Introduction to Structural Geology

Patrice F. Rey

CHAPTER 1

Introduction

The Place of Structural Geology in Sciences

Science is the search for knowledge about the Universe, its origin, its evolution, and how it works. Geology, one of the core science disciplines with physics, chemistry, and biology, is the search for knowledge about the Earth, how it formed, evolved, and how it works. Geology is often presented in the broader context of Geosciences; a grouping of disciplines specifically looking for knowledge about the interaction between Earth processes, Environment and Societies.

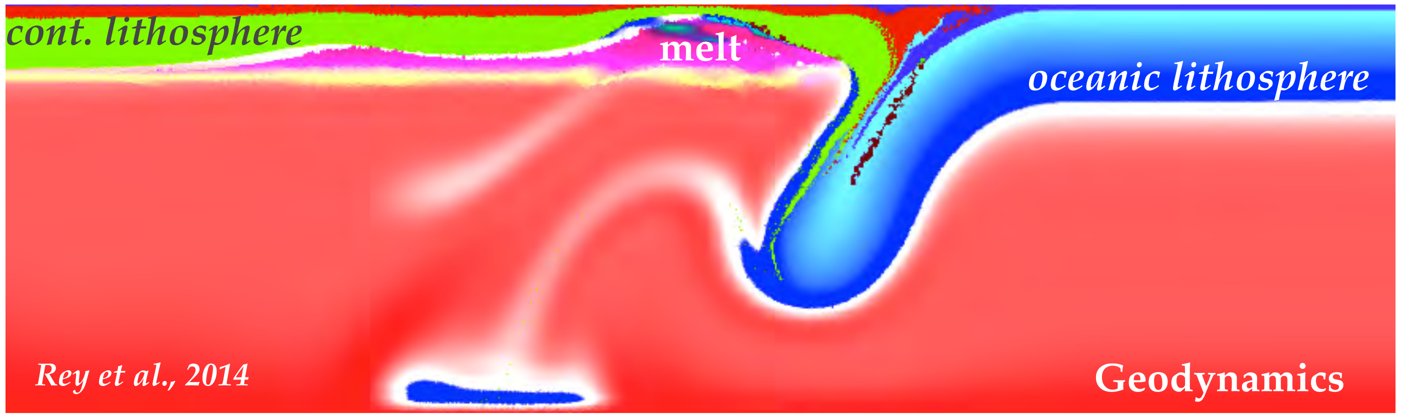
Structural Geology, Tectonics and Geodynamics form a coherent and interdependent ensemble of sub-disciplines, the aim of which is the search for knowledge about how minerals, rocks and rock formations, and Earth systems (i.e., crust, lithosphere, asthenosphere ...) deform and via which processes.

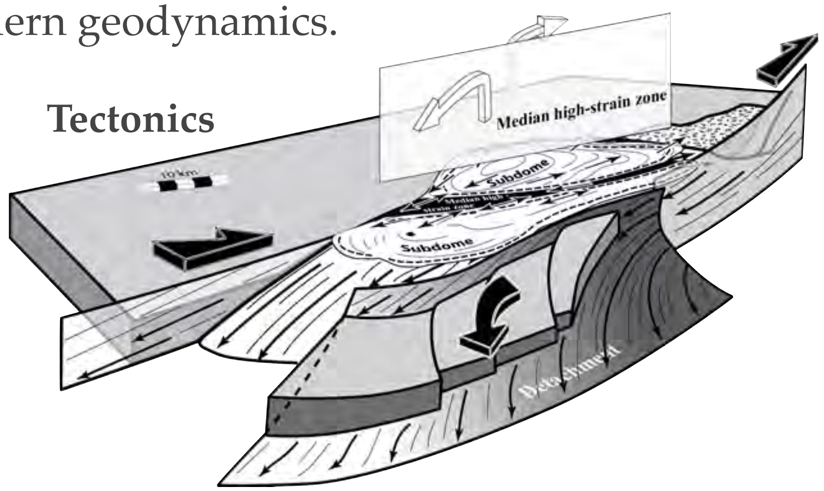
Structural Geology In Geosciences.

Structural Geology aims to characterise deformation structures (*geometry*), to characterize flow paths followed by particles during deformation (*kinematics*), and to infer the direction and magnitude of the forces involved in driving deformation (*dynamics*). A field-based discipline, structural geology operates at scales ranging from 100 microns to 100 meters (i.e. grain to outcrop).

Tectonics aims at unraveling the geological context in which deformation occurs. It involves the integration of structural geology data in maps, cross-sections and 3D block diagrams, as well as data from other Geoscience disciplines including sedimentology, petrology, geochronology, geochemistry and geophysics. Tectonics operates at scales ranging from 100 m to 1000 km, and focusses on processes such as continental rifting and basins formation, subduction, collisional processes and mountain building processes etc.

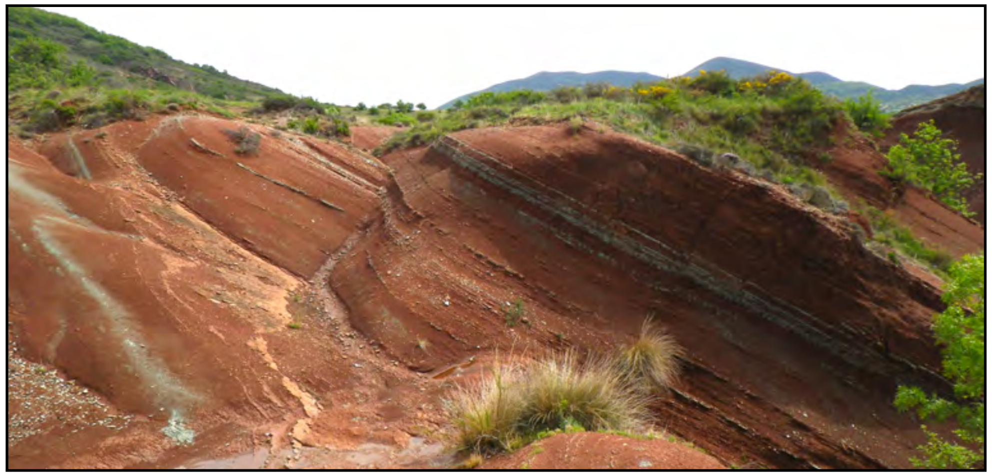
Geodynamics focusses on the forces that drive mantle convection, plate motion and deformation of Earth's material. Geodynamics is concerned with deep mantle processes such as mantle convection, cold drips, hot plumes and their links to plate motion, including dynamic plate subsidence and uplift, and plate tectonic processes. Geodynamics involves working at scales > 100 km. Numerical modeling is at the core of modern geodynamics.





The Scientific Approach

As all scientists, structural geologists follow research strategies that call upon concepts such as: fact, hypothesis, model, theory, and law. A good understanding of these terms is essential to all scientists.



A **fact** is a bit of truth. For a structural geologist a “fact” could be the dip direction of a bedding plane. Having measured that north is to the left on the photo on the right, then it is a fact that the dip direction of the bedding is to the south.

An **hypothesis** is an assumed fact. It is a short statement one makes to go further into a reasoning. For instance, assuming that the bottom right photo contains the stretching lineation (hypothesis), then one can infer that the sense of shear deduced from the tilling of K-feldspars in this orthogneiss is top to the right.

A **model** is a self-consistent framework providing a coherent explanation for the observed facts. A model combines as many facts as possible and as little hypotheses as possible. A good model allows to make verifiable predictions. A model is proven wrong if key predictions are not verified. It can be iteratively strengthened via minor modifications to account for both the facts and the predictions.

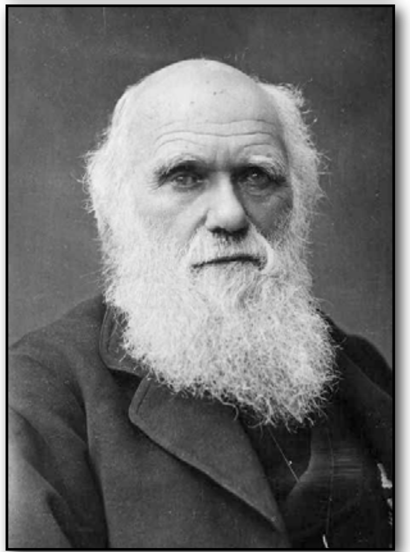
A **theory** is a very robust model which accounts for a large number of independent facts; and whose numerous predictions have been verified over a long period of time. Evolution and Plate Tectonics are two theories.

A **law** is a simple, fundamental concept that is always verified by experiments and that underpin our understanding of the world. For instance, the law of gravity and the laws of thermodynamics underpin our understanding of Physics and Chemistry.

Truth is not a scientific concept.

Scientific Methods: Francis Bacon (1561-1626) vs Charles Darwin (1809-1882)

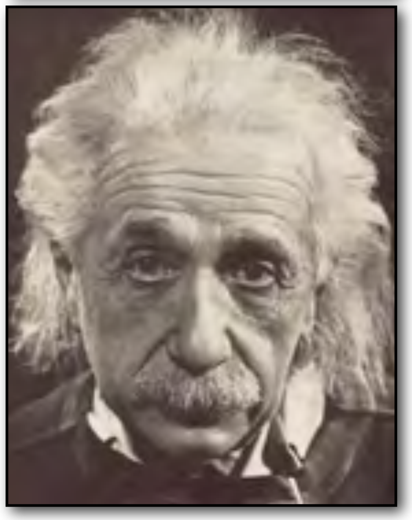
The **Baconian method**: This method, sometimes called the “induction approach”, is based on the collection of facts without regard to a particular model. Eventually the growing dataset self organizes into a model. This is the “zero hypothesis” approach. Isaac Newton, a fervent adept of Francis Bacon Induction Approach, once said: “I don’t make hypotheses”. This approach is at the core of modern Data Mining.

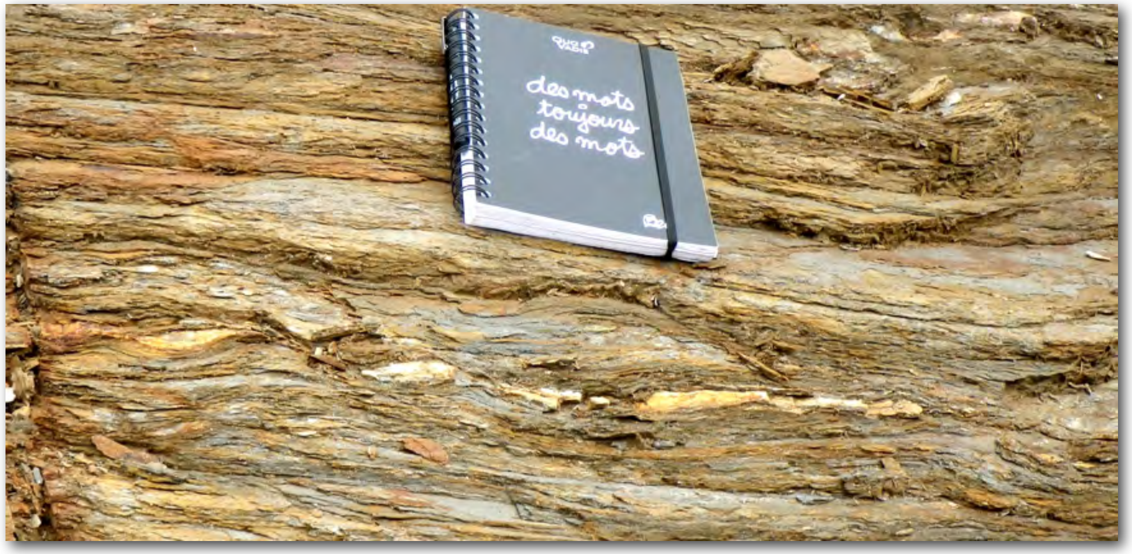


The **Darwinian method**: A model is built from of a set of facts. The model is used to make verifiable predictions. The predictions are verified by the acquisition of new data or via experimentation, if necessary the model is modified. This iterative process eventually leads to a robust model.

There is no need to put in opposition the Baconian and the Darwinian methods. Both have earned their place in Science.

The **Reality**...: Scientific progresses are almost never the result of strictly rational scientific methods. Intuition, non-rational and non-logical thinking make Science, fun, exciting and surprising. Einstein once said: "The only real valuable thing is intuition." ... and also that “Imagination is more important than knowledge.”





Workflow of Structural Geology & Tectonics

Structural Geology and Tectonics combines two aspects:

1/ Description and analysis of 3D structures and microstructures (Structural Geology *sensu stricto*). Structural geologists are concerned with features resulting from deformation. These include fractures, faults, folds, boudins, shear zones, cleavages (also knows as schistosities), foliations and lineations.

From the analysis of these structures, they aim at understanding **finite strain** (i.e., the ultimate product of long, sometimes polyphased deformation histories), and **incremental strain** (i.e., the small increments of deformation, the accumulation of which leads to the finite strain).

They are interested to understand "**strain fields**" by mapping deformation features such as foliations and stretching lineations that tell us the orientation of the principal shortening direction and principal lengthening direction respectively.

In the case of faults and shear zones, they are interested to understand their **kinematics** (i.e., the relative sense of motion of the blocks they separate), and the magnitude of the displacement involved.

They are interested to infer the direction of maximum and minimum stress directions from small deformation features such as centimeter-scale extensional fractures and associated stylolitic joints.

Watch Gallery 1.1 on Flickr

Gallery 1.1 What do structural geologists look at?

Basaltic dike intrusive in shales, (South France). A dike is an extensional fracture that was filled with lava at the time of opening. The direction of open-up is parallel to the direction of minimum stress (Photo credit: P. Rey).

1 of 11

2/ Design of tectonic models (Tectonics).

The purpose of these models is to explain the deformation history that led to the observed 3D strain fields. Tectonic models incorporate a broad range of data from other disciplines. No matter how tectonicists design these models (following hours of pure rational thinking or via flashes of insight after a heavy night), tectonic models should always be:

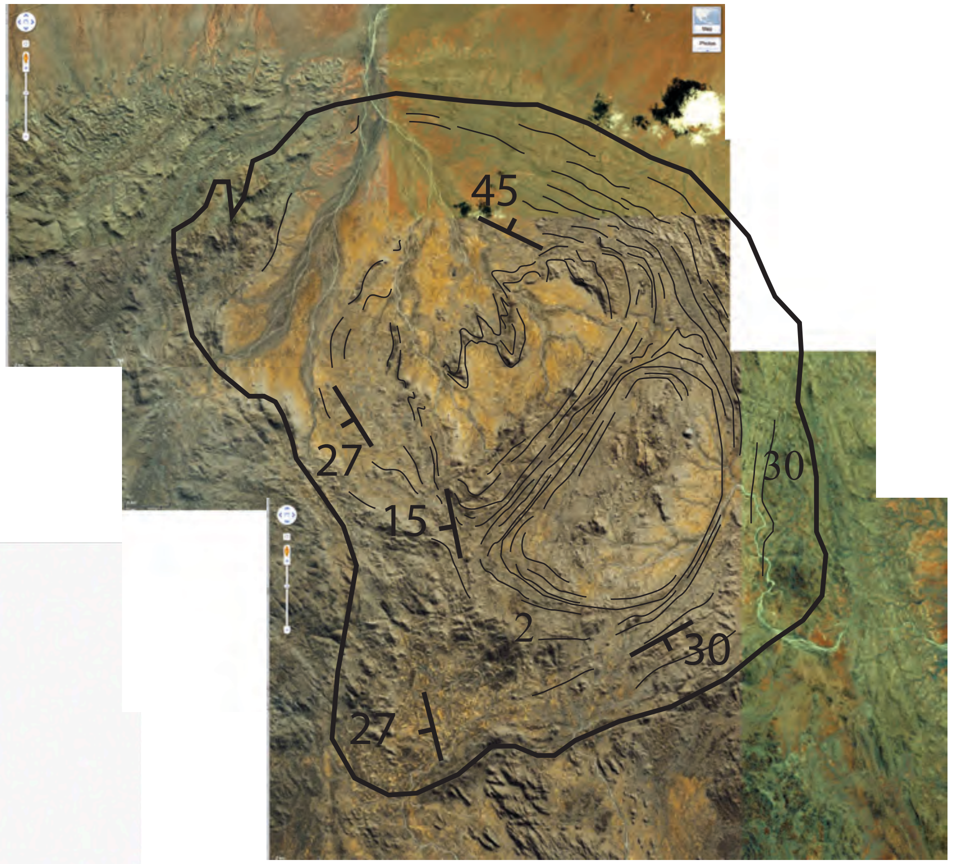
- **Physically valid**: They must be obey the law of physics, sounds trivial but not easy to meet this requirement without computational modelling.

- **Testable**: They must provide testable predictions (structural, sedimentological, petrological, geochemical, geophysical ...) that can be verified.

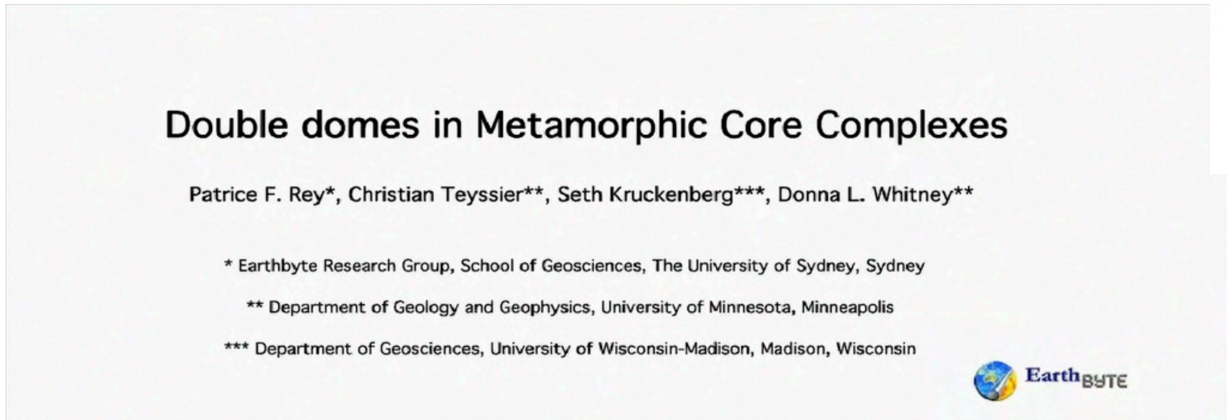
- **Robust**: They must explain a large number of unrelated facts,

- **Lean**: Hypotheses should be kept at a minimum compared to the number of fact models explain.

The computer model predicts a double-dome structure for migmatite-cored gneiss dome. The Entia dome in central Australia shows such an internal structure.



Movie 1.1 A predictive model of a gneiss dome (Metamorphic core complex)



Computational tectonic model of a gneiss dome (Rey, Teyssier, Kruckenberg and Whitney, Geology, 2011).

Watch this movie on you tube.

Data acquisition: Field Geology

The world of structural geologists is by nature three dimensional (3D). To unravel 3D architecture, structural geologists process a lot of structural measurements.

In the field, structural geologists measure the strike-dip-dip direction of planar features (bedding, cleavage, fault, fold axial surface ...), and plunge plunge direction of linear features (fold axes, intersecting lineations...).

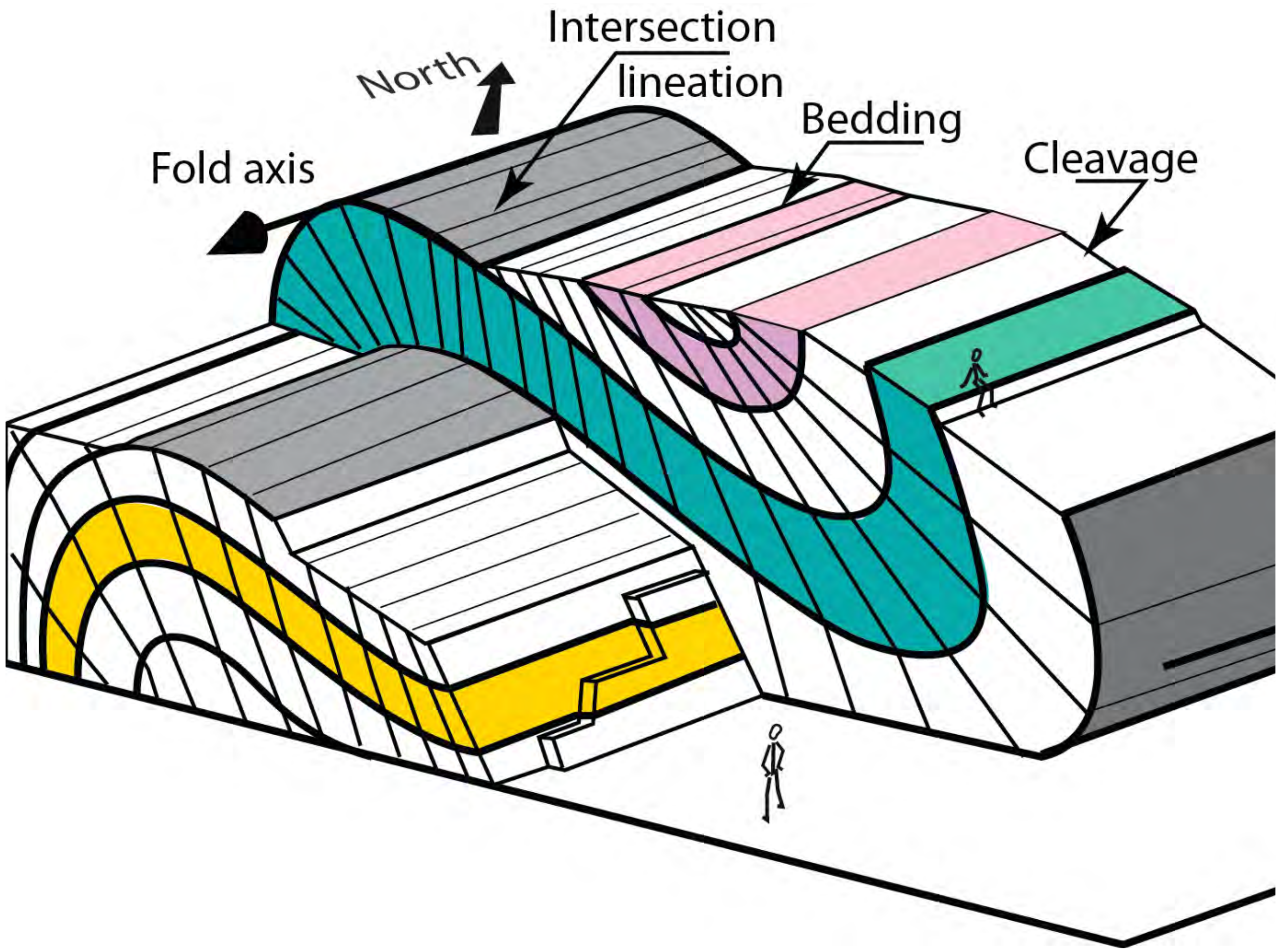
They gather information about the orientation, and when possible the magnitude, of strain and stress, and they determine the relative sense of displacement across brittle faults and ductile shear zones.

Based on cross-cutting relationships, they determine the sequence of geological and deformational events, they characterise the strain (incremental and finite strain analyses).

On aerial photographs and satellite images, structures to large to be seen in the field become obvious. Ultimately, 3D structures must be consistent across all scales.

Watch Gallery 1.2 on Flickr.

Gallery 1.2 Structural Data



Planar surfaces are oriented in space by their strike (azimuth of an horizontal line on the planar surface), dip (angle from horizontal down to the plane) and dip direction (geographic direction toward which the plane is sloping). Folds are oriented by the strike-dip-dip direction of their axial plane, the the plunge and plunge direction of their axis (line running along their hinge).

Data acquisition: Geophysics

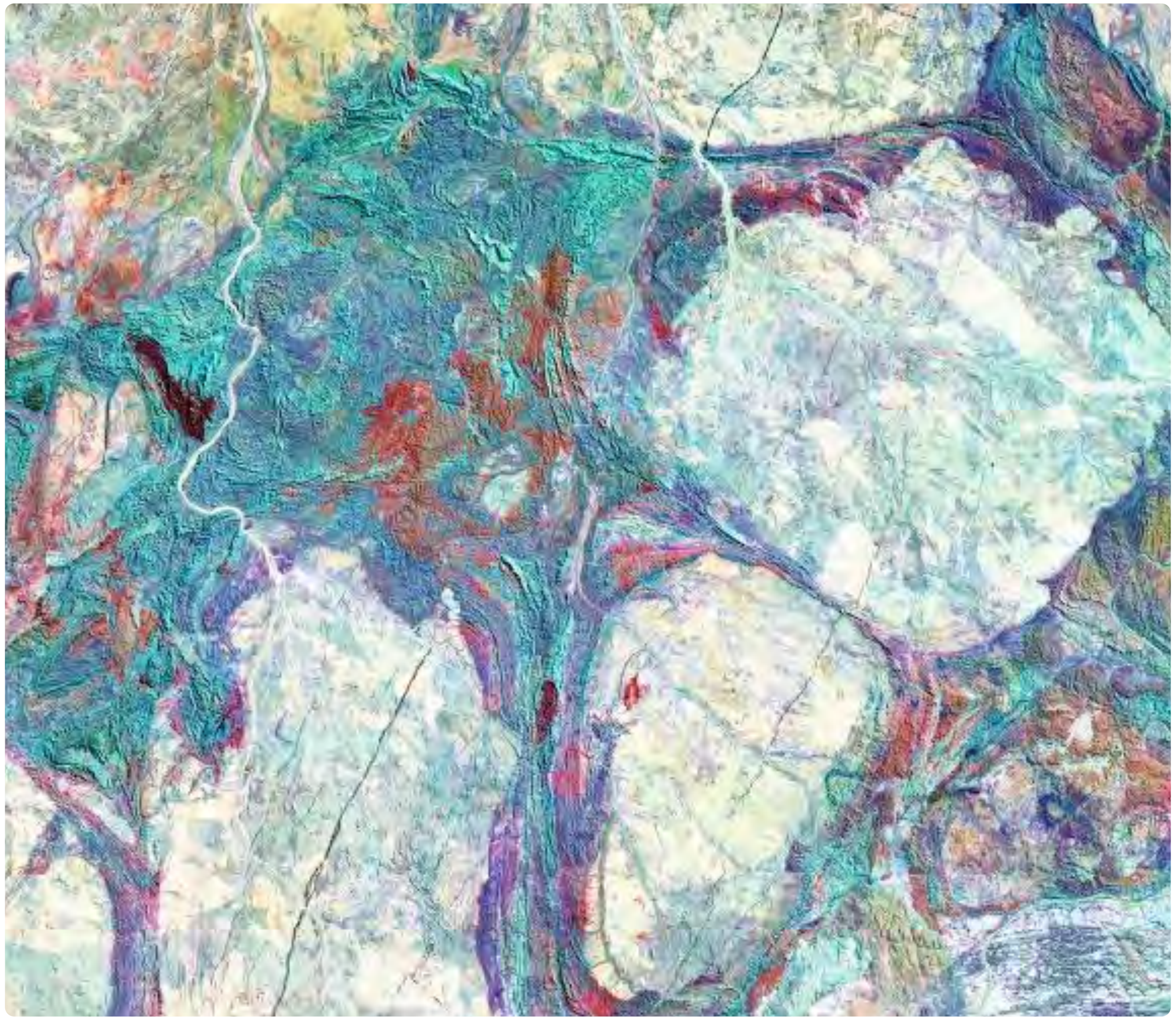
When the surface geology is buried underneath a regolith (in-situ blanket of weathered rocks) or a vegetation covers, geophysical images such as gravity anomaly maps, radiometric and aeromagnetic images etc can reveal many information on the nature of the subsurface geology and deeper structures.

Remote sensing techniques (airborne and satellite) are expanding very fast. Multispectral (e.g., ASTER satellite) and hyperspectral imaging (airborne) allow geologists to have access to high-resolution images over a range of electromagnetic wavelengths covering visible (400-700 nanometer), infrared to near infrared (NIR: 700-1000 nanometer), shortwave infrared (SWIR: 1000-2500 nanometer) and far infrared (FIT: >2500 nanometer). These images allow for the mapping of the distribution of minerals at the Earth surface.

(http://portal.auscope.org/portal/gmap.html).

Watch Gallery 1.3 on Flickr.

Gallery 1.3 Structural data from geophysics



Landsat image of the east Pilbara (WA). The pale rounded features are granitic domes. In blue green are greenstone belts (continental flood basalts). The straight lines running SSW-NNE are Proterozoic dikes.

Data acquisition: Geophysics (cont.)

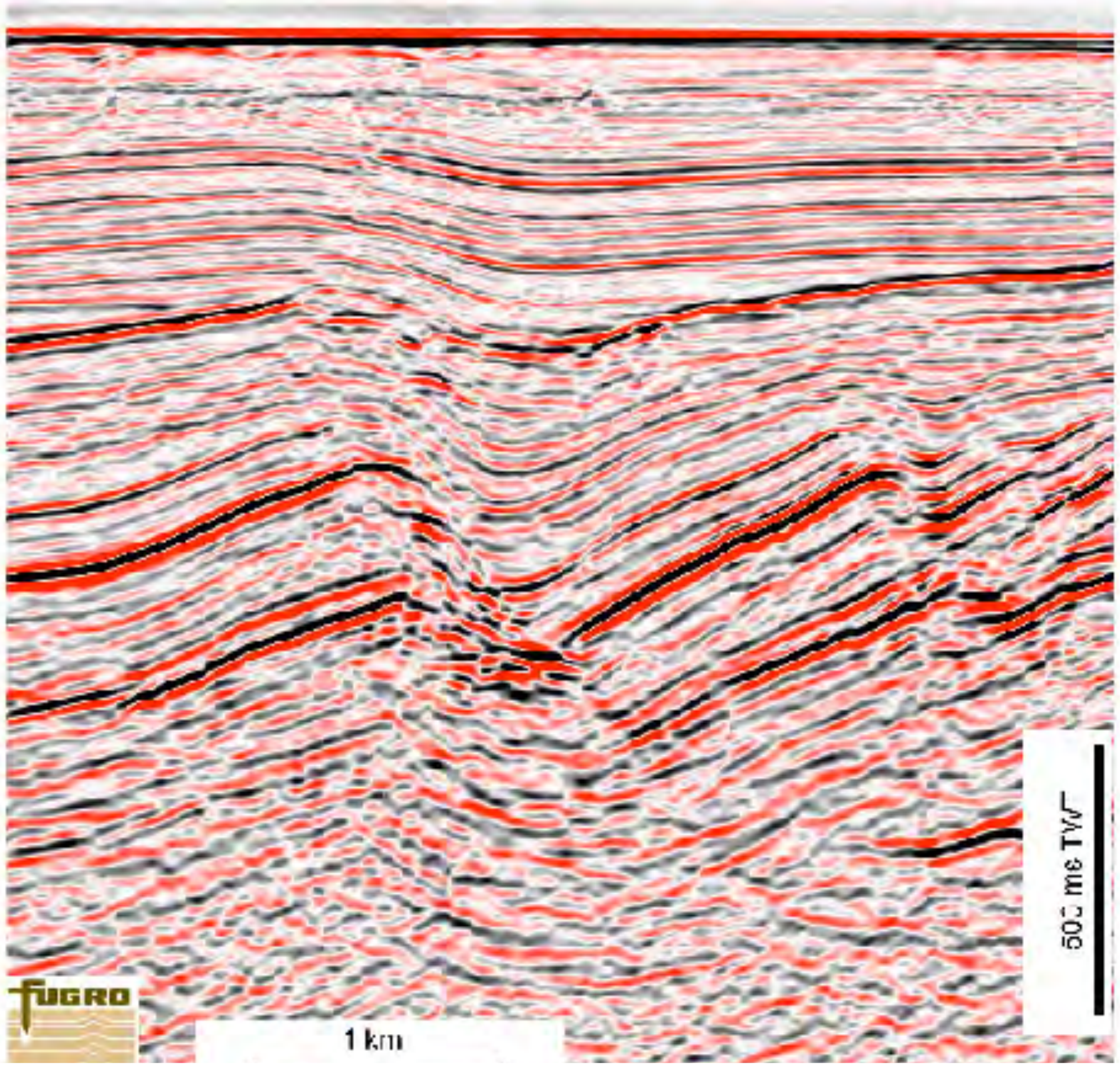
Information about deep geology are gathered directly via drilling and indirectly via geophysical methods such as gravimetry and seismic surveys amongst others. Gravimetry gives information about the distribution of rocks density below the surface, whereas refraction and reflection seismology reveal variation in rocks' elastic properties.

Seismic reflection is at the core of hydrocarbon exploration. Elastic waves, artificially induced at the Earth's surface via explosive or vibration trucks, propagate through rock formations reflecting and refracting at acoustic impedance contrasts (i.e. contrast in the product velocity x density). The processing of waves traveling back to the surface can reveal in minute details the underground geology.

Visit the Virtual Seismic Atlas: see-atlas.leeds.ac.uk:8080

Watch Gallery 1.4 on Flickr

Gallery 1.4 Structural data from geophysics



Virtual Seismic Atlas Author: Rob Butler. Normal fault in the Inner Moray Firth using Fugro 2D data.

Data synthesis and analysis :

Structural data are summarized in various documents:

1/ Geological maps and cross sections show the distribution of rock formations and structures (e,g, faults and folds) at the Earth surface. A geological map is a very powerful document, as one can reconstruct the subsurface geology.

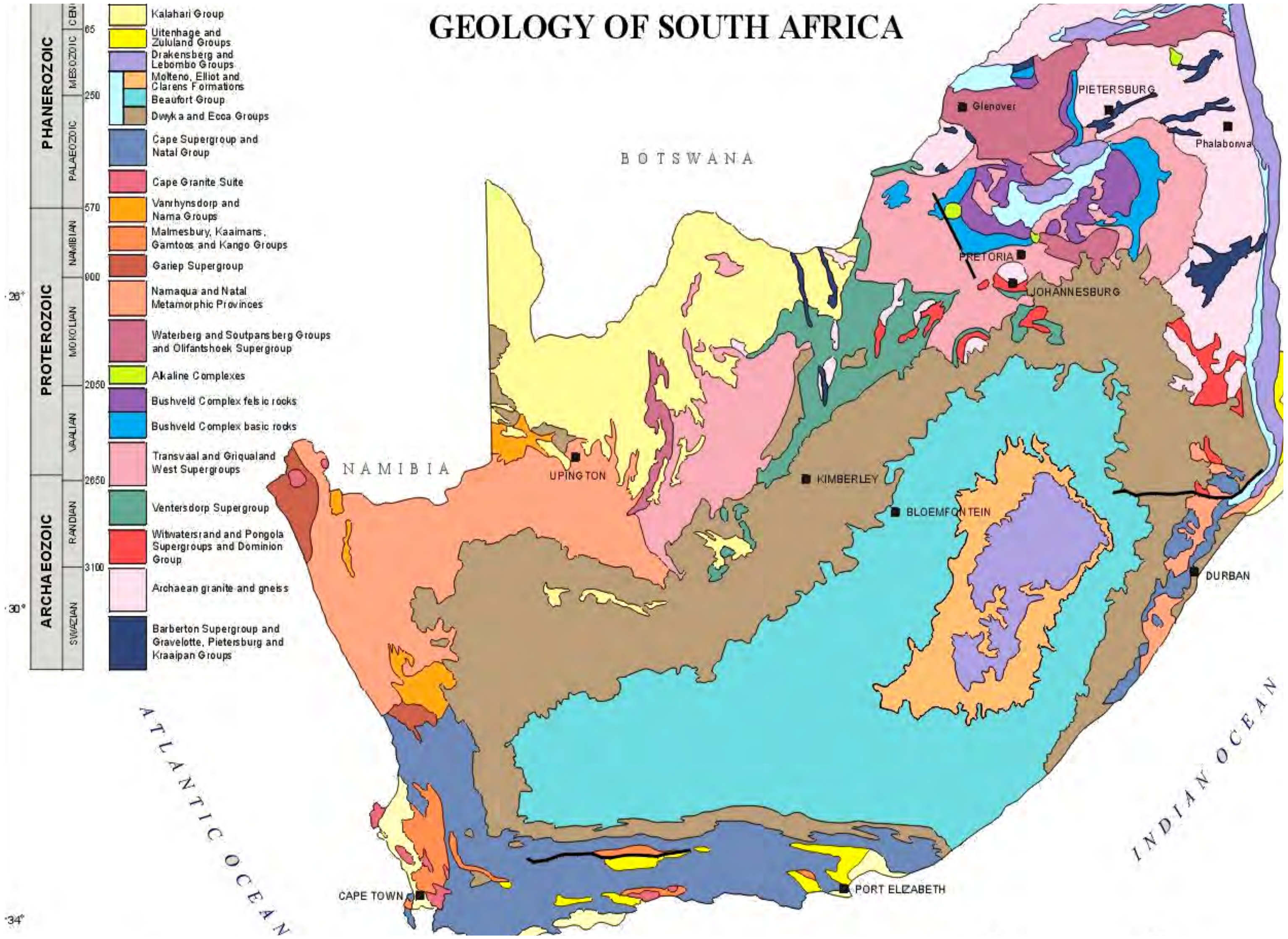
2/ Tectonic maps and structural profiles show the distribution of deformation-related structures such as faults and shear zones, foliations and lineations, distribution of fold axes, strain magnitude etc.

3/ Structural sketch-maps are simplified geological maps in which rock formations are grouped in packages separated by unconformities, each group sharing the same tectonic history.

4/ Block diagrams, tectonograms: Illustrative 3D representation of structures.

[Watch Gallery 1.5 on Flickr]

Gallery 1.5 Synthesis of structural data



Geological map of South Africa.

1 of 11

Models generation and validation :

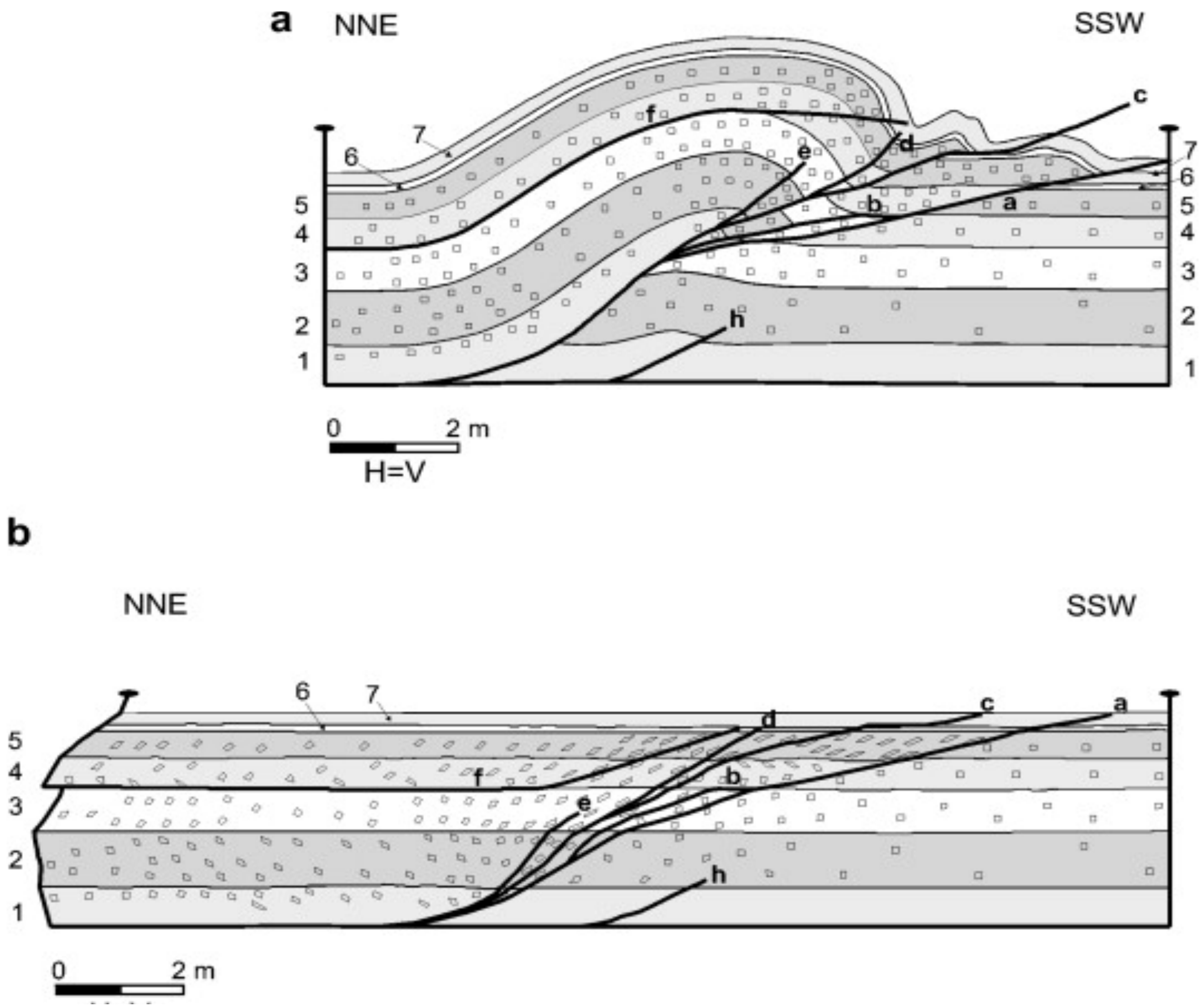
Geological maps and cross-sections are models. They combine data (measurements and observations made directly in the field, and from drill cores) and hypotheses. Indeed, in places where no rock is exposed geologists must hypothesize to fill observation gaps.

To validate maps and cross-sections geologists use the concept of surface conservation. This concept is based on the premise that a rock layer maintains its surface area during deformation. This premise holds true as long as rock formations deform with little in-bed mass transfer. A cross-section is said to be balanced (i.e. geometrically consistent) when, upon restoration (i.e. retro-deformation), lithological interfaces recover their original horizontal position, and when there is no overlap or gap.

A 4D tectonic model (3D plus time), often presented in the form of a time sequence of block diagrams, must also be thermally and mechanical consistent. Verifying both aspects requires computational modelling, which in addition to its capacity of validation presents the additional advantage to be predictive.

Watch Gallery 1.6 on Flickr

Gallery 1.6 Model Validation



Example of cross-section restoration in a fault-propagation fold (Masini et al., Journal of Structural Geology, 2010).

Who Needs Structural Geology ?

•Structural geology is at the core of hydrocarbon and mineral exploration, as structures control the migration, trapping and escape of hydrocarbon fluids. Structural geology is the first stage to any regional geophysical and geochemical surveys aiming at identifying new mineralized provinces. It is also critical for the interpretation of geophysical, geochemical, and geochronological data. At the mine camp scale, structural geology guide the mining process.

•Structural geology is at the core of geotechnical site assessment for bridges, dams, tunnels, nuclear reactors, waste disposals etc.

• Because of the obvious relationship between faults and earthquake , structural geology is that core of earthquake prevention and earthquake seismology.

•Structural geology is central to any study of past and present mountain belts and sedimentary basins. No geological, geochemical or geophysical study can be done without the input of structural geology.

What makes a good structural geologist?

•The ability to think in 3D and to solve large scale 4D puzzles.

•The ability to interact with a large range of geoscientists over a wide range of geological and environmental problems.

•The ability to link field studies to computational modelling.

Aims and Objectives

The objective of this iBook is to provide a robust and enjoyable initiation to structural geology.

Its readers will develop a good understanding of structures and microstructures that result from contractional and extensional deformation of the Earth's lithosphere. Readers will gather enough information and knowledge to learn independently from advanced Structural Geology textbooks.

This iBook covers the basics about faults, folds, shear zones and their related fabrics. We will learn to use fractures and faults to conduct paleostress analysis, a fundamental constraint for hydrocarbon and mineral exploration, as well as risk assessment in seismically active regions . We will learn to use folds, shear zones and fabrics to perform strain analysis in order to understand strain regime and strain magnitude.

Finally, this iBook will motivate its readers to go in the field and understand geology from a structural geology perspective.

Review 1.1

Question 3 of 5

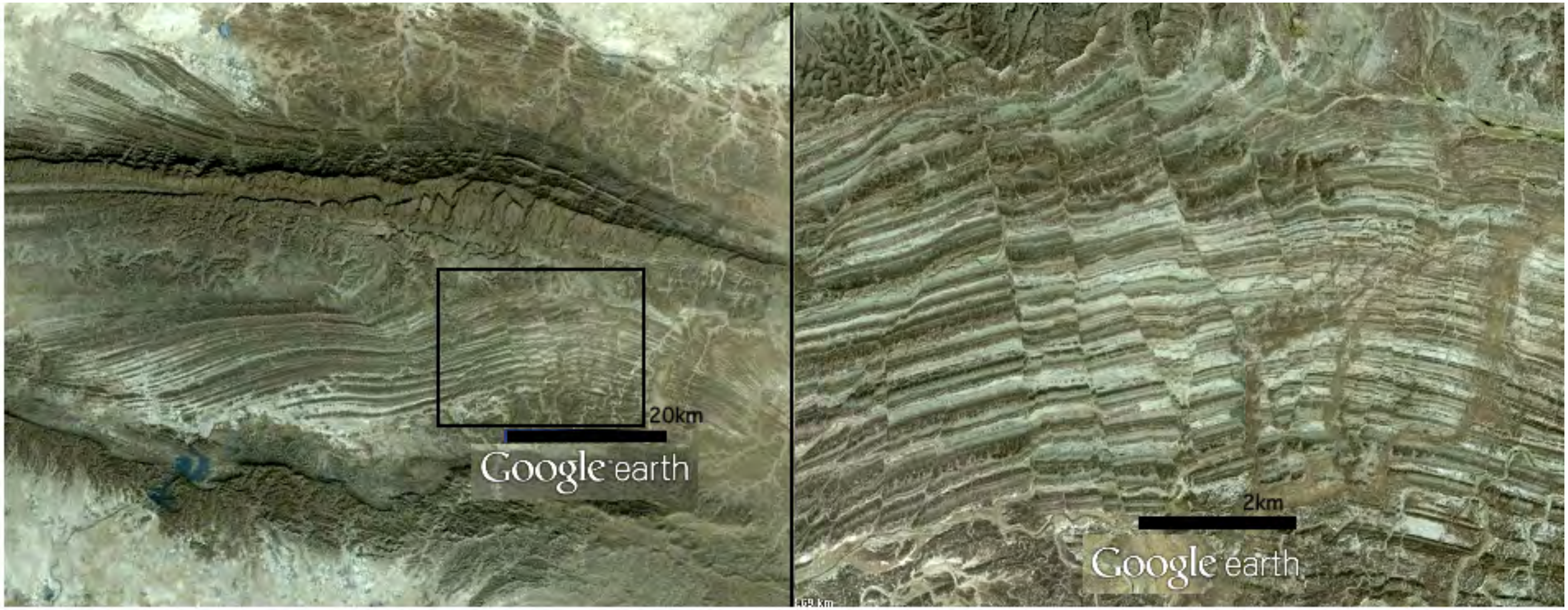
Charles Darwin developed another approach to conduct scientific investigations based on:

- ✓ **A.** The survival of the fittest scientist.
- **B.** A model to be tested, rejected or improved via experiments and observations.
- **C.** A logical construction involving assumptions and hypotheses.
- **D.** A logical construction based onfacts and only facts.

Check Answer

CHAPTER 2

Fractures and Faults



Fractures and faults are prominent in the upper part of the continental and oceanic lithosphere, where they are often associated with earthquake activity. The above Google Earth images show a fracture field in southern Pakistan (N25º35/E62º10). Open Google Earth and check for yourself how many phases of faulting you can argue for.

The Concept of Structural Level

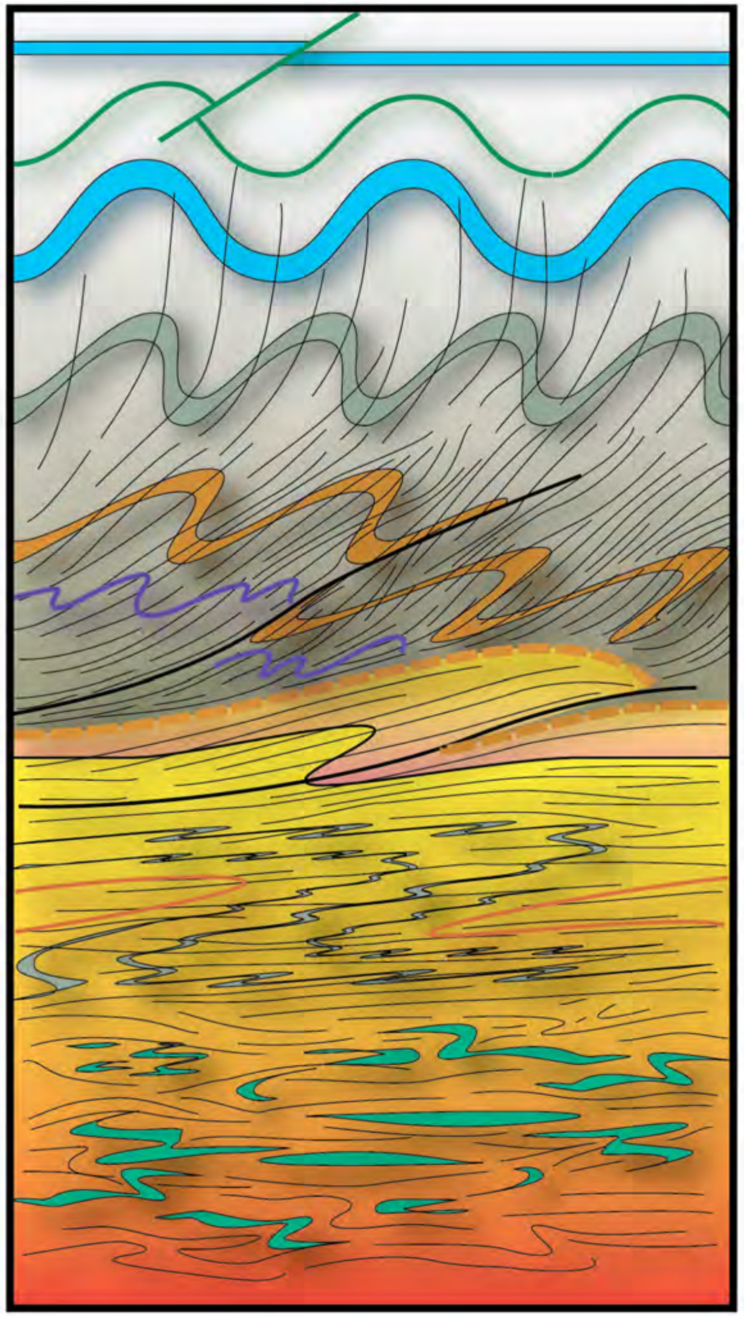
The concept of Structural Level is based on the observation that the style of deformation changes with depth due to changes in temperature and confining pressure (the product between density, depth and gravitational acceleration). With depth, strain fabrics become more pervasive, syn-metamorphic, and often sub-horizontal.

The **Upper Structural Level** (0-15km) is the domain of brittle deformation (faults and fractures), upright isopach folds, extensional fractures and stylolitic joints. Bedding and early fabrics are always recognizable.

The **Intermediate Structural Level** (10-25km) starts at the schistosity front, where cleavage begins to form. The style of folding includes: similar folds, tight folds and overturned folds with a strong axial planar schistosity. Pressure solution is the dominant cleavage-forming mechanism, quartz veins testify for dewatering of rocks due to metamorphism. Ductile deformation dominates over fracturing. Metamorphic grade does not exceed the greenschist to mid-amphibolite facies.

In the **Lower Structural Level** (>20 km) the style of deformation style includes: metamorphic nappes, large scale recumbent folds and shallow dipping ductile shear zones. Deformation is intense and pervasive, tectonic transposition makes the mapping of early fabric difficult if not impossible, fabrics are sub-horizontal. Metamorphic grades ranges from amphibolite facies to granulite facies, and partial melting is often present.

Gallery 2.1 Structures and structural level.



Illustrative structural cross-section through the continental crust (from surface to Moho) documenting the concept of structural level. Faults and fractures are prominent in the upper structural level.

1 of 13

Joints, Stylolithes and Stylolitic Joints

Joints: Planar discontinuities involving no relative displacement of the adjacent blocks. Joints develop during the exhumation of rocks following erosion of the overburden. Joints result from contraction and expansion due to cooling and decompression respectively.

Stylolites and **stylolitic joints**: Stylolitic joints are discontinuities that result from a deformation mechanism called "pressure-solution". They form through stress-induced dissolution along an irregular surface. Dissolution is triggered by stress concentration at the contact between grains. This process puts into solution molecules detached from minerals and clastic grains.

Stylolitic joints are often darker than their host rocks as iron-coated insoluble particles accumulate in the joint. In section, stylolitic joints are made of tooth-like cones. The cones axes can be either perpendicular to the joint or can make an angle, but they always point in the direction of the maximum stress at the time of their formation.

Gallery 2.2 Joints and Stylolites

Columnar jointing in a felsic volcanic. Devil Tower, Wyoming (Ph. Credit: Rosyew)

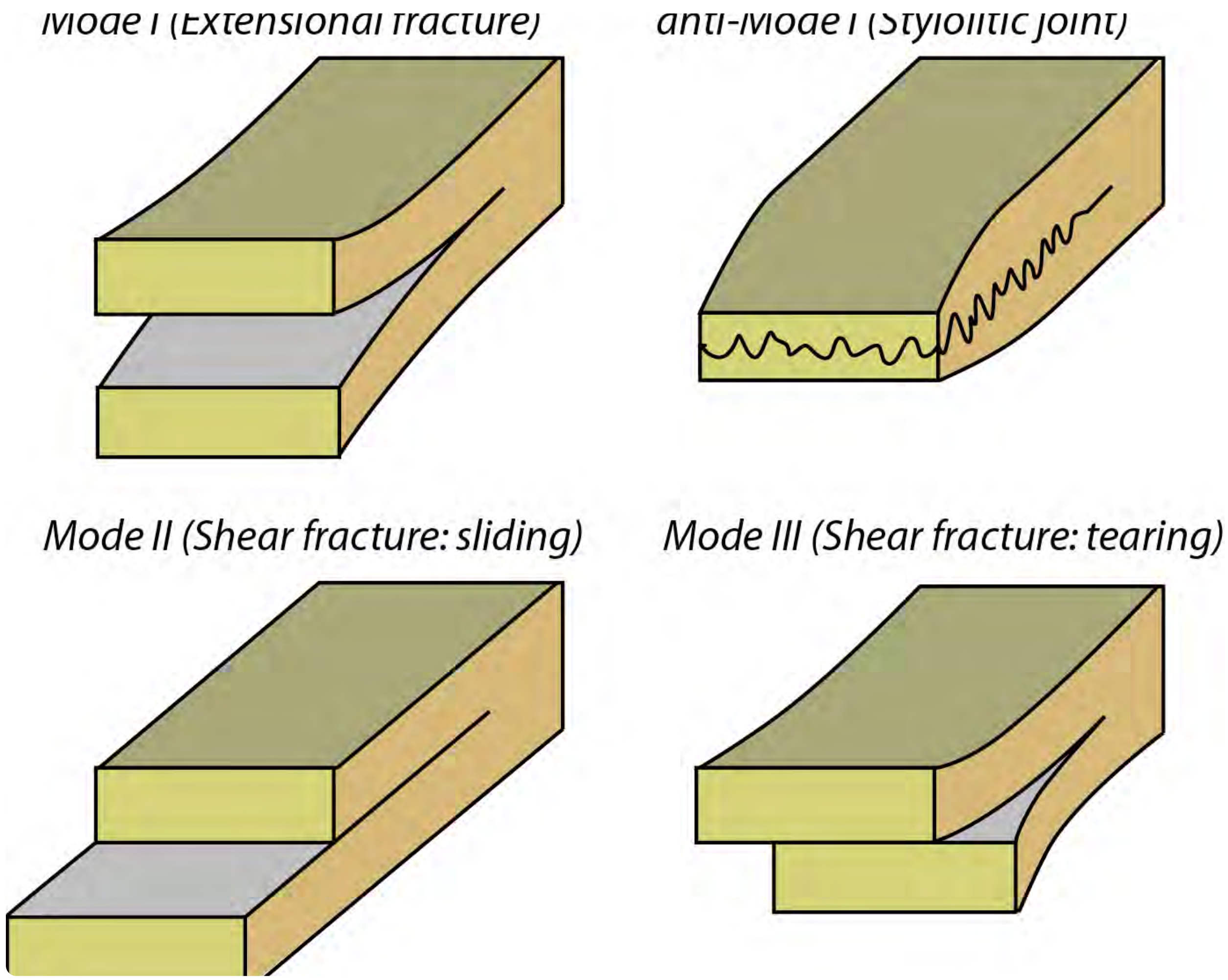
Extensional Fractures and Shear Fractures

Fractures are discontinuities with limited displacement. They form when applied stress reaches the yielding threshold, i.e. the stress at which rock fractures. There are two types of fractures classified into 3 modes:

• **Extensional Fractures** form when the adjacent blocks move away from each other in a direction sub-perpendicular to the fracture plane. The direction of opening of the fracture is parallel to that of the least resistance (i.e. the least stress). Often, extensional fractures define "en échelon" array or even "conjugated en échelon array". Extensional fractures are also known as “tension gashes”. Very often these fracture are cemented with minerals that precipitate from the solution filling the rock’s pore space. Quartz in silica-rich rocks and calcite in carbonate-rich rocks commonly seal the fractures.

Extensional fractures and stylolitic joints are often associated and form Mode 1 and anti-Mode 1 of fracturing. Together they reveal the orientation of the three principal stress axes. This micro-structure association forms the basis of paleostress analysis, which consist in mapping stress trajectories.

Gallery 2.3 Extensional Fractures

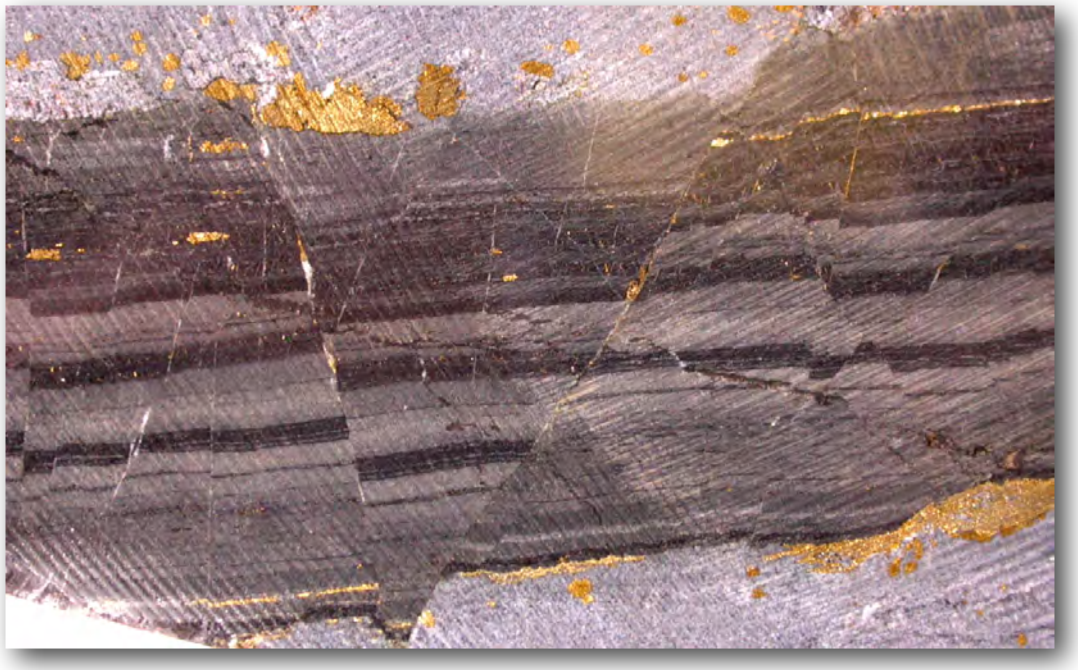


Fractures are classified into 3 main modes:

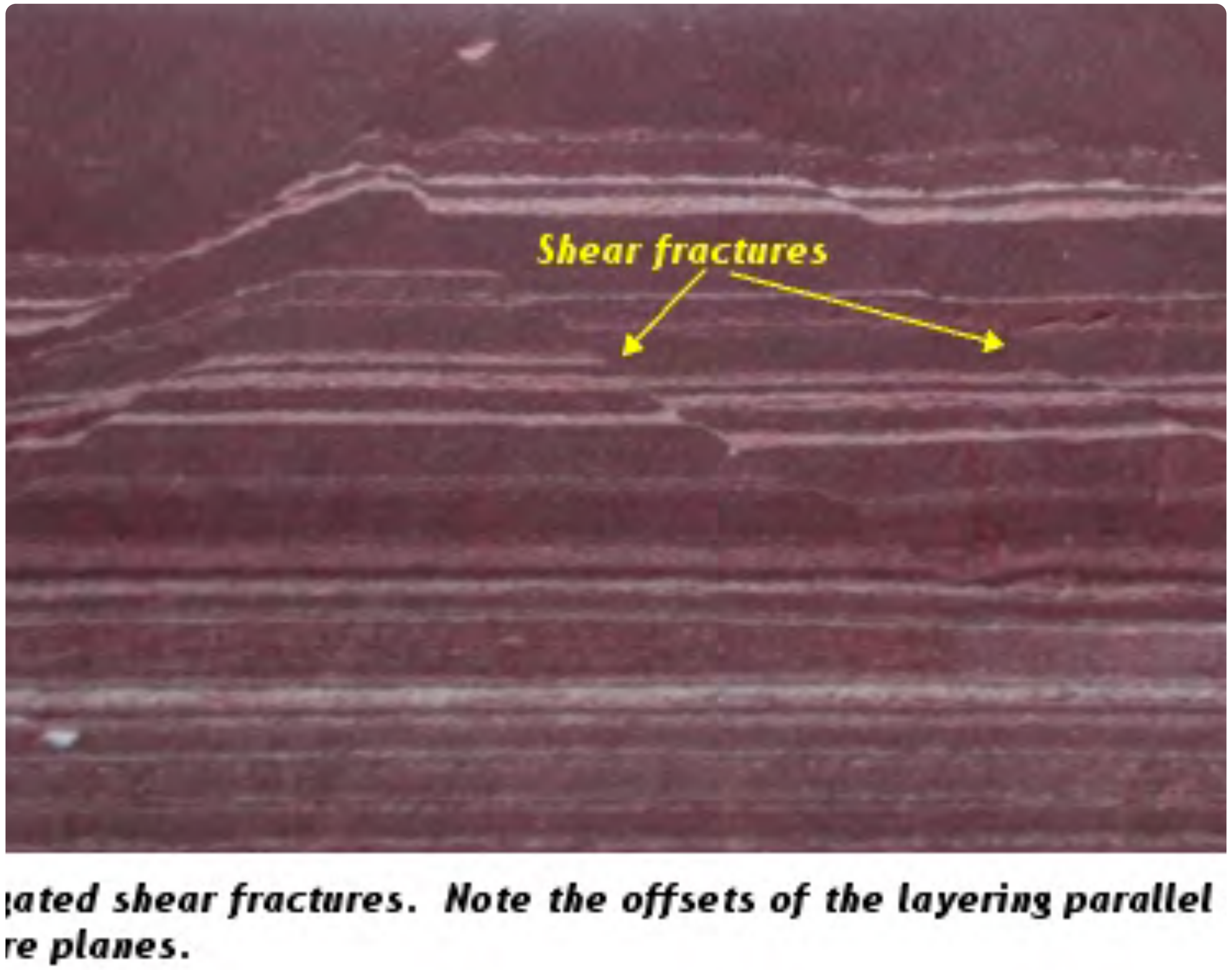
1 of 12

• **Shear Fractures** involve displacement of adjacent blocks parallel to the fracture plane. As adjacent blocks slip along each others deformation affected the region of contact (i.e. damage zone). Drag folds and small offset in pre-existing layering in the damage zone help to infer the kinematic of shear fractures. In structural geology we called "kinematic of a fault" or "kinematic of a shear fracture" the relative sense of motion parallel to the discontinuity.

• Shear fractures exist at any scale from microns to hundreds of kilometers, and are often seismogenic (i.e. they are associated with earthquakes).



Gallery 2.4 Shear Fractures



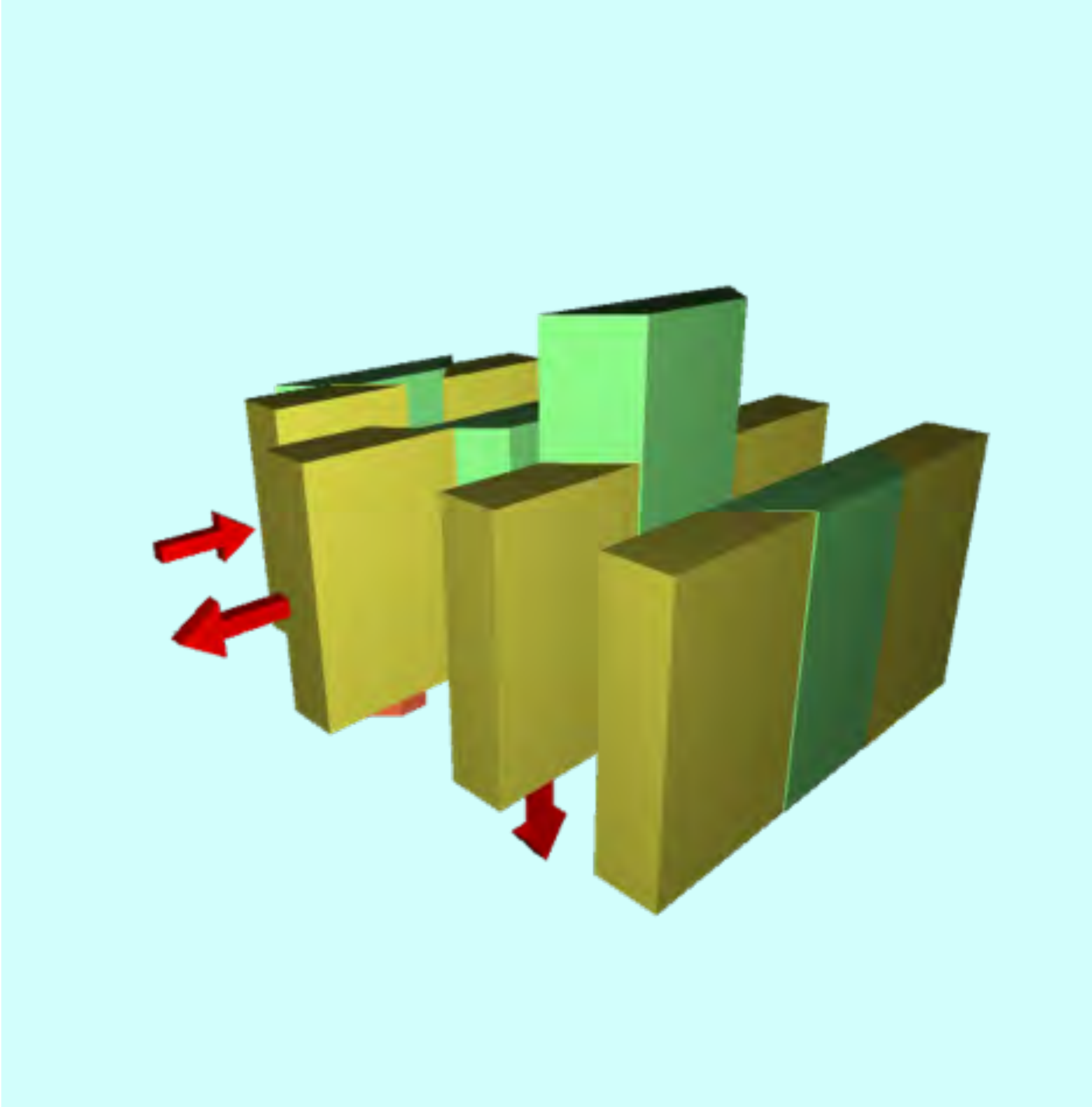
Micro-scale shear fracture in a finely laminated shale (length of the photo is about 4 cm, Photo credit: P. Rey)...

Faults and Tectonic Regimes

•**Faults**: A fault is a fracture across which two blocks have slipped; the displacement of adjacent blocks is parallel to the fault plane. Faulting corresponds to the brittle failure of an undeformed rock formation or, alternatively, involves frictional sliding on a pre-existing fault plane. Faulting occurs when the maximum differential stress (i.e., maximum stress σ_1 minus minimum stress σ_3) exceeds the shear strength of an intact rock formation, or the frictional strength of a pre-existing fault.

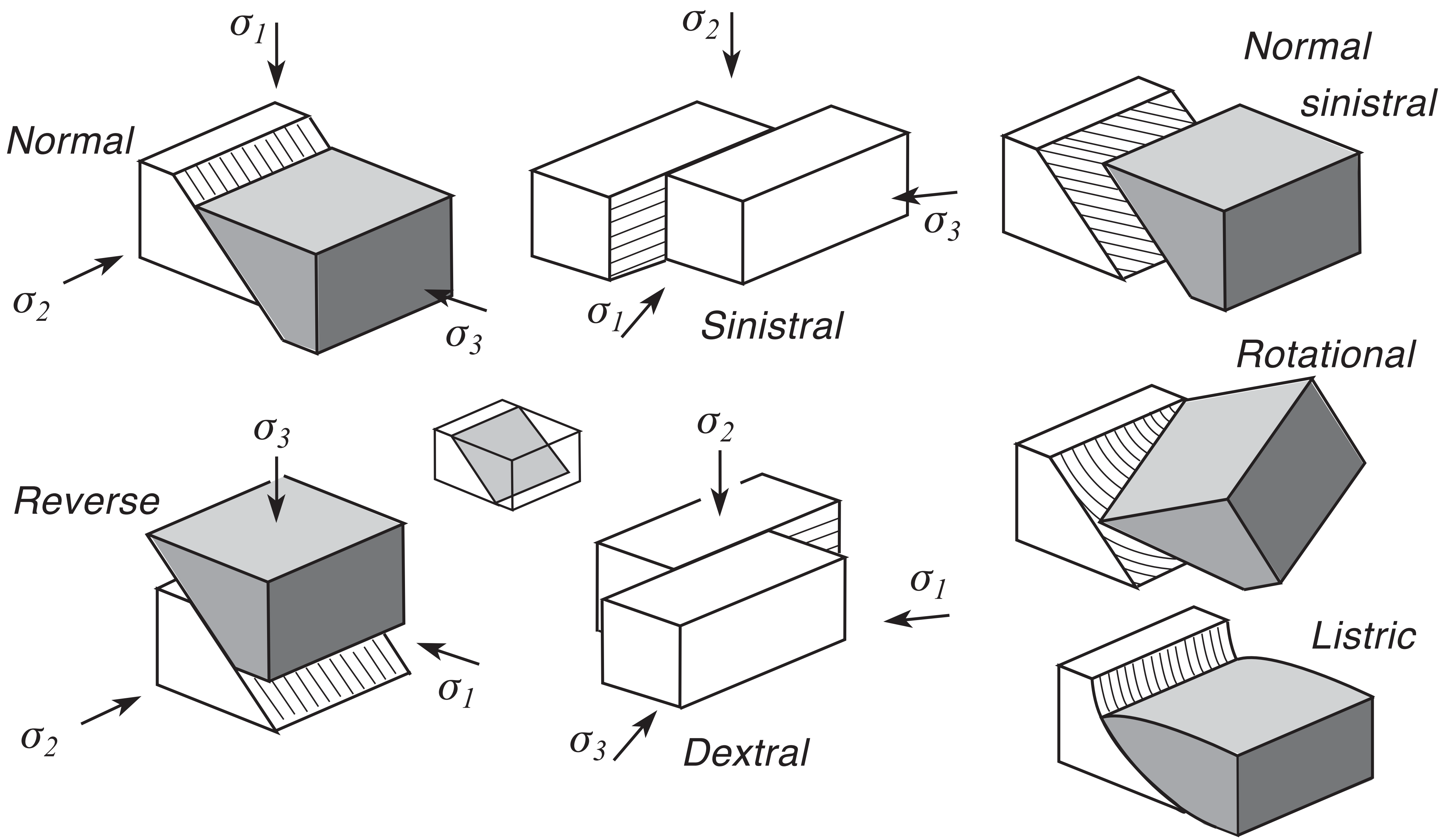
•**Fault types**: There are three types of faults.
Normal faults: the hanging wall moves down dip relatively to the footwall. Normal faults dominates in **extensional tectonic regime** (the maximum stress σ_1 is vertical).
Reverse faults: the hanging wall moves up dip relatively to the footwall. Reverse fault are common in **contractional tectonic regime** (the minimum stress σ_3 is vertical).
Strike-slip faults (dextral or sinistral): the blocks move horizontally past one another. Strike-slip faults often indicate a **transcurrent tectonic regime** (the intermediate stress σ_2 is vertical).

Interactive 2.1 Faults and fault blocks



Three tectonic regimes.

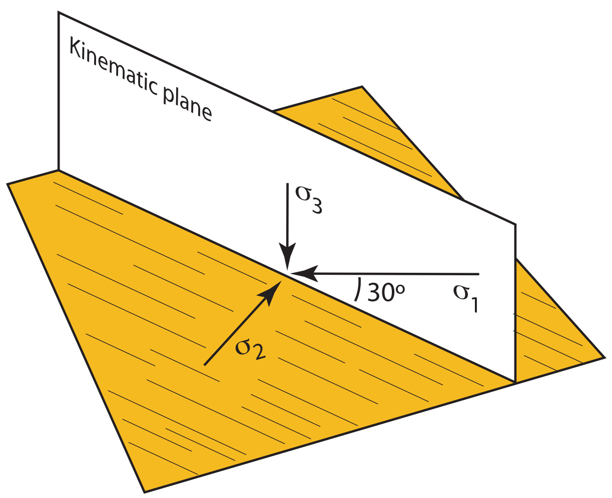
These sketches illustrate various examples of faults. In the simple cases of normal, reverse and strike-slip faults, one of the principal stress axes is vertical, in which case the stress regime is said to be **Andersonian**. The geometry of faults can however be a bit more complicated. The slip direction can be oblique to the strike of the fault (e.g., fault kinematic can be either normal sinistral, normal dextral, reverse sinistral or reverse dextral). The offset can vary along strike, the fault is said to be rotational and described as a scissor fault. Finally fault planes are not always planar surfaces and can be curved. A listric fault has a dip that decreases with depth.



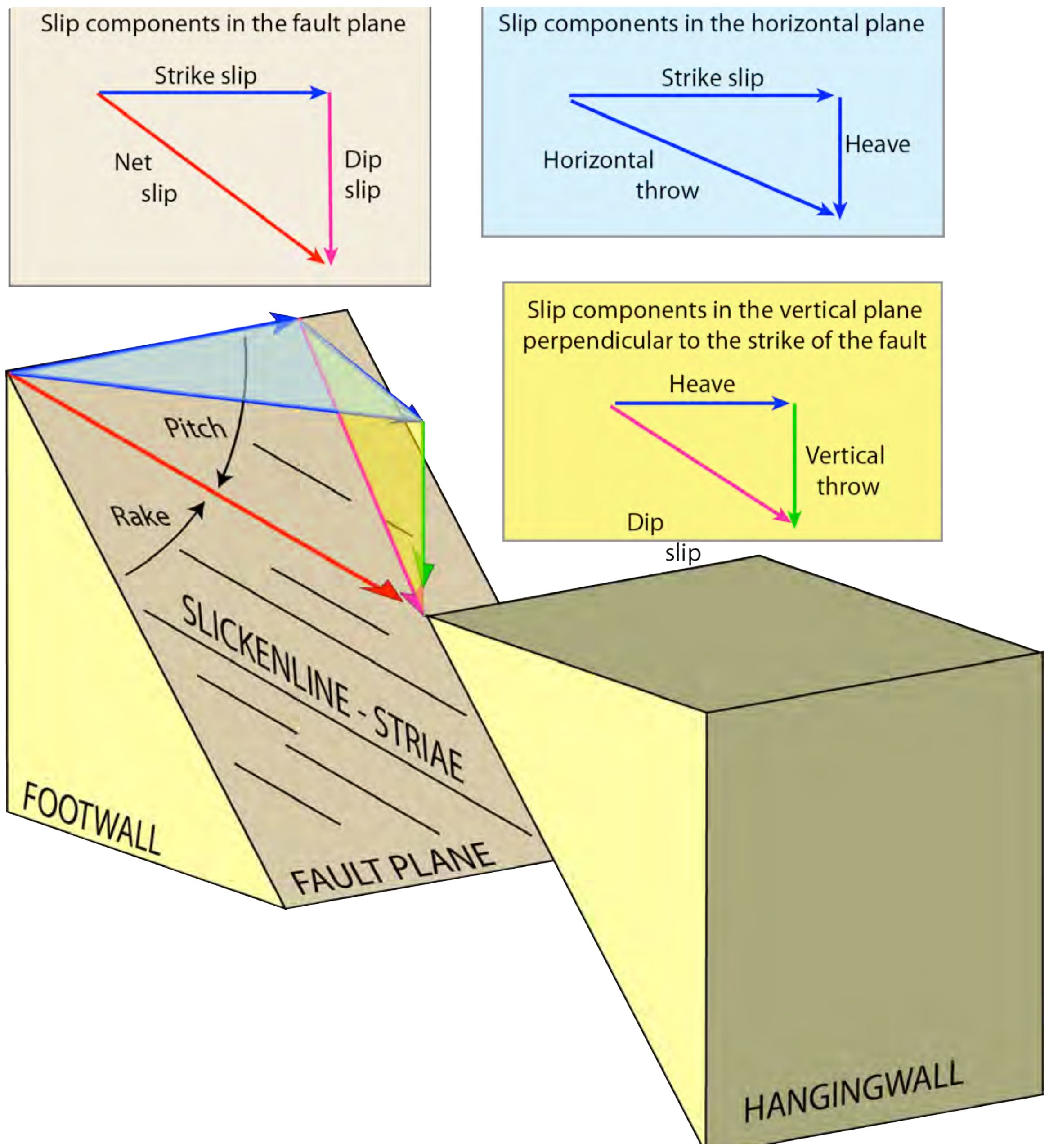
Measuring Fault Slip

Structural geologists are interested in “faults kinematic". In other word they want to found out the relative sense of motion of blocks on either side of faults, as well as in the orientation and amplitude of the slip. Fault slip is characterized by a vector called the net slip. Its direction is that of the slip and its length is the amplitude of the slip. On a fault plane the direction of the net slip is often given by striae (friction mark). The net slip can be decomposed into either 1/ two orthogonal components on the fault plane (strike-slip and dip slip components); or 2/ two orthogonal components in the vertical plane that contains the net slip vector (horizontal heave and vertical throw), or 3/ three orthogonal components in the geographic system (strike slip, heave, and vertical throw).

The "kinematic plane" is the plane which is perpendicular to the fault plane and parallel to the net slip vector (ie the striae). For newly form faults the kinematic plane contains the principal stress axis σ_1 and σ_3 with σ_1 at 30° from the fault plane.



Gallery 2.5 Slip vector and striae



The net slip vector and its components.

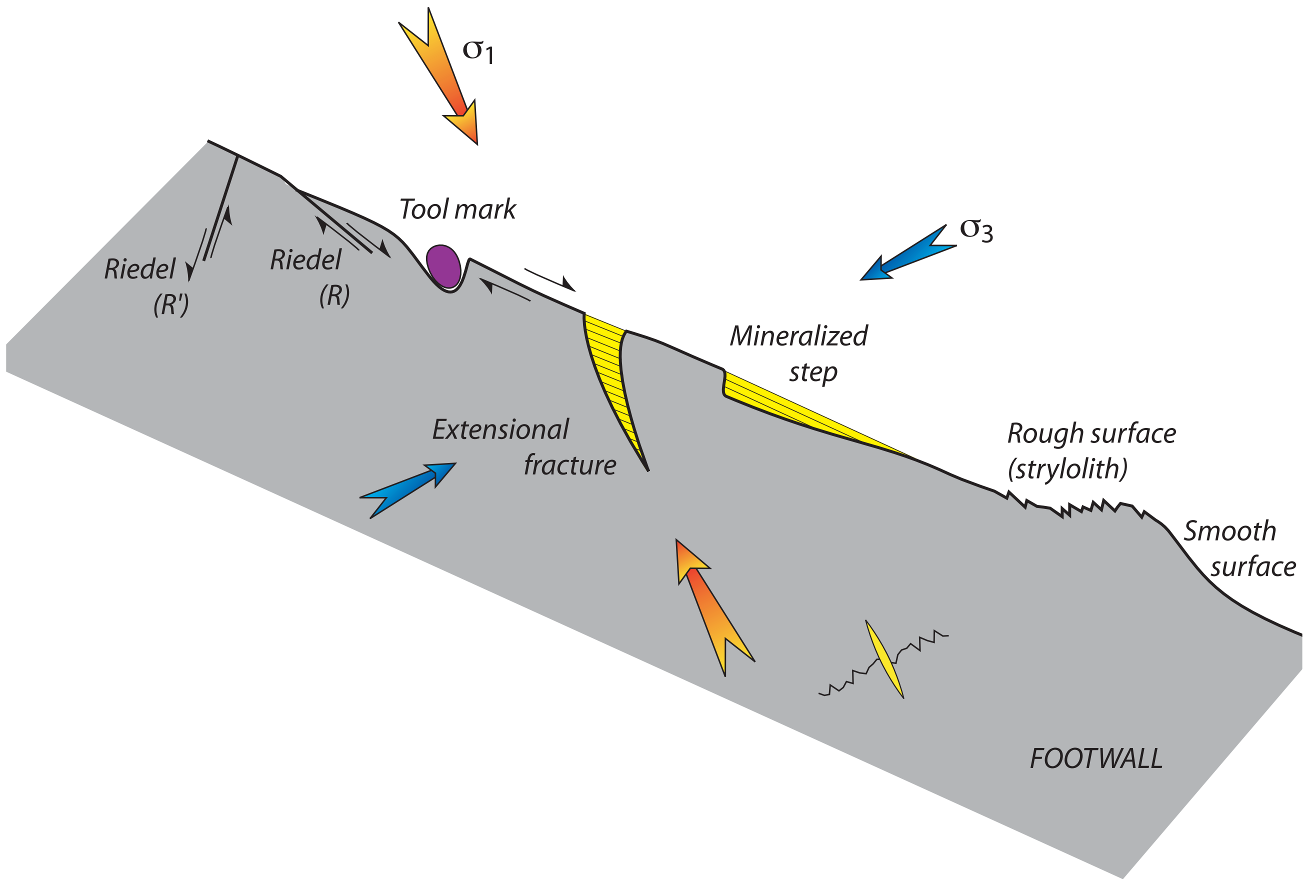
Fault Kinematic Analysis

Kinematic analysis is the art to figure out the relative sense of motion across faults and shear zones.

To do this, structural geologists use "kinematic criteria" i.e. structures and microstructures that develop during faulting and whose geometric characteristics depend on the sense of shear.

The main kinematic criteria for brittle faults are:
1/ **Riedel shear fractures** (R and R'): R are synthetic at 10-15° to the fault plane; R' are antithetic (opposite sense of shear) and oriented at 70-80° to the fault plane.
2/ **Tool marks**: Cavities formed by the mechanical erosion of the fault plane by hard inclusions.
3/ **Extensional fractures** at ca. 30° angle to the fault plane.
4/ **Mineralized steps**: Step-shaped cavities filled with fibrous minerals (often quartz or calcite).
5/ **Dry steps**: same as above but with no crystallization.
6/ **Rough surfaces** (usually with strylolith) form due to pressure solution, and smooth (or polished) surface .

Gallery 2.6 Kinematic analysis



Kinematic criteria shown on a cross-section through a fault. Only the footwall block is shown.

A Little Quiz …

1/ Define the following terms: a fact, an hypothesis, a model, a theory and a law.

2/ Define the Darwinian scientific method.

3/ A scientific model should always verify a number of characteristics. What are they ?

4/ How do stylolitic joints form?

5/ What are the two main type of fractures?

6/ Draw a stylolite / extensional fracture association and give the orientation of the principal stress axes.

7/ What are the three main types of faults?

8/ Describe the three modes of fractures?

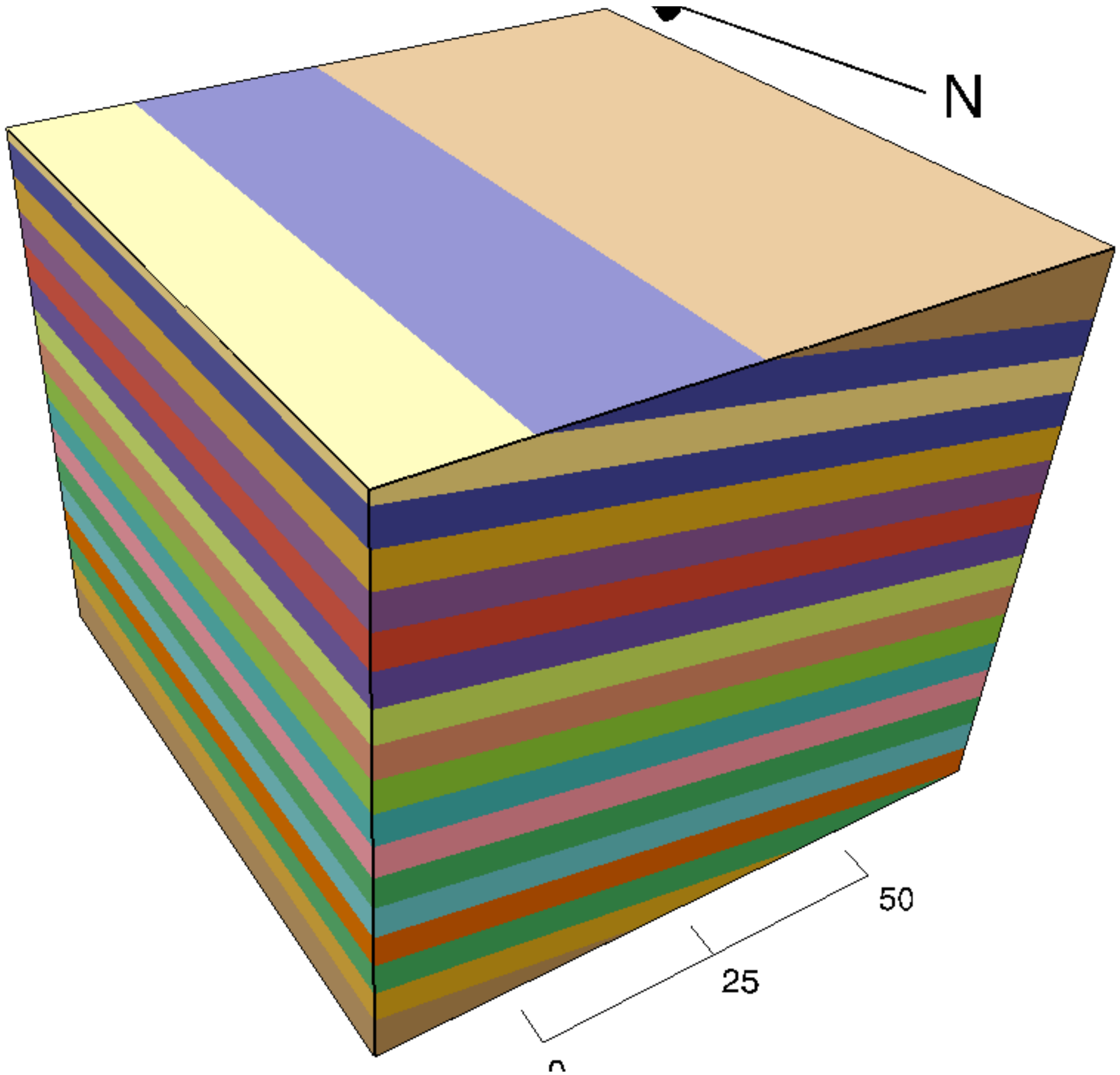
9/ Define the following concepts: a/ A listric fault.
b/ The kinematic plane.

10/ Define the following concepts: Vertical and horizontal throw, the heave, the net slip?

The picture below shows a cemented breccia, it is the result of faulting. The rock crumbled into a numerous angulous clasts. A silica-rich fluid circulated through the fault zone precipitating quartz that cemented the clasts together.

A LITTLE BRAIN TWISTER ...

Gallery 2.7 Mind the gap !



Produced with http://www.visible-geology.appspot.com/

A sedimentary rock formation is gently tilted to the east...

Review 2.1

Question 1 of 7

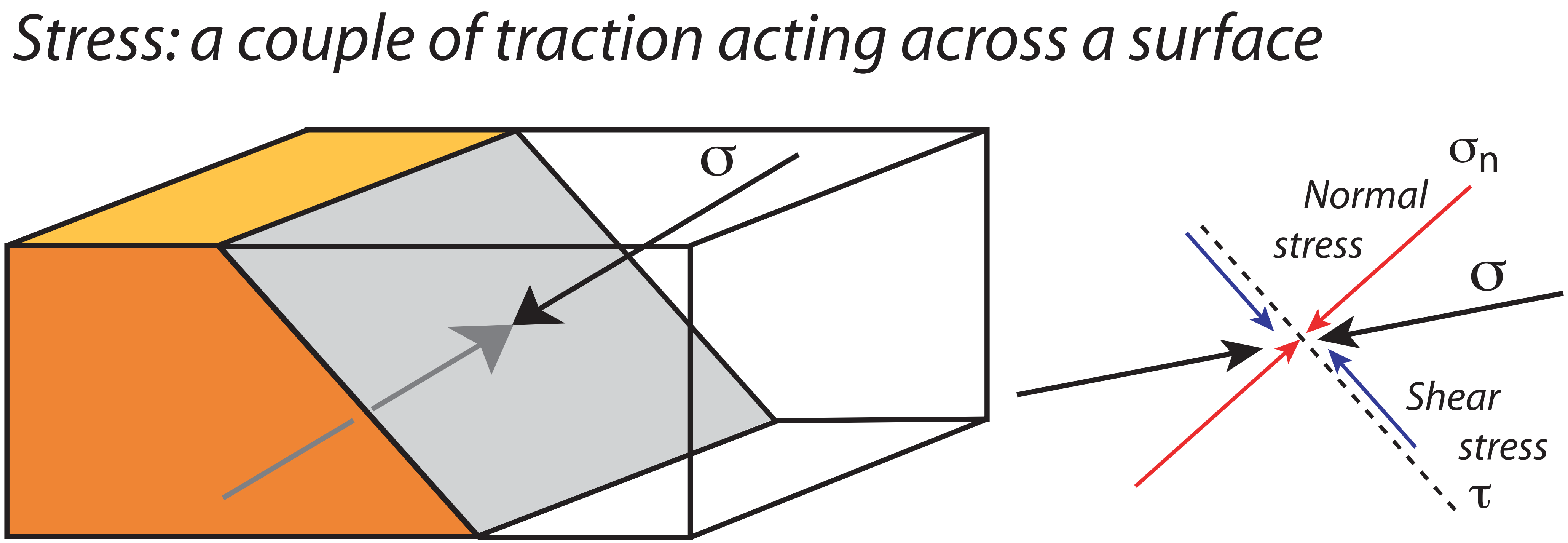
The concept of "*structural level*" refers to:

- **A.** The level of structural complexity.
- **B.** The partitioning of strain style with depth.
- **C.** The boundary between brittle deformation and ductile deformation.
- **D.** The number of phase of deformation.

Check Answer

CHAPTER 3

Force, Traction and Stress



We have seen, in the former chapter, that the orientation of newly formed (as opposed to reactivated) faults and fractures can be easily used to infer the orientation of the principal stress axes that produced faulting. At this point we need to clarify the concepts of force, traction and stress. Forces, tractions, and stresses are the causes for deformation.

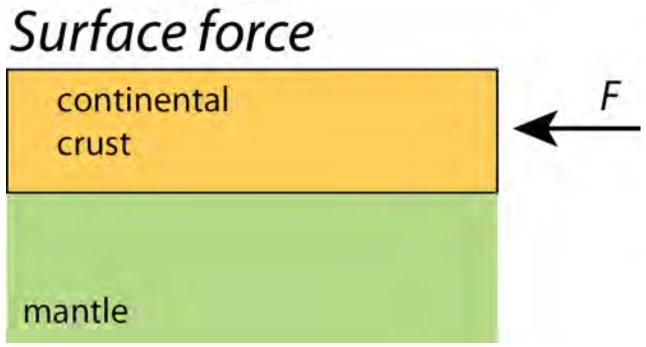
The Concepts of Force and Traction

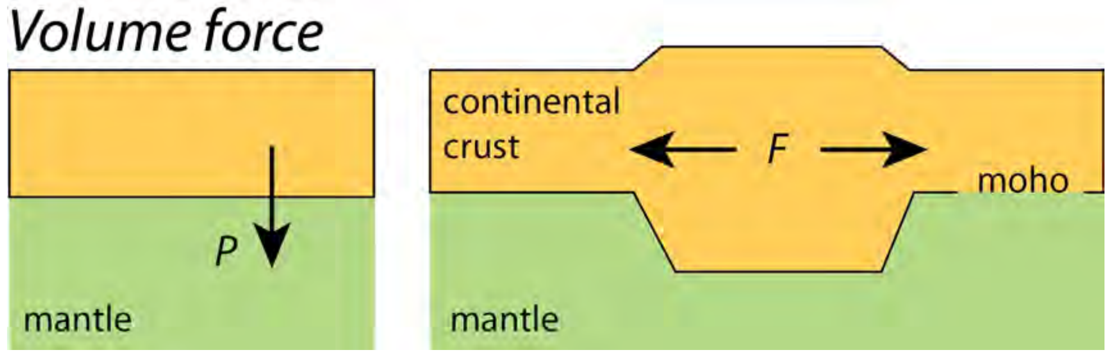
According to Newton's second law of motion, a force is a physical entity which tends to change either the state of rest or the uniform motion in a straight line of a body. A force is described by a vector, its SI unit is the Newton (N). Its magnitude is equal to the rate of change of momentum of the body. The force $\boldsymbol{F}$ producing the acceleration $\boldsymbol{a}$ (m . s^{-2}) of a body of mass $\boldsymbol{m}$ (kg) is therefore given by: $\boldsymbol{F} = \boldsymbol{m}.\boldsymbol{a}$. Hence, a force of 1 Newton accelerates a 1 kg object by 1 m per second per second.

There is two types of forces:

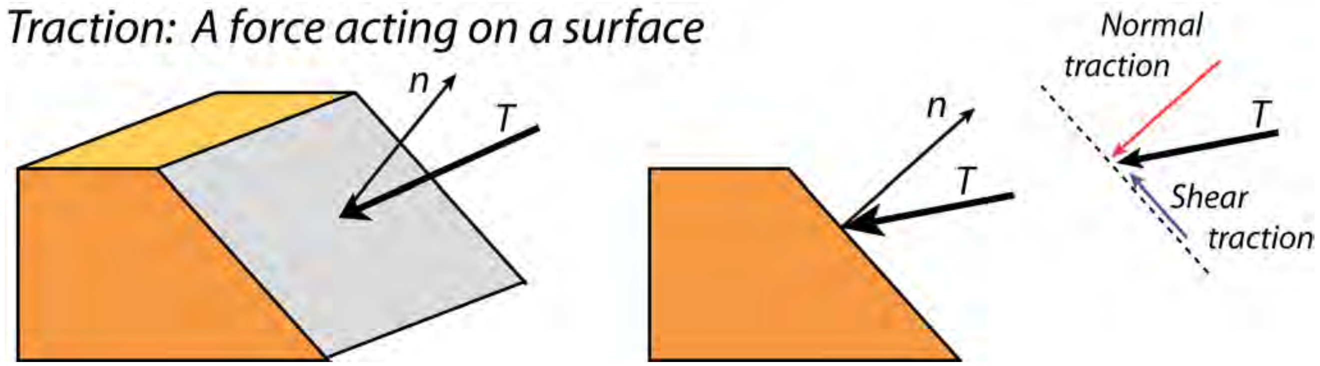
Surfaces forces act on the surface of a body. For instance the tectonic forces (e.g. ridge push and slab pull) acting on a lithospheric plate are surface forces, they are often called external forces.

Body forces act inside the body, they are often called internal forces. In a lithospheric plate, body forces arise due to gravity pulling every molecules toward the center of the Earth (P), and heterogeneities in density (e.g. lateral density changes due to crustal thickening).





The concept of **Traction**: In mechanic, a traction is a pressure vector that represents the limit of the ratio of force over area as area tends to zero. This force can have any orientation with respect to the surface. A traction is represented by a vector whose orientation is that of the force and its magnitude the ratio of the force (N) over the area (m^2) of the surface. The unit of a traction is therefore that of pressure: N.m^{-2}. Tractions can be decomposed into a shear component (parallel to the surface) and normal component (normal to the surface).



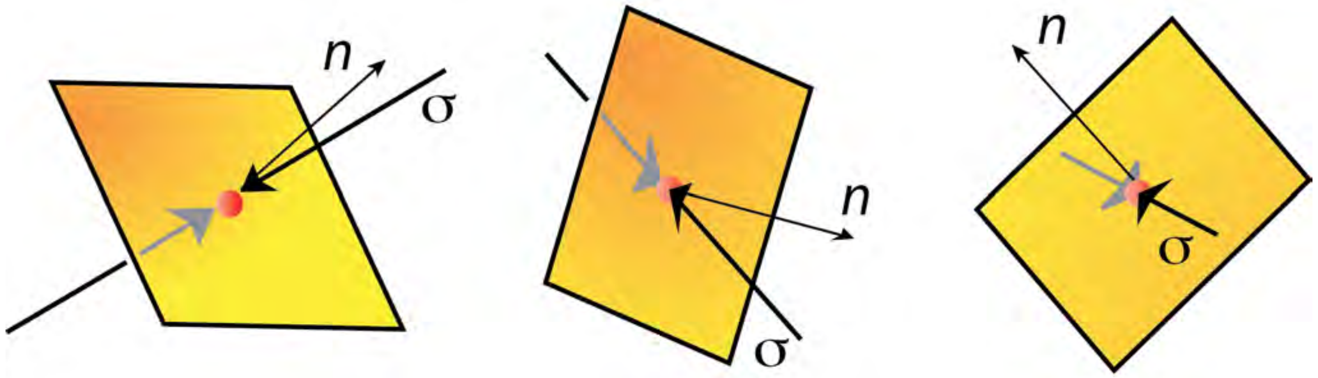
The Concept of Stress

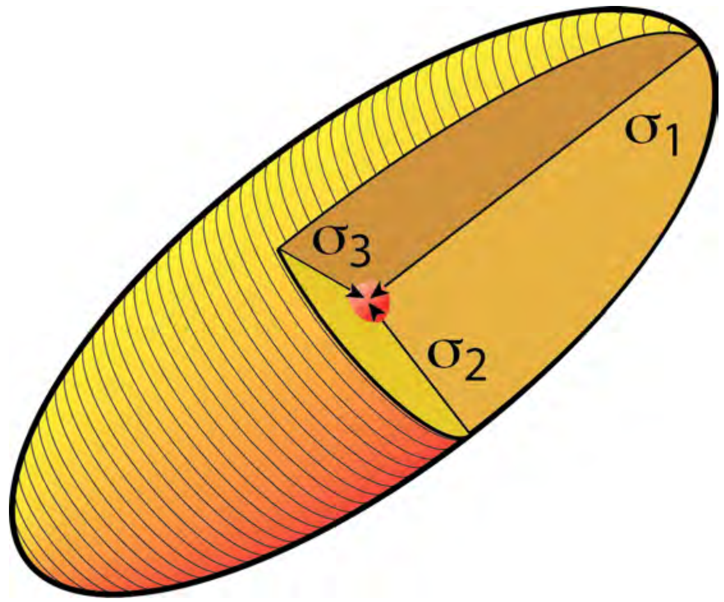
In a volume of rock, lets imagine a physical point at rest, and lets imagine a small surface centered on that point. The orientation of the small surface is characterized by its "normal" $\boldsymbol{n}$ (i.e. the vector orthogonal to the surface, the length of which is proportional to the surface area).

The stress acting across this surface is defined by the couple of traction vector acting on the opposite sides of the surface. Unbalanced tractions acting on a surface do not give rise to stress; they cause acceleration. Hence, the concept of stress applies to a body at equilibrium, - in a state of rest or uniform rectilinear motion.

Because the surface is at rest, these tractions have same magnitude (i.e. length) but opposite direction. The magnitude and orientation of the stress change with the orientation of the small surface.

If one could record the orientation and length of the stress as the orientation of the surface varies about its centre, one could see that the end tips of the stress define an ellipsoid. The **stress ellipsoid** is characterized by three principal orthogonal stresses (i.e. 3 pairs of equal but opposite tractions) σ_1, σ_2 and σ_3 with $\sigma_1 \geq \sigma_2 \geq \sigma_3$. It can be shown that there is only three positions of the surface for which the stress is perpendicular to it, and that σ_1, σ_2 and σ_3 are the **normal stress vectors**.



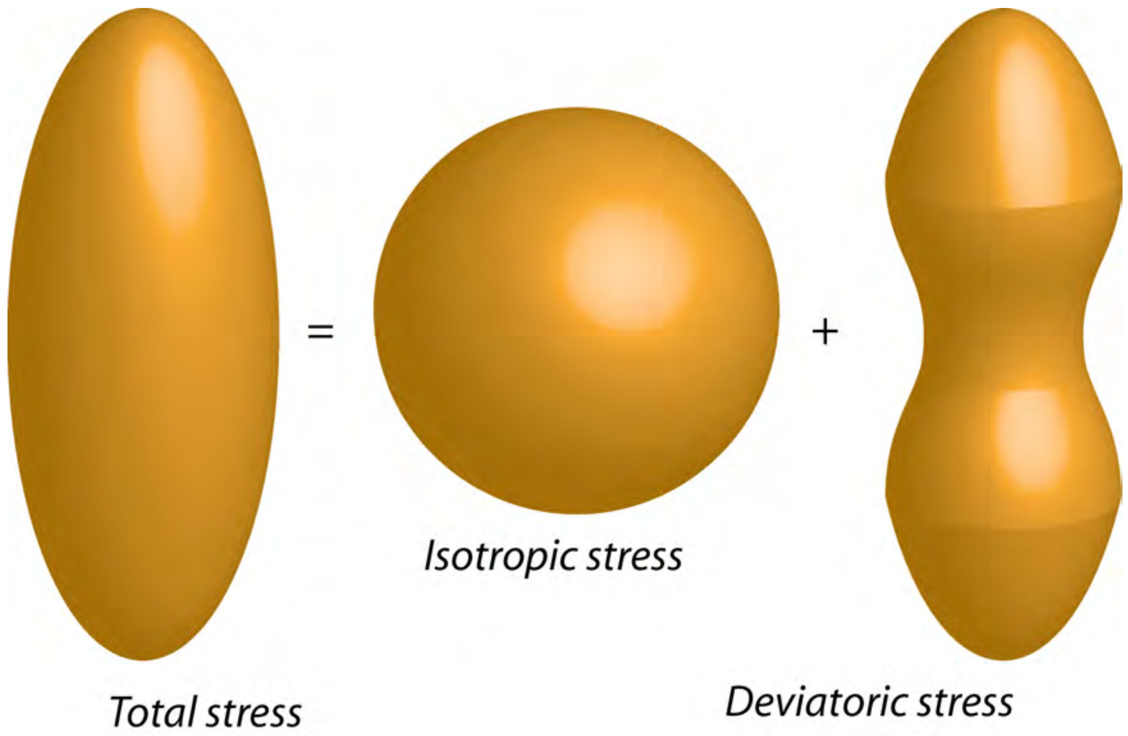


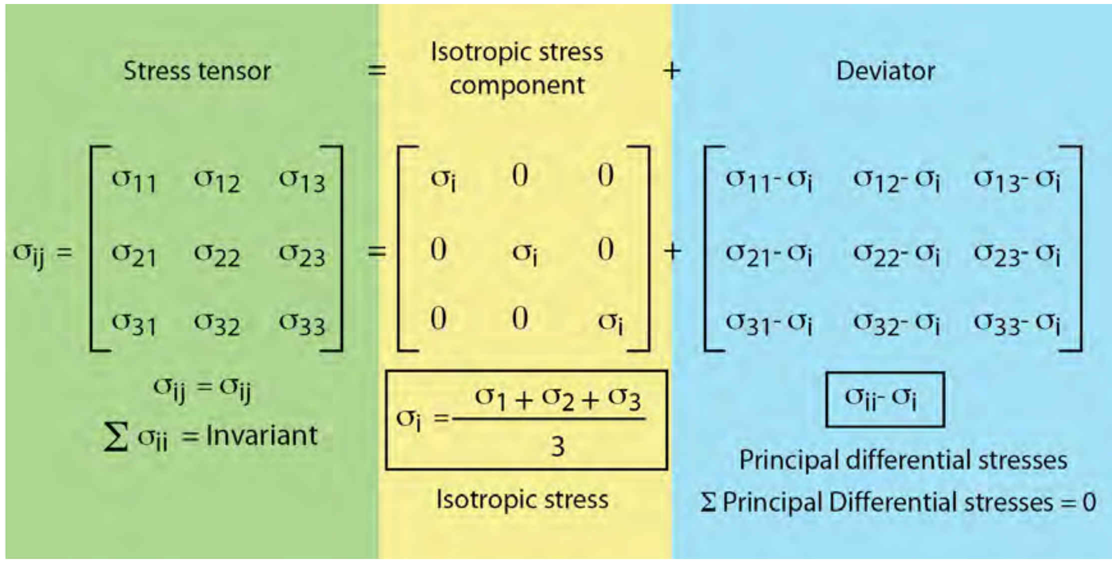
The state of stress acting on a material point is characterized by an ellipsoid called the stress ellipsoid. It is defined by three perpendicular axes called the principal stresses: σ_1, σ_2 and σ_3. All stresses are positive (i.e. directed toward the material point). Extensional structures result from material moving or flowing in the direction of least stress.

The state of stress acting on any point in the Earth's is characterized by a stress ellipsoid. The simplest stress ellipsoid is a sphere: $\sigma_1=\sigma_2=\sigma_3$. In such a case, the stresses are the same in all directions and the state of stress is **isotropic**. Such a state of stress is also said to be **hydrostatic** or **lithostatic**. The magnitude of the stress (i.e., the radius of the sphere) is simply the pressure due to the weight of the column of rock above the considered point. This pressure, often called the confining pressure, comes with the same intensity from all direction and its magnitude is given by: $\rho.g.z$, where ρ is the density, g is the gravitational acceleration and z is depth. Lithostatic pressure does not drive deformation.

When the state of stress is **anisotropic**, the stress ellipsoid can be decomposed into an **isotropic stress** component of magnitude $\sigma_i = (\sigma_1+\sigma_2+\sigma_3)/3$, and a **deviatoric stress** component that accounts for the difference between the **total stress** and the isotropic stress. The deviatoric stress component is responsible for deformation.

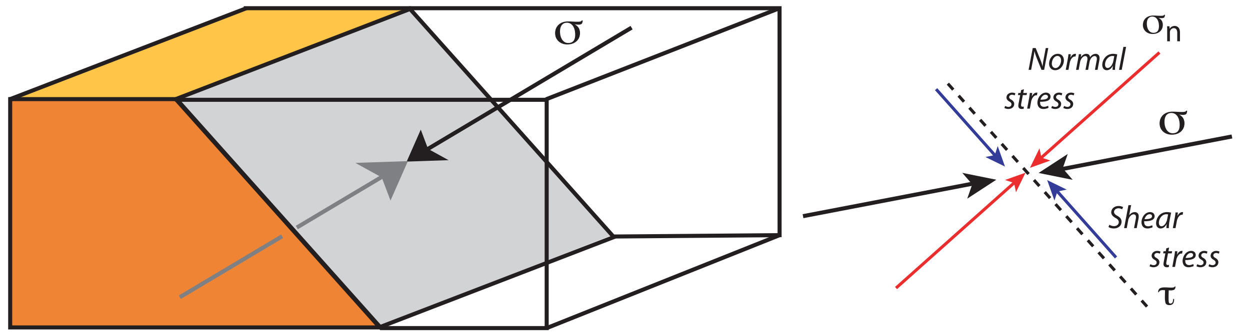
Mathematically the state of stress is a 2nd order tensor (9 components). This tensor is symmetric ($\sigma_{ij}=\sigma_{ji}$) and the sum of its diagonal components ($\Sigma\sigma_{ii}$=constant) is invariant (the value of each component changes as one changes the coordinate system, however $\Sigma\sigma_{ii}$ is independent of the coordinate system). This tensor can be decomposed into an isotropic component and a deviator. It is always possible to choose a coordinate system so that the tensor is reduced to its principal stress components: i.e.: σ_{ij}=0, and $\sigma_{11}=\sigma_1$, $\sigma_{22}=\sigma_2$, $\sigma_{33}=\sigma_3$.





The stress acting on a pre-existing fault plane is represented by a couple of traction vectors having similar magnitudes (i.e. length) but opposite directions. For convenience, this stress can be decomposed into a **shear stress component (τ)**, and **normal stress component (σ_n)**. Both are represented by a couple of vector. The normal stress tends to prevent faulting by pushing both blocks towards each other. In contrast, the shear stress promotes faulting.

Stress: a couple of traction acting across a surface



From experiments we observe that for a newly formed fault (i.e. developed from a fracture-less volume of rock):

1/ σ_1, n and σ_3 are always within the same plane. This plane is called the **kinematic plane**.

2/ Shear stress and normal stress also belongs to the kinematic plane.

3/ The **slip vector** on the fault plane is parallel to the shear stress.

4/ The angle between the fault plane and σ_1 is close to 30°.

If pre-existing faults exist then it is possible that these faults will slip before new faults are created. In the case of fault reactivation, one can observe from experiments that for a given fault orientation, and for a given state of stress defined by σ_1, σ_2 and σ_3 :

1/ The slip vector on the fault plane (i.e. the direction of which is parallel to the striae) is parallel to the shear stress.

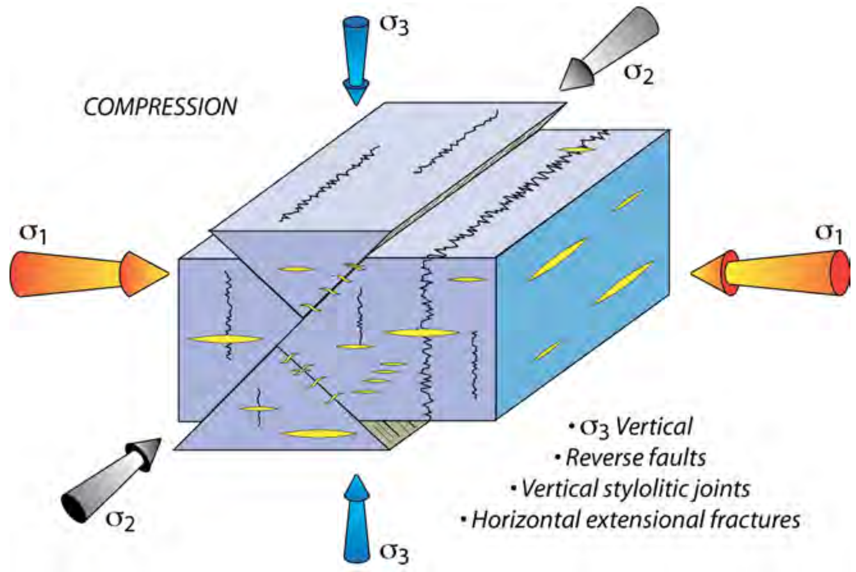
2/ The orientation of the shear stress depends on the orientation of n, σ_1, σ_2 and σ_3 and $R = (\sigma_1 - \sigma_2) / (\sigma_2 - \sigma_3)$

3/ It can be shown that for a state of stress stable in orientation, the striae can take any orientation depending on R.

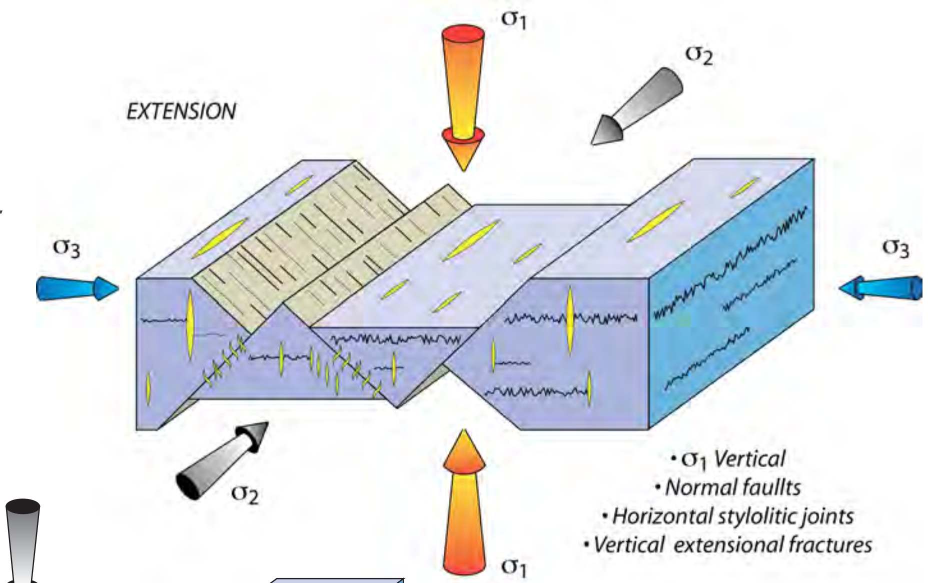
Therefore, one can infer from the processing of a large number of faults/striae/kinematic data, the orientation in space of the stress ellipsoid responsible for faulting, as well as the ratio R of the stress ellipsoid.

Introduction to Paleostress Analysis

The determination in the field of the orientation in space of the **paleostress ellipsoid** responsible for the development of stylolites, fractures and faults is relatively easy. We have seen previously that there is a simple set of relationships between the orientation of the paleostress ellipsoid and the orientation of stylolitic joints, shear fractures and extensional fractures that develop in response to an applied stress.

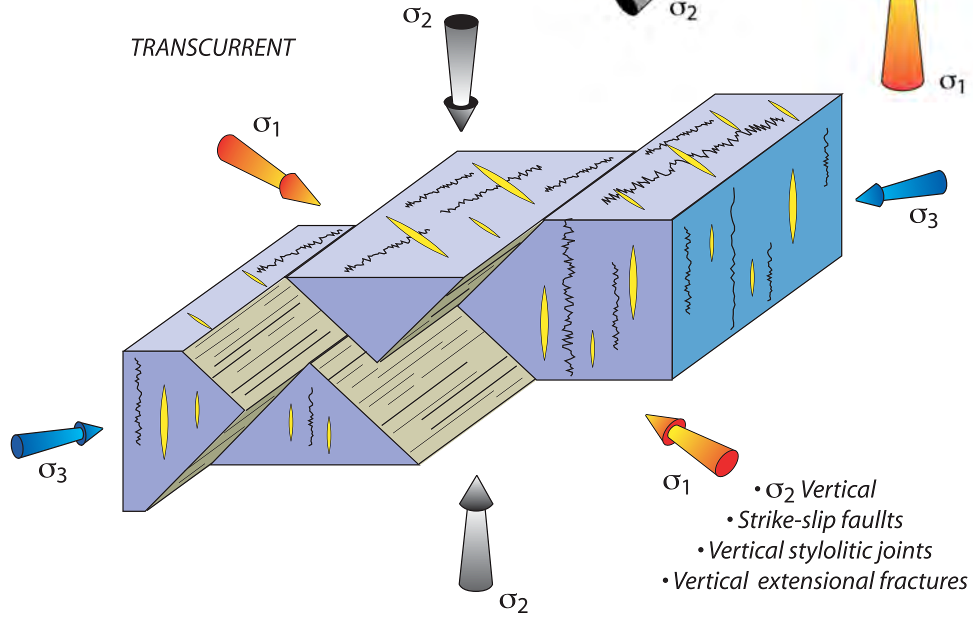


The sketch on the top right shows a set of microstructures that develop due to a tectonic regime in compression. From a stress point of view, a **compressional tectonic regime** is characterized by σ_3 being the vertical stress axis. From a strain point of view it is characterized by vertical stylolitic joints and horizontal extensional fractures.The stylolitic cones point in the direction of σ_1. The normal of the extensional fractures is parallel to σ_3. The intermediate stress σ_2 is perpendicular to both σ_1 and σ_3.



In a **extensional tectonic regime** σ_1 is vertical. Stylolitic joints are therefore horizontal, whereas extensional fractures are vertical. Note that horizontal stylolitic joints and vertical extensional fractures can also develop during the compaction of sediments during burial.

In a **transcurrent tectonic regime** σ_2 is vertical. Therefore, both stylolitic joints and extensional fractures are vertical. The stylolitic cones points in the direction of σ_1, the normal to the extensional fracture being parallel to σ_3.

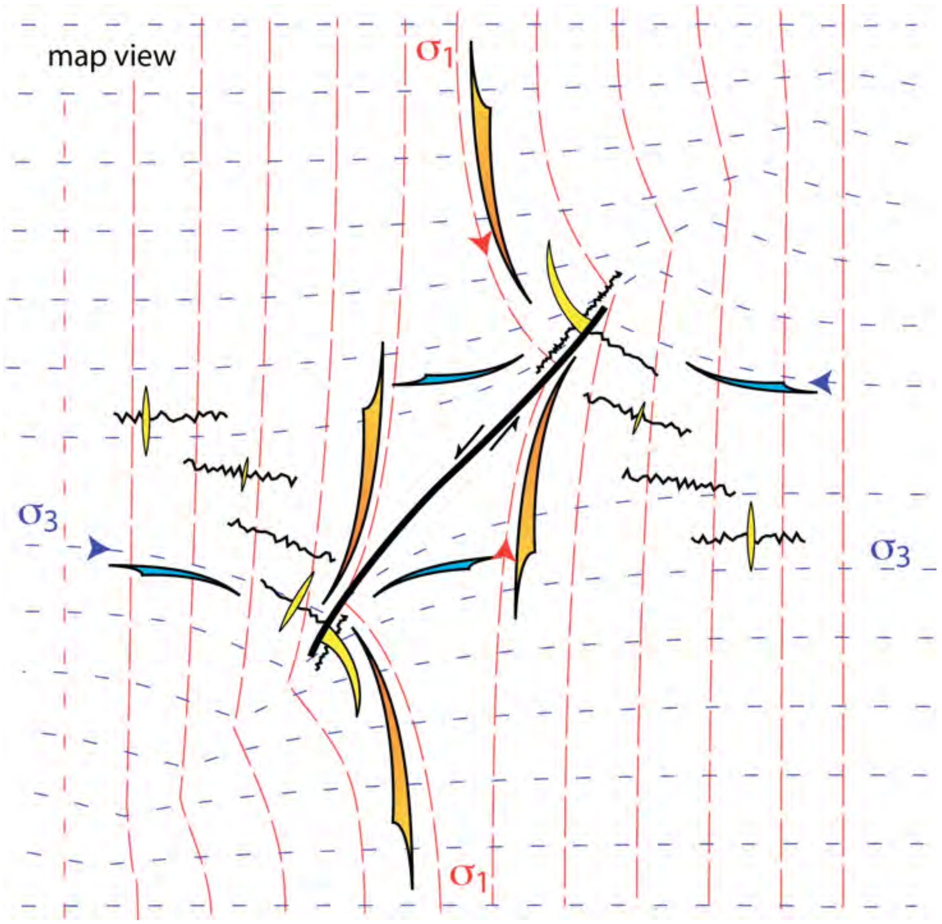


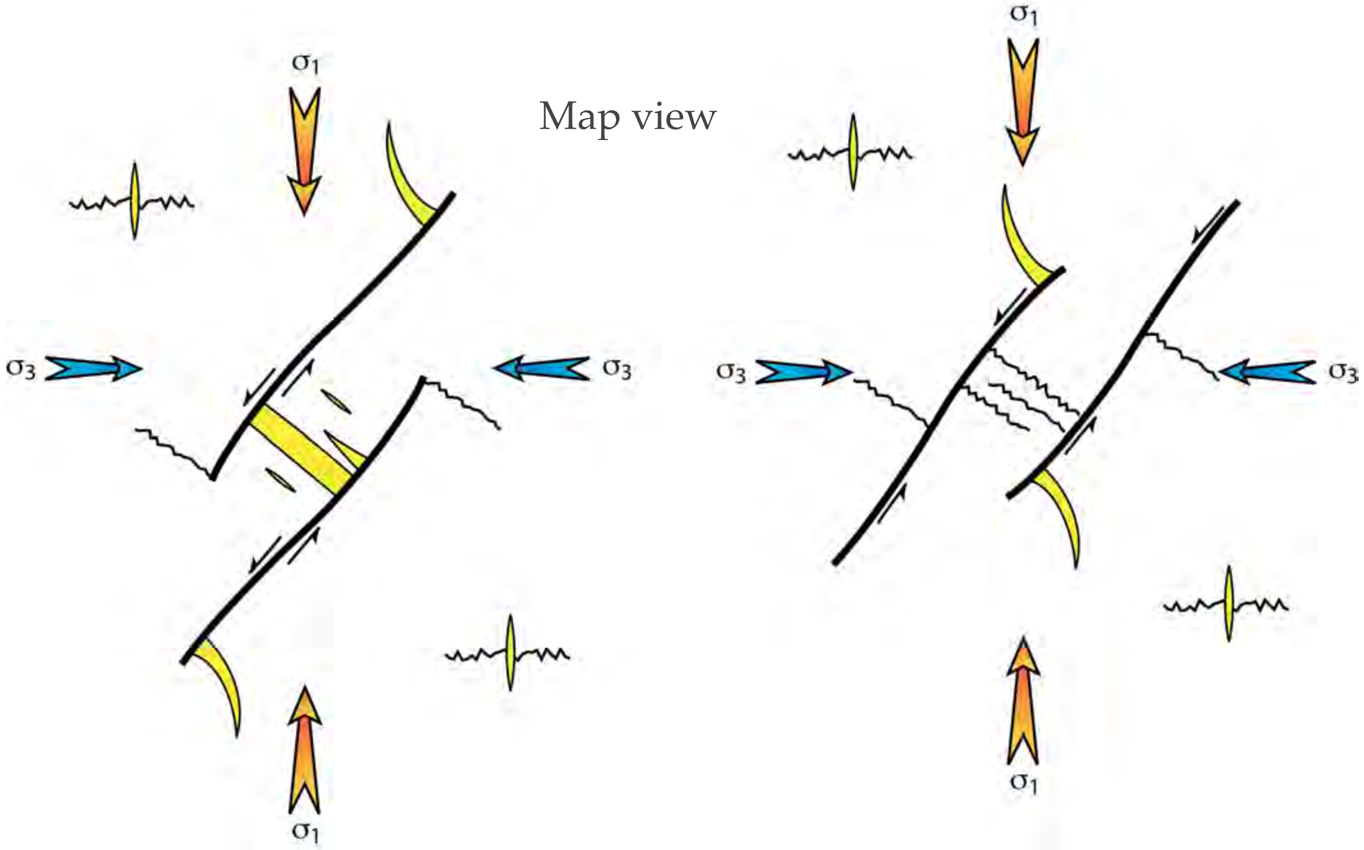
Stress Perturbation

Stresses are transmitted through rocks without perturbation as long as the material through which stress is transmitted is mechanically isotropic. This is rarely the case in nature. The stress field changes, in both magnitude and orientation, in the vicinity of mechanical heterogeneities such as faults.

The sketch on the right illustrates that point. The progressive rotation of both extensional fractures and stylolitic joints show that σ_1 (red trajectories) and σ_3 (blue trajectories) rotate around σ_2 in the vicinity of the fault.

Faults overlap can be responsible for drastic stress perturbations in the region where faults overlap. The sketch below illustrates this point.





A Little Quiz ...

1/ Define the concepts of force, traction and stress.

2/ The stress acting on a surface can be decomposed into two components. What are they?

3/ The stress on a material point is represented by an ellipsoid. Describe this ellipsoid when the only source of stress is the weight of rocks?

4/ What is the deviatoric stress?

5/ How is σ_i mathematically defined?

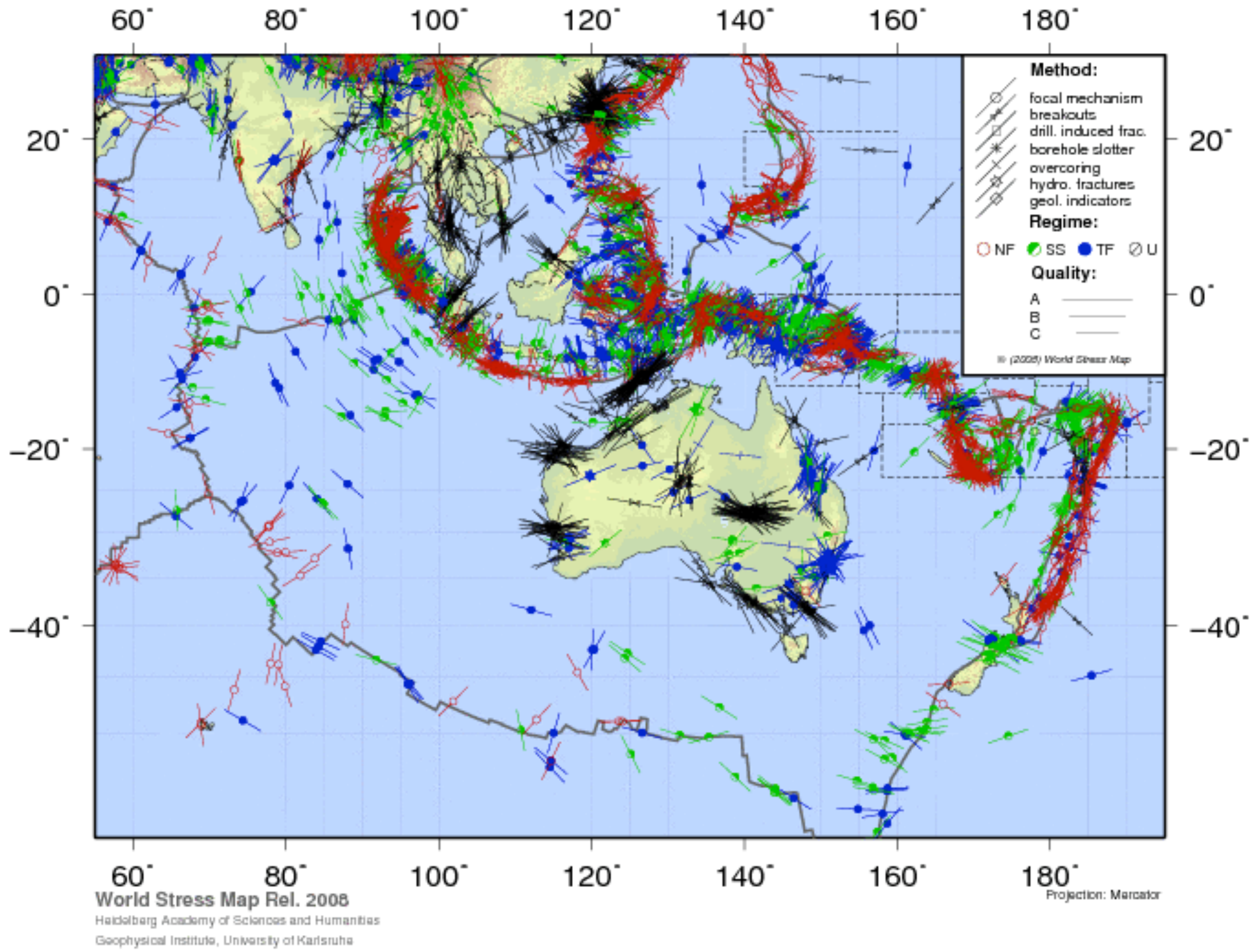
6/ How are stylolitic joints oriented in a compressional tectonic regime?

7/ How are extensional fractures oriented in an extensional tectonic regime?

8/ How is the stress ellipsoid oriented in a transcurrent tectonic regime.

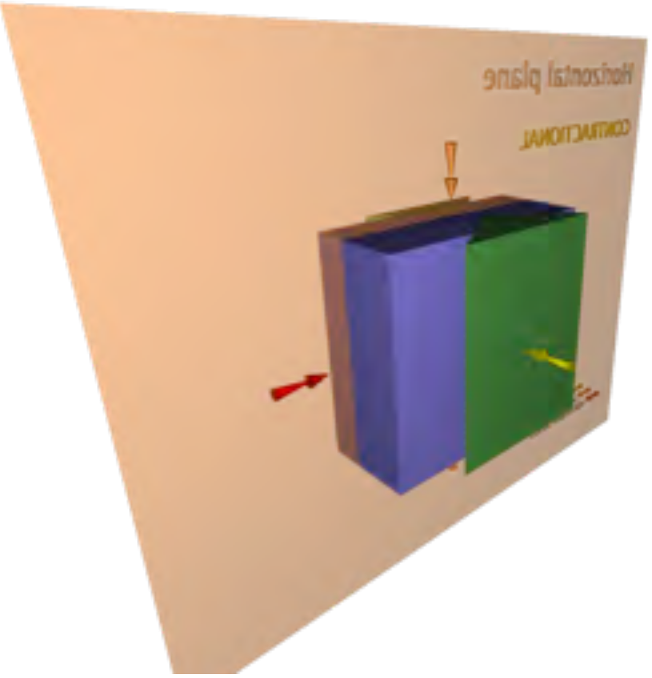
9/ What causes stress field perturbation?

Interesting place to visit: http://www.world-stress-map.org

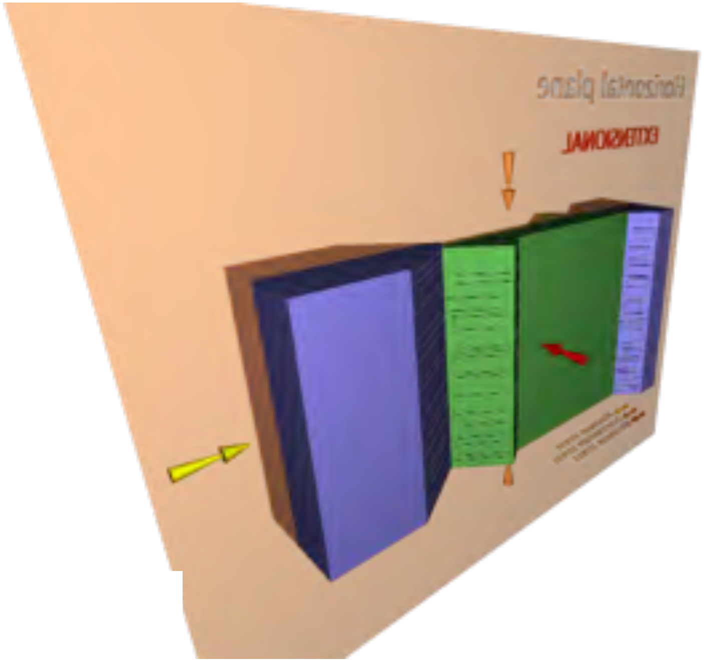


Tectonic Regime and Principal Stress Axes

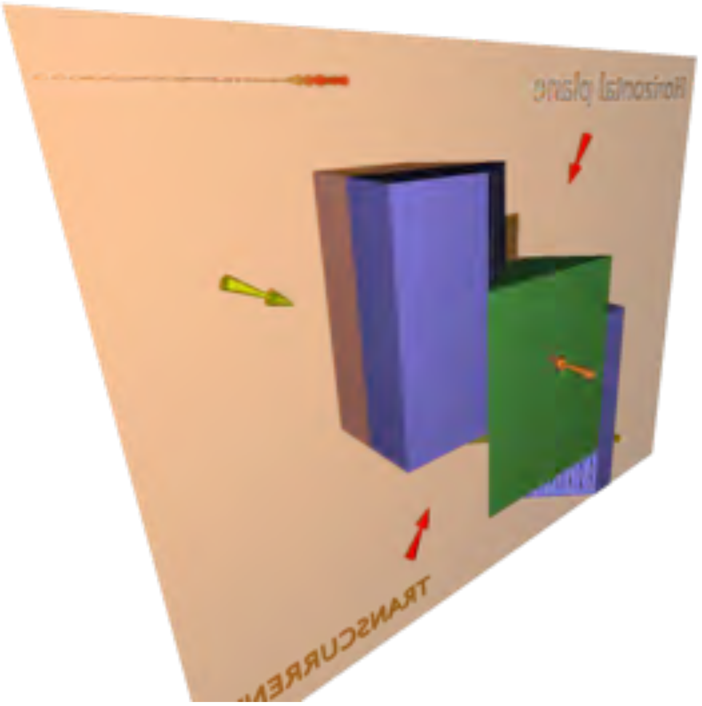
Contractional Tectonic Regime



Extensional Tectonic Regime

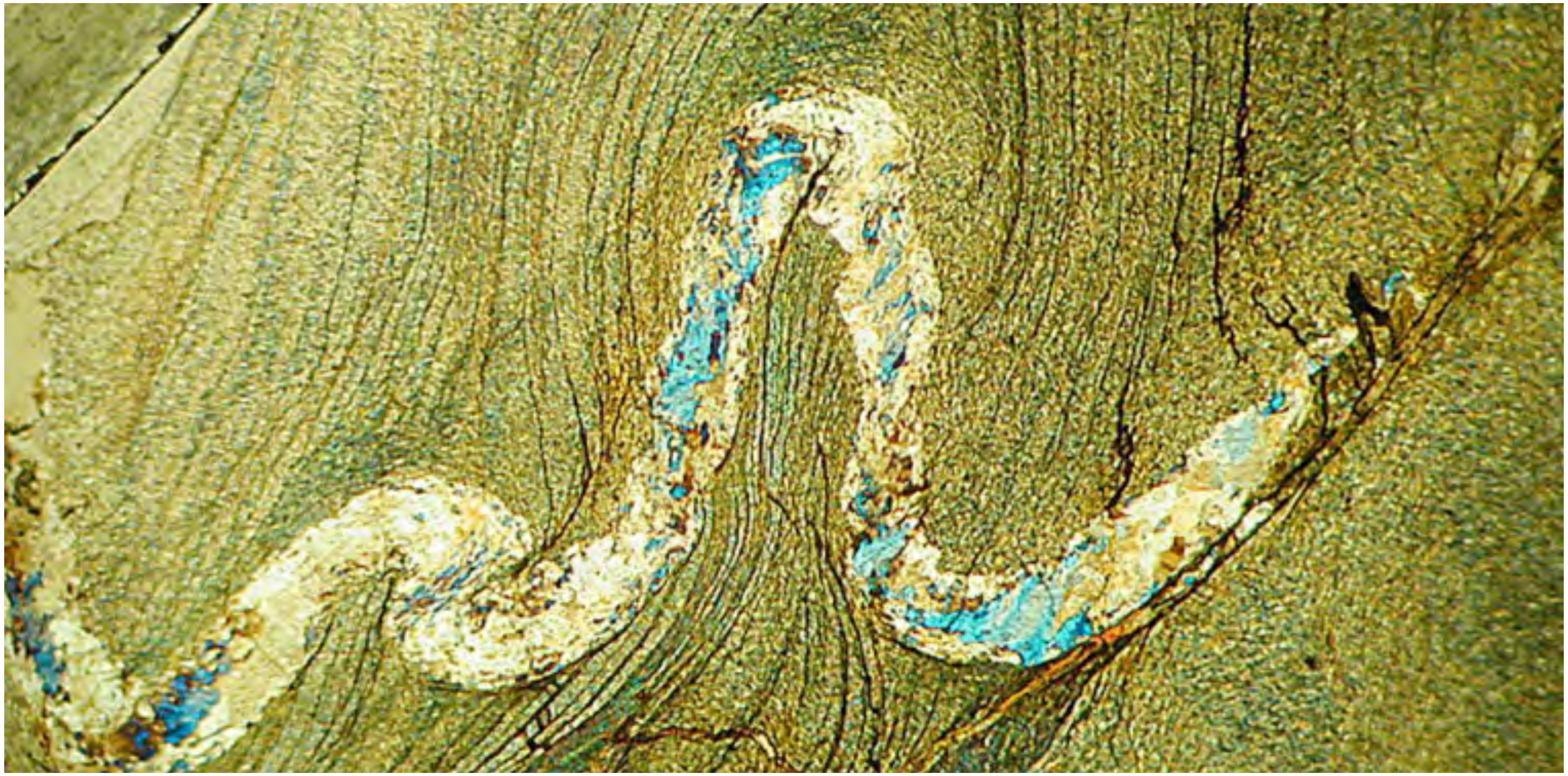


Transcurrent Tectonic Regime



CHAPTER 4

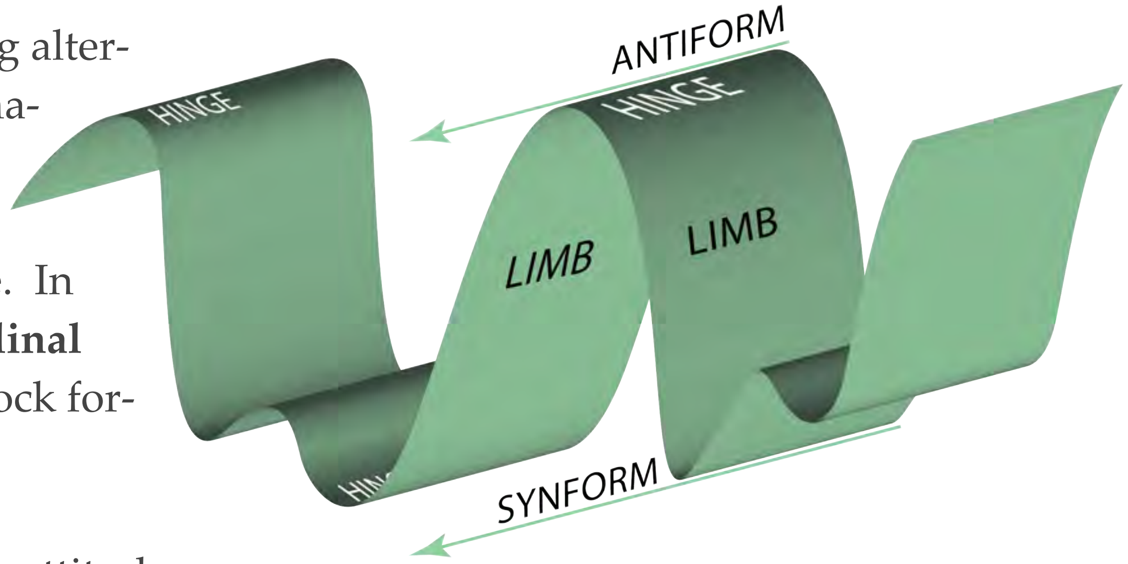
Folds and Folds Systems



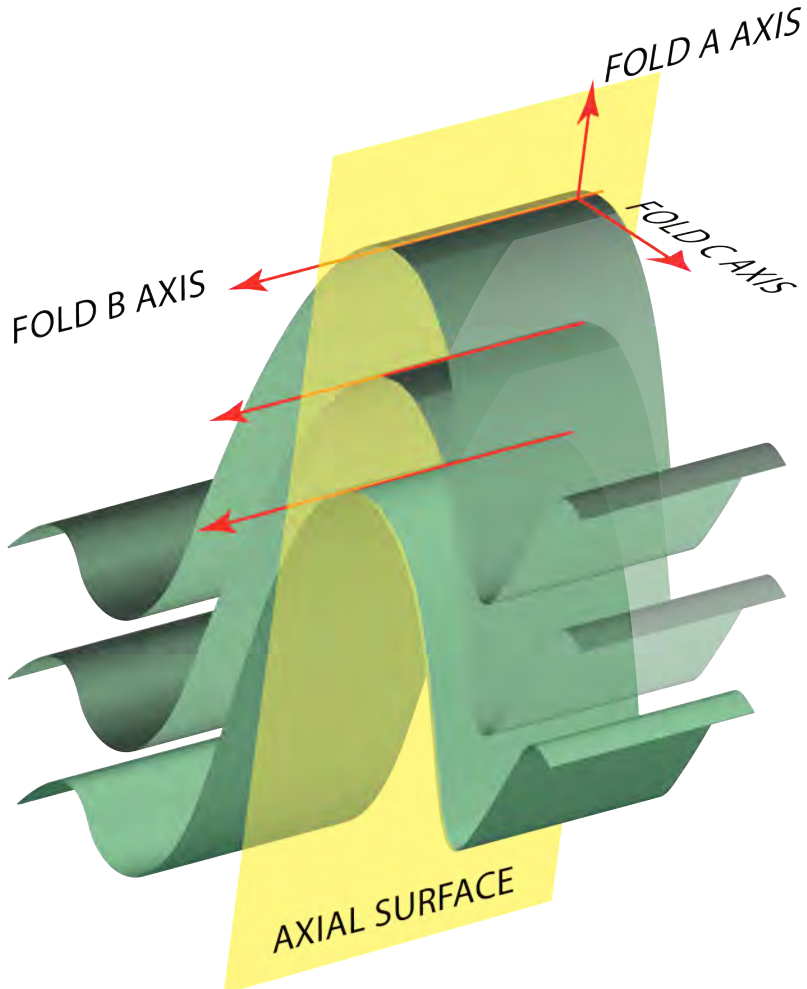
At depth, fracturing and faulting are inhibited by increasing confining pressure as well as increasing temperature which give rocks the ability to flow rather than break. At depth, rock formations organized into layered systems of alternating stronger and less strong layers, buckle under the action of deviatoric stress to form folds and fold systems, or alternatively stretch to form boudins.

Folds Descriptors

Folds form when shortening affects a layered rock formation involving alternating competent and less competent layers. Upon folding, rock formations are bended and buckled into a series of **antiform** and **synform** folds. A **hinge** zone is a region where the dip of the folded surface changes over small distance. Such a region is also called a fold closure. In contrast, the dip is rather constant along a fold **limb**. The terms **anticlinal** and **synclinal** apply when an upward younging arrangement of the rock formations has been verified.



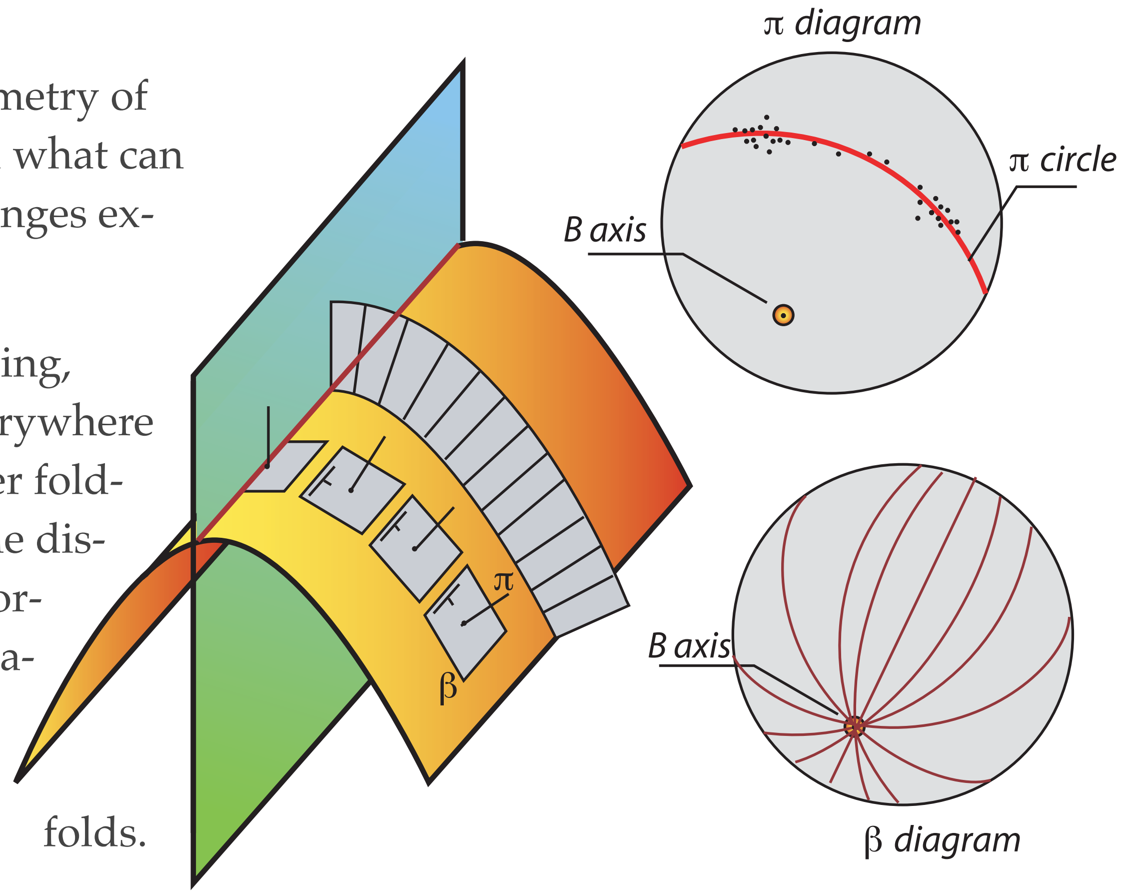
The attitude of folds (their orientation in space) is characterized by the attitude of both their **axial surface** and their B axis also called the **fold axis**. The B axis corresponds to the fold hinge line, the line that links points of maximum curvature on a folded surface. The axial surface is defined as the surface containing all the hinge lines on successive surfaces folded about the same fold. The axial surface can be planar of not, and fold axis can be curved.



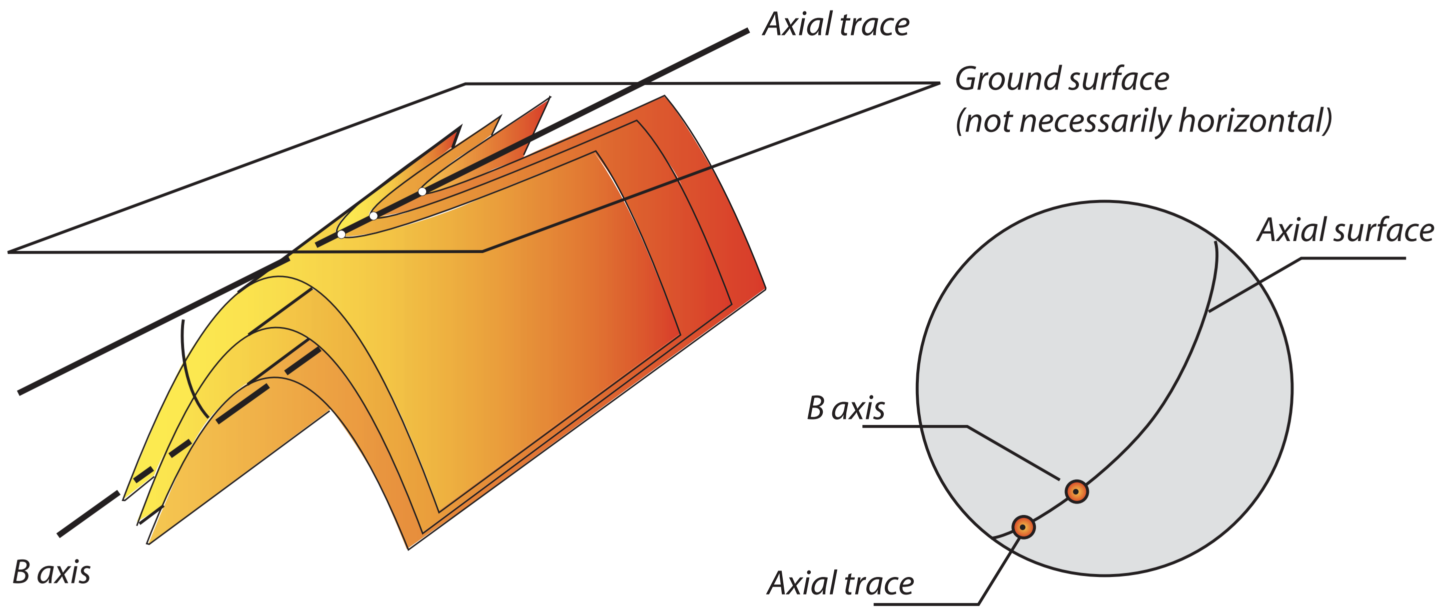
Folds Description Using The Stereonet

Geologists have designed various methods to characterise the geometry of folds from field data, in particular when the size of folds is beyond what can be practically measured directly in the field, typically when fold hinges extend over several hundred meters.

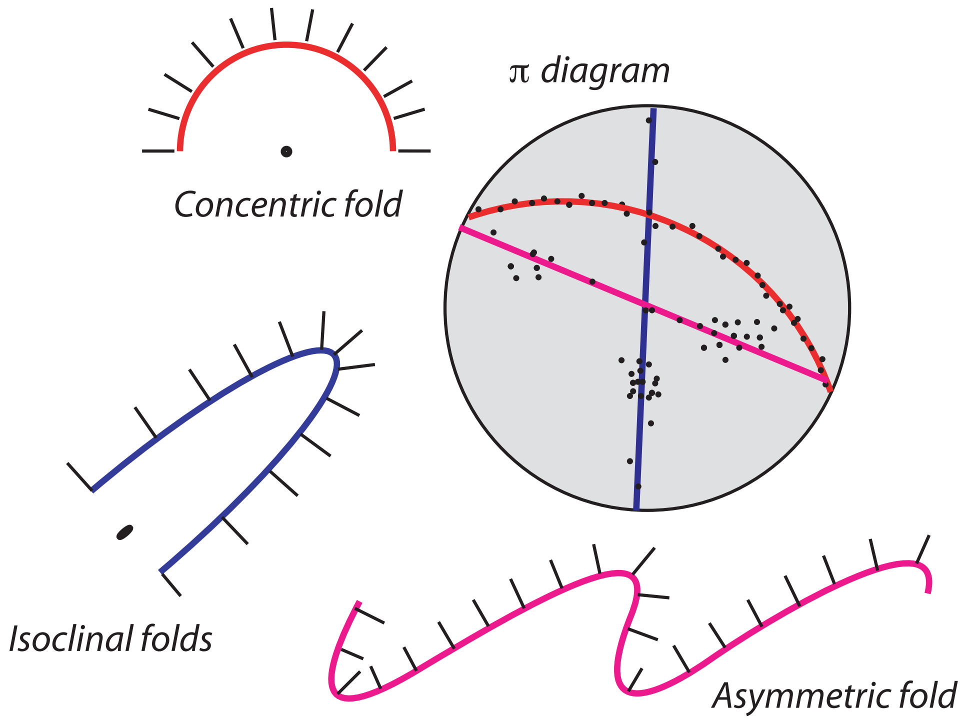
One of these methods involves the use of the stereonet. Before folding, rock formations are sub-horizontal and the pole to beddings is everywhere vertical, hence plotting at the center of the stereonet. However, after folding the poles to the folded surface are no longer vertical but become distributed along a great circle (called the ***π*** circle), of pole of which corresponds to the fold ***B*** axis. This is know as the ***π*** diagram. Alternatively the fold ***B*** axis can be inferred from the intersection, on a stereonet, of great circles (***β*** circle) representing the stereographic projection of bedding surfaces randomly distributed about the folds. This is know as the ***β*** diagram.

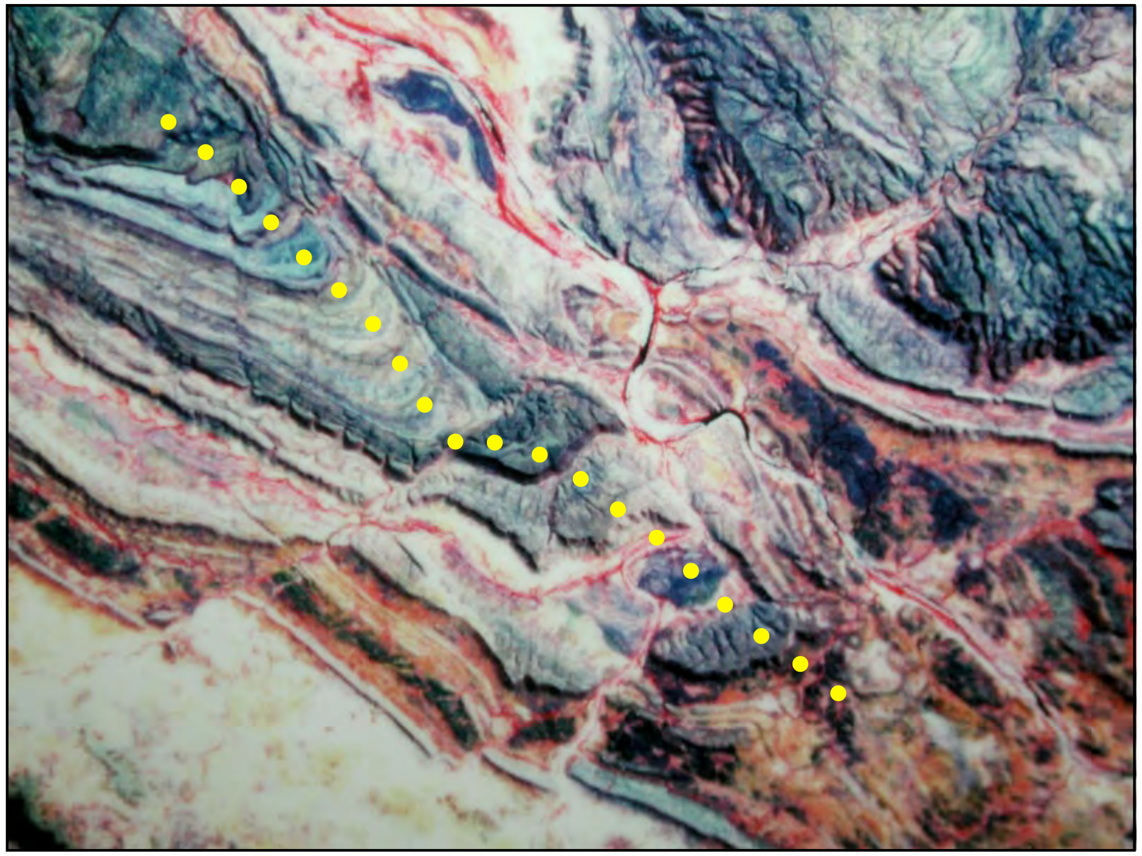


π and β diagrams alone cannot constrain the attitude of the axial surface. This can be achieved by plotting on a stereogram the axial trace of the fold as well as its axis. The axial trace of a fold is the line that links, on the ground surface, points of maximum curvature on successive folded surfaces. By definition the axial trace, since it is defined by points of maximum curvature, lies within the axial surface. Since a planar surface is fully defined by two lines within it (cf. Euclidian geometry), the axial surface can be deduced from the axial trace and the fold hinge.



Processing pole to bedding data on a stereonet can be used to infer the shape of folds. For instance, π diagram of isoclinal folds (i.e. folds with parallel limbs) have two strong pole clusters, as random bedding measurements will over-sample limbs compared to that of hinge regions. Asymmetric folds typically have a long limb and a short limb. In this case the long limb will be over-represented leading to one strong cluster and a much smaller one. This contrast with concentric folds for which pole to beddings are homogeneously distributed over a great circle.



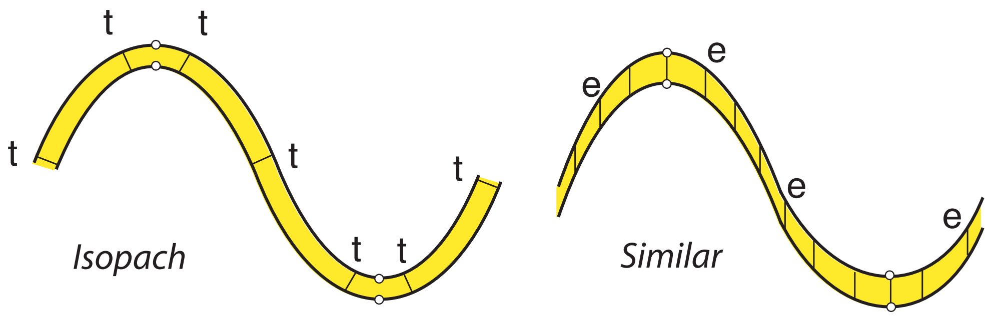


Top: Satellite view of folded Proterozoic rock formations from the Kimberley (WA). The doted line shows the fold axial trace.
Bottom: Upright fold in Carboniferous rocks with Permian unconformity (Portugal, Photo O. Matte).

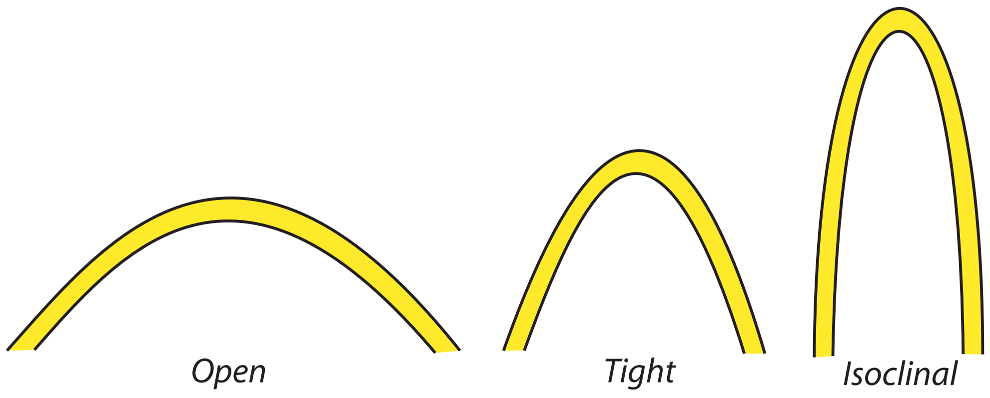
Folds Classification

There are many ways to classify folds based on: i/ the thickness of folded layers, ii/ the angle between limbs, iii/ the dip of the axial surface, iv/ the plunge of the fold axis, v/ the general shape of folds ... The following introduces a number of terms commonly used to describe folds.

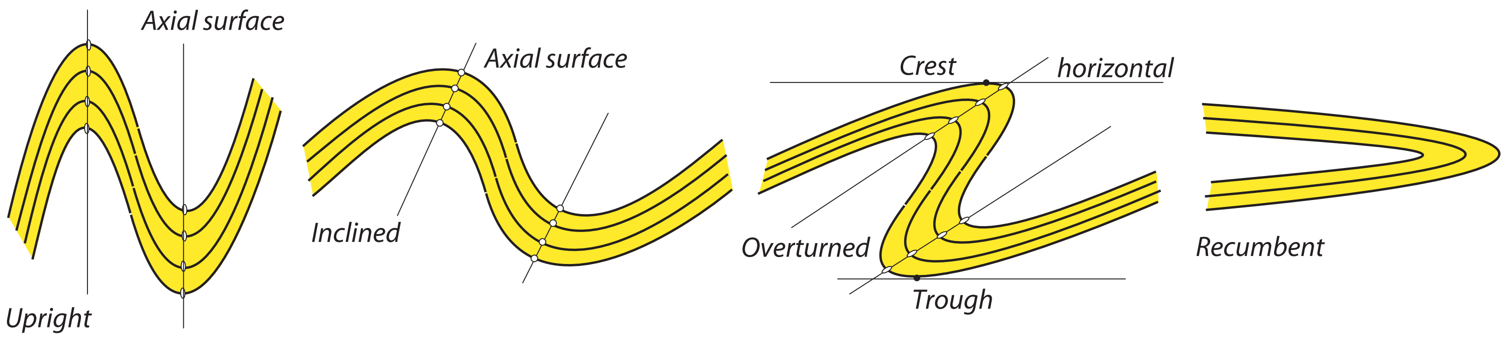
Isopach folds are folds in which the thickness ***t*** of each layers keeps constant. In **similar folds** it is the apparent thickness ***e*** measured parallel to the axial surface that remains constant.



Open, tight and isoclinal, are terms referring to the angle between two successive fold limbs.



Upright folds have a vertical axial surface, they may or may not be symmetric. **Overturned folds** have one limb with younging direction pointing downward, whereas **recumbent fold** have sub-horizontal axial surfaces.



Recumbent folds in gneiss beneath the Indus Suture (Photo Credit: Gerold Zeillinger, diogenes.ethz.ch)

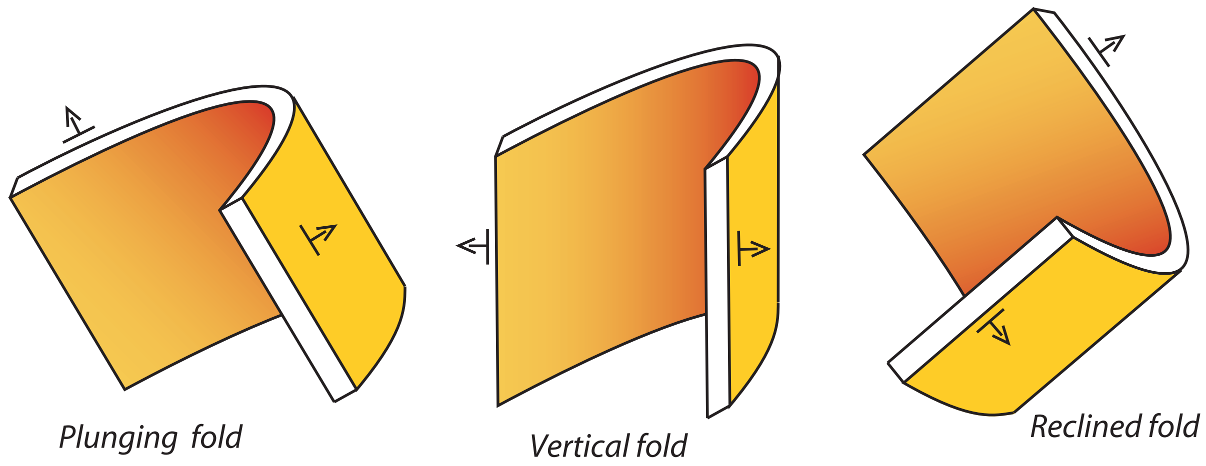
Horizontal, **vertical**, **plunging** and **reclined** are terms used to describe the plunge of the fold axis:

• Horizontal folds have horizontal fold axes.

• Vertical folds have vertical fold axes.

• Plunging folds have plunging fold axes.

• Reclined folds have plunging fold axes AND younging pointing downward.



Folds can have all sorts of weird shape and consequently all sorts of weird names.

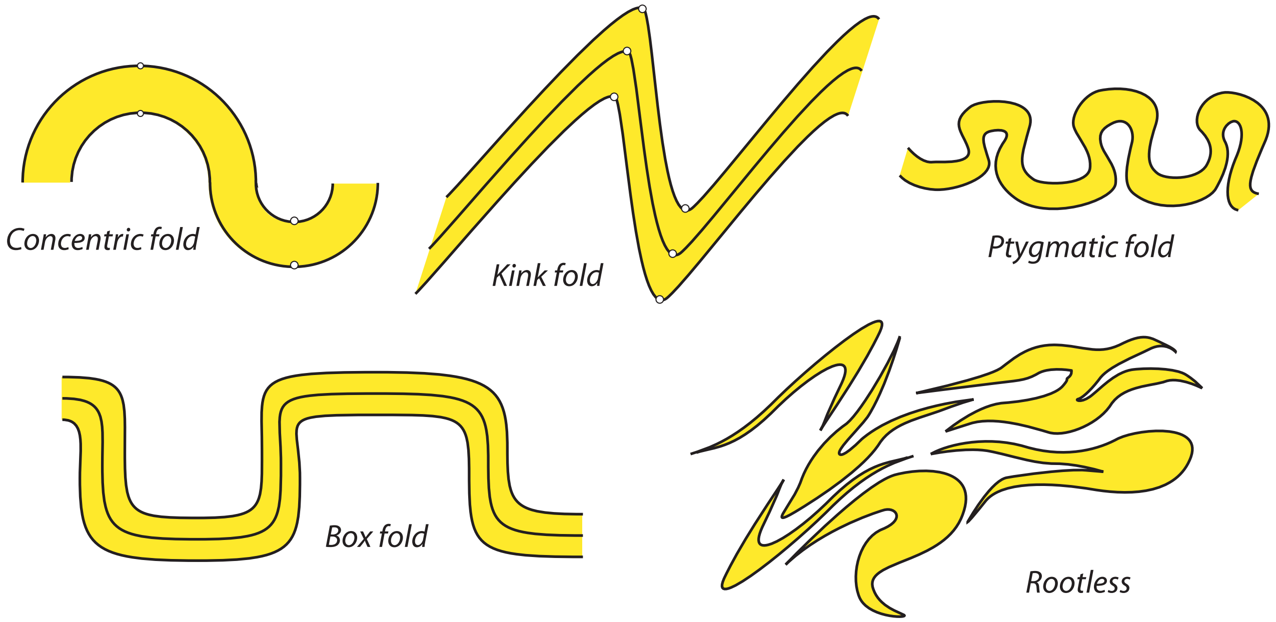
• **Concentric** folds have a center of symmetry.

• **Chevron** folds (also called **kink** folds) have narrow hinges relatively to the length of their limbs.

• **Ptymatic** folds have short limbs relative to the their hinges.

• **Box** folds somehow have three limbs and two hinges.

• **Rootless** folds have broken limbs due to shearing.

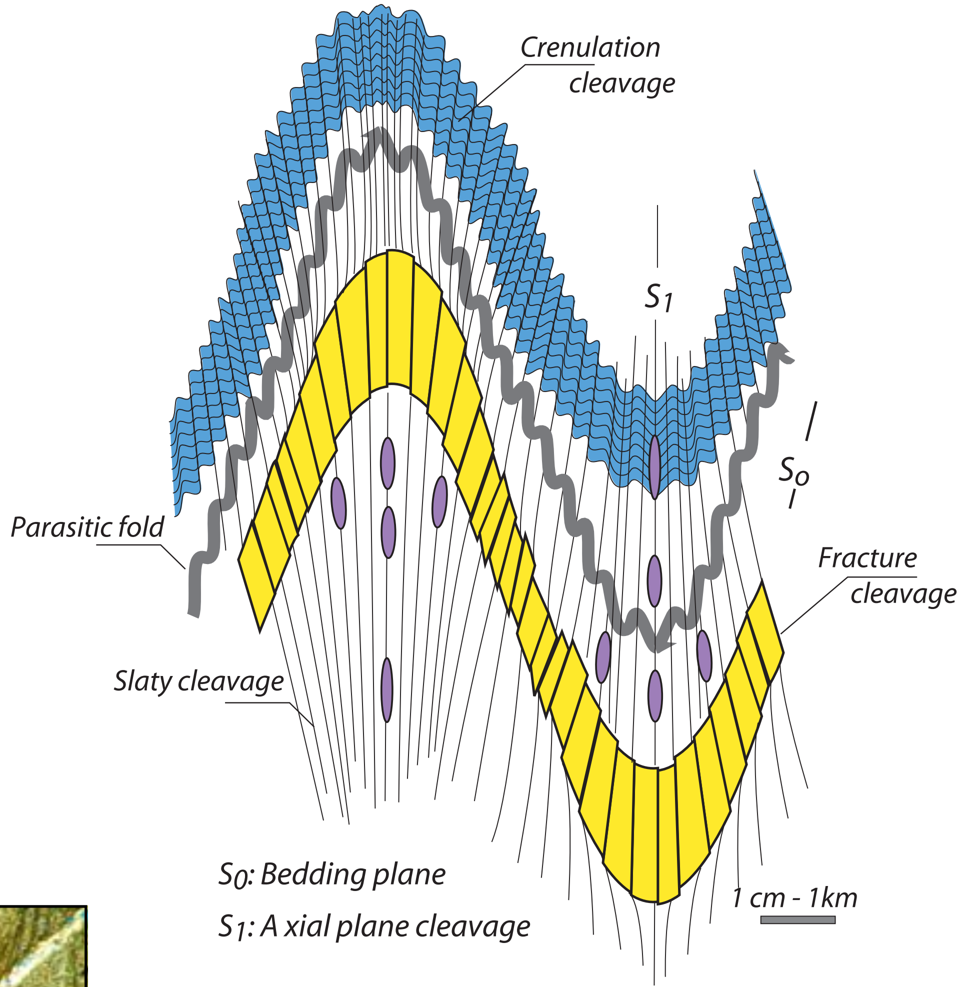


Gallery 4.1 Folds

Chevron folds in a paragneiss (Olary block, SA, Photo P. Rey).

Folds Related Microstructures

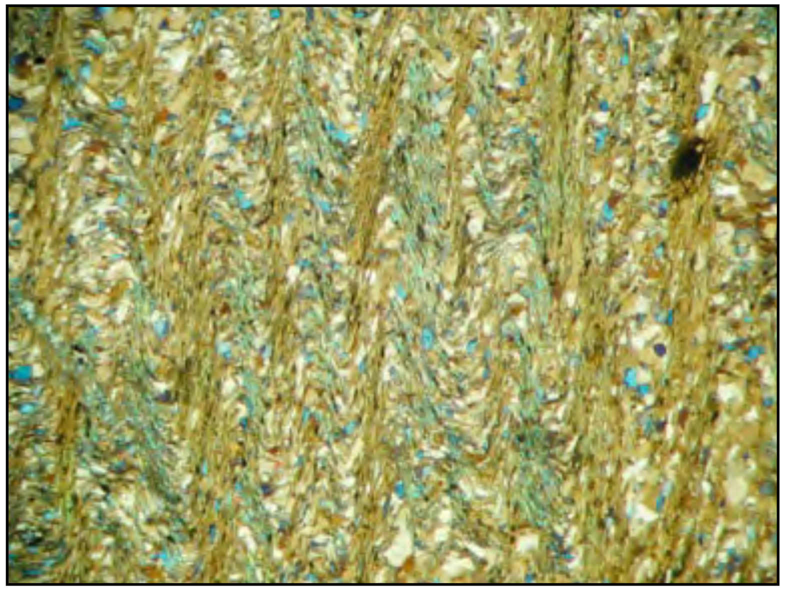
During folding, the bending of bedding surfaces (S_o) is accommodated by the deformation of rocks at grain scale. This deformation may produce the rotation and the alignment of mineral grains and biogenic clasts parallel to the fold axial surface. This produces a secondary anisotropy plane called a cleavage plane (S_1).



Deformation can also change the shape of grains through a mechanism called pressure-solution. According to this mechanism of deformation, the part of the grain enjoying the larger stress is dissolved and the material removed migrates toward areas of lower stress. Through pressure-solution, a grain of spherical shape is transformed into an ellipsoid whose flattening plane (defined by its long and intermediate axes) tends to be parallel to the fold axial surface, hence participating in the development of a cleavage plane.

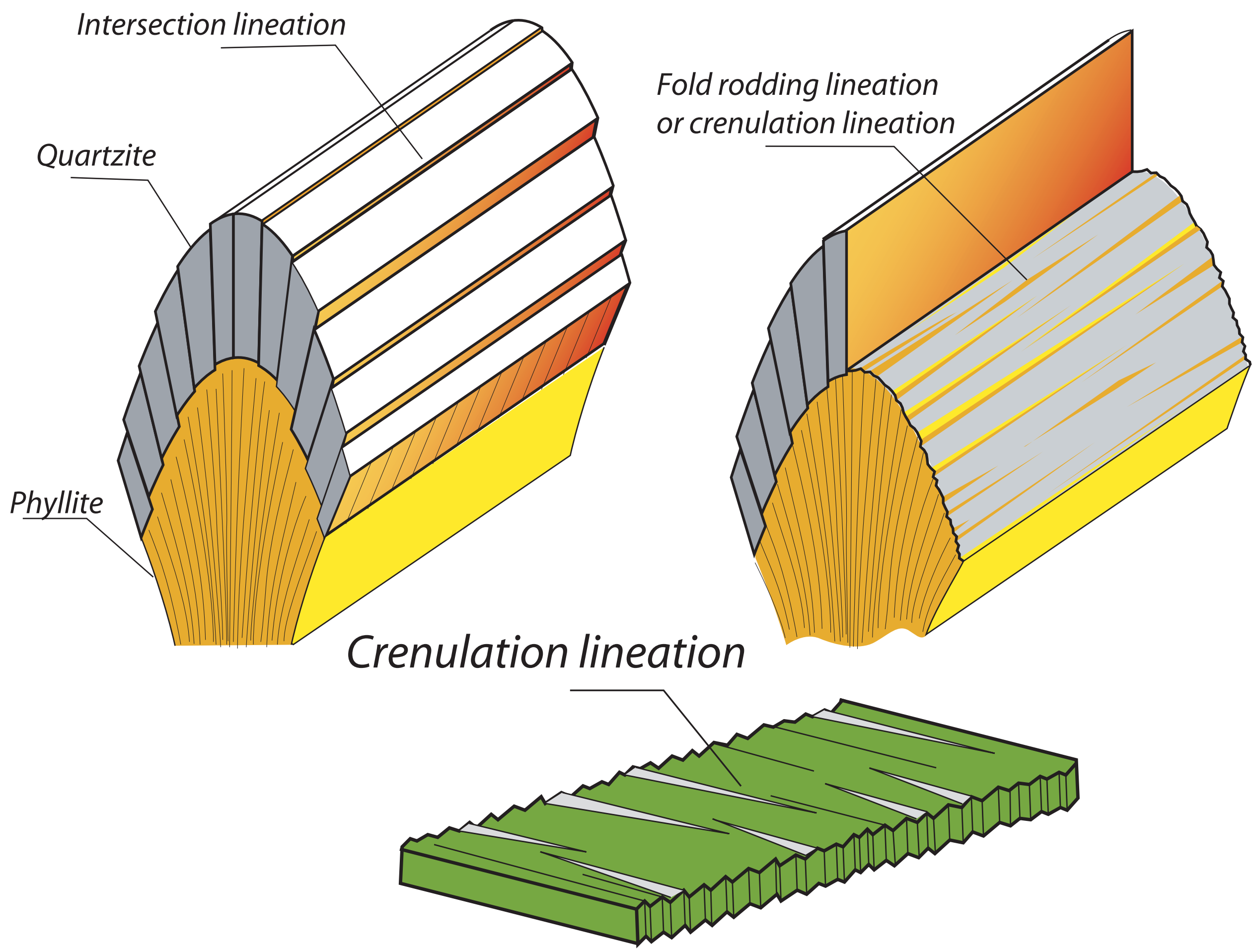
Two others mechanisms participate to the development of axial planar cleavage. Fracture cleavage involves the development of shear fractures in competent (hard) layers. These shear fractures tend to be parallel to the fold axial surface. Finally, crenulation cleavage develops because of the preferential alignment of limbs in micro-folds.

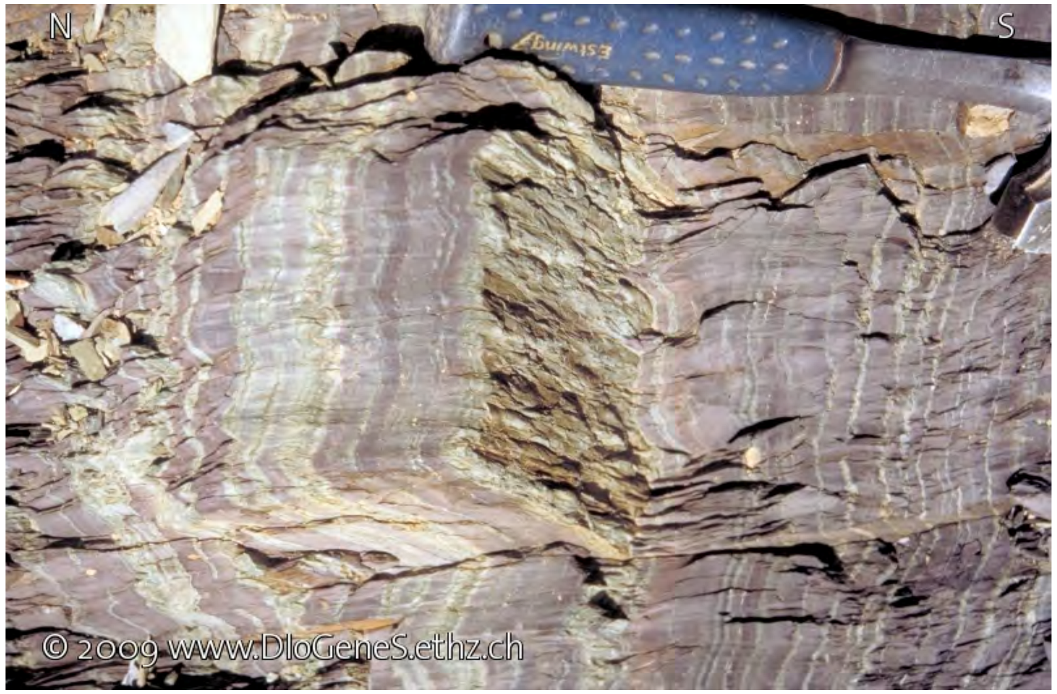
Crenulation in a low-grade schist, the photo is ca. 2cm across. On the right small detail of the above photo (Photo P. Rey).



Linear structural features associated to folding develop as the result of micro-folding and surfaces intersection.
Fold rodding lineations, also called **crenulation lineations**, correspond to the hinge of micro-folds along bedding planes. Cleavage-bedding intersections are called **intersection lineations**. These lineations appear on cleavage and bedding surfaces.

Both type of lineation run parallel to the fold axis, and therefore can be used as a proxy for fold hinges (i.e., the plunge and plunge direction of these lineations is the same than that of the fold axis).



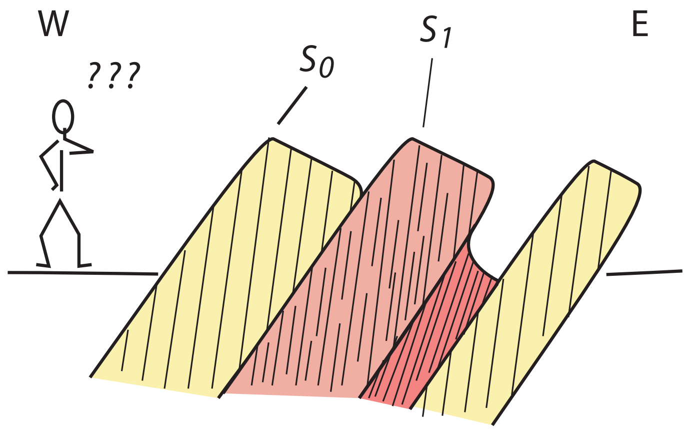


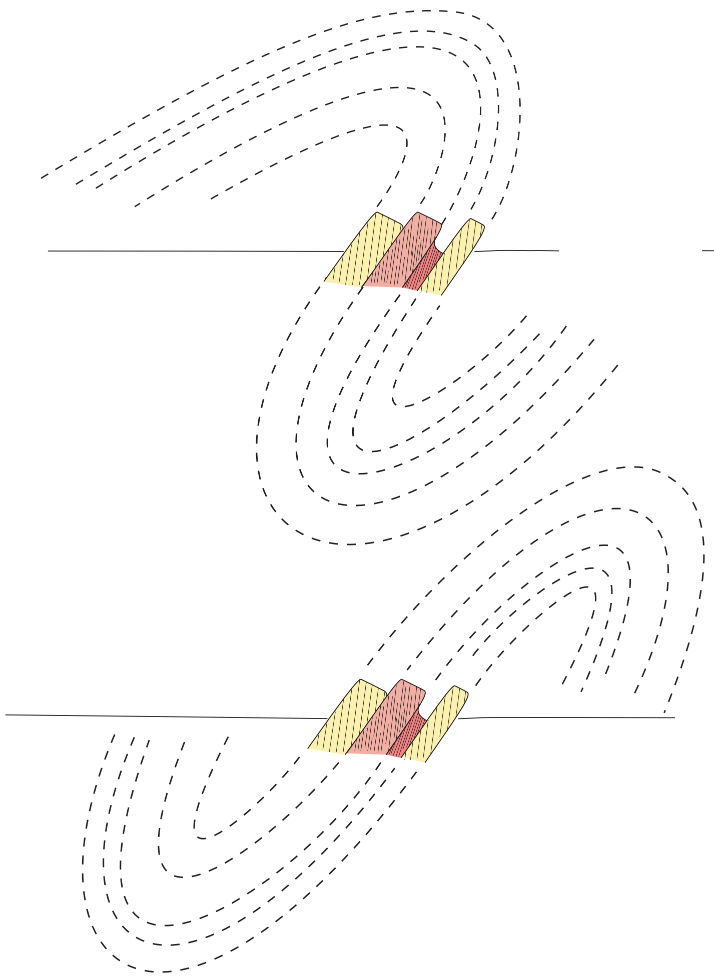
Bedding and cleavage fabrics in a low grade schist (Photo credit: J.-P. Burg, diogenes.ethz.ch)

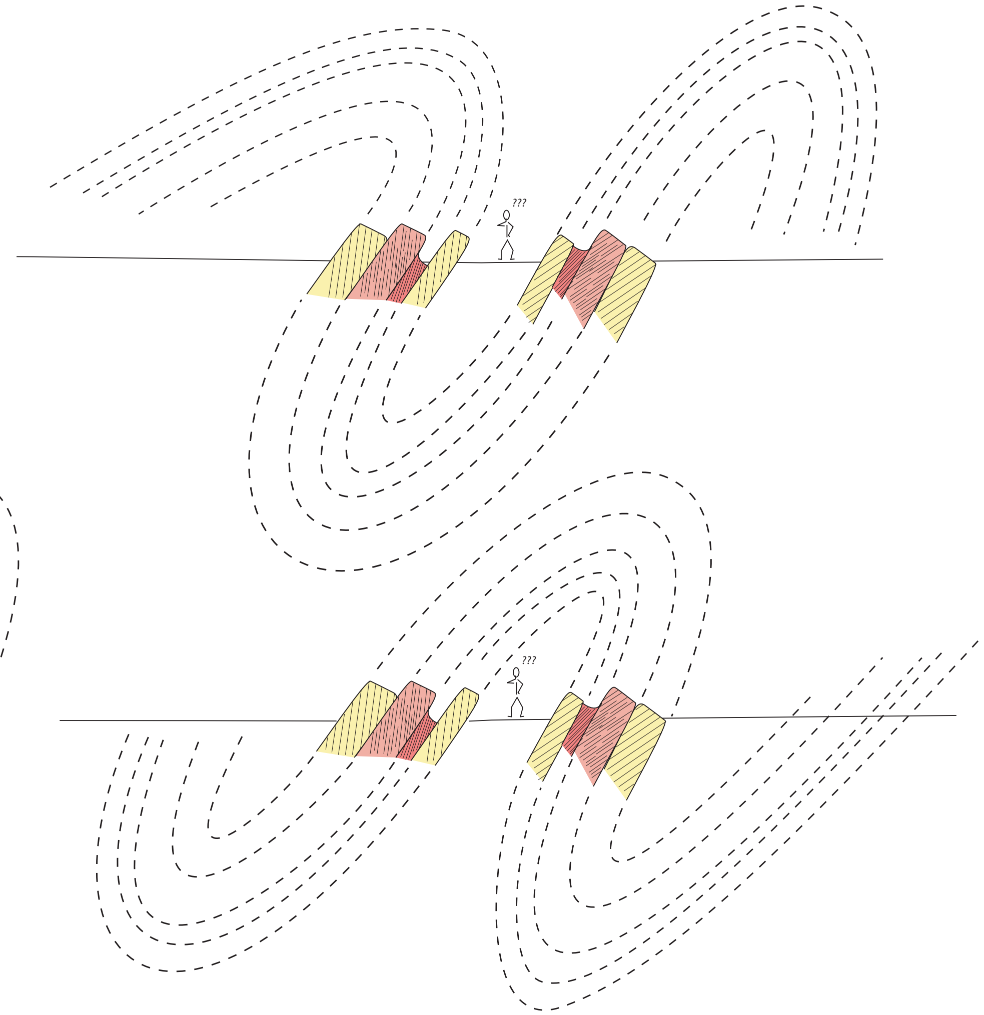
Crenulation lineation in a low grade schist (Photo credit: J.-P. Burg, diogenes.ethz.ch)

Folds Systems: Cleavage-Bedding Relationships

One problem that geologists face is to figure out, in poor outcropping areas, the succession of anticlinal and synclinal closures adjacent to a given outcrop. The geologist below tries to figure out the position of the next anticline and syncline with respect to the outcrop. The next sketch on the right shows the two possible solutions geometrically equally valid until one considers the cleavage-bedding angular relationship. Looking eastward at the next outcrop (sketch on the far right) the succession of rock formation is on the reverse order suggesting that a fold closure has been passed. To find out which of the top of bottom fold system is correct, one we must consider that cleavages diverge away and upward in antiformal closures, and away and downward in synformal closures. From the angular relationships between S_o and S_1 there can be only one valid solution which is given on the next page.

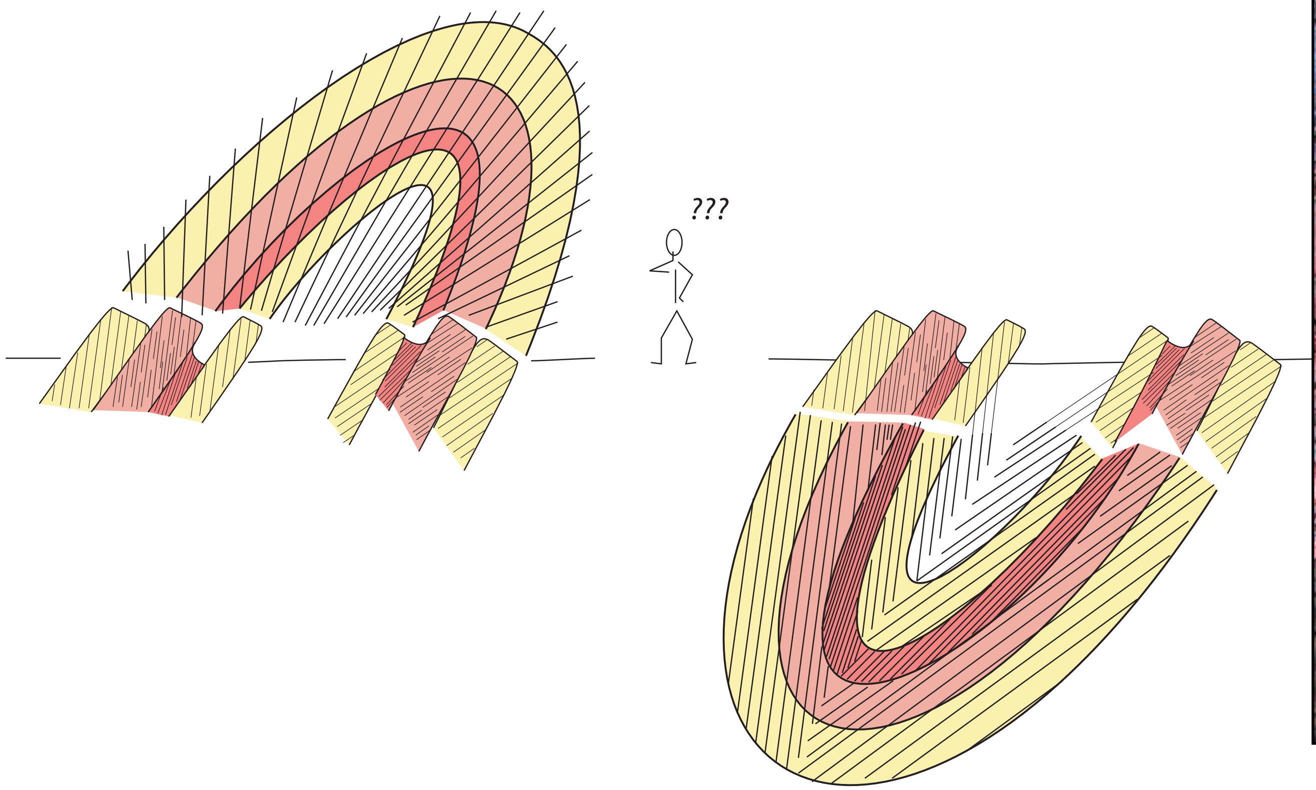






Cleavage diverges away from the fold closure, upward in an anticlinal closure and downward in a synclinal closure. The correct solution is therefore given by the sketch on the left, where the cleavage diverges upward away from the core of the anticline. In contrast the sketch on the right shows that the cleavage converges downward toward the core of the synform, this is never observed in nature.

In conclusion, cleavage-bedding relationships help structural geologists 1/ to infer the position of a given outcrop in a fold system, 2/ to infer the succession of adjacent fold closures with respect to an outcrop.



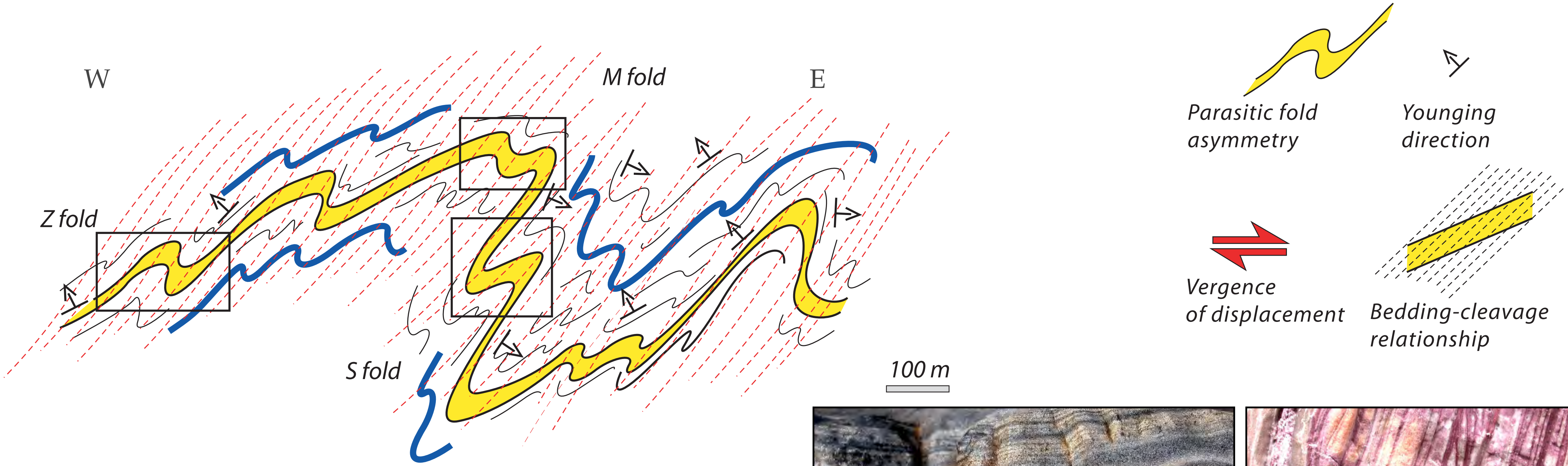
Cleavage may not always develop with a fan distribution. Here an axial planar cleavage parallel to the fold axial plane in low grade schist. This suggests that there is little strength contrast between beds (Photo credit: P. Rey). NB: Stratigraphic layering is shown by change is color, texture and/or weathering.

Folds Systems: The Concepts of Vergence and Facing

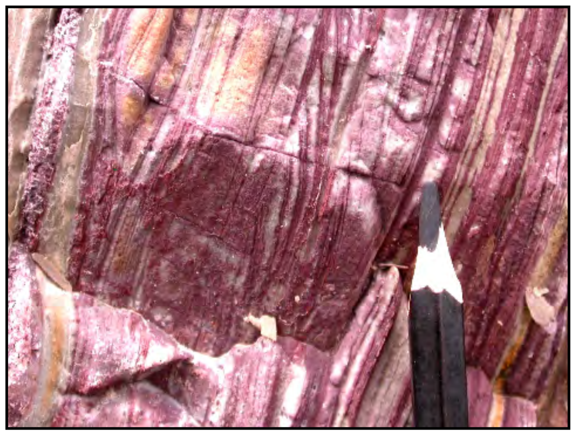
The **facing** of a fold system refers to the geographic direction of younging (shown with an arrow) of the long limbs of its parasitic folds. In a fold system, such as the one presented below, the facing is changing as one crosses major fold hinges. Indeed from west to east, this fold system is facing west upward, then east downward, then west upward, and east.

The concept of **vergence** refers to the general sense of shear involved in the development of asymmetric folds. The fold systems shown below is verging east as the asymmetry is the result of a shearing toward the east. Unfortunately vergence is also used to refer to the direction of the next anticlinal closure.

Changes in fold asymmetry, cleavage-bedding relationships, facing, and shear vergence occurs across fold hinges. Determination of two of these criteria constrain the two others.



Younging criteria are sedimentological features informing about the relative position between younger and older layers.
Left: Loading cast sedimentary structure showing upward younging.
Right: Example of cross-beds showing younging to the left (Photo Credit: P. Rey).



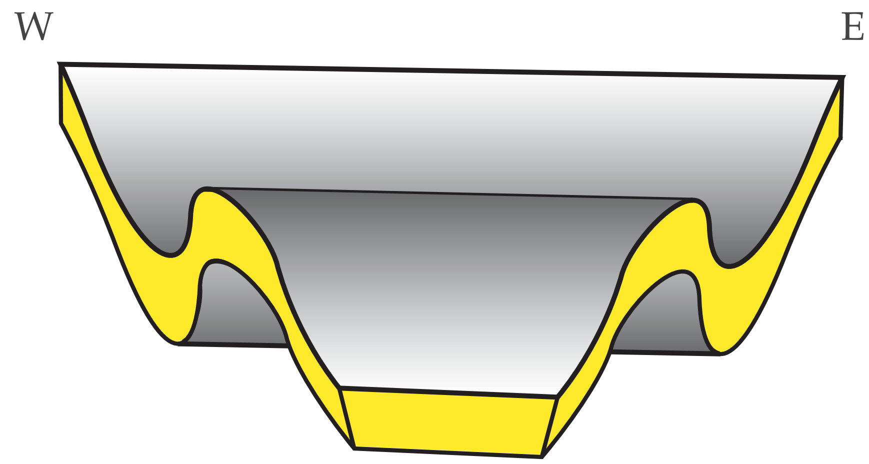
Mind the Gap …

The asymmetry of parasitic folds involves either a clockwise rotation (Z-shaped folds) or an anti-clockwise rotation (S-shaped folds) of the folded surface. The asymmetry of parasitic folds change across fold hinges as S-shape folds occur in one limb and Z-shaped folds occur on the other. Therefore one can use this change to track down the position of large-scale fold hinges in region of poor exposures.

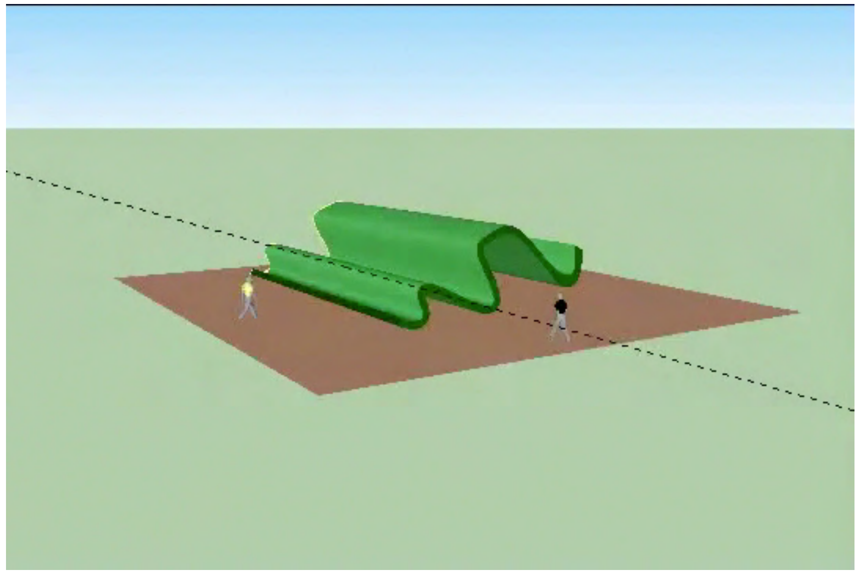
When doing this some caution should be exercised. In particular it is important to realize that the sense of fold asymmetry (S or Z) depends on the direction toward which the observation is made. The sketch on the right shows a parasitic fold. Looking from east to west the fold appears as a Z-shaped asymmetric fold. In contrast, when looking from west to east the fold appears as an S-shaped fold. This change in asymmetry is not the result of having crossed a fold hinge but simply the consequence of looking at the same parasitic fold in two different directions.

To avoid any mistake, fold asymmetry should be determined looking toward the same direction, usually toward the plunge direction of the fold axis in plunging or reclined folds.

Another very common source of mistake is entrenched in the fact the 2D sections through 3D object can be extremely misleading in representing the true fold morphology. Indeed, a simple upright symmetric fold can appear as an apparent overturned to recumbent fold on a 2D vertical section cutting at an angle to the fold axis.



Movie 4.1 Mind the gap!



A Little Quiz ...

1/ What is the fold axis?

2/ What is the axial trace?

3/ What is the axial planar surface?

4/ Draw an overturn, tight, isopach fold.

5/ Draw an inclined, open, similar fold.

6/ What is a recumbent fold?

7/ What is a reclined fold?

8/ How do we call a fold with long limbs and narrow hinges?

9/ What is a crenulation cleavage?

10/ What information do intersection lineations provide?

Gallery 4.2 Mind the gap!

Comment on the geometry of the folds (Photo Credit: P. Rey).

Interactive 4.1 Fold axis and fold axial surface.

Review 4.1

Question 1 of 6

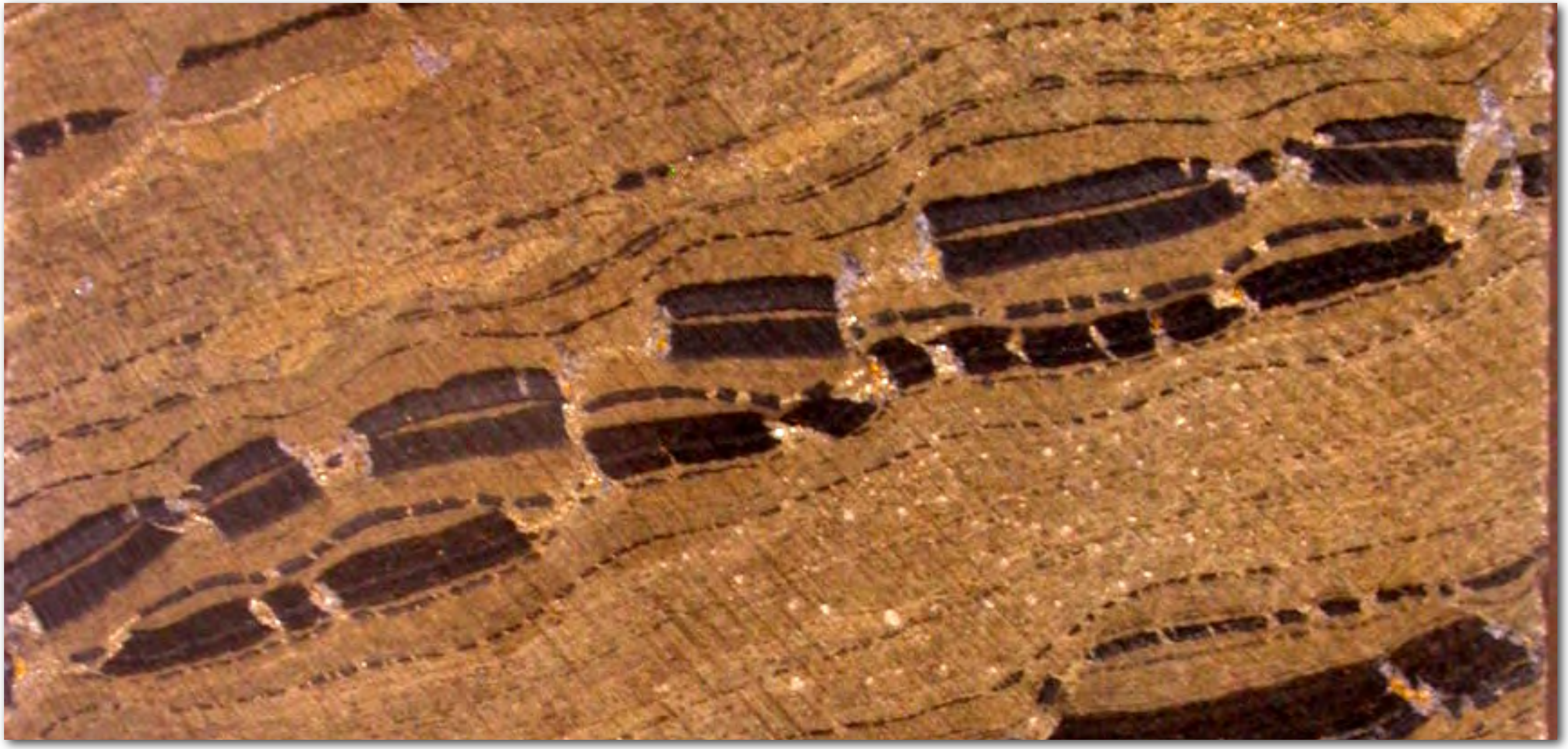
The attitude of folds and fold systems is or can be fully characterized by:

- **A.** Strike, dip and dip direction of the axial planar surface.
- **B.** The pole to beddings plotted on a stereonet canvas.
- **C.** The plunge and plunge direction of the fold axis.
- **D.** A and C together.
- **E.** The plunge and plunge direction of the fold axis, and the plunge and plunge direction of an axial trace

Check Answer

CHAPTER 5

Boudins and Boudinage



Whereas folds are an expression of contractional deformation, boudins and boudinage result from extensional deformation applied to rock formations made of alternating stronger and less strong layers.

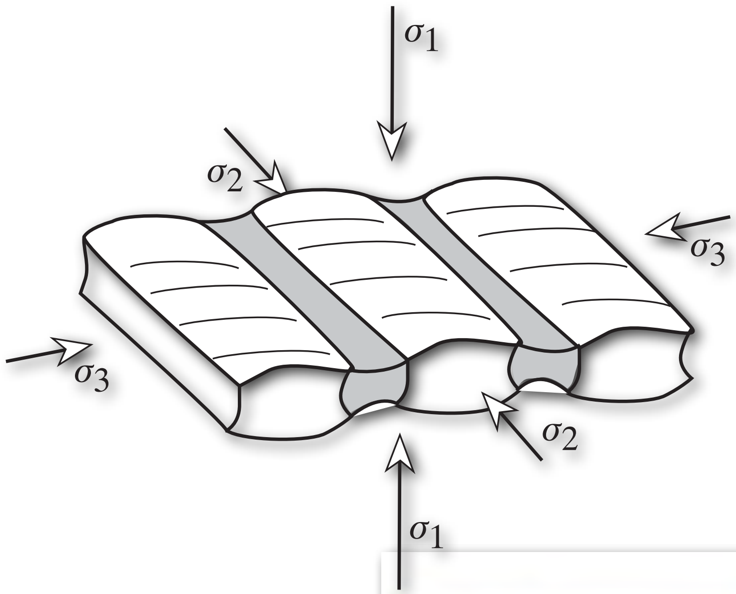
Boudins Descriptors

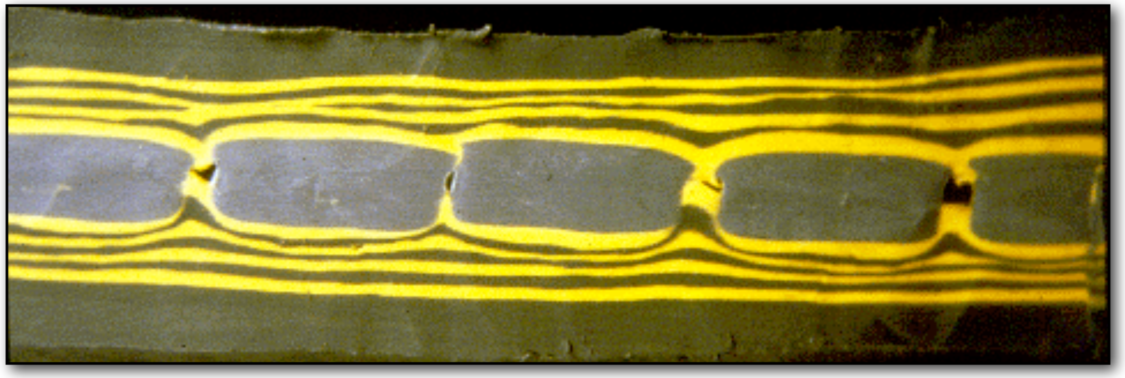
Boudins form due to a process called **boudinage**. Boudins form when lengthening affects a layered rock formation involving competent layers embedded into a less competent, easily deformable, host rock.

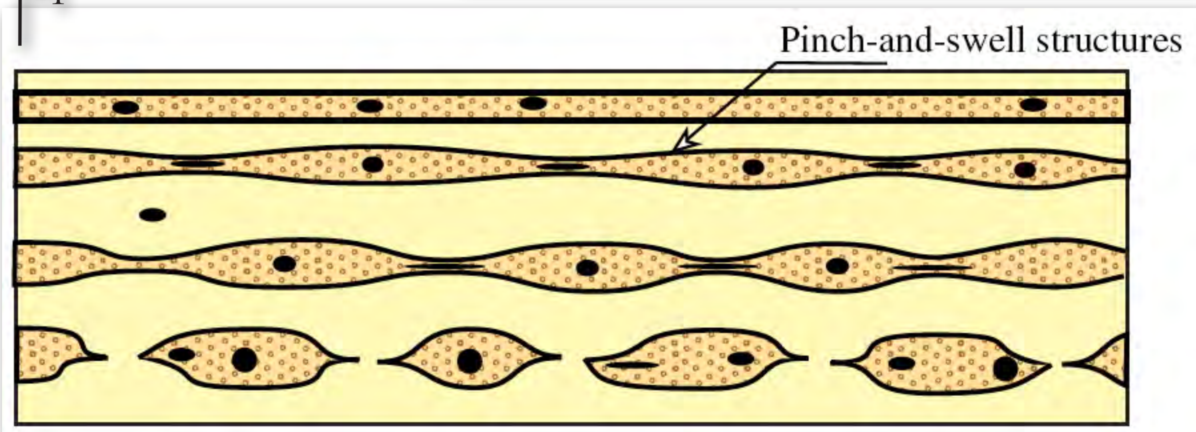
Upon extension, the stronger layers lengthen via heterogeneous thinning leading to the development of **pinch and swell** structures (i.e. thinning of the strong layer is periodic).

Amplification of thinning in the pinched regions eventually led to the segmentation of the stronger layers into boudins separated by **necks**.

The strength contrast and the direction of extension with respect to the layer impose a strong control on the geometry of the boudins.



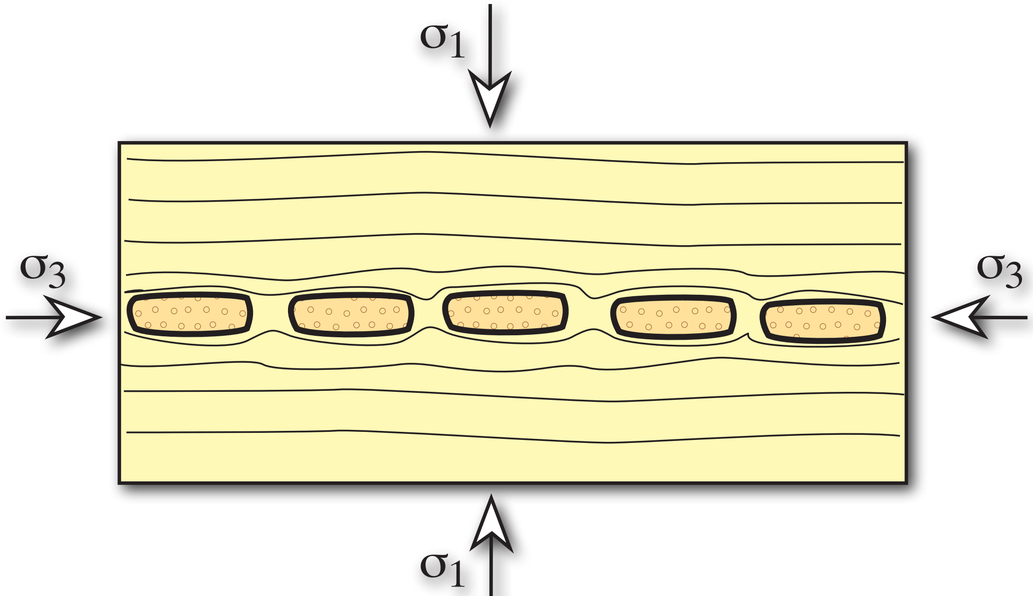


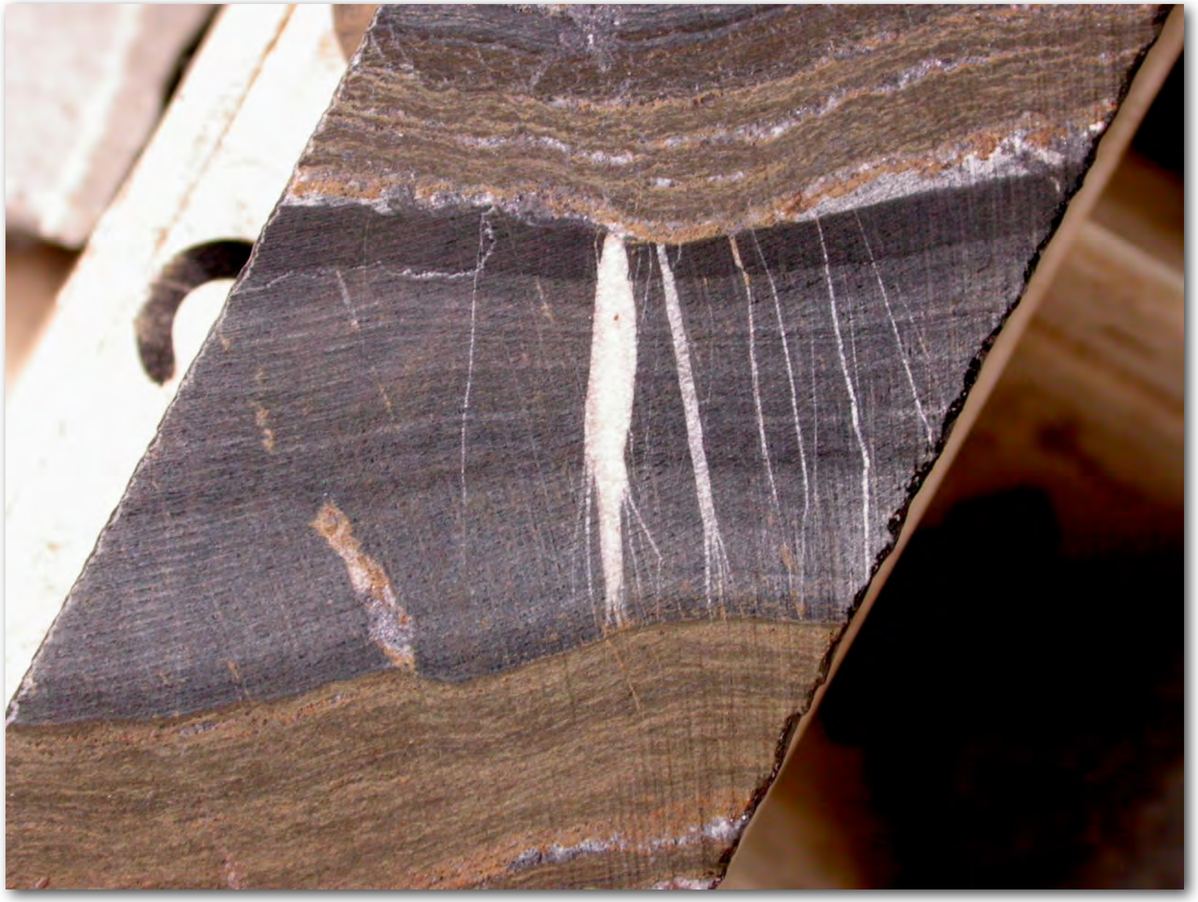


Symmetric Boudinage

The direction of extension, with respect to the orientation of the layering, imposes a strong control on the geometry of the boudins.

Extension parallel to layering led to symmetric boudinage. Thinning and necking in the stronger layers often initiate via the development of extensional fractures orthogonal to the layering. As extension proceeds, boudins evolve with a symmetric shape, and boudins do not rotate during extension.





Example of extensional fractures orthogonal to bedding in a nascent neck region, the photo is ca. 8 cm long (Photo credit: P. Rey).

Example of symmetric boudinage of a granitic vein in a psammitic schist (Broken Hill, NSW, Photo credit: P. Rey).

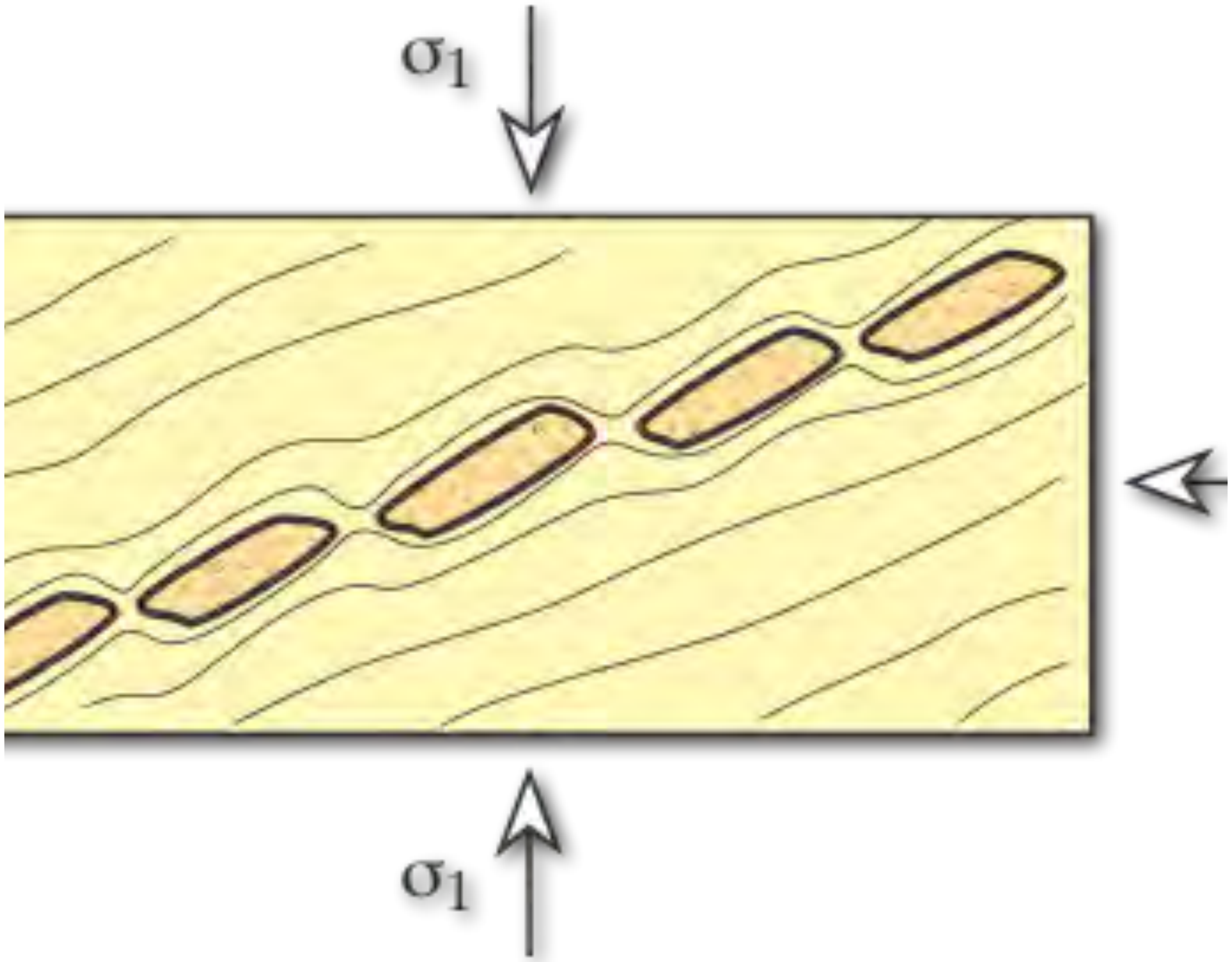
Asymmetric Boudinage

Asymmetric boudinage can develop fol-loling two processes.

1/ When extension occurs at an angle to the layering, necking and thinning in stronger layers can initiate via the development of shear fractures. The boudins evolve with a strong asymmetric shape, and each boudin rotates during extension, while developing a sigmoid shape.

2/ Asymmetric boudinage can also evolve from shearing when the shear zone cut through a layered rock formation. In this case the sense of shear can be inferred by the sigmoid shape of the boudins, and/or the curvature of the fabric of the host rock against the inferred shear bands.

Gallery 5.1 Asymmetric boudinage



Mind the Gap ...

Folding and boudinage are NOT characteristics of contractional and extensional tectonics respectively. Both types of structure can be found in any tectonic regimes. In fact boudinage can be the consequence of folding.

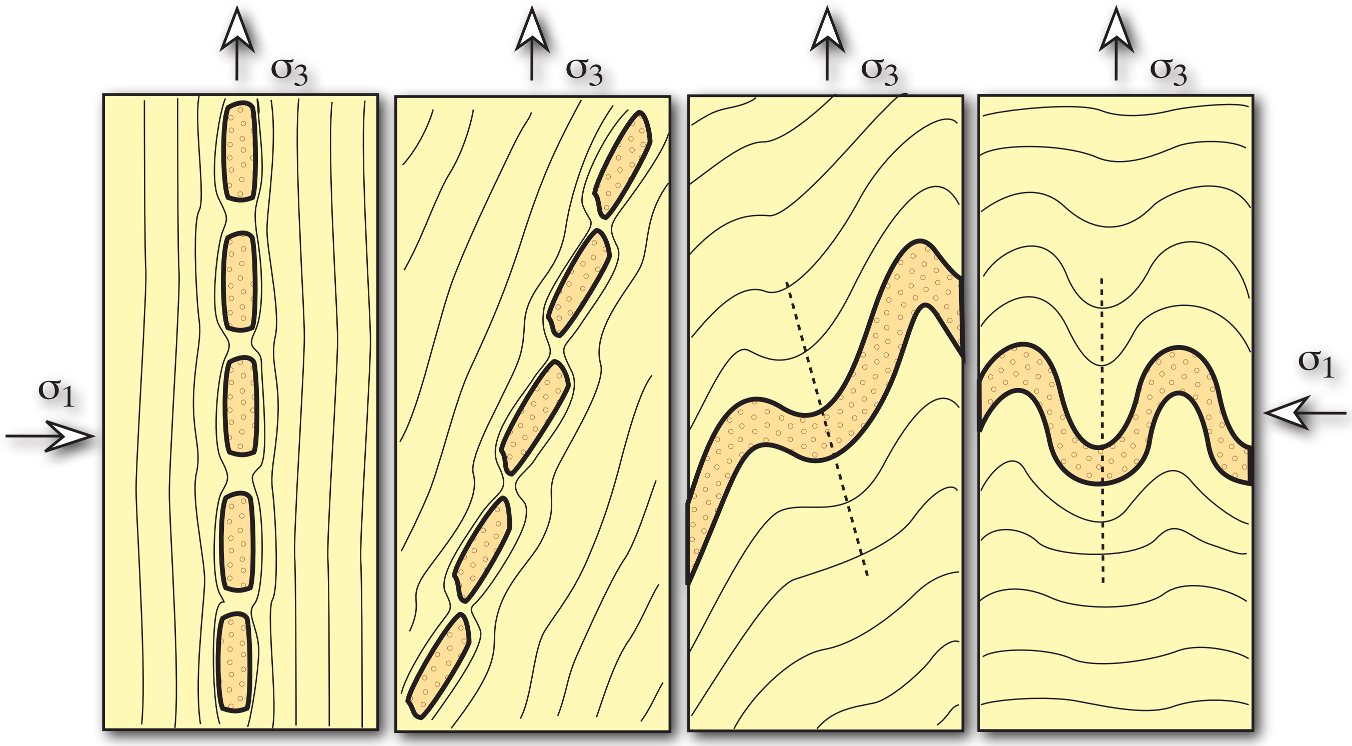


Photo on top: Folds and boudins (Montagne Noire, France, Photo credit: P. Rey).
Photo at bottom: Folds and boudinage in ore body, the picture is ca. 8 cm long (Mt Isa, Queensland, Photo credit: P. Rey)

CHAPTER 6

Ductile Shear Zones

Lithospheric scale ductile shear zone in south Madagascar (S24°30′ - E44°56′, north is to the right, length of the picture: ca. 50 km). The rock body in the middle is an Neoproterozoic anorthosite. The shear fabric wraps around this anorthosite developing a sigmoide pattern, which suggests a top to the north sense of shear. However the stretching lineation is sub-vertical ...

Definition

Ductile shear zones develop as a results of slow, progressive deformation over long period of time. Deformation is typically continuous and develop without macro-scale fracturing. Deformation is said to be ductile as opposed to brittle. Shear zones are therefore different to brittle faults, which involve sudden mechanical instabilities that explain earthquakes.

While faulting and fracturing typically develop at low temperatures (<250ºC), and/or high-strain rates, and/or high-deviatoric stresses, ductile shearing is the mode of deformation at higher temperatures (>250ºC), low strain-rates, and low deviatoric stresses. Ductile shear zones tend to form localised bands of deformation, in an more or less homogeneously ductile strain field.

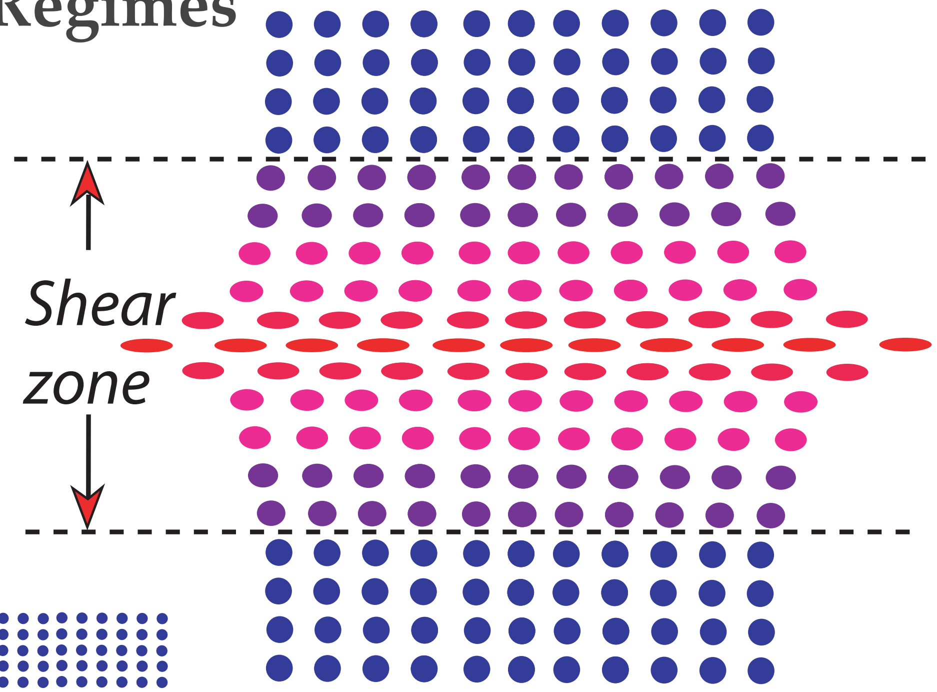
Ductile shear zones are scale-independent and form from mm scale shear bands, to transcontinental shear zones.

Gallery 6.1 Ductile shear zones

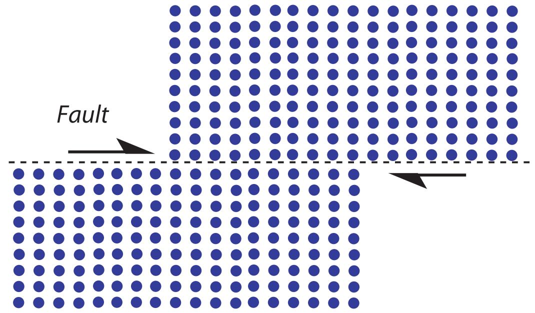
South part of Madagascar (North is to the right). White arrow point to the anorthosite massif shown on the first page of this chapter.

Ductile Shear Zones: Pure vs Simple Shear Strain Regimes

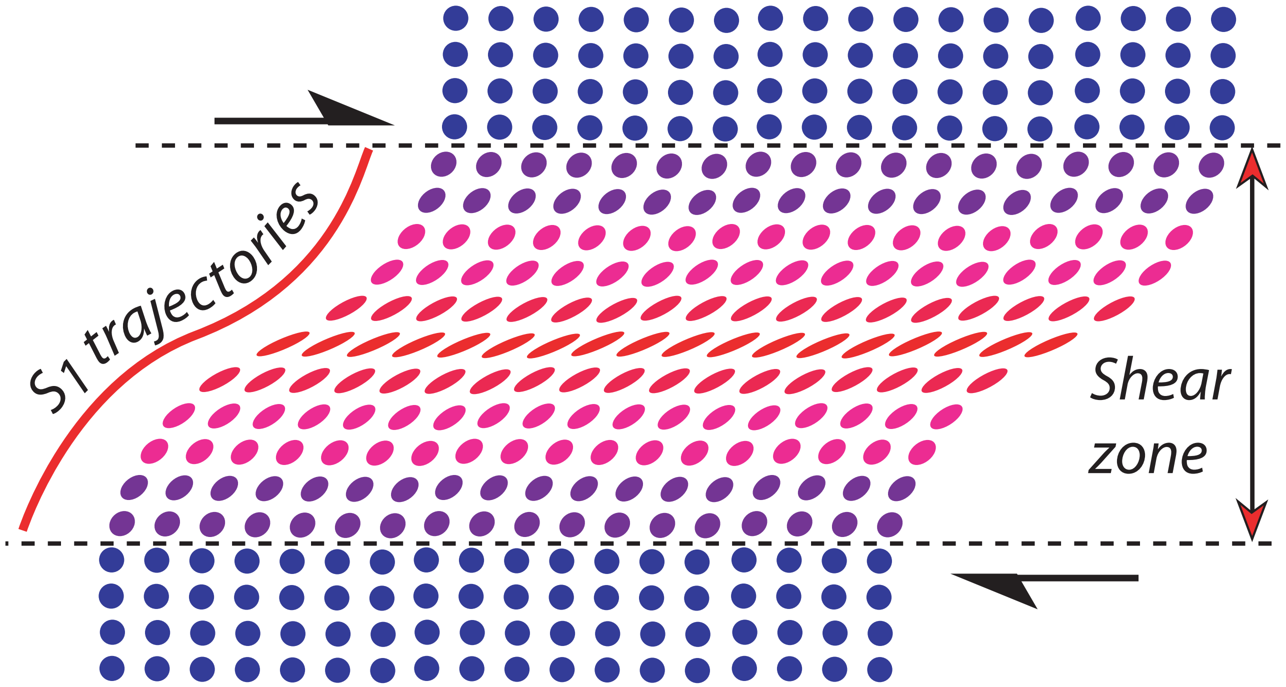
Ductile shear zones can develop as a result of shearing (*simple shear strain regime* as shown on the sketch below) or "squeezing" (*pure shear strain regime*) as illustrated on the sketch on the right. In both cases, the ductile shear zone extends over a band in which strain progressively increases toward the center of the shear zone. As a result, a foliation planar fabric (S_1), i.e. a flattening plane analogous to the cleavage plane in folds, develops.



Foliation trajectories are asymmetric in a simple shear ductile shear zones, i.e. they form an angle with respect to the center of the shear zone. As shear strain accumulate this angle decreases as the foliation becomes progressively parallel to the shear zone. This obliquity between the foliation fabric and the shear zone is a kinematic criteria.

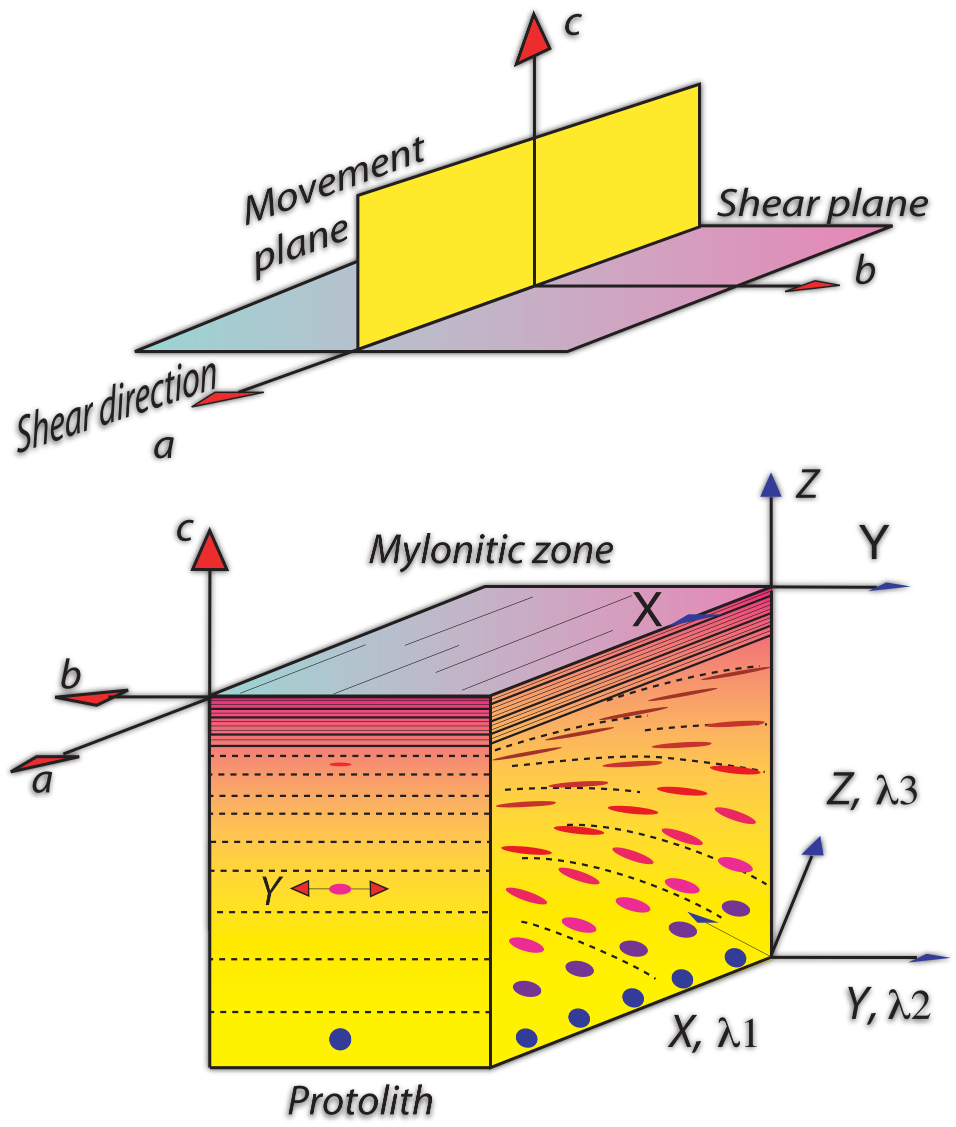


In a pure shear ductile shear zone, the foliation trajectories are parallel to the center of the shear zone, and remain parallel has strain accumulates.



Ductile Shear Zone Descriptors

The *mylonite*, is the central part of the shear zone where deformation is the most intense. In a mylonite, the grain size is significantly reduced and hardly visible to naked eyes. Mineral clasts appear to float in a fine-grained matrix made of recrystallized grains. The *protolith* corresponds to the undeformed rock from which the shear zone developed.



Two reference frames are used to describe shear zones:
The first is related to the finite strain. It consists of three orthogonal axes: X, Y, Z (or λ_1, λ_2, λ_3). Together, X and Y define the flattening plane (i.e. foliation plane). X is parallel to the direction of maximum elongation (i.e. the maximum stretching direction), therefore it is parallel to mineral and stretching lineation formed by the progressive rotation and stretching of mineral and mineral aggregates. Z is the pole of the foliation plane.

The second framework is related to the displacement field, it is called the kinematic frame. It consists of three orthogonal axes: *a*, *b*, and *c*. Together *a* and *b* define the shear plane in which *a* corresponds to the shear direction. This plane is parallel to the mylonitic zone. The axes *a* and *c* define the movement plane. This plane is perpendicular to the shear plane and parallel to the shear direction. The kinematic reference frame remains constant in orientation throughout the shear zone. In contrast, the finite strain reference frame progressively rotates around the axis Y to parallel the kinematic frame in the mylonitic zone. The sense of rotation is a kinematic criteria.

Shear Criteria and Kinematic Analysis

Pressure shadows

Kinematic analysis is the art to figure out the relative sense of shear in shear zone, when the shear zone involves a strong component of simple shear.

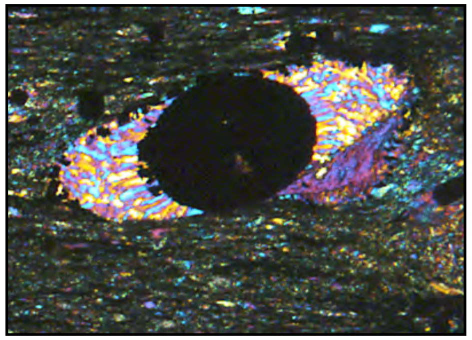
Gallery 6.1 Pressure shadows and crystallization tails

Caledonian (ca. 400 Ma) eclogite facies ductile shear zone, Holsnoy (Norway)

1 of 12

One class of kinematic criteria is based on the asymmetric flow and asymmetric finite strain that result from to the presence of mechanical heterogeneities introduced by minerals and mineral clasts more resistant to deformation than the enclosing matrix. Upon shearing, zones of *pressure shadows* and zones of pressure concentration develop around these clasts. As fluids and their solutes migrate from high to low pressure, mineral growth occurs in pressure shadows, while dissolution affects zones of pressure concentration. The asymmetry of *crystallization tails* around clasts depends on the sense of shear and as such can be used as kinematic criteria. Crystallization tails develop around a clast being progressively dissolved. The rate of dissolution is faster for a sigma pressure shadows than for a delta pressure shadows.

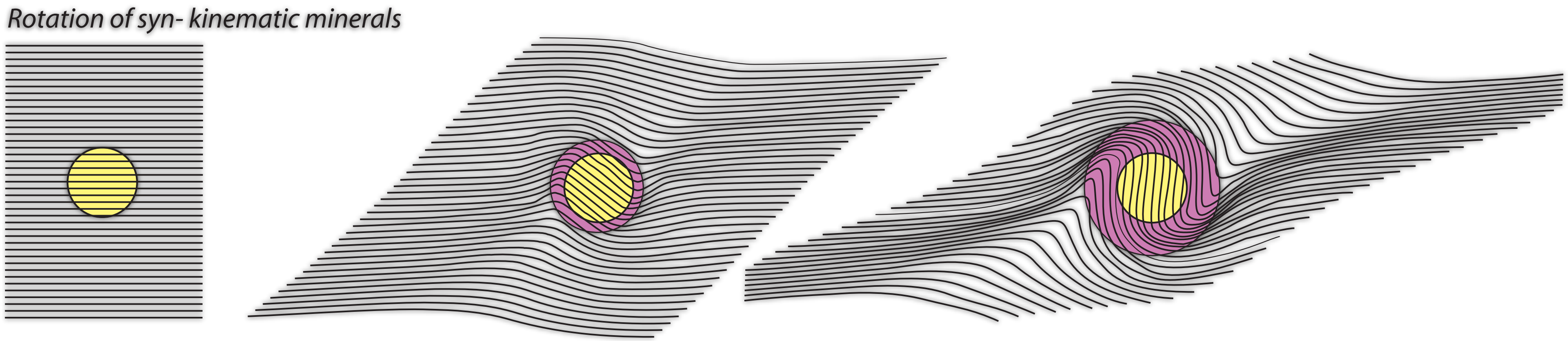
Pyrite grains in shale is an extreme case of hard clasts in soft a matrix. As pyrite rotates during shearing, space incrementally open up at the contact pyrite/matrix. These spaces are filled with fluids that precipitates minerals ofter in a fibrous form such a calcite and quartz.

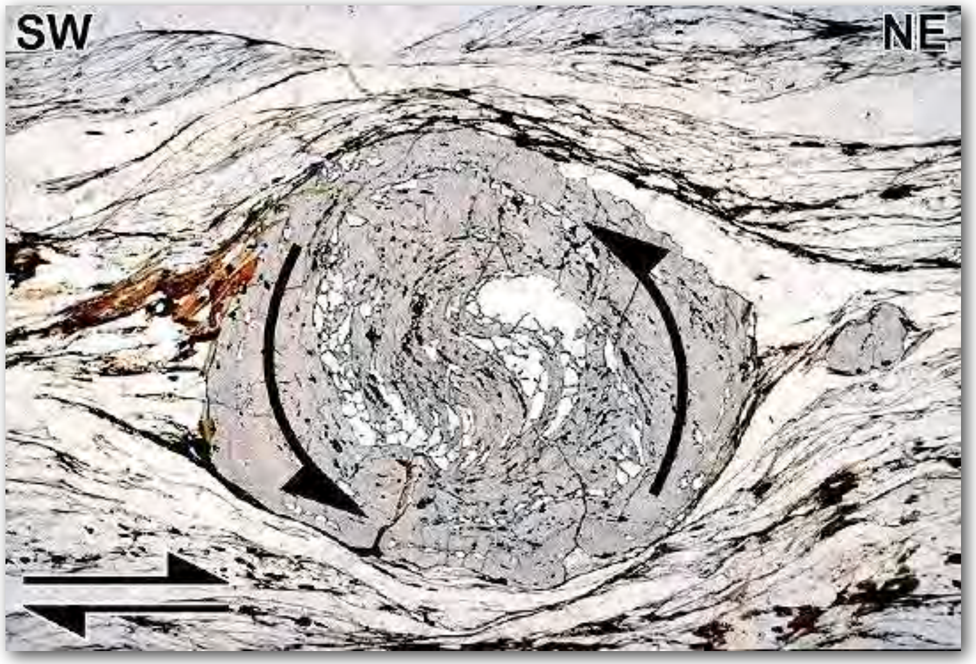


@ Jörn Wichert

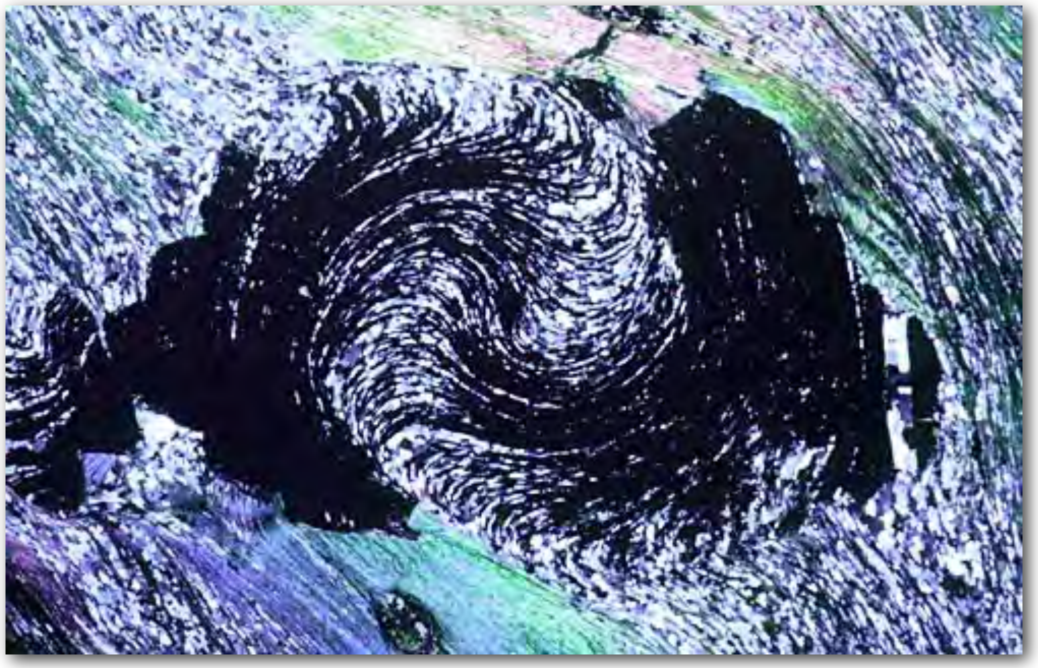
Helicitic inclusions

Helicitic inclusions in porphyroblasts- Some minerals like garnet and staurolite can growth during shearing. These so called *porpyroblasts,* as opposed to *porphyroclasts* which are old fragments of mineral, act as tape recorder for deformation. As they growth porphyroblasts "freeze" the schistosity that develops in the surrounding matrix. An internal schistosity is recorded whose pattern reflects the kinematic of the shearing.





@ Pierre Dèvez: Syntectonic garnet in a metapelite. Helicitic inclusion trails indicate top-to-the-SW rotation. Shear sense criteria in the matrix indicate an opposite shearing associated to a more recent shearing event.

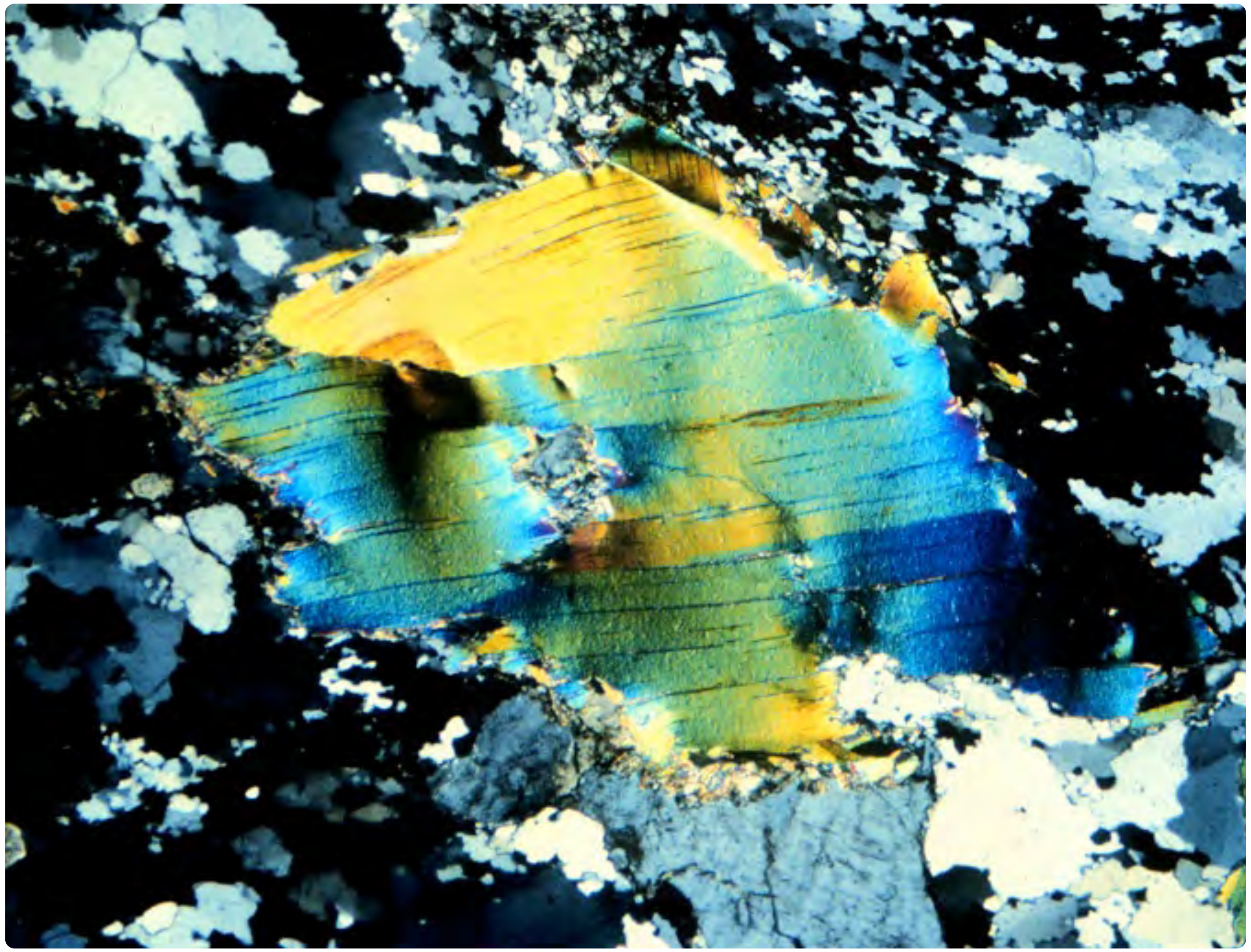


@ Scott Johnson: Syntectonic garnet porphyroblast in a metapelitic rock. Helicitic inclusion trails indicate clockwise rotation of the gar-net during shearing.

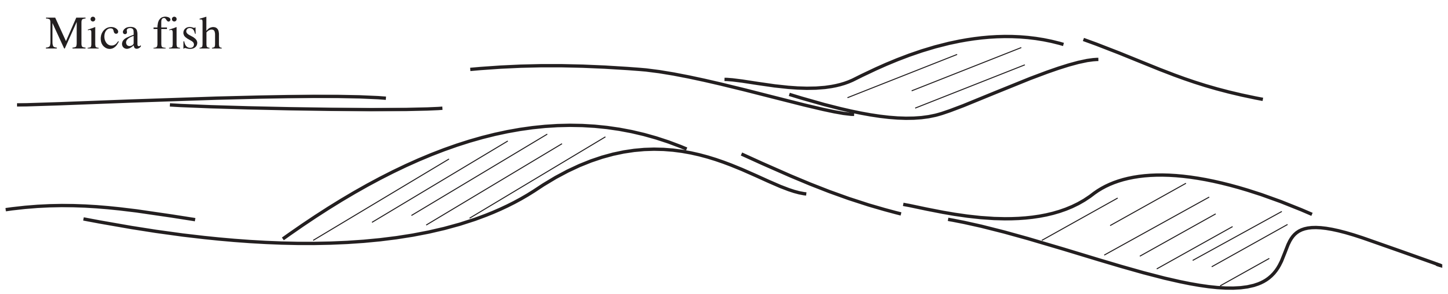
Mica fish

Mica fish- Mica fish, usually muscovite, progressively rotate during deformation. At some stage their cleavages, which corresponds to a plane of easy slip, become sub-perpendicular to the direction of maximum stress. When this happens, the cleavage plane of the mica become locked. Deformation, jump to the margin of the mica where micro-shear bands initiate. These micro-shear bands progressively lengthen to become shear bands.

Gallery 6.2 Mica fish



Large muscovite grain



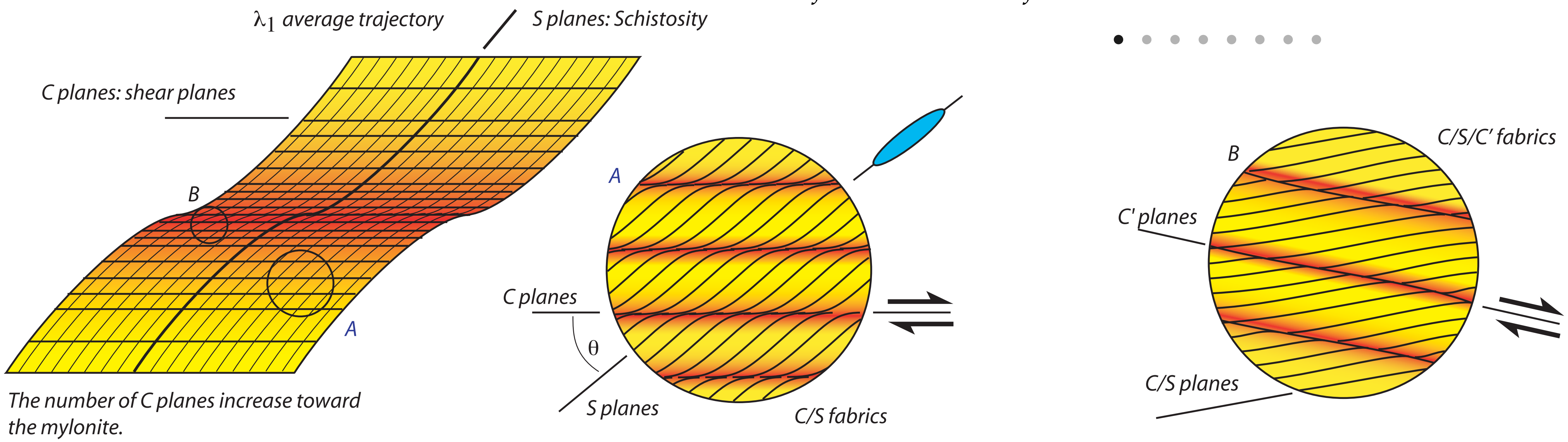
C-S and C-S-C′ shear fabrics

C-S and C-S-C′ shear fabrics - A class of kinematic criteria is based on the obliquity between the kinematic and the finite strain reference frame. Throughout a shear zone the foliation - or S - plane - (S for schistosity) rotates to parallel the shear plane - or C plane - (C for the french work cisaillement). As the shearing increases the angle between S and C decreases (see below). This rotation is consistent with the kinematic of the shear zone i.e. a clockwise rotation of the S plane implying a clockwise sense of shear on the C plane.

In the mylonitic core, where C and S are sub-parallel, a new generation of shear plane called C' may develop with a small angle (10-15°) to the C plane. This is illustrated in the sketch showing a CSC' mylonite.

Gallery 6.3 Ductile shear zone in a leucogranite

Gamma ~1, foliation clearly visible (leucogranite du Gueret, North part of the French Massif Central).



A Little Quiz ...

1/ What is a shear zone?

2/ Define the concept of pure shear strain regime?

3/ How can one tell when a shear zone is the result of a simple shear strain regime?

4/ Define the following terms: Mylonite, Protolith.

5/ What is the difference between the movement plane and the shear plane.

6/ Define the strain reference frame and the kinematic reference frame.

7/ What are kinematic criteria?

8/ Slide 36 shows the development of pressure shadows around a pyrite grain. What is the kinematic?

9/ What is an SC mylonite?

10/ Why does SC mylonite cannot form during a pure shear strain regime?

Review 6.1 Lorem Ipsum dolor amet, consectetur

Question 1 of 2

Ductile shear zones develop at:

- **A.** Temperature > 250°C
- **B.** Low strain rates
- **C.** High differential stress
- **D.** Only during simple shear

Check Answer

CHAPTER 7

Foliations and Lineations

During deformation, rock forming grains and minerals change their orientation and shape, giving deformed rocks organized planar and linear structures called fabrics. Foliation (the result of flattening) and lineation (most of the time the result of elongation) are planar and linear fabrics respectively that record the finite strain.

Definitions

Planar fabrics resulting from deformation are called schistosity or foliation. Foliation results from the ductile flattening of grain aggregates (e.g. quartz), and/or the change in orientation of tabular minerals (e.g. micas), and/or the anisotropic growth of newly formed minerals. Often, this flattening is not isotropic, i.e. a sphere is not flatten into a circular pancake but into an elliptic one. In this case, the foliation plane carries a linear fabric called a lineation. This lineation is due to the stretching of grain aggregates, the re-orientation of elongated minerals (e.g. amphibole, rutile), and the preferential growth of newly formed minerals. The lineation corresponds to the direction of maximum stretching (X) within the foliation plane (XY).

In the field, the attitude of a foliation plane is determined by its strike, its dip and its dip direction.

Gallery 7.1 Foliations

Schistosity fabric in a finely bedded sedimentary rock (psammite, north of Broken Hill, NSW).

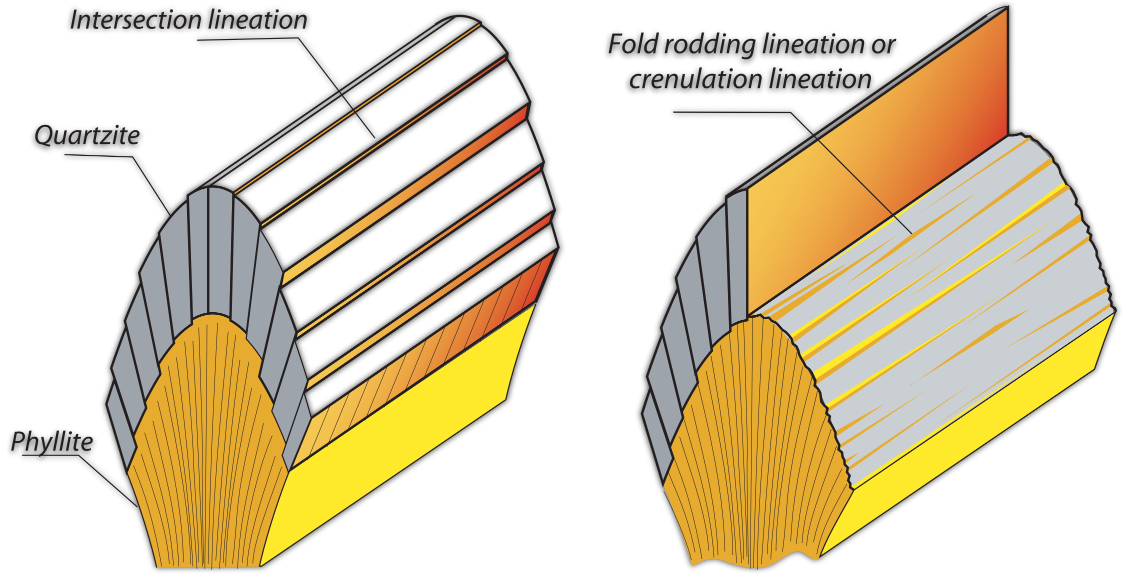
The pictures in the gallery 7.2, illustrate an example of strong linear fabrics. The outcrop shows a deformed rhyolite (felsic volcanic rock equivalent to granite) of the Wyman formation (ca. 3.3 Ga) in the east Pilbara (WA). Such a strong linear fabric is referred to as a constrictional fabric. In the field, the attitude of a lineation is fully characterized by its plunge (angle from an horizontal surface down to the lineation) and plunge direction (azimuth of the imaginary vertical plane carrying the lineation).

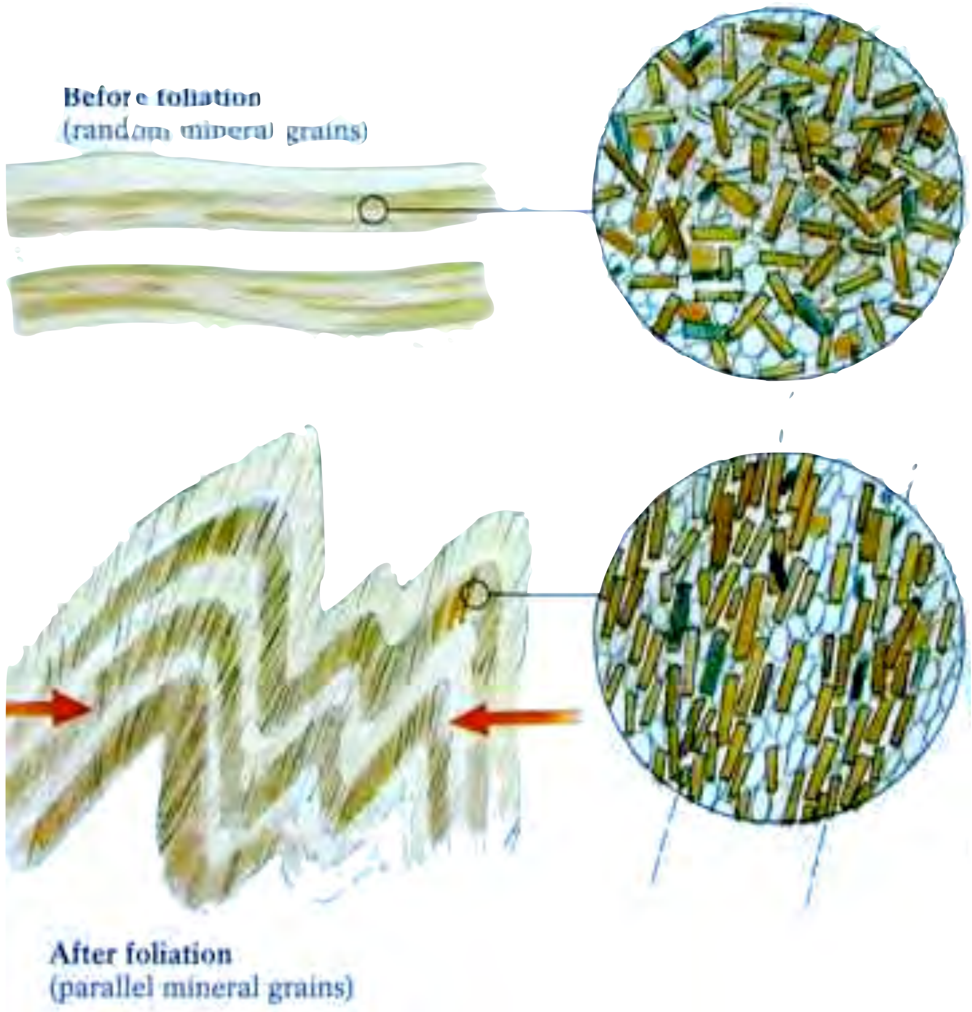
Gallery 7.2 Lineations

The outcrop shows a deformed rhyolite (felsic volcanic rock equivalent to granite) of the Wyman formation (ca. 3.3 Ga) in the East Pilbara (WA). This outcrop shows a very strong steeply dipping linear fabrics and a rather weak to very weak flattening plane.

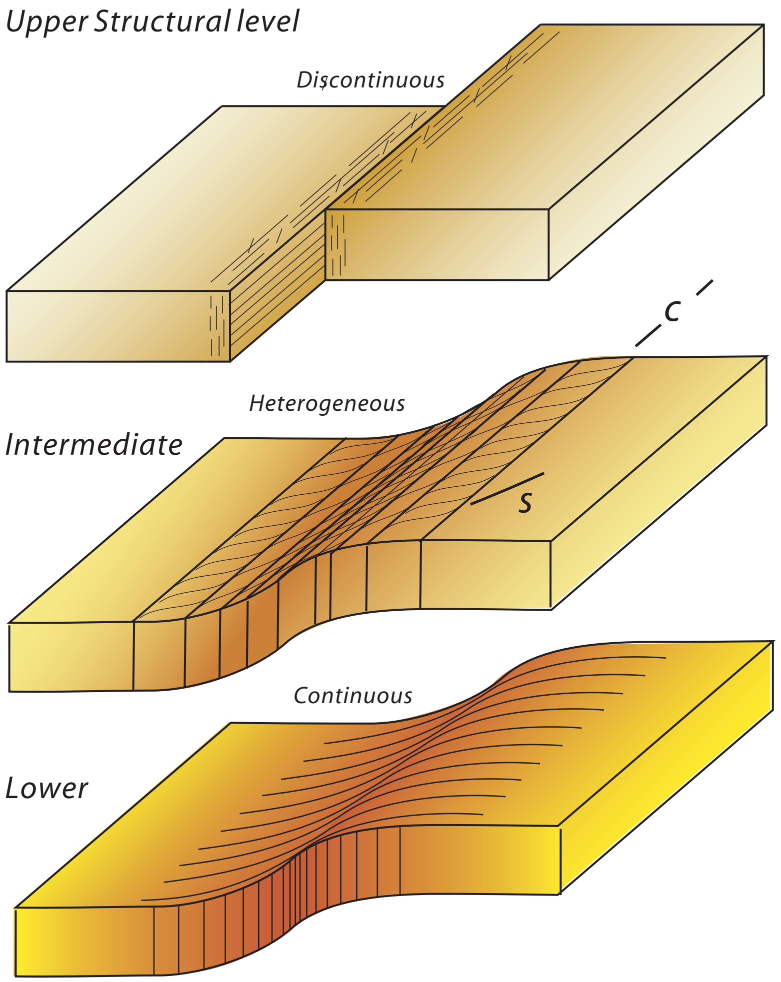
Foliation and Lineation Forming Processes

1/ *Folding* - During folding, grains and minerals are re-oriented and flattened into a planar fabric called axial planar fabric. This fabric may "refract" (i.e., change direction) across beds (picture on the lower right). Where this tectonic fabric intersects a pre-existing fabric, such as a bedding plane, intersection lineations form. These lineations runs parallel to fold closures.



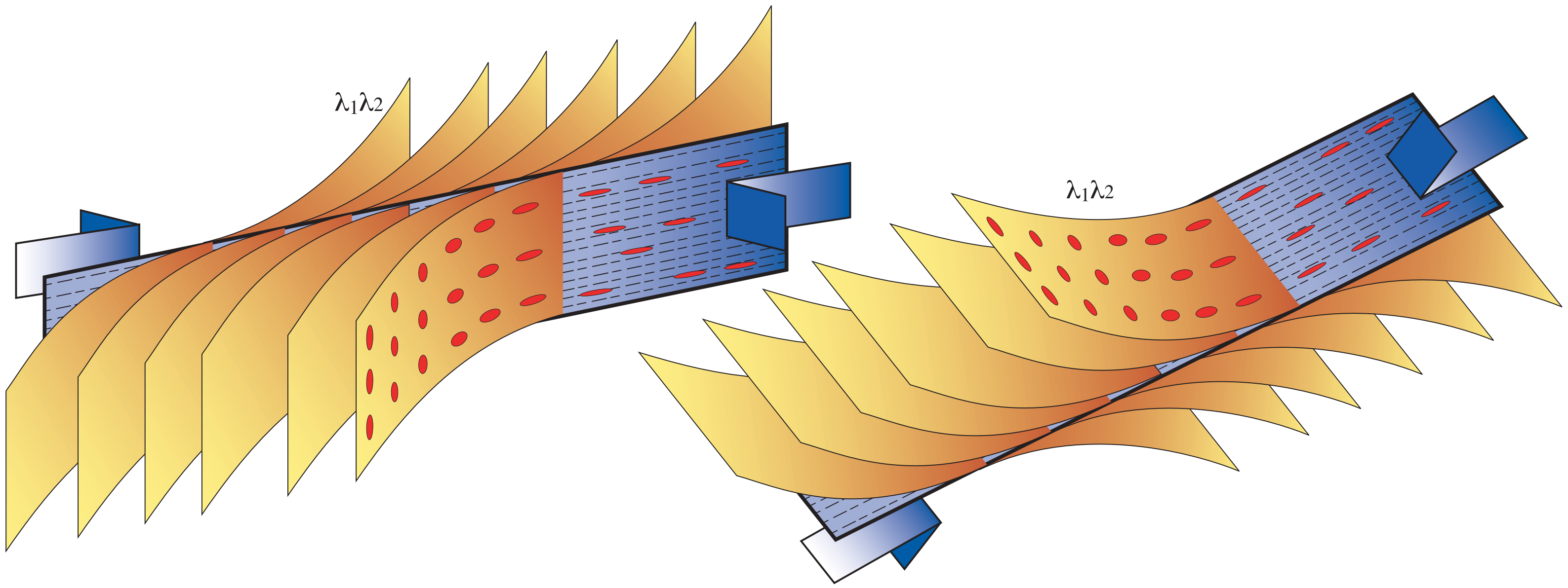


2/ *Shearing* - Shearing leads to the flattening and stretching of rock's forming grains and minerals. As temperature/depth increases, shearing evolves more pervasive/continuous fabrics. At relatively low temperature (250-450°C) shearing is more localized and strong minerals such as feldspar are brittle. At relatively high temperature (>600°C) strain is more homogeneous as feldspar becomes ductile.



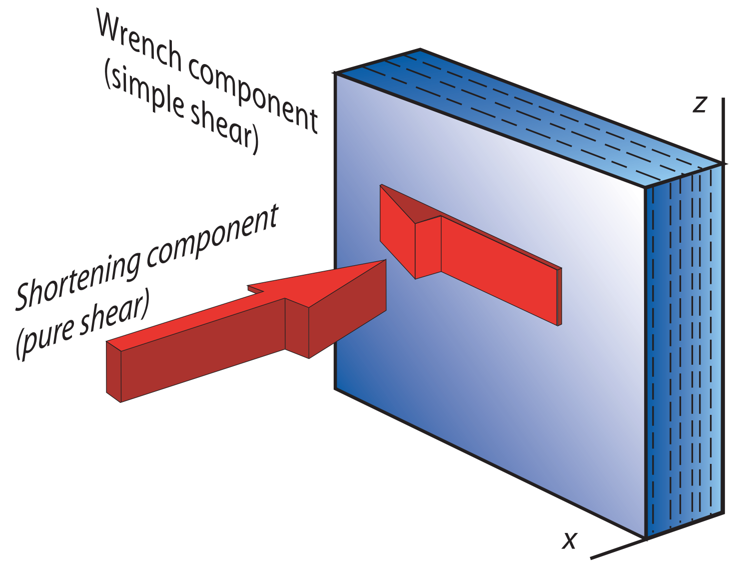
Gallery 7.3 Shear foliation and lineation

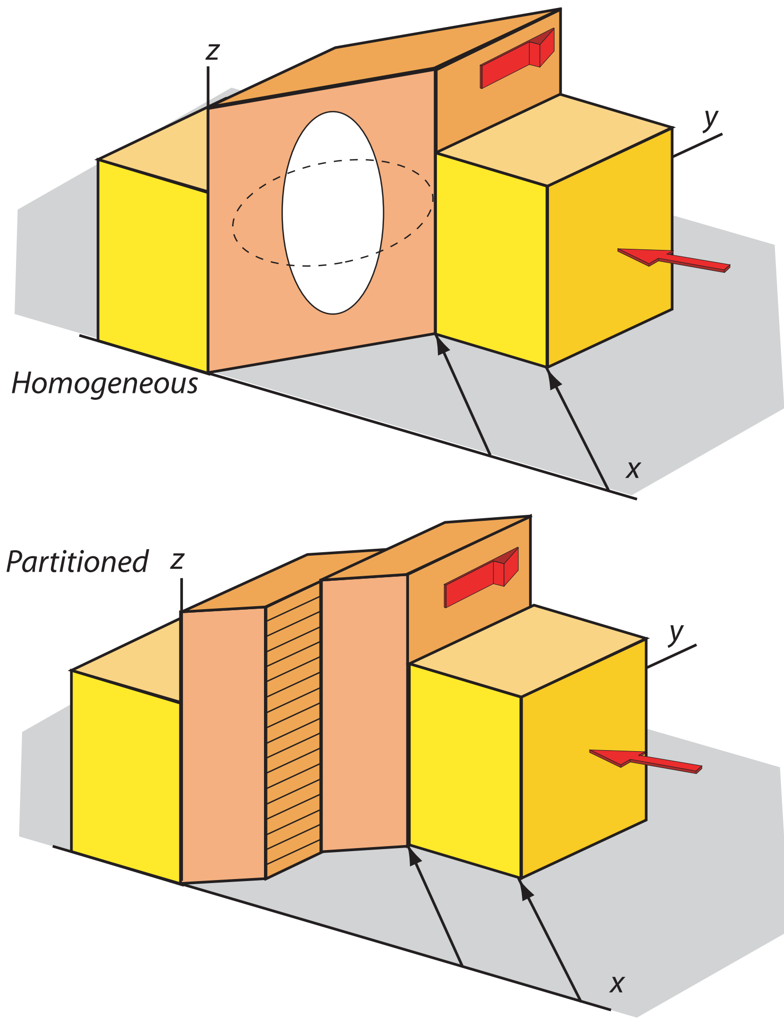
Shear zone with pressure shadows around garnets (Barberton Greenstone Belt, SA).

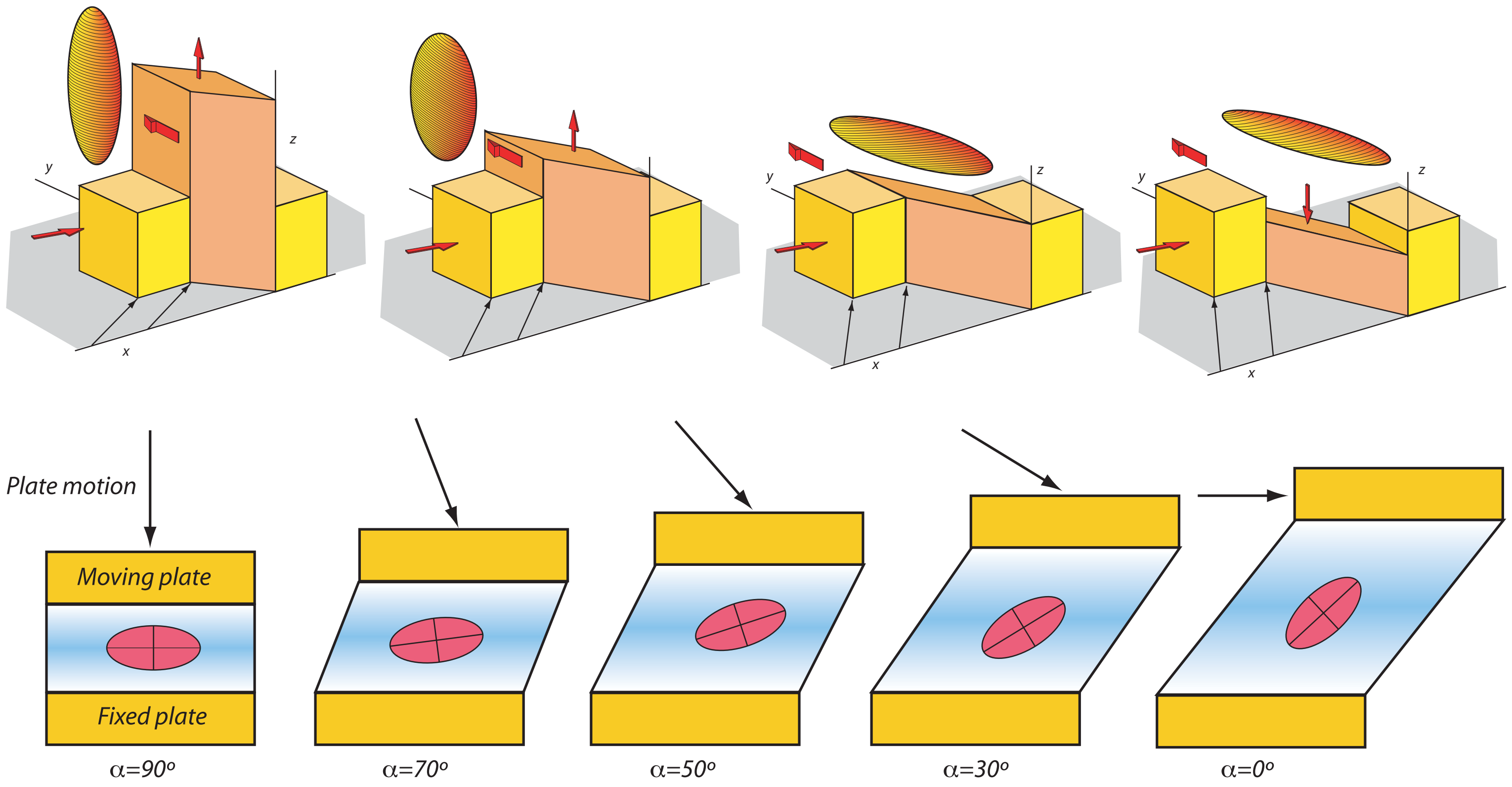


Strain partitioning and triaxial deformation

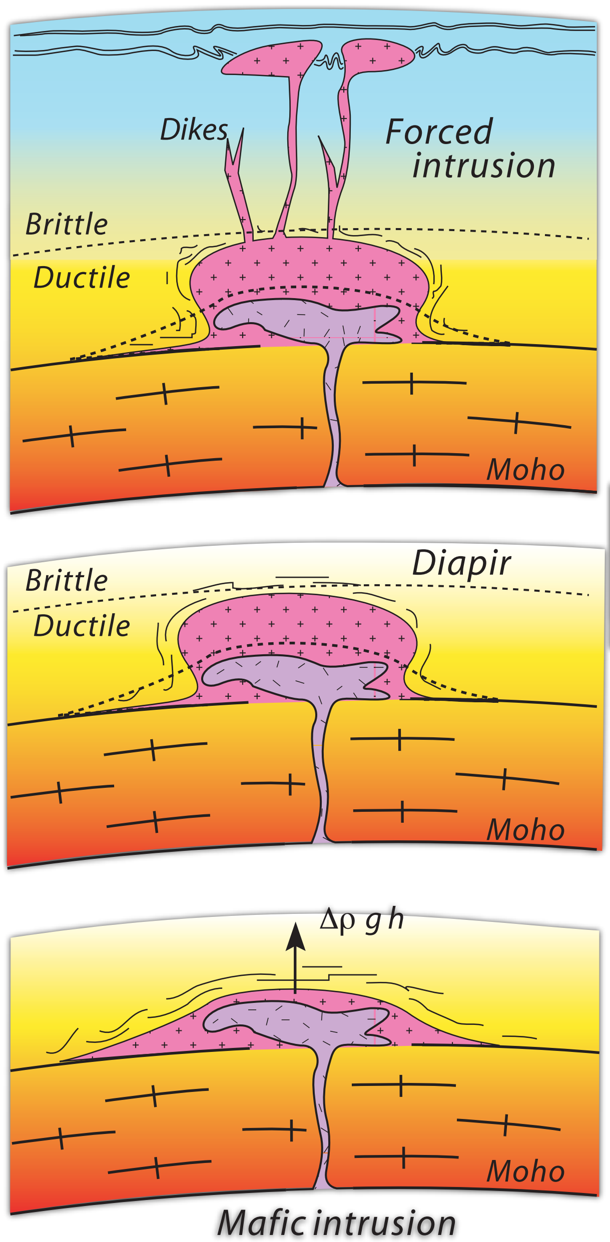
Simple shear and pure are only two end-members of an infinite gamut of shear in which both pure shear and simple shear are involved. In these cases, the relationship between finite strain framework and the kinematic framework is complex and may led to some unexpected observation. For instance, in a triaxial shear, stretching lineation can be strong to non-existent, and its plunge can be either vertical or horizontal depending of the contribution of each strain regime. The process of strain partitioning can explain further complexity. Indeed, strain can be partitioned into region experiencing contrasting strain regimes.

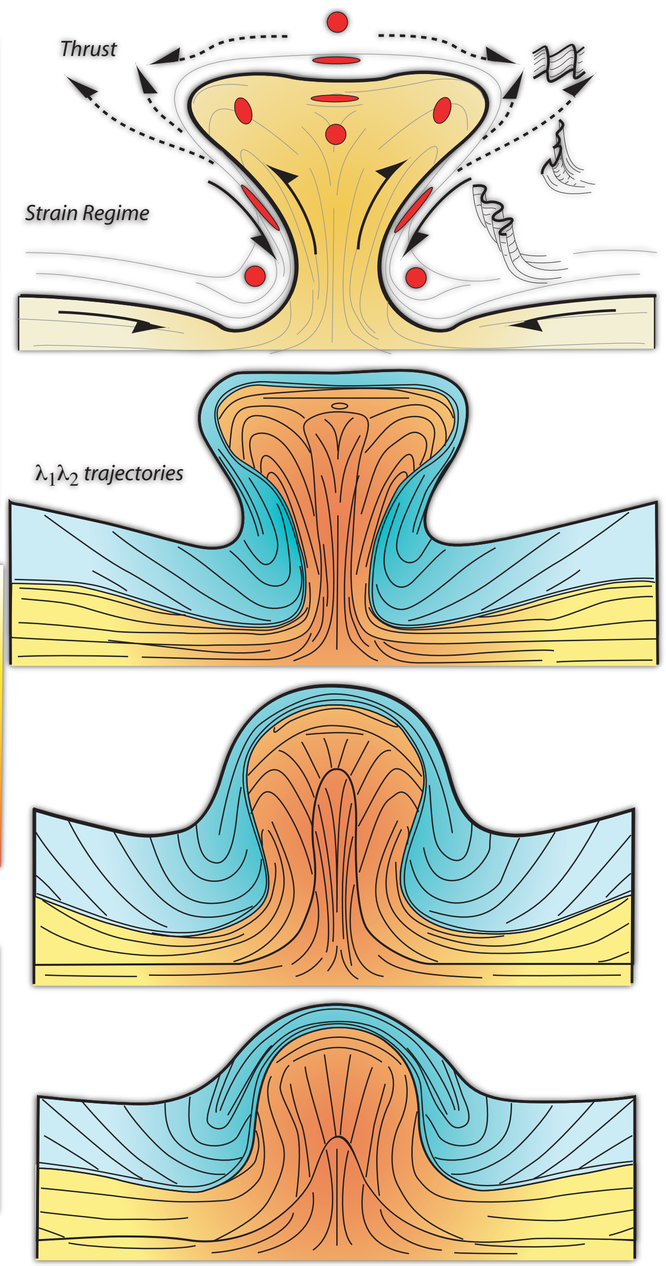




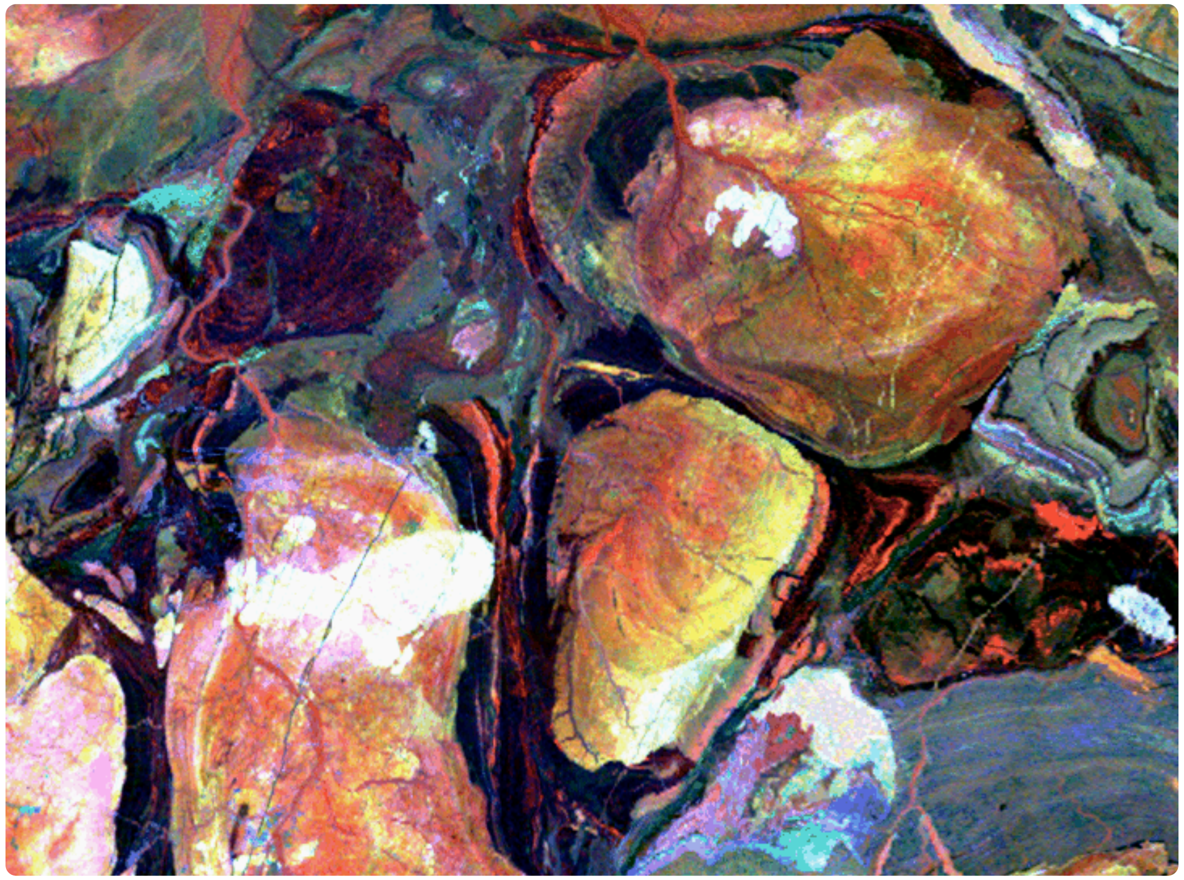


3/ *Flow of magma* results in the rotation of minerals into magmatic foliations and lineations. Magmatic foliation does not say much about the direction of magmatic flow. Like any other tectonic fabrics, magmatic fabrics only inform about finite strain (i.e. X,Y and Z axes of the finite strain framework). In the field, it is relatively easy to distinguish between magmatic foliations and solid-state foliation. Magmatic foliations are best seen with a bit of distance from the outcrop. Indeed, as one look close a the scale a few times the average grain size, the foliation is no visible. Solid-state foliations are visible at all scale.



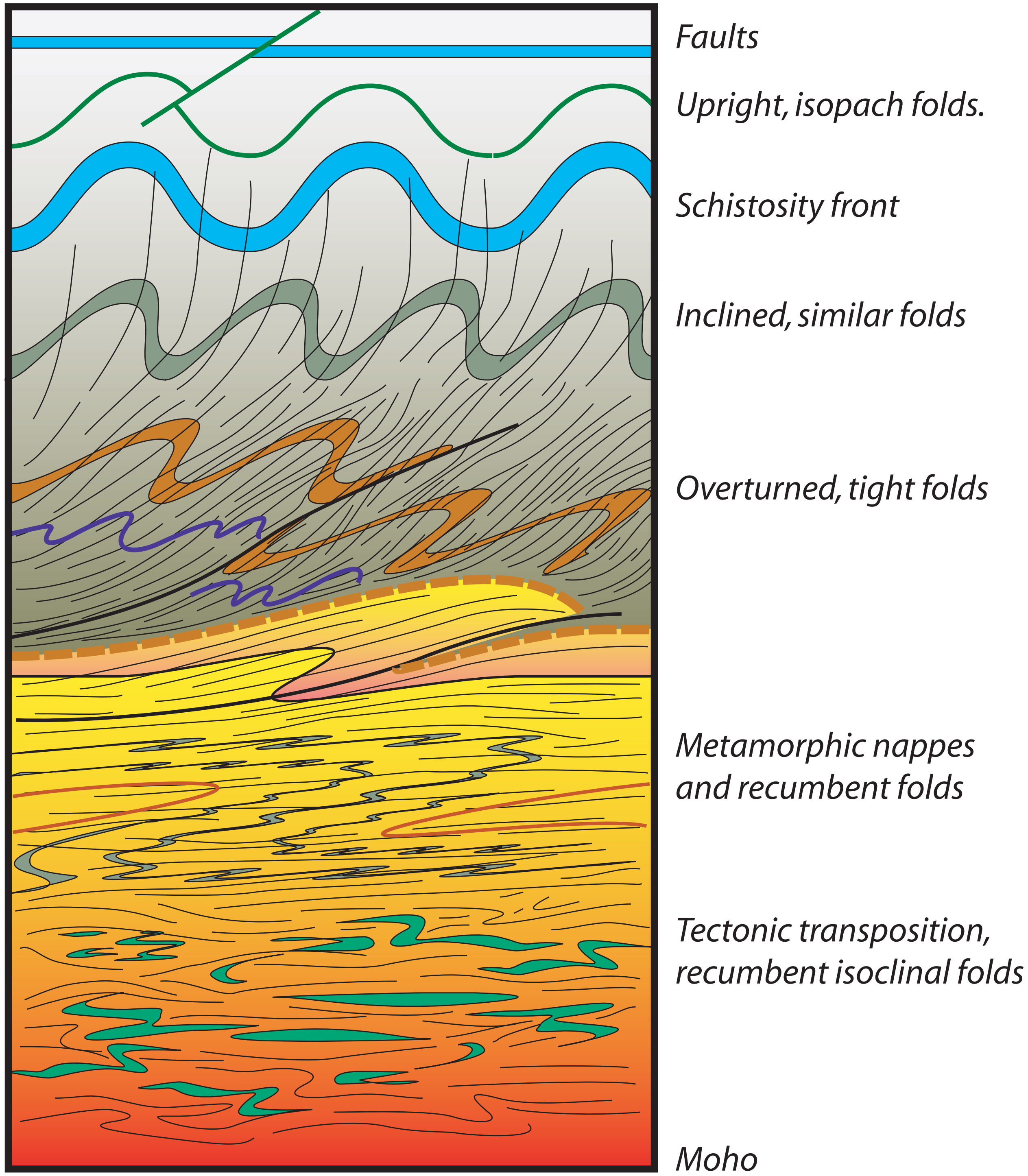


Gallery 7.4 Magmatic foliations and lineations

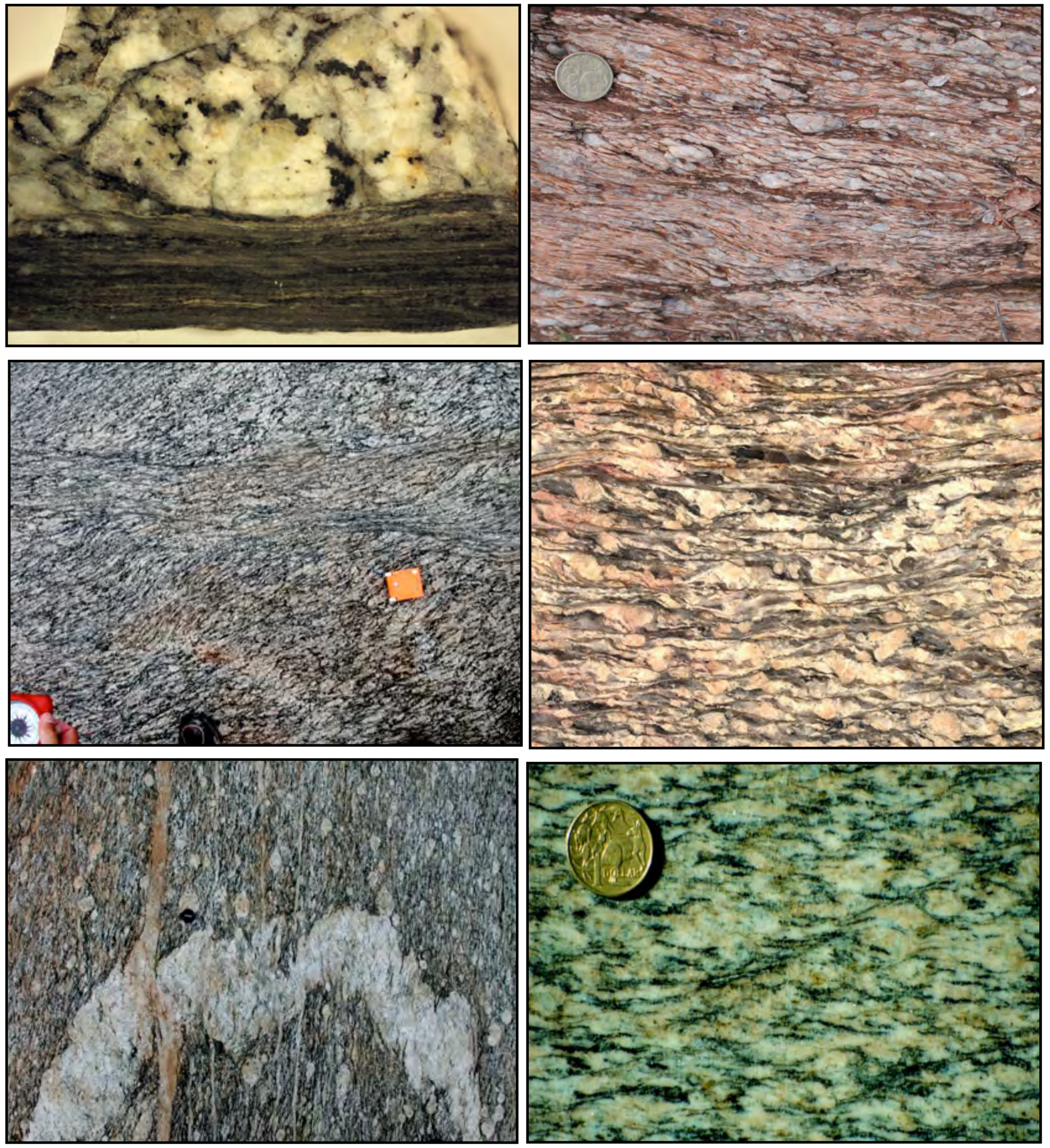


Radiometric image of the dome and basin pattern in the East Pilbara Craton (WA).

Fabrics in the Continental Crust



As temperature increases with depth, rocks become weaker and their strength contrast decreases. This explains the growing homogeneous character of tectonic fabric with depth.

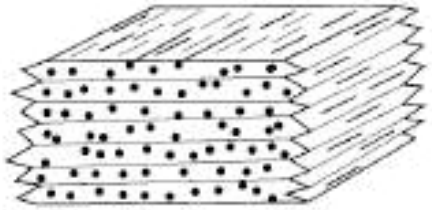


Tectonites Classification

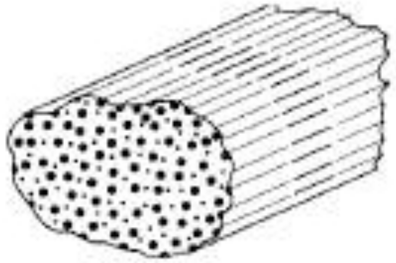
The relative strength (ie intensity) of the planar fabric and the linear fabric is used as a qualitative criteria to classify tectonites. S-tectonites are characterized by a strong and pervasive schistosity and no lineation. S-tectonites are the result of isotropic flattening in which there is one direction of shortening and radially symmetric stretching. In SL tectonites the foliation plane carries a mineral and/or stretching lineation. Simple shear strain regime is often involved in the formation of SL tectonites. L-tectonites are characterized by a prominent lineation and a no schistosity plane. L-tectonites form when there are multiple direction of shortening and one direction of stretching.

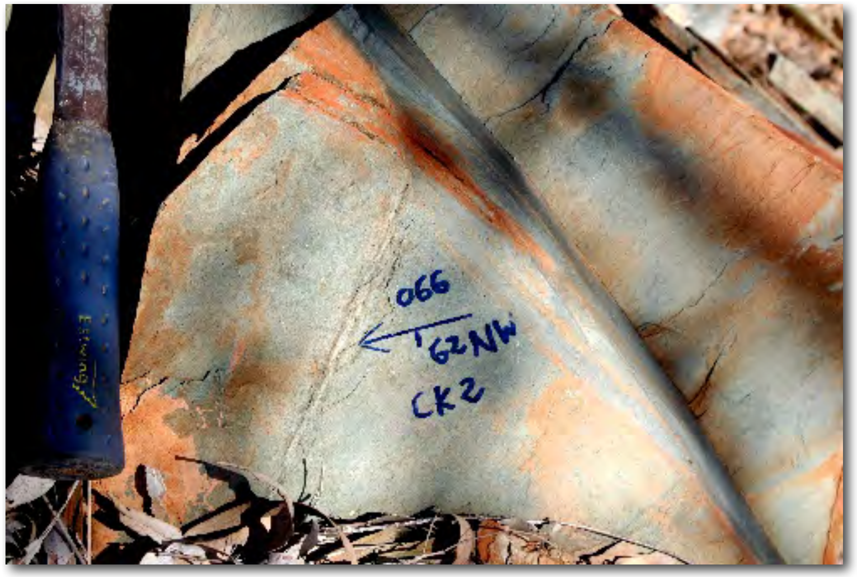
S - Tectonites

SL - Tectonites



L - Tectonites





A Little Quiz

1/ In structural geology what is a "fabric"?

2/ What are the main fabric-forming processes?

3/ In a granite, how can we tell that a foliation formed at a temperature of about 400ºC from one formed at a temperature of ca. 700ºC.

4/ What is a tectonite?

5/ Define the three main types of tectonites.

6/ Can a ductile shear zone results in the formation of a S-tectonites?

7/ What is the difference between an intersecting lineation and a stretching lineation?

Gallery 7.5 Lorem Ipsum dolor amet, consectetur

L tectonite (Klondyke district, East Pilbara, WA)

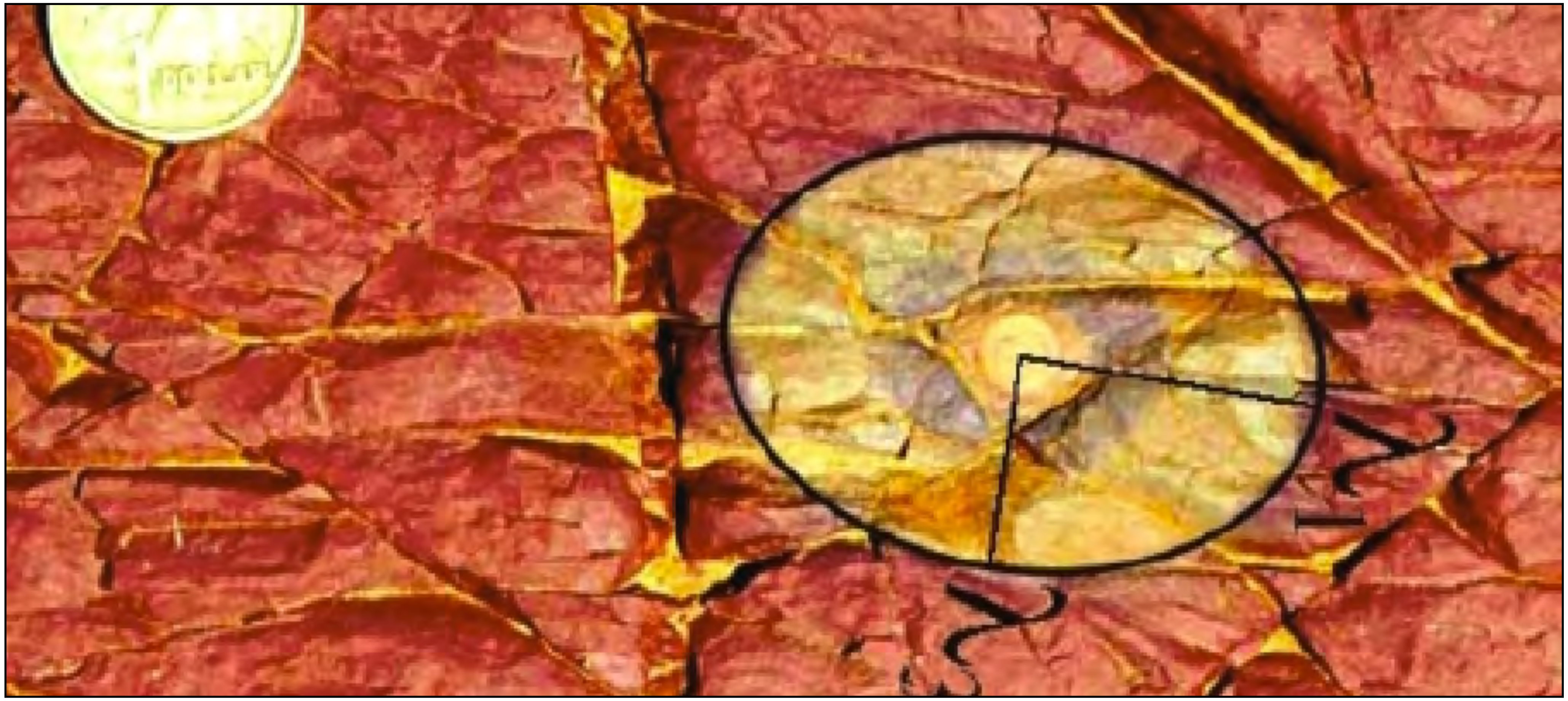
8/ Are stretching lineations automatically linked to a foliation plane?

9/ Can stretching lineations pierce through a foliation?

10/ The attitude (ie orientation in space) of a foliation plane is measured through its strike-dip and dip direction. Draw a sketch showing showing the concepts of strike, dip and dip direction.

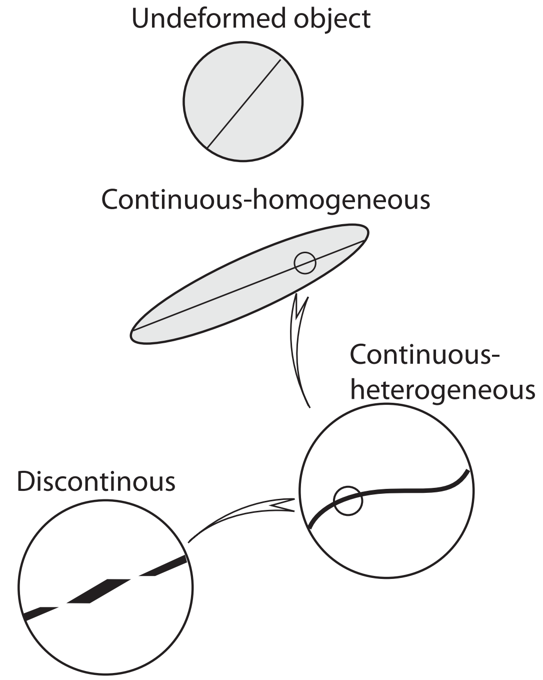
CHAPTER 8

Strain and Strain Analysis



Structural geologists observe and document structures, such as faults and fractures, ductile shear zones, folds and boudins, foliations and lineations, not because they are pretty, but because they give information about finite and incremental strains. This chapter focusses on understanding progressive strain as a continuum process, and developing a strategy to quantify strain.

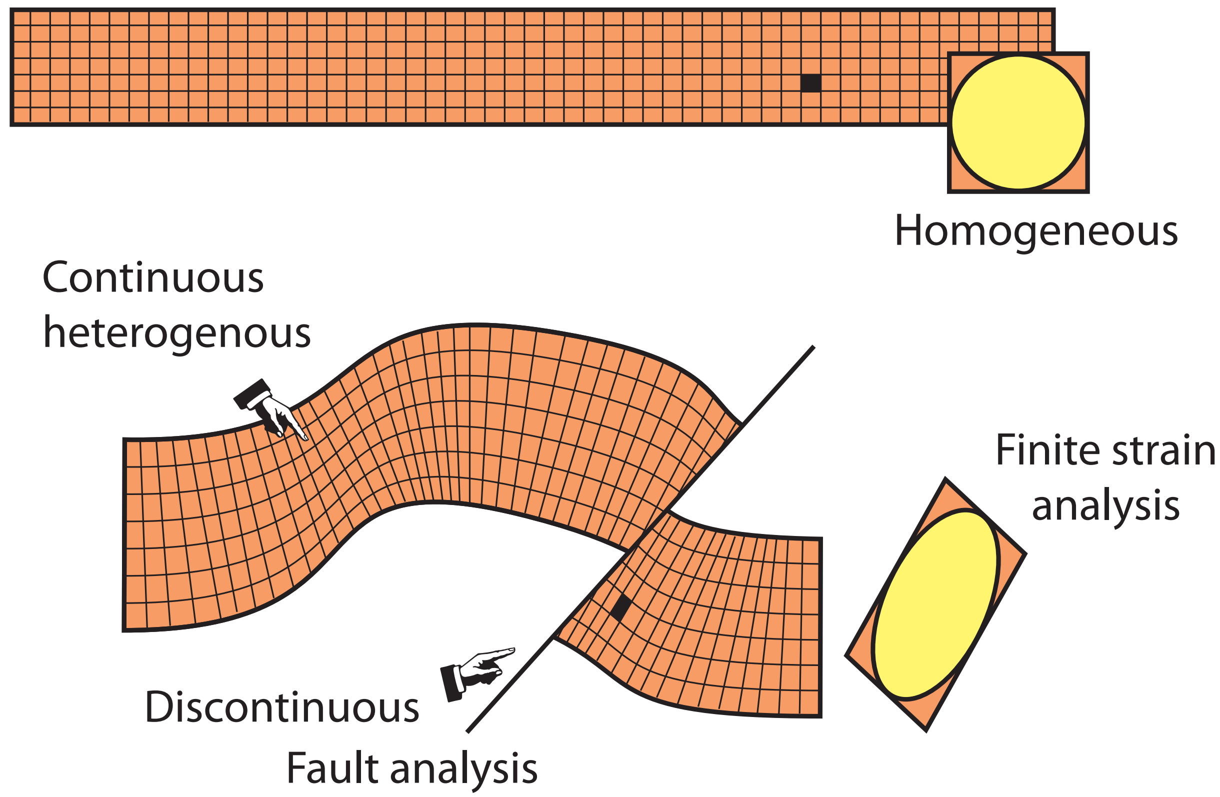
Continuous vs Discontinuous Strain



Deformation is very often partitioned between discontinuities (faults and shear zones) that limit domains where deformation is continuous (cf. sketches below). Finite strain analysis allows the characterisation of the final state of deformation (the finite strain) in domains where deformation is continuous, whereas fault analysis characterises strain associated with discontinuities. Both analyses are necessary to fully characterise finite strain fields.

The analysis of faults and shear zones consists in documenting at the local scale their orientation (strike-dip-dip direction), thickness, geometry (single discontinuity plane, anastomosed network of shear zones or brittle faults, overlapping fault segments, etc.), their kinematic and kinematic history (relative sense of displacement through time), their amount of displacement, and finally to derive the orientation of the paleostress through time that resulted in the formation of the observed fault or shear zones.

Finite strain analysis consists in measuring, at the local scale, the direction of maximum shortening and lengthening, characterising the geometry of the strain (flattening, constriction, plane strain, etc.), determining the intensity of the strain, assessing the strain history (big squeeze or a large shearing), and when appropriate determining the kinematic of the strain.



The sketch on the right shows a block before and after deformation. Shortening is accommodated by a fault and rather complex but continuous internal deformation. To characterise the internal deformation of the two blocks we divide them in a number of small cells in which strain can be considered, in first approximation, as homogeneous (=> no strain gradient). When deformation is homogeneous, an imaginary sphere enclosed in each cell of the block before deformation will be transformed into an ellipsoid from which strain can easily be characterised.

Finite strain analysis is only valid when strain is considered at a scale at which strain is homogeneous. The measurement of the characteristics of strain in a large number on cells across the entire blocks fully characterises the Finite Strain Field.

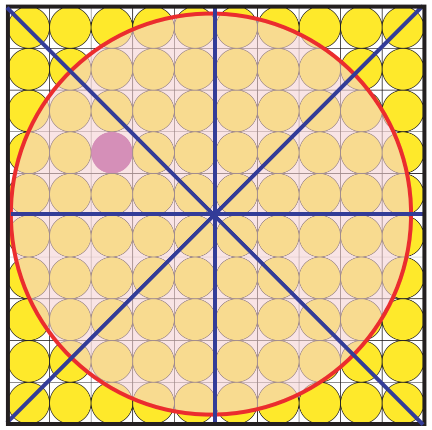
Homogeneous vs Heterogeneous Strain

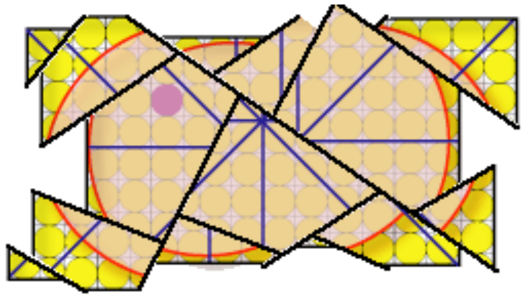
In structural geology, "*deformation*" and "*strain*" are not synonymous.The term "*deformation*" includes *translation*, *rotation*, *change in volume* and *change in shape*. The term "*strain*" refers only to the change in shape, a synonymous term would be "*distorsion*". Therefore, strain is only one component of deformation. In the field, translation, rotation and change in volume are difficult to assess. Strain analysis focuses on the characterization of the change in shape.

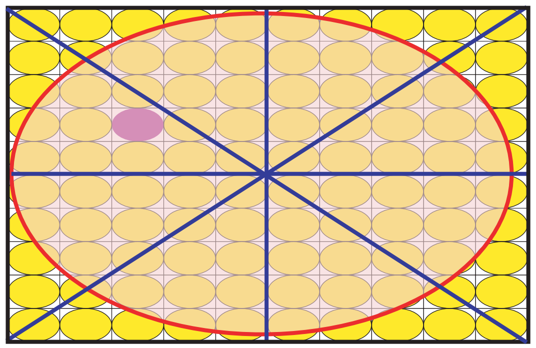
Geometric description of strain

Faults and fractures produce *discontinuous strain*. In this case, strain is assessed by the description of the network of faults and fractures as well as the rotation and translation of individual blocks. When strain involves "viscous" flow then the strain is said to be *continuous* (cases B and C). If the strain is the same at any location of the deformed body (i.e. no strain gradient as in B, the strain is said to be *homogeneous*. In contrast, if strain varies in shape or intensity from one location to another, then strain gradients exist and the strain is said to be *heterogeneous* (case C).

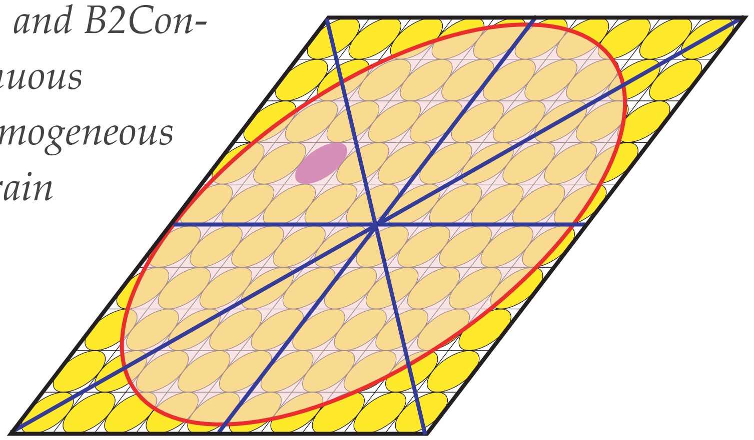
Initial state

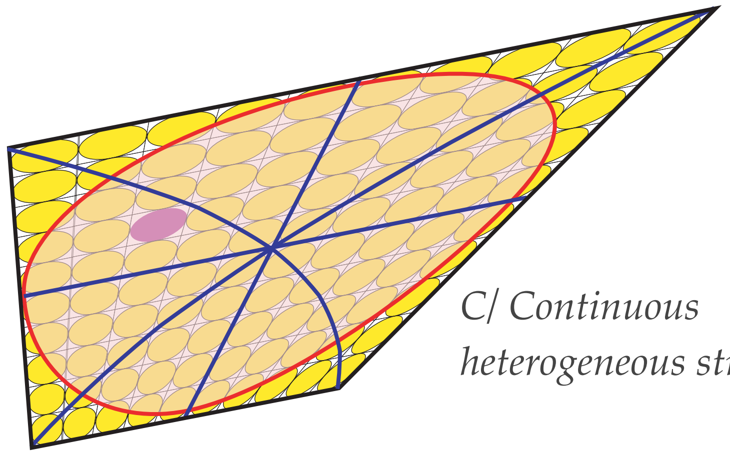






B1 and B2Continuous homogeneous strain





C/ Continuous heterogeneous strain

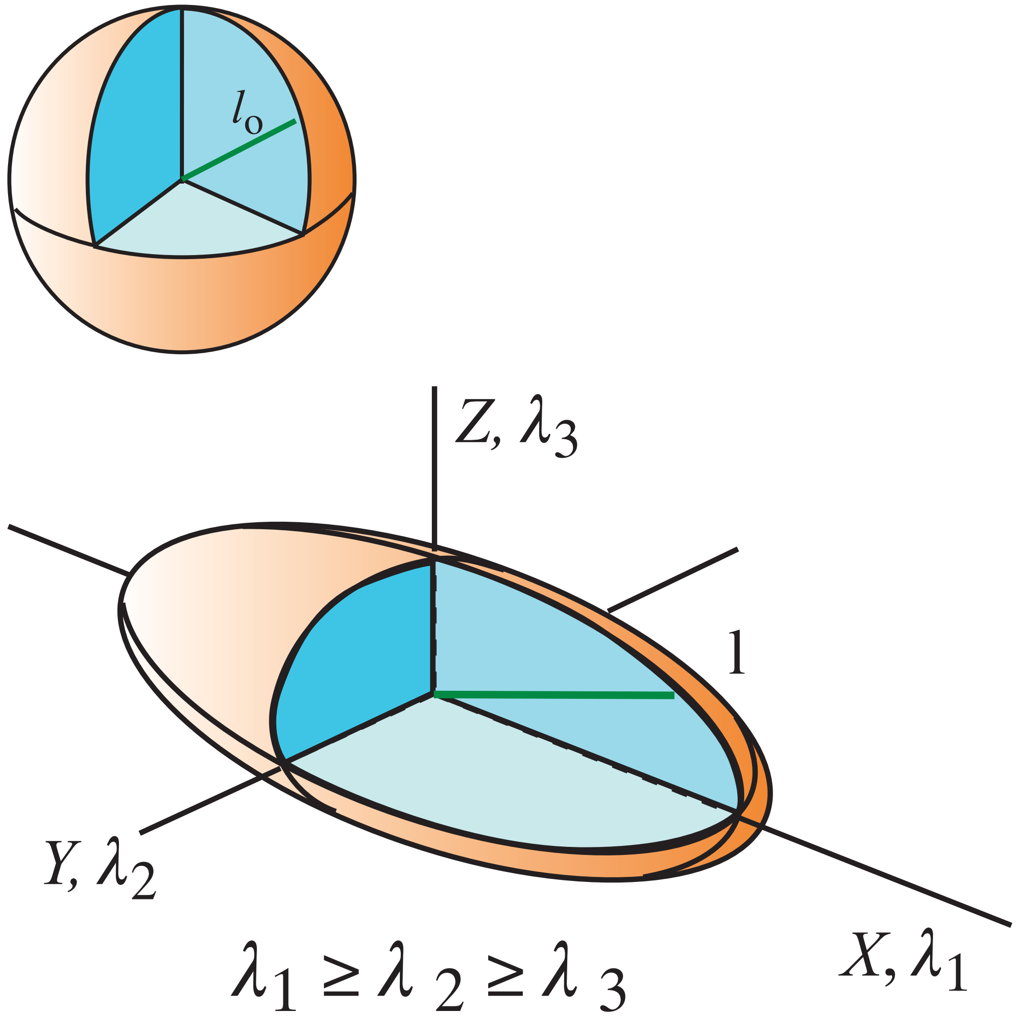
The Finite Strain Ellipsoid

When strain is homogeneous, deformation transforms a marker of spherical shape into a regular ellipsoid (3 perpendicular axes $\lambda_1 \geq \lambda_2 \geq \lambda_3$). This ellipsoid is called the *Finite Strain Ellipsoid* (*FSE* for short).

This ellipsoid offers an easy access to characterise the finite strain in terms of shape and magnitude. When strain is heterogeneous it transforms a spherical marker into a "potatoid", the characterisation of which is extremely difficult. Fortunately it is always possible to define a scale at which strain is, in first approximation, homogeneous.

A regular ellipsoid is fully characterized by two parameters *K* and *D*, which define the style of strain (shape of ellipsoid) and the amount of strain (i.e. how far it is from the initial perfect sphere) respectively. As shown on the right these two parameters are both function of the ratio λ_1/λ_2 and λ_2/λ_3.

Importantly, *K* and *D* do not request knowledge of the radius of the initial sphere only knowledge of the principal axes of the finite strain ellipsoid.



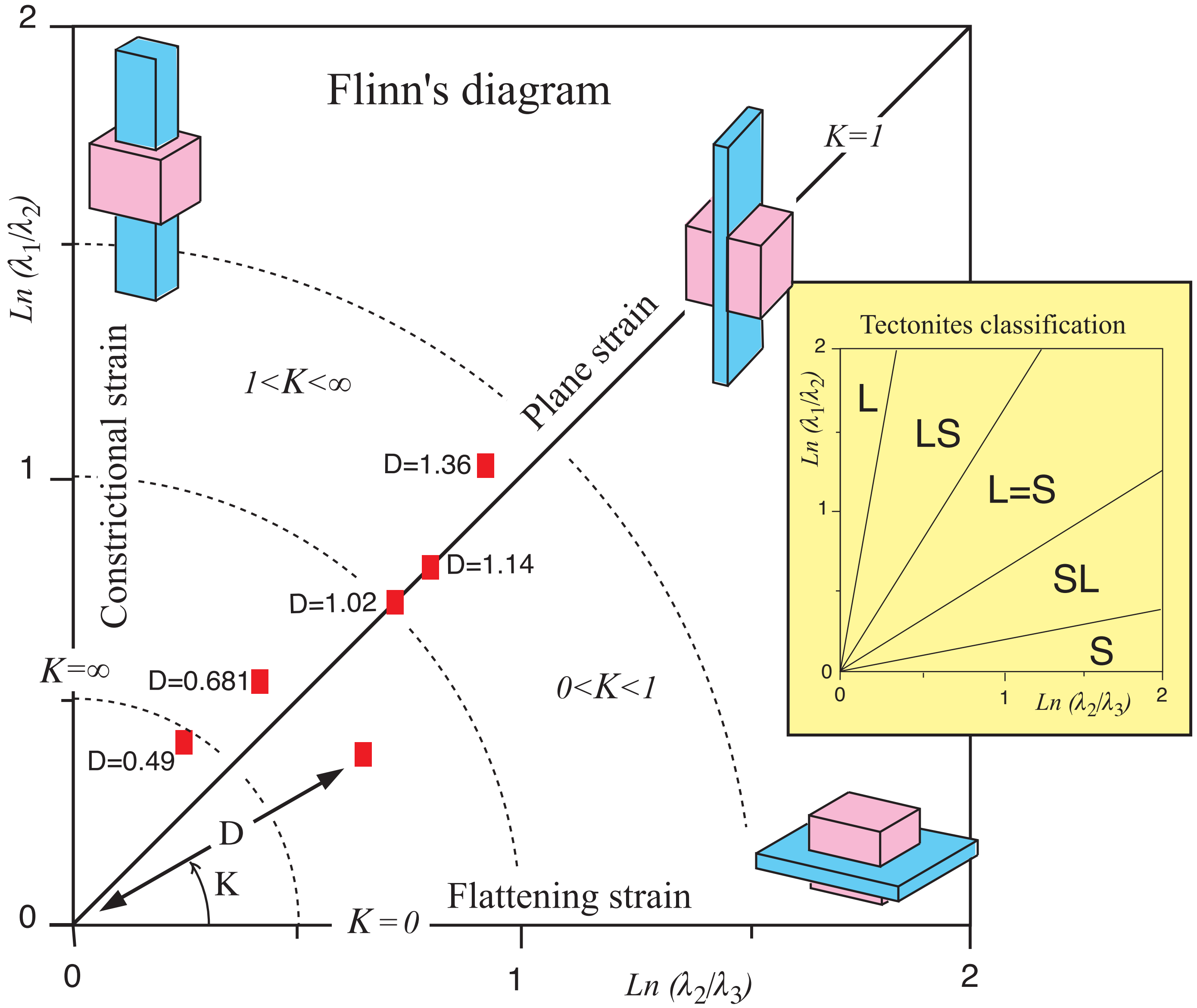
$$K = \frac{\ln[\lambda_1/\lambda_2]}{\ln[\lambda_2/\lambda_3]}$$

$$D = \sqrt{[\ln[\lambda_1/\lambda_2]]^2 + [\ln[\lambda_2/\lambda_3]]^2}$$

The Flinn's Diagram

The Flinn's diagram allows the representation of every type of regular ellipsoid. In this diagram, the ratio λ_1/λ_2 is the ordinate axis whereas the ratio λ_2/λ_3 is the abscissa axis. The logarithm function conveniently scale the strain axes ratios. The parameter D is the distance between the origin of the graph (that represent the initial sphere) and the ellipsoid (in red on the diagram). The parameter K is the slope between the abscissa axis and the line joining the ellipsoid and the origin of the diagram.

Cigar shaped ellipsoids locate along the ordinate axis (i.e. K is infinite) where the strain is said to be *constrictional*. Pancake shaped ellipsoids locate along the abscissa axis (K=0) where the strain is said to be *flattening*. *Plane strain* (K=1) characterises the ellipsoids for which λ_2 axis remains constant despite strain.



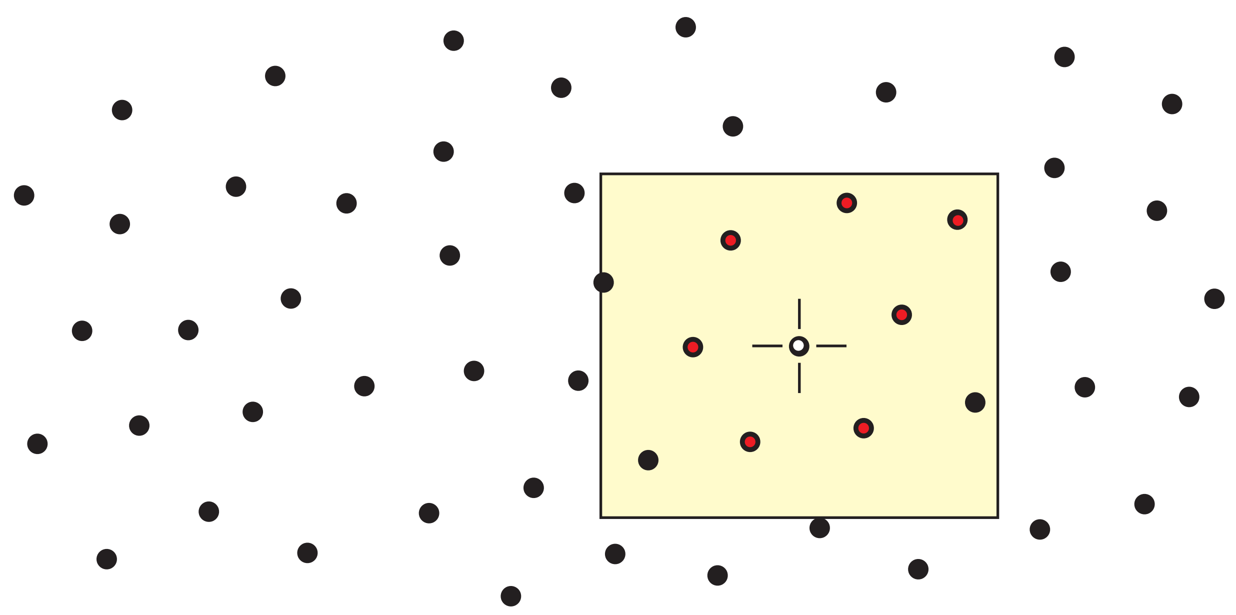
Strain-related fabric depend on the shape of the finite strain ellipsoid. Pancake shaped ellipsoids lead to *S tectonites* (strong schistosity, no lineation), cigar shaped ellipsoids lead to *L tectonites* (strong lineation, no schistosity). *L=S tectonites* are produced by plane strain.

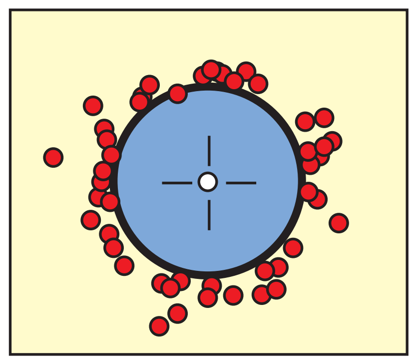
Techniques Of Strain Analysis

Structural geologists have invented various methods to extract FSE from analysis of rock fabrics and textures.

The Fry Method

This is one of the most elegant and easier method to determine strain in rocks made of particles initially randomly distributed in a matrix. The particle can be anything: quartz grains and quartz aggregates in a rhyolites, pre-strain metamorphic minerals such as garnet in metamorphic rocks, pebbles in matrix supported pebbly sandstones, etc. The main assumption is that before deformation the spacing of these particles should be statistically isotropic i.e. the distance between two particles does not depend on the direction in which the distance is measured. One way to demonstrate this is to plot on a tracing paper the position of particles (in red on the sketch below on the left) neighbouring a chosen particle (crossed white spot) and to repeat this operation for as many particles as possible. The result is shown on the sketch below on the right. This sketch shows that particles are disbributed around a circle of radius the average distance between particles. There is no strain.

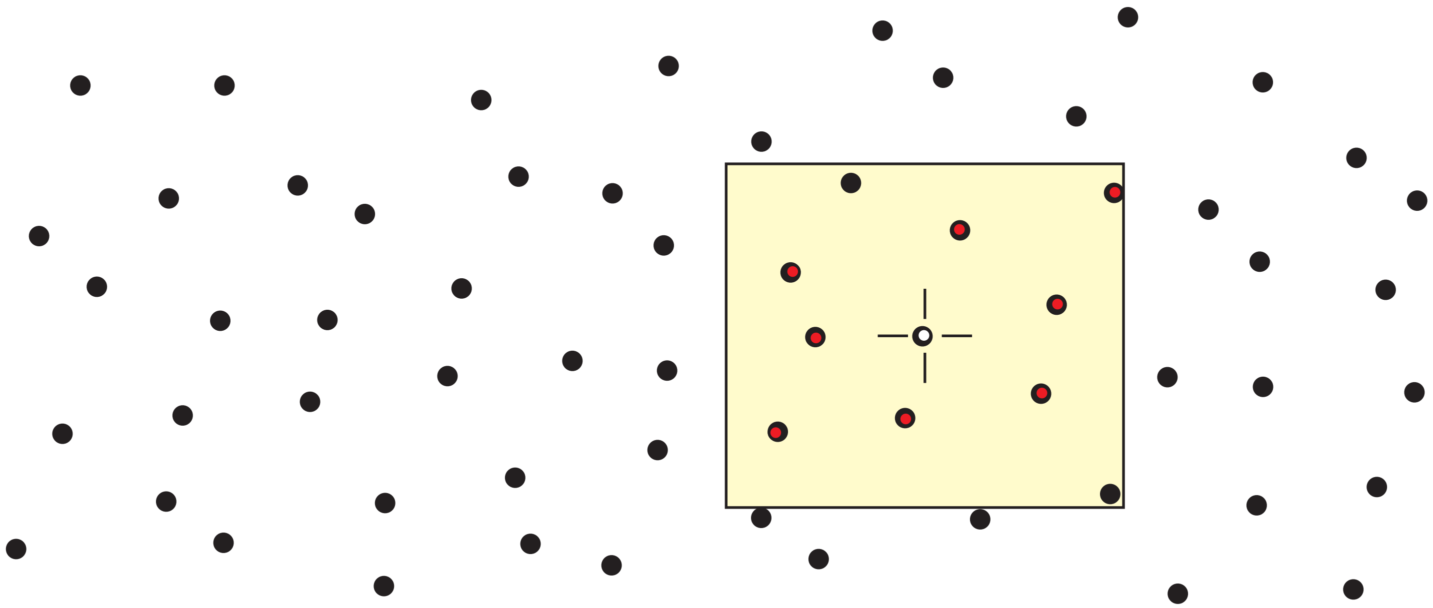


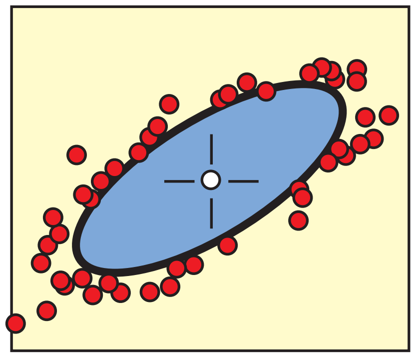


The Fry Method cont.

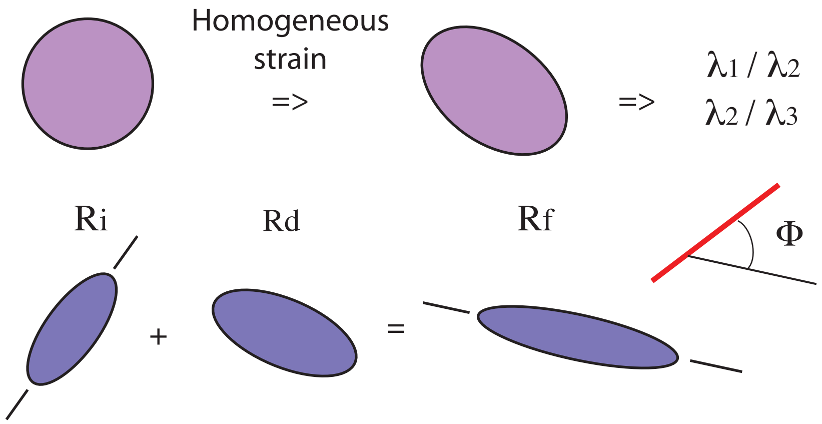
After deformation the distance between two particles aligned with $\lambda 1$ increases whereas two particles aligned in the direction of $\lambda 3$ got closer. If strain is homogeneous, the sphere is transformed into an ellipsoid.

To determine the three axes of this ellipsoid structural geologists work successively on two perpendicular sections (thin sections, saw cuts through hand specimens, photographs) containing two of the three principal strain axes. The distance between a given particle (cross-hair below) and its neighboring particles is plotted on a piece of tracing paper. The tracing paper and the cross is displaced successively over as many particles as possible and their closer neighbors are plotted. The sketches below show on the left a 2D section through a deformed rock. At first glance the particles seem to be randomly distributed. The Fry analysis reveals that in reality that sample has been deformed quite significantly since the neighboring particles are distributed around an ellipse. The ratio long axis over short axis is a measure of the strain intensity. Plotting on a Flinn diagram the results obtained on two perpendicular sections each containing two of the three principal axes one can fully characterise the 3D finite strain ellipsoid.





The Rf /Φ (Rfi) Method



Strain intensity can be assessed by the shape of deformable sub-spherical objects. Quartz aggregates in granitic rocks, pebbles in conglomerates, and gas vacuoles in basaltic rocks all form with a sub-spherical shape. Following homogeneous strain these spherical objects are changed into ellipsoids. By measuring the axial ratios of those ellipsoids and plotting them on a Flinn diagram, it is possible to determine where the shape of the strain and its intensity. This method can only underestimate the finite strain as stronger objects record only a fraction of the total strain recorded by the bulk of the rock.

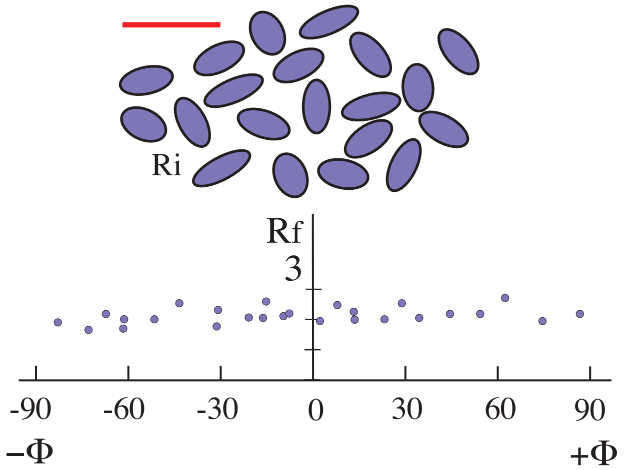
From a 2D section through a population of ellipsoidal objects of axial ratio *Rf* (sketch on the right), the *Rf /Φ* method allows the evaluation of: 1) *Ri* : the axial ratio of the objects before deformation, and 2) *Rd* : the axial ratio of the finite strain ellipse. This method is extremely useful when the initial shape of the strained objects is an ellipsoid.

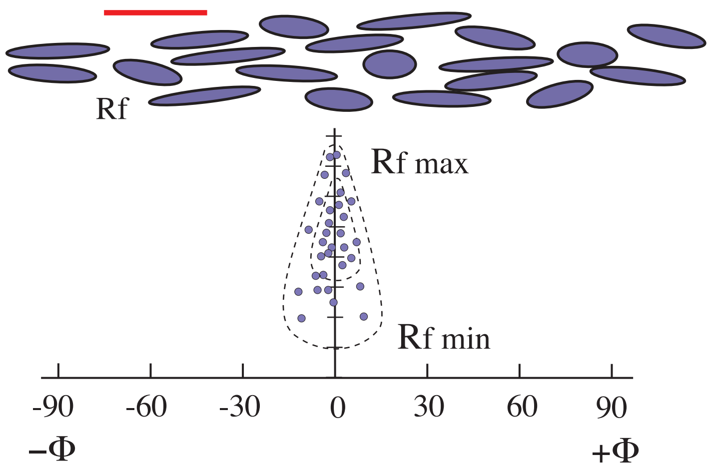
$$Rd^2 = Rfmax \,.\, Rf\ min$$

$$Ri^2 = Rfmax \,/\, Rf\ min$$

$$Rd = \lambda i / \lambda j \qquad i \neq j$$

In this method the axial ratio of the particles is plotted against *Φ*, the angle between the long axis of the particle and an arbitrary direction (red line below), usually that of the foliation. When there is no strain *Φ* varies from +90° to -90°. When the rock is strained, the range of *Φ* decreases and the range of axial ratio of the particles (difference between *Rf max* and *Rf min*) increases. *Ri* and *Rd* are simple function of *Rf max* and *Rf min*.

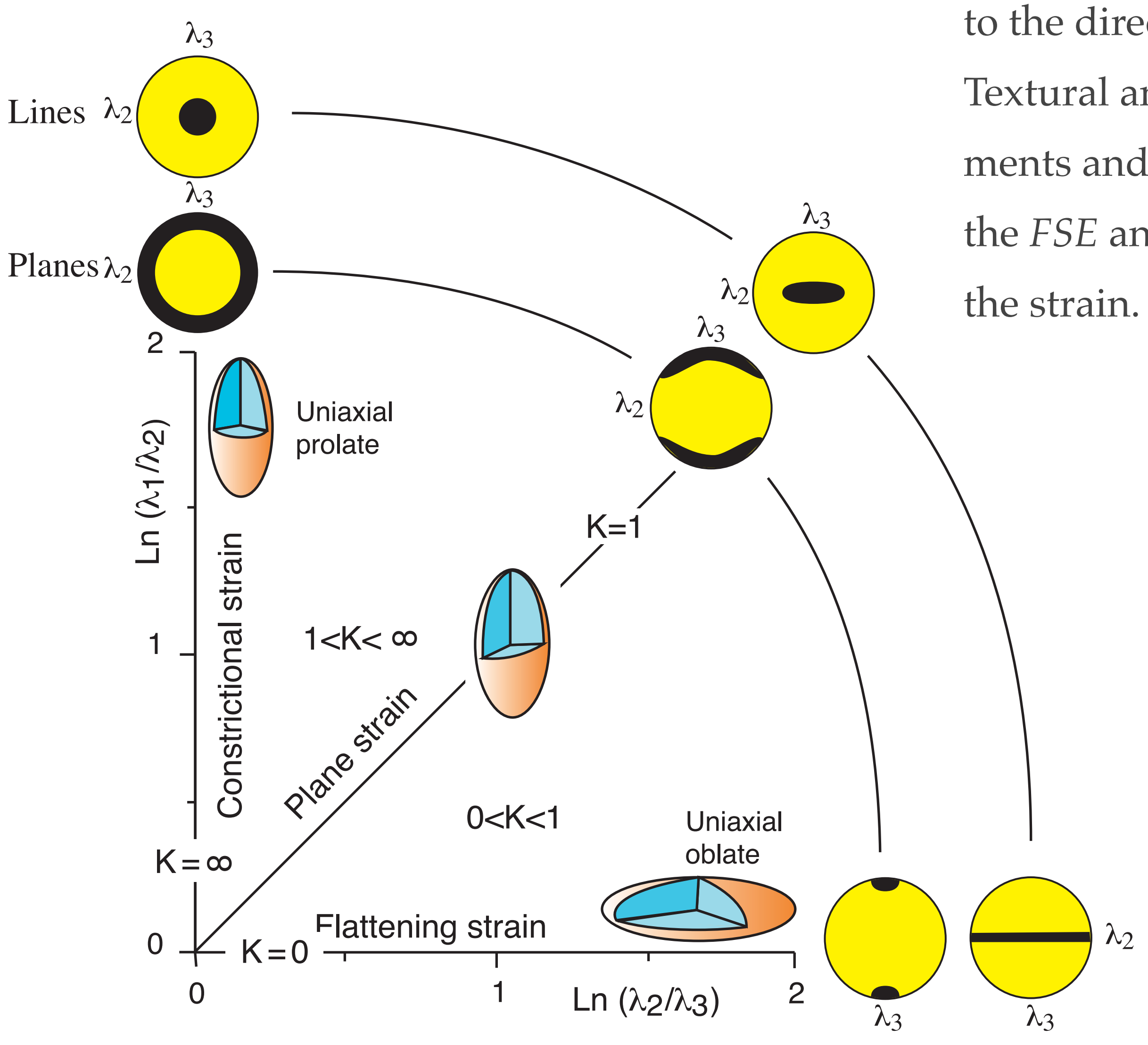




Before deformation, planar particles such as micas are randomly distributed. On a stereonet the distribution of their poles is homogeneous. As deformation proceeds the particles rotate so their poles tend to align with the direction of maximum shortening λ_3. One can demonstrate that the orientation of planar elements after deformation is a simple function of their initial orientation and of the axial ratios (λ_1/λ_2; λ_2/λ_3; λ_1/λ_3) of the Finite Strain Ellipsoid.

A similar rotation affects linear elements which tend to become parallel to the direction of maximum lengthening (λ_1).

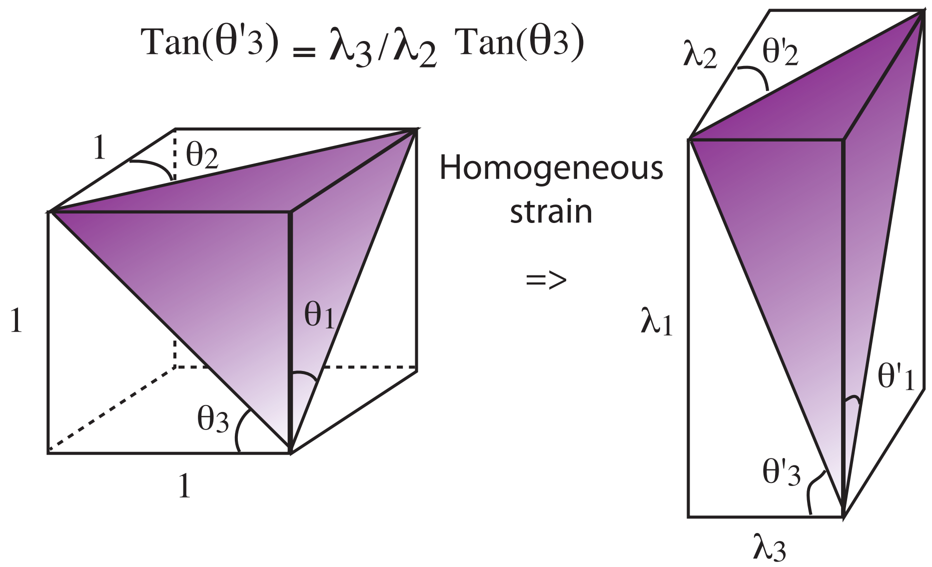
Textural analysis consists in plotting on a stereonet the pole of planar elements and linear elements. Their distribution is related to the shape of the *FSE* and the intensity of the anisotropy is related to the intensity of the strain.



$$\mathrm{Tan}(\theta'_1) = \lambda_3/\lambda_1\ \mathrm{Tan}(\theta_1)$$

$$\mathrm{Tan}(\theta'_2) = \lambda_2/\lambda_1\ \mathrm{Tan}(\theta_2)$$

$$\mathrm{Tan}(\theta'_3) = \lambda_3/\lambda_2\ \mathrm{Tan}(\theta_3)$$



A Little Quiz ...

1/ Define discontinuous deformation.

2/ Define continuous heterogeneous strain.

3/ How can you tell if strain is homogeneous.

4/ What happens to a sphere when it is deformed by heterogeneous strain?

5/ What is the Finite Strain Ellipsoid?

6/ What is the Flinn's diagram?

7/ Define the concept of "Plane Strain".

8/ What is an L tectonite?

9/ Describe the Fry method of strain analysis.

10/ Describe the Rf /Φ method of strain analysis.

It is often said that the best geologist is the one who has seen the most rocks; like starring at something long enough would suffice to understand it. Indeed, many experienced geologists have reached the wrong conclusion because they were oblivious of the difficulty to understand the 3D structural context of the rock samples.

Structural geology helps to develop an acute sense of observation. In an age where digital cameras capture the world at ultra high-resolution, structural geologists keep drawing sketches in their field notebooks. They do so for two reasons: first cameras capture the world in 2D only. One cannot understand geology in 2D. Second, sketching forces careful observation, and demands the understanding of volumes. A structural geologist knows how easy it is to be mislead by superficial observations.

I hope this iBook, will help initiate your journey in structural geology. One of the main advantage of the iBook format is its capacity to handle interactive 3D models. I have drawn mine using *Sketchup*.