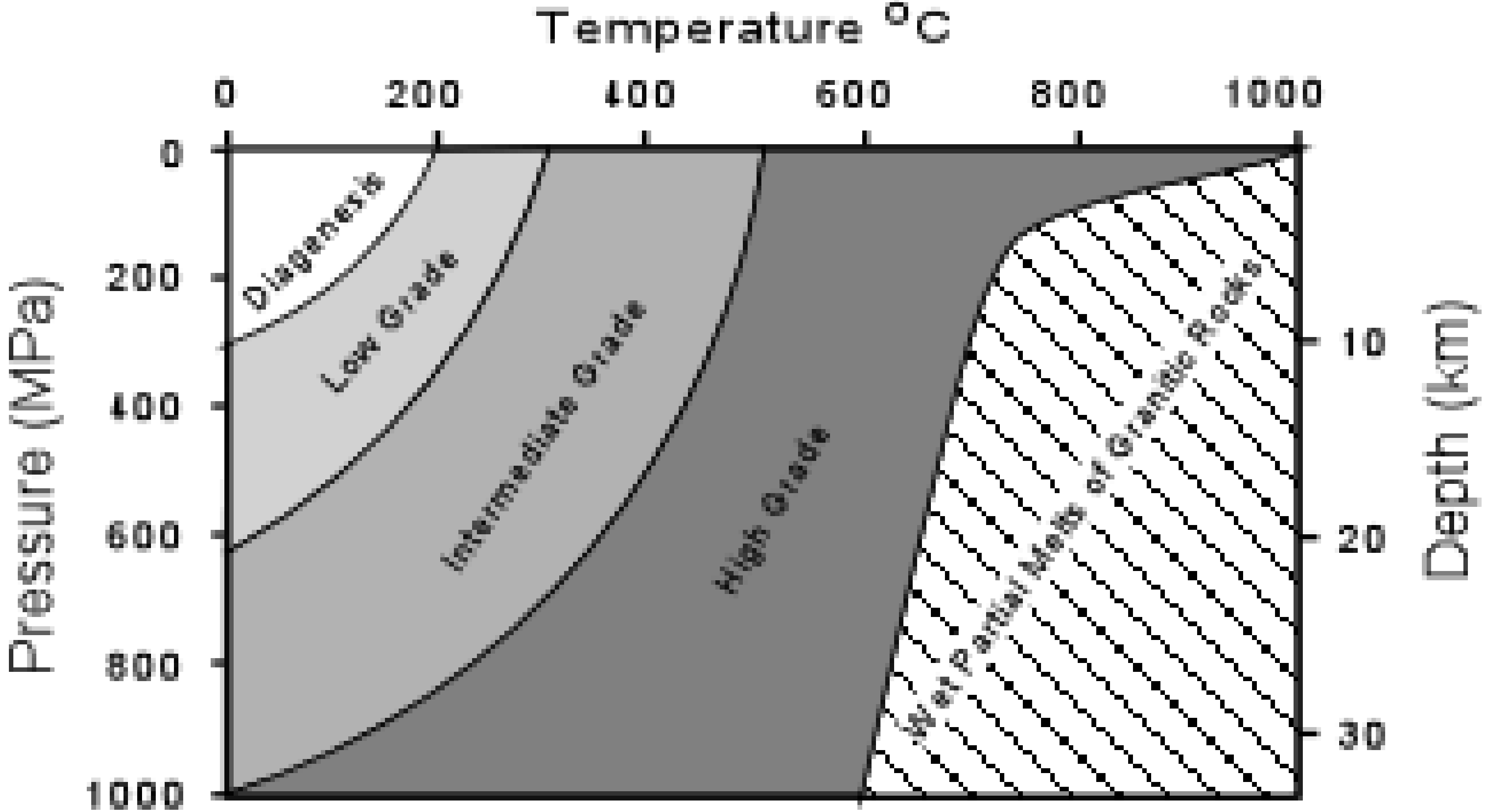
Metamorphic grade: The relative T and P conditions under which metamorphic rocks form.

Prograde metamorphism: increase of T and/or P increases on a body of rock.



As metamorphic grade increase, new minerals form

Low-grade metamorphism: 200 to about 300 ^{o}C and relatively low P.

Characterized by an abundance of *hydrous minerals:*

- Clay Minerals (hydrous Al-phyllosilicates)
- Serpentine ($Mg_3Si_2O_5(OH)_4$)
- Chlorite $(Mg,Fe,Al)_6\ (Si,Al)_4O_{10}(OH)_8$

High-grade metamorphism: T > 320 ^{o}C and relatively high P.

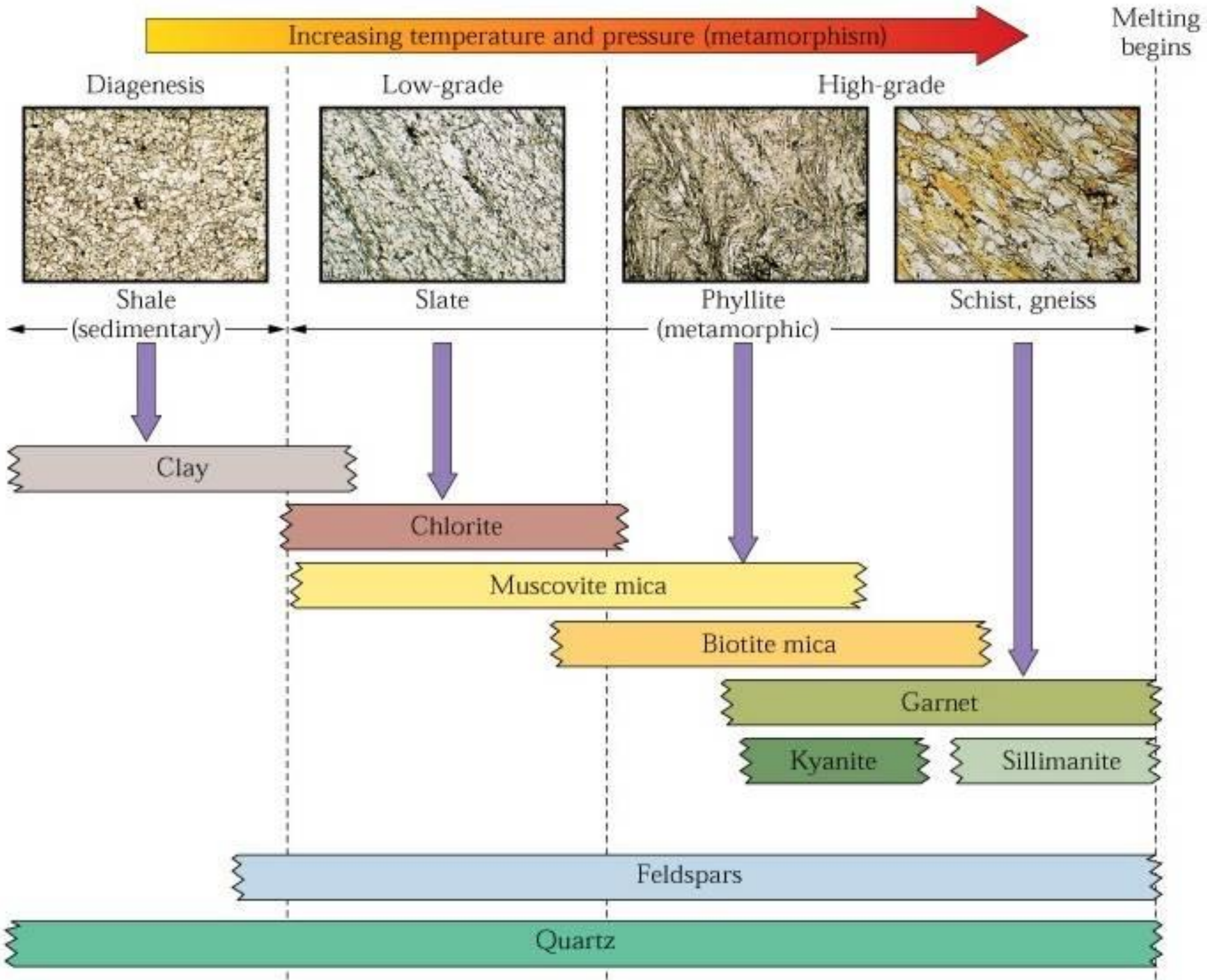
With higher T and P – less hydrous minerals, loss of H_2O, more common non-hydrous minerals.

Minerals of higher grade metamorphic rocks:

<u>Muscovite</u> – hydrous, eventually disappears at the highest grade of metamorphism

<u>Biotite</u> – hydrous, stable to high grades of metamorphism.

<u>Pyroxene, Garnet</u>- non hydrous minerals.



Kyanite, Sillimanite Al_2SiO_5

Retrograde metamorphism: Mineralogical adjustment of relatively high-grade metamorphic rocks to temperatures lower than those of their initial metamorphism

Mechanism: uplift and cooling of a rock

Retrograde metamorphism much less common than prograde metamorphism.

Should we get back the original pre-metamorphic rocks? Generally, No

Reasons:

• Chemical reactions much slow with decreasing T.

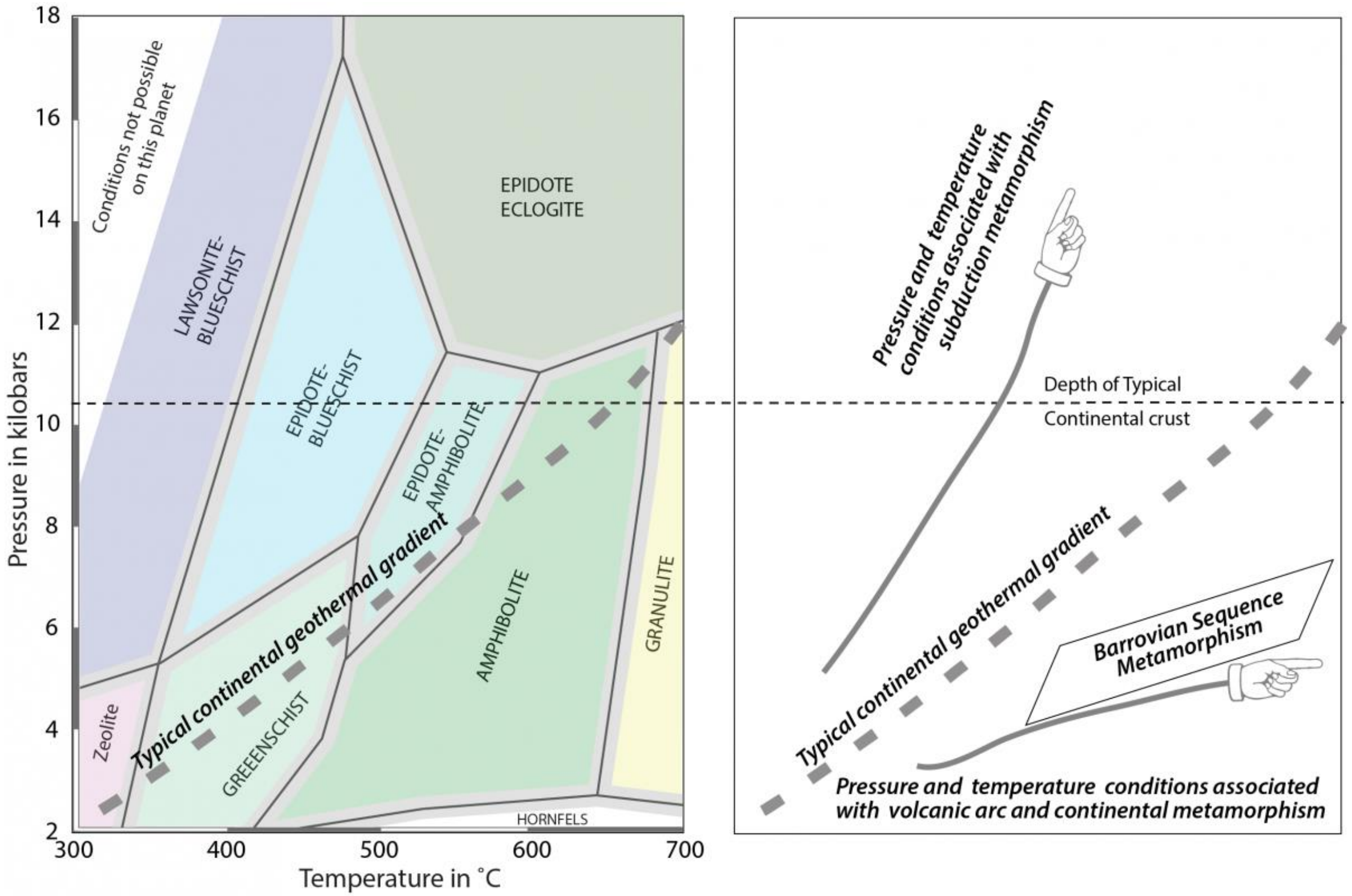
• During prograde metamorphism, fluids (H_2O and CO_2) are driven off, which are necessary to form the hydrous minerals of low-grade rocks.

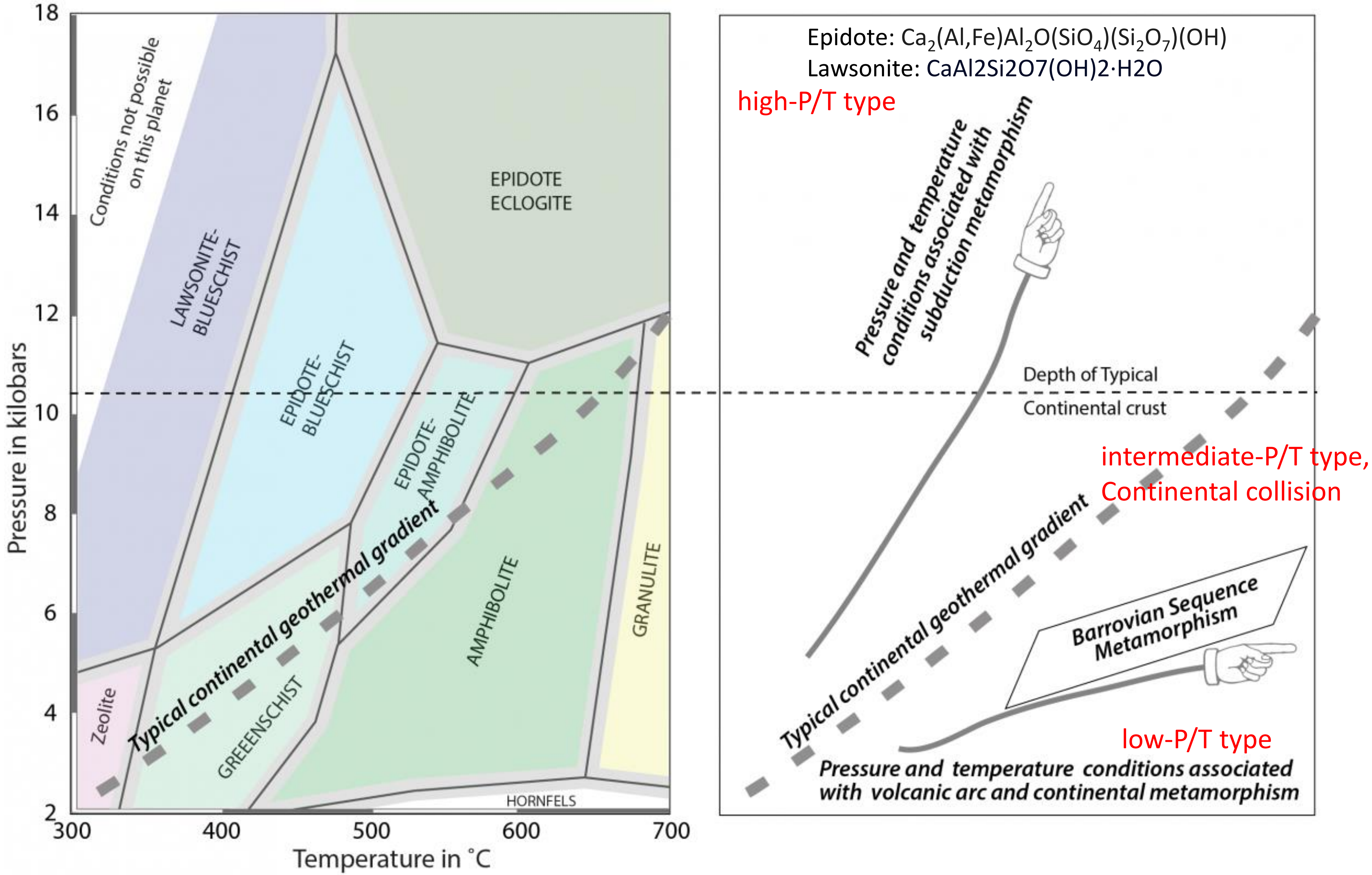
• More rapid chemical reactions in presence of fluids, they are not available to speed up reactions during retrograde metamorphism.

Metamorphic facies: Groups of minerals (mineral assemblages) that are stable over a range of P and T.

Represents unique sets of mineral assemblages that form under the same P and T conditions in various kinds of rocks.

Provide information about the metamorphic history of a rock.

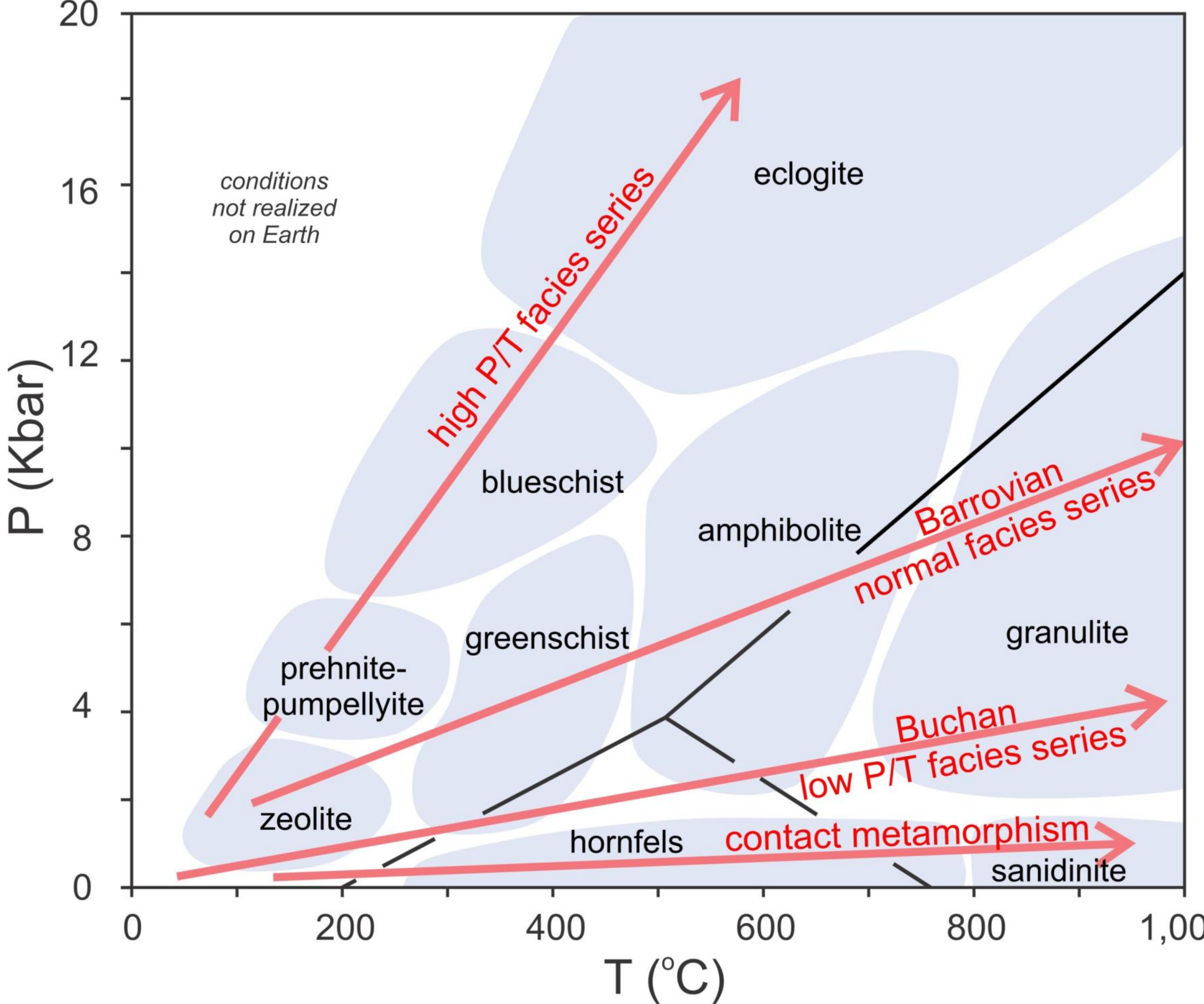


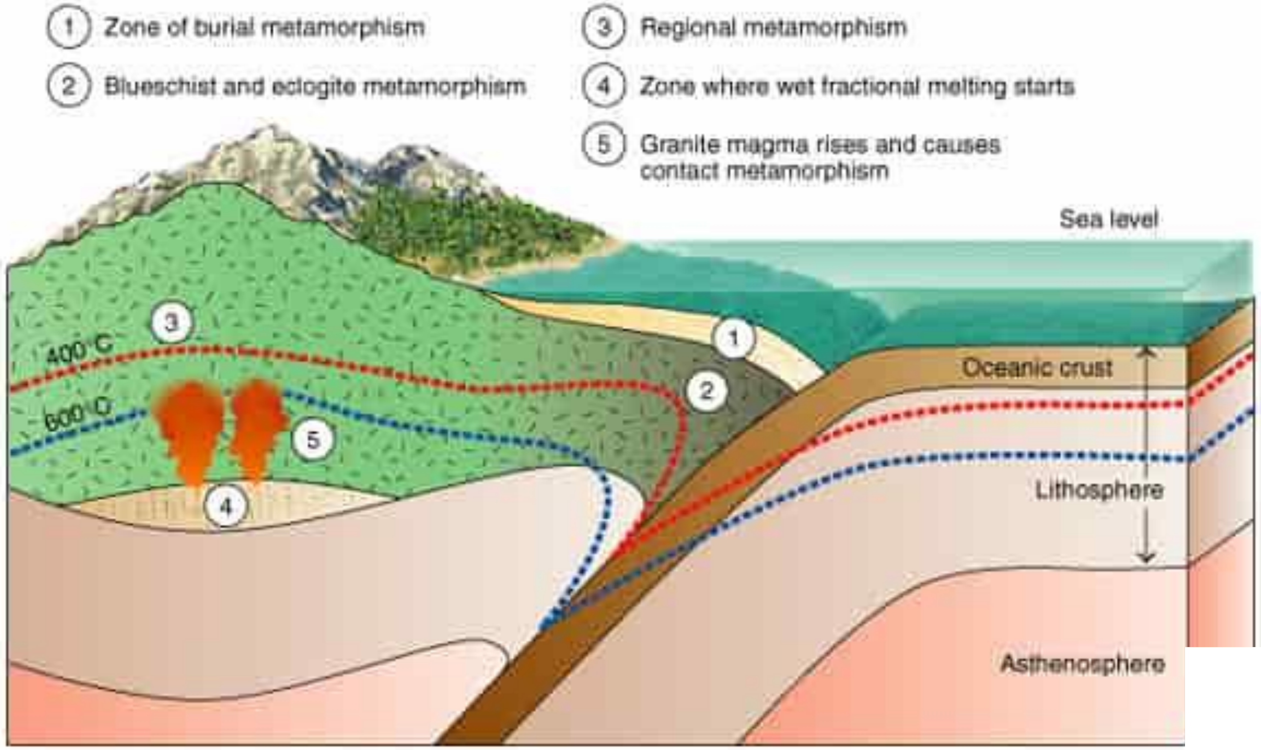


Epidote: $Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$
Lawsonite: CaAl2Si2O7(OH)2·H2O
high-P/T type
Pressure and temperature conditions associated with subduction metamorphism
Depth of Typical
Continental crust
intermediate-P/T type,
Continental collision
Typical continental geothermal gradient
Barrovian Sequence Metamorphism
low-P/T type
Pressure and temperature conditions associated with volcanic arc and continental metamorphism
Conditions not possible on this planet
LAWSONITE-BLUESCHIST
EPIDOTE-BLUESCHIST
EPIDOTE ECLOGITE
EPIDOTE-AMPHIBOLITE
AMPHIBOLITE
GRANULITE
GREENSCHIST
Zeolite
HORNFELS
Typical continental geothermal gradient
Pressure in kilobars
Temperature in °C
18
16
14
12
10
8
6
4
2
300
400
500
600
700

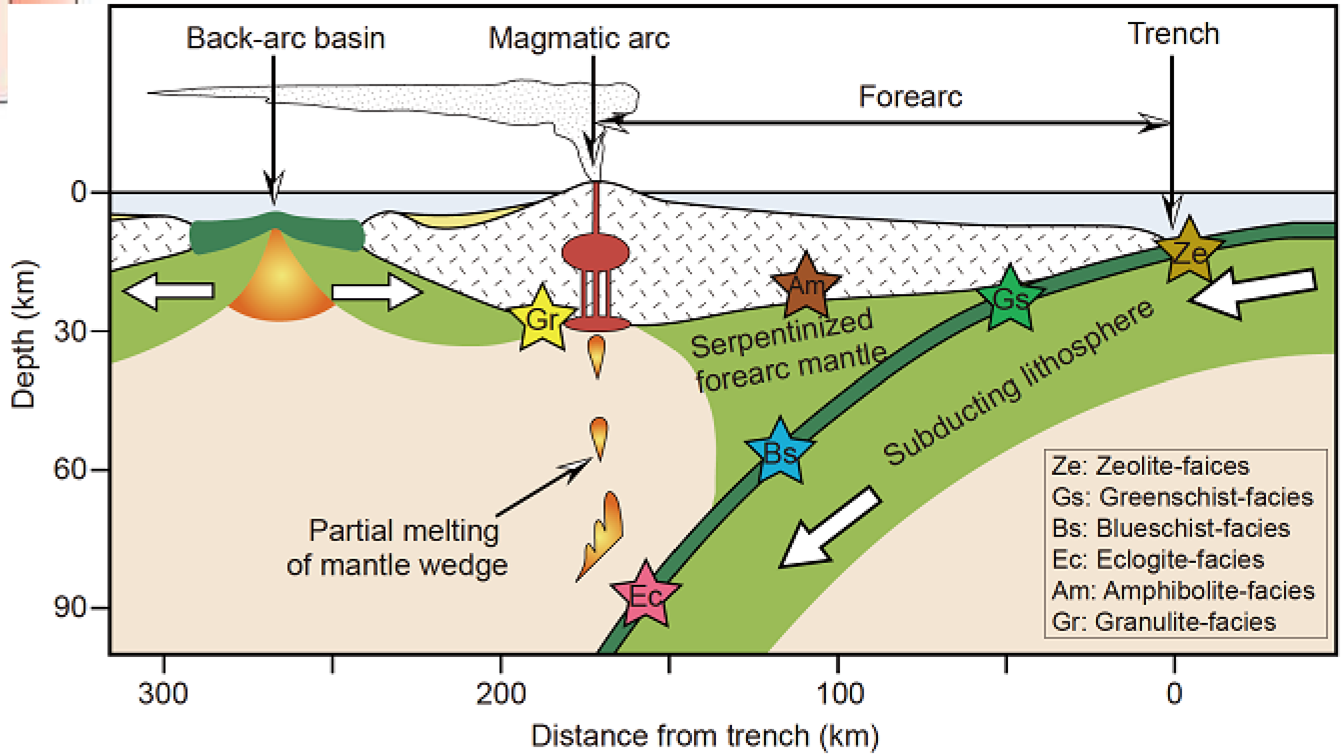
The high-P/T type metamorphic facies – Prehnite-Pumpellyite facies to blueschist facies to eclogite facies

Representing a low geothermal gradient caused by a cooling - subduction of cold oceanic crust and sediments.





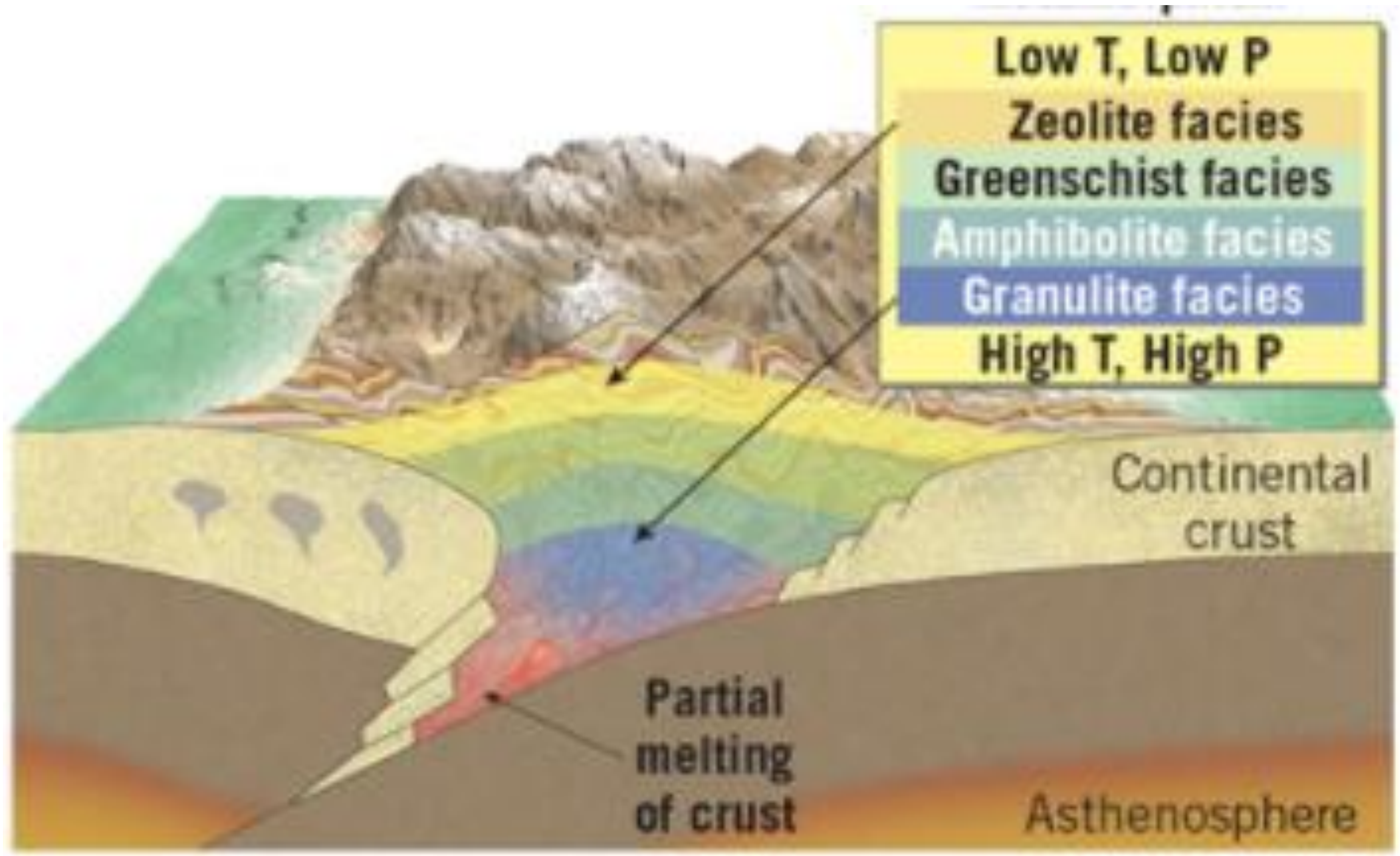
1 Zone of burial metamorphism
2 Blueschist and eclogite metamorphism
3 Regional metamorphism
4 Zone where wet fractional melting starts
5 Granite magma rises and causes contact metamorphism
Sea level
400°C
600°C
Oceanic crust
Lithosphere
Asthenosphere



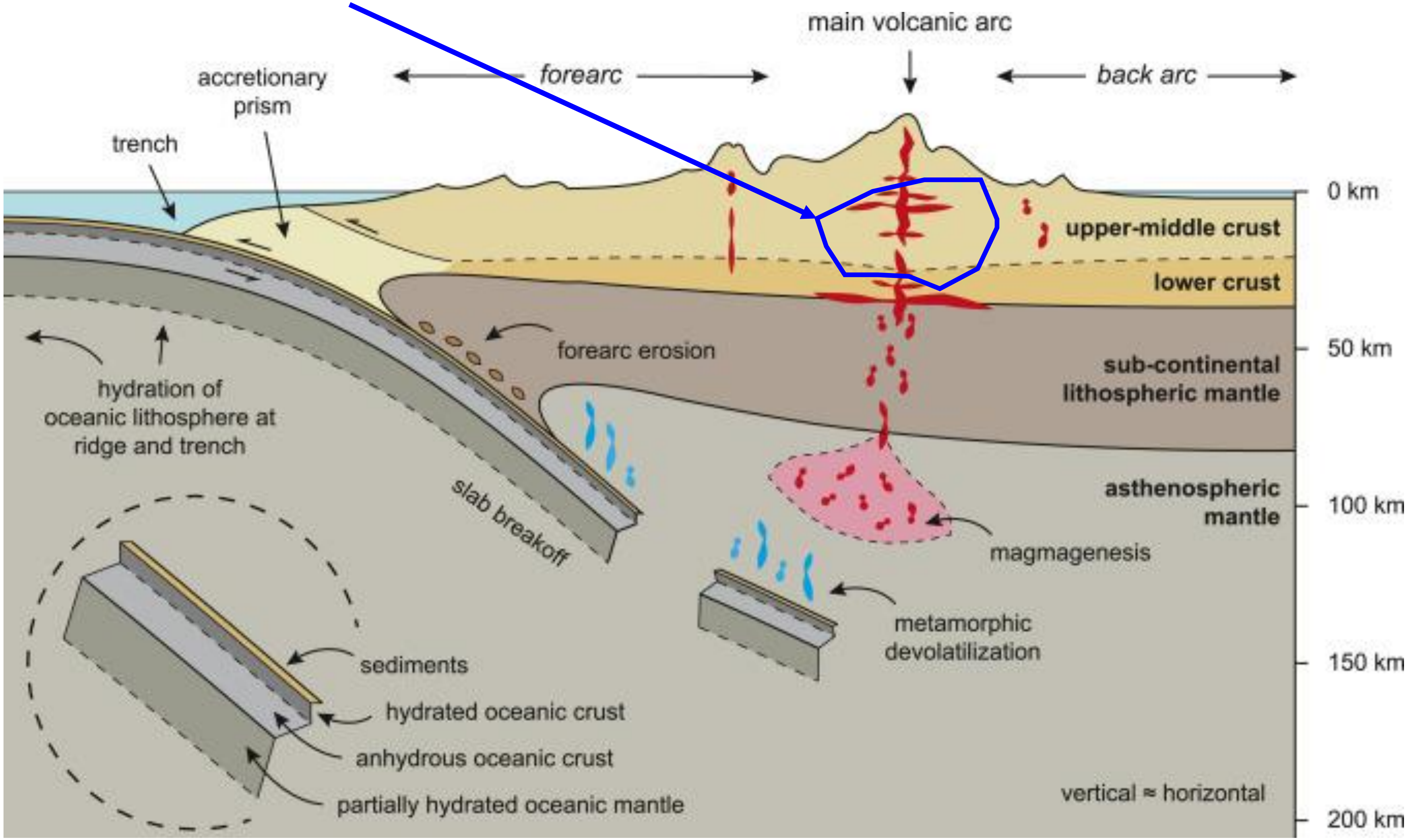
Back-arc basin
Magmatic arc
Trench
Forearc
Serpentinized forearc mantle
Subducting lithosphere
Partial melting of mantle wedge
Ze
Am
Gs
Gr
Bs
Ec
Depth (km)
0
30
60
90
300
200
100
0
Distance from trench (km)
Ze: Zeolite-faices
Gs: Greenschist-facies
Bs: Blueschist-facies
Ec: Eclogite-facies
Am: Amphibolite-facies
Gr: Granulite-facies

Intermediate-P/T type metamorphic facies - change from greenschist facies to amphibolite facies to granulite facies.

Representing an intermediate geothermal gradient caused by crustal thickening.



The low-P/T type metamorphic facies series - occurs in an arc -high geothermal gradient, resulting in change from greenschist facies to amphibolite to granulite facies.



Types of metamorphism

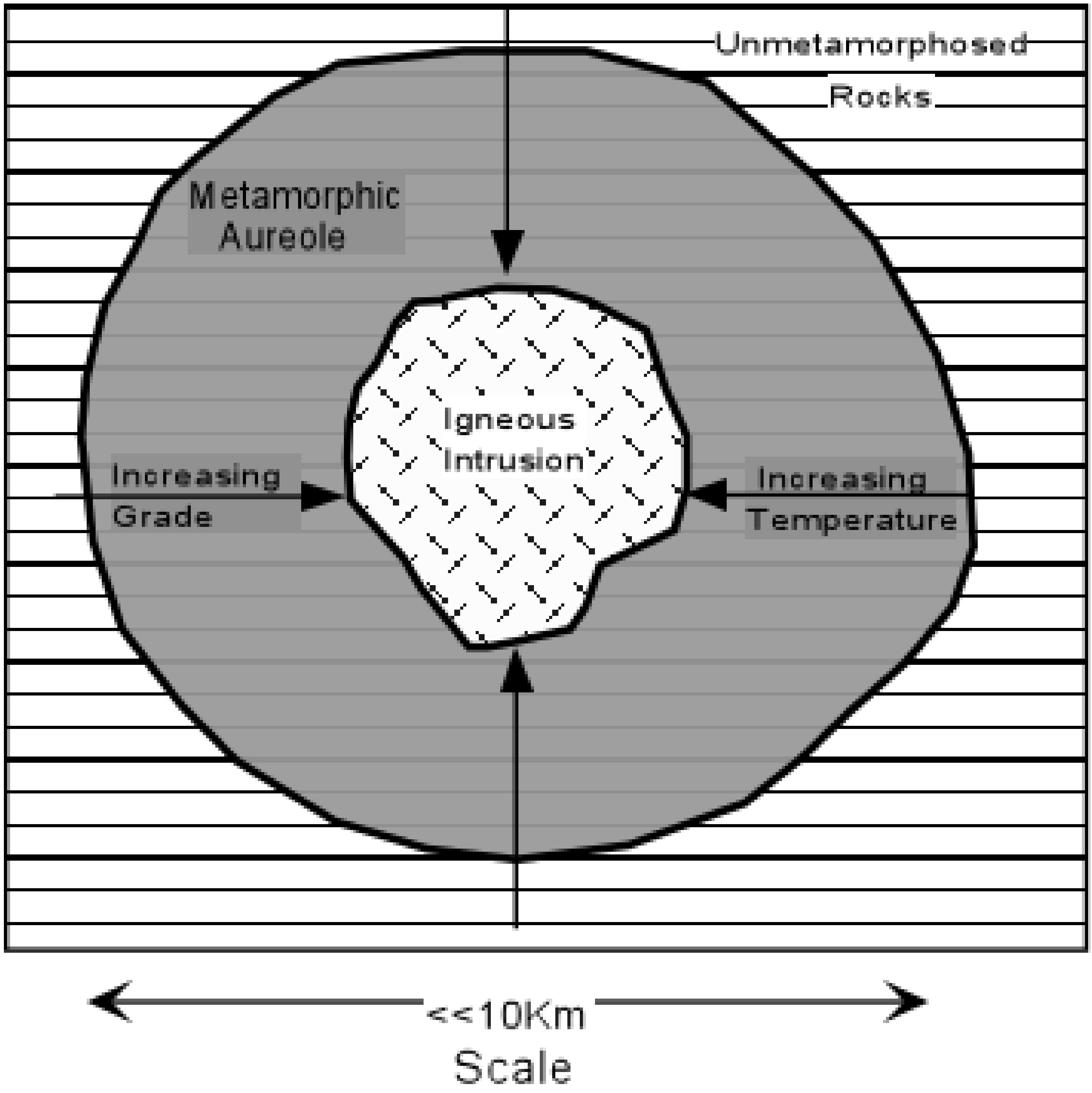
1. <u>Contact metamorphism</u>

Results from high T associated with the igneous intrusion.

Metamorphism is restricted to a small zone surrounding the intrusion - *metamorphic or contact aureole.*

Few mm to several 100s mts wide zone.

The rock produced - fine-grained, no foliation, called a <u>hornfels</u>.



Unmetamorphosed
Rocks
Metamorphic
Aureole
Igneous
Intrusion
Increasing
Grade
Increasing
Temperature
<<10Km
Scale


1 km
Unaltered mudstone
Granite
Spotted rock
Hornfels


Intrusion
Marble
Limestone
Marli Miller, University of Oregon

2. Regional metamorphism

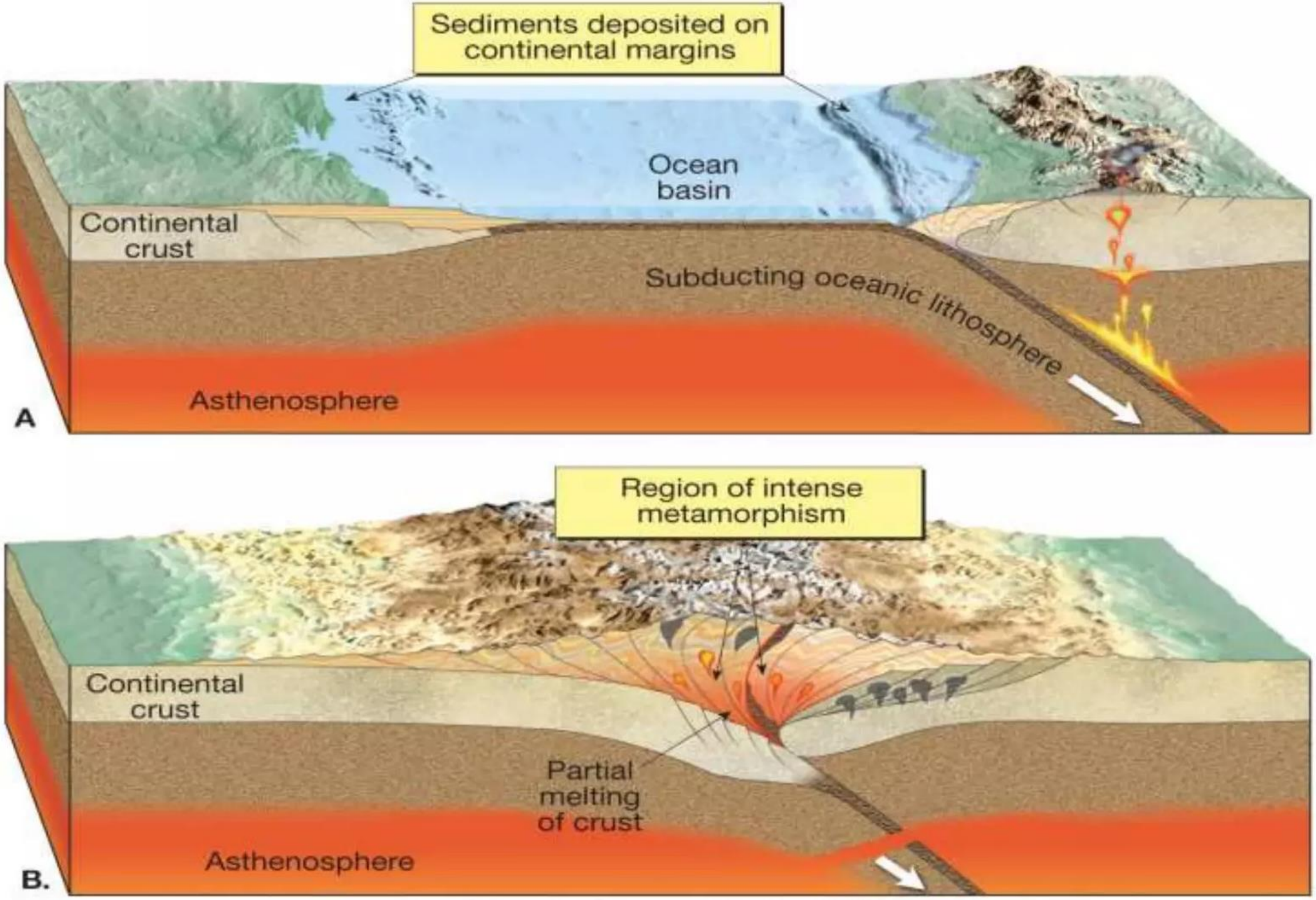
Affects large volumes (regions) of rock.

Deformation under differential compressional stress conditions.

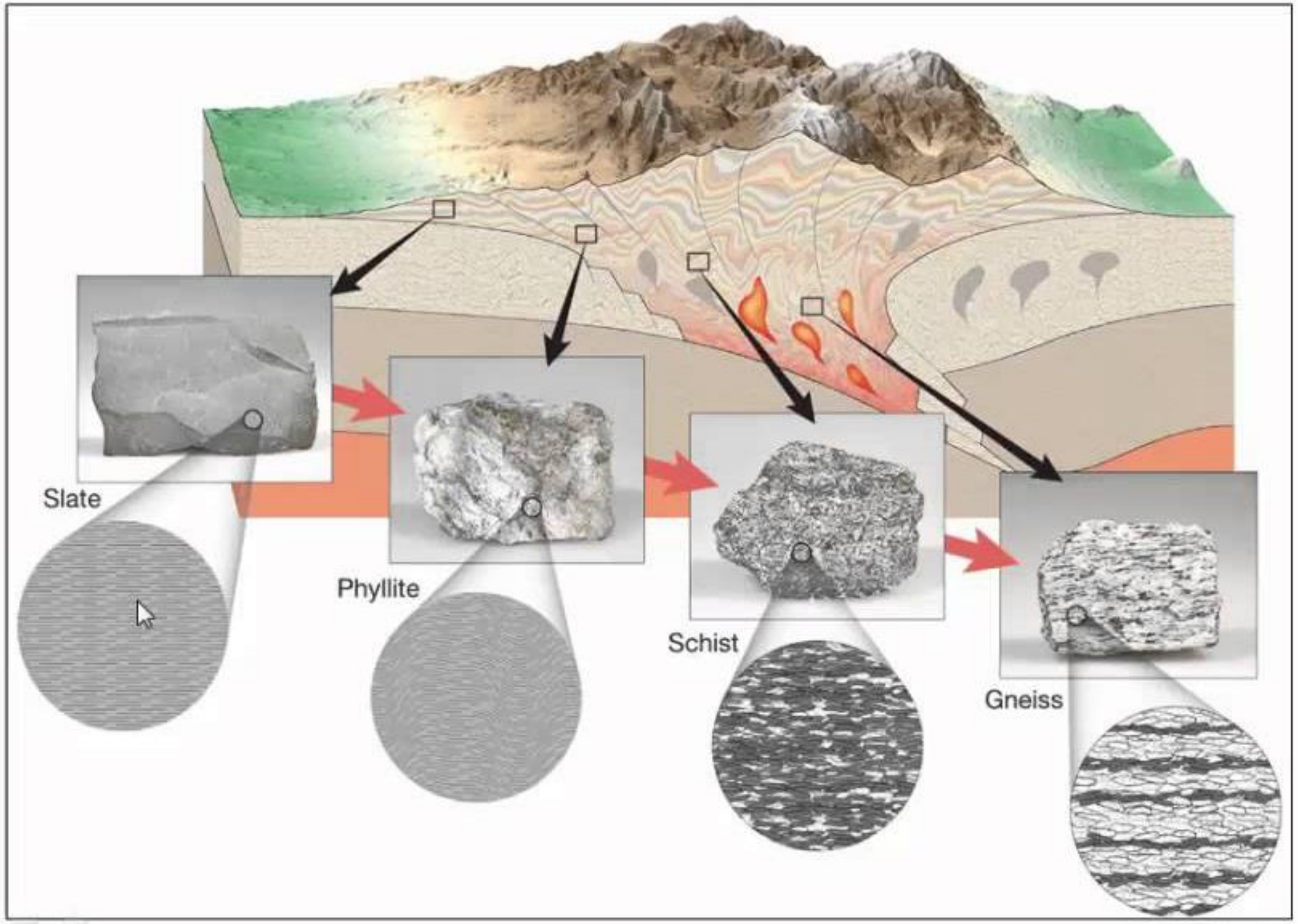
Results in metamorphic rocks that are strongly foliated - slates, schists, and gneisses.

Wide range of T (generally 200 to 800 ^{o}C) and P (2 to 10 kbar or 5 to 35 km depth, sometimes more)

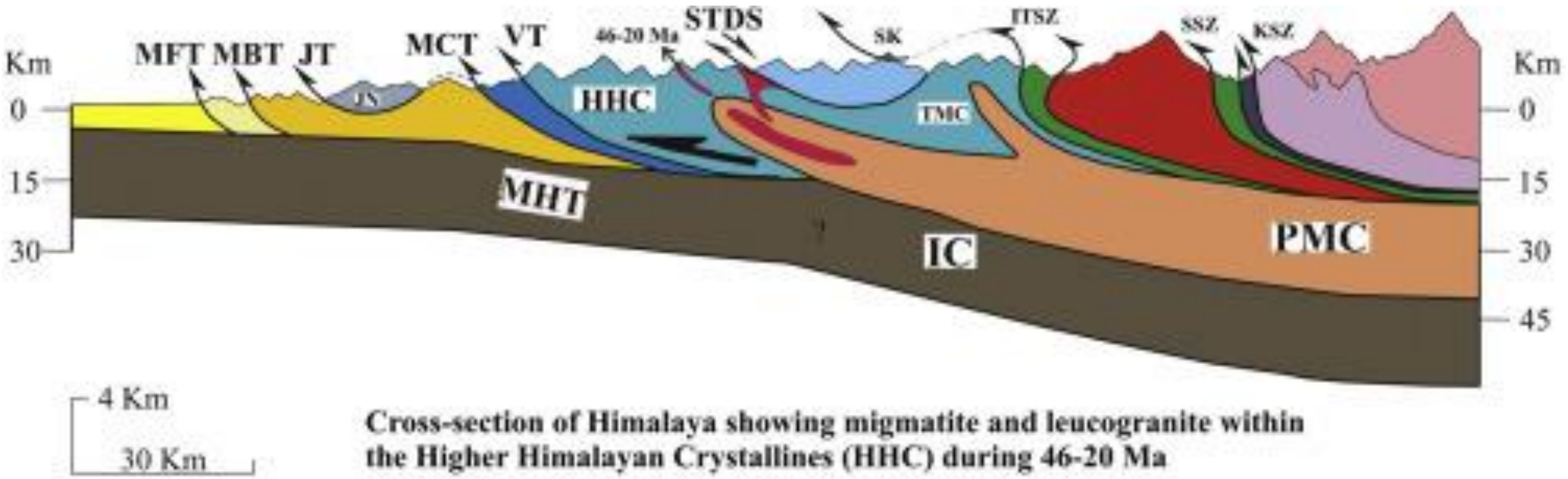
Regional Metamorphism



- The differential stress results from tectonic forces in areas like continental collision zones.
- In the cores of fold/thrust mountain belts or in eroded mountain ranges.
- Folding of rocks and thickening of the crust - pushing rocks to deeper levels - higher T and pressures.

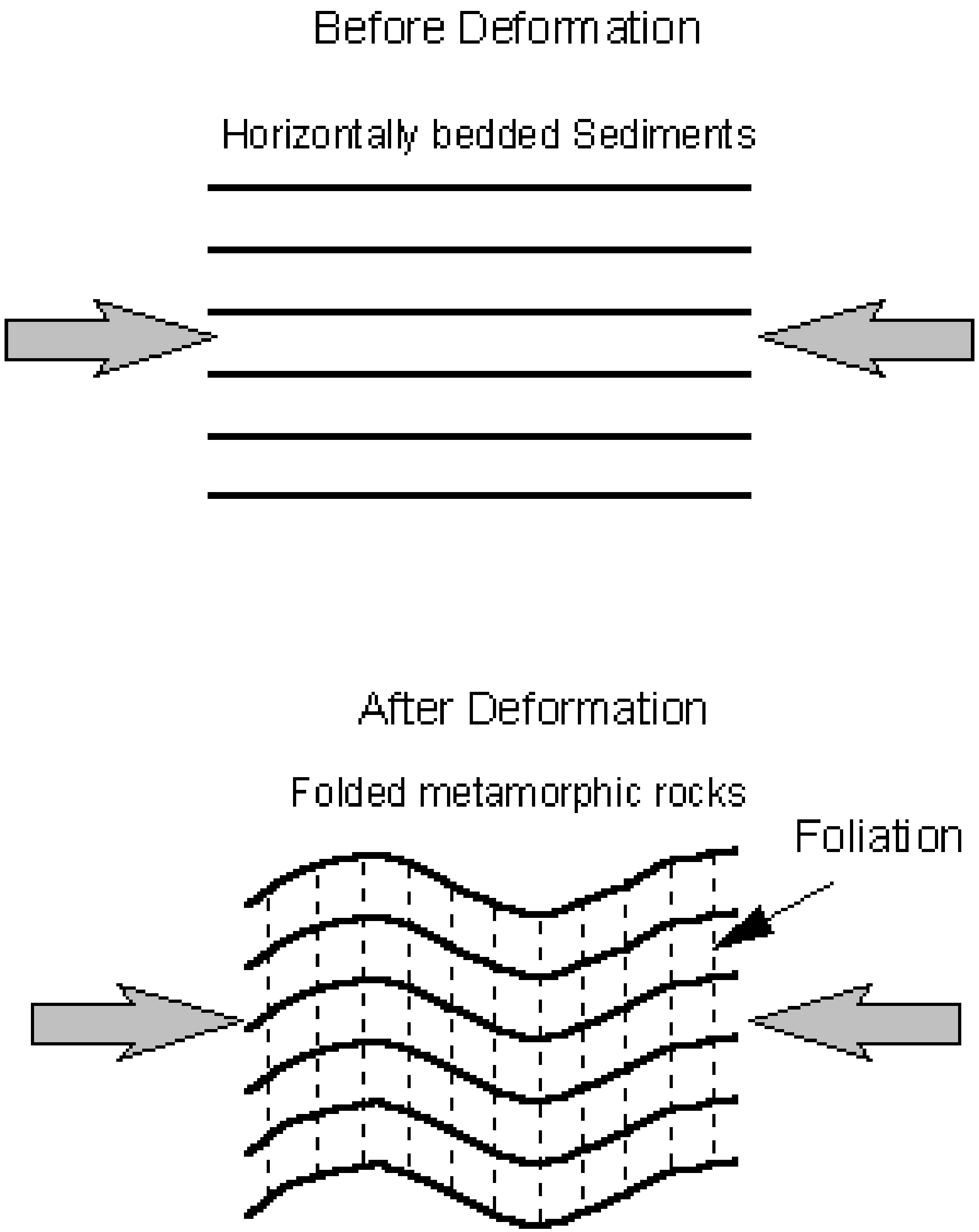


Regional metamorphism terranes. Alps. Convergence of lithosphere plates



Cross-section of Himalaya showing migmatite and leucogranite within the Higher Himalayan Crystallines (HHC) during 46-20 Ma

Regional metamorphism terranes. Himalayas. Convergence of lithosphere plates



Regional metamorphism results in forming strongly foliated metamorphic rocks, such as slates, schists, and gneisses.

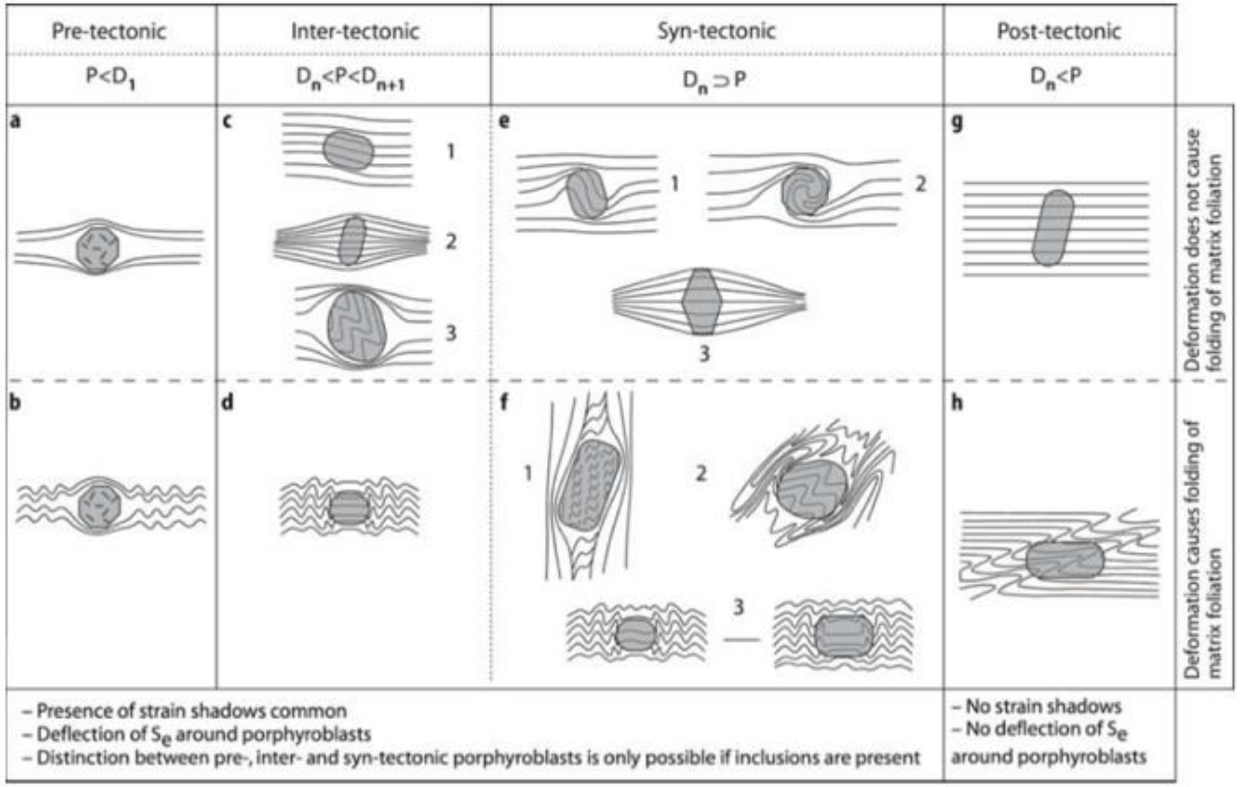
Porphyroblastic texture

Porphyroblasts (porphyry, plus Greek blastos, to grow):

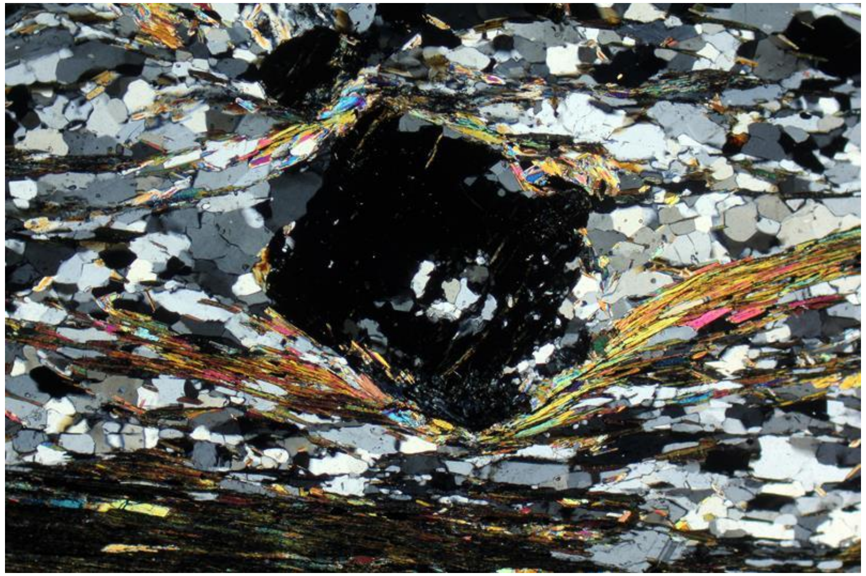
Relatively large single crystals formed by metamorphic growth in a more fine-grained matrix.

Porphyroblasts - valuable source of information on tectonic & metamorphic evolution.

Key in determination of pressure-temperature-deformation-time (P-T-D-t) paths.



Pre-tectonic
P<D1
Inter-tectonic
Dn<P<Dn+1
Syn-tectonic
Dn ⊃ P
Post-tectonic
Dn<P
a
b
c
1
2
3
d
e
1
2
3
f
1
2
3
g
h
Deformation does not cause folding of matrix foliation
Deformation causes folding of matrix foliation
– Presence of strain shadows common
– Deflection of Se around porphyroblasts
– Distinction between pre-, inter- and syn-tectonic porphyroblasts is only possible if inclusions are present
– No strain shadows
– No deflection of Se around porphyroblasts



Porphyroblastic texture

3. Burial Metamorphism

Due to burial of sedimentary rocks under overlying sediments.

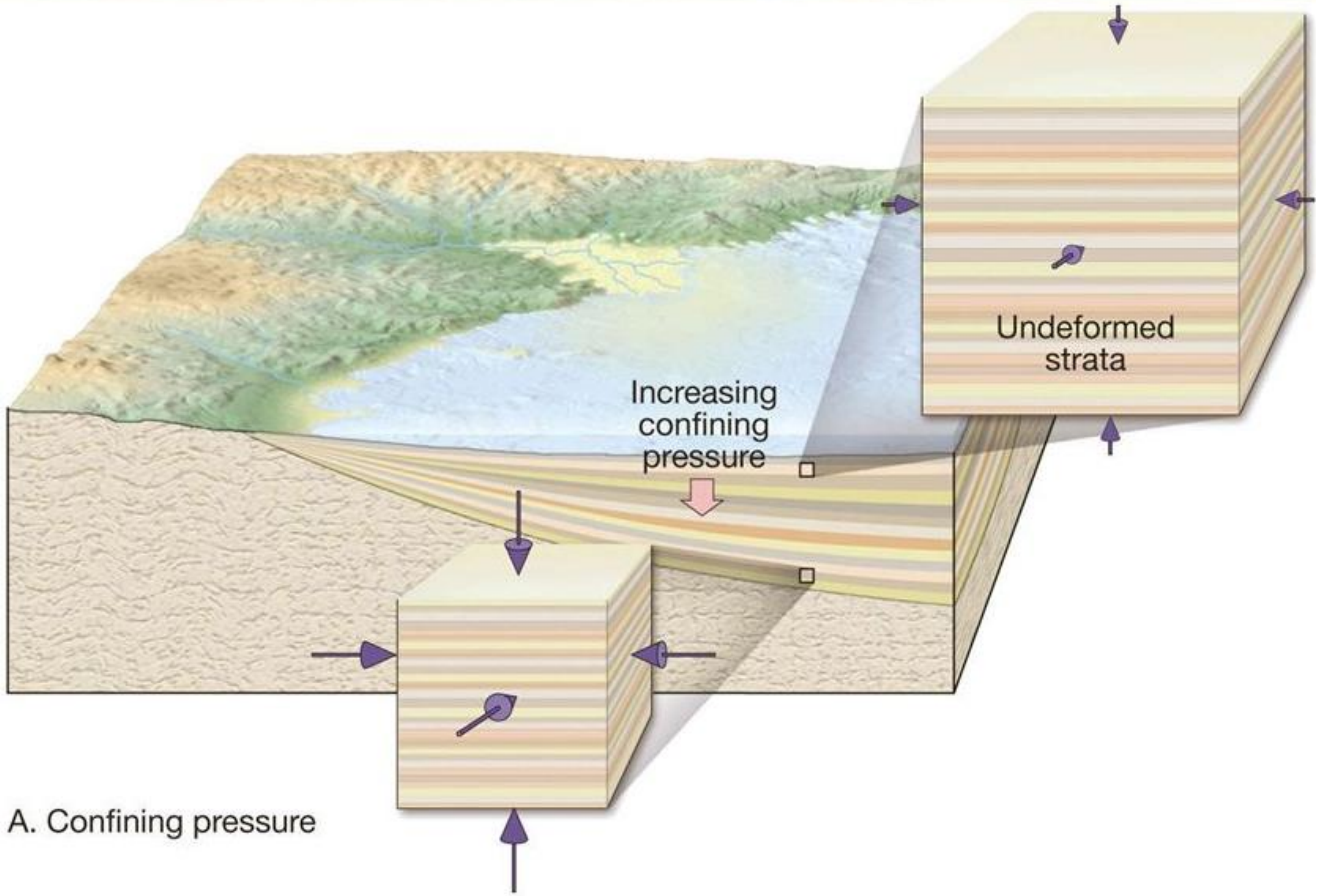
Increase in P and T (> 300 ^{o}C) due to depths – several kms

Absence of differential stress – reduced presence of deformation structures.

New minerals grow – mainly zeolites (hydrous aluminosilicate).

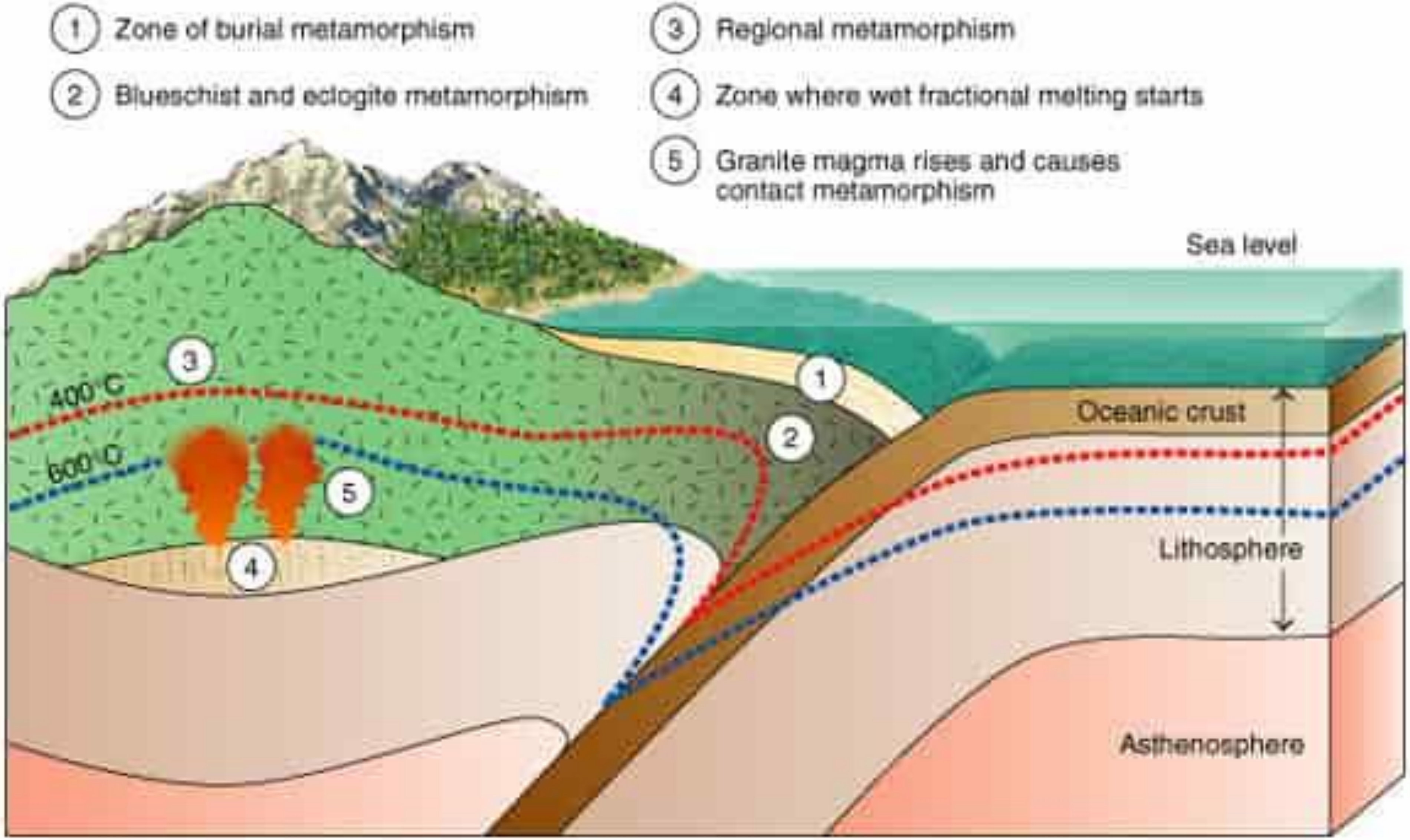
Grades into regional metamorphism as T and P increase.

Burial Metamorphism



Increasing P & T

No directed stress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Oceanic crust
Lithosphere
Asthenosphere

4. Shock Metamorphism (Impact Metamorphism)

Due to impact of meteorite with the Earth.

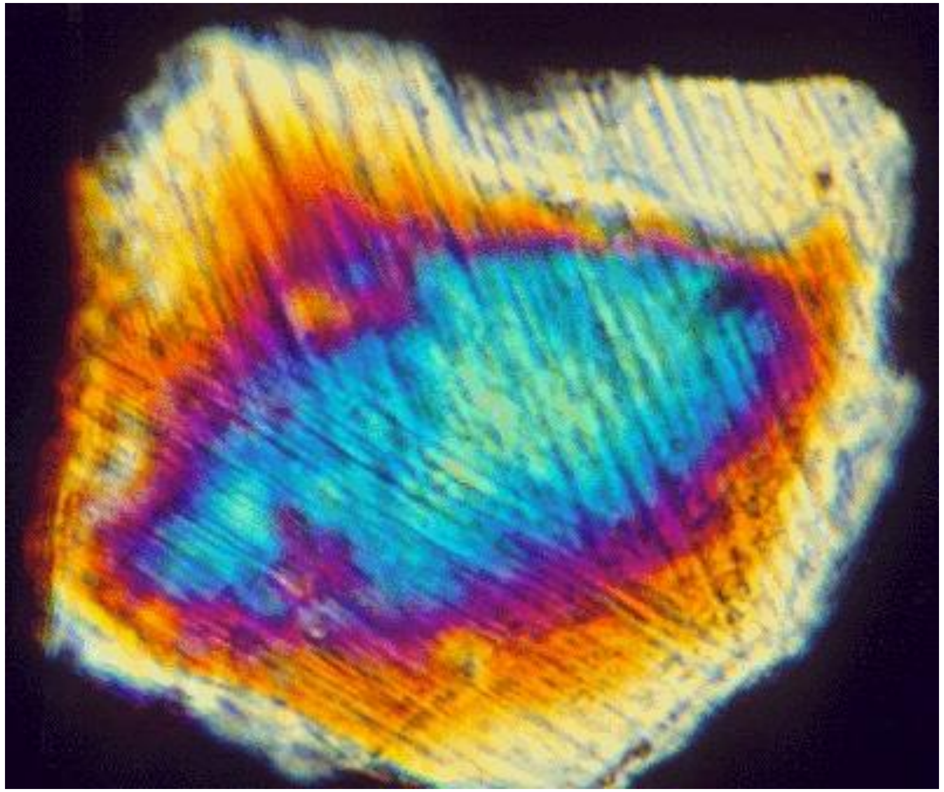
Ultrahigh P.

Produce minerals that are only stable at very high pressure –

e.g. SiO_2 polymorphs coesite and stishovite.

Textures - shock lamellae in mineral grains, shatter cones.

Ejecta from Sudbury impact (1.8 Ga)



Shock lamellae in a quartz grain.

Shatter cone.

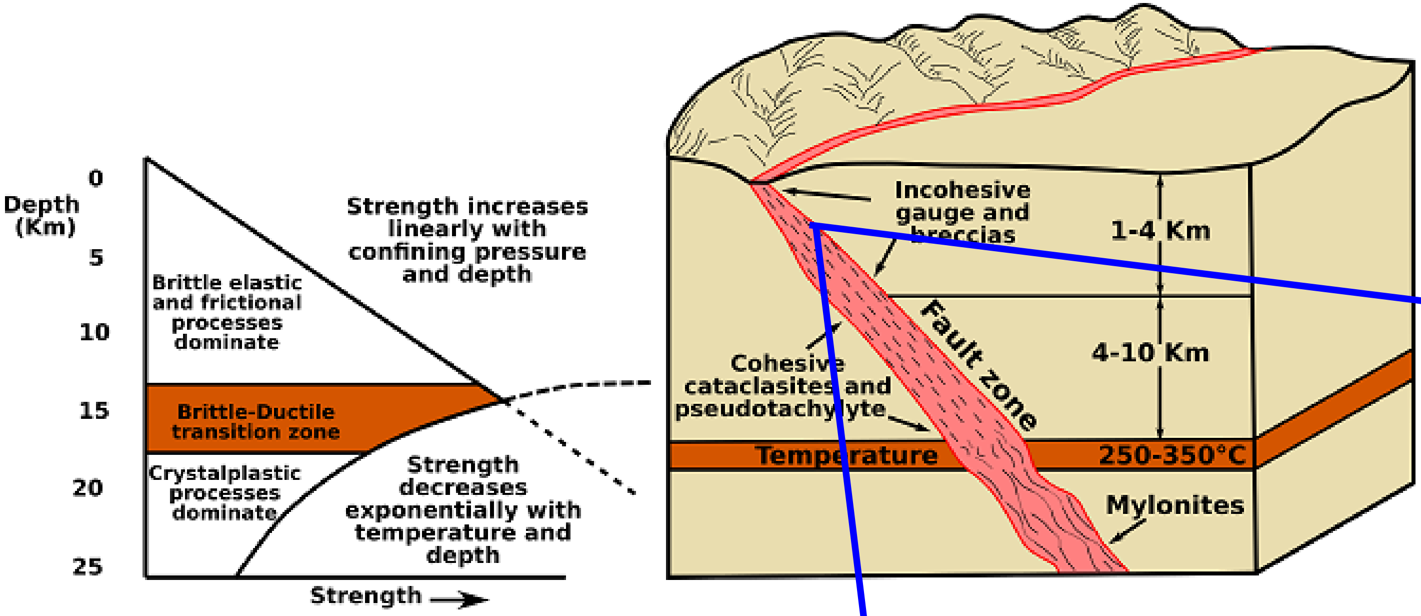
5. Cataclastic (dynamic) Metamorphism

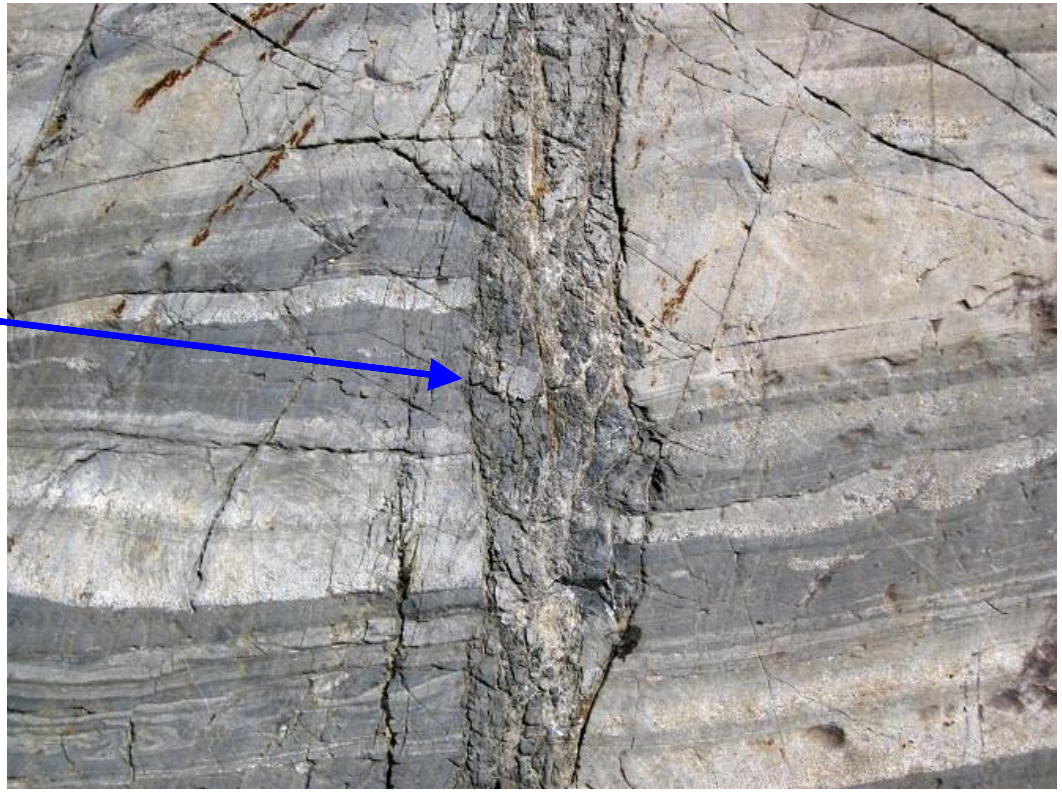
Due to mechanical deformation.

Two bodies of rock slide past one another along a fault zone.

Generation of heat and shearing.

Crushing of rock.

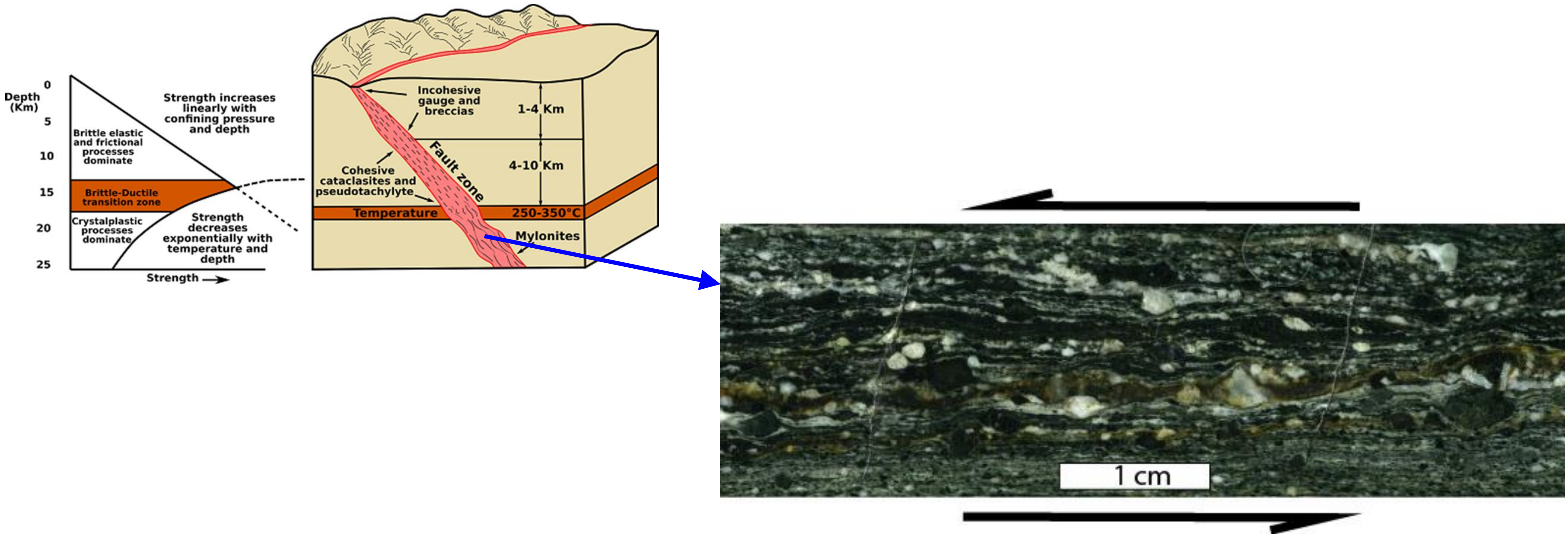




Cataclasite – brittle deformation

At greater depths, directed shear forces result in reduction of grain size.

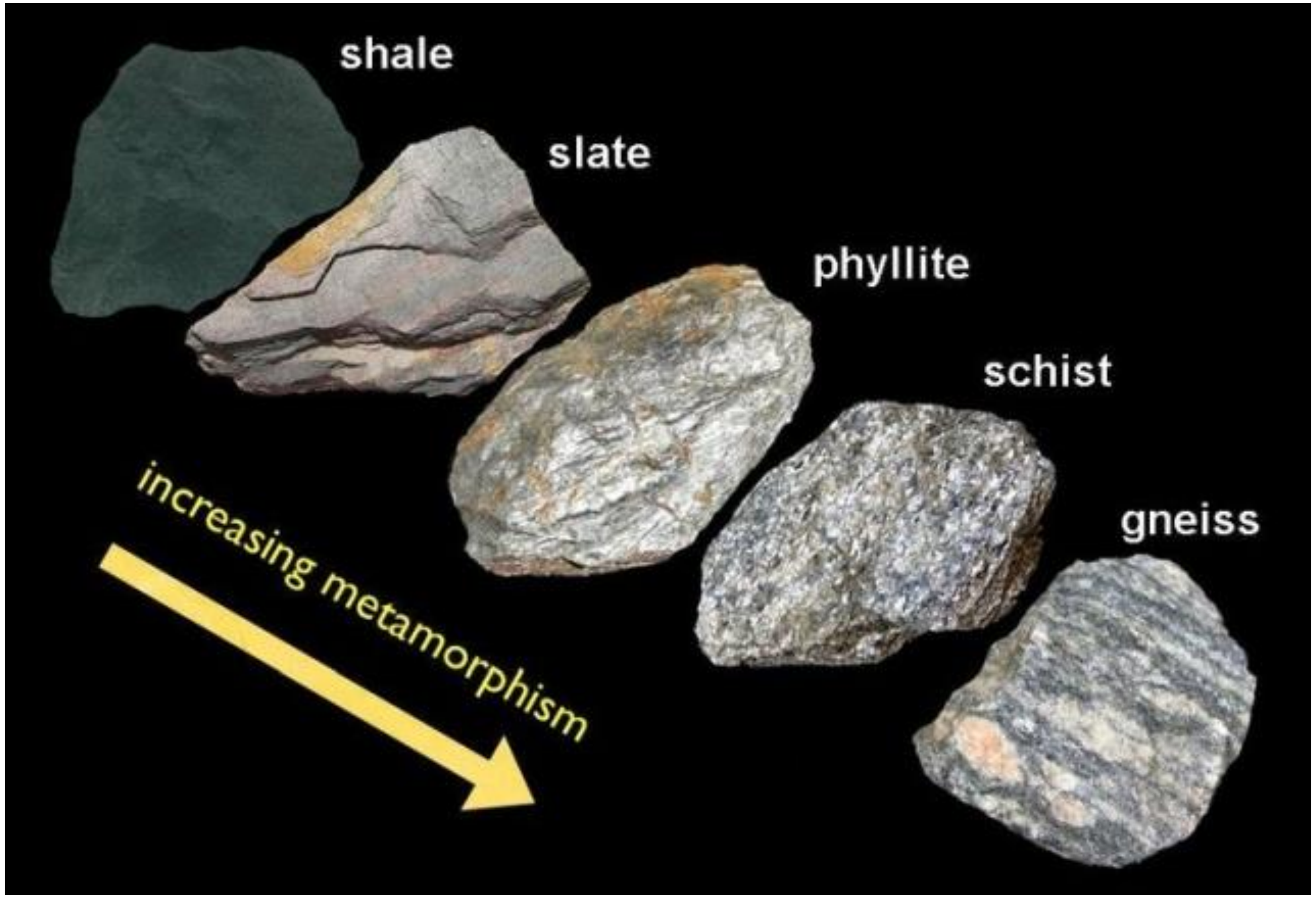
Mylonites, a sheared finer grained rock formed. Due to ductile deformation.



Metamorphic rocks according to protolith composition

Pelitic rock (shale, mudstomne) – Al rich clay minerals.

Al rich metamorphic minerals form - micas, chlorite, garnet, kyanite, sillimanite & andalusite form.



Metamorphic rocks according to protolith composition

Mafic protolith – basalt, gabbro – Mg, Fe rich, low Si
Metamorphis minerals formed – biotite, hornblede, plagioclase.

Basalt

Amphibolite with plagioclase (white) and hornblende (black)

Garnet amphibolite sample with plagioclase (white), hornblende (black) and garnet (red).