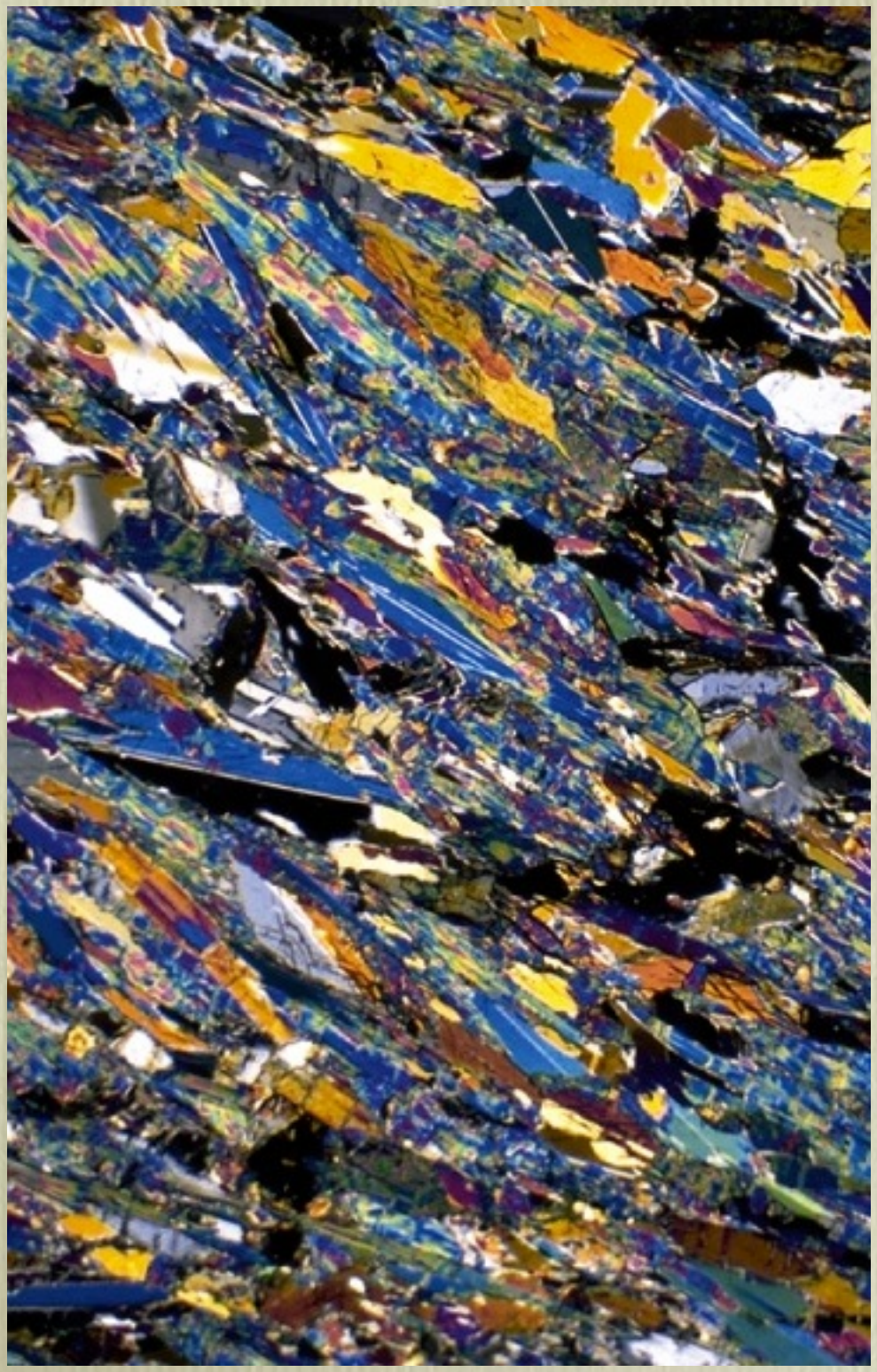


Metamorphic Rocks:

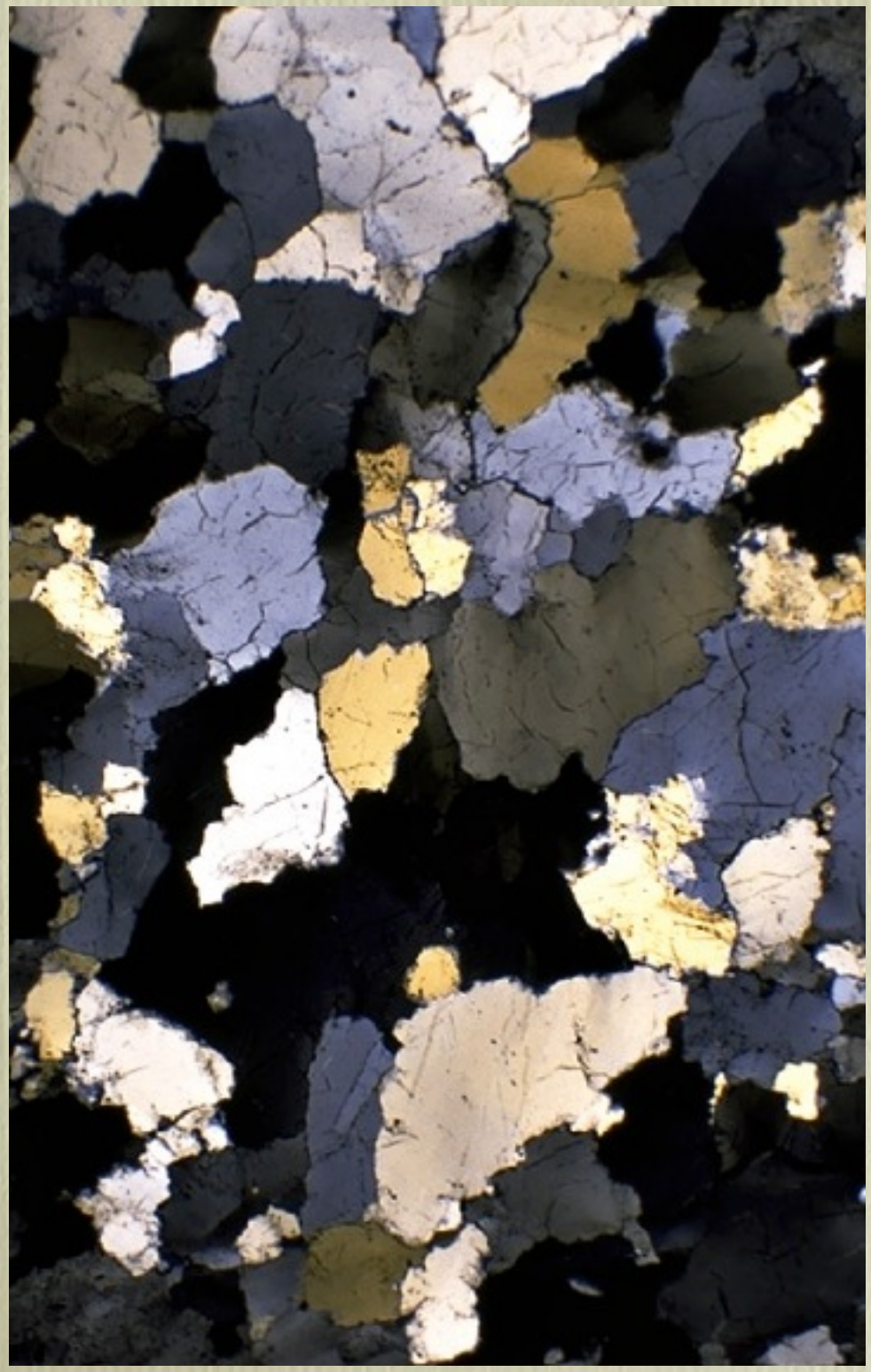
Rocks changed because of changes in their environment, up to (but not including) melting

Igneous dikes intruding metamorphic rock as observed in the wall of an open-pit mine at the Homestake gold mine, Black Hills, South Dakota

Important Factors in Metamorphism

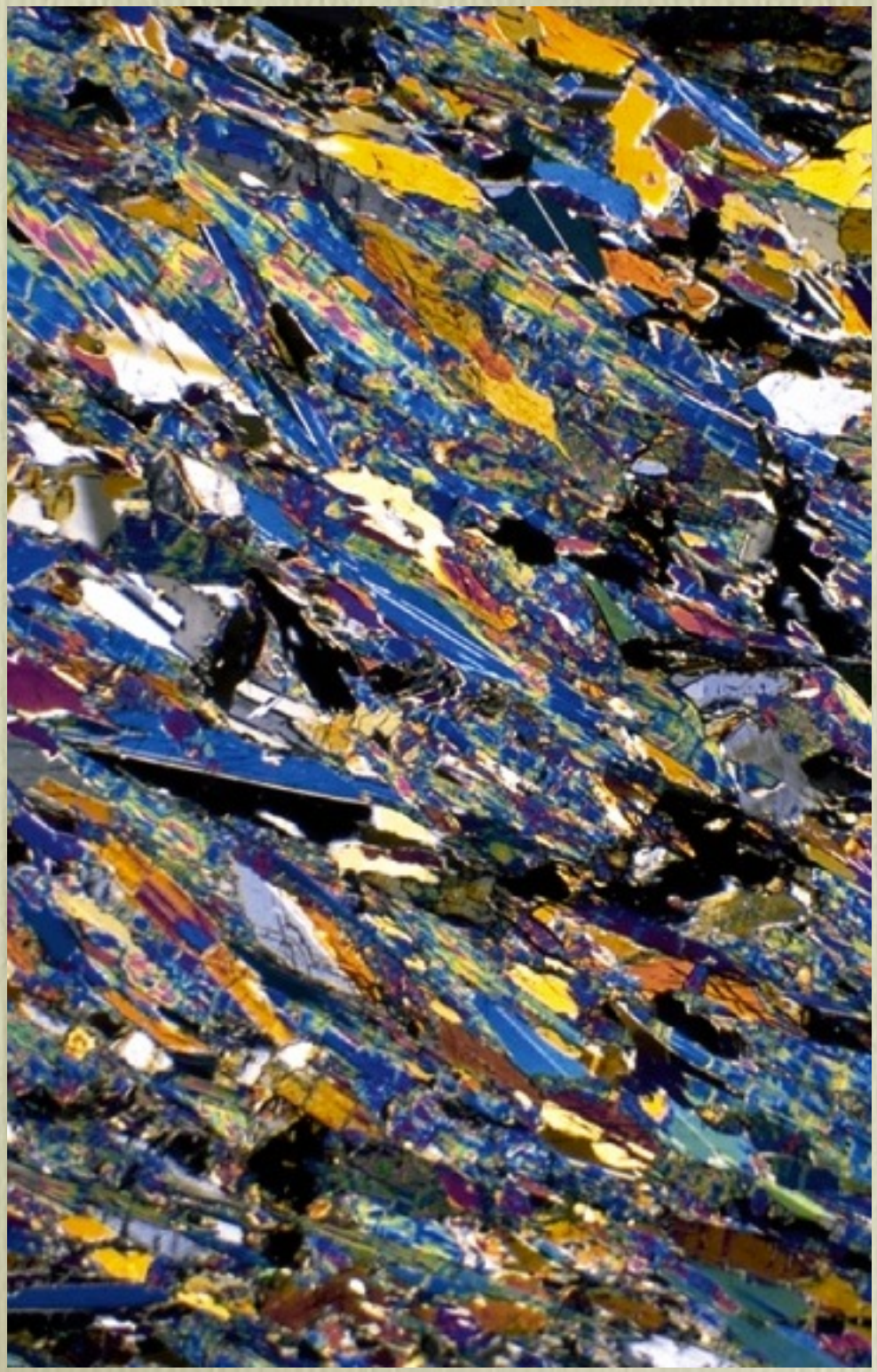
- Pressure and stress
- Temperature
- Chemistry (reactivity)
- Pre-existing rock fabric
- Time

Pressure is a system or field of forces directed perpendicular to all surfaces of a given solid object with the same magnitude everywhere.

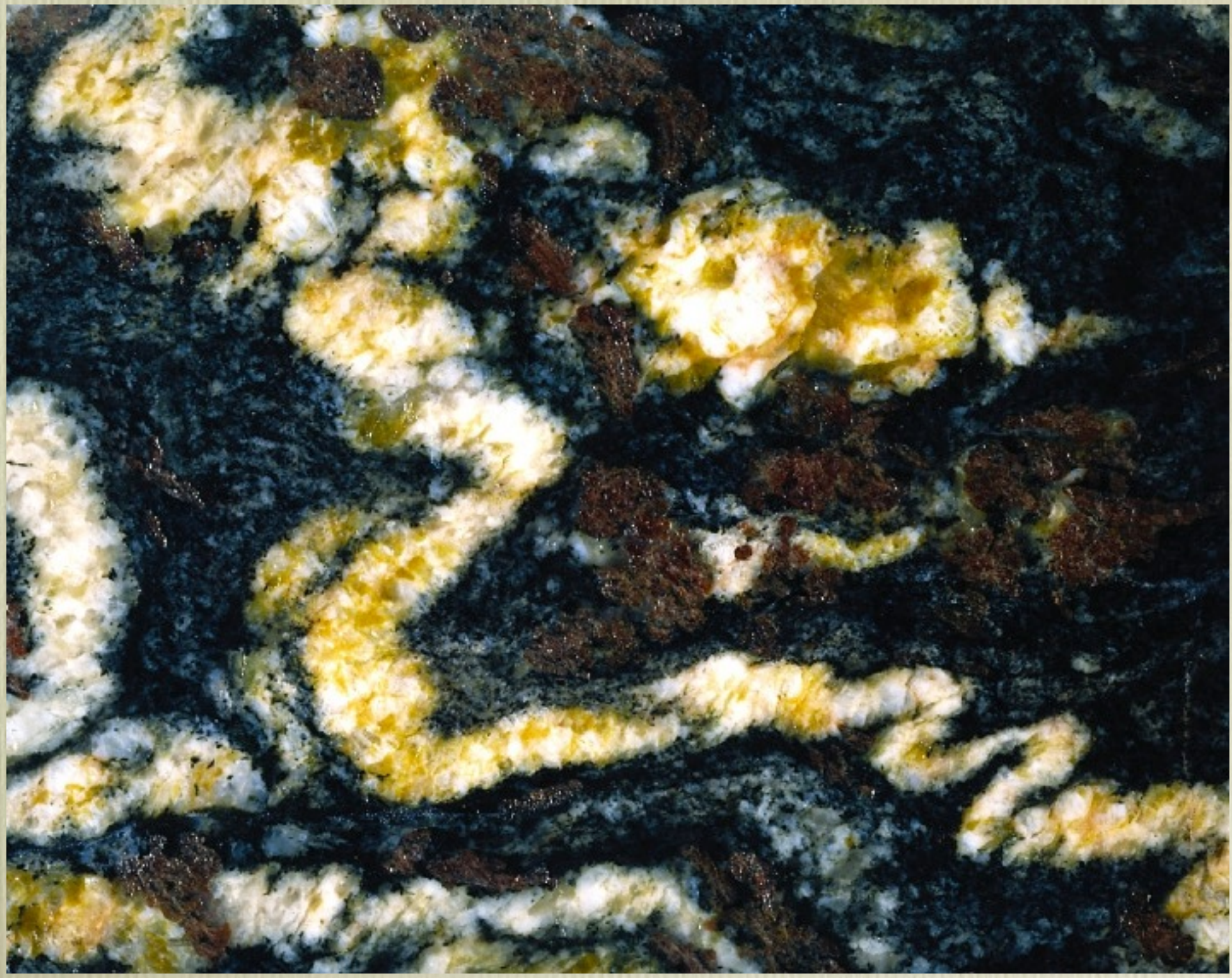


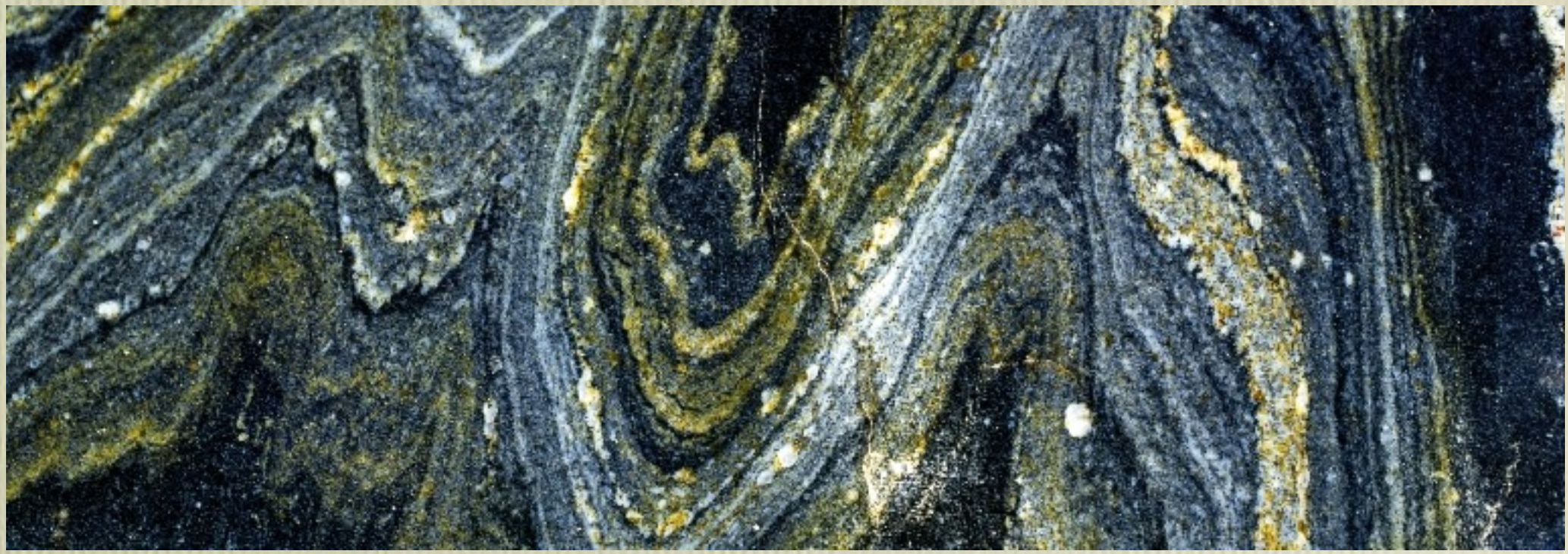
Photograph of a thin section of quartzite, taken through a geological microscope using cross-polarized light.
The quartz grains form a dense mosaic of interlocking crystals.

Stress is a system or field of forces acting on a surface in which the magnitude of the stress is dependent on the orientation of the surface.



Photograph of a thin section of schist, taken through a geological microscope using cross-polarized light.
The long, flat mineral grains are mica minerals, and they are aligned nearly parallel to each other.

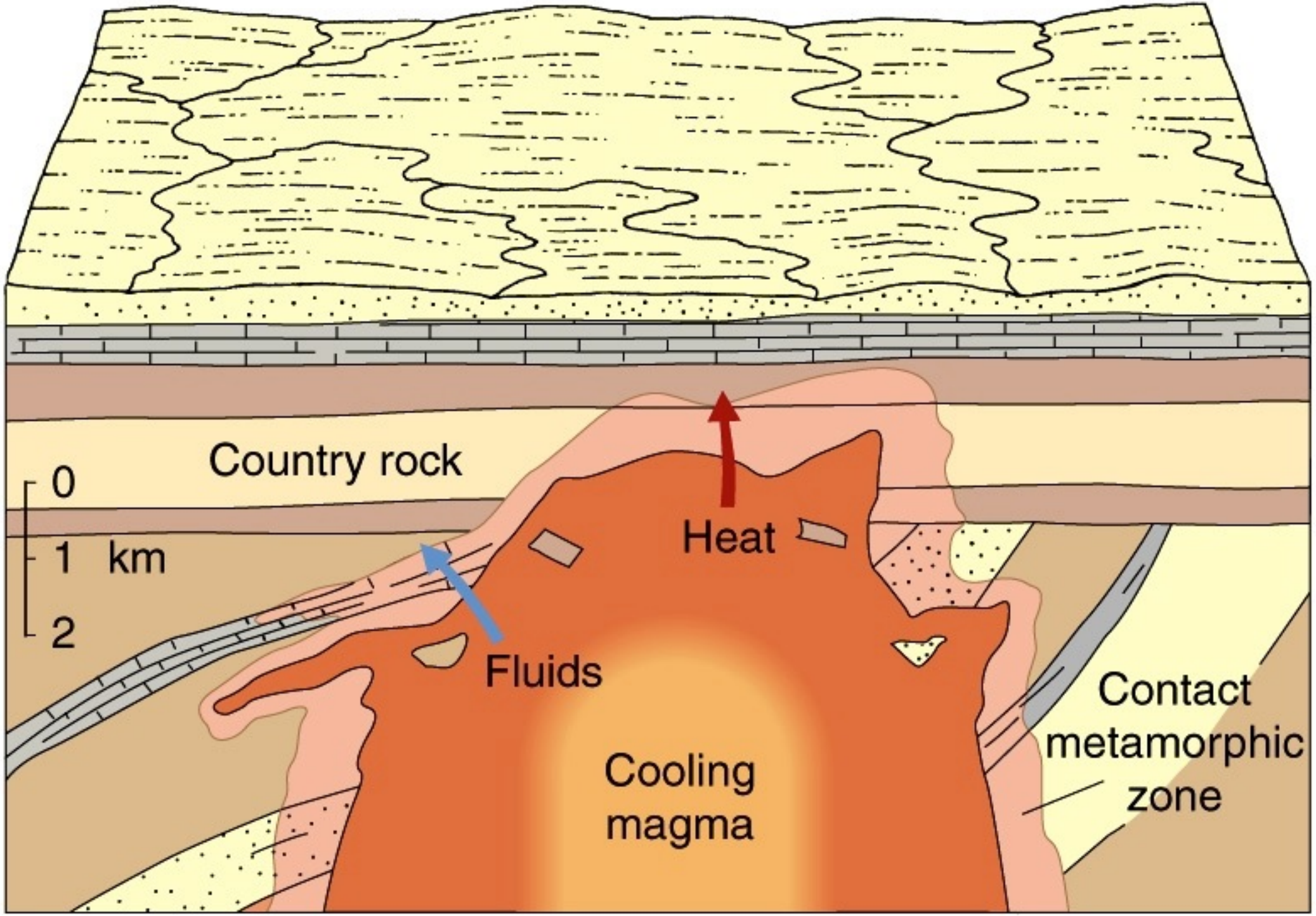




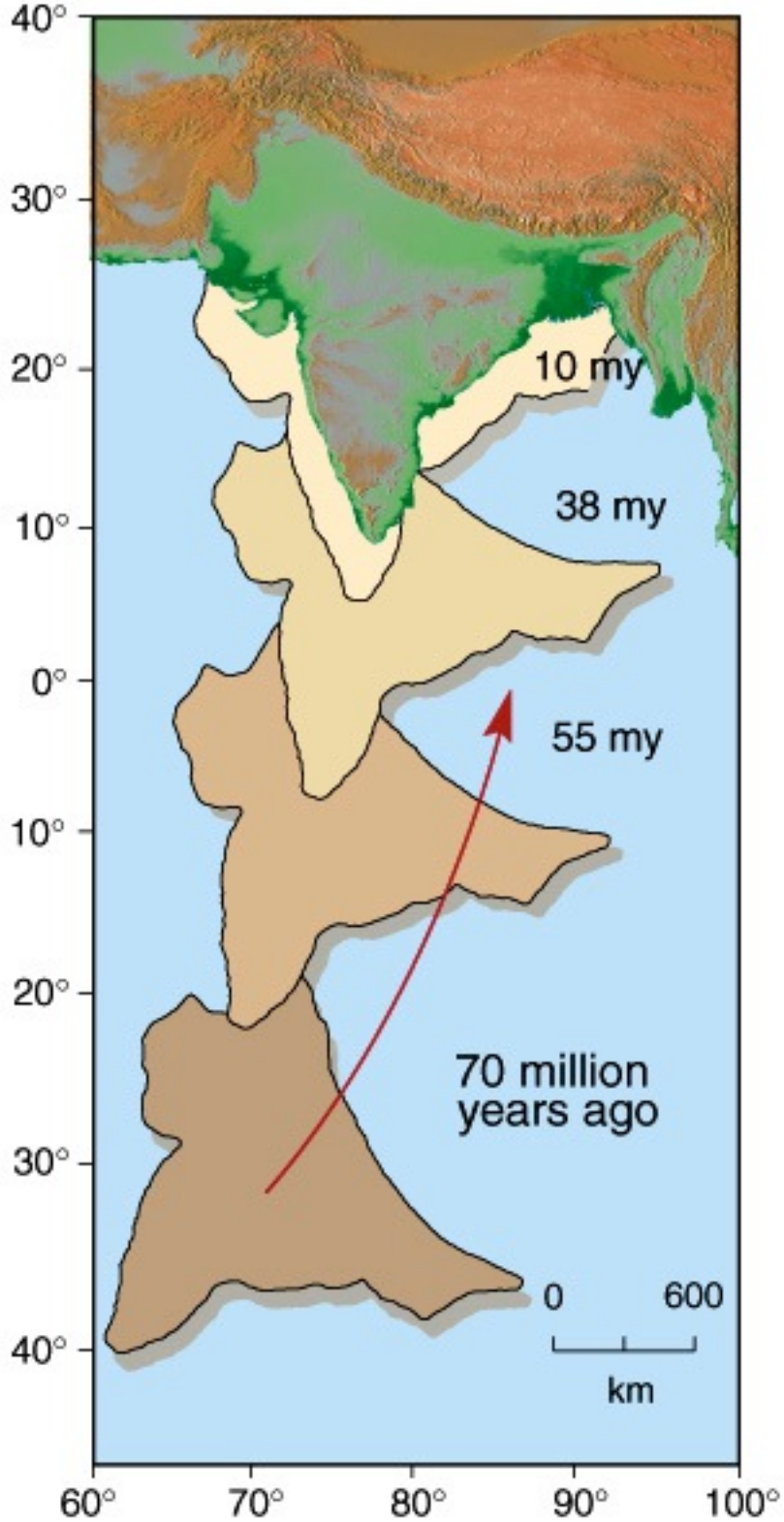
Distribution of metamorphic rocks exposed at Earth's surface.

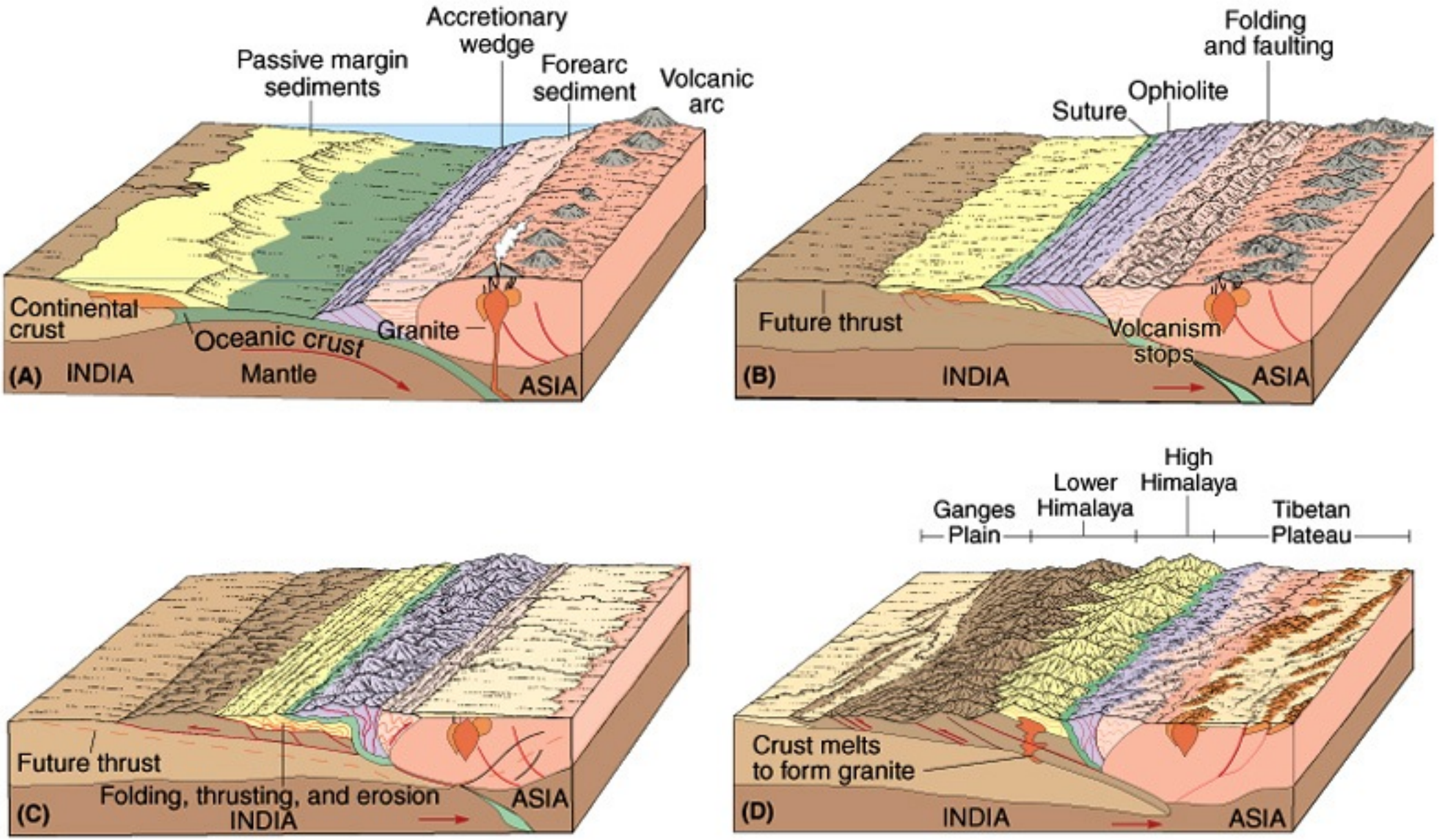
Types of metamorphism

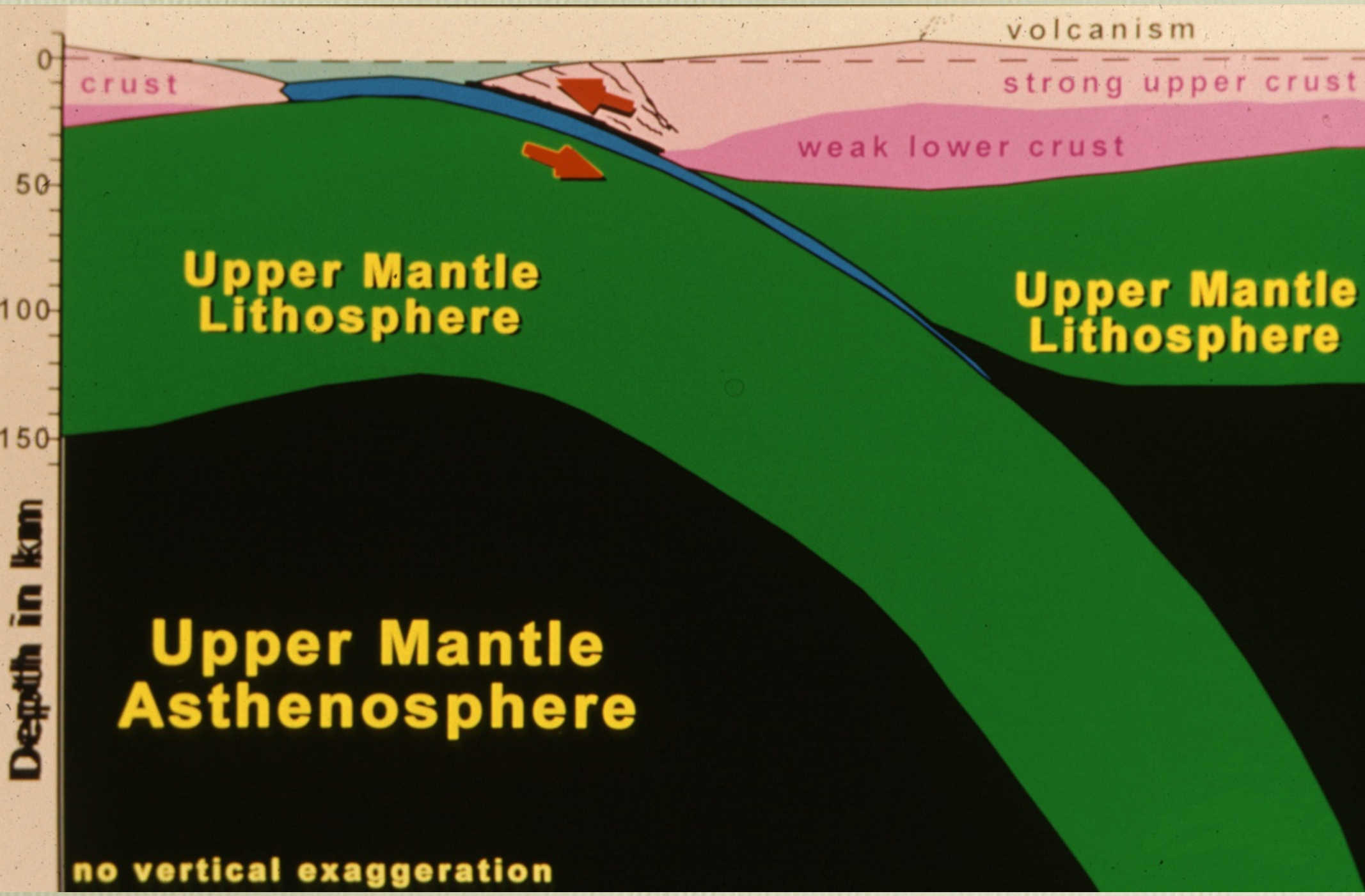
- Contact
- Burial
- Regional
- Hydrothermal

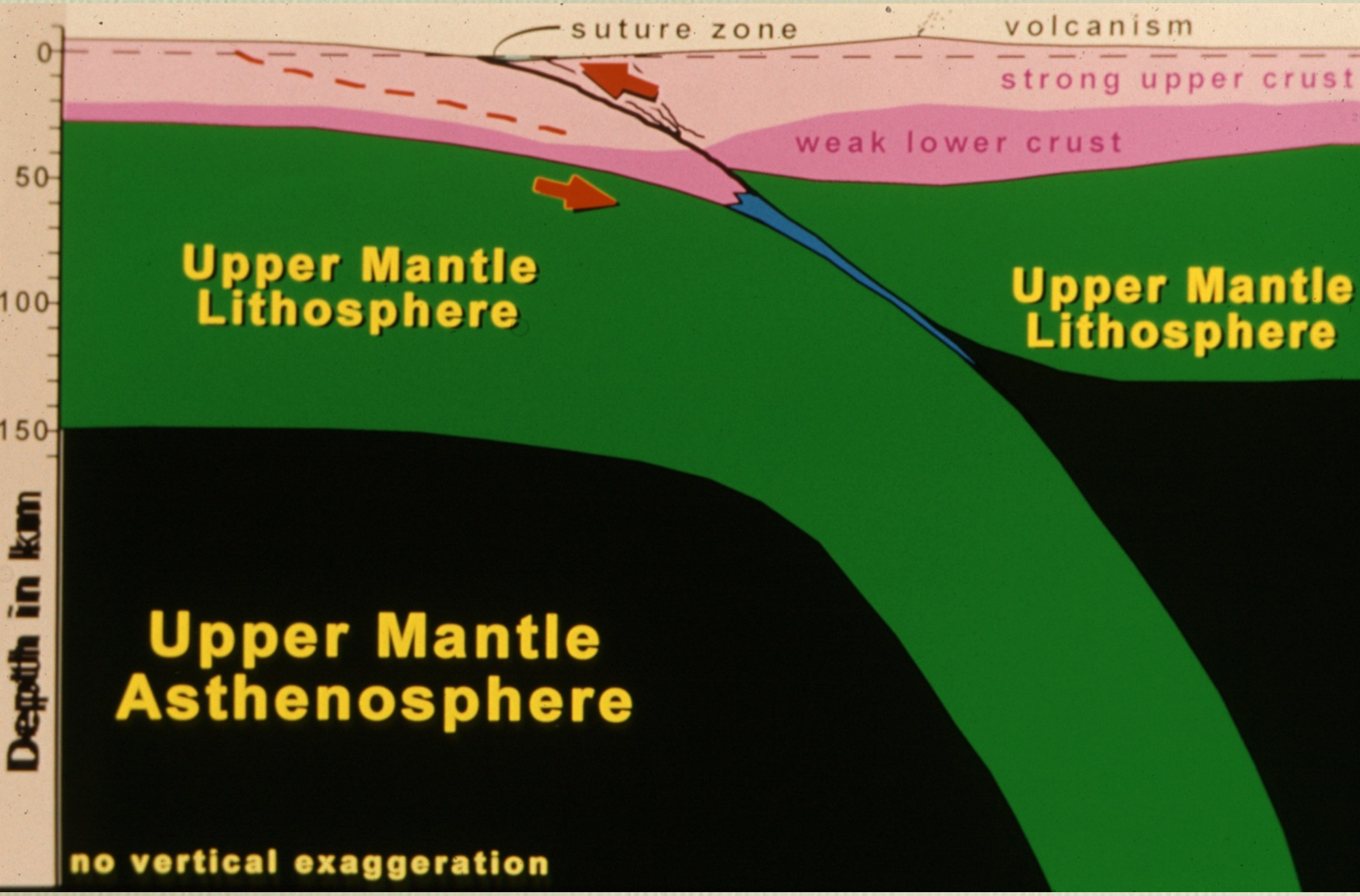

Country rock
0
1 km
2
Heat
Fluids
Cooling
magma
Contact
metamorphic
zone

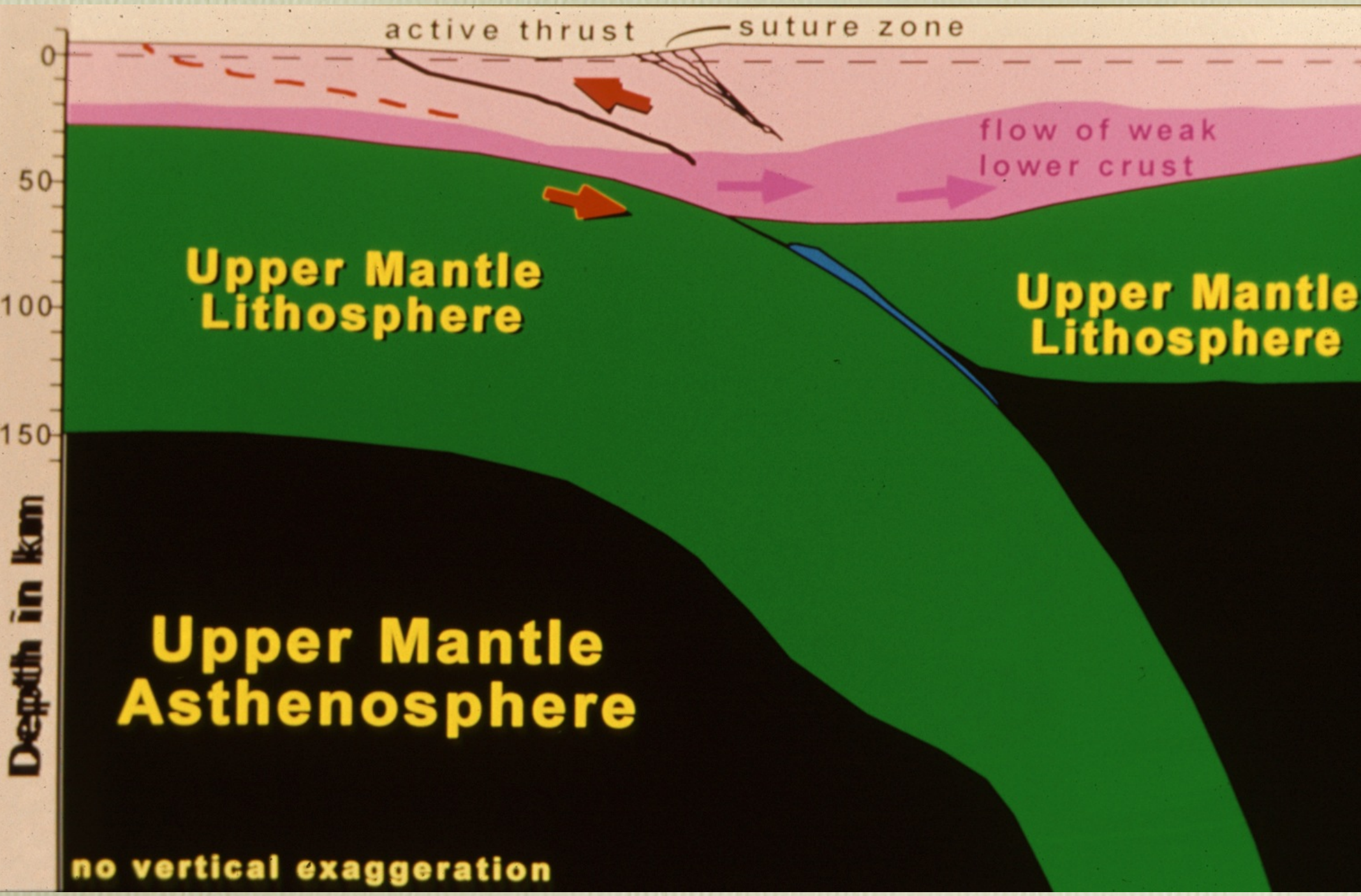
Plutons intruding metamorphic country rock, Australia. False-color image from satellite sensors.

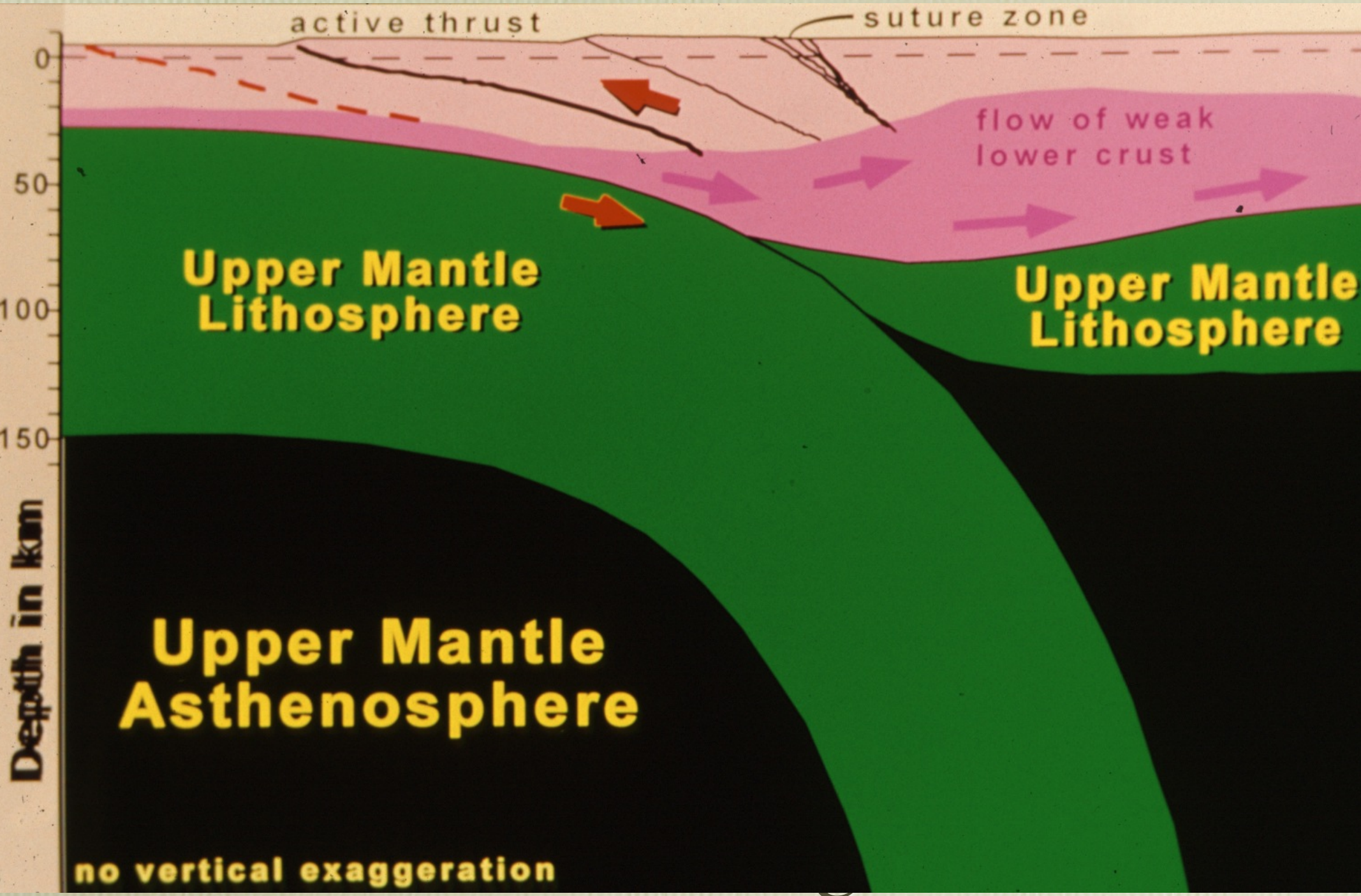

40°
30°
20°
10°
0°
10°
20°
30°
40°
60°
70°
80°
90°
100°
10 my
38 my
55 my
70 million
years ago
0
600
km

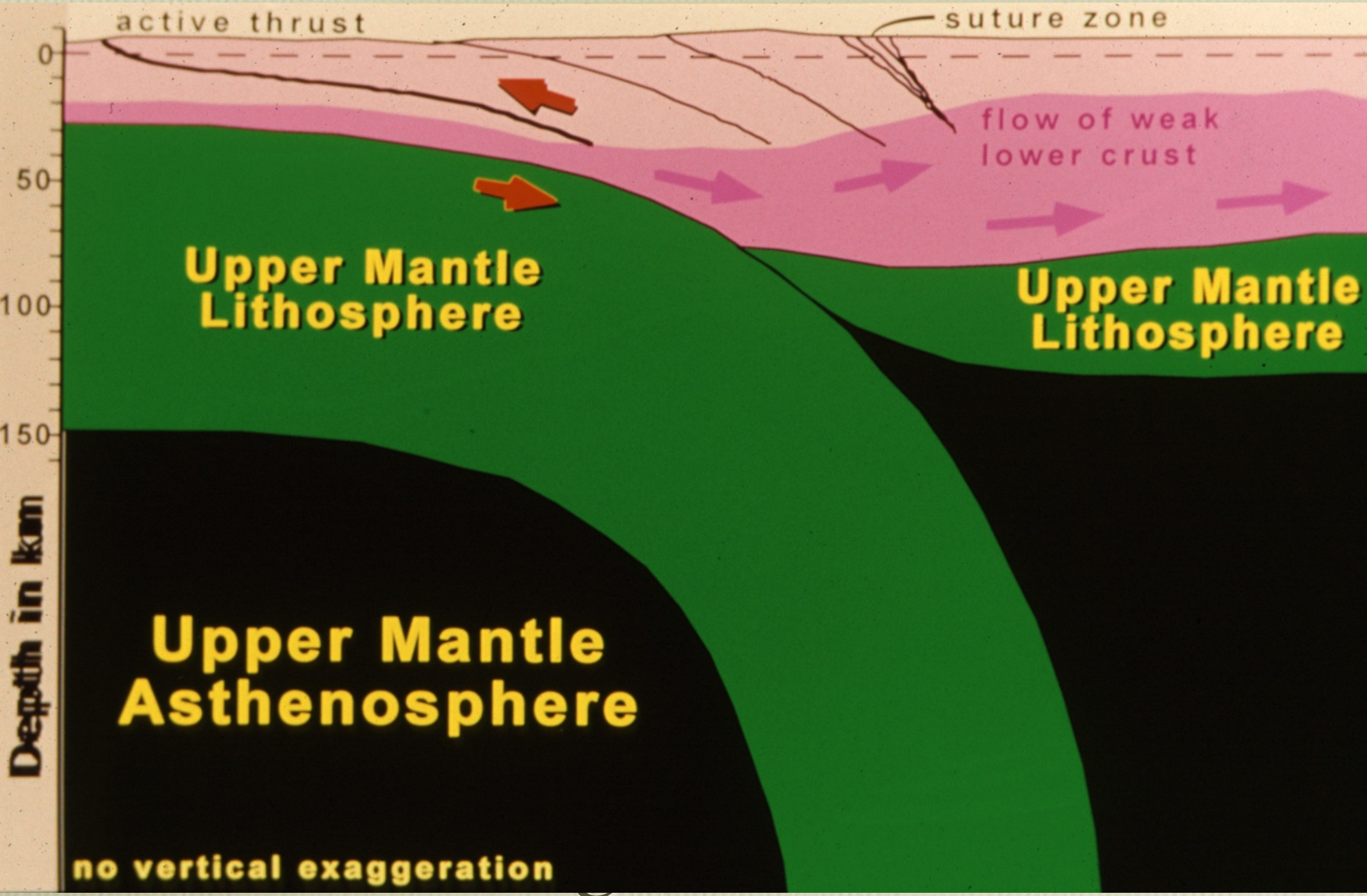

Accretionary wedge
Passive margin sediments
Forearc sediment
Volcanic arc
Continental crust
Oceanic crust
Granite
(A) INDIA
Mantle
ASIA
Folding and faulting
Ophiolite
Suture
Future thrust
Volcanism stops
(B)
INDIA
ASIA
High Himalaya
Lower Himalaya
Ganges Plain
Tibetan Plateau
Future thrust
Folding, thrusting, and erosion
(C)
INDIA
ASIA
Crust melts to form granite
(D)
INDIA
ASIA

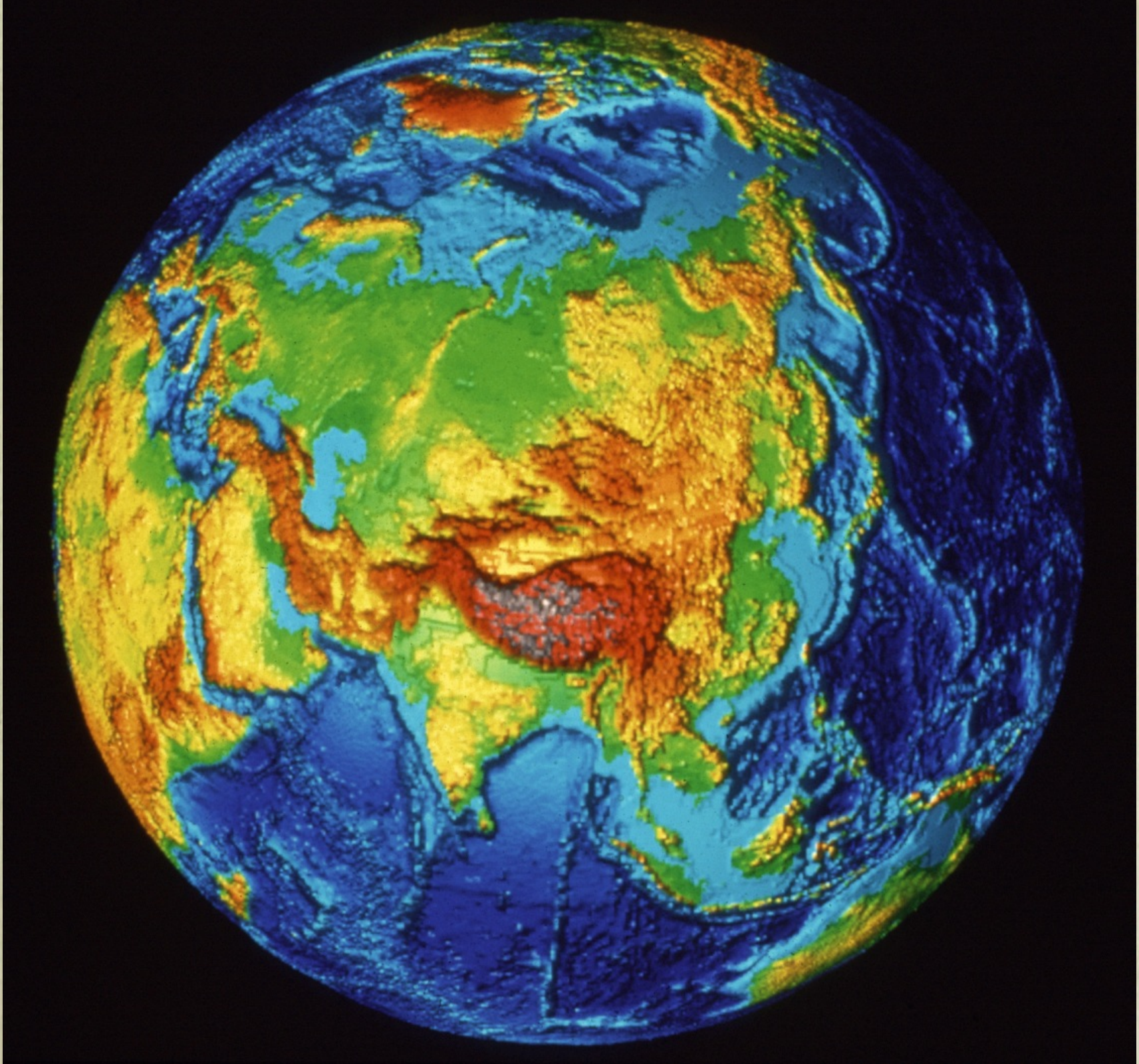

volcanism
crust
strong upper crust
weak lower crust
0
50
100
150
Depth in km
Upper Mantle
Lithosphere
Upper Mantle
Lithosphere
Upper Mantle
Asthenosphere
no vertical exaggeration

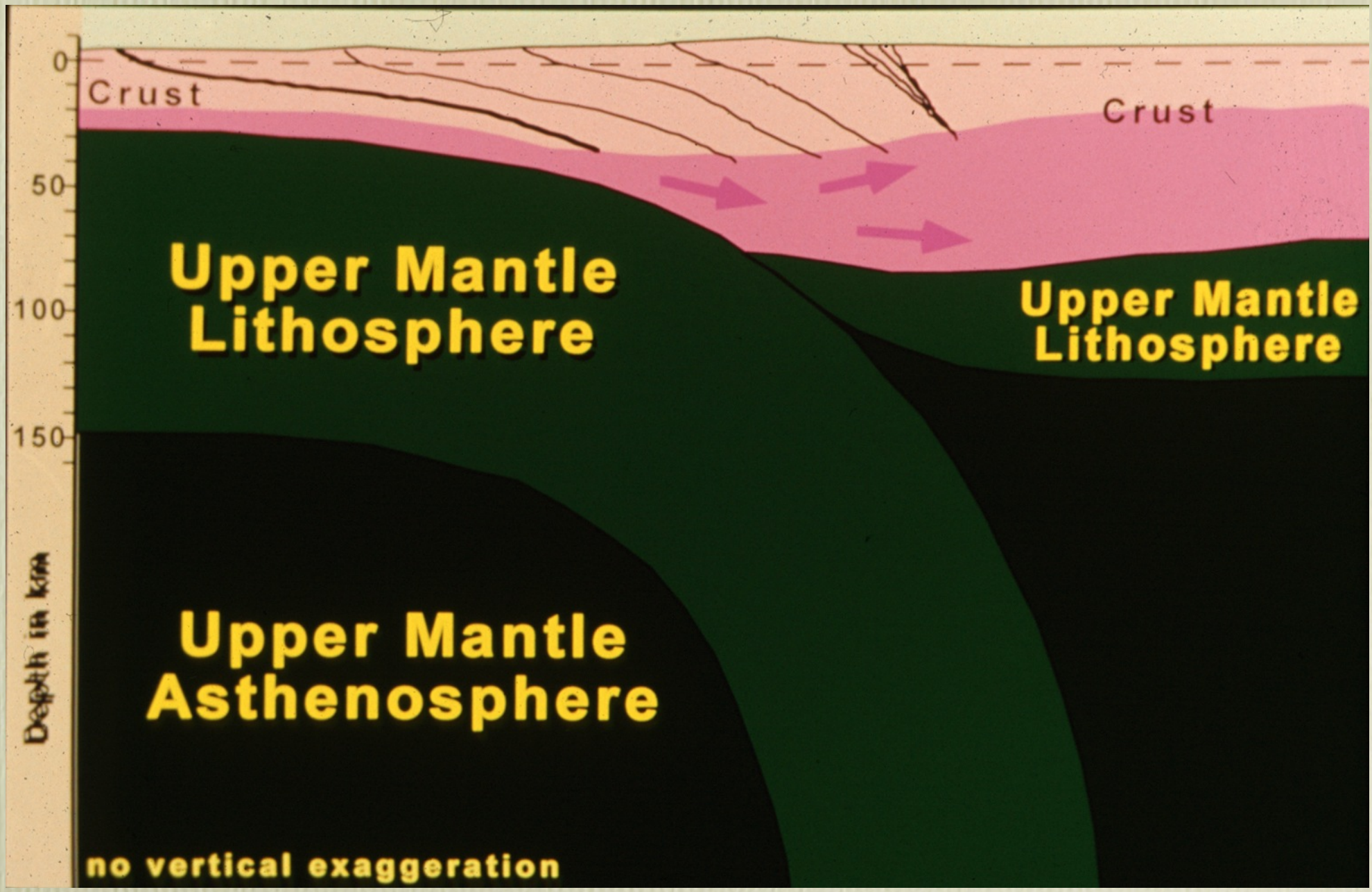

suture zone
volcanism
strong upper crust
weak lower crust
0
50
100
150
Depth in km
Upper Mantle
Lithosphere
Upper Mantle
Lithosphere
Upper Mantle
Asthenosphere
no vertical exaggeration


active thrust
suture zone
flow of weak
lower crust
Upper Mantle
Lithosphere
Upper Mantle
Lithosphere
Upper Mantle
Asthenosphere
Depth in km
0
50
100
150
no vertical exaggeration

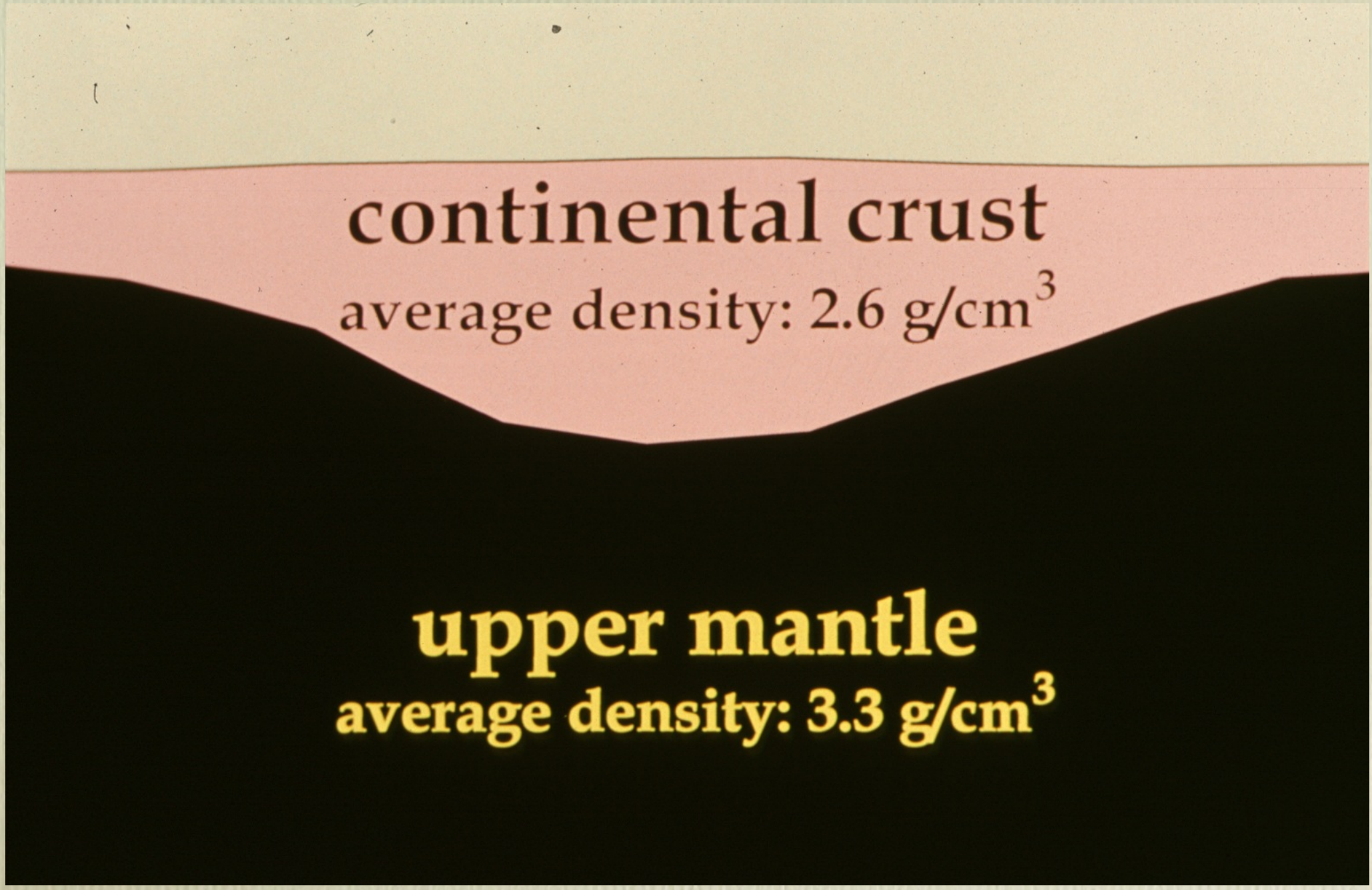

active thrust
suture zone
flow of weak
lower crust
Upper Mantle
Lithosphere
Upper Mantle
Lithosphere
Upper Mantle
Asthenosphere
Depth in km
0
50
100
150
no vertical exaggeration

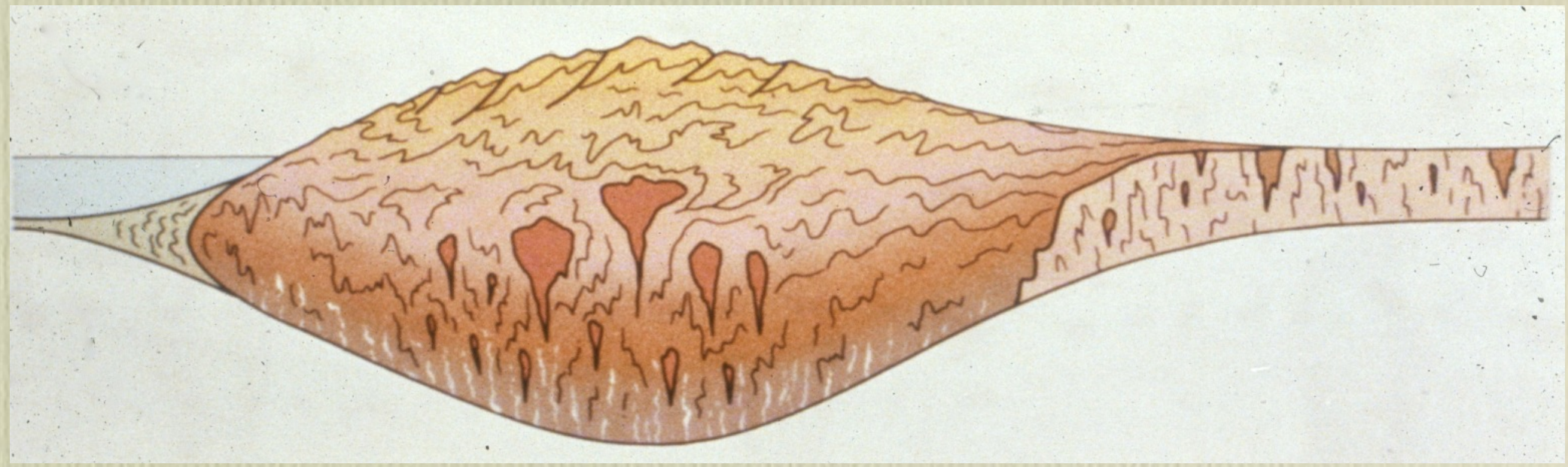

active thrust
suture zone
0
50
100
150
Depth in km
flow of weak
lower crust
Upper Mantle
Lithosphere
Upper Mantle
Lithosphere
Upper Mantle
Asthenosphere
no vertical exaggeration

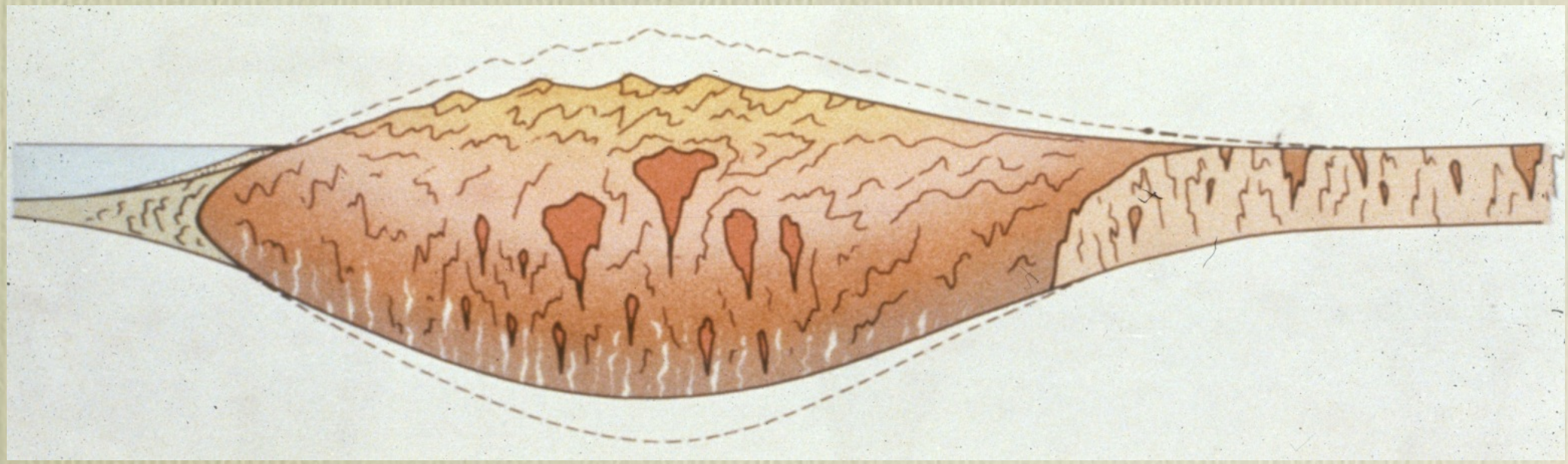


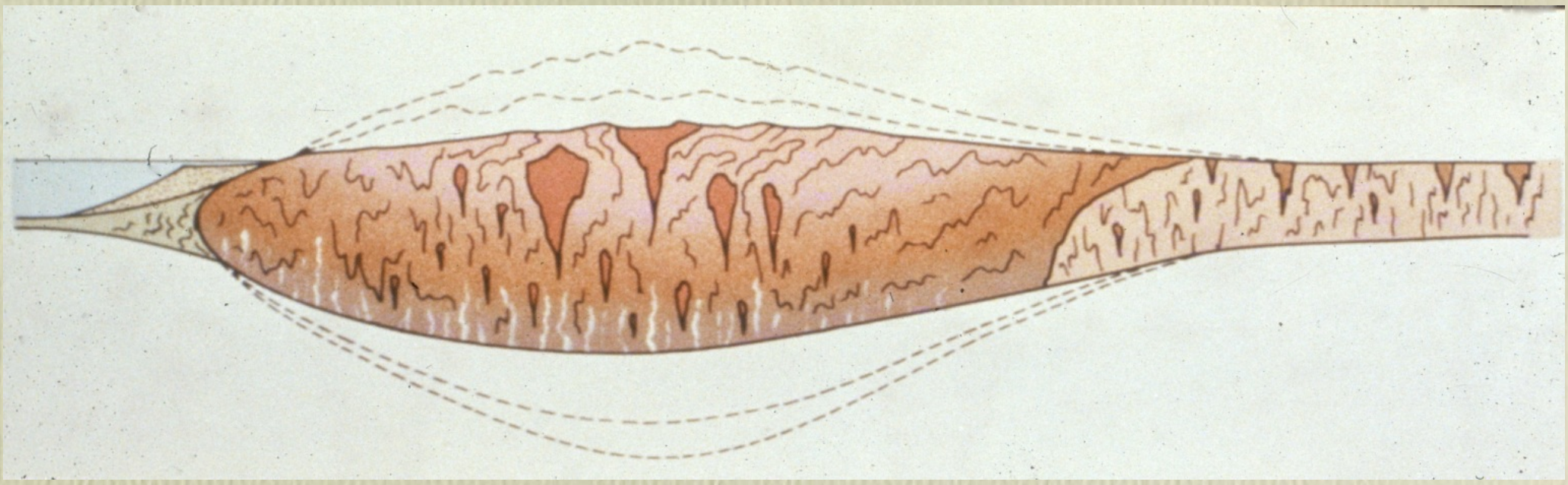


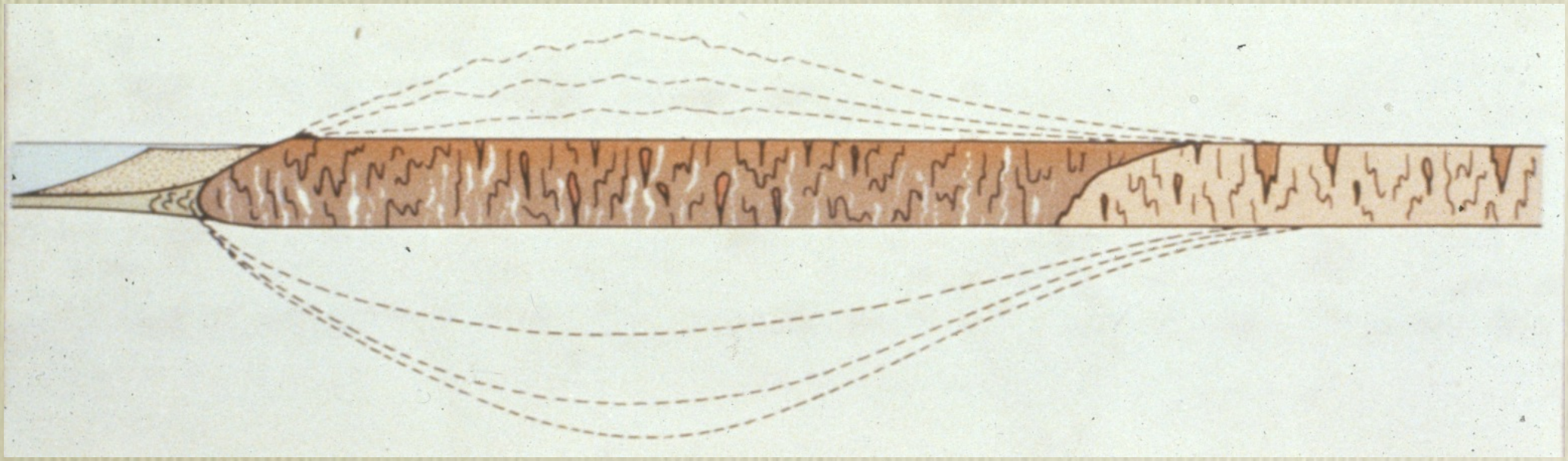
Late stage of collision

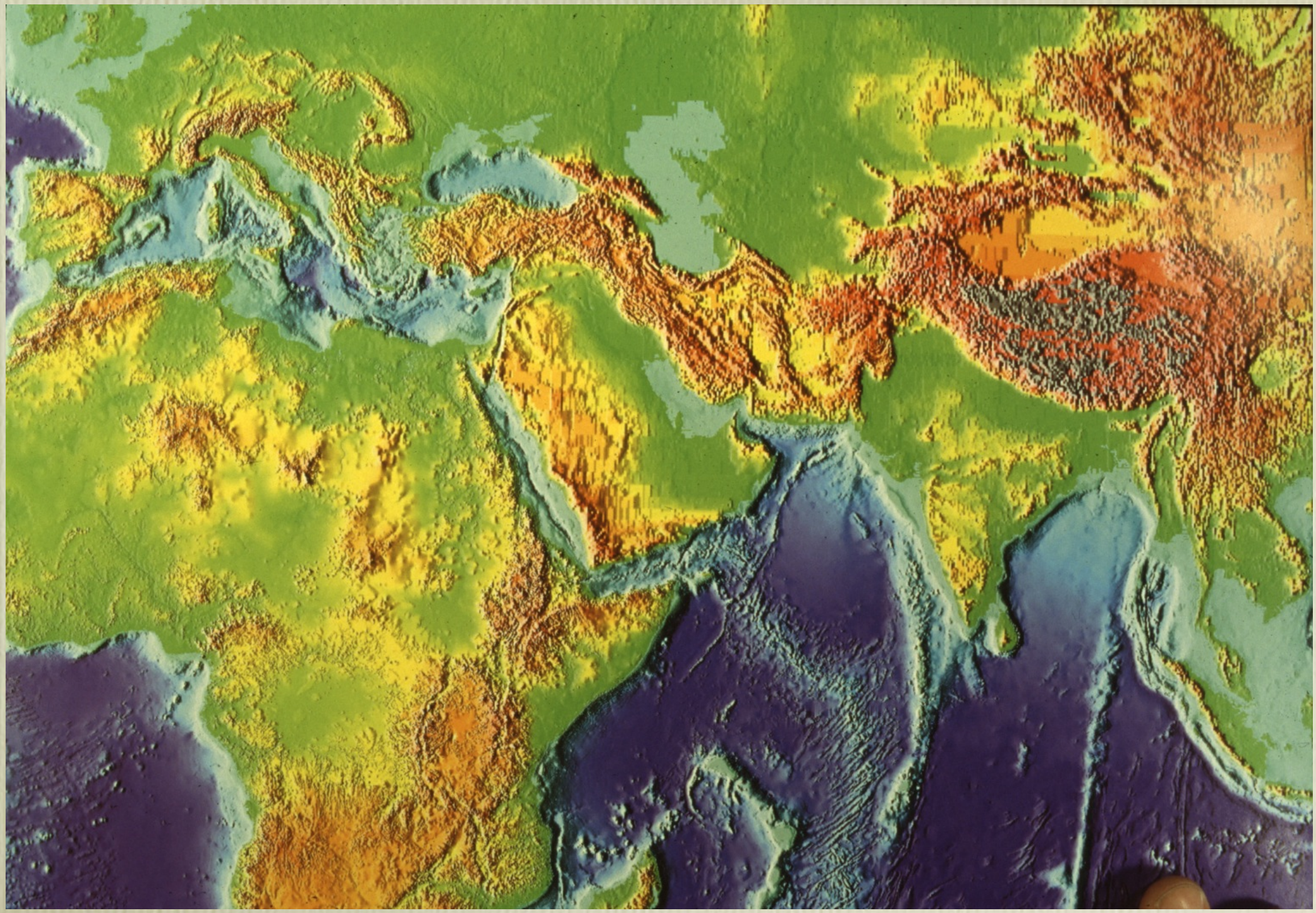

continental crust
average density: 2.6 g/cm3
upper mantle
average density: 3.3 g/cm3

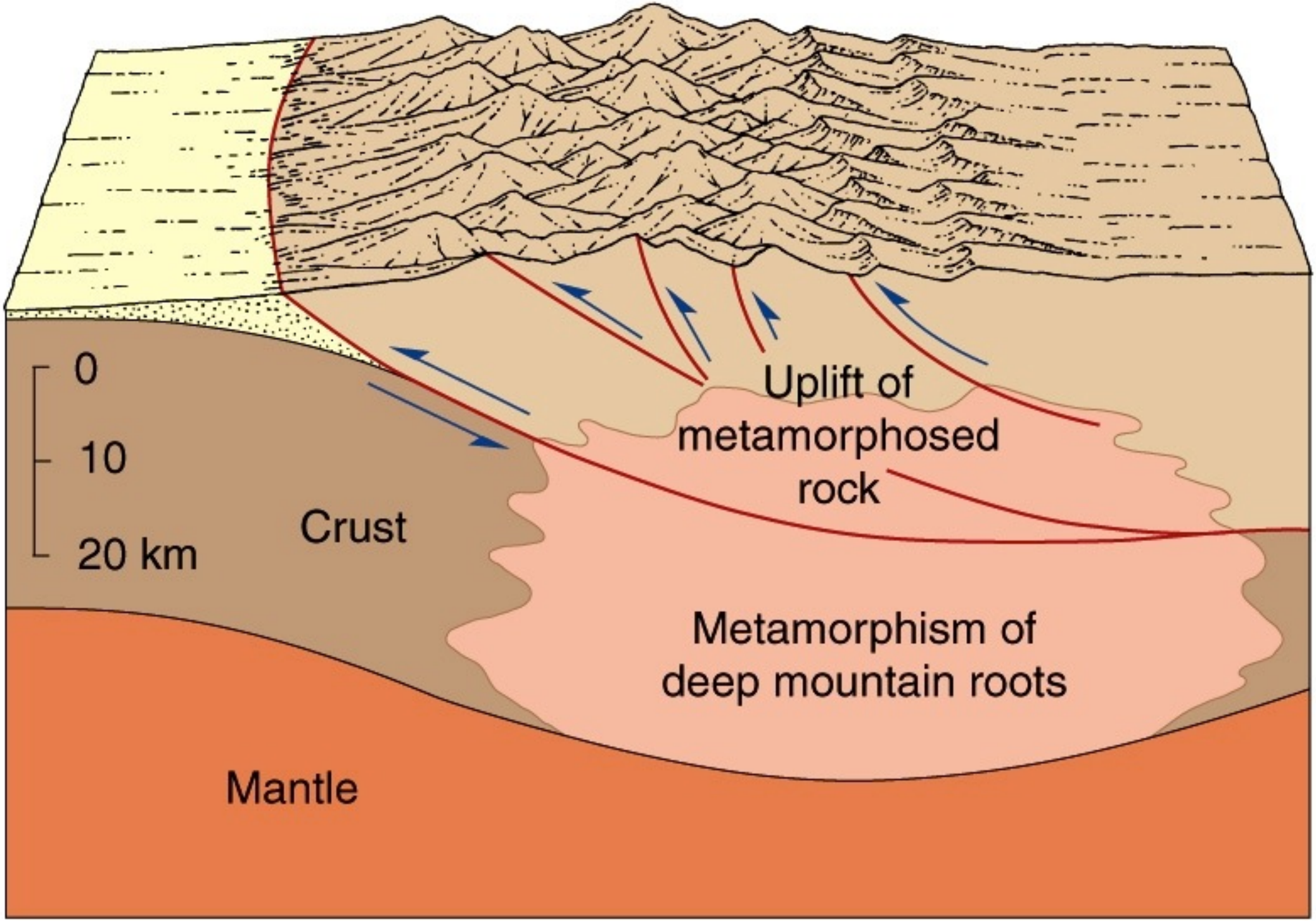


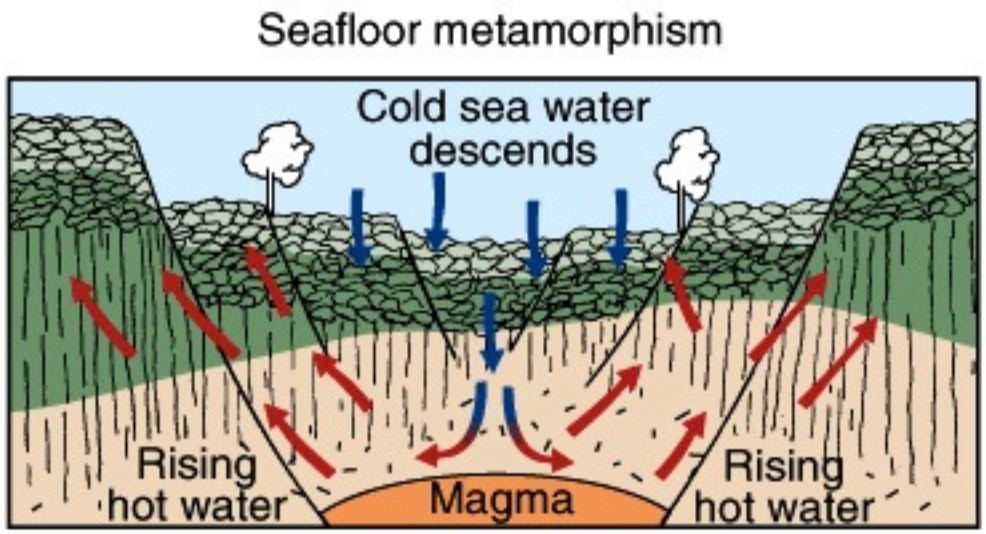


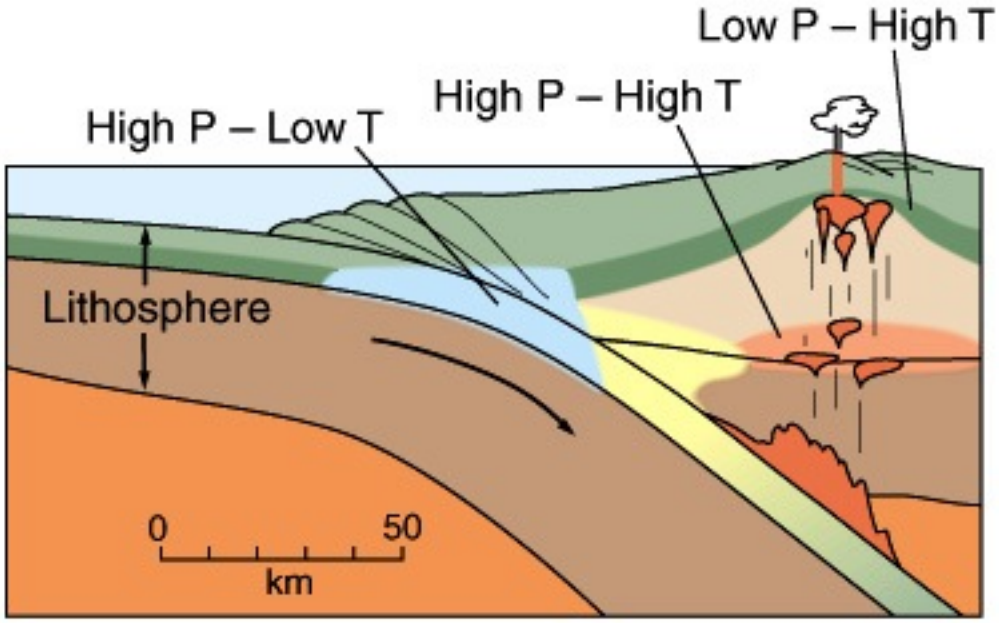


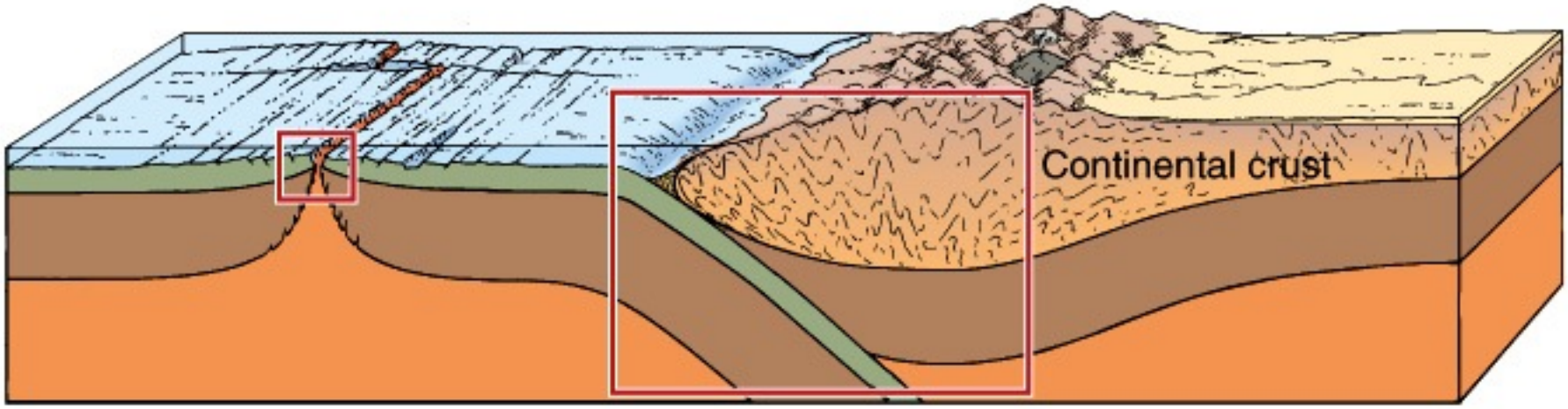





0
10
20 km
Crust
Uplift of
metamorphosed
rock
Metamorphism of
deep mountain roots
Mantle

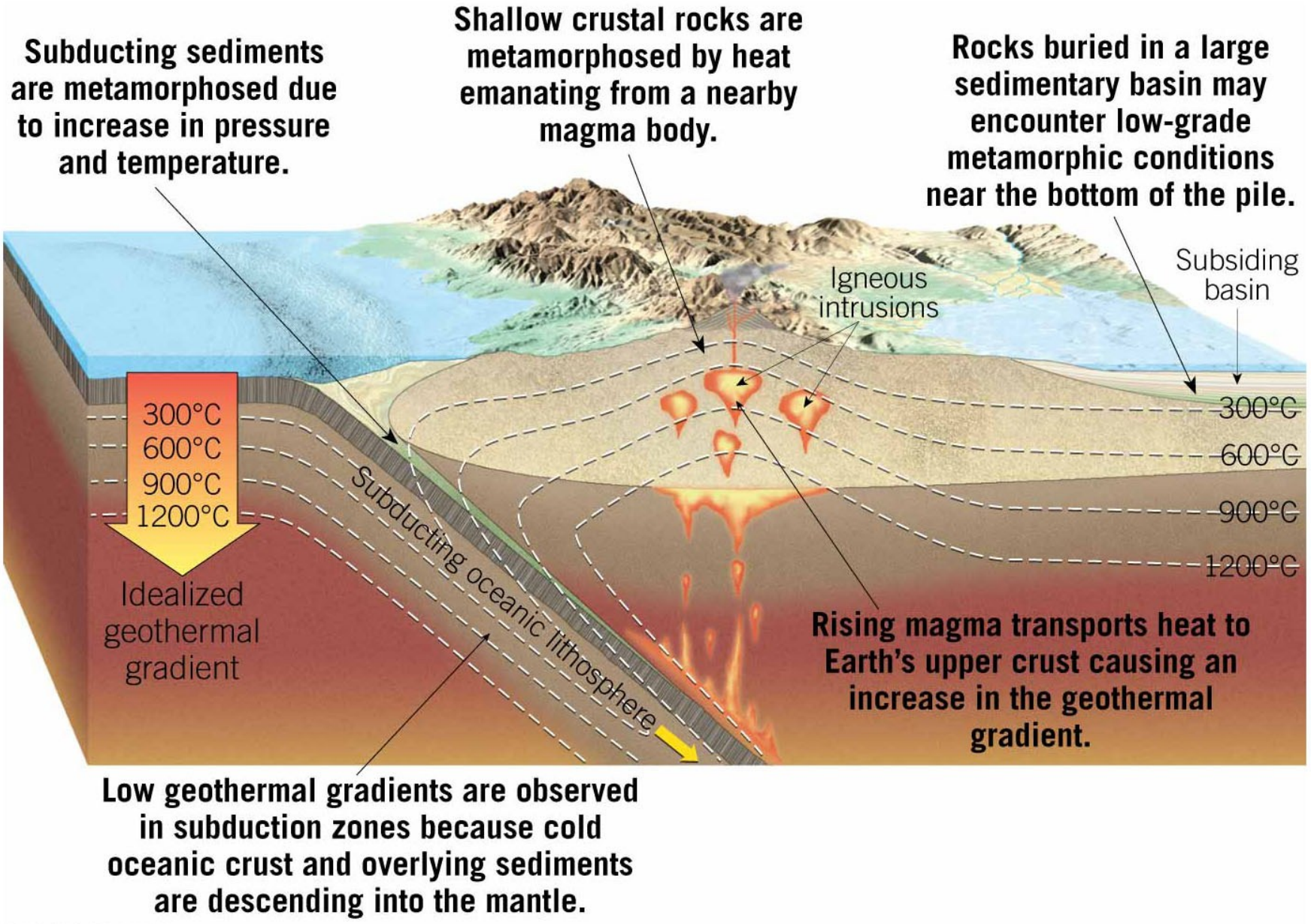


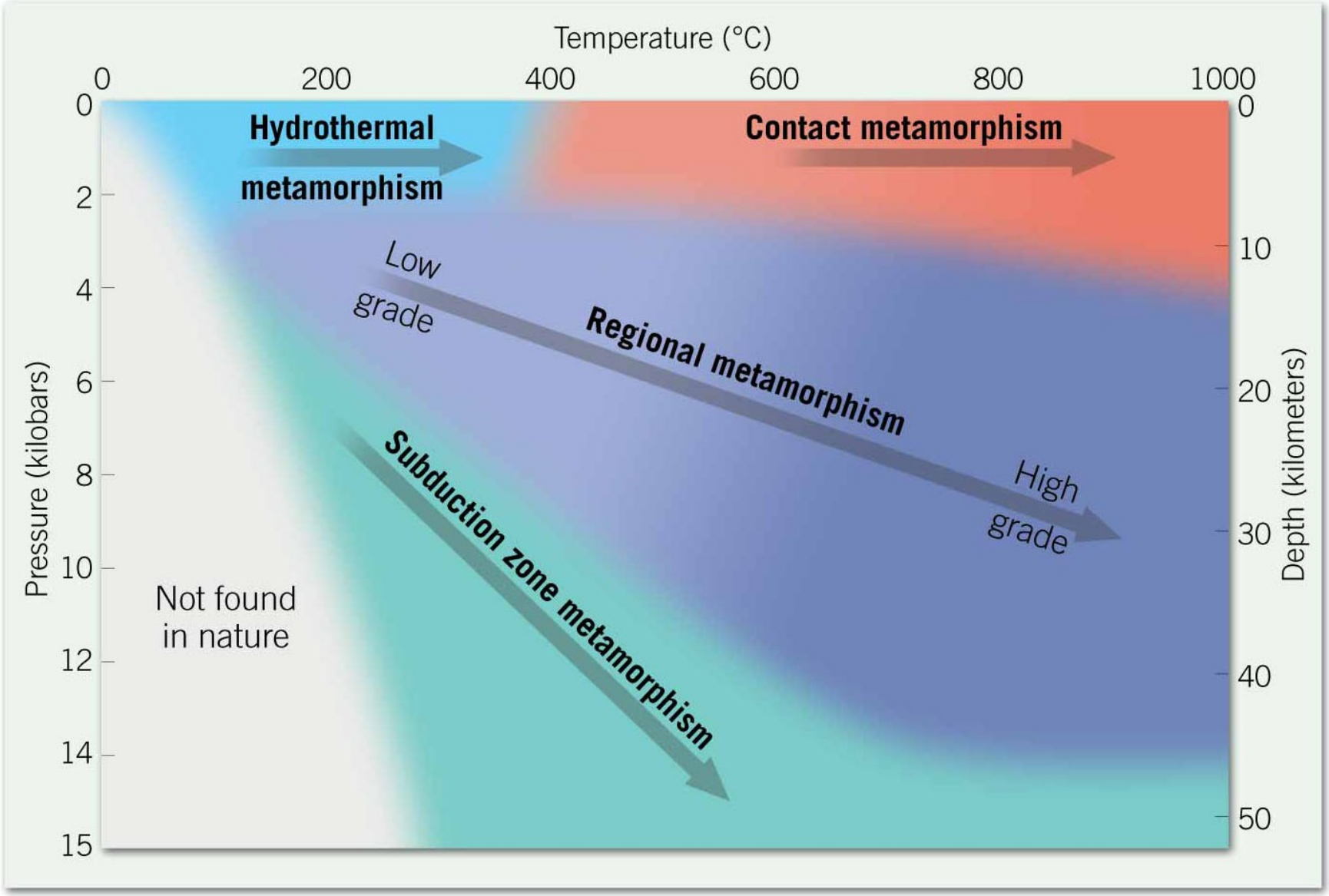


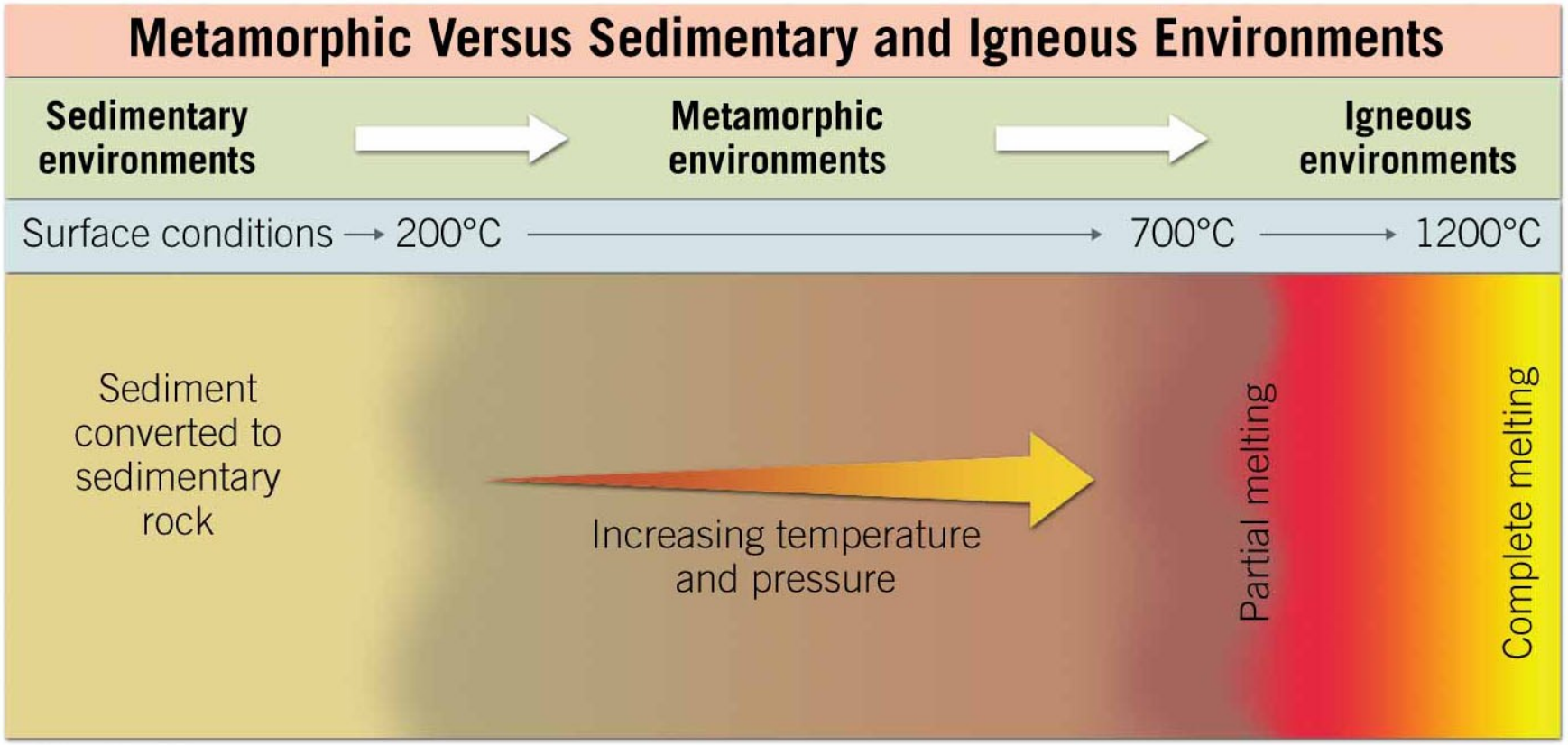


Metamorphic Facies

- Zeolite
- Greenschist
- Amphibolite
- Blueschist
- Eclogite
- Granulite

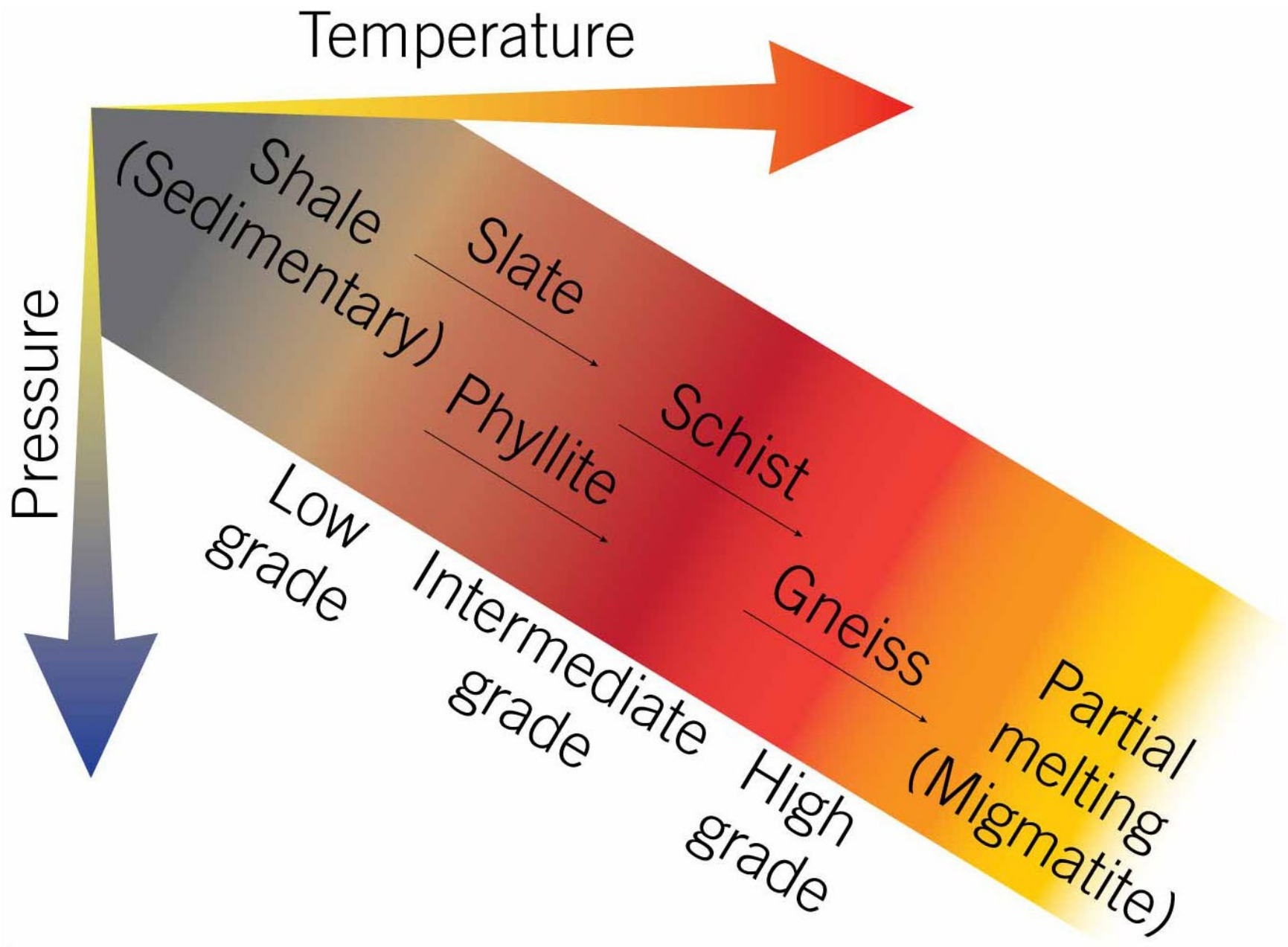

Subducting sediments are metamorphosed due to increase in pressure and temperature.
Shallow crustal rocks are metamorphosed by heat emanating from a nearby magma body.
Rocks buried in a large sedimentary basin may encounter low-grade metamorphic conditions near the bottom of the pile.
Subsiding basin
Igneous intrusions
300°C
600°C
900°C
1200°C
Idealized geothermal gradient
Subducting oceanic lithosphere
Rising magma transports heat to Earth's upper crust causing an increase in the geothermal gradient.
Low geothermal gradients are observed in subduction zones because cold oceanic crust and overlying sediments are descending into the mantle.


Temperature (°C)
0
200
400
600
800
1000
Pressure (kilobars)
0
2
4
6
8
10
12
14
15
Depth (kilometers)
0
10
20
30
40
50
Hydrothermal
metamorphism
Contact metamorphism
Low
grade
Regional metamorphism
High
grade
Subduction zone metamorphism
Not found
in nature


Metamorphic Versus Sedimentary and Igneous Environments
Sedimentary environments
Metamorphic environments
Igneous environments
Surface conditions
200°C
700°C
1200°C
Sediment converted to sedimentary rock
Increasing temperature and pressure
Partial melting
Complete melting

Grades of metamorphism

- **Low-grade** metamorphism involves more water-bearing minerals, such as clays, micas, amphiboles, “wet” quartz
- **Intermediate-grade** metamorphism
- **High-grade** metamorphism involves more “dry” minerals, such as garnet, kyanite, sillimanite

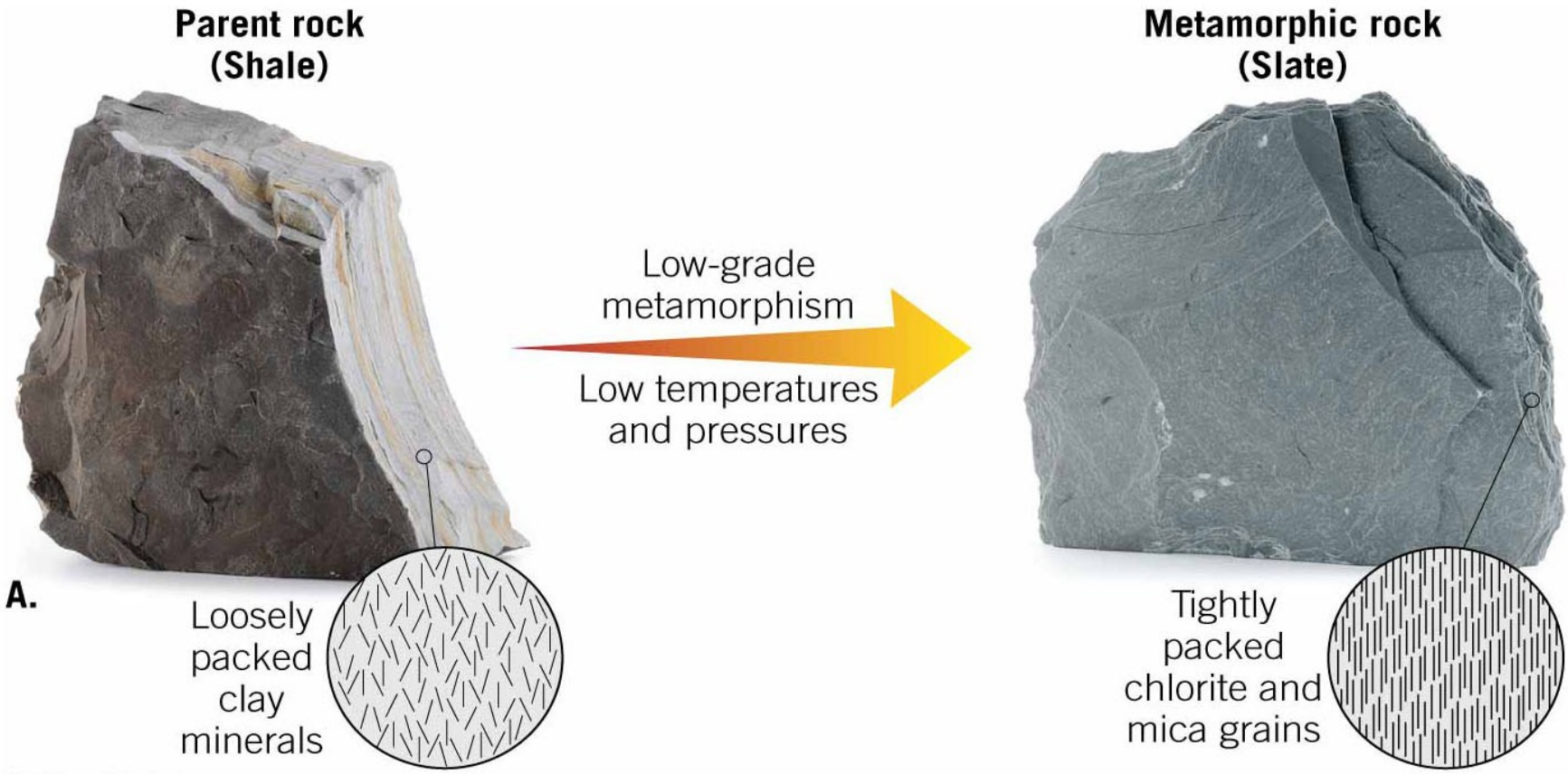

Temperature
Pressure
Shale
(Sedimentary)
Slate
Phyllite
Schist
Gneiss
Low
grade
Intermediate
grade
High
grade
Partial
melting
(Migmatite)

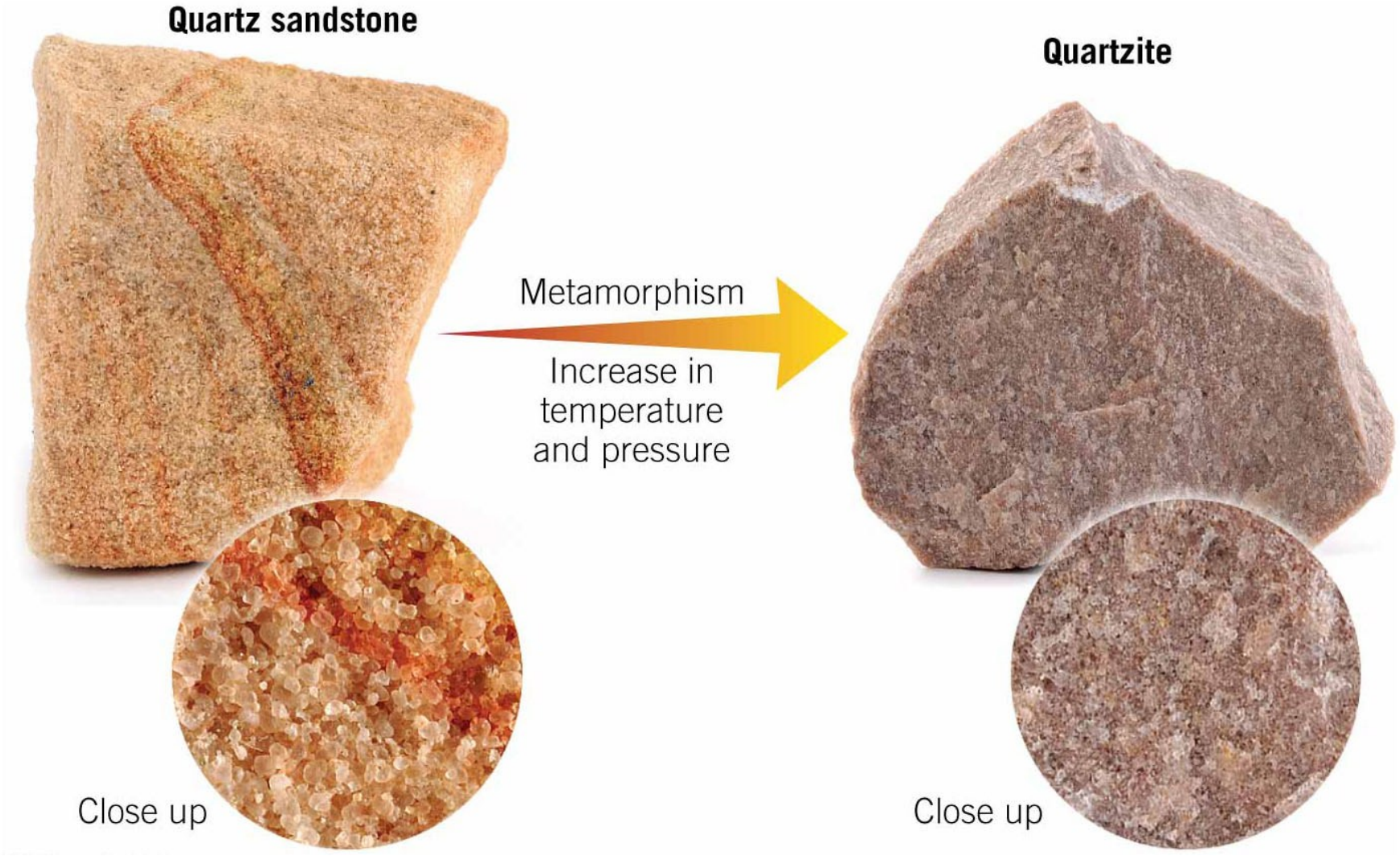
Some metamorphic processes

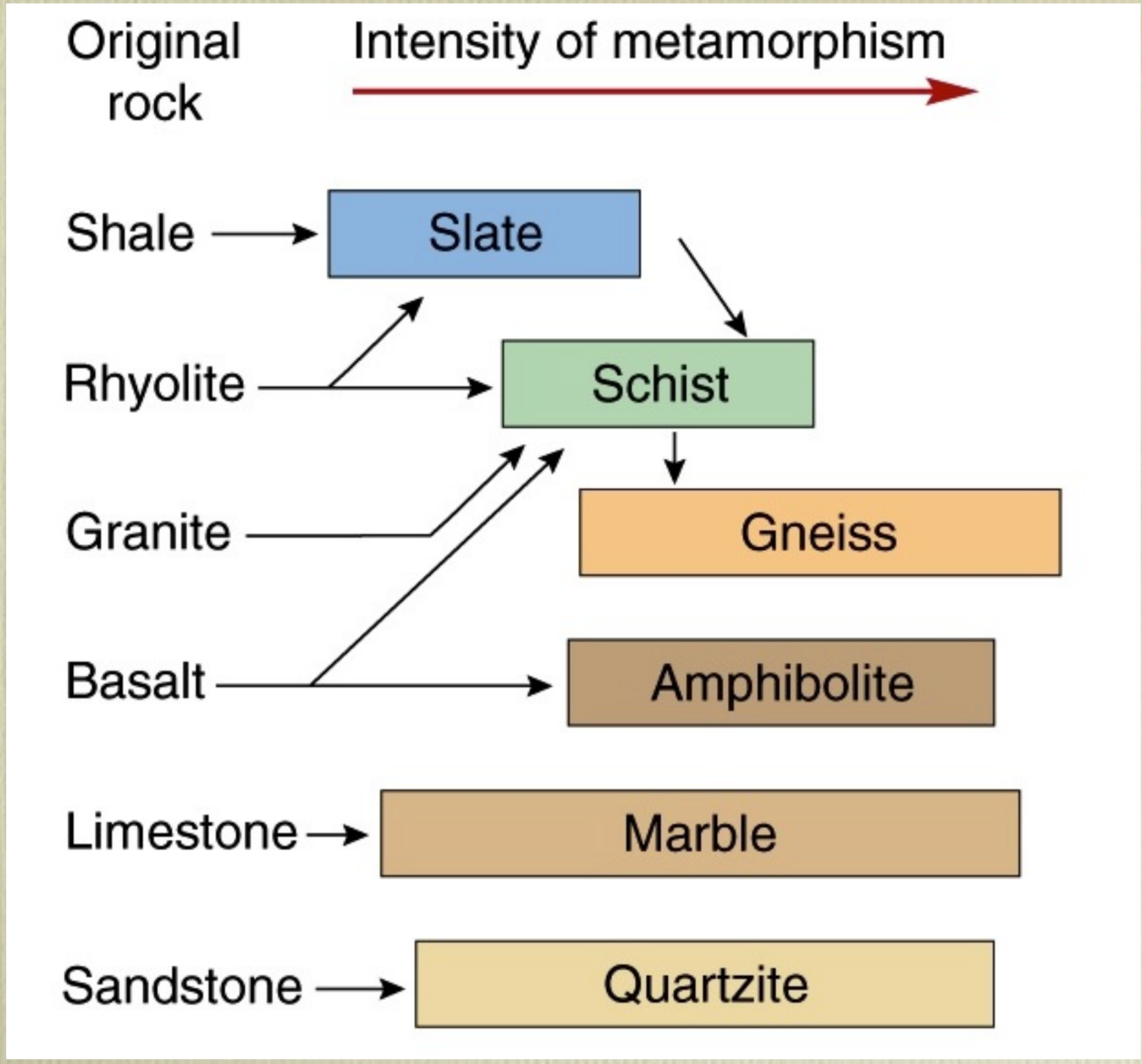
- Recrystallization
  - Closed system: mineral A in, mineral A out
- Neomorphism
  - Closed system: mineral A in, mineral B out
- Metasomatism
  - ***Open*** system: mineral A in, mineral B out

Directions of metamorphism

- **Prograde** metamorphism involves ***increasing*** the magnitude of environmental variables such as temperature, pressure, stress
- **Retrograde** metamorphism involves ***decreasing*** the magnitude of critical environmental variables


Parent rock
(Shale)
Metamorphic rock
(Slate)
Low-grade
metamorphism
Low temperatures
and pressures
A.
Loosely
packed
clay
minerals
Tightly
packed
chlorite and
mica grains

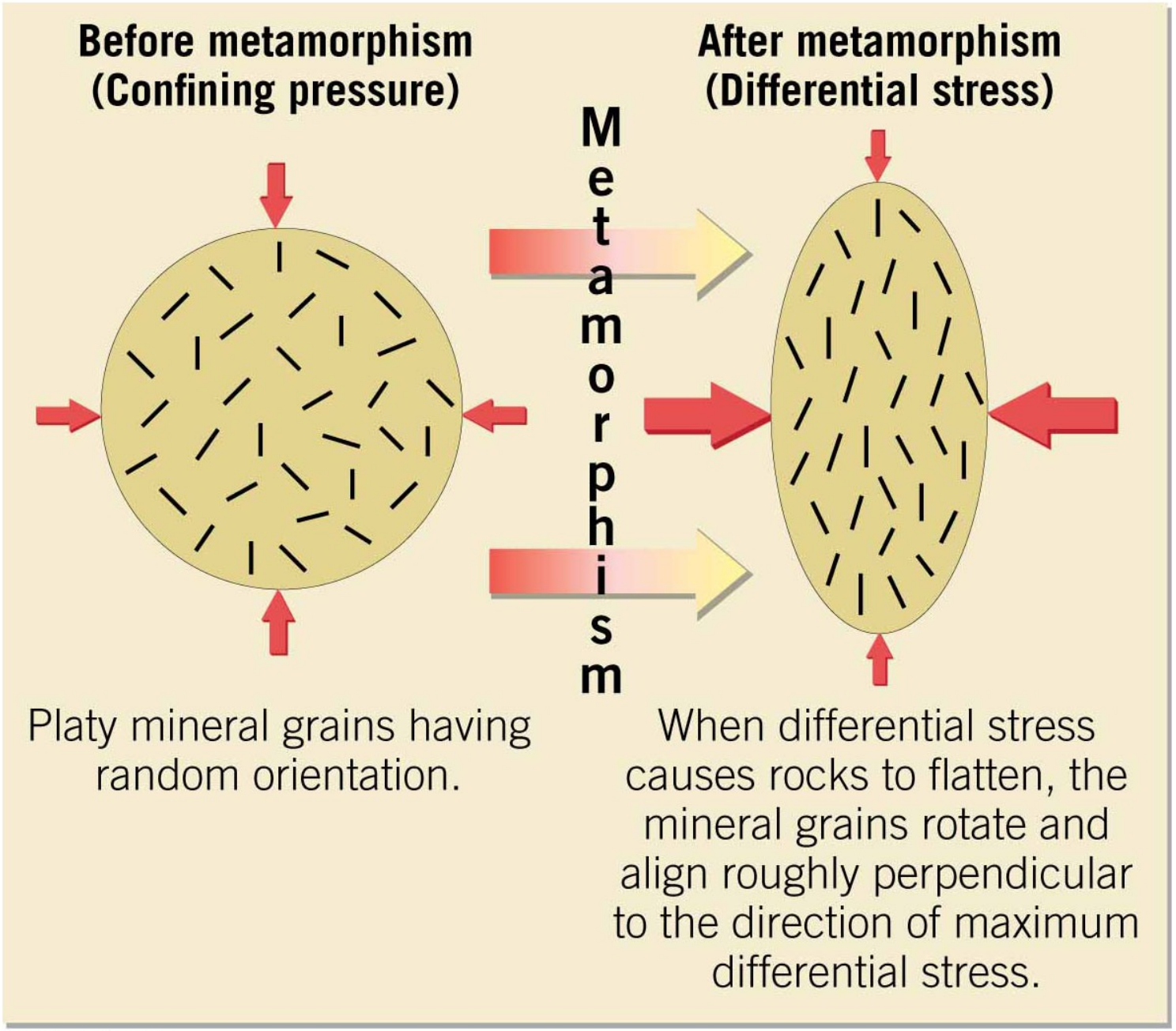

Quartz sandstone
Metamorphism
Increase in temperature and pressure
Quartzite
Close up
Close up

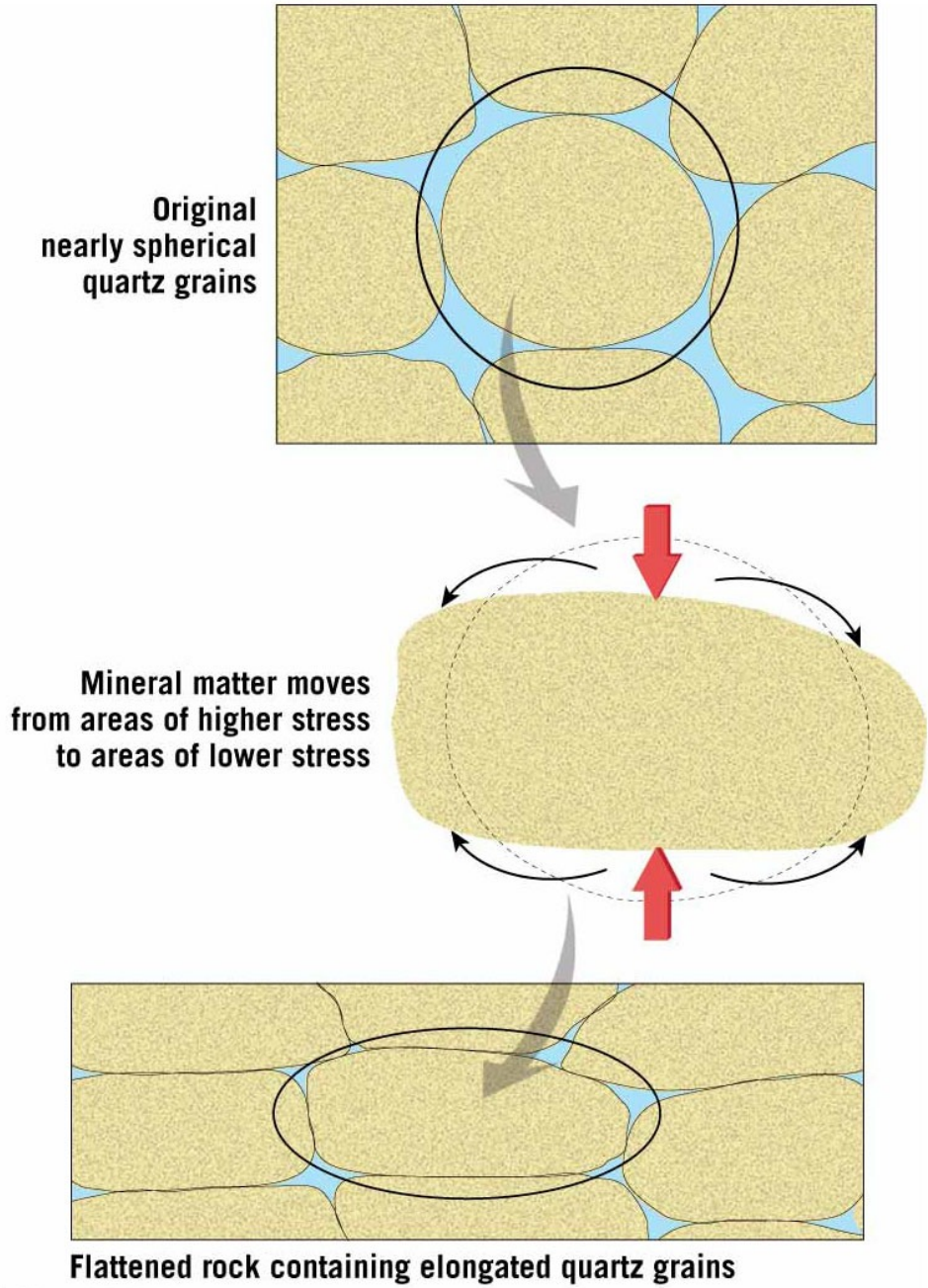

Original rock
Intensity of metamorphism
Shale
Slate
Rhyolite
Schist
Granite
Gneiss
Basalt
Amphibolite
Limestone
Marble
Sandstone
Quartzite

Amphibolite

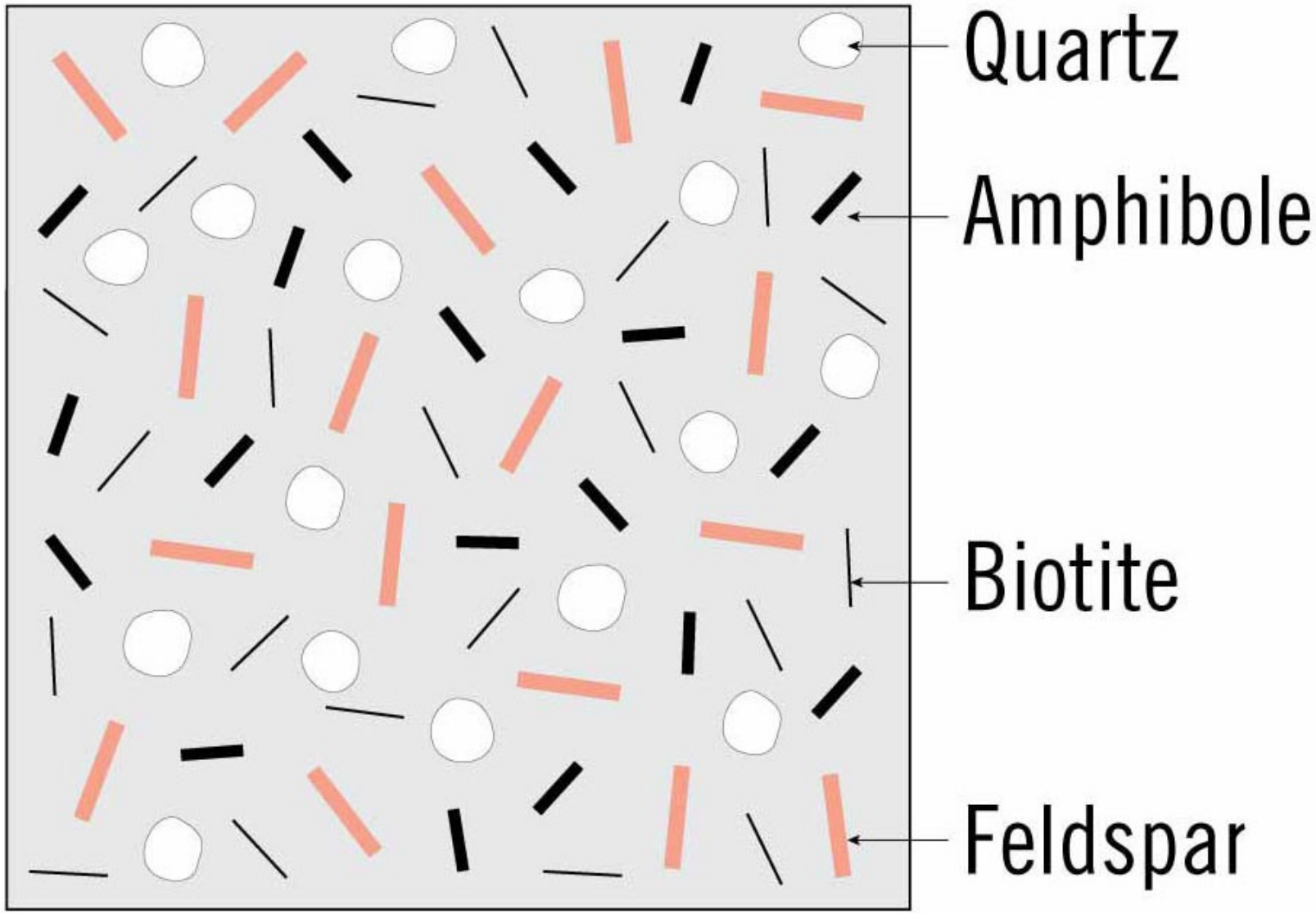
Foliated Metamorphic Rocks

- Slate (slaty cleavage)
- Phyllite (phyllitic layering)
- Schist (schistocity)
- Gneiss (gneissic layering or compositional banding)

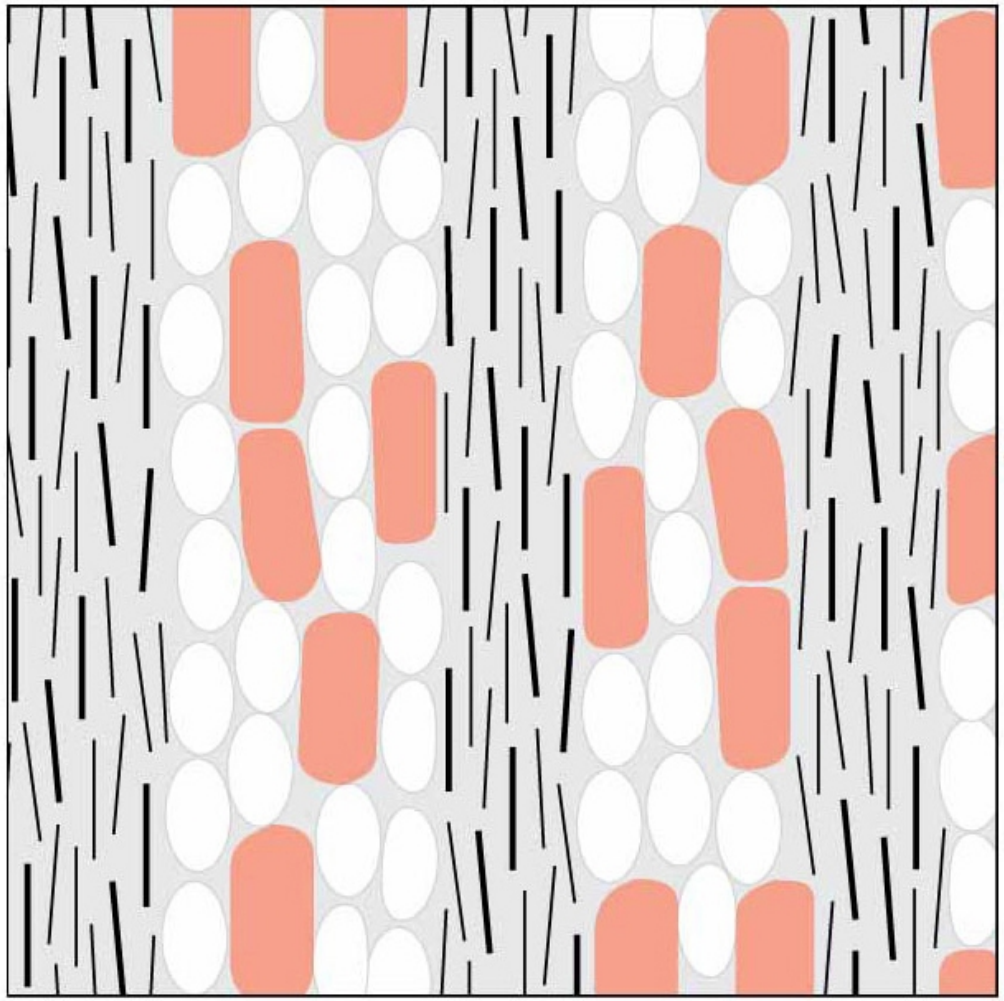

Before metamorphism
(Confining pressure)
After metamorphism
(Differential stress)
Metamorphism
Platy mineral grains having random orientation.
When differential stress causes rocks to flatten, the mineral grains rotate and align roughly perpendicular to the direction of maximum differential stress.


Original
nearly spherical
quartz grains
Mineral matter moves
from areas of higher stress
to areas of lower stress
Flattened rock containing elongated quartz grains

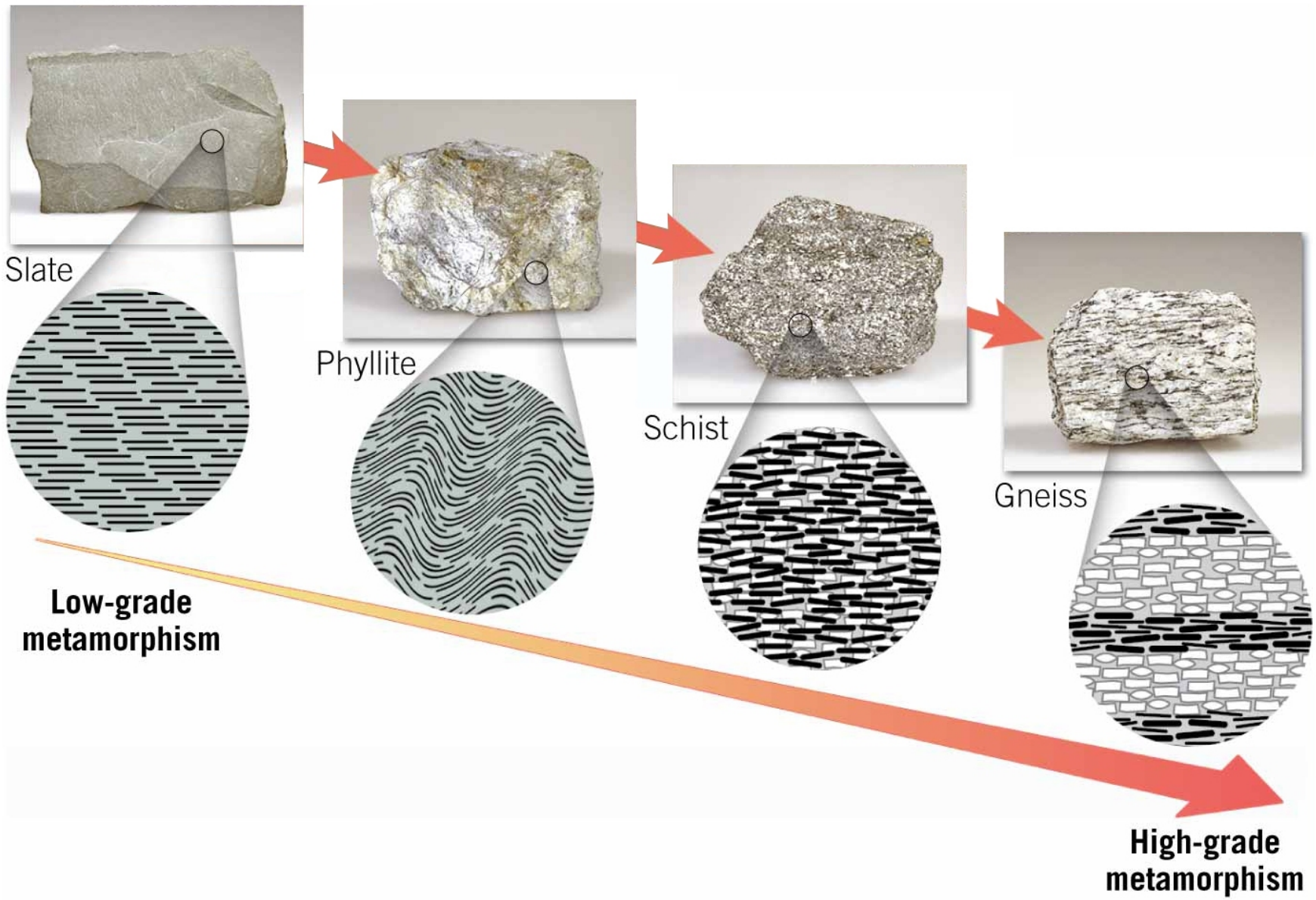

Differential stress
Maximum
Maximum

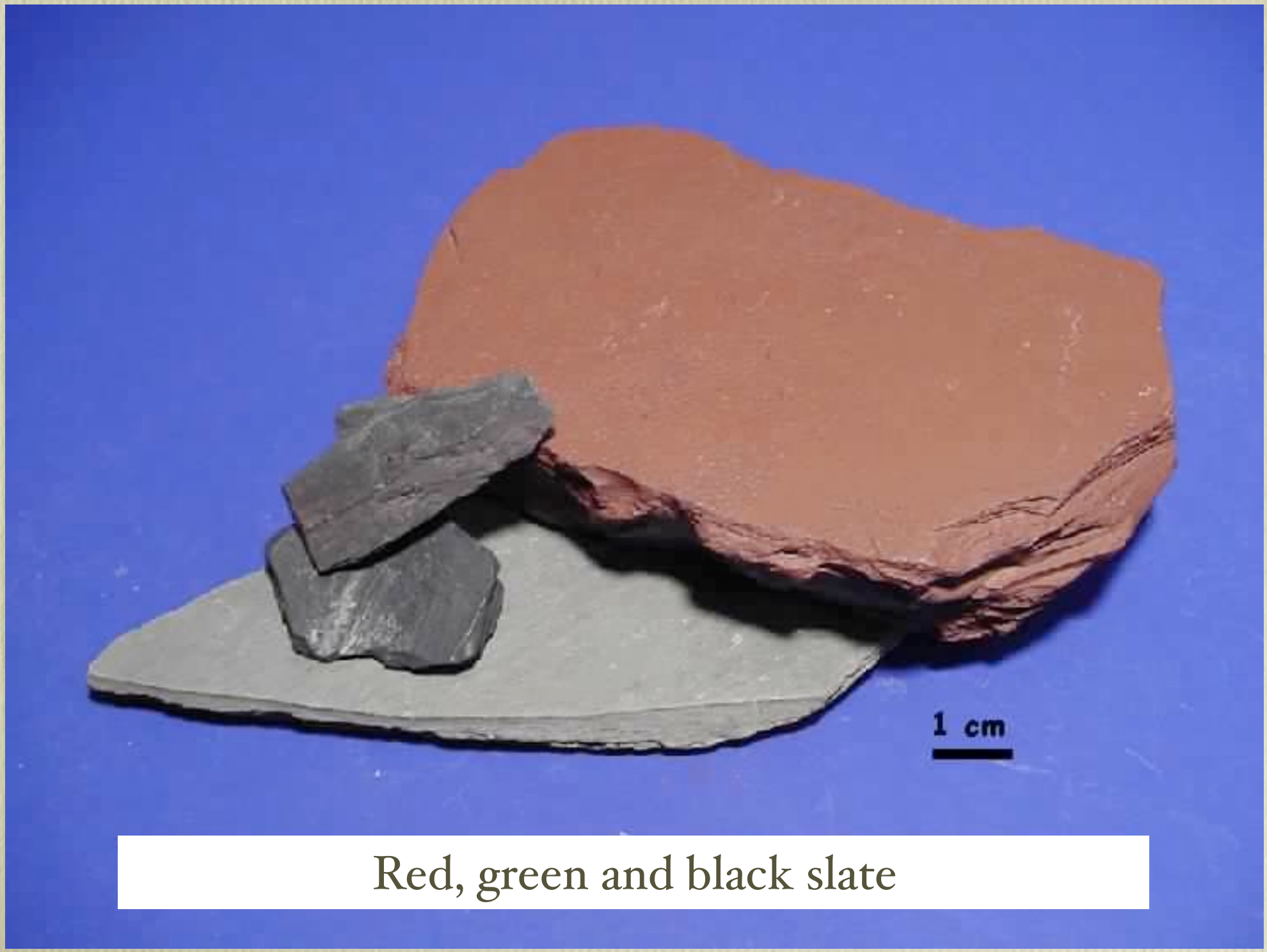


Unmetamorphosed

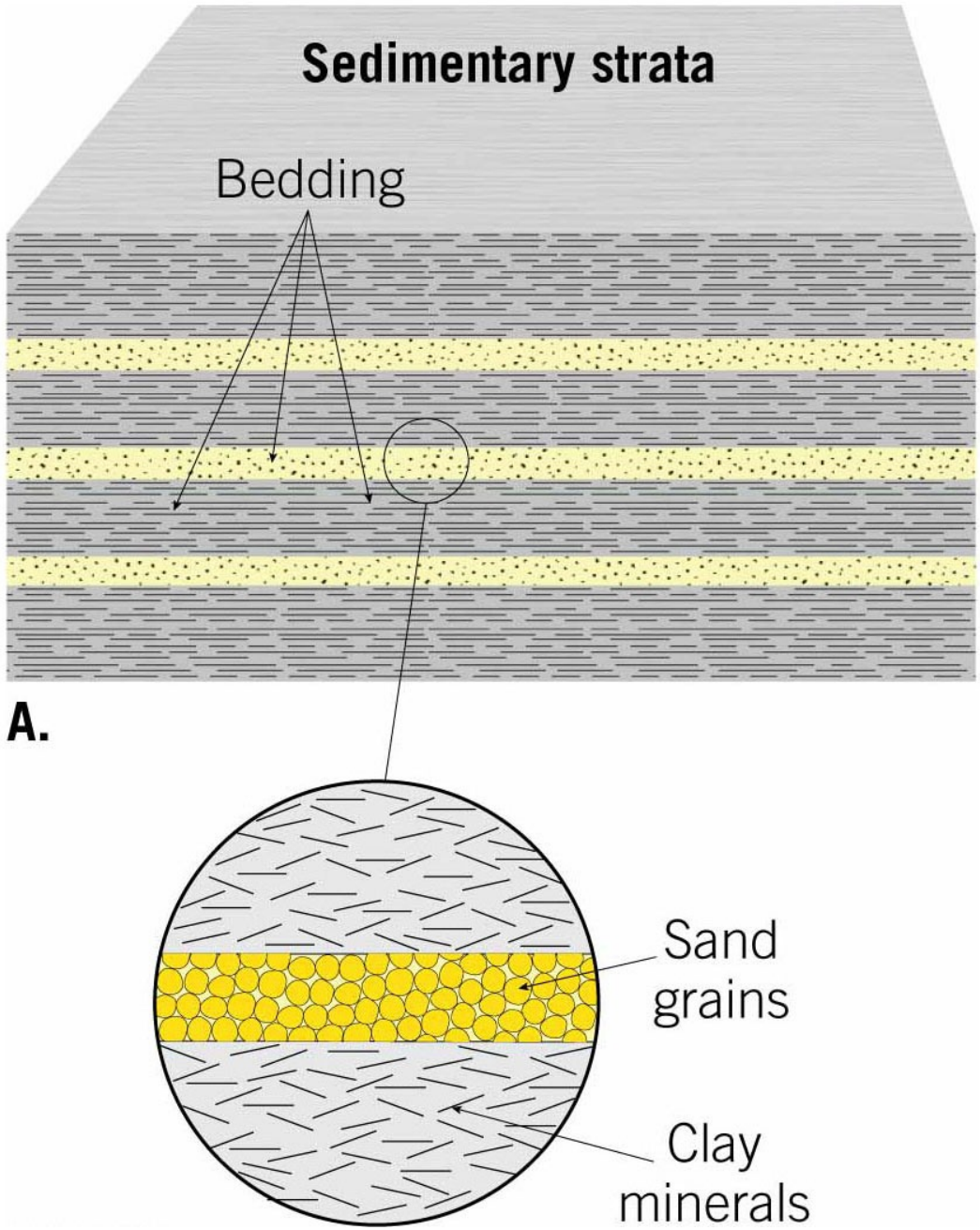


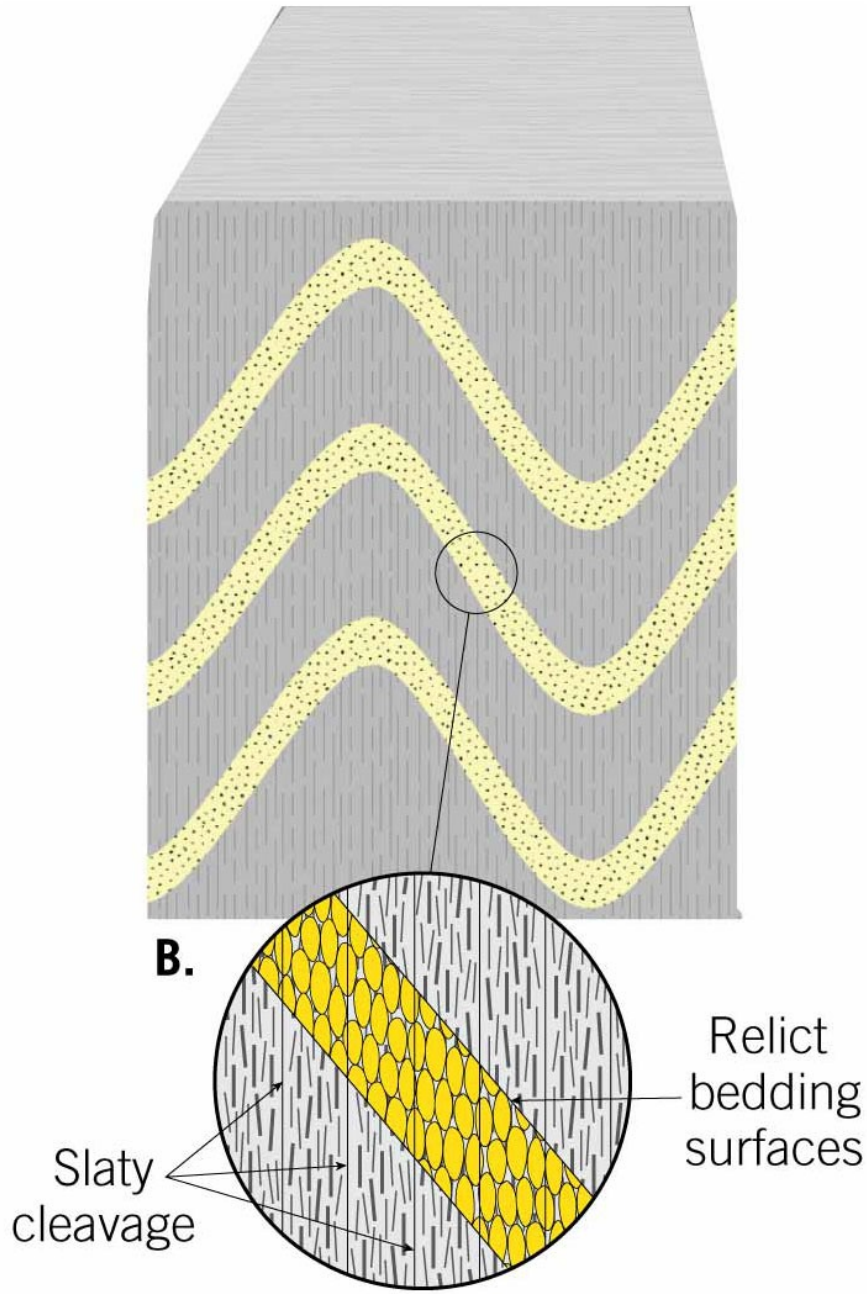
High-grade metamorphism


Slate
Phyllite
Schist
Gneiss
Low-grade metamorphism
High-grade metamorphism



Red, green and black slate


Sedimentary strata
Bedding
A.
Sand grains
Clay minerals

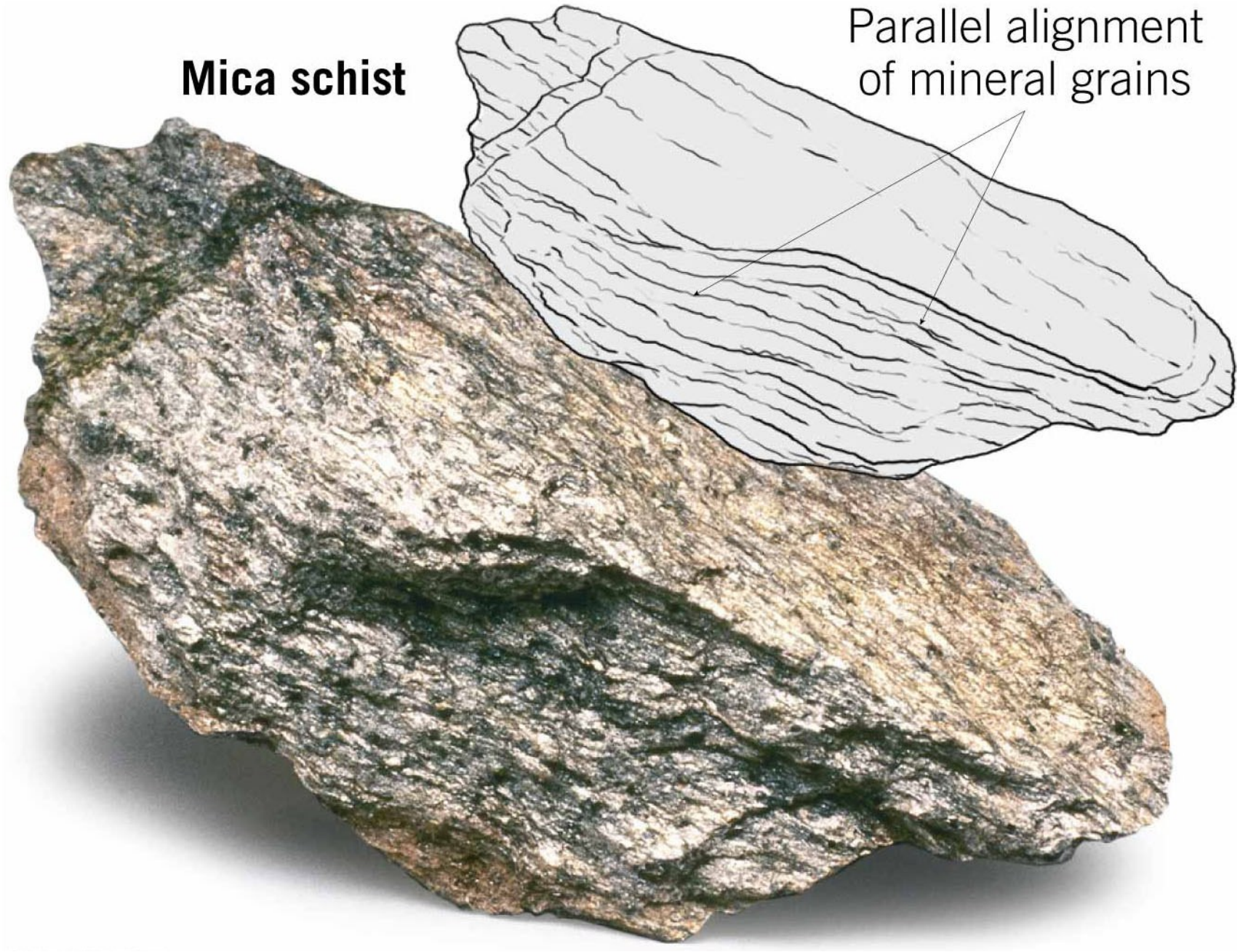

B.
Relict
bedding
surfaces
Slaty
cleavage

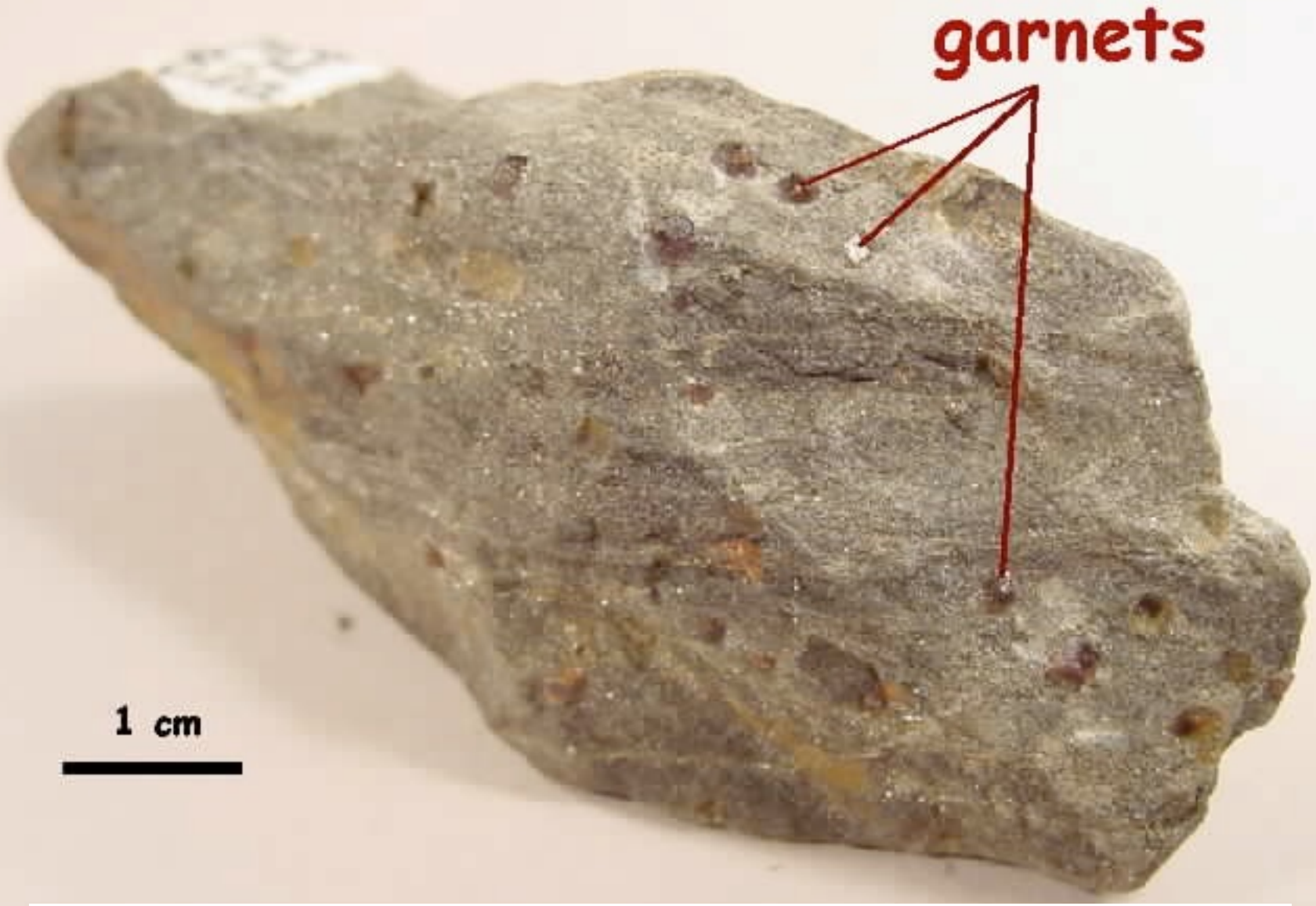
C. Callan Bentley

Phyllite (pronounced “FILL ite”

Phyllite, showing silky sheen


Schist


Mica schist
Parallel alignment
of mineral grains



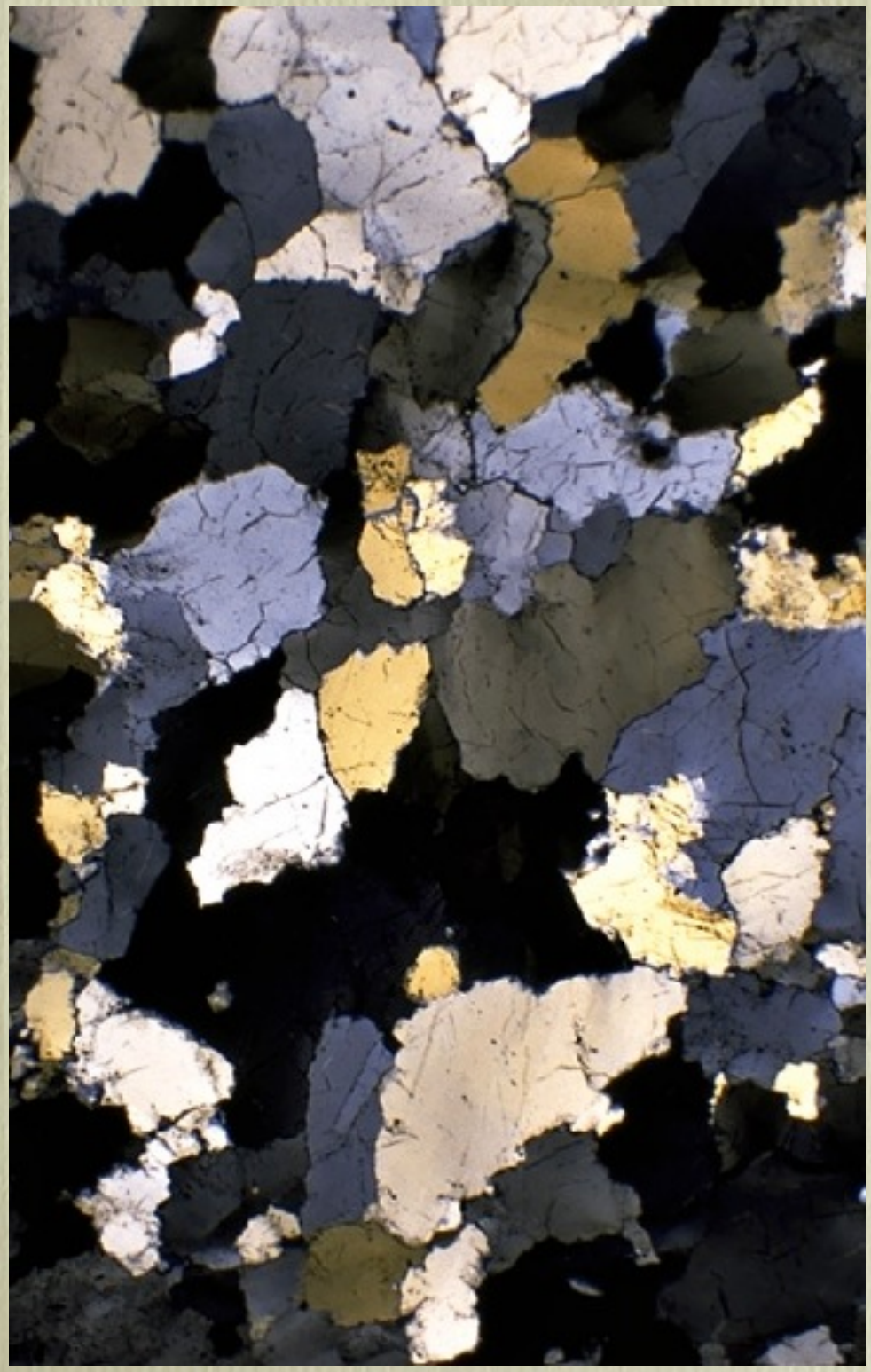
Garnet schist

Gneiss (pronounced “nice”)

Dennis Tasa

Non-Foliated Metamorphic Rocks

- Quartzite
  - May display relict bedding
  - Metamorphosed quartz sandstone
- Marble
  - May display relict bedding
  - Metamorphosed limestone

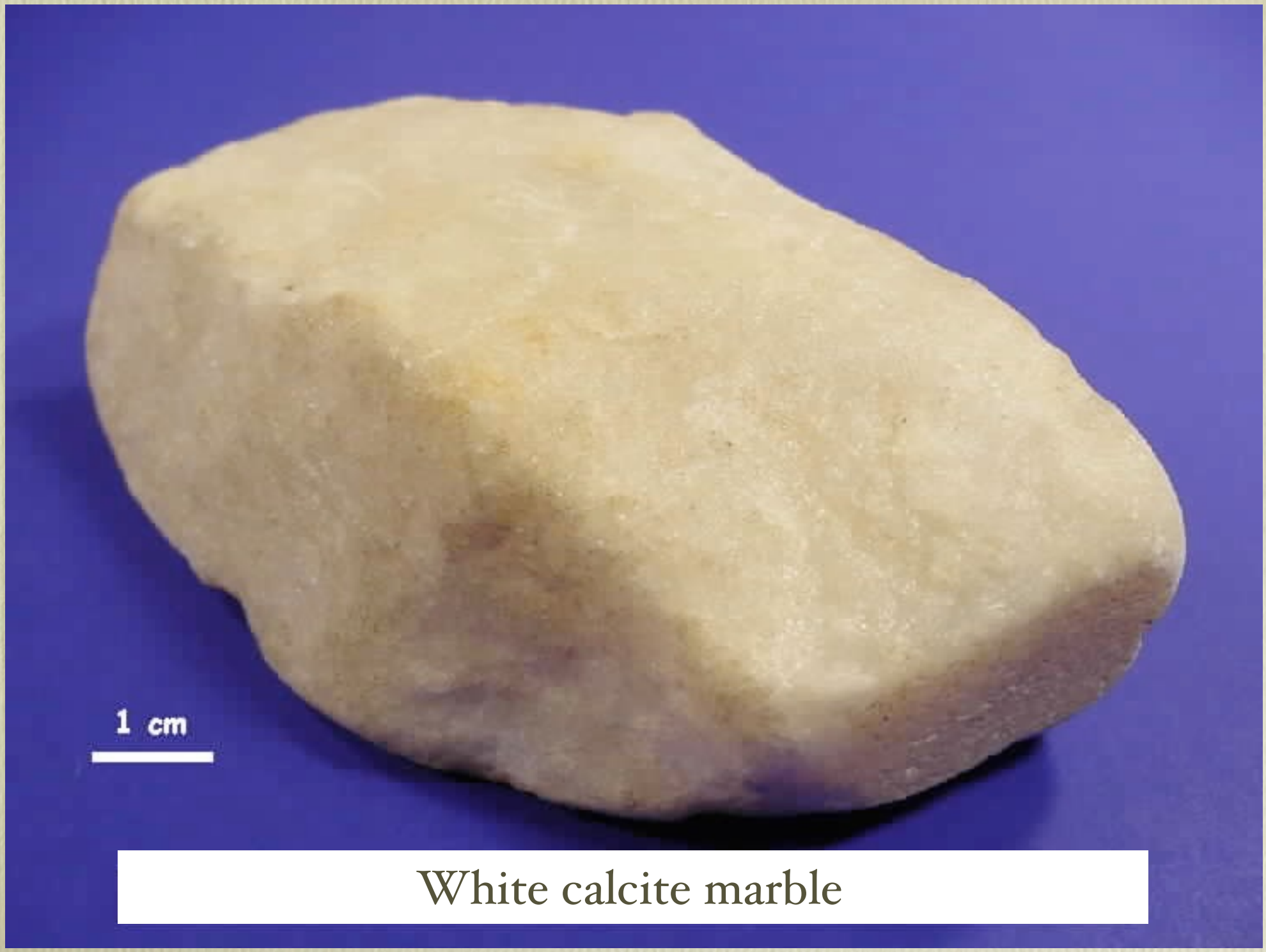


Photograph of a thin section of quartzite, taken through a geological microscope using cross-polarized light.
The quartz grains form a dense mosaic of interlocking crystals.

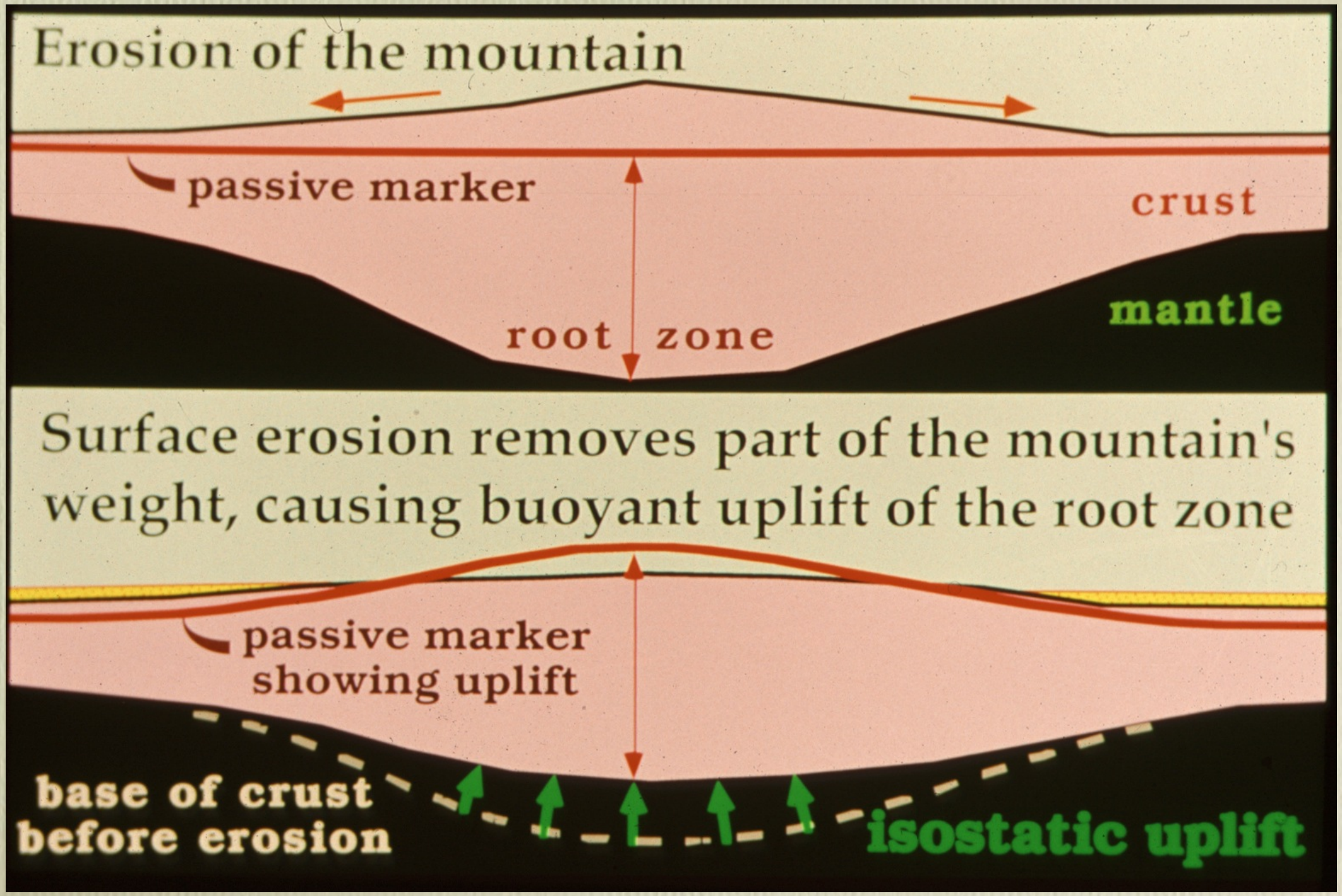
Pink quartzite from Baraboo, Wisconsin

Glamorous wife of a paunchy geology professor stands perilously close to a dark foliated metamorphic rock (a phyllite) in contact with a light-colored non-foliated metamorphic rock (a quartzite). Van Hise Rock near Rock Springs, Wisconsin.


Nikon



White calcite marble


Erosion of the mountain
passive marker
crust
mantle
root zone
Surface erosion removes part of the mountain's weight, causing buoyant uplift of the root zone
passive marker showing uplift
base of crust before erosion
isostatic uplift