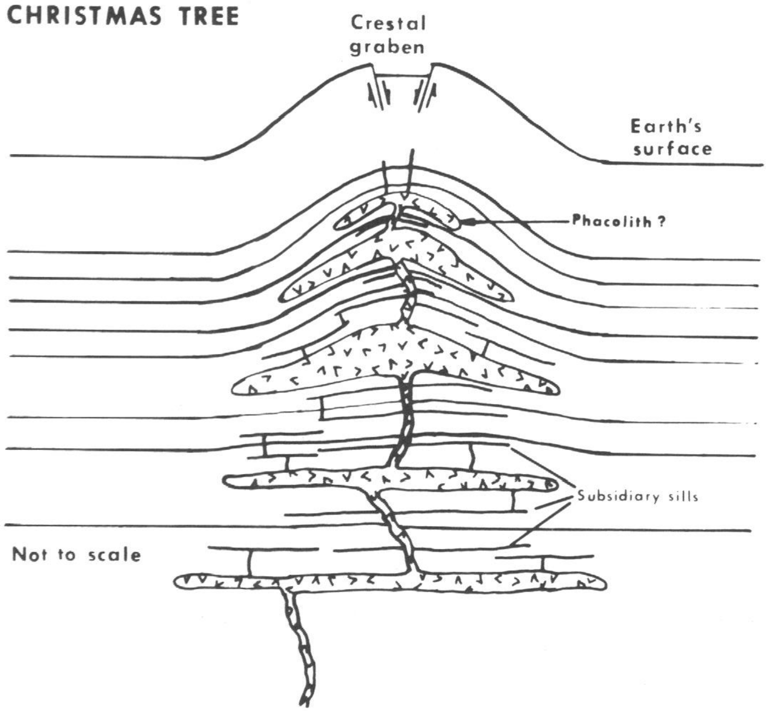


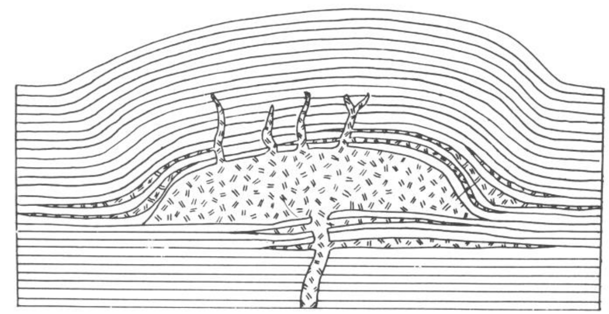
Obligated to upper (brittle) – crustal conditions

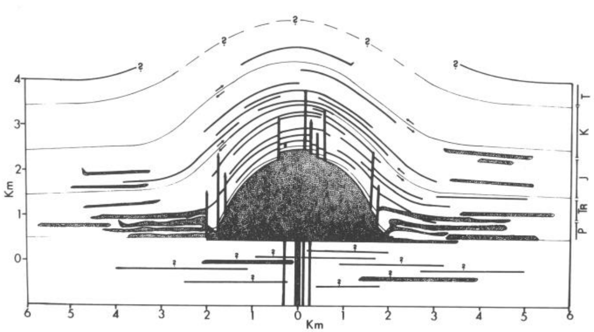
Lacolite


PUNCHED
Earth's surface
Not to scale

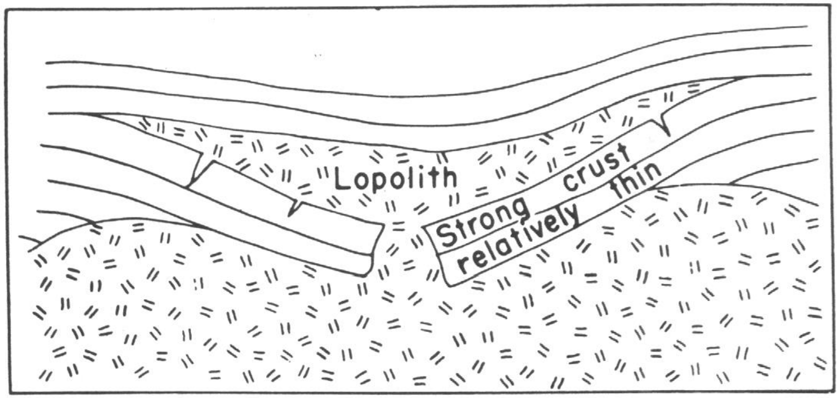


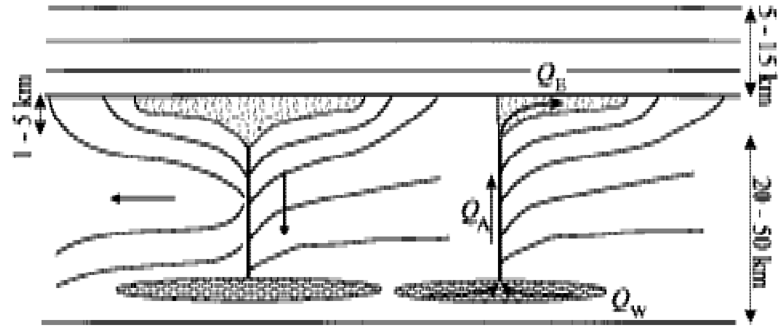

CHRISTMAS TREE
Crestal graben
Earth's surface
Phacolith ?
Subsidiary sills
Not to scale

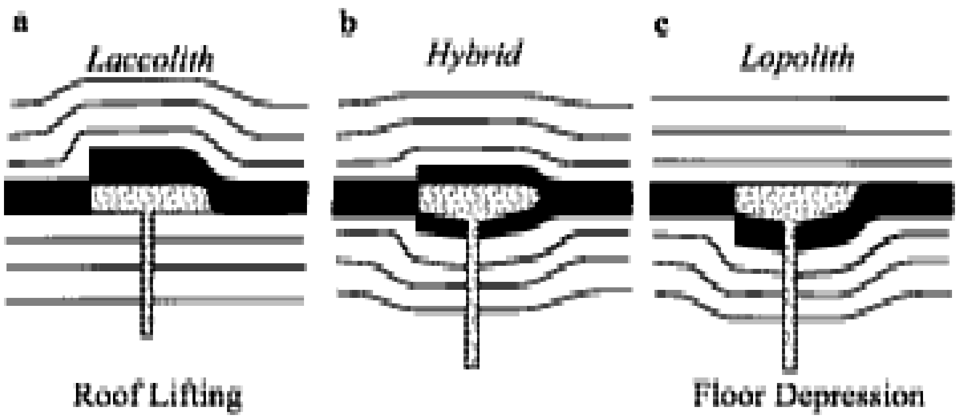


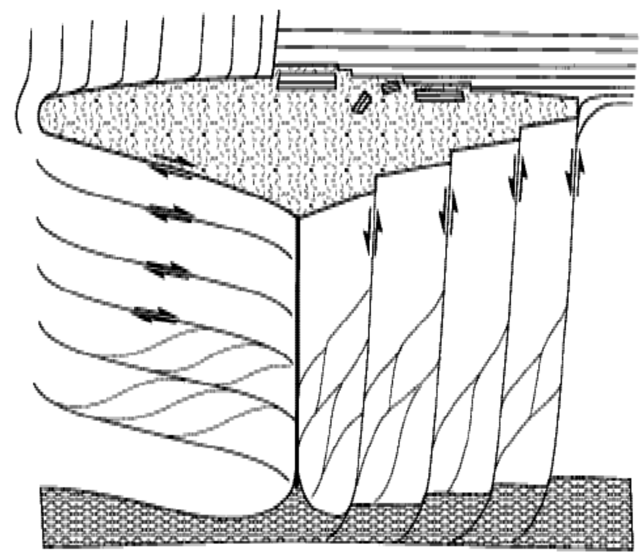

Km
Km
T
K
J
TR
P

Lopolite



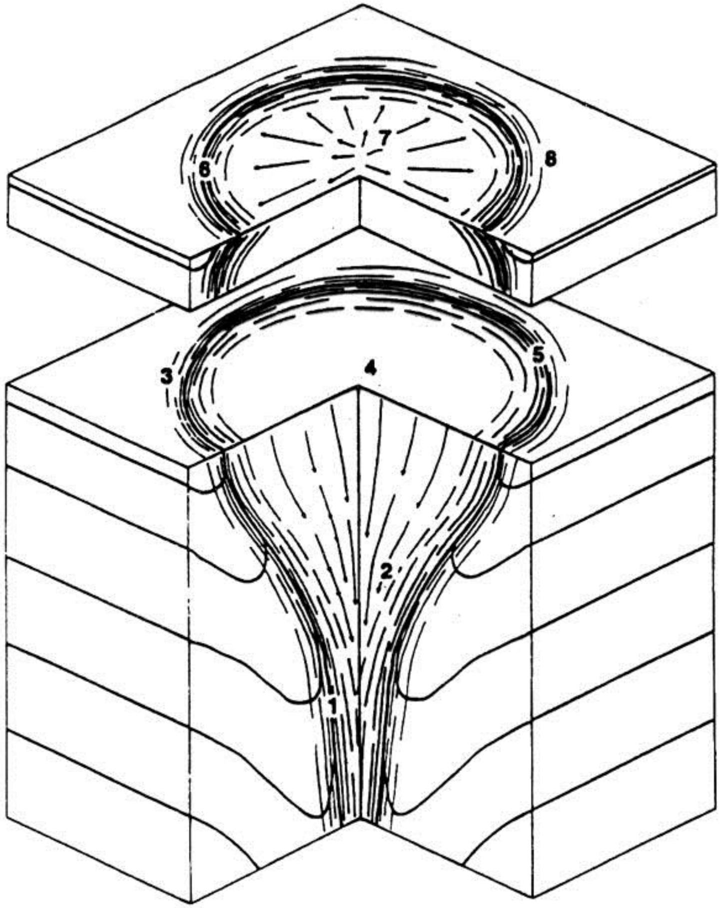






Tabular body concaved downward with rigid roof restricted to upper-crustal conditions

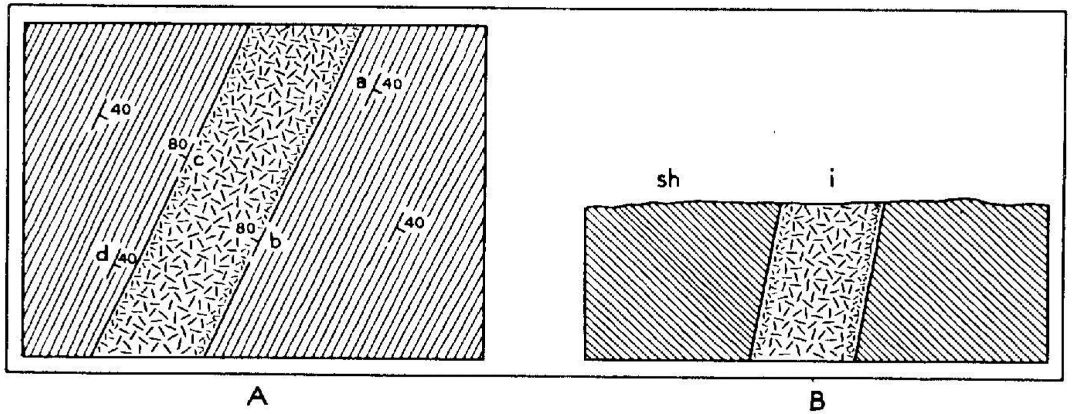
Magmatic diapires



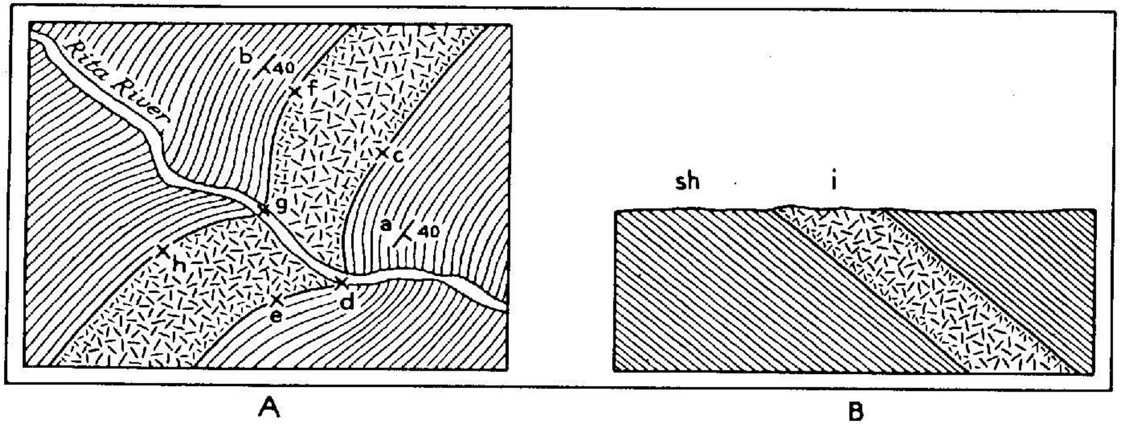
Cartoon of a granitic diapir showing the major structural features that should be developed in the granite and the surrounding country rock. Numbers refer to features mentioned in the text. The arrowheads on the lineations indicate plunge directions, rather than flow senses.

Steep-sided regular magmatic body with the shape of reverse tear.

Structural relationships between magmatic bodies and host rocks



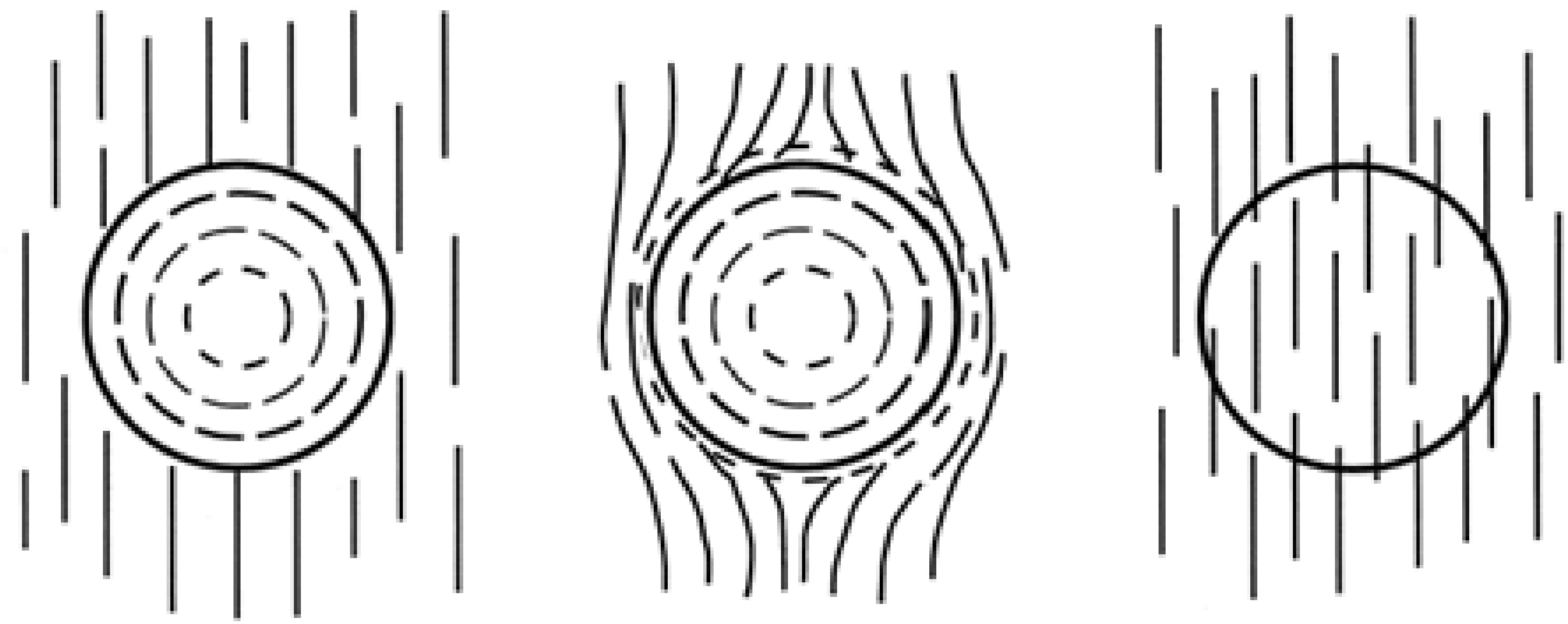
Discordant bodies



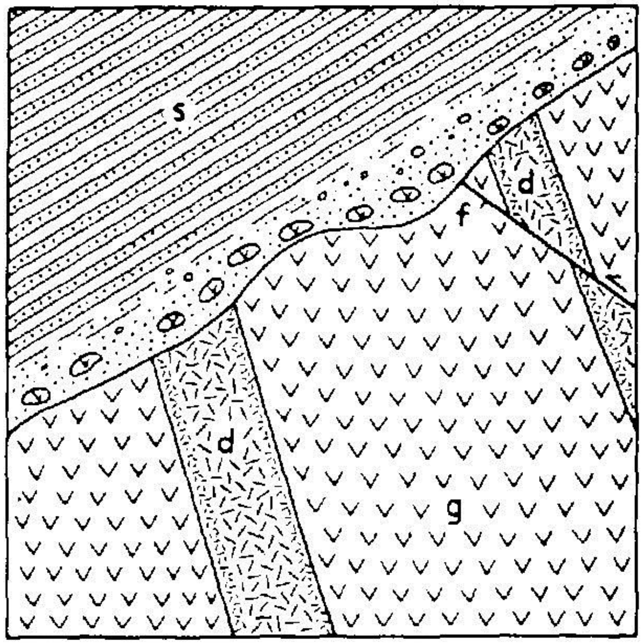
Concordant boides

Structural relationships between magmatic bodies and host rocks

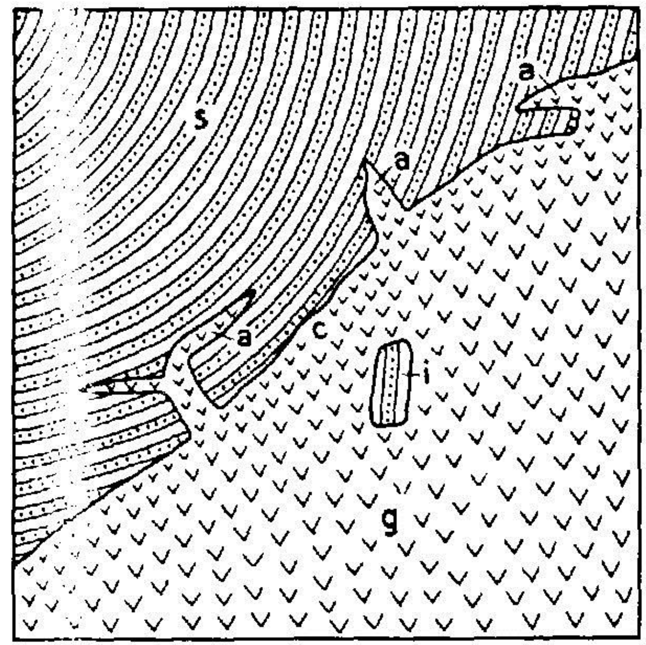
Posttectonic | Syntectonic | Pretectonic



Contacts of magmatic bodies in the geological map



A

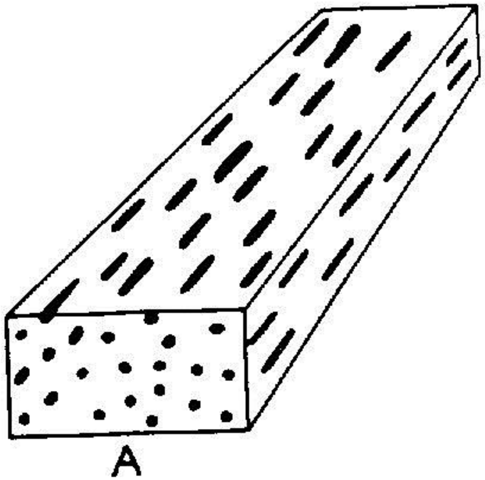


B

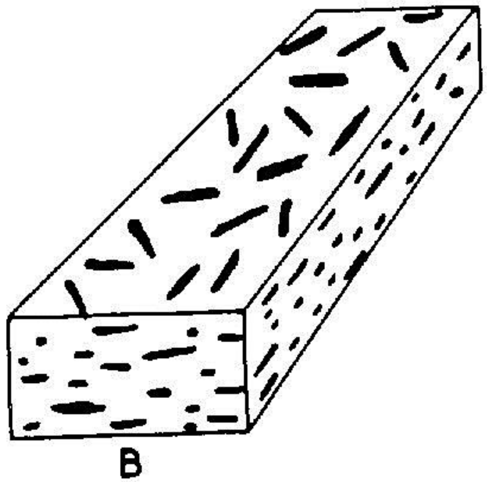
Contact / structural aureole

Chilled margins

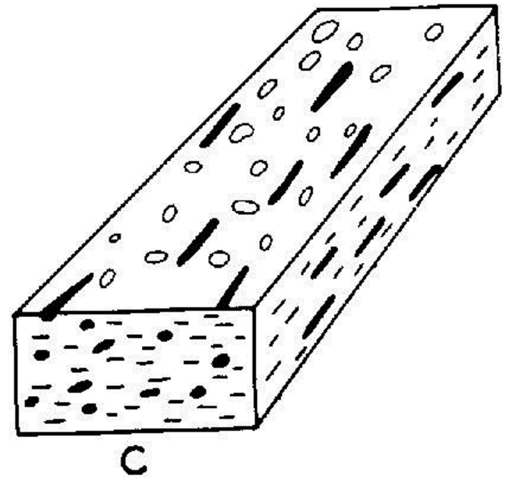
Fabrics and structures of magmatic rocks



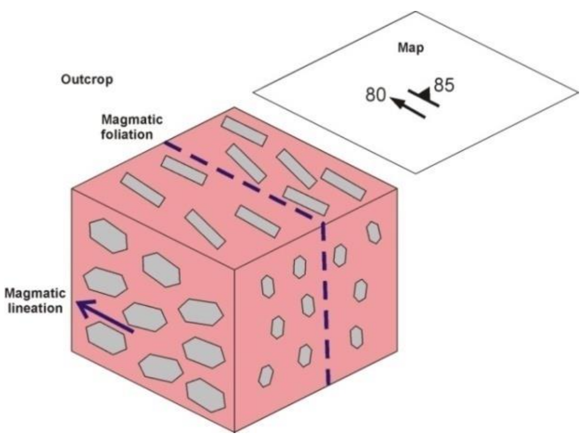
LINEAR



PLANAR

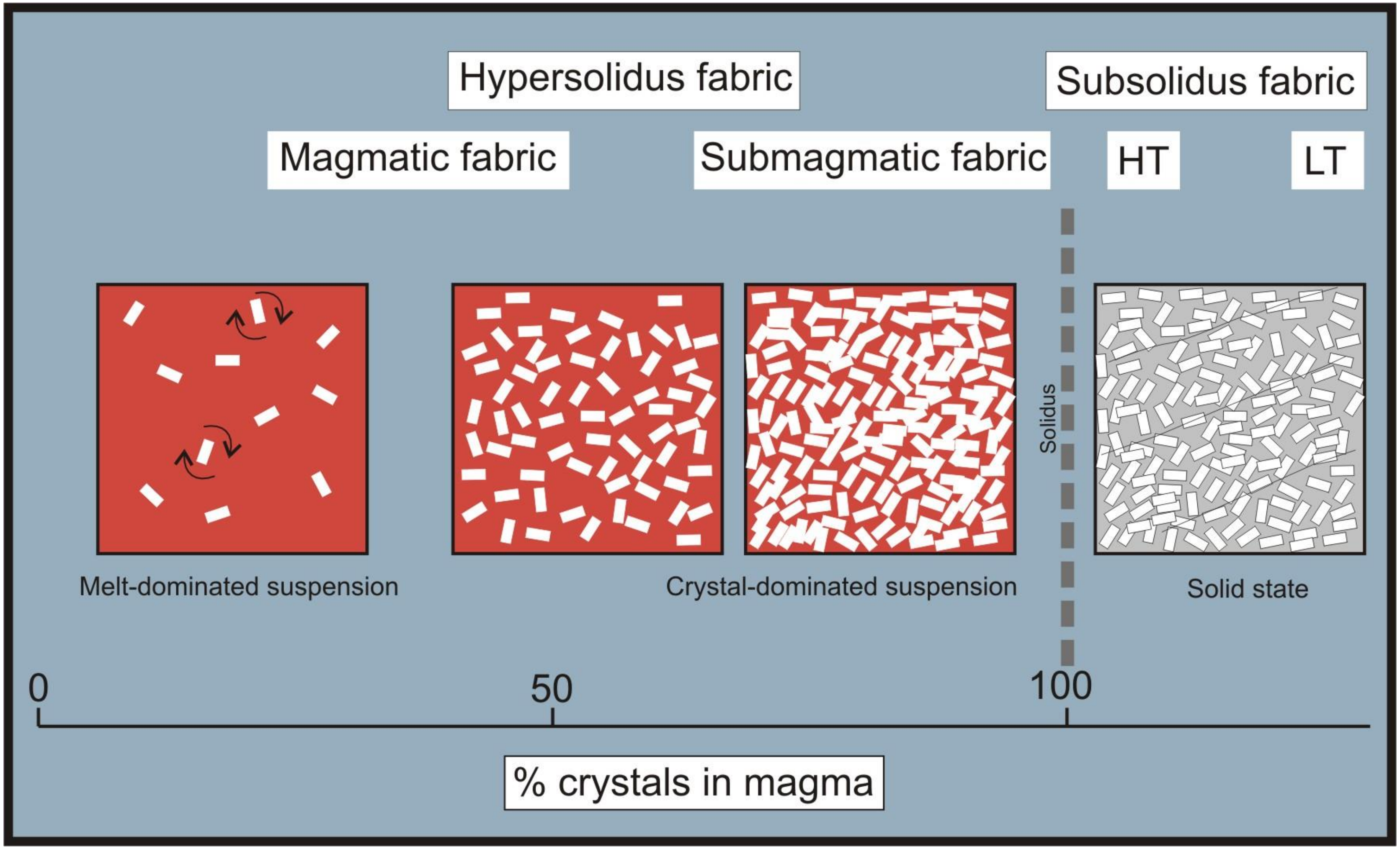


LINEAR-PLANAR

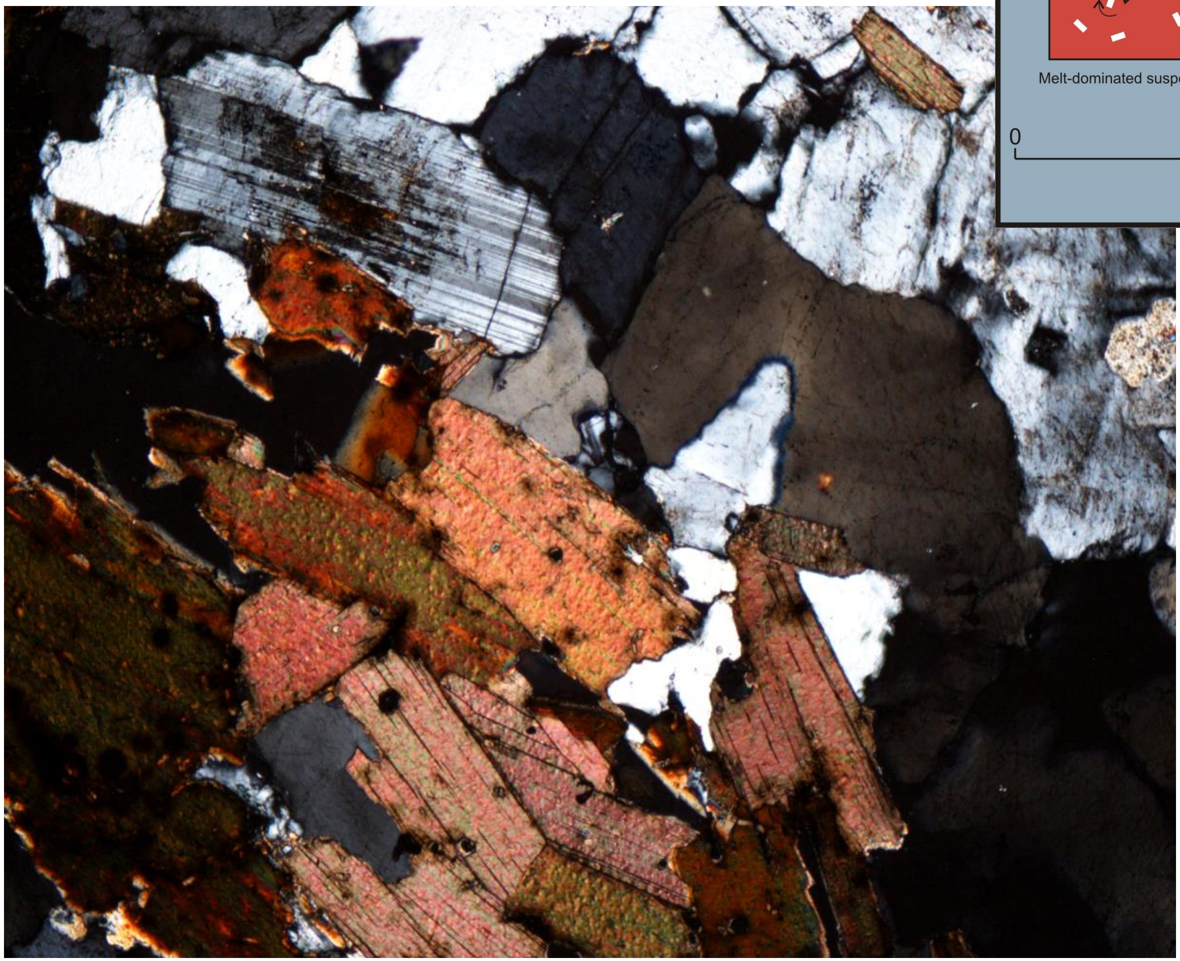


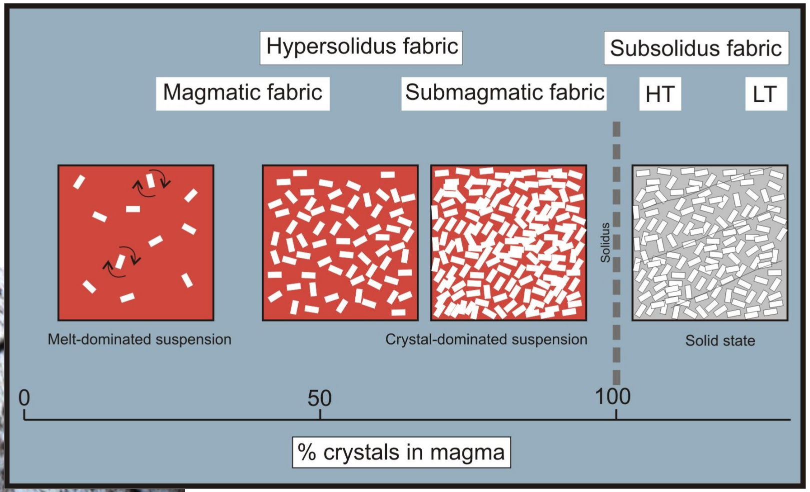
MAGMATIC FOLIATION
MAGMATIC LINEATION

Types of fabrics in magmatic rocks



Hypersolidus fabrics





No evidence or rare evidence for crystal-plastic deformation

Magmatic foliation

Porphyritic biotite granite

Flow magmatic foliation

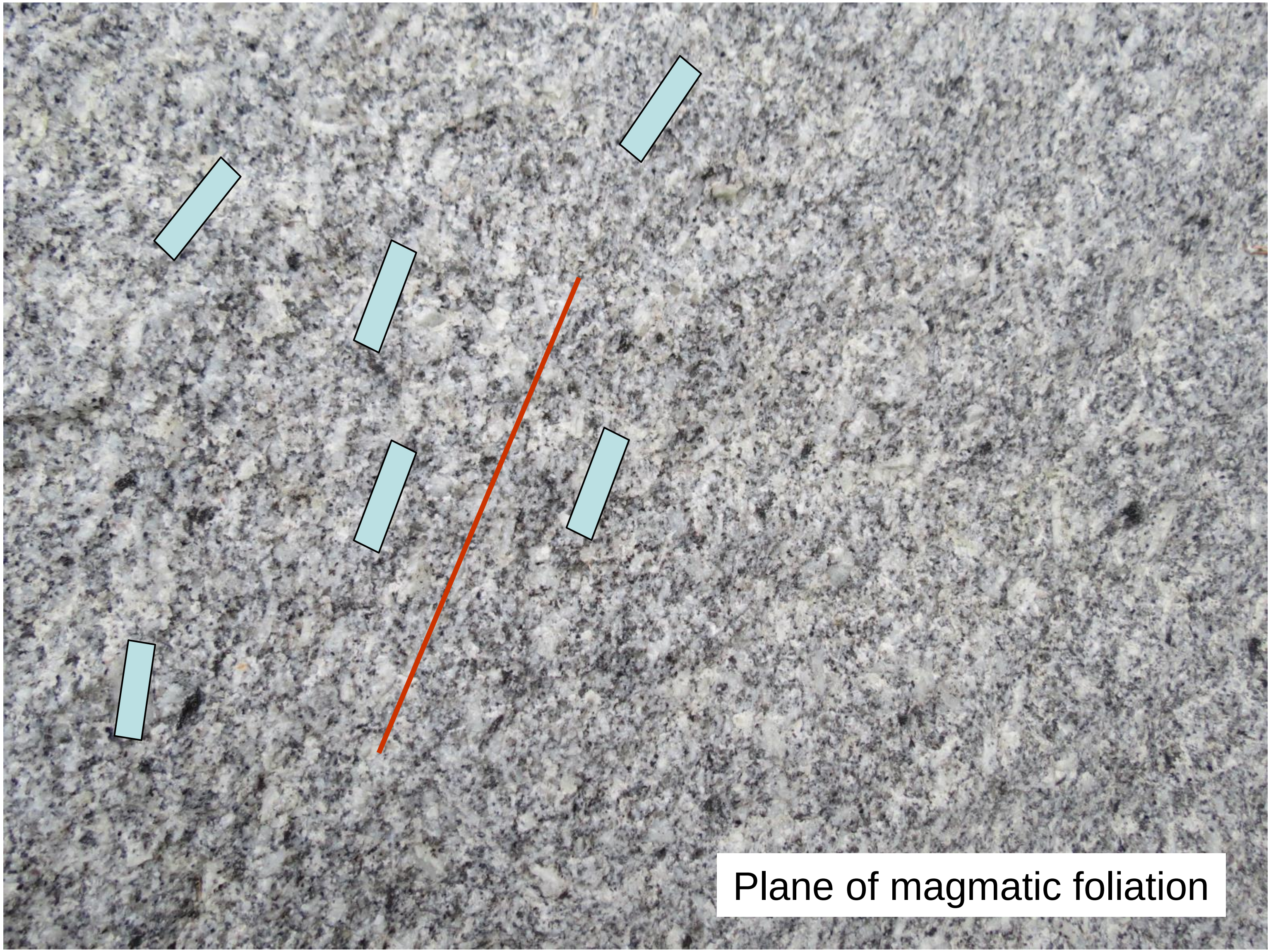
Rhyolite

Magmatic foliation

Medium-grained tonalite

Magmatic lineation

Medium-grained weakly porphyritic granite

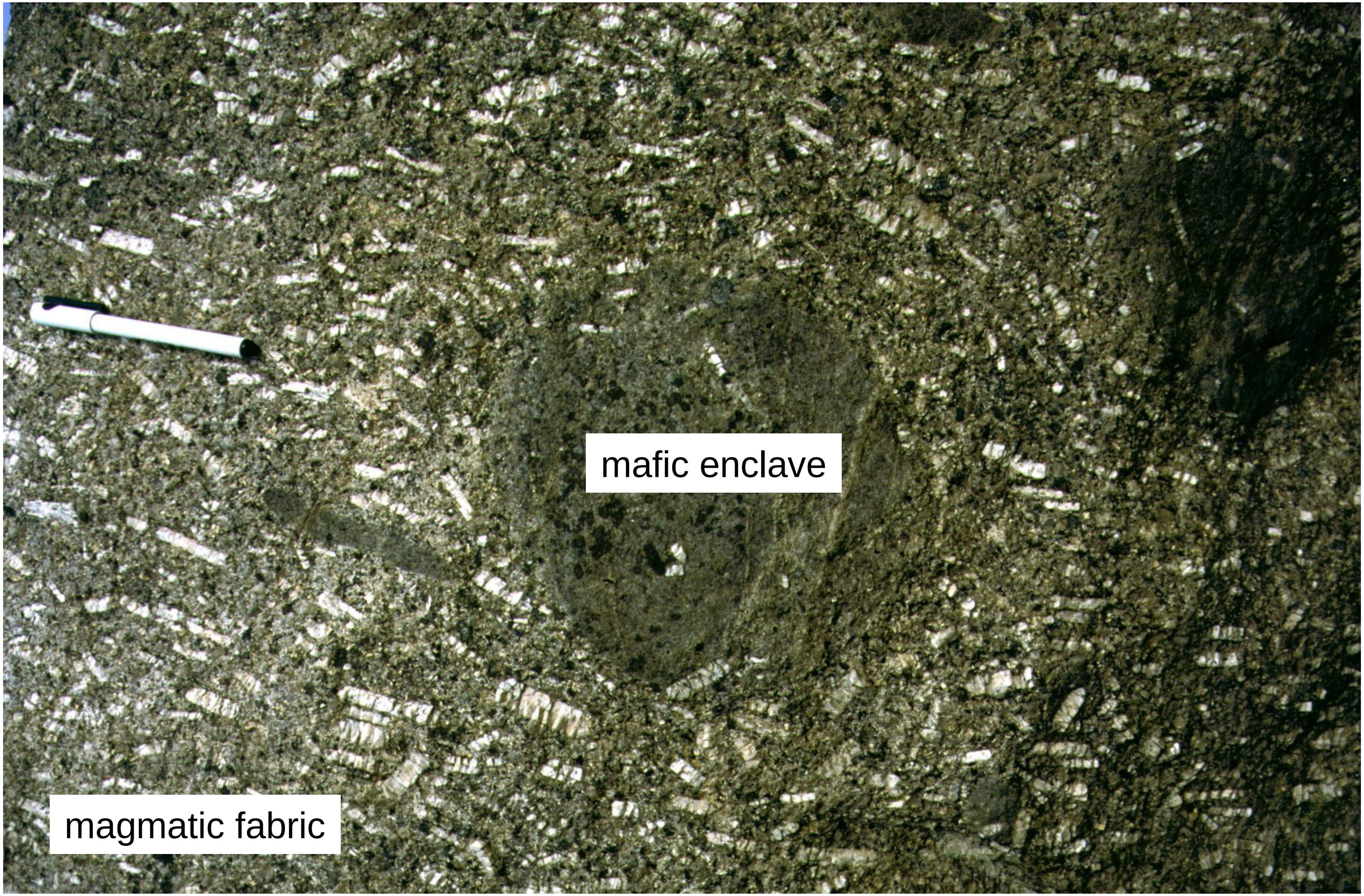


Magmatic foliation

Preferred orientation of mafic enclaves

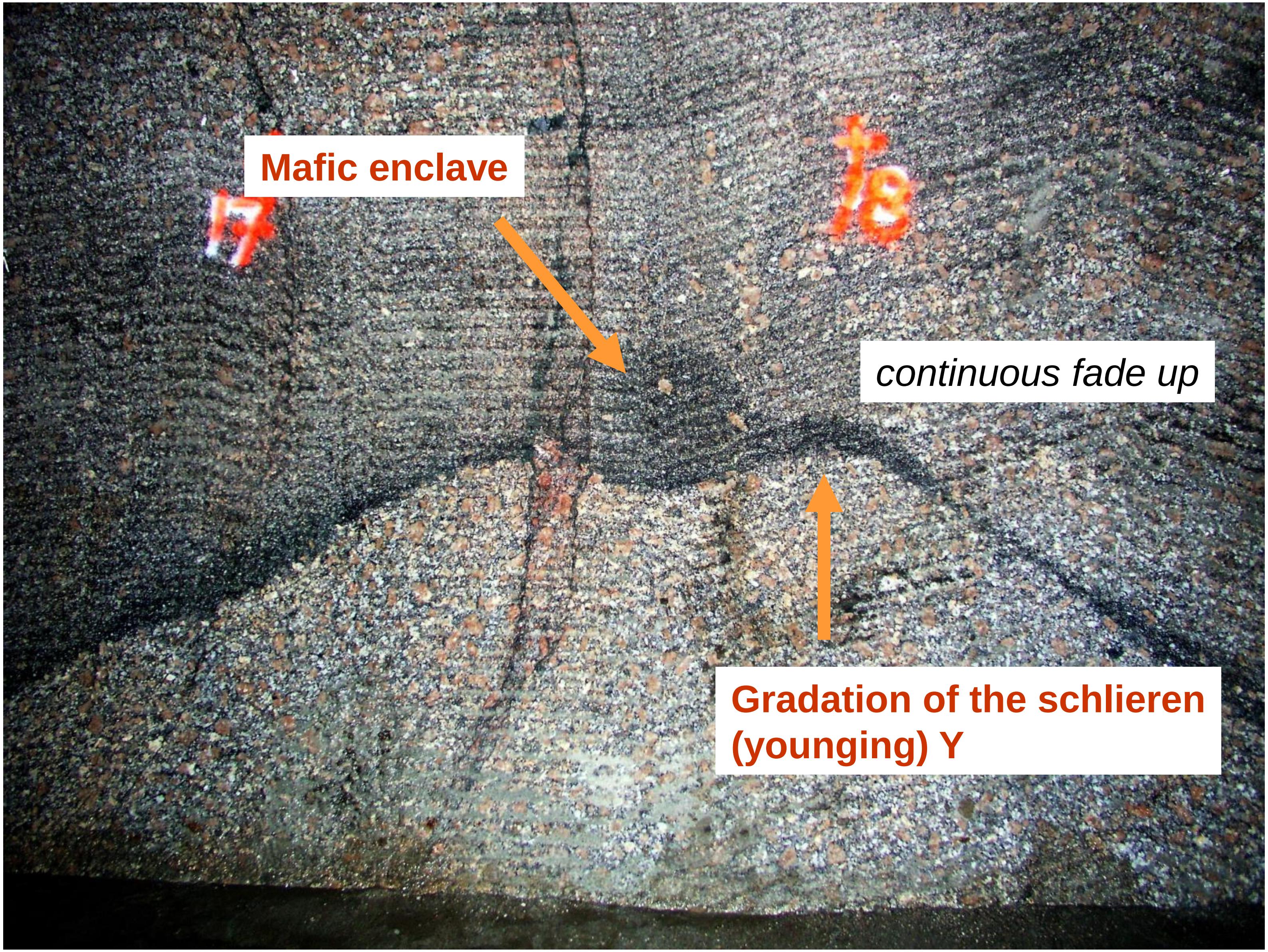
Magmatic foliation

Deflection of K-feldspars around rigid objects



Schlieren layers

Residues after magma mixing
Accumulation of mafic minerals

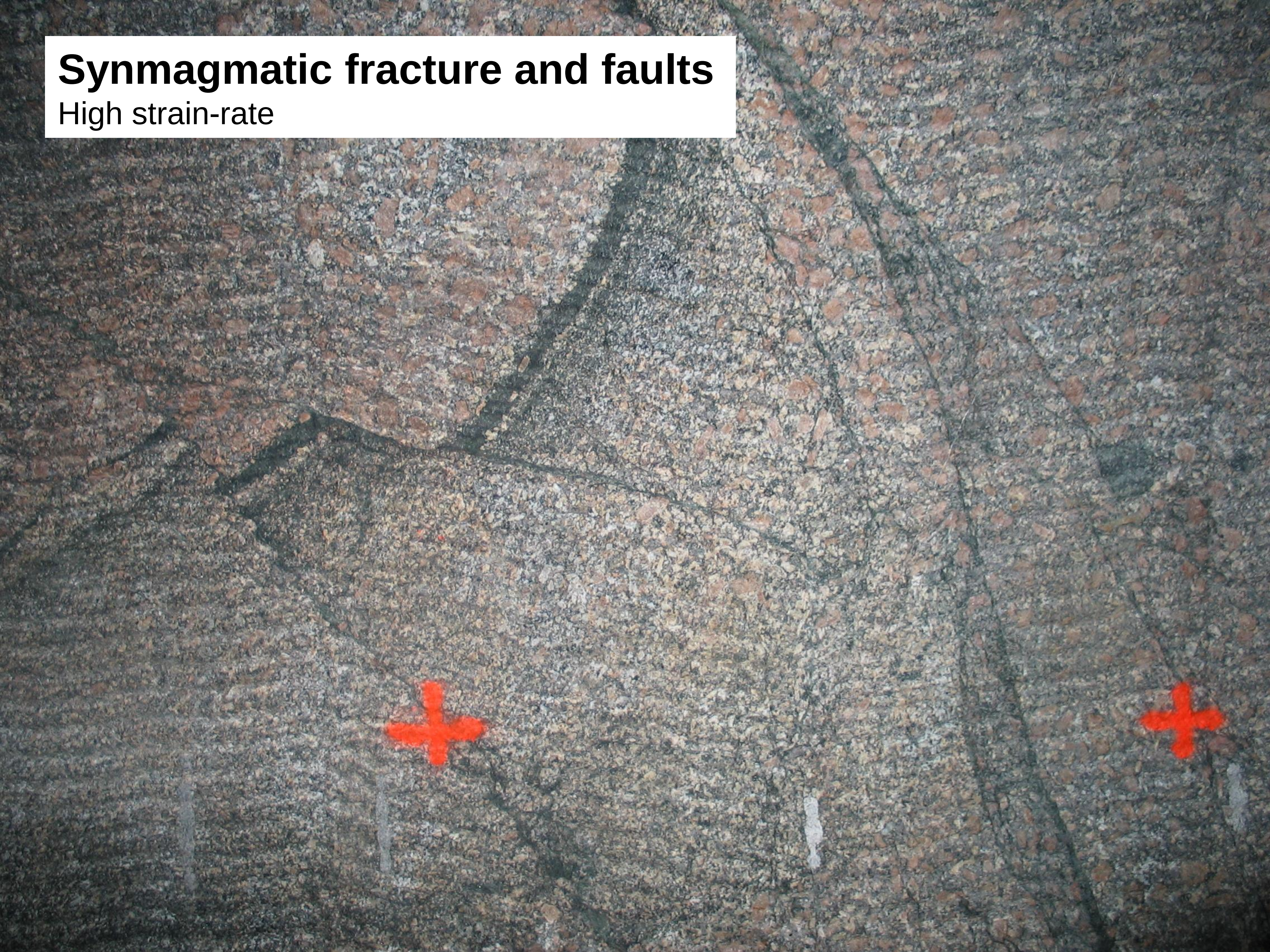


Synmagmatic fracture and faults

High strain-rate

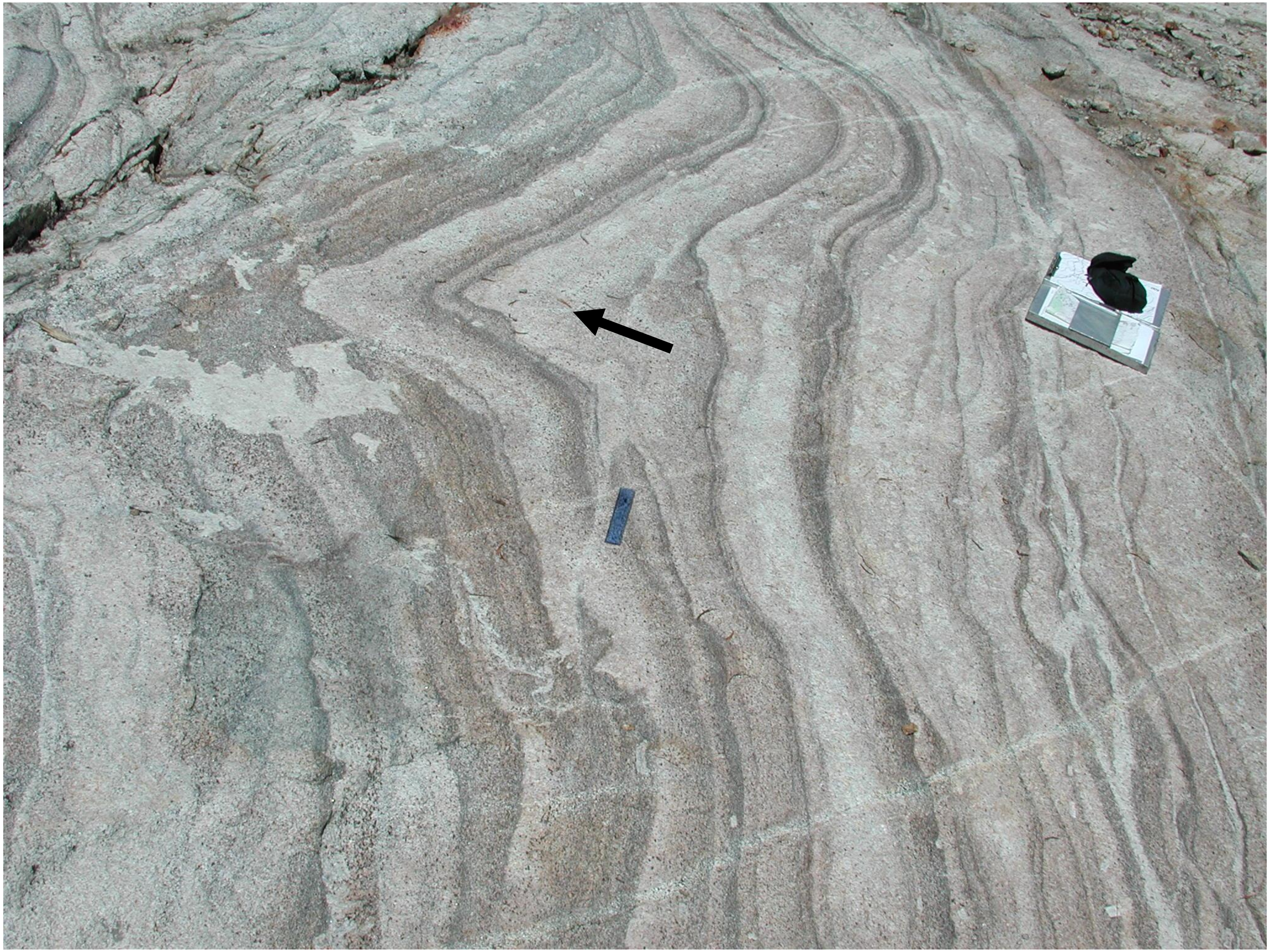
Synmagmatic fracture and faults

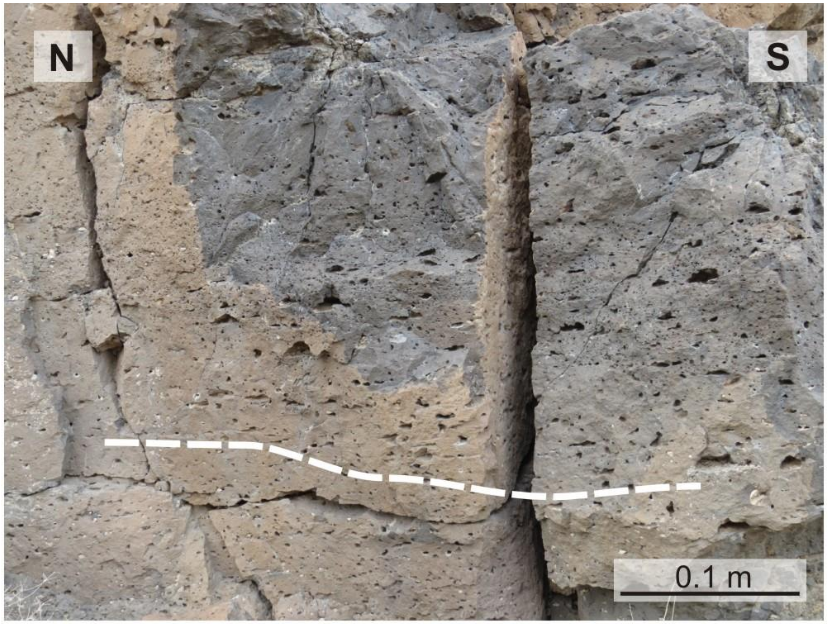
High strain-rate

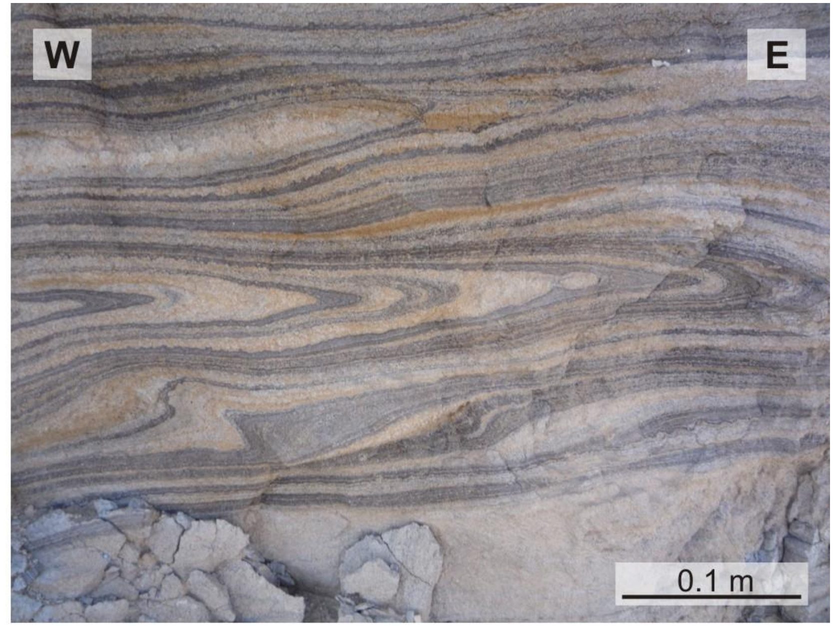


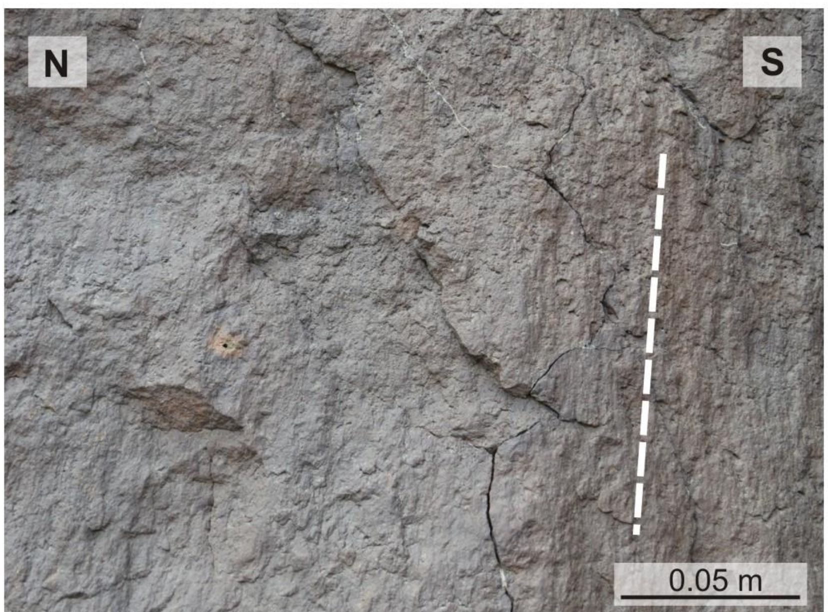
Magmatic folds

Low strain-rate









Magmatic flow-folds

Low strain-rate

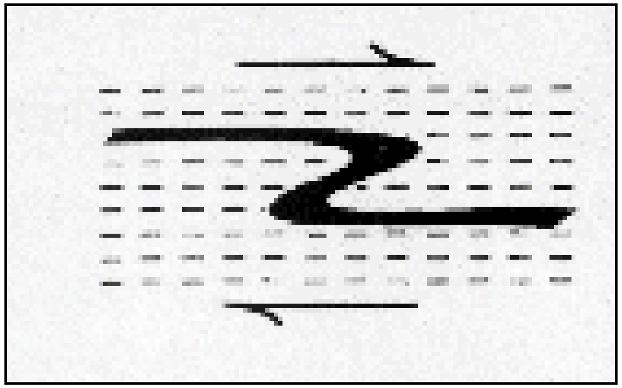
Magmatic layering

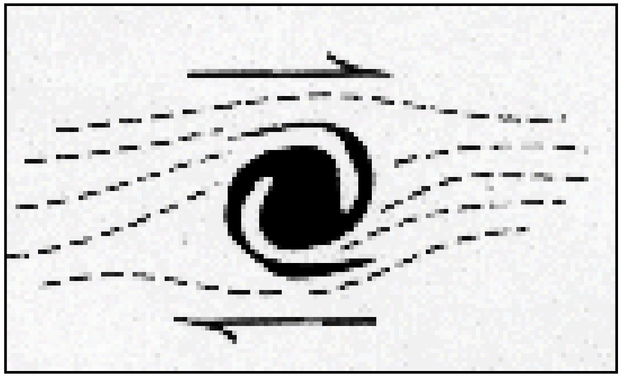
Flow foliation

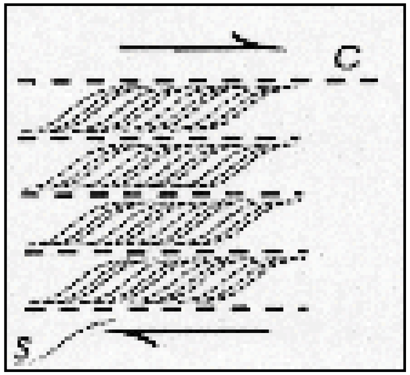
Subsolidus fabrics

Exclusivelly deformational fabrics in magmatic rocks related with recrystallization

HT (>450ºC)

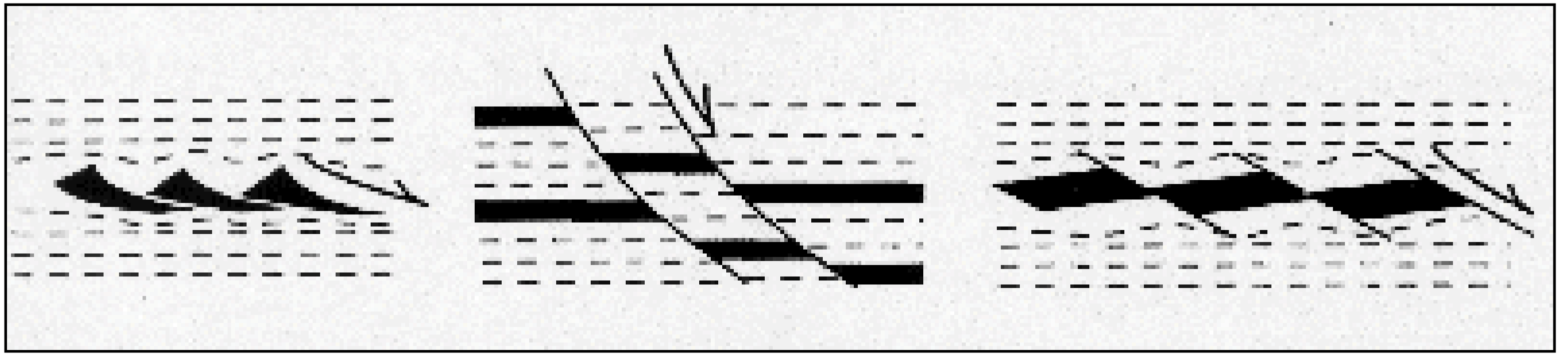






Ductile (asymmetric folding and shearing, rotate porfyroblasts, S-C fabrics)

LT (<450ºC)



Brittle (fracturation, segmentation of rigid parts, faulting)

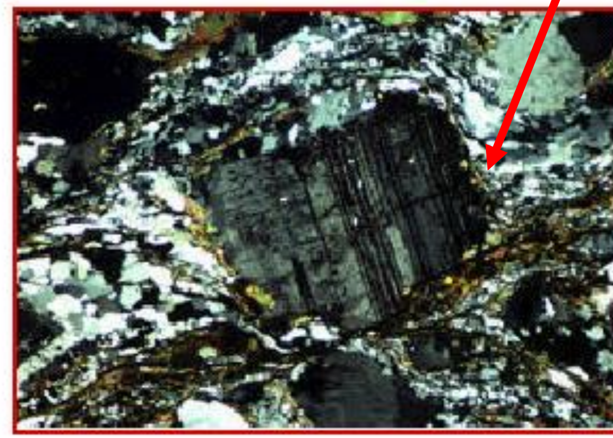
Localized shear zones, S-C fabrics

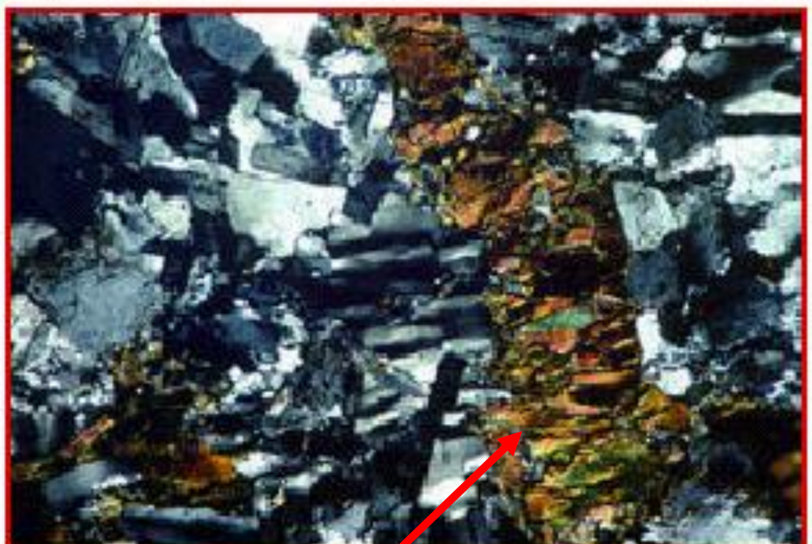
Ribbons of quartz aggregates and elongated biotite

Microstructural evidence for subsolidus fabrics

Undulose extinction
In quartz aggerates

Recrystallization in pressure shadows

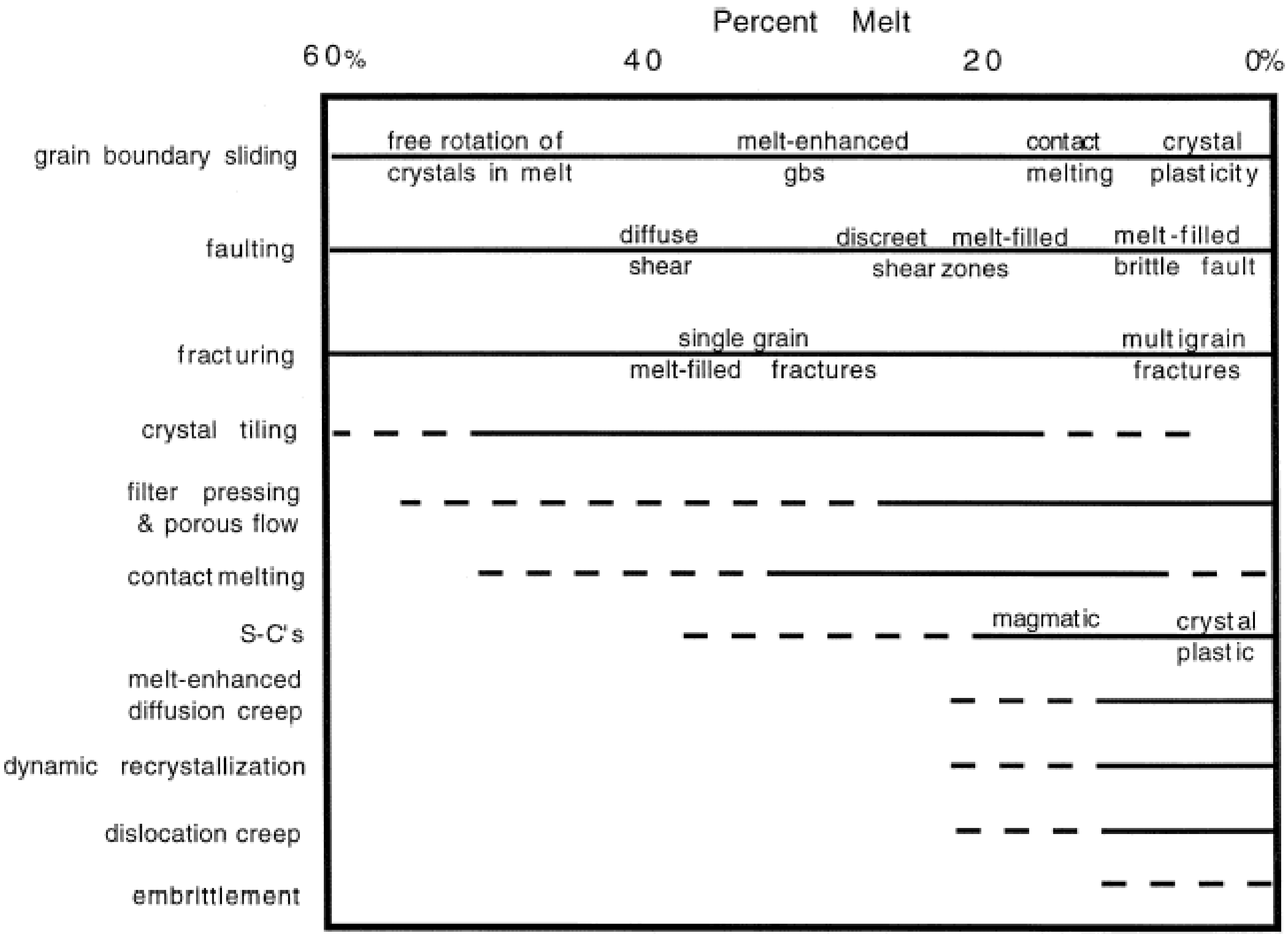




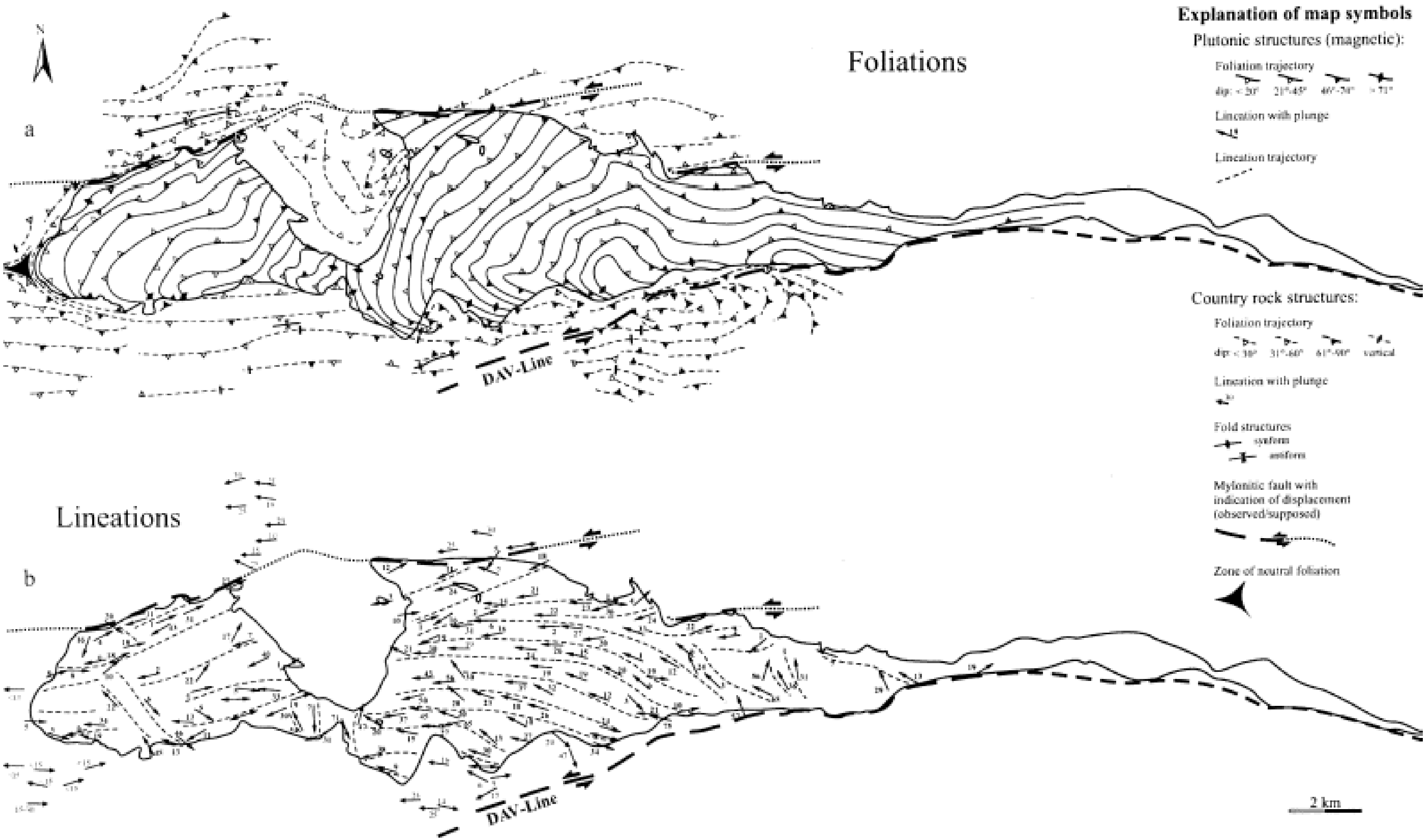
Deformation of biotite aggregates

Grain-size reduction

Overview of possible deformational mechanisms depending on melt (%)



Fabrics of magmatic rocks in the geological map



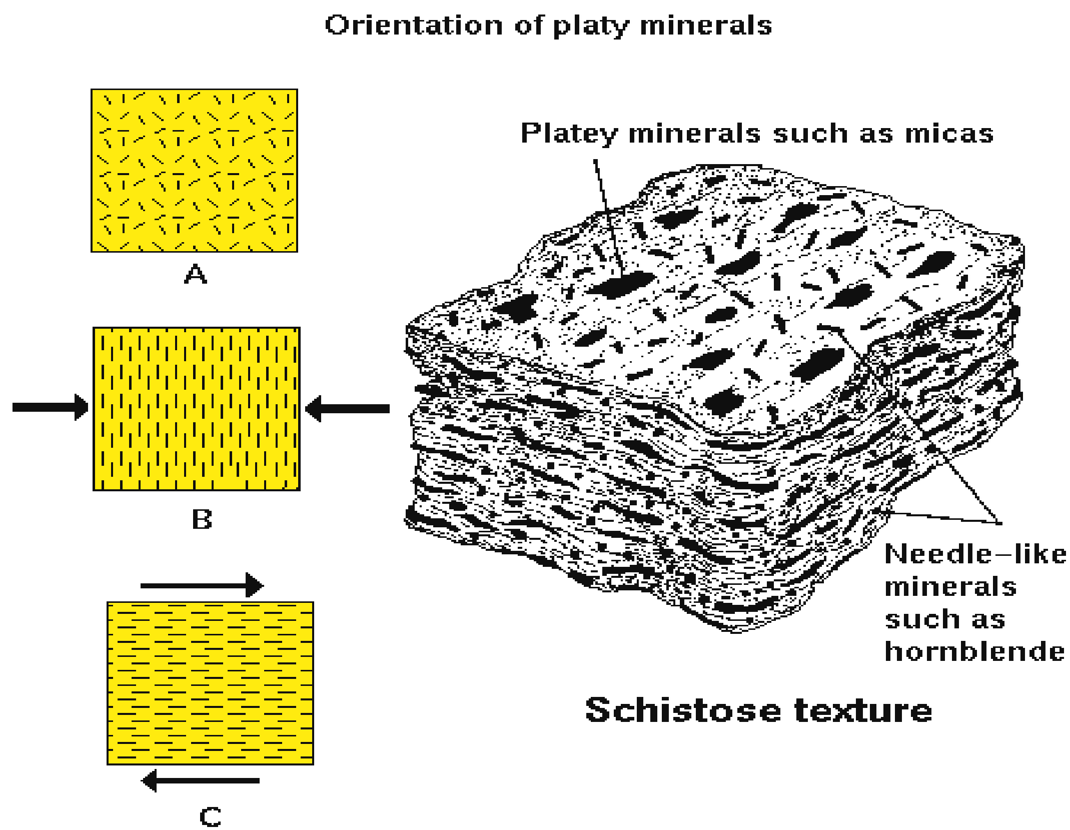
Fabrics of metamorphic rocks

FOLIATION

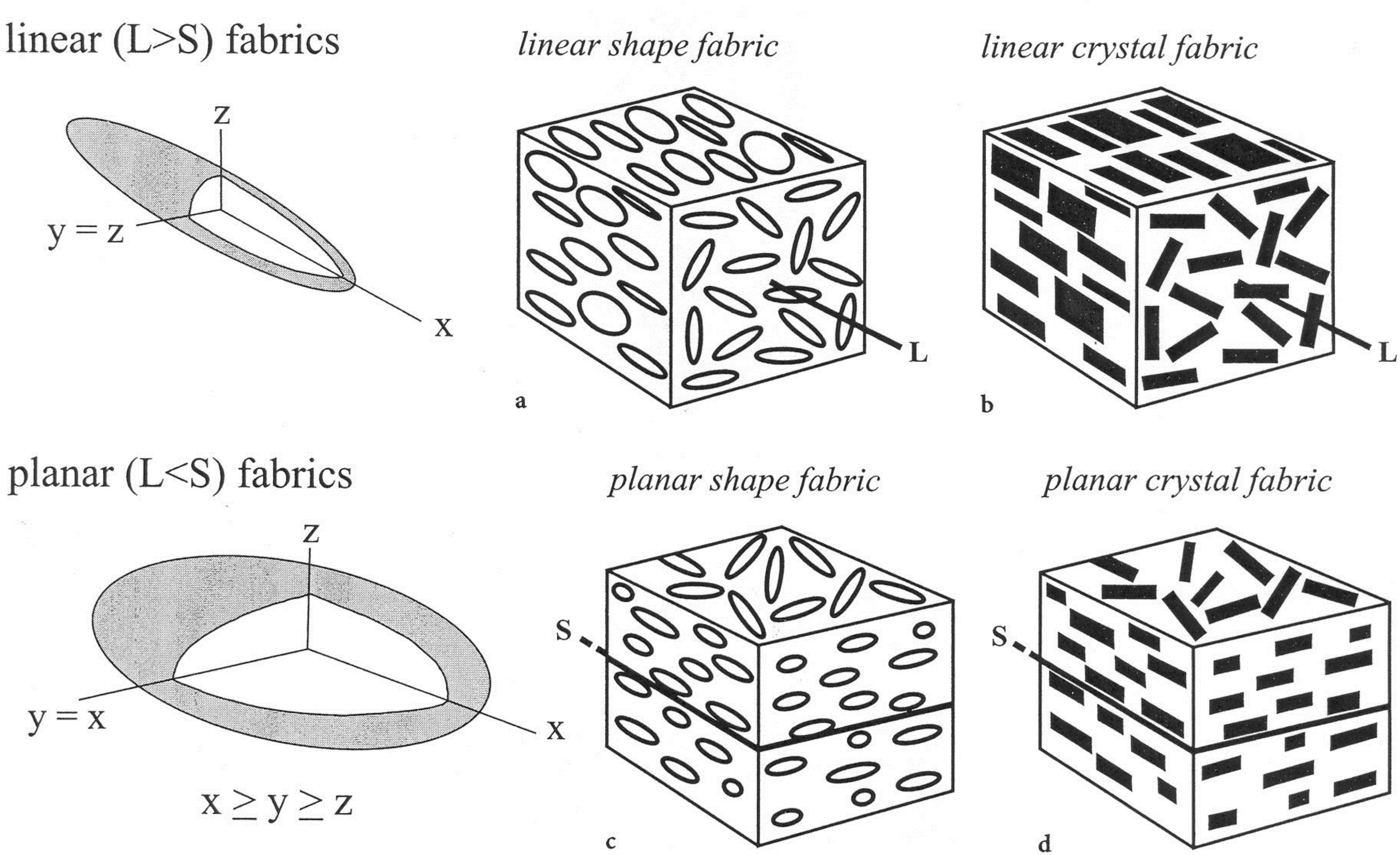
A mesoscopically penetrative parallel alignment of planar fabric elements in a rock, usually a metamorphic or magmatic rock.

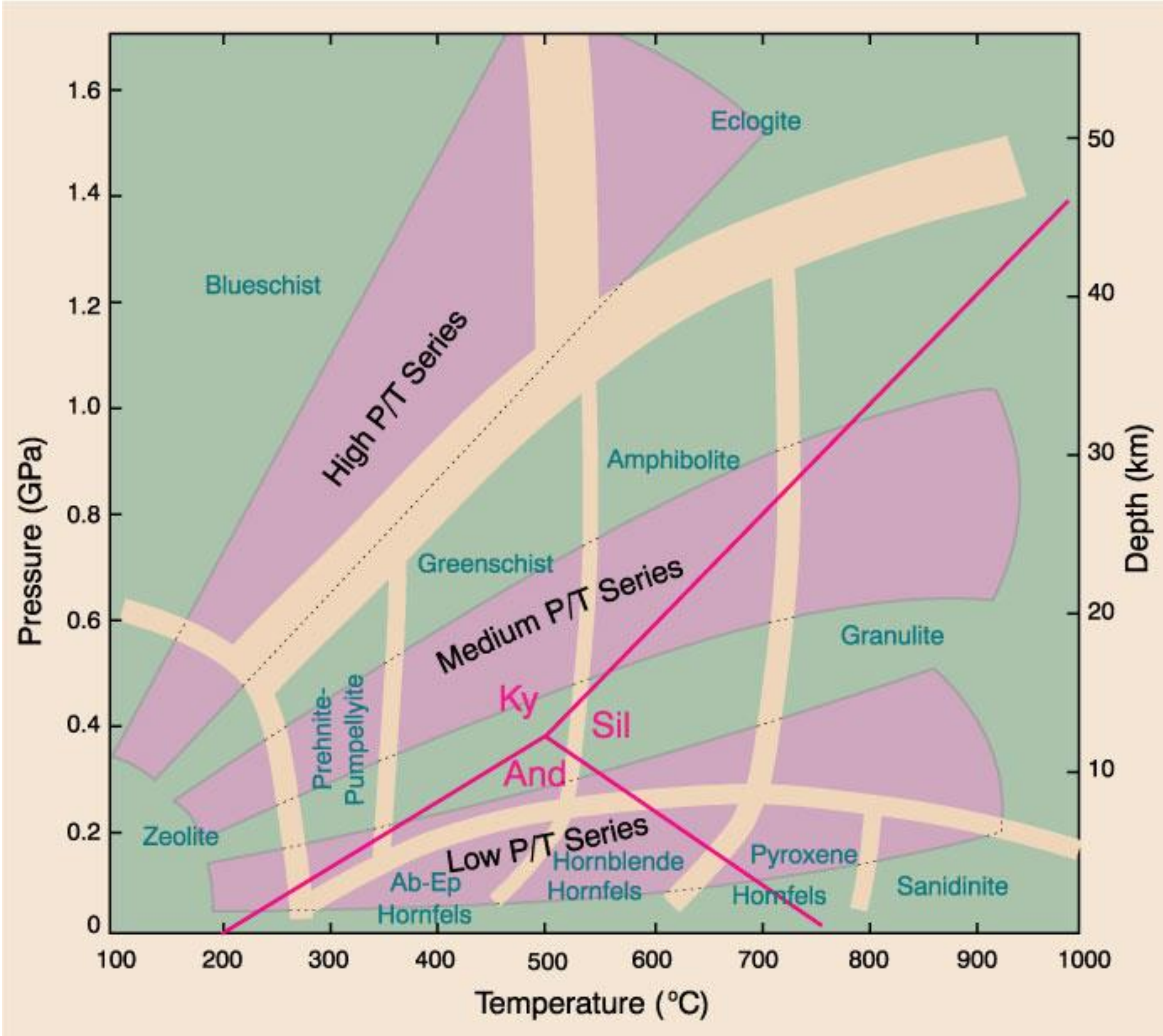
LINEATION

The subparallel to parallel alignment of elongate, linear fabric elements in rocks.



L, S, a LS fabrics





Eclogite
Blueschist
High P/T Series
Amphibolite
Greenschist
Medium P/T Series
Granulite
Prehnite-
Pumpellyite
Ky
Sil
And
Zeolite
Low P/T Series
Hornblende
Hornfels
Pyroxene
Hornfels
Ab-Ep
Hornfels
Sanidinite
Pressure (GPa)
Depth (km)
Temperature (°C)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
10
20
30
40
50
100
200
300
400
500
600
700
800
900
1000

Metamorphic foliation

Metamorphic foliation is a penetrative planar fabrics usually produced by deformation and recrystallization of mineral grains to produce planar preferred orientation of new minerals.

Designated as „S“ (So to Sx)

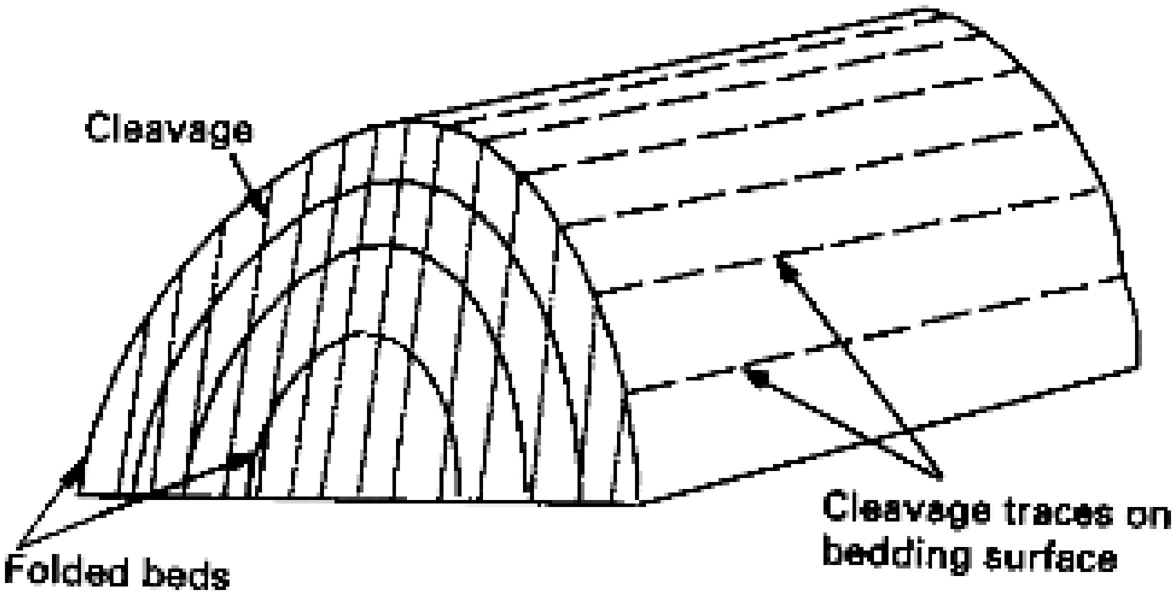
Individual types of metamorphic foliation:

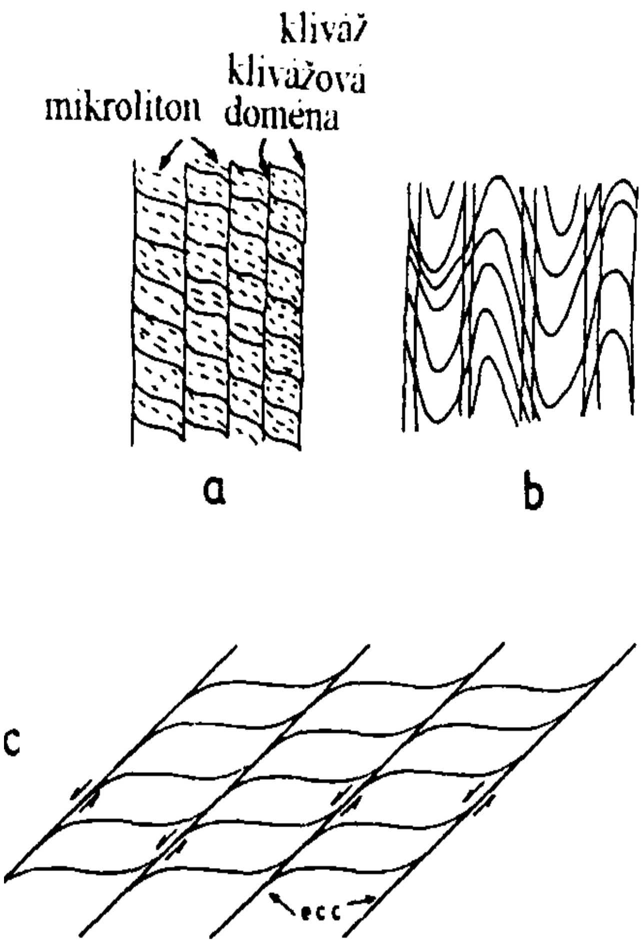
1. Cleavage (slaty cleavage)

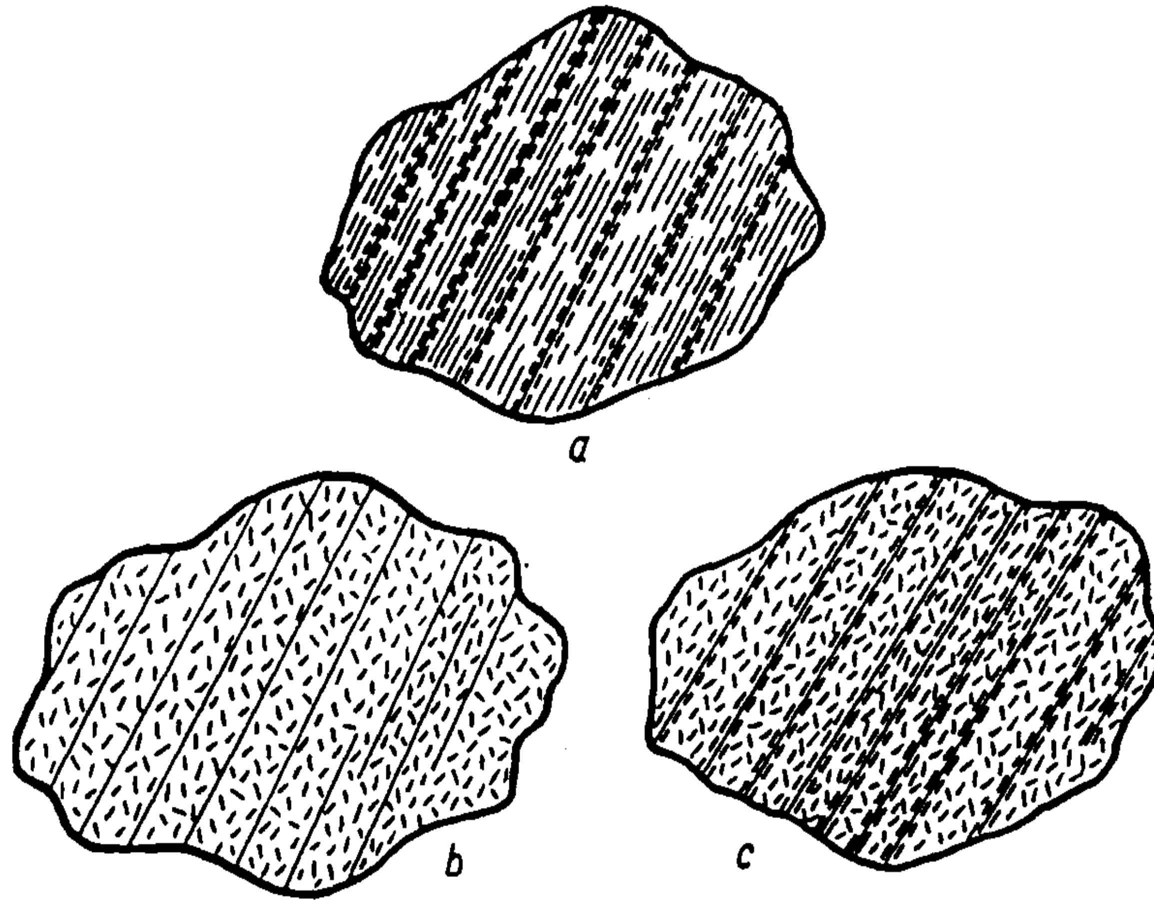
Sharply superimposed penetrative planar fabric **in low-grade** fine-grained rocks

Crenulation cleavage is produced by microfolding of a preexisting foliation
Fracture cleavage consists of closely-spaced fractures
Pressue-solution cleavage produces a mineral segregation along the planes
Slaty cleavage

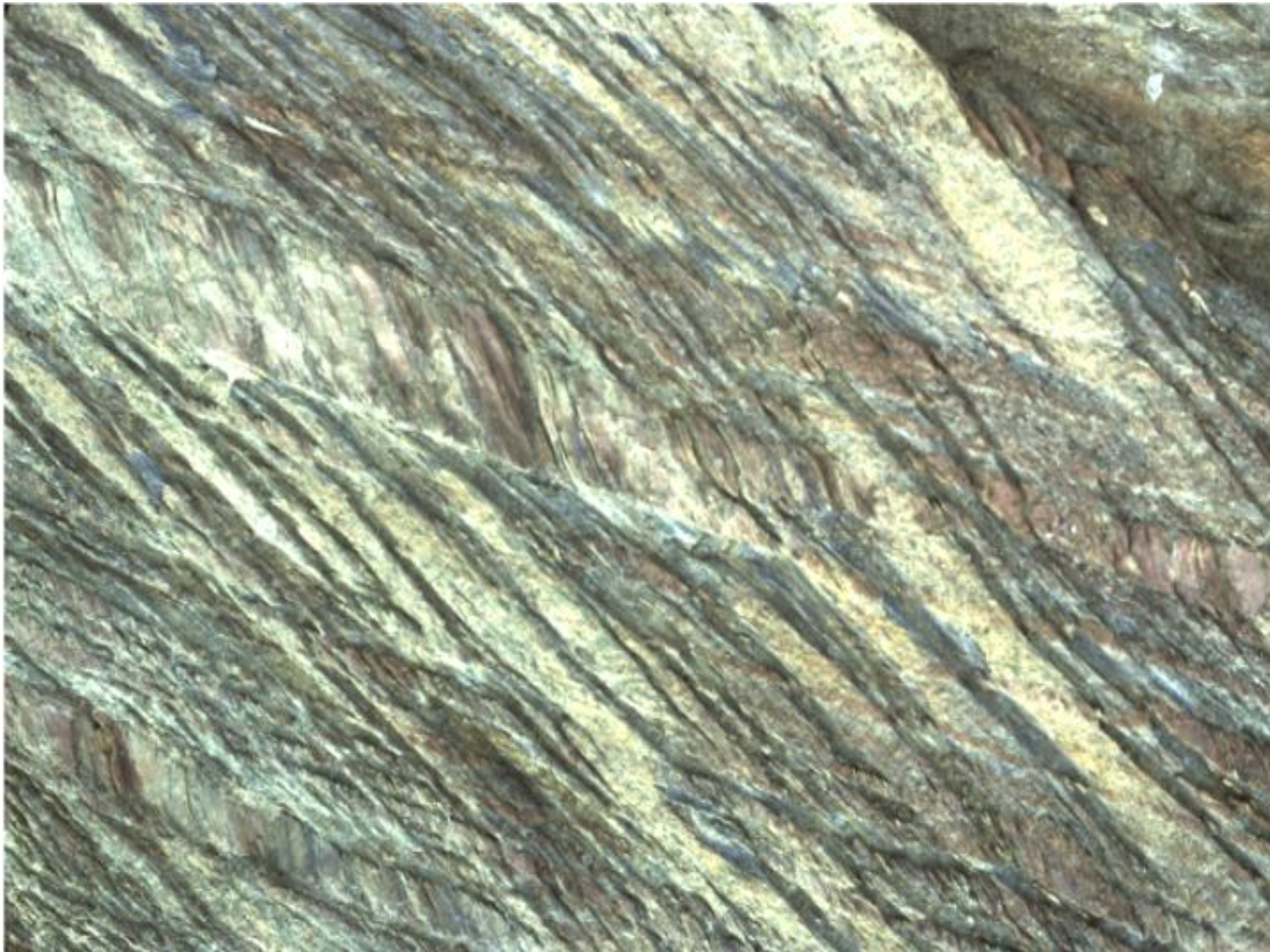
Cleavage plane




kliváž
klivážová
mikroliton
doména
a
b
c
ecc


a
b
c

Cleavage (slaty cleavage)



Individual types of metamorphic foliation:

2. Metamorphic foliation

Original or superimposed planar fabric **in higher-grade** metamorphic rocks

Schistosity – foliation defined by preferred orientation of phylosilicates and / or mineral segregation into bands parallel with the foliation

Compositional banding

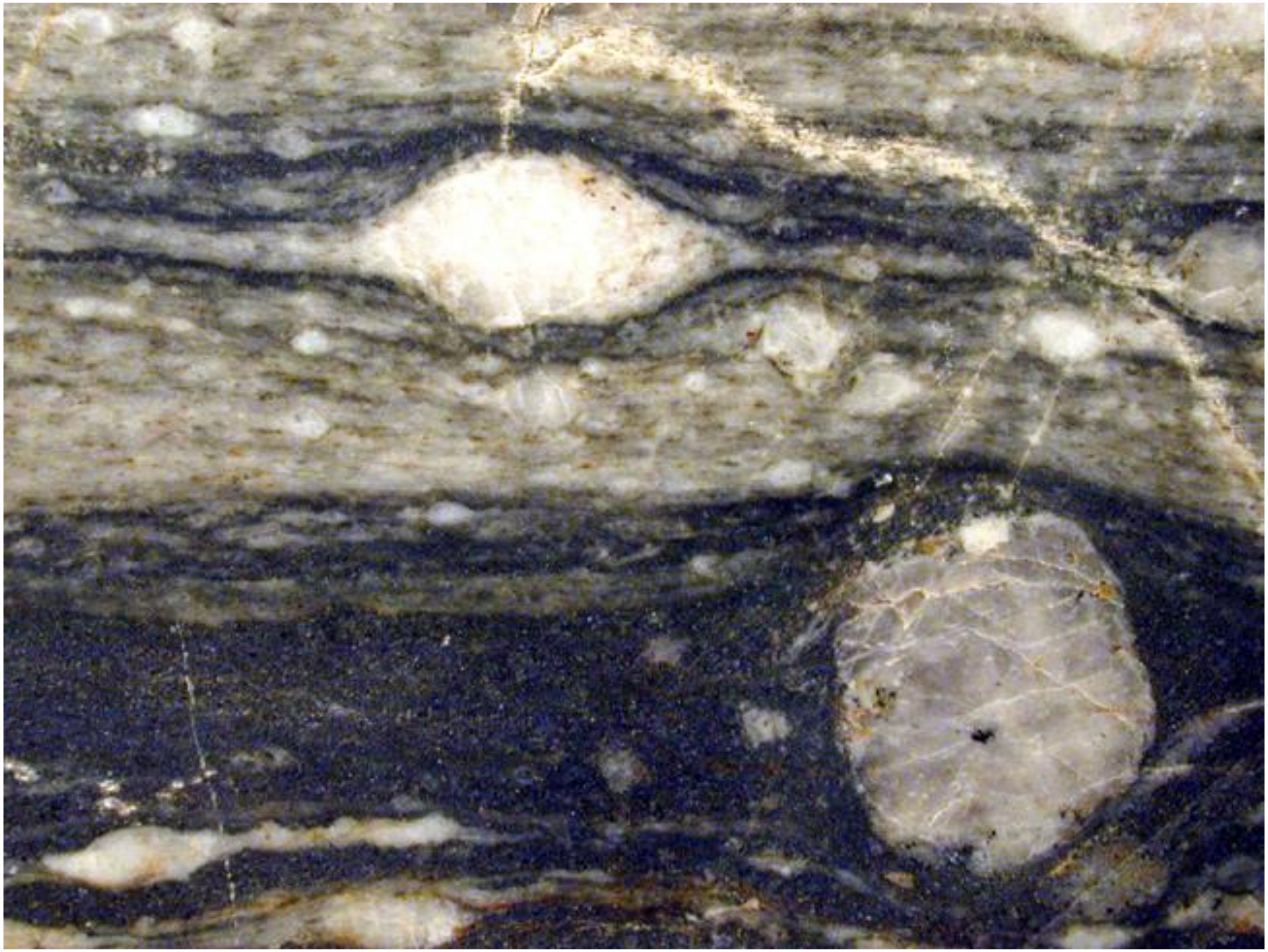
Mylonitic foliation – a penetrative foliation developed in zones of high-shear strain (ductile shear zones). Typical is tectonic reduction in grain-size of the rocks.

Schistosity defined by preferred orientation minerals

Compositional banding defined by preferred orientation minerals or banding parallel with the foliation

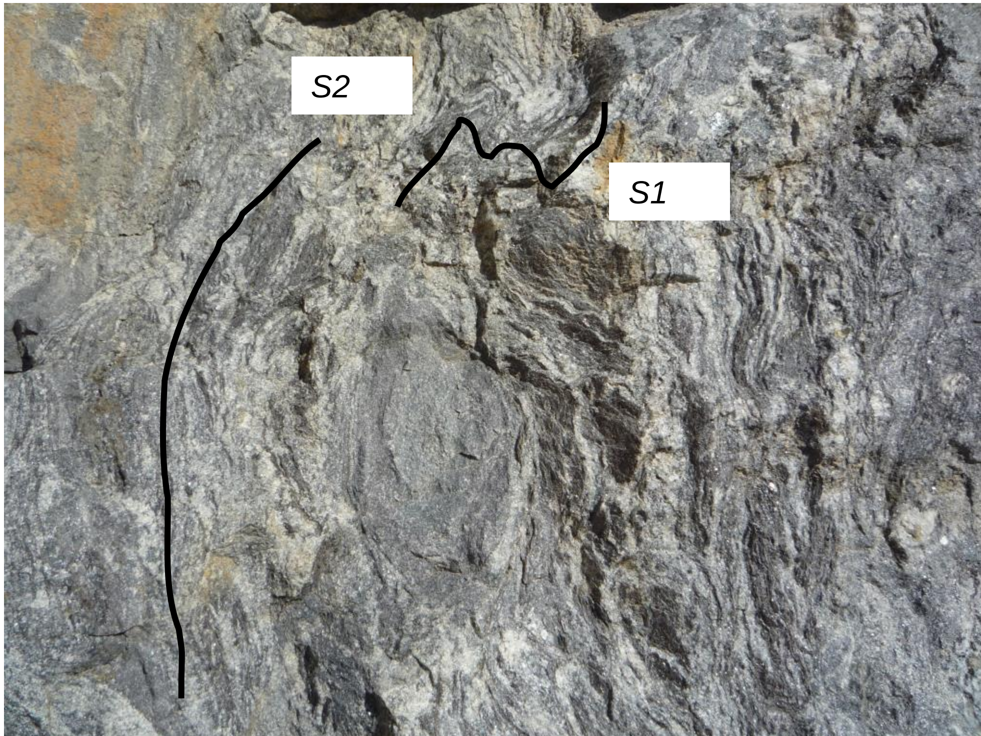
migmatite

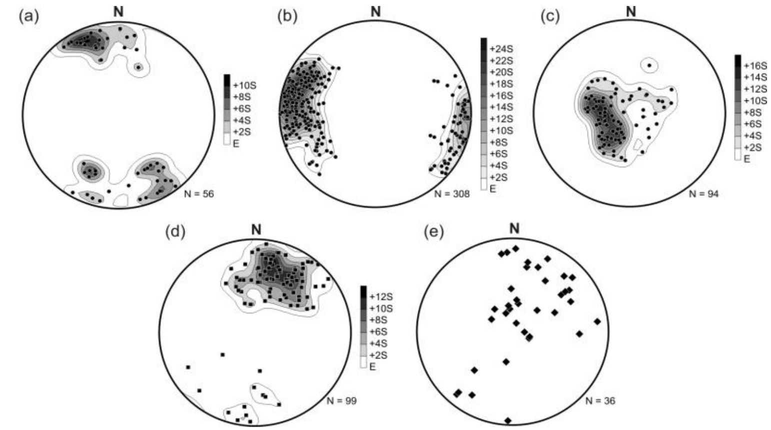
Mylonitic foliation –foliation developed in high strain shear zones.

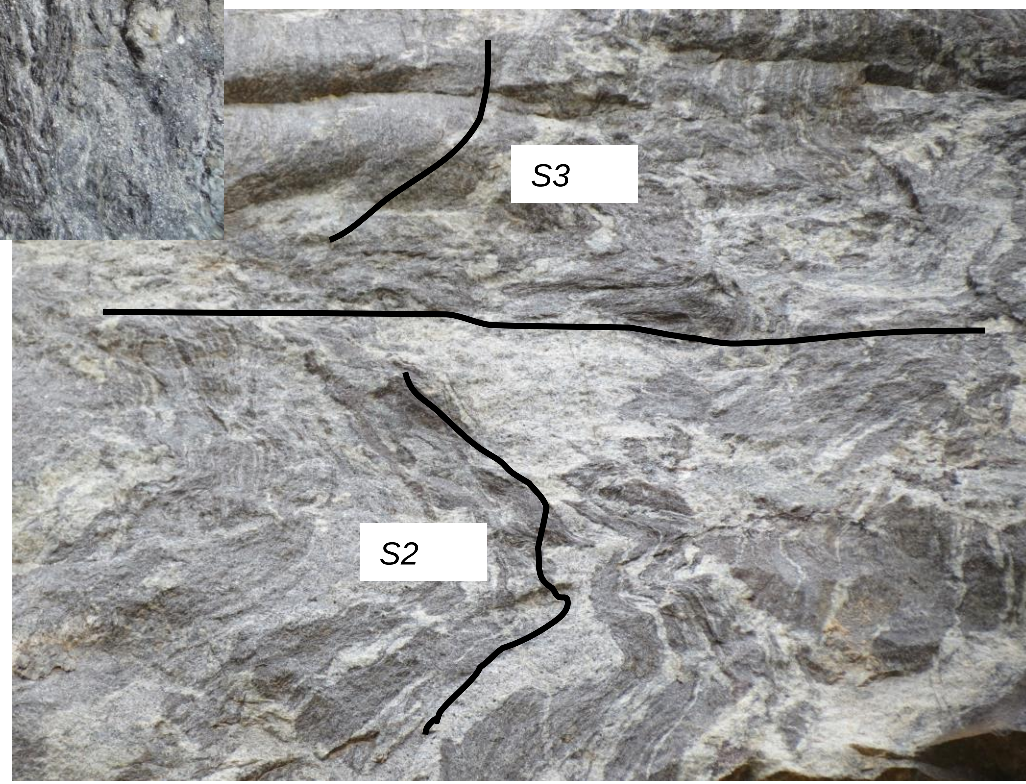


Mylonite developed along fault zones

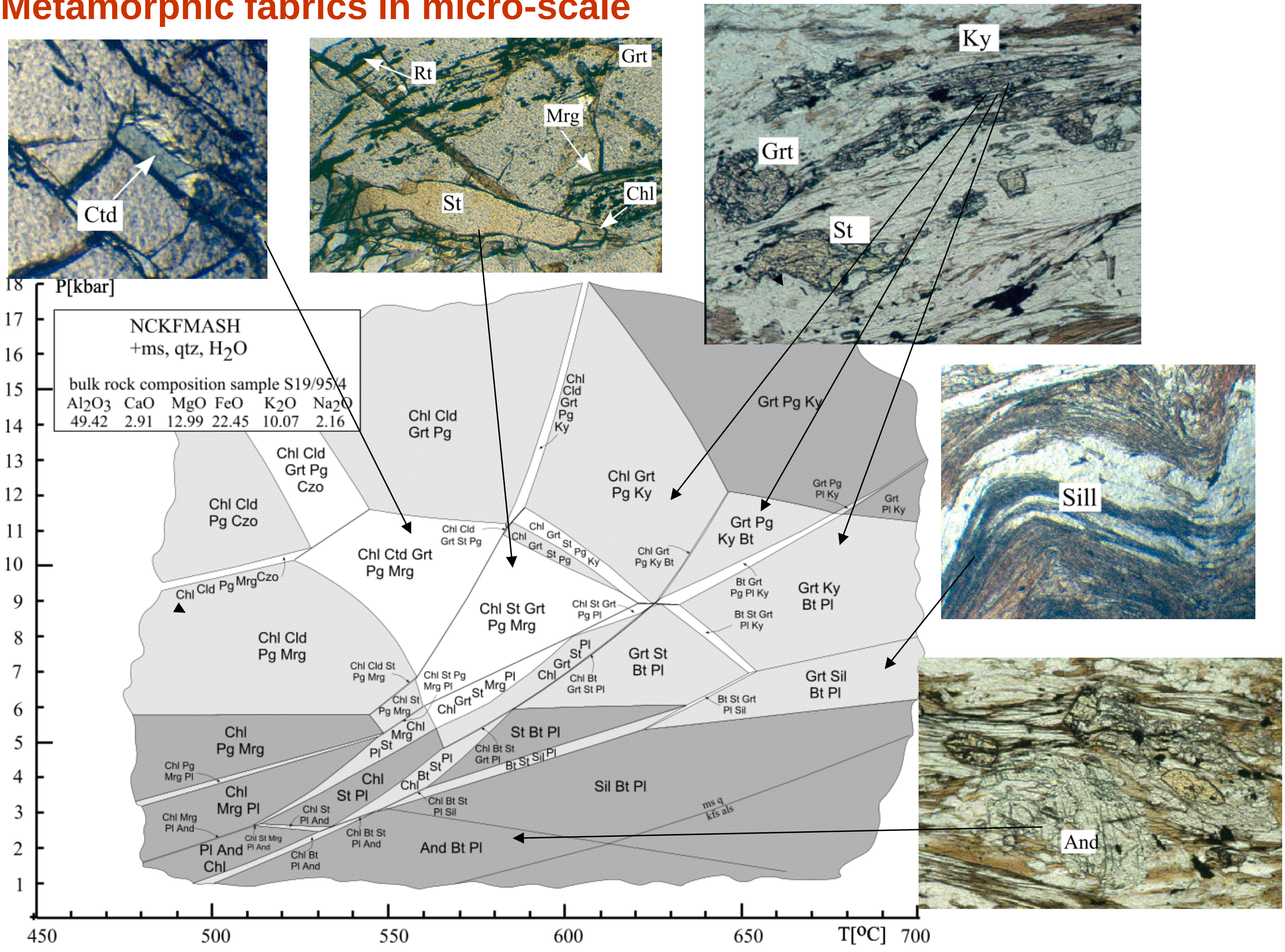
SUPERIMPOSITION OF METAMORPHIC FABRICS







Metamorphic fabrics in micro-scale

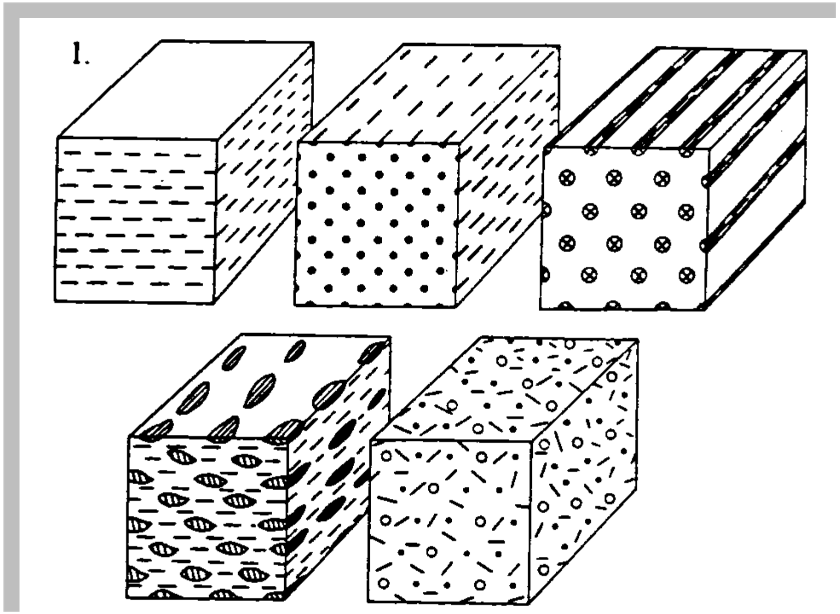


Metamorphic lineation

Linear structures are important in structural mapping as than can be used to:

distinguish various deformation phases

determine the kinematics of deformation



Metamorphic lineation

Mineral lineation
Stretching lineation
Crenulation lineation
Intersection lineation
Linear preferred orientation of boudins

FOLDS

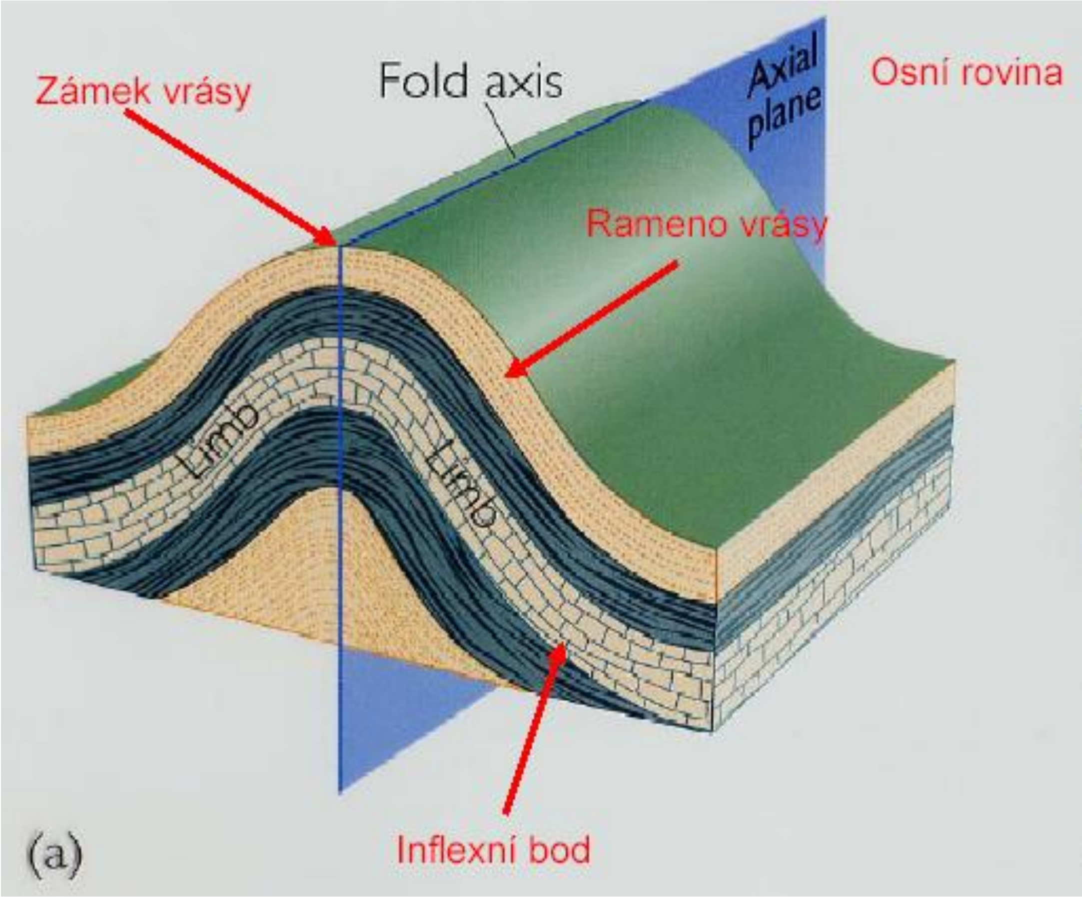
Folds are continuous compressional structures. Their origin are related with the deformation of rocks mainly in compressional regime.

Three main structural elements determine the geometry of the fold in space

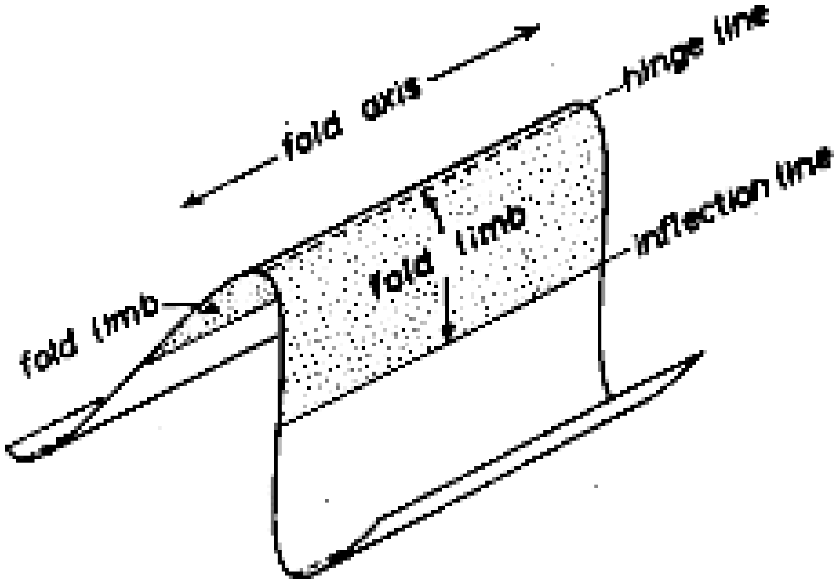
Fold axis / Hinge line/
The line of maximal curvature

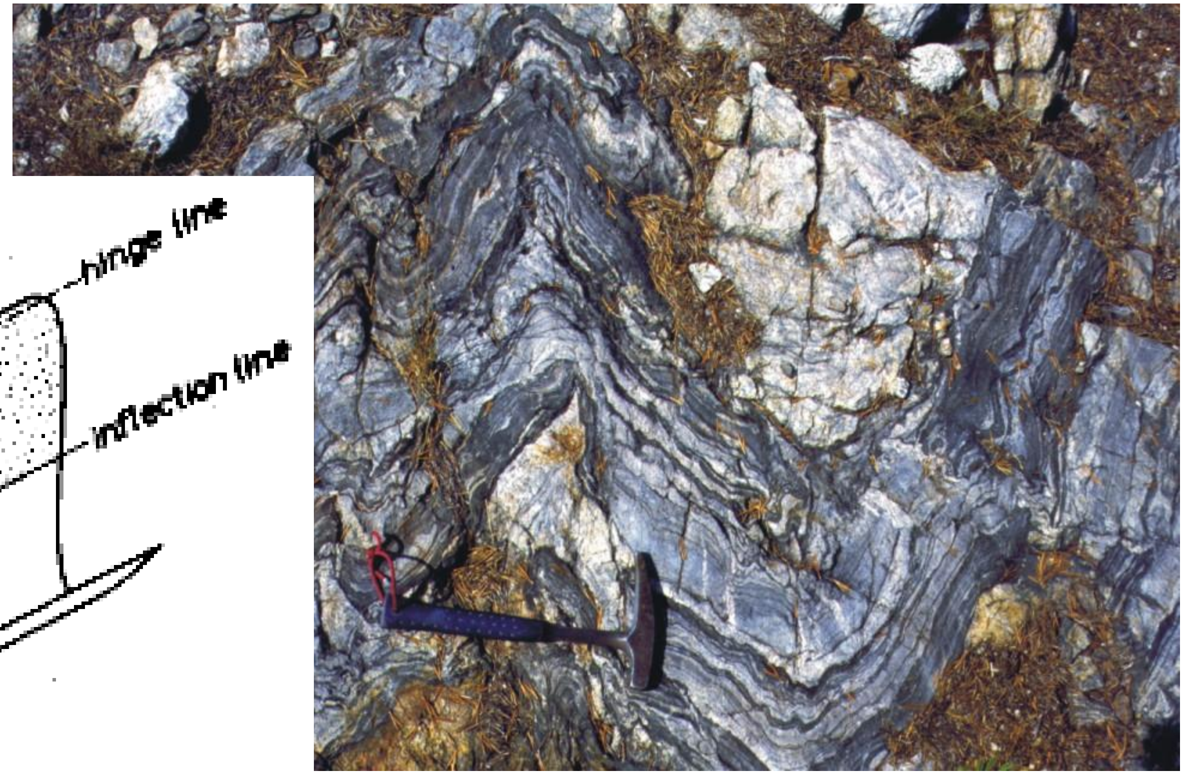
Axial plane
Imaginary plane defined by fold axis and interlimb angle

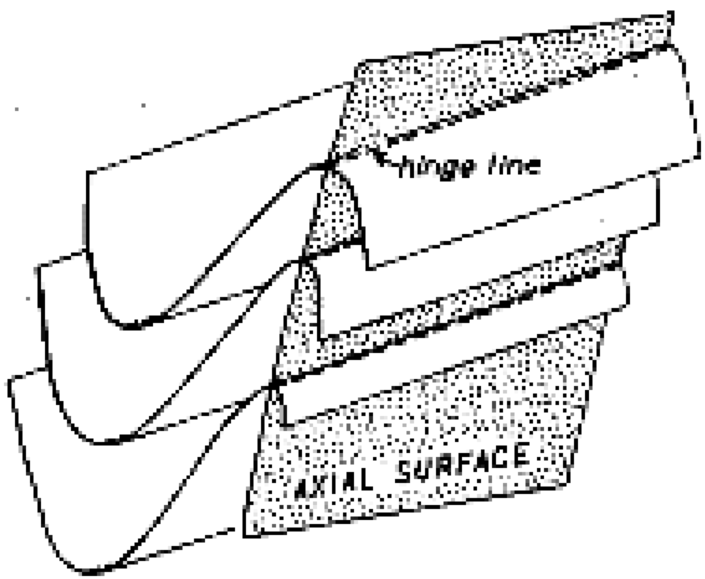
Wavelength
The distance between adjacent fold axes



Geometry of folds

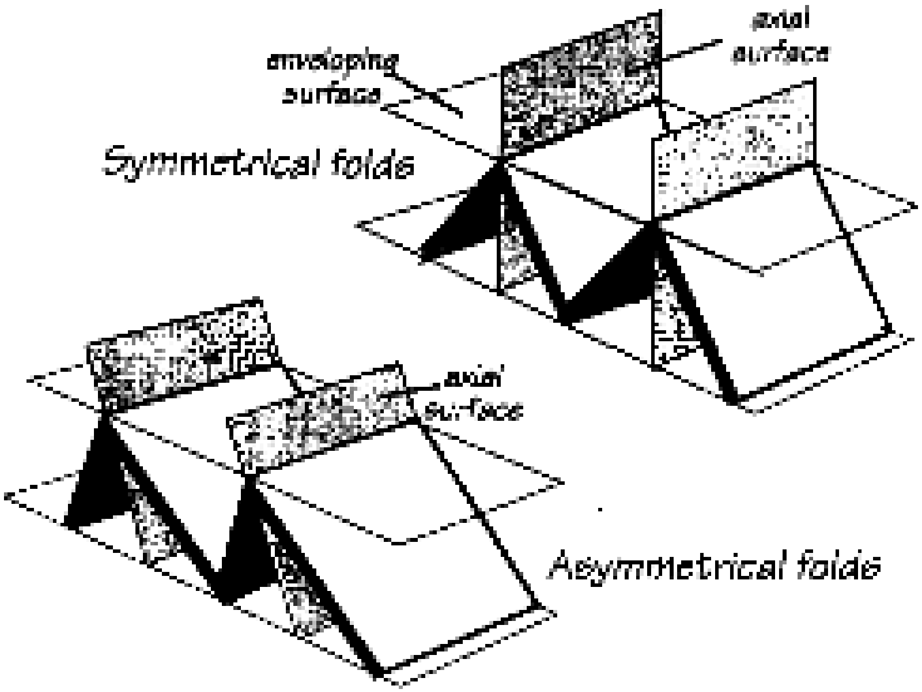






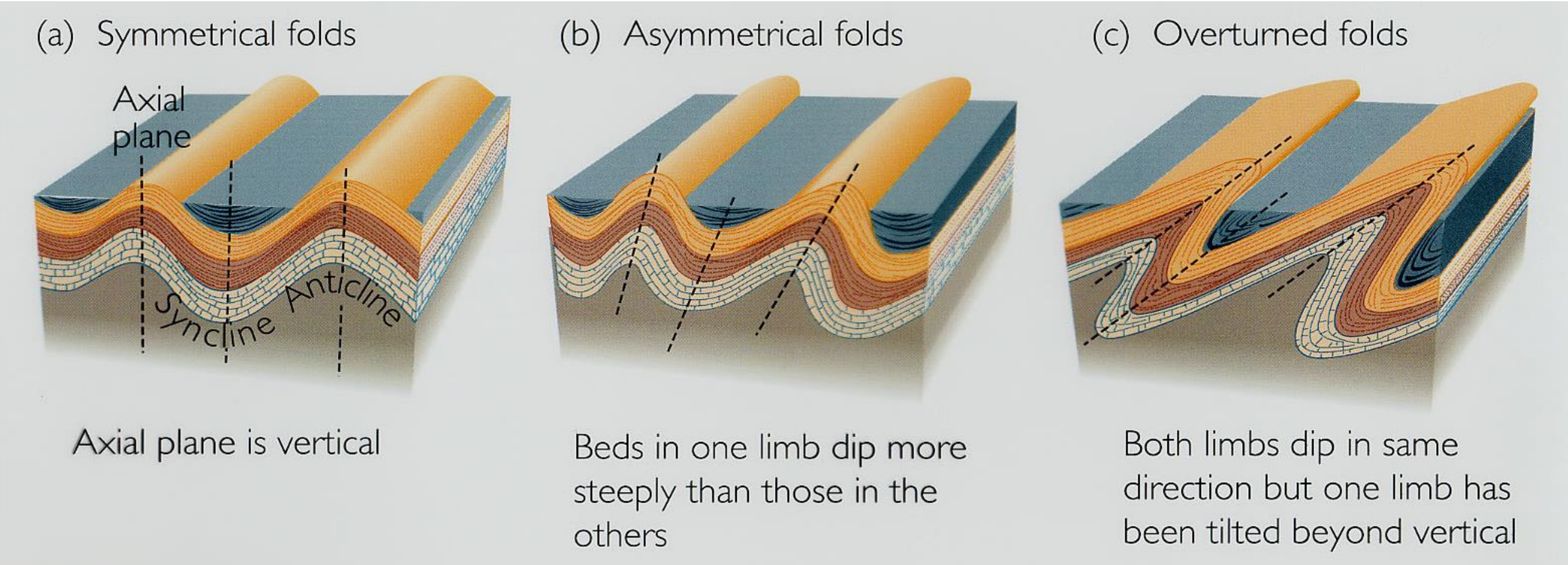
- Fold plane (cleavage)
- Fold axis (b-axis)

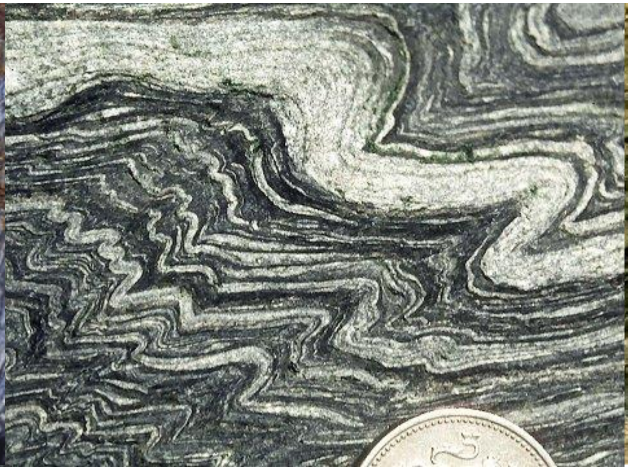
Geometry of folds



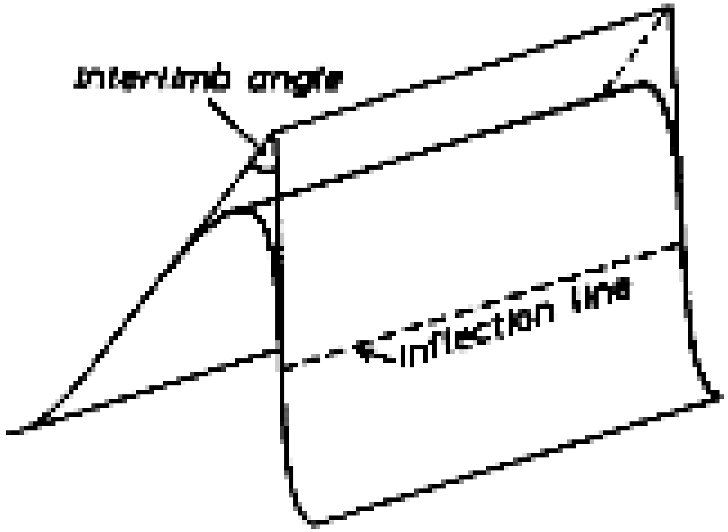
Symmetric and asymmetric folds

Fold axis and symmetry



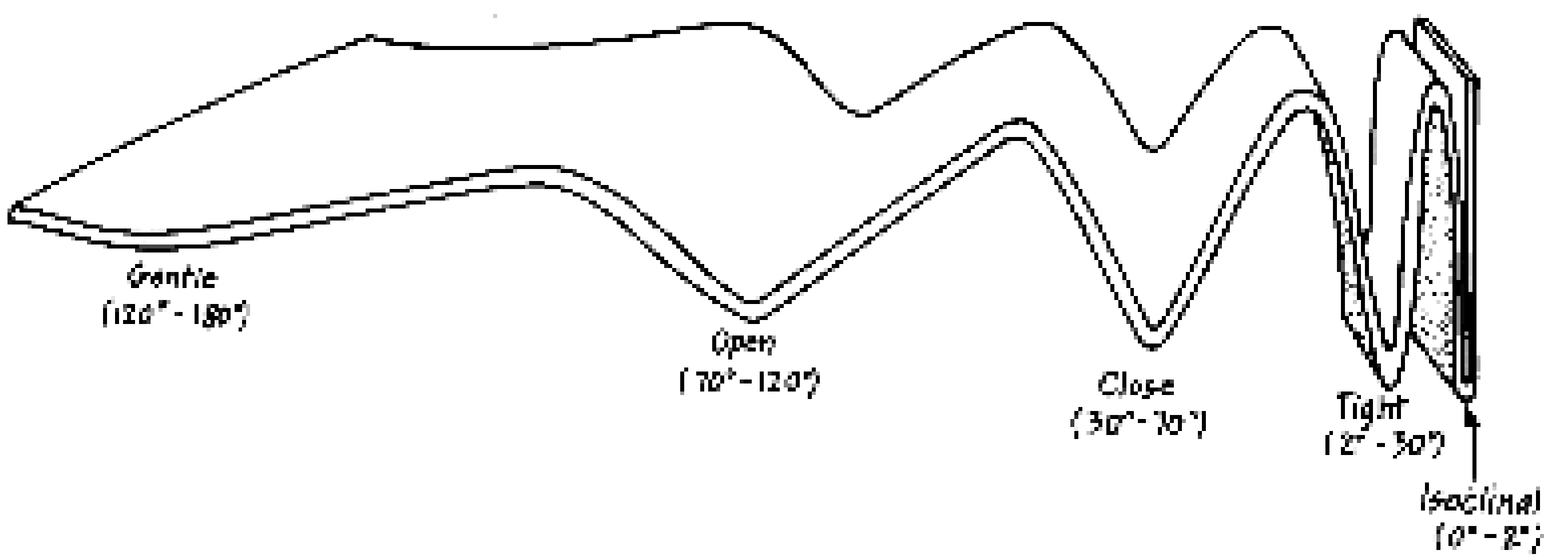


Clasification of fold based on interlimb angle

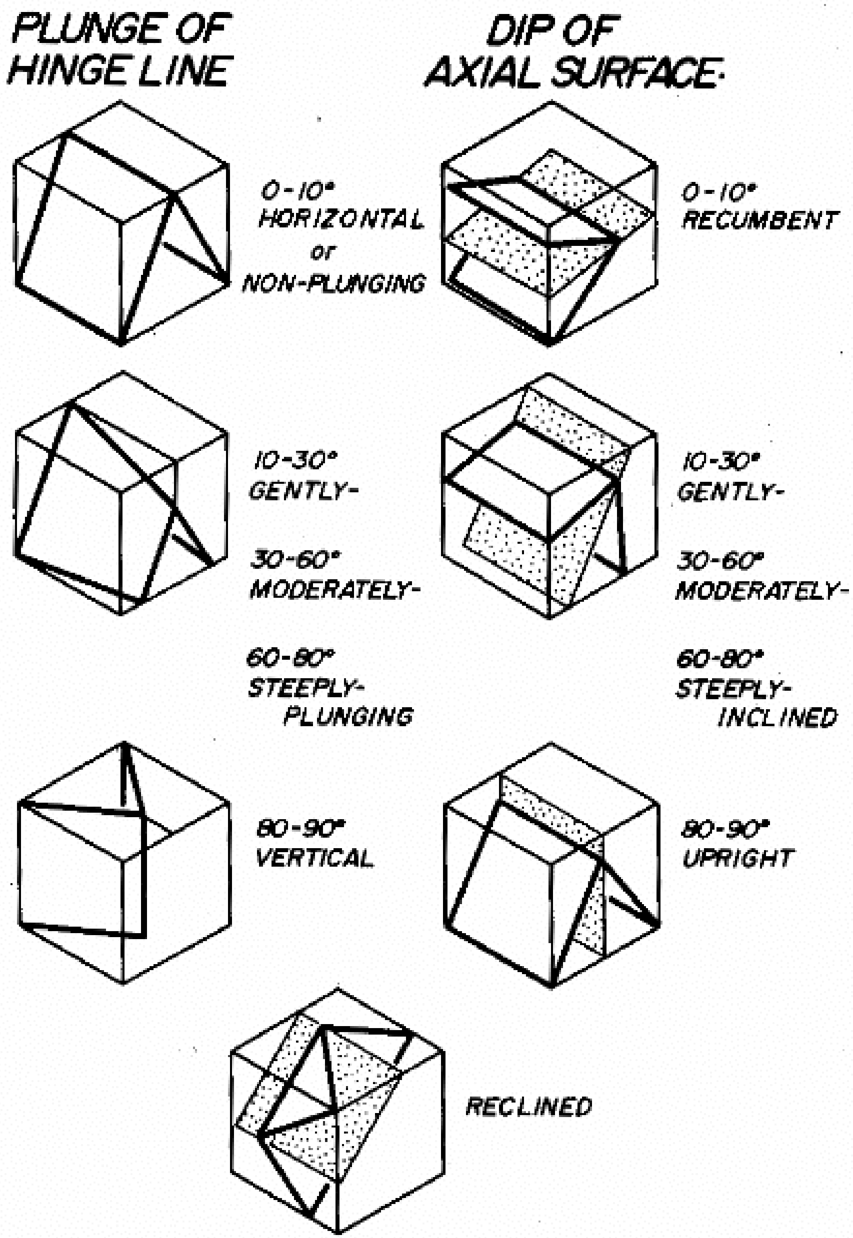


Interlimb angle classification

- Gentle 180°–120°
- Open 120°– 70°
- Close 70°– 30°
- Tight 30°– 0°
- Isoclinal 0°



Clasification of fold based on plunge of hinge-line and dip of axial surface



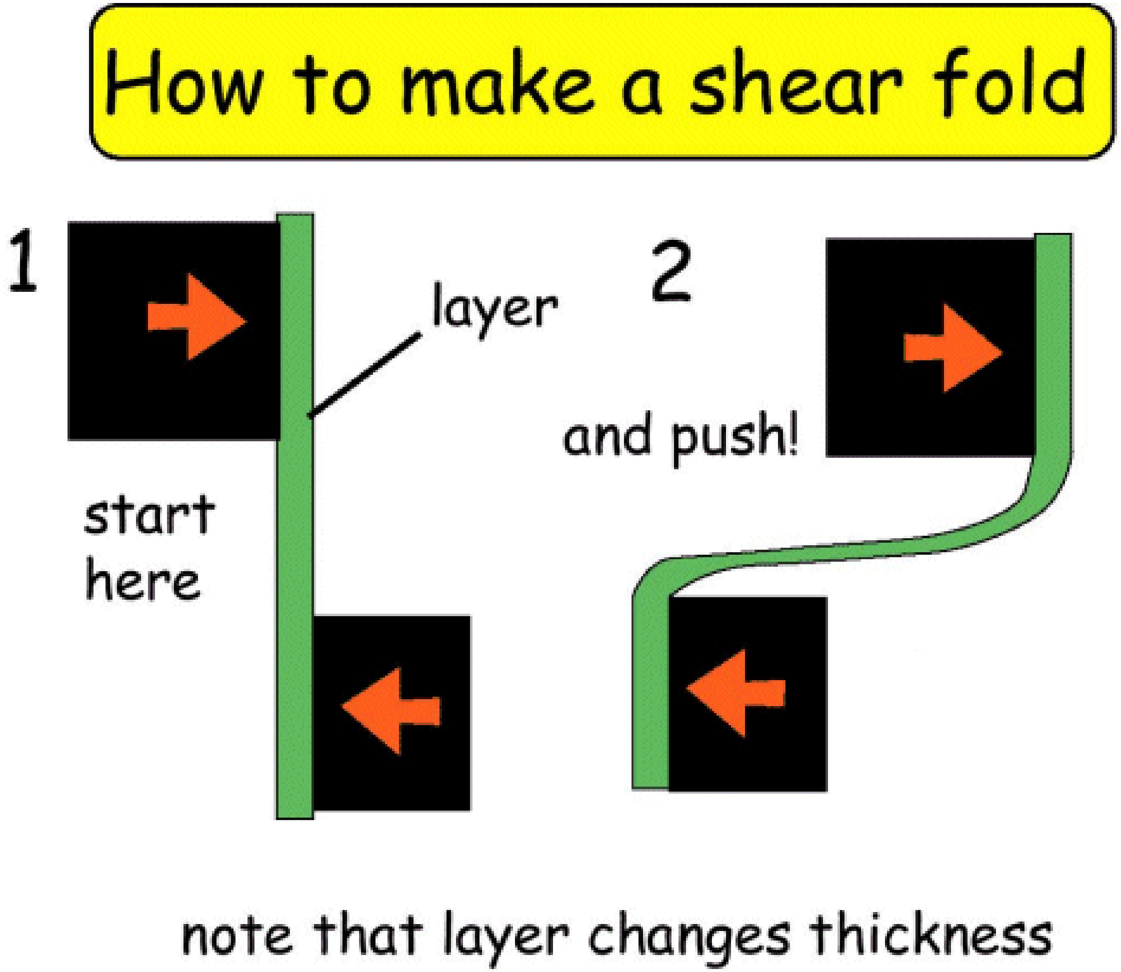
Dip of axial surface

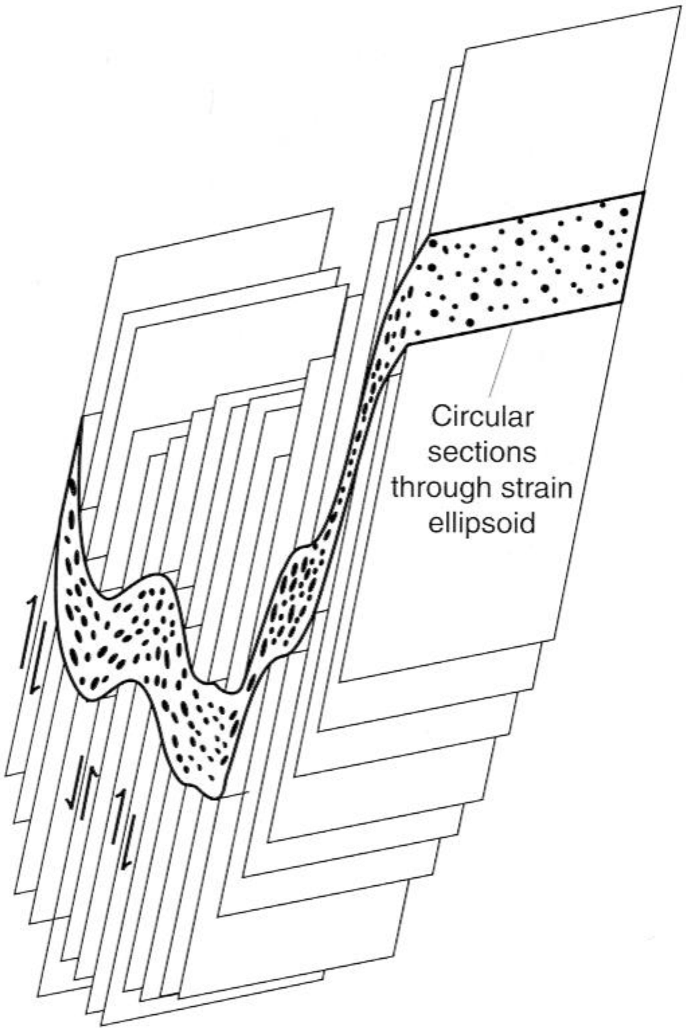
Upright folds
Inclined folds
Recumbent folds

Plunge of hinge line

Horizontal
Plunging
Vertical

Shear folds

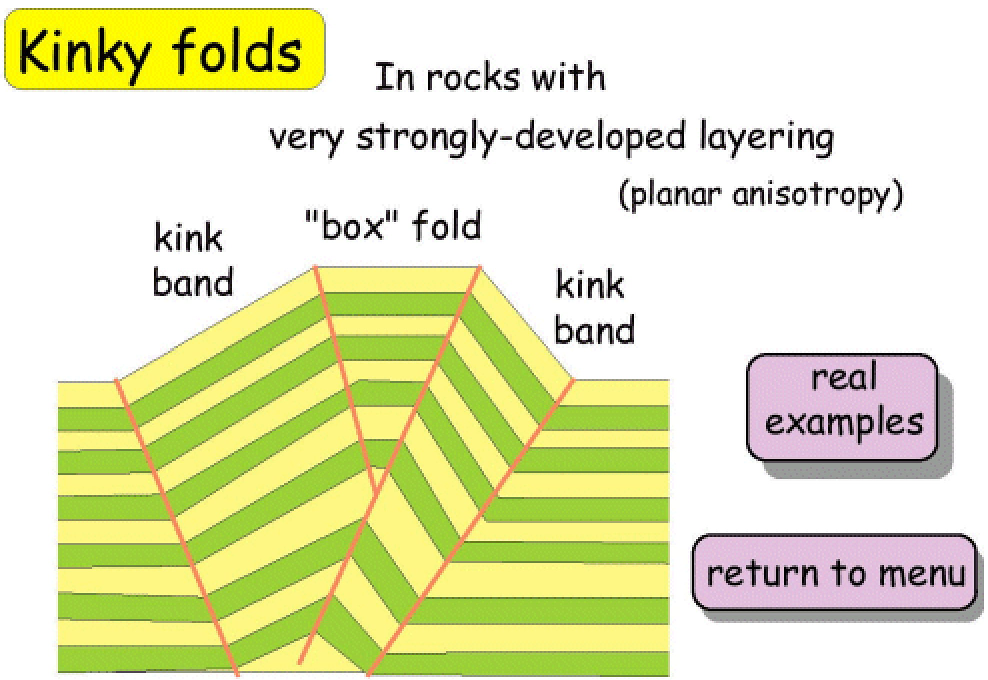


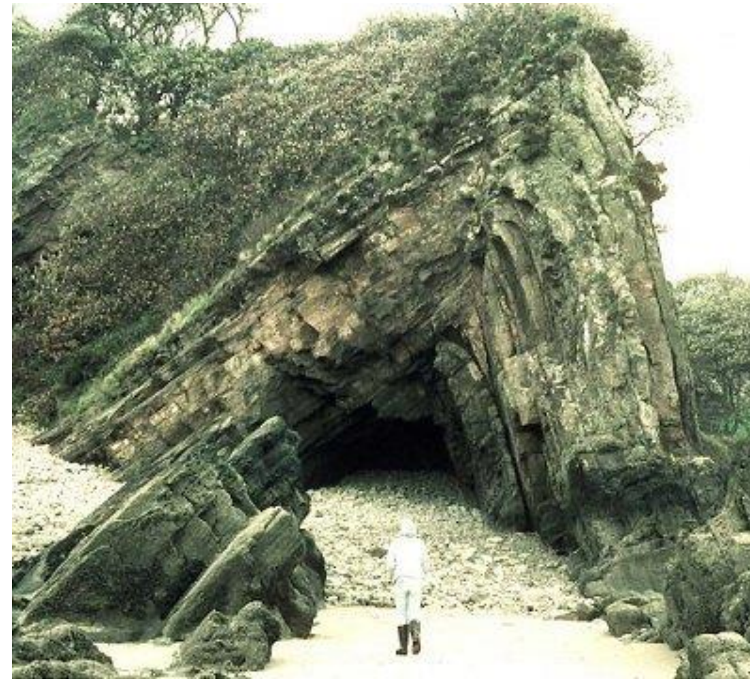


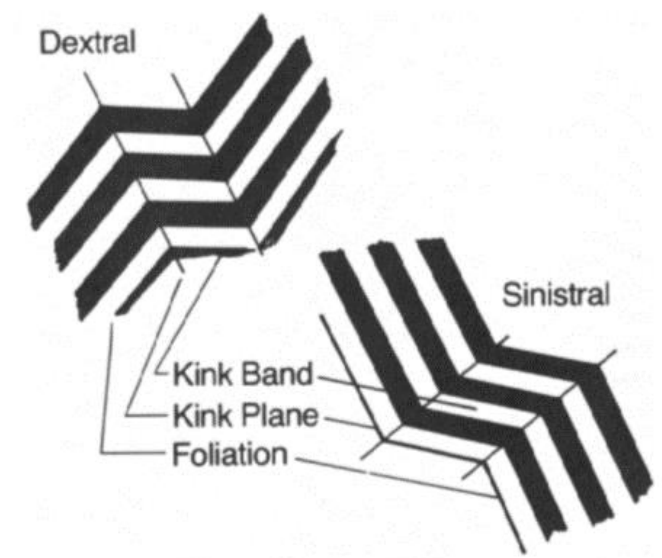
PASSIVE

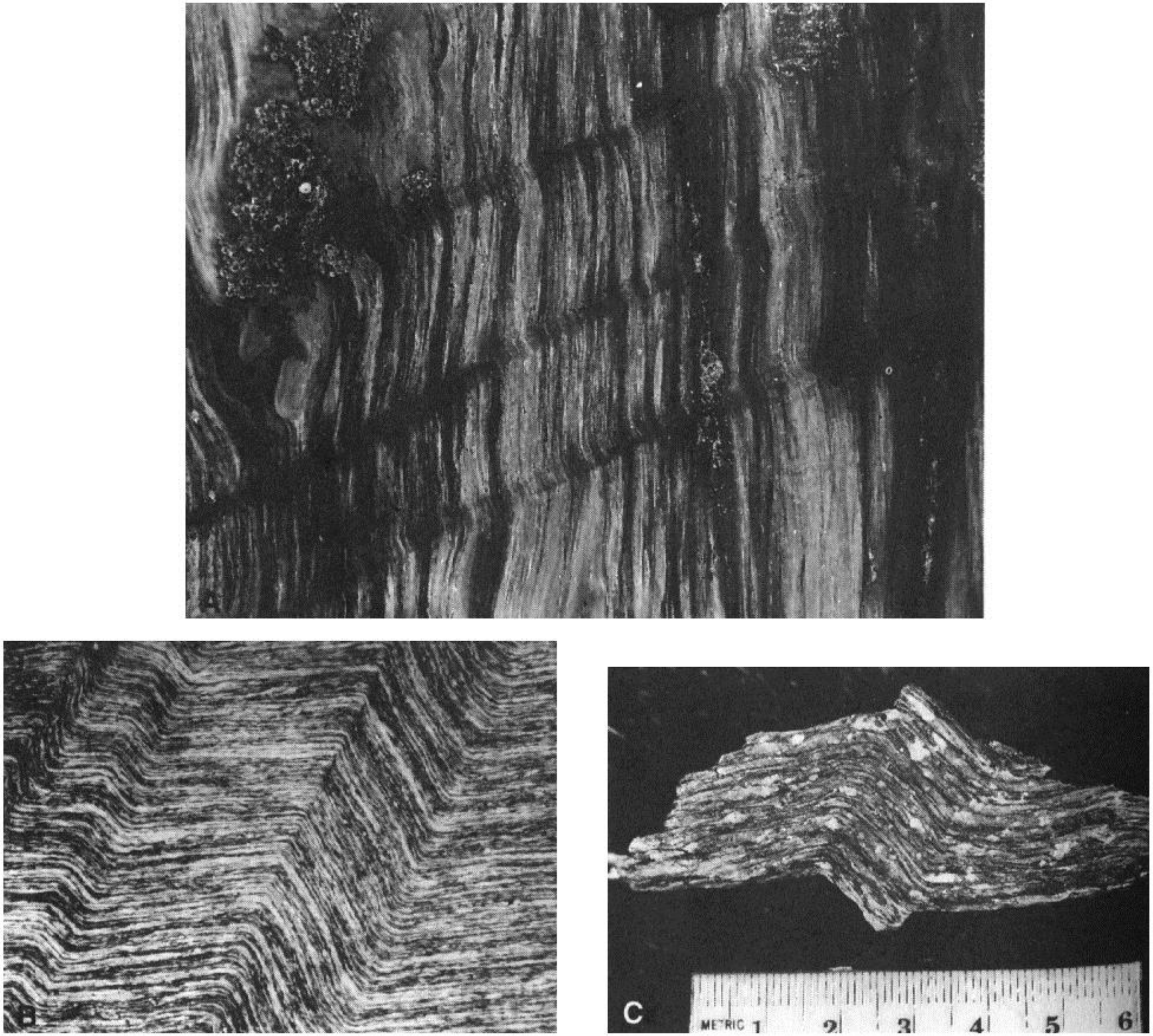
Kink-bands

Kink-bands folds occur in strongly foliated rocks

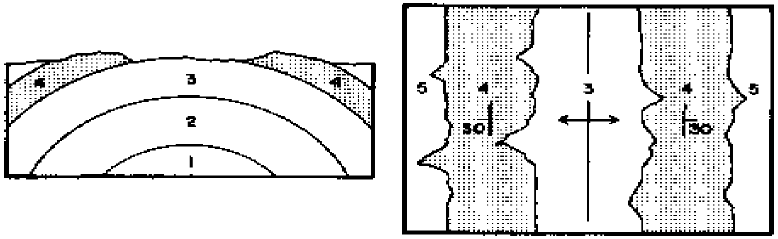




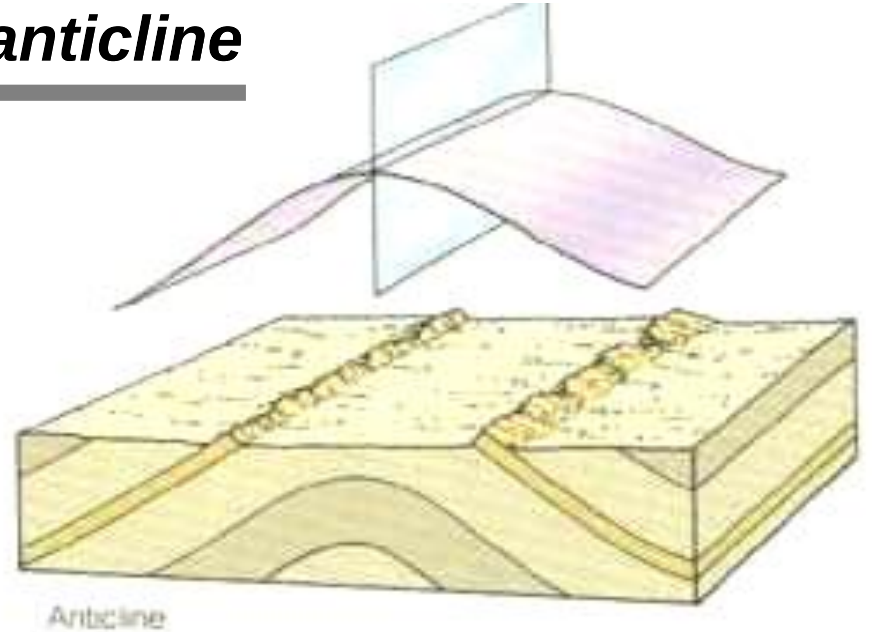



A
B
C
METRIC 1 2 3 4 5 6

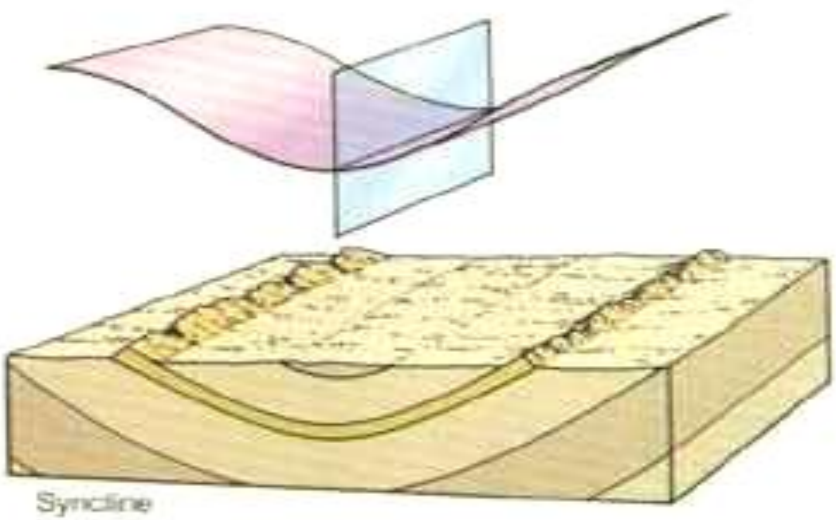
Large-scale folds

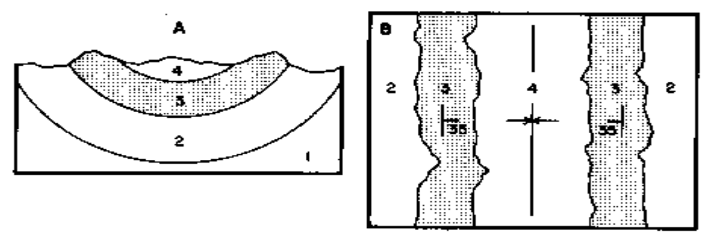


anticline

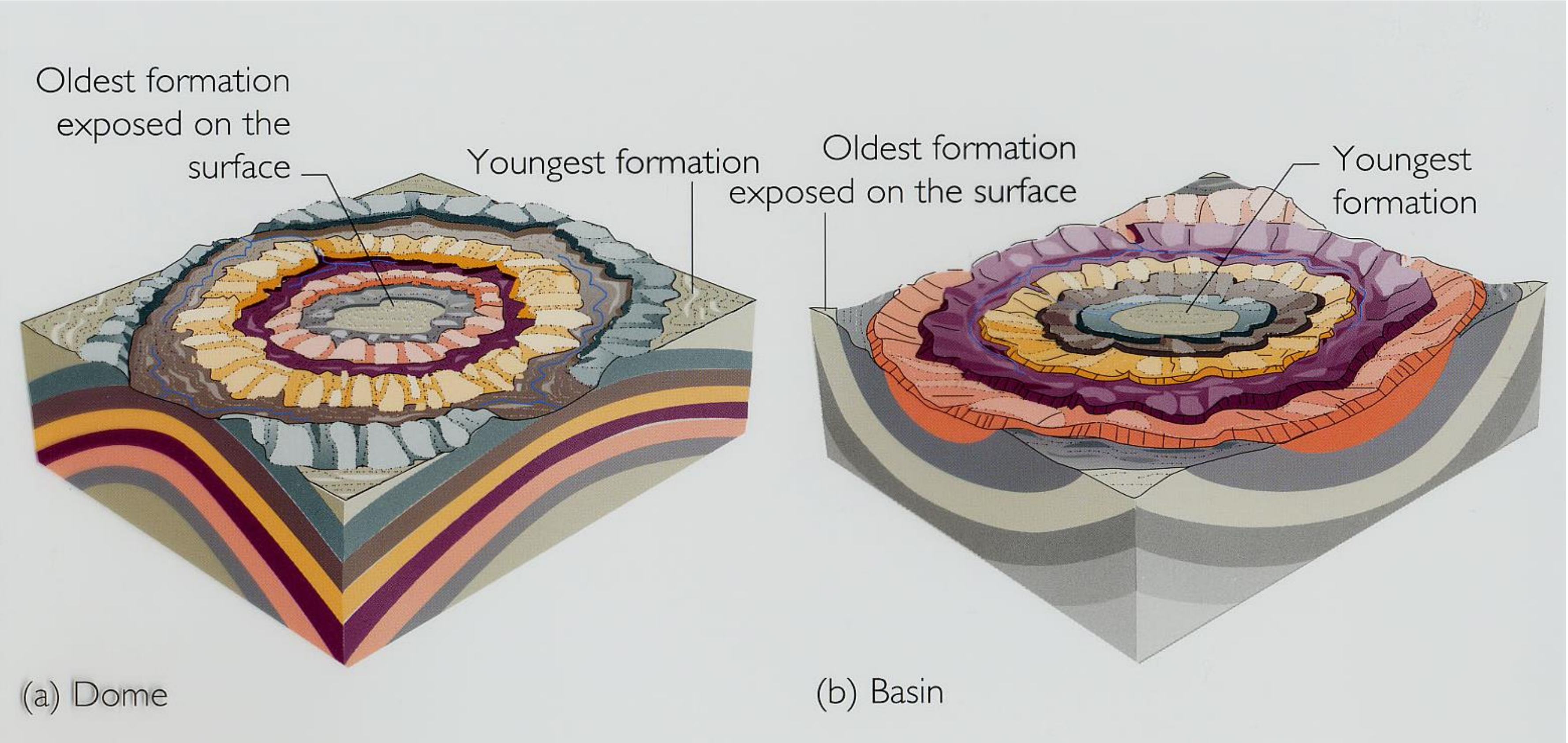


syncline





Dome and basin structures



Interference of folds

Brittle structures

FAULTS

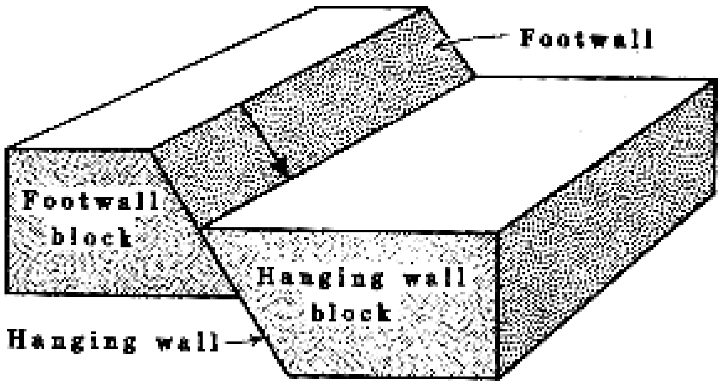
Faults are brittle to semi-brittle planar discontinuites along which significant displacement has occured

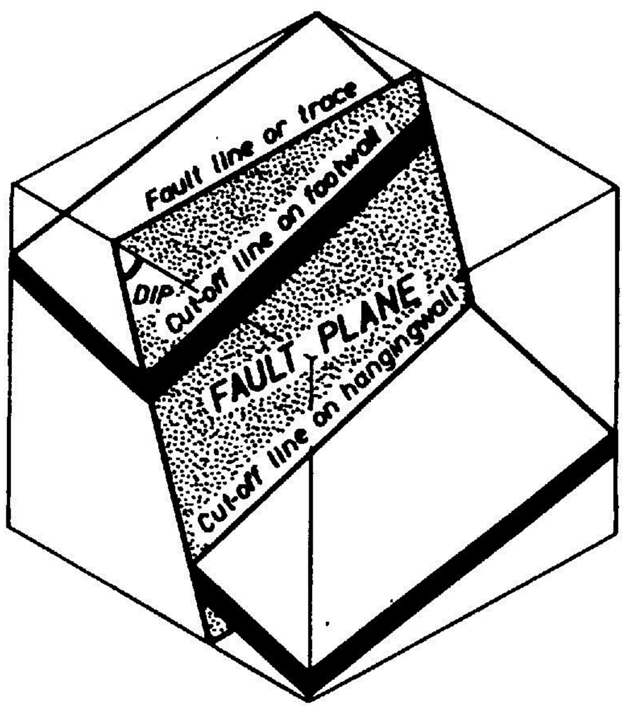
The origin and evolution of **faults** usually form in the upper crust (less than 15 km).

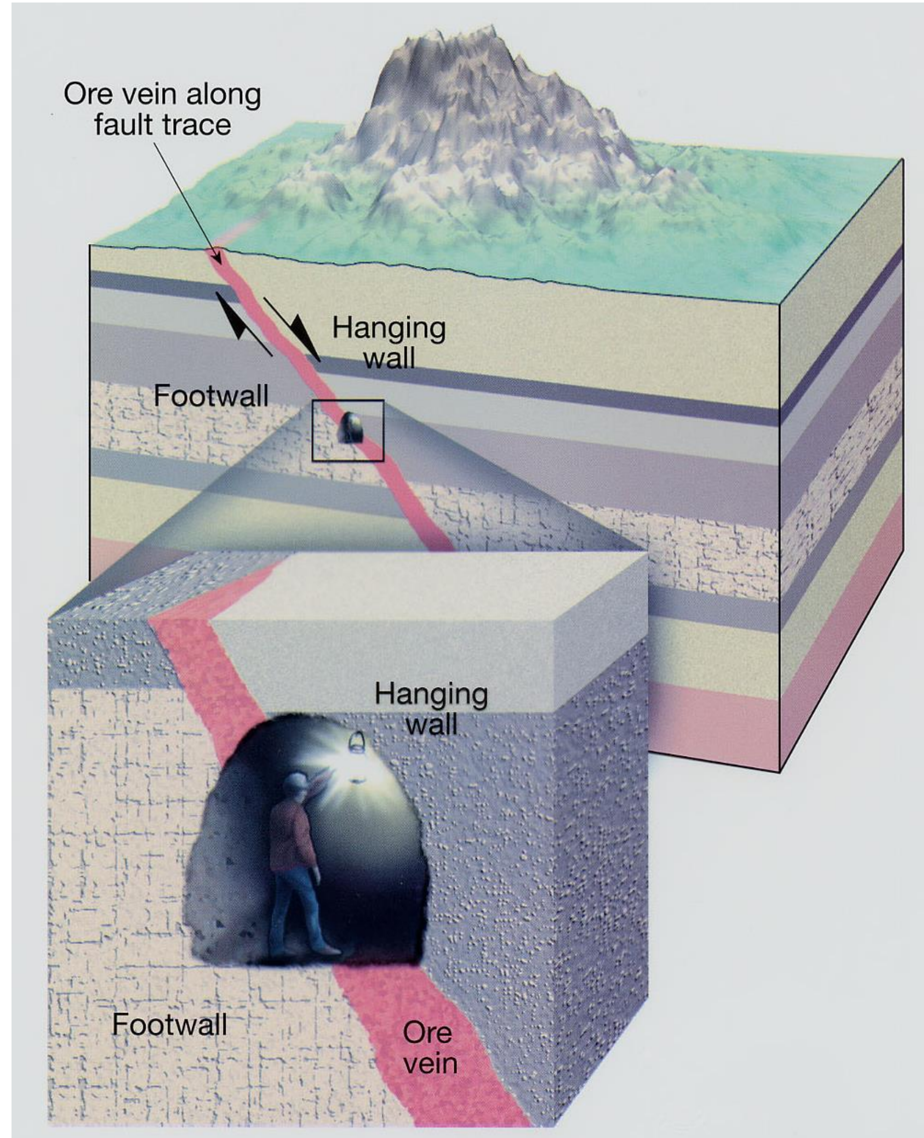
Indentification of faults in the field

- Faults on outcrops
- Evidence for movement (slickensides)
- Brittle deformation of rocks (cataclastic deformation)
- Secondary mineralization and alteration
- Fault-related morphology
- Linear distribution of springs

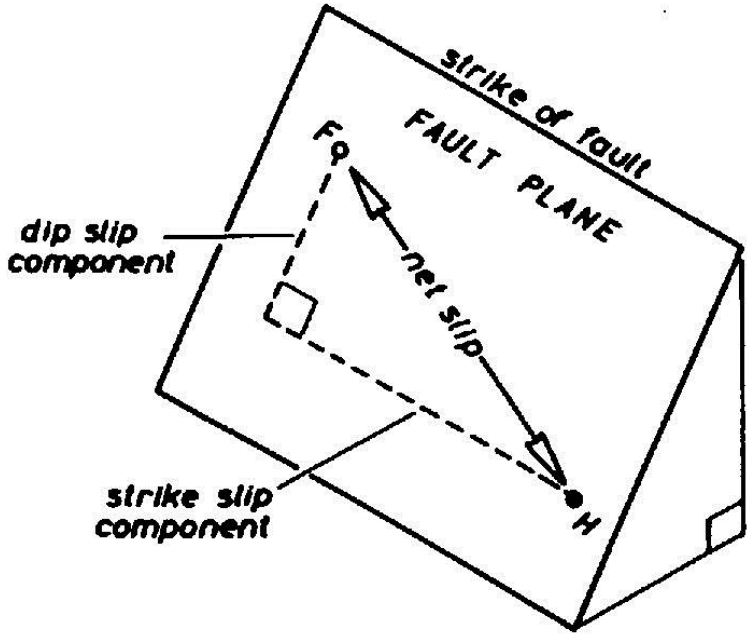
Faults

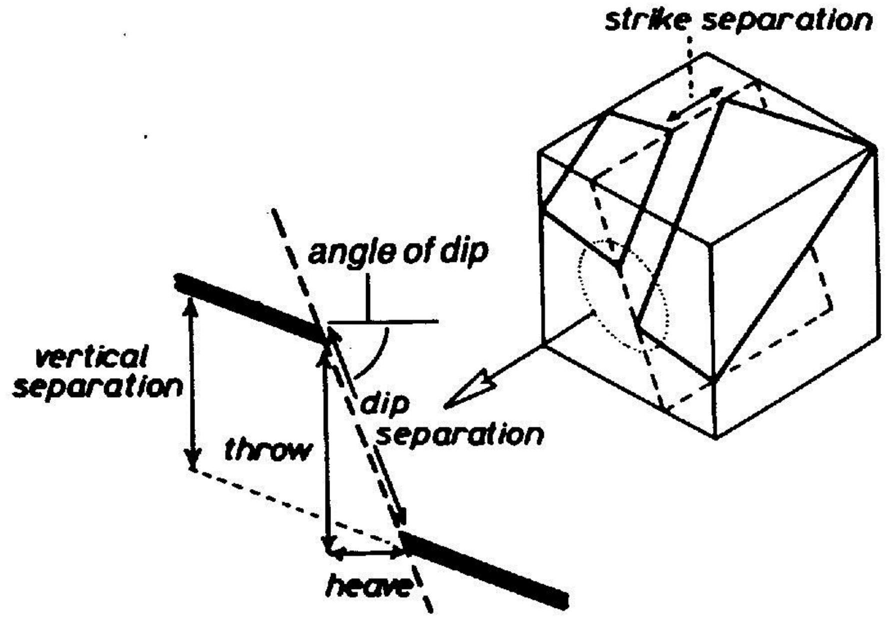

Footwall
Footwall block
Hanging wall block
Hanging wall


Fault line or trace
Cut-off line on footwall
DIP
FAULT PLANE
Cut-off line on hangingwall


Ore vein along fault trace
Hanging wall
Footwall
Hanging wall
Footwall
Ore vein

Vector of displacement along the fault plane



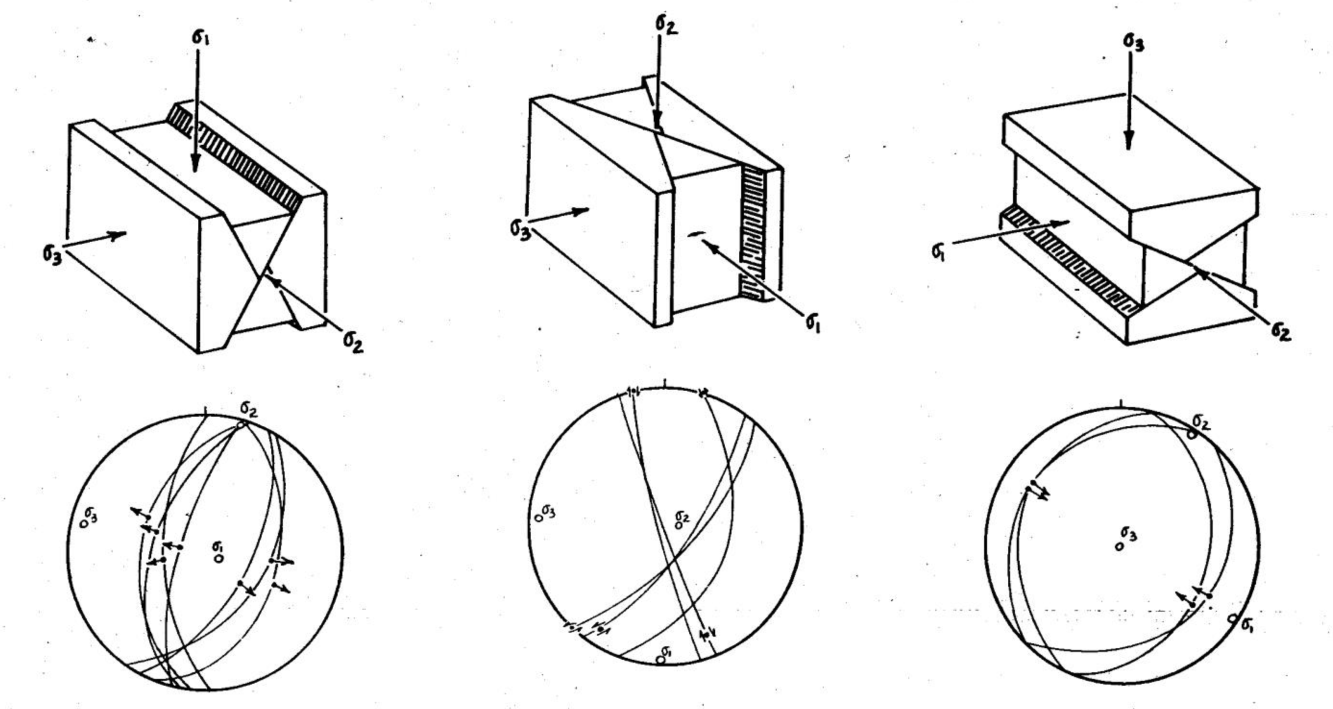


- Displacement along the fault plane
- Dip-slip and strike-slip component

Geometric classification of faults

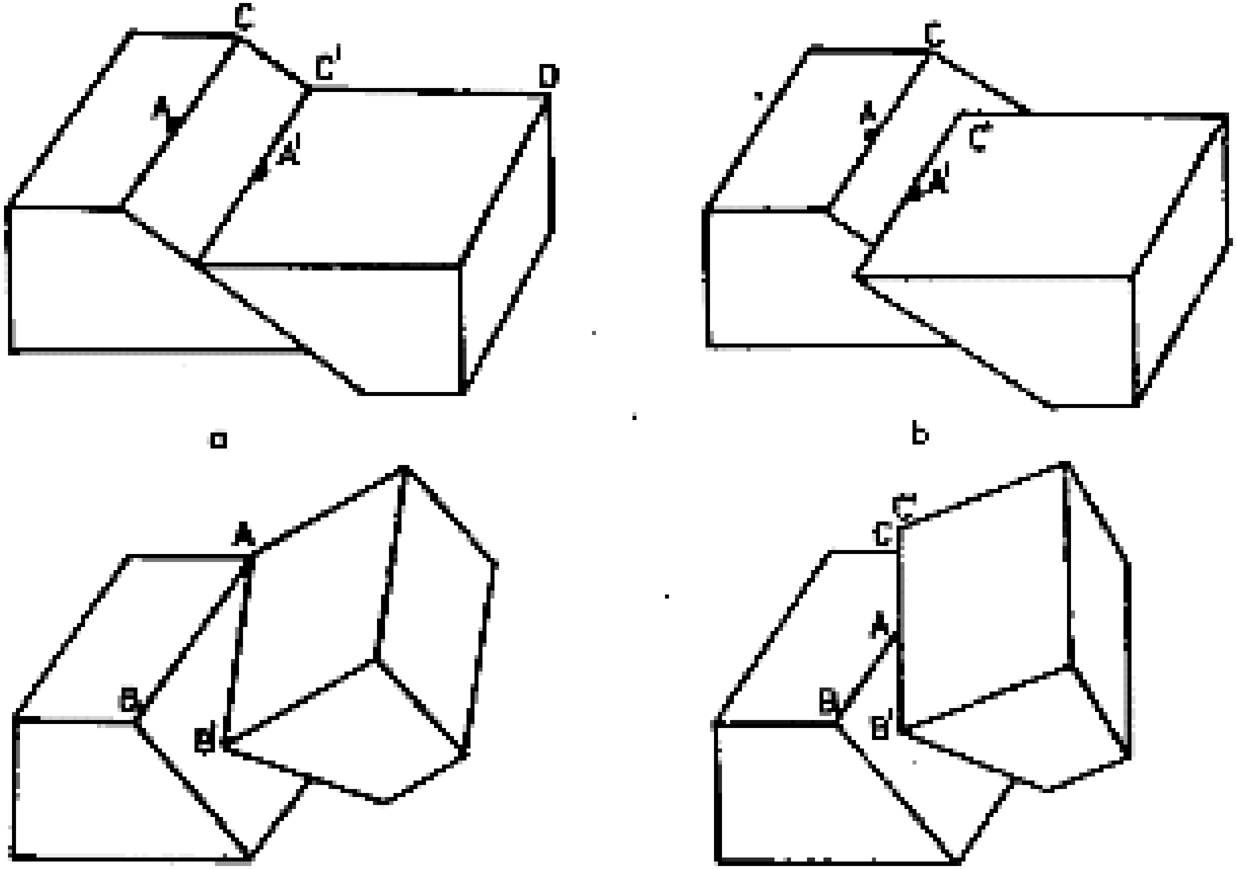
Anderson´s dynamic classification of faults consideres the stress field responsible for the faulting and simple descriptive scheme based upon the geometry and separation across a fault plane.

Normal faults **Strike-slip faults** **Reverse-slip (thrust) faults**

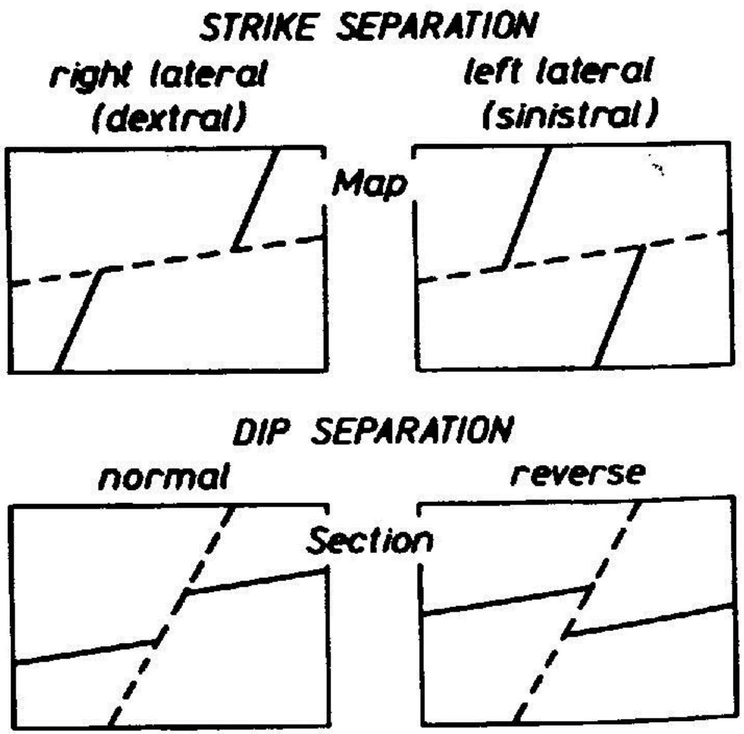


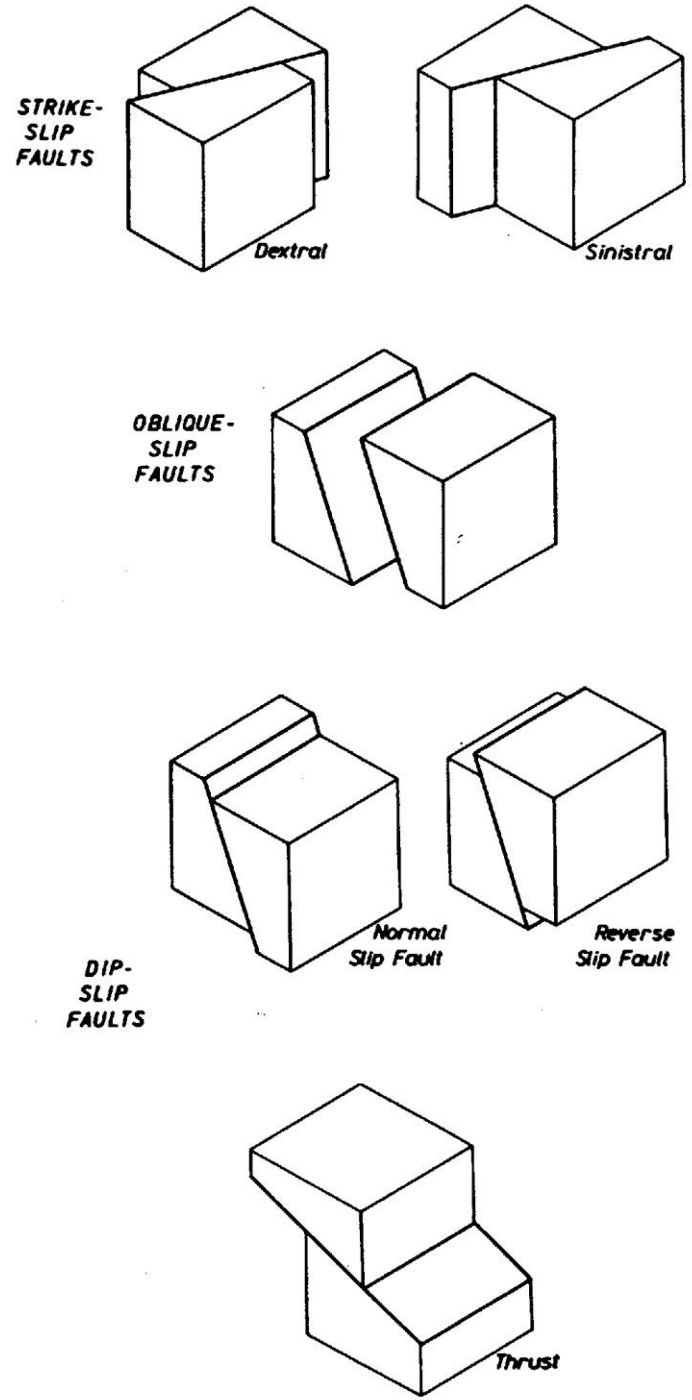
Stereographic projection of the faults and stress systems

Translation and rotation faults



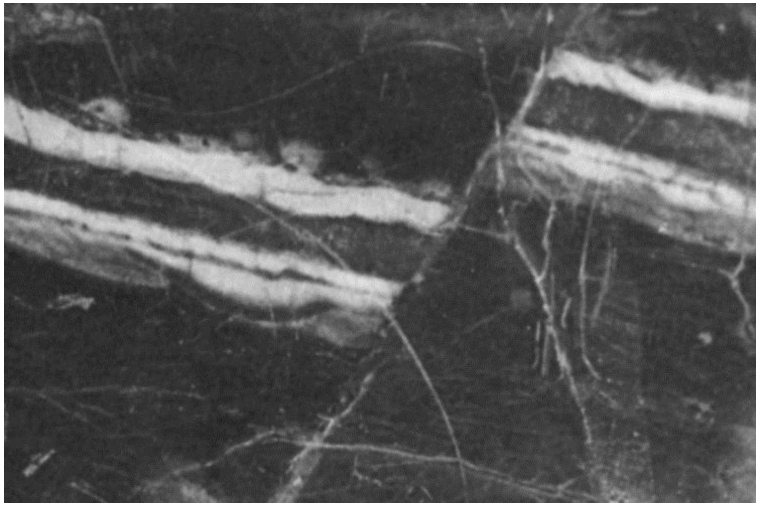
Kinematic classification of faults

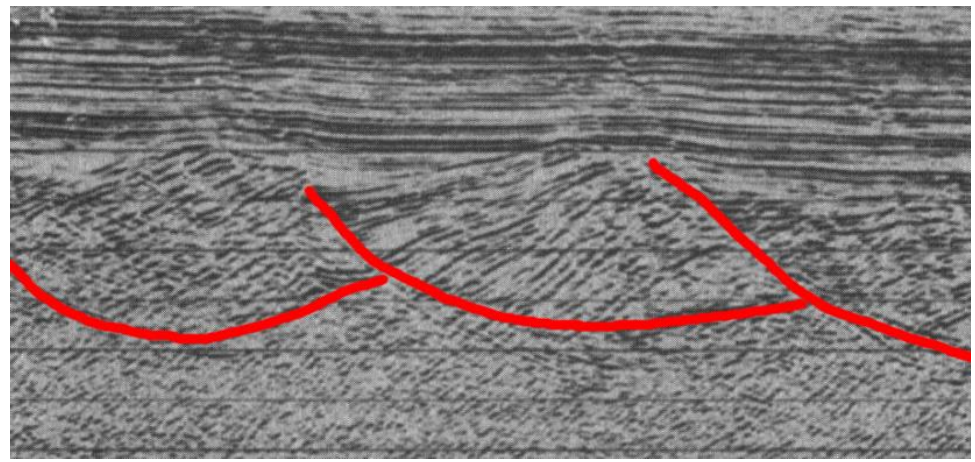


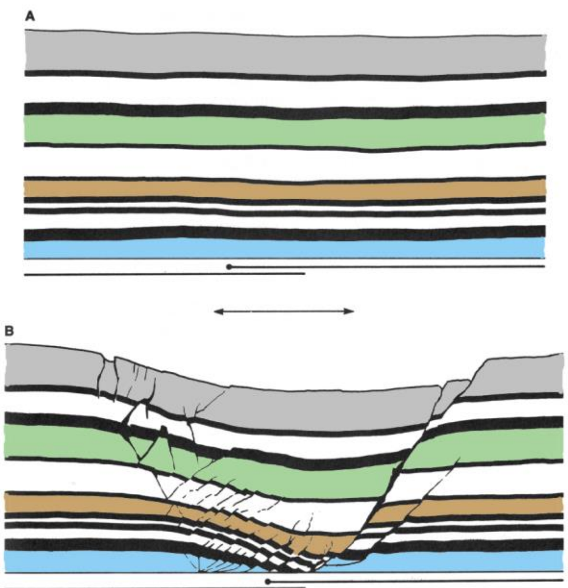


Normal fault

Normal fault as the evidence of regional exstension







Thrusting fault

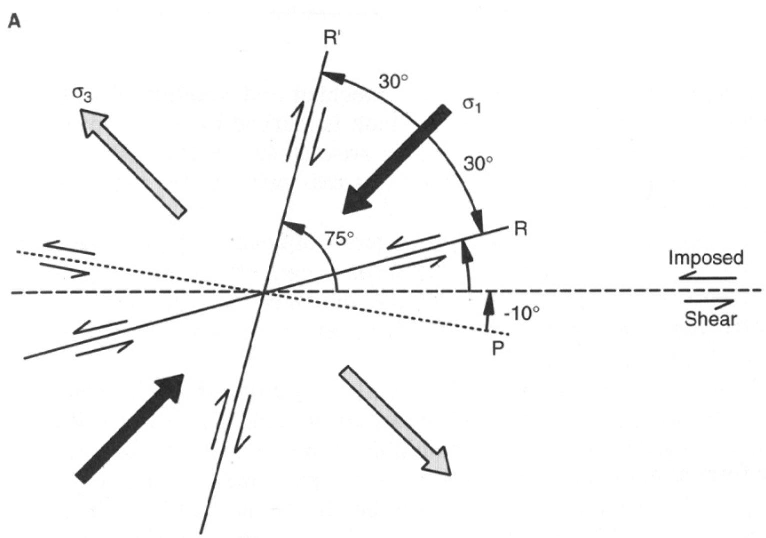
Thrusting fault

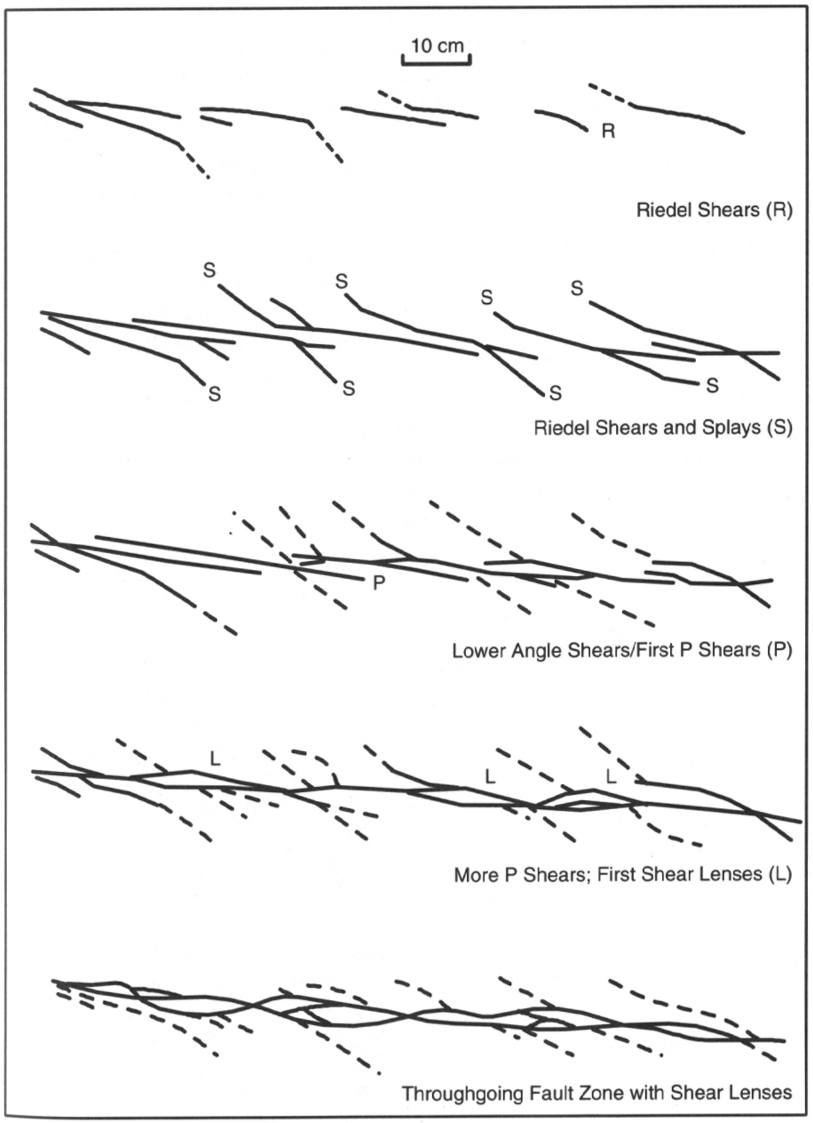
Brittle deformation of rocks (tectonic breccia)

Slickensides (fault lineation) on the fault plane

slickensides

Strike-slip fault

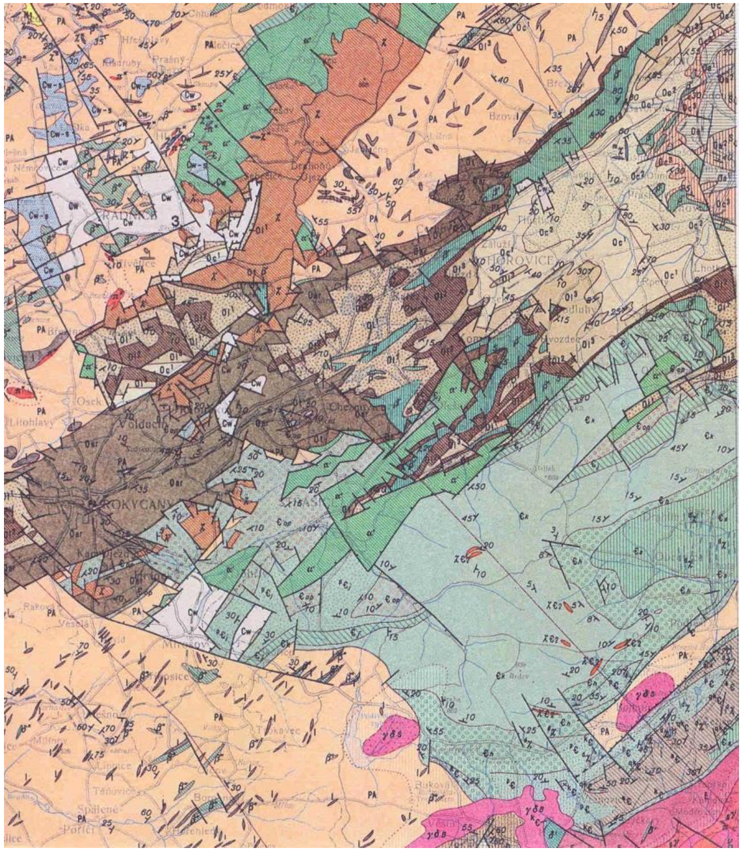




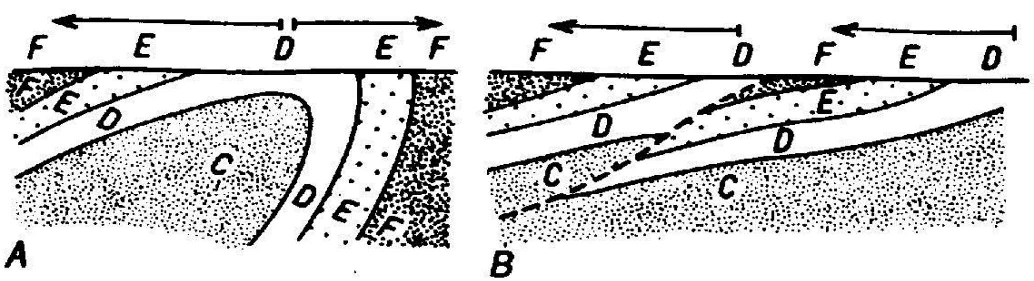
Strike-slip fault

Psedotachylites

Display of faults in geological maps and cross-sections

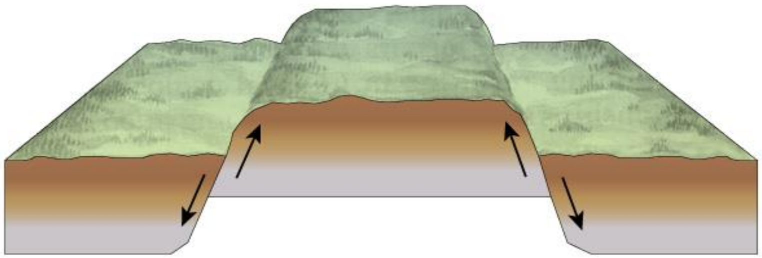


- Discontinuity of geological units
- Termination of geological units and bodies perpendicular to regional fabrics and lithological contacts
- Repeating of similar sedimentary layers

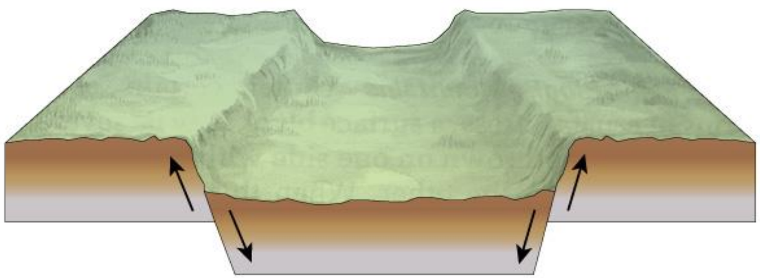


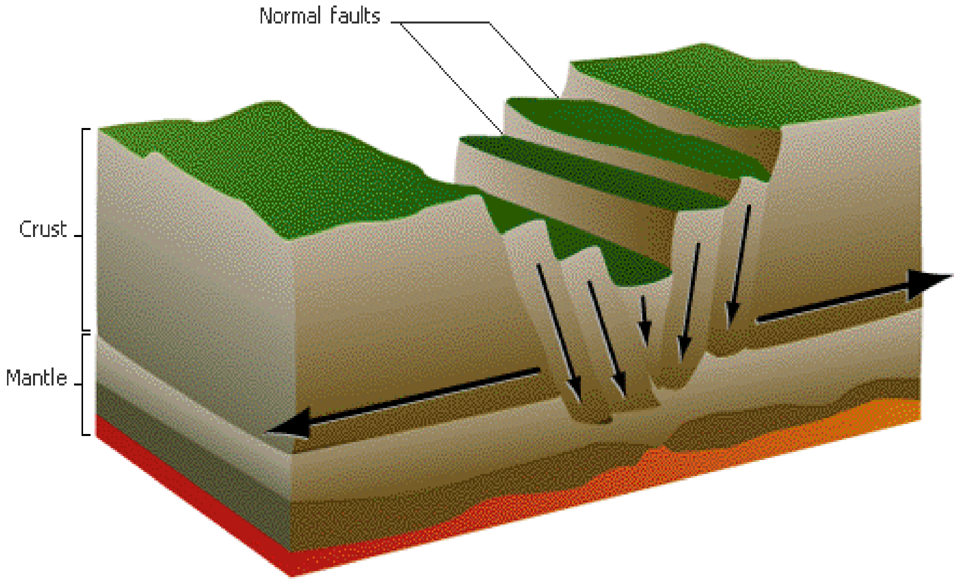
Large-scale faults

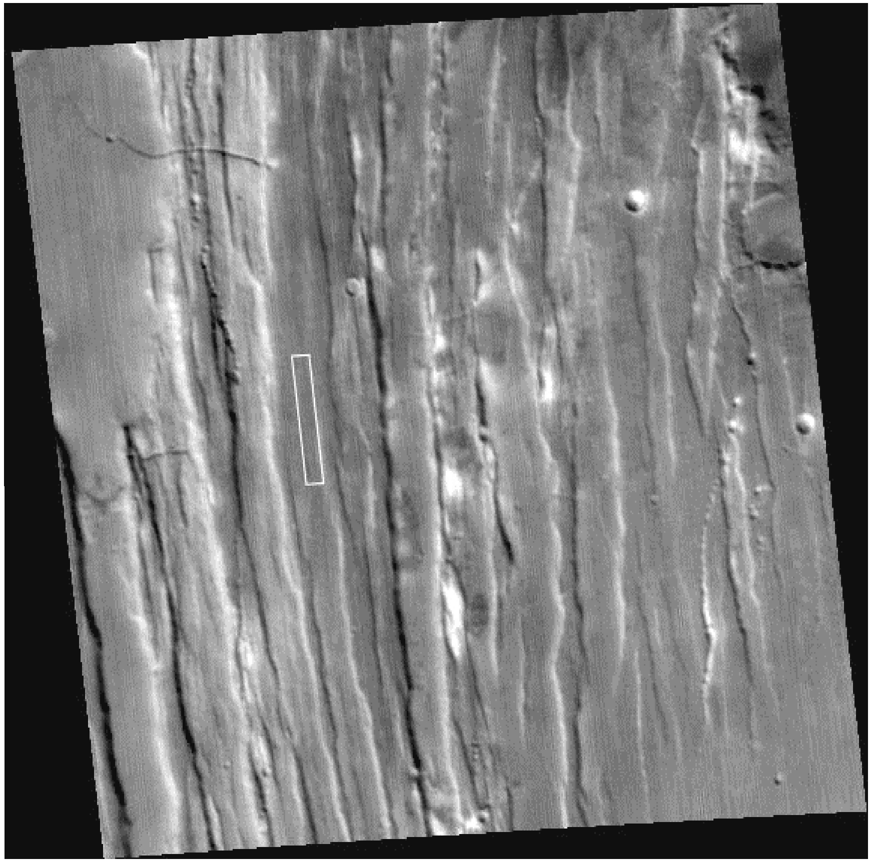
Horst



Graben







Joints

Joints are planar fracture (cm to km in length) with the origin related with tension (extension) often infilled with remobilised minerals.

Stretch (σ1) is parallel to the plane of fracture. In some cases evidences of weak shear deformation can be present.

Three genetical groups of joints:

Dilational joints are extensional joints with the fracture plane normal to the principal stress (σ3) during joint formation

Shear joints reveal small amounts of shear displacement. They are often conjugate enclosing angle of 60° or more

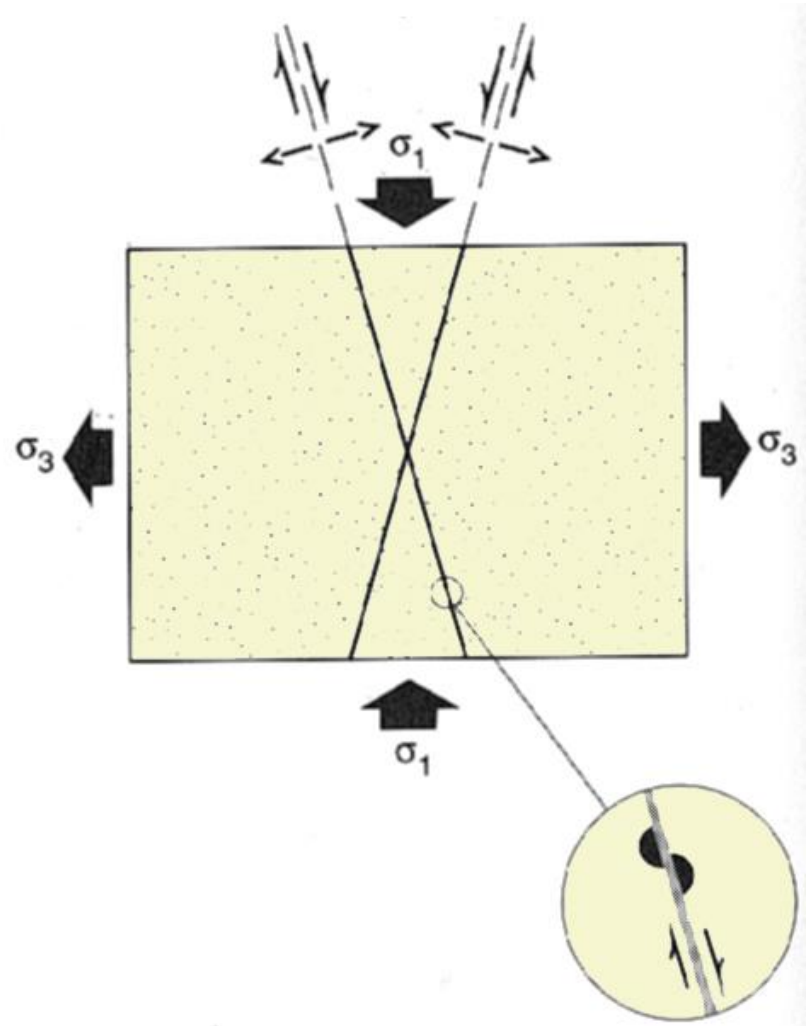
Hybrid joints show components of both dilatational and shear displacement


Dilational joints

Dilational joints

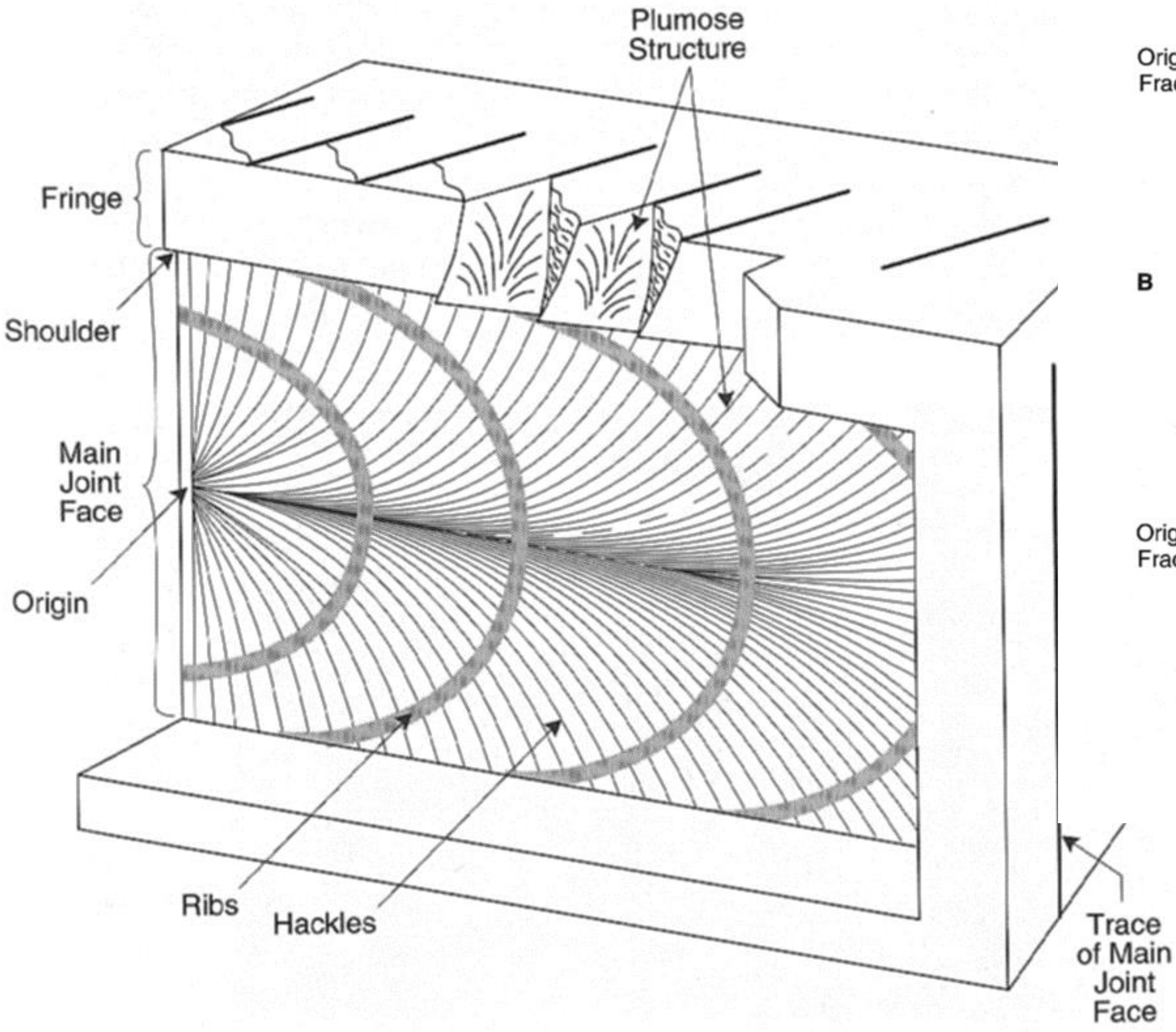
Shear joints

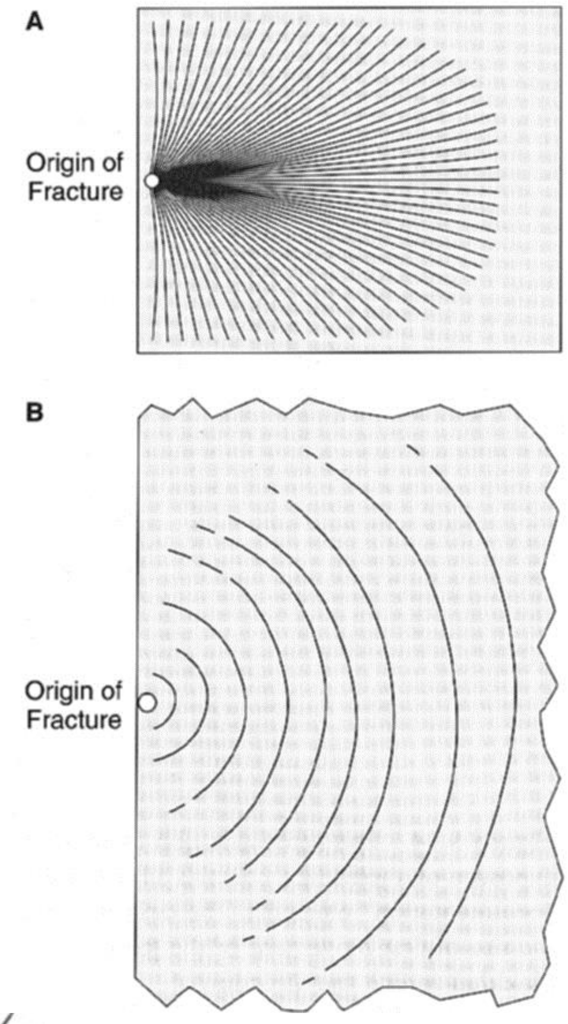
Shear joints reveal evidence for displacement (slickensides) similar to minor faults



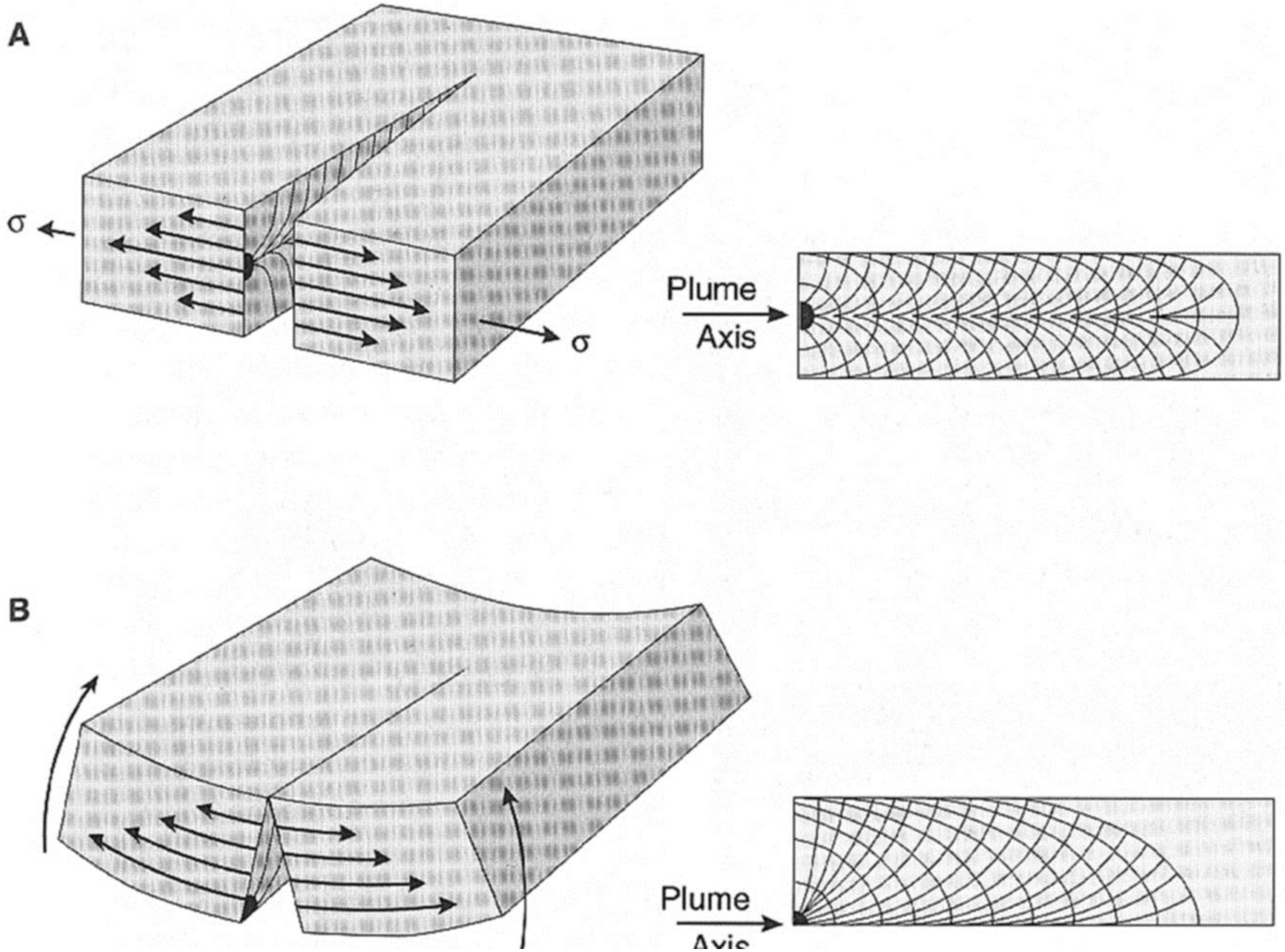
Shear joints are often conjugate

SURFACE OF THE JOINTS





Asymmetry of the hackles indicates character of joint origin



Joints often contain **some ornaments** that indicate the beginning of the promotion of cracks and also show the direction in which the crack propagated.

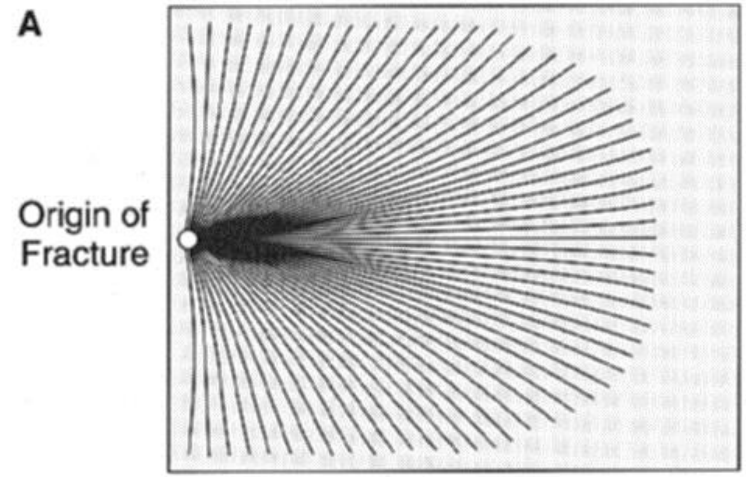
These characters are:

The beginnings - the original promotion places, which are analogous to the promotion of earthquake hypocenter. These points correspond to locations of defects in the material.

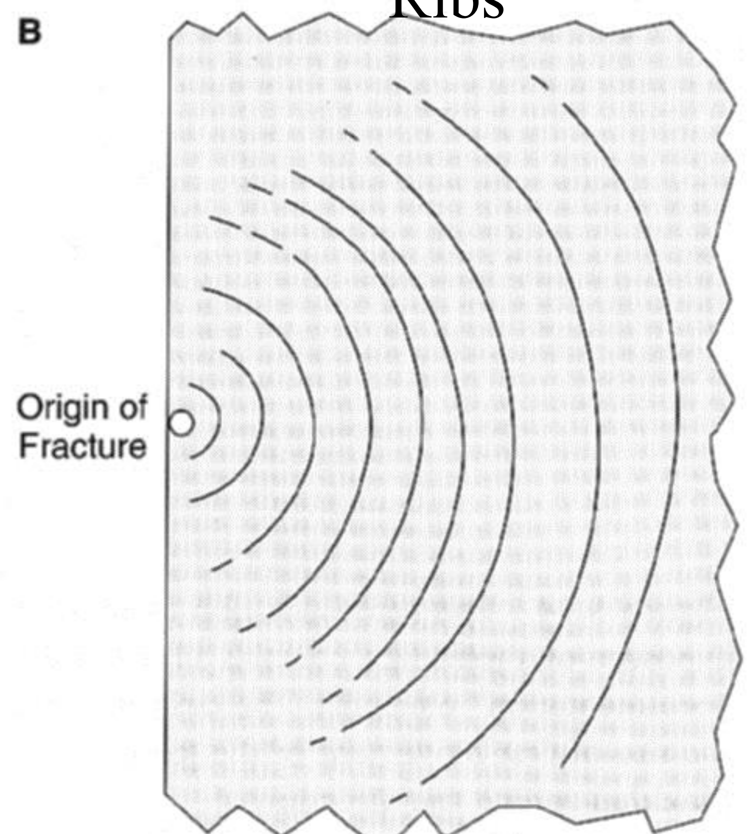
"Vochle“- are straight or curved lines that begin at the beginning, to which also converge.

Ribs - represent the position of the front propagation of cracks during the joint origin. The ribs are generally perpendicular to the vochle.

Hackles



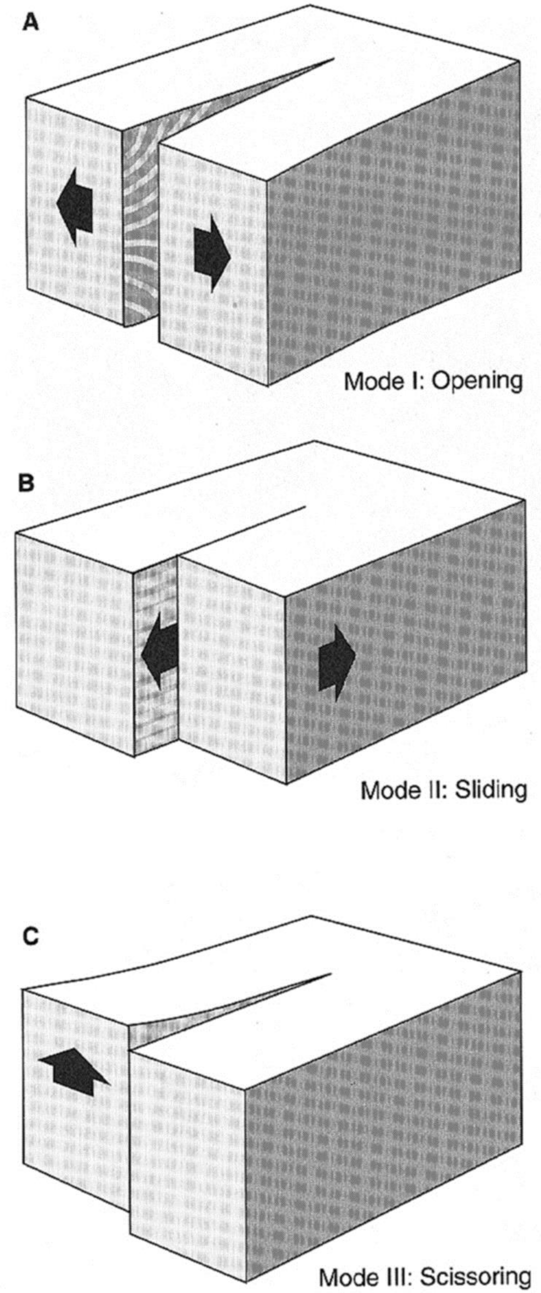
Ribs



Joints

Three diferent genetical modes of joints:

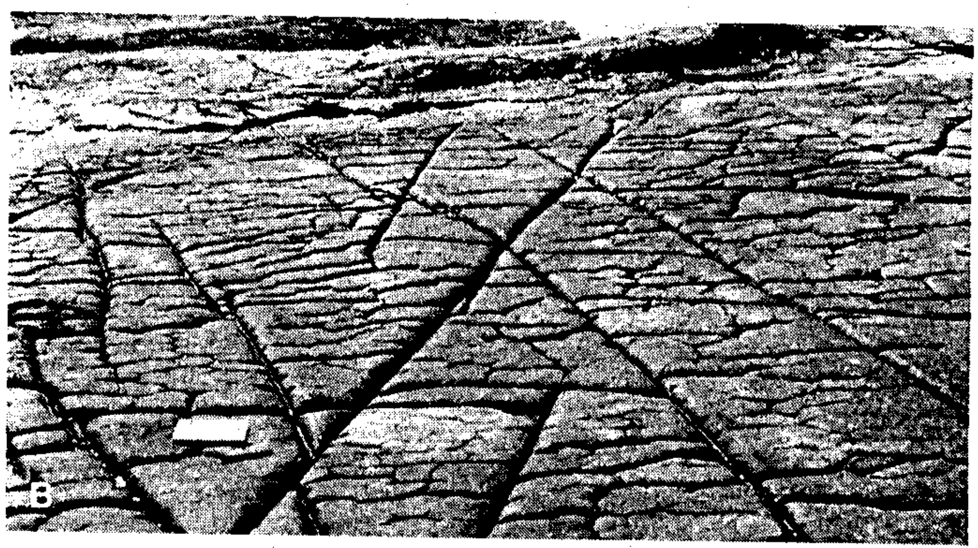
1) Mode I. – Opening
2) Mode II. – Sliding
3) Model III – Scissoring



Age relationships of joints

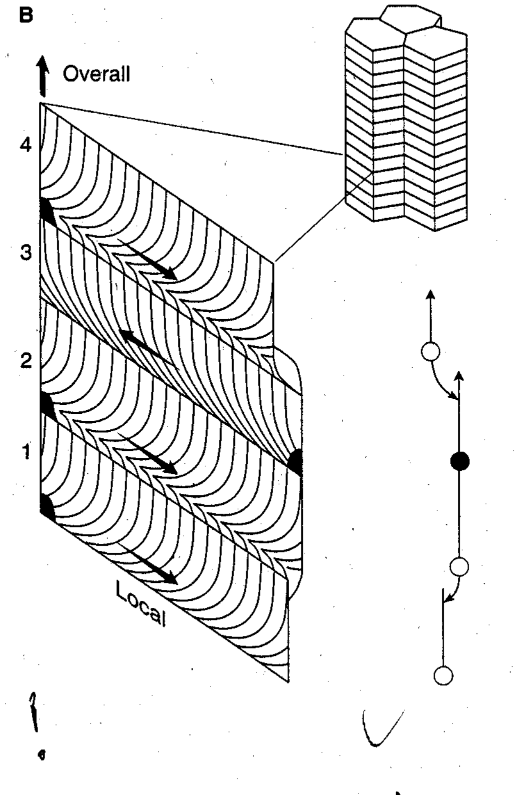
X – intersection of joints. It is possible to distinguish relatively younger and older system of joints

Younger joint do not generally cut older joints. They have T or H patterns (upright of the T or the cross-bar of the H)

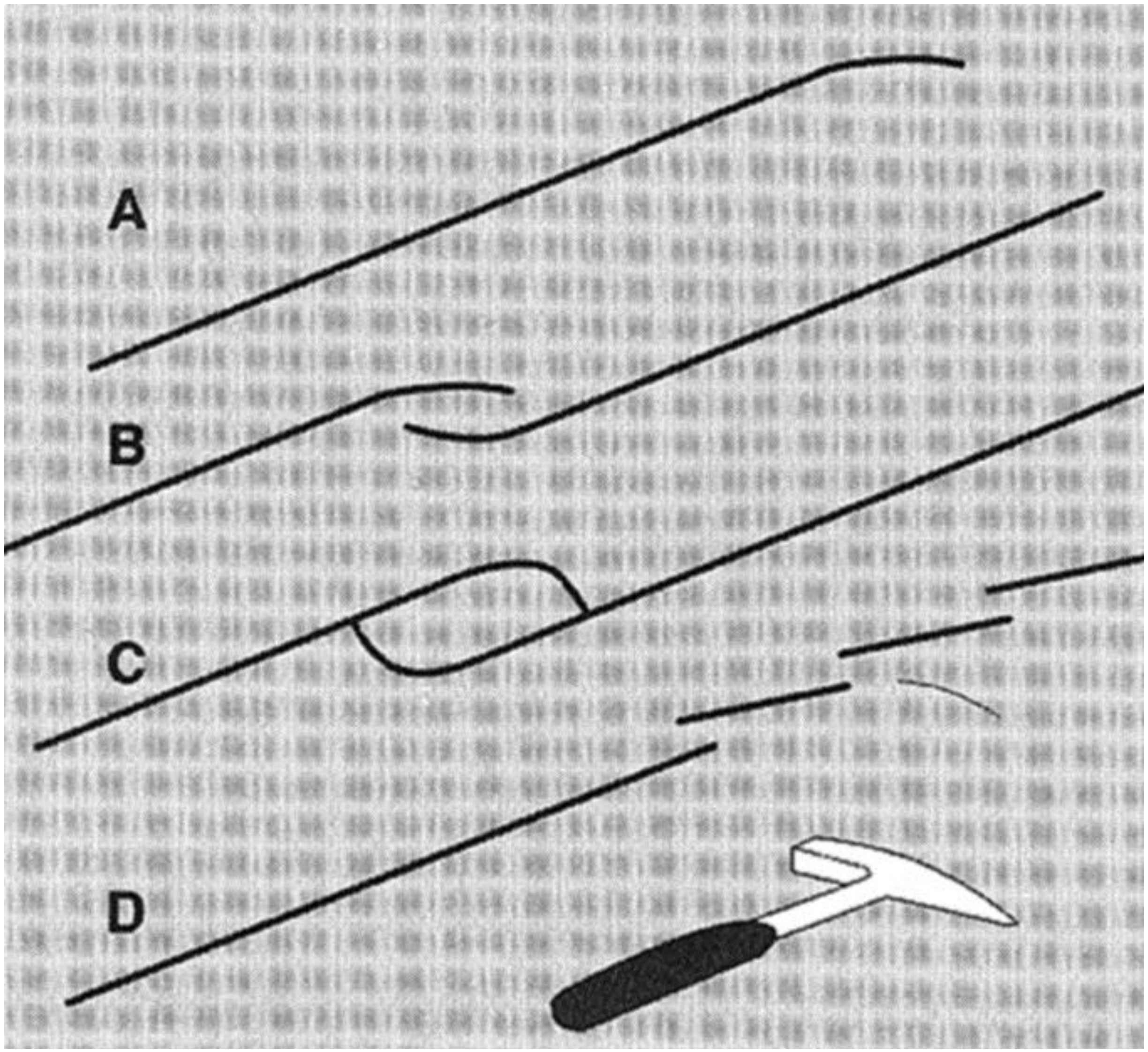


Column joints in volcanic rocks

The origin of column joints depens on magma flow and rate of magma cooling



Joint is usually terminated by hook shape



Geological map and structural cross-section

Geological map

- Views intersection of geological bodies with the Earth's surface
- Plotted in the horizontal plane (the plane topographic maps)

Geological map provides a three-dimensional image of the distribution, age, shape and orientation of geological bodies and their contacts on the displayed area

Geological and structural cross-section

- Display of geological structures and their relationships below the surface

Cross-section is plotted in the vertical plane (section) below the selected line in the geological map

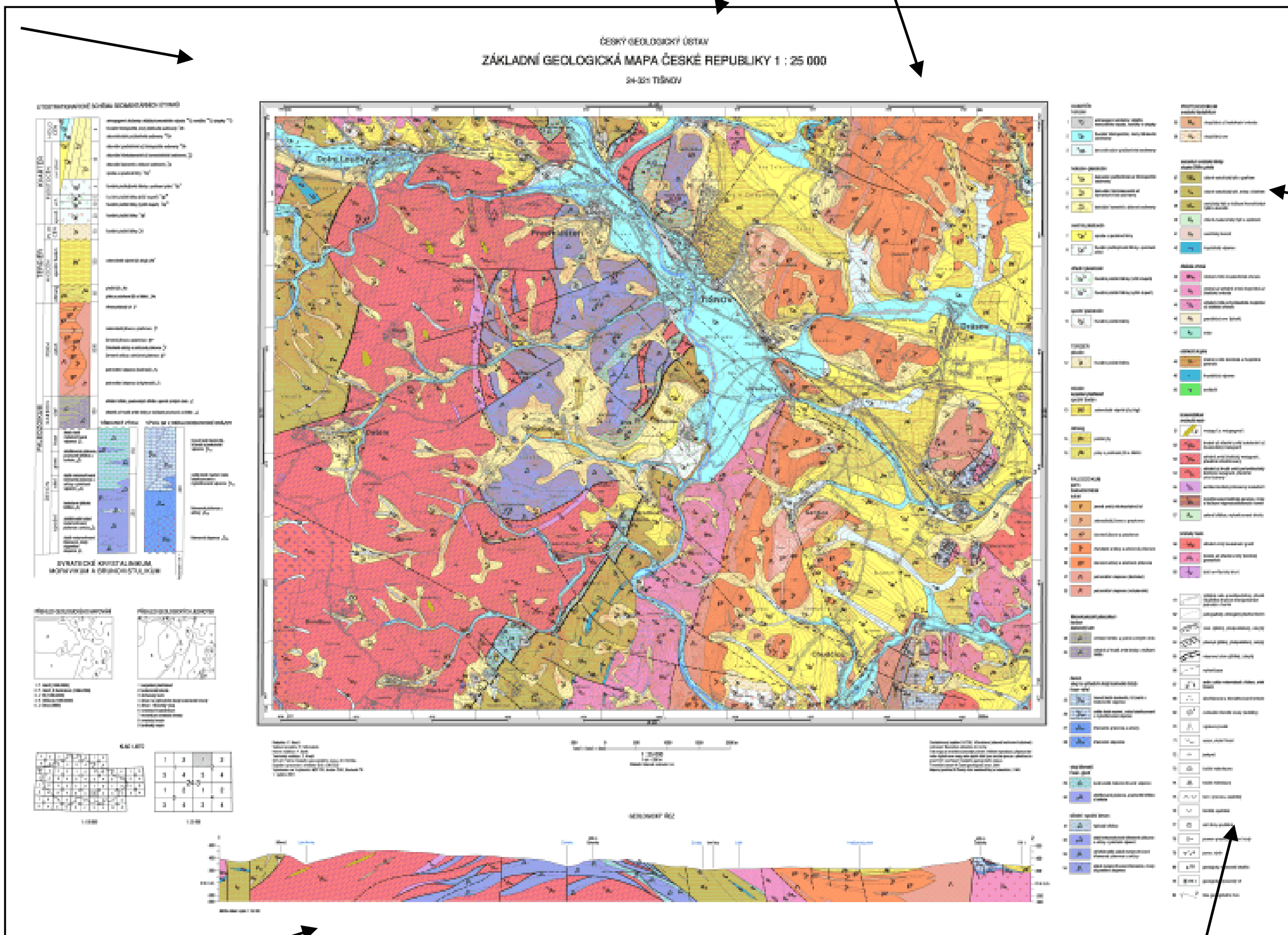
Blockdiagram

- The combination of geological maps and structural cross-section

Geological map 1:25.000

Name of the map, scale and coordinates

Stratigraphic chart



Legend

Cross section

Lithological and structural symbols

Necessary field data for processing of the geological / tectonic map

Locality number

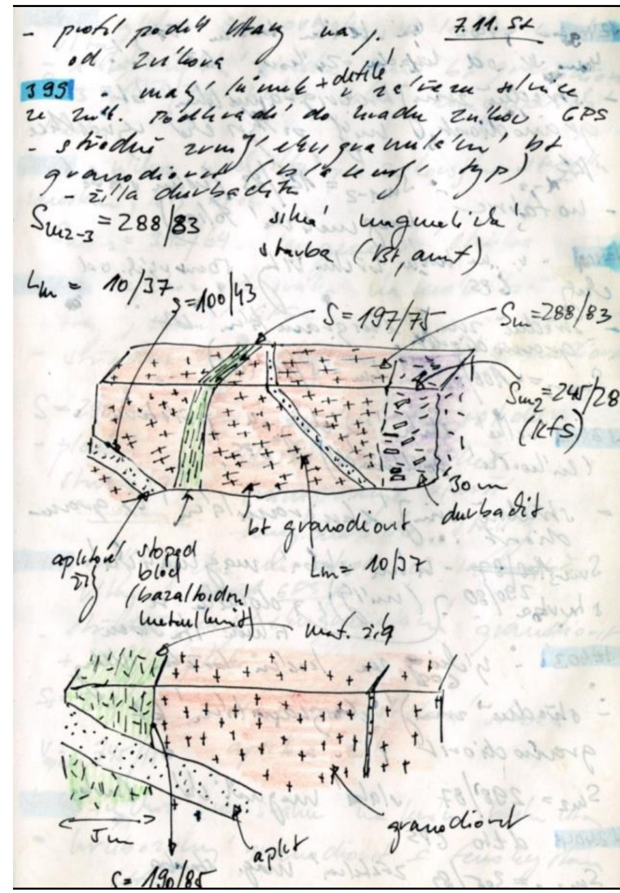
Geographic localization and coordinates

Outcrop description

Lithology and mineral composition

Description and orientation of structural data

Regional fabrics and their relationships
Lithological / tectonic contacts
Brittle structures (joints, faults)



Drawing of schematic blockdiagram or photograph (oriented)

Orientation data in structural geology

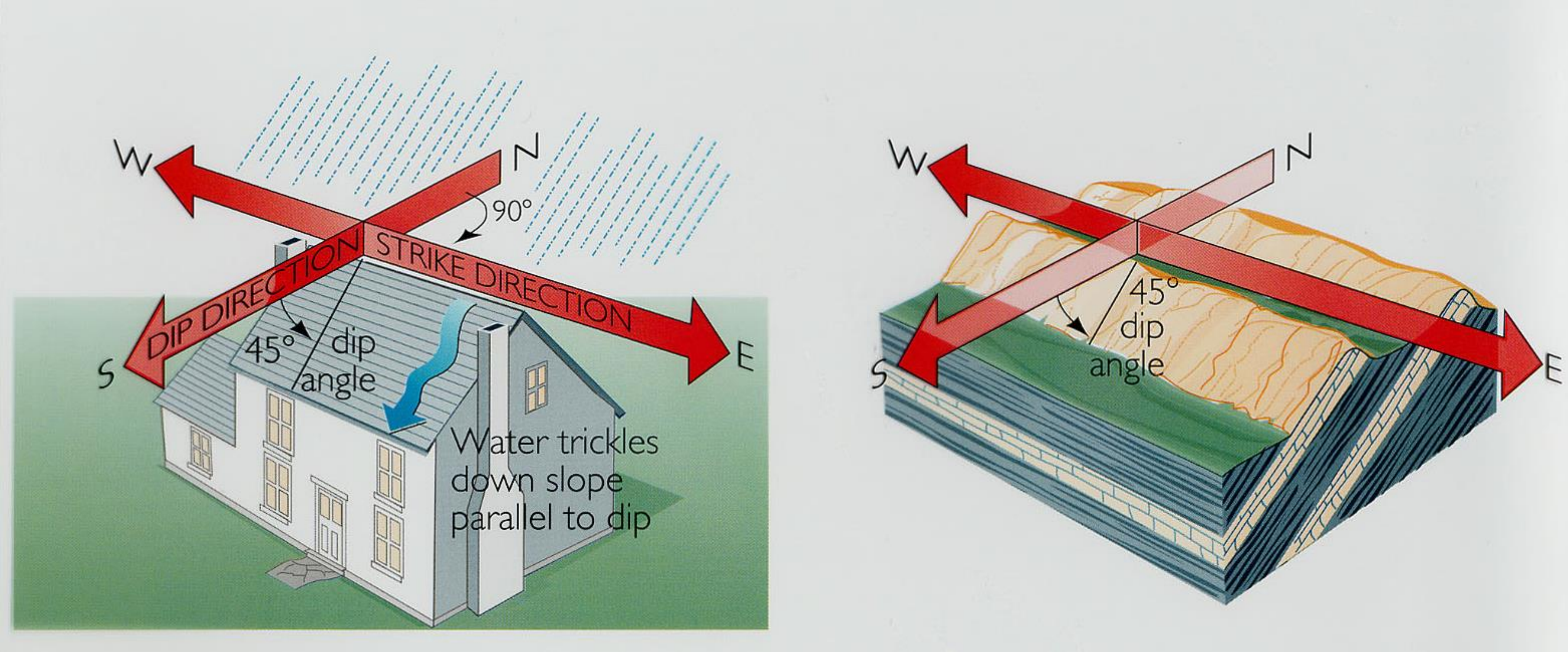
Azimuth – angle of the line from north (0 ° = 360 °), measured in the horizontal plane

Circular data - 2D, measured either in the horizontal plane as the azimuth or in any plane as an angle relative to the reference line

Axial data
Directional data (vectors)

Spherical data - orientation of structural elements in 3D

Spherical data - orientation of structural elements in 3D



Three the most important numbers

Direction of the plane (azimuth)
Dip direction of the plane (= direction + 90°)
Dip of the plane

How to measure structures

Foliation (S)

schistosity, schistosité, Schieferung

Strike and Dip

Strike (0°- 360°)

Dip (0°- 90°)

S = 320°/50°

Transfer:

The right hand rule

Dip direction and Dip

Dip direction (0°- 360°)

Dip (0°- 90°)

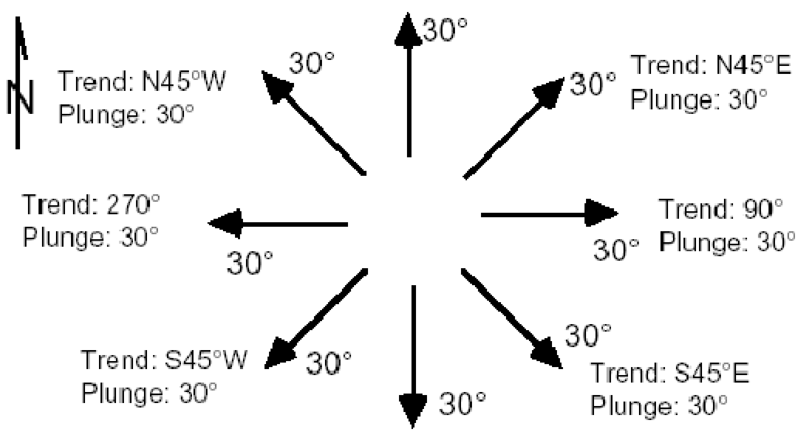
S = 230°/50°

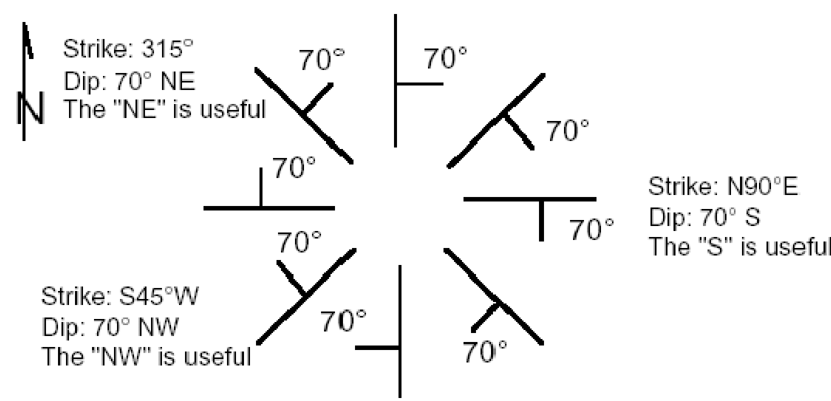
Lineation (L)

L = 351/53

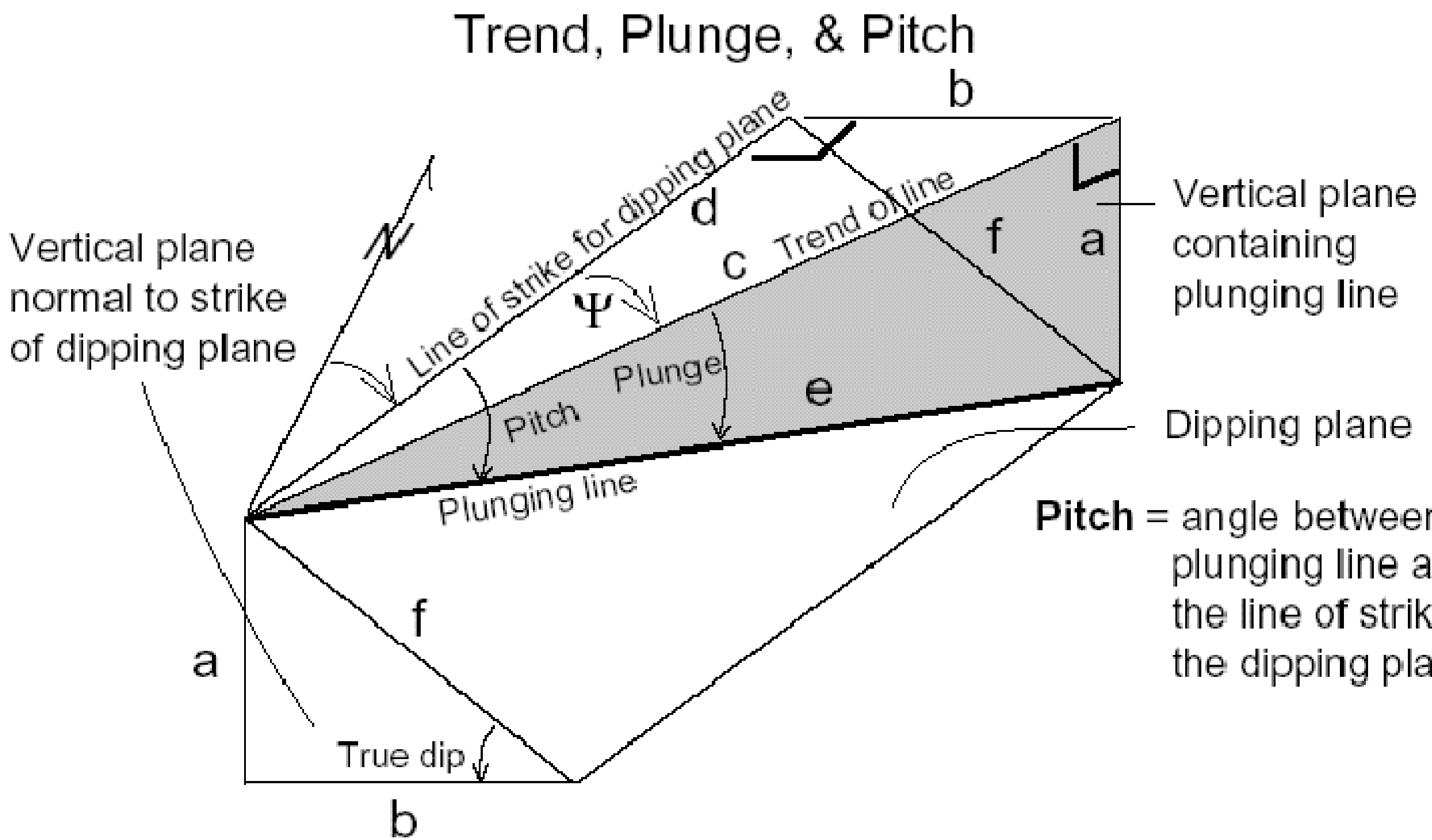
Quadrant method:

S = N40°W/50°SE





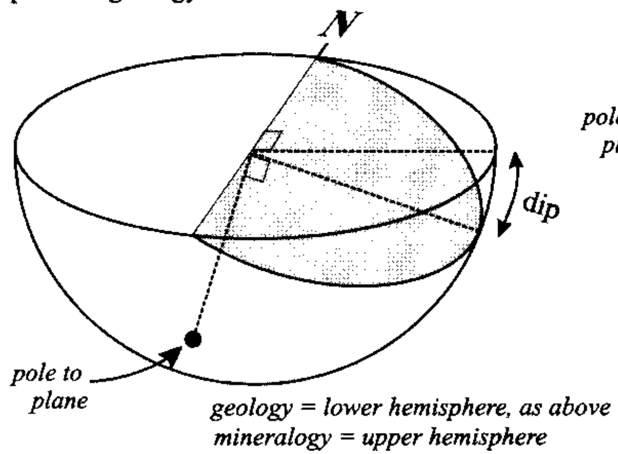
Strike, dip, trend, plunge, pitch



Pitch = angle between plunging line and the line of strike for the dipping plane

Display of planes and lines in the stereographic projection

Coordinate system for plane in geology

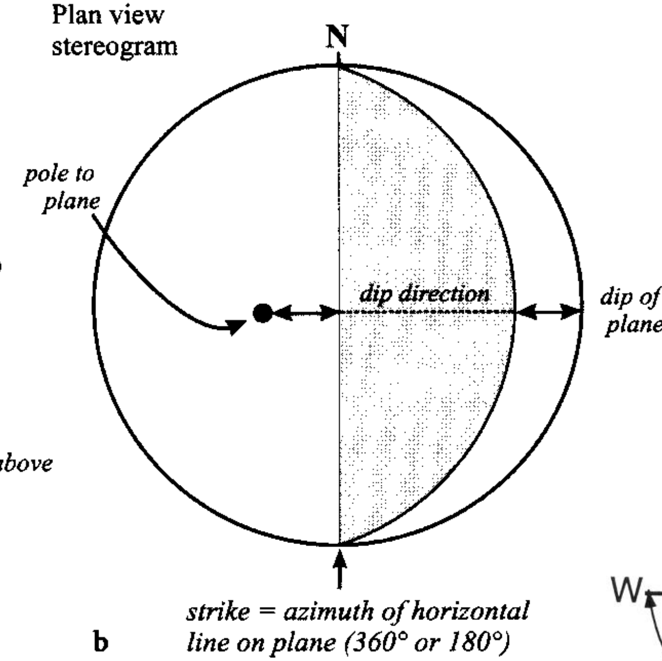


For plane shown, convention for strike is:
Right-hand convention.....strike / dip = 360/20
Left-hand convention.....strike / dip = 180/20
Dip direction & dip convention = 090/20

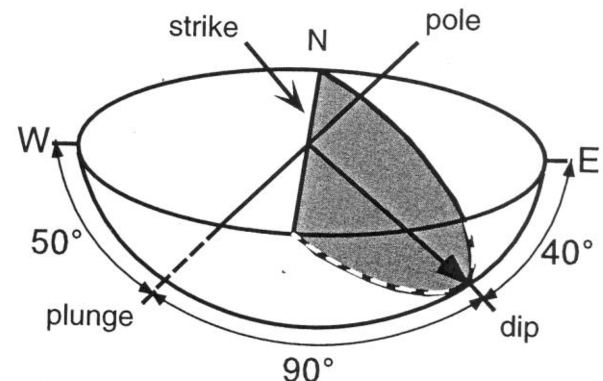
Strike & dip convention = 180/20E or 360/20E
(least ambiguous reporting)

a

Plan view stereogram

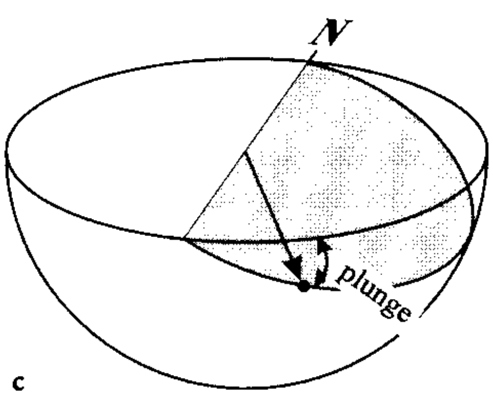


b



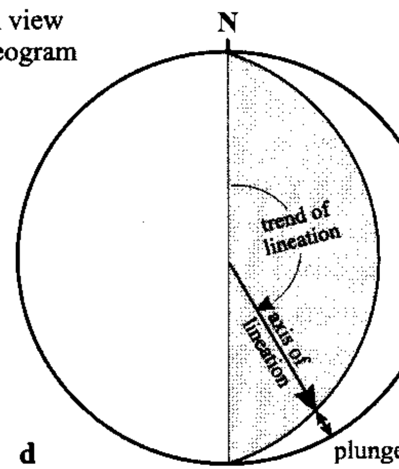
b

Coordinate system for axis (line) in geology shown within plane from (a) and (b)



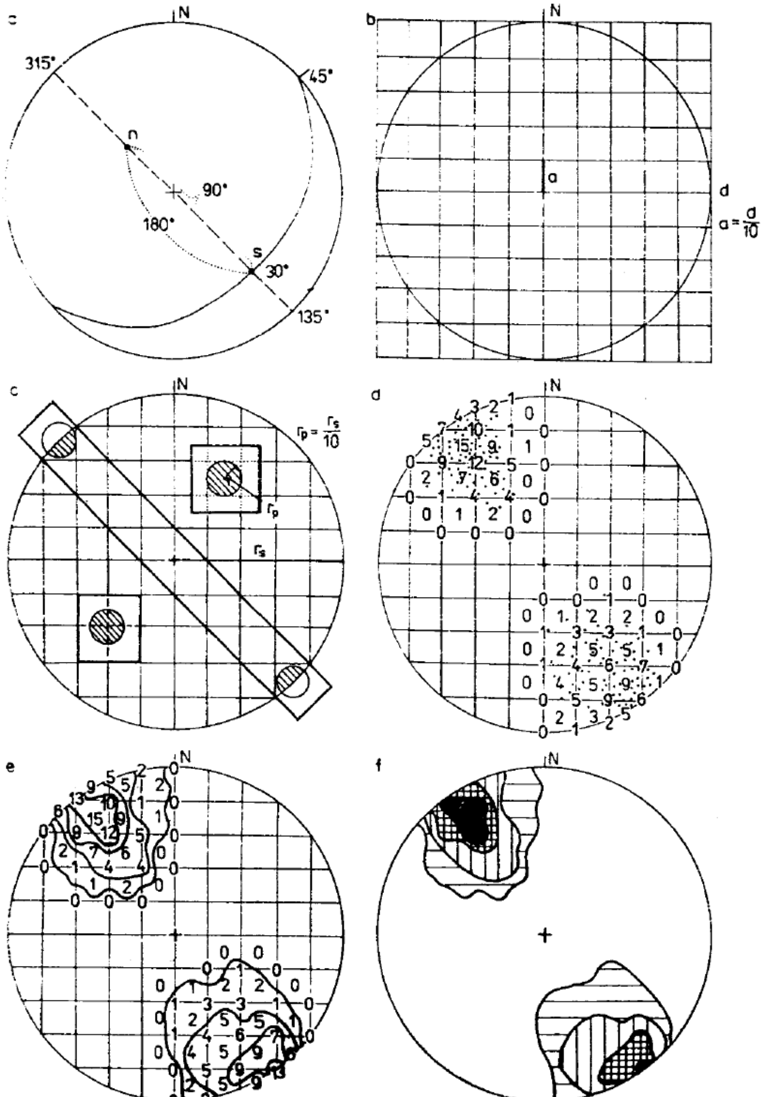
c

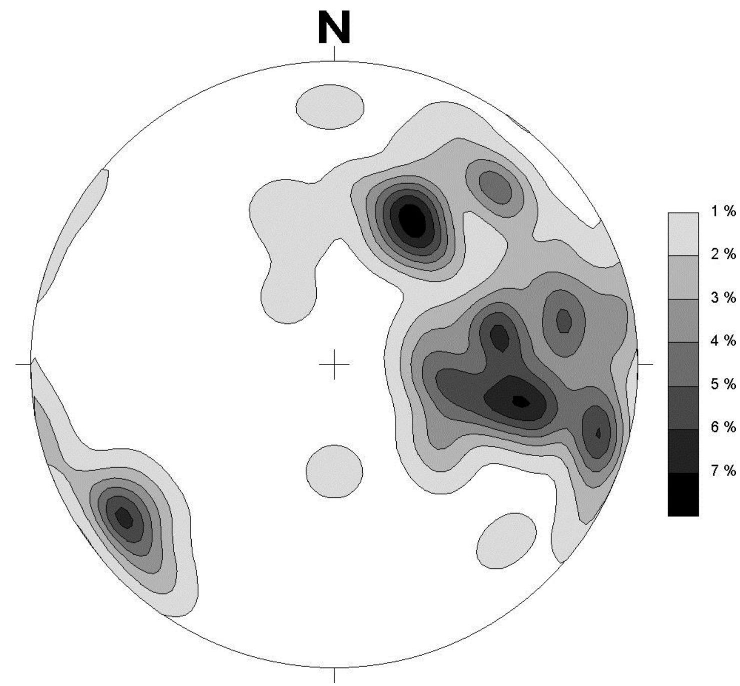
Plan view stereogram



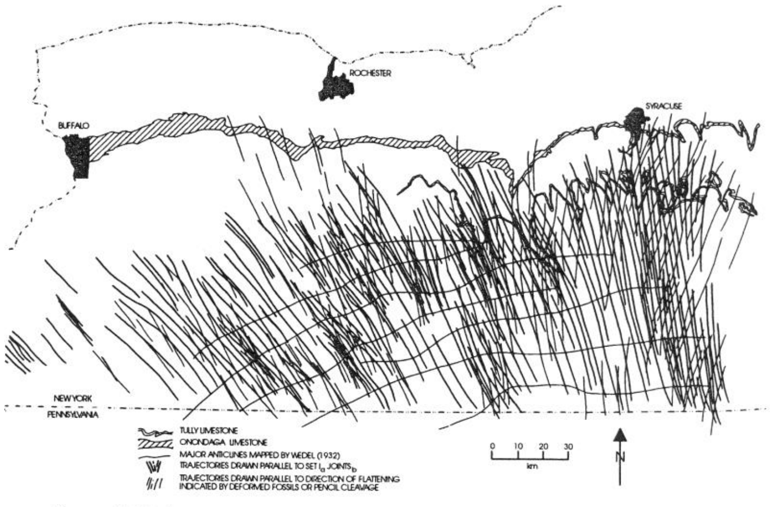
d

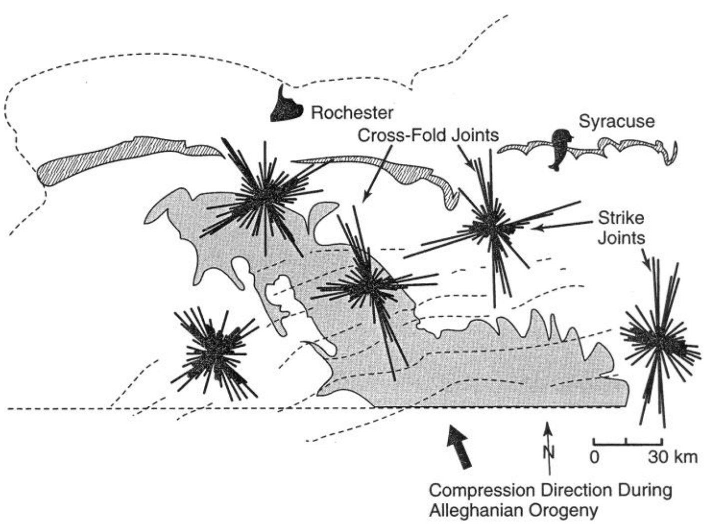
Contour orientation diagram

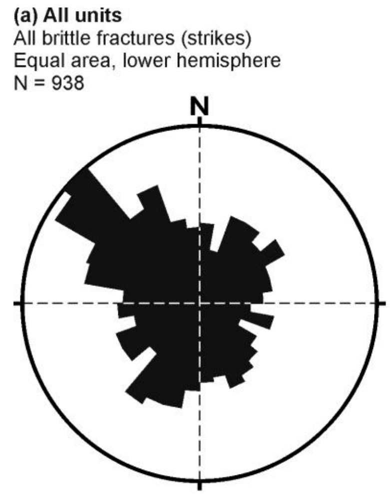


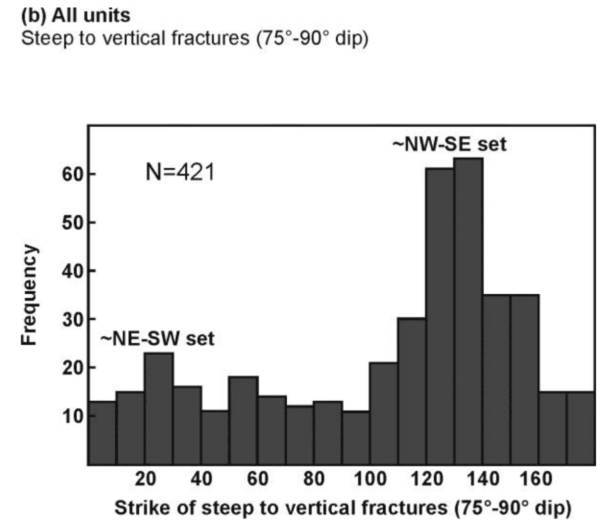


Directional orientation of joints or faults



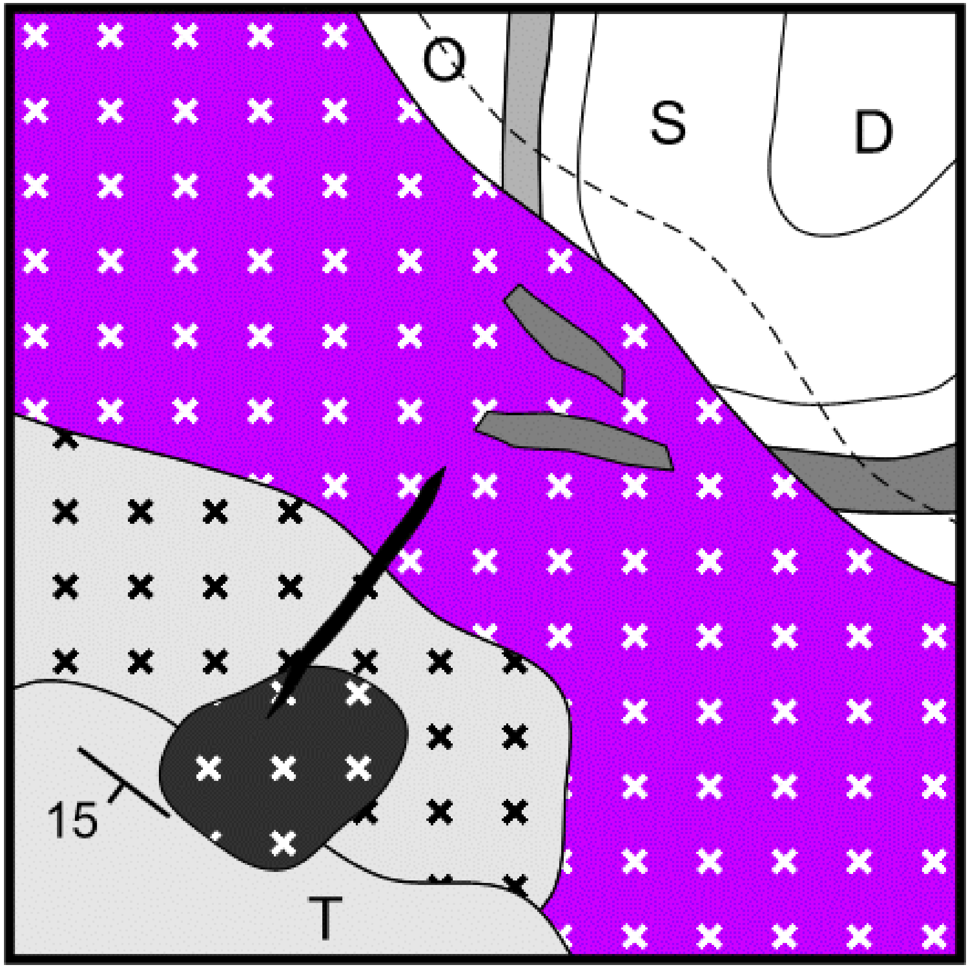






Principles of geological intersection

Principles of geological intersection



Summary of the field research (Arba Minch)