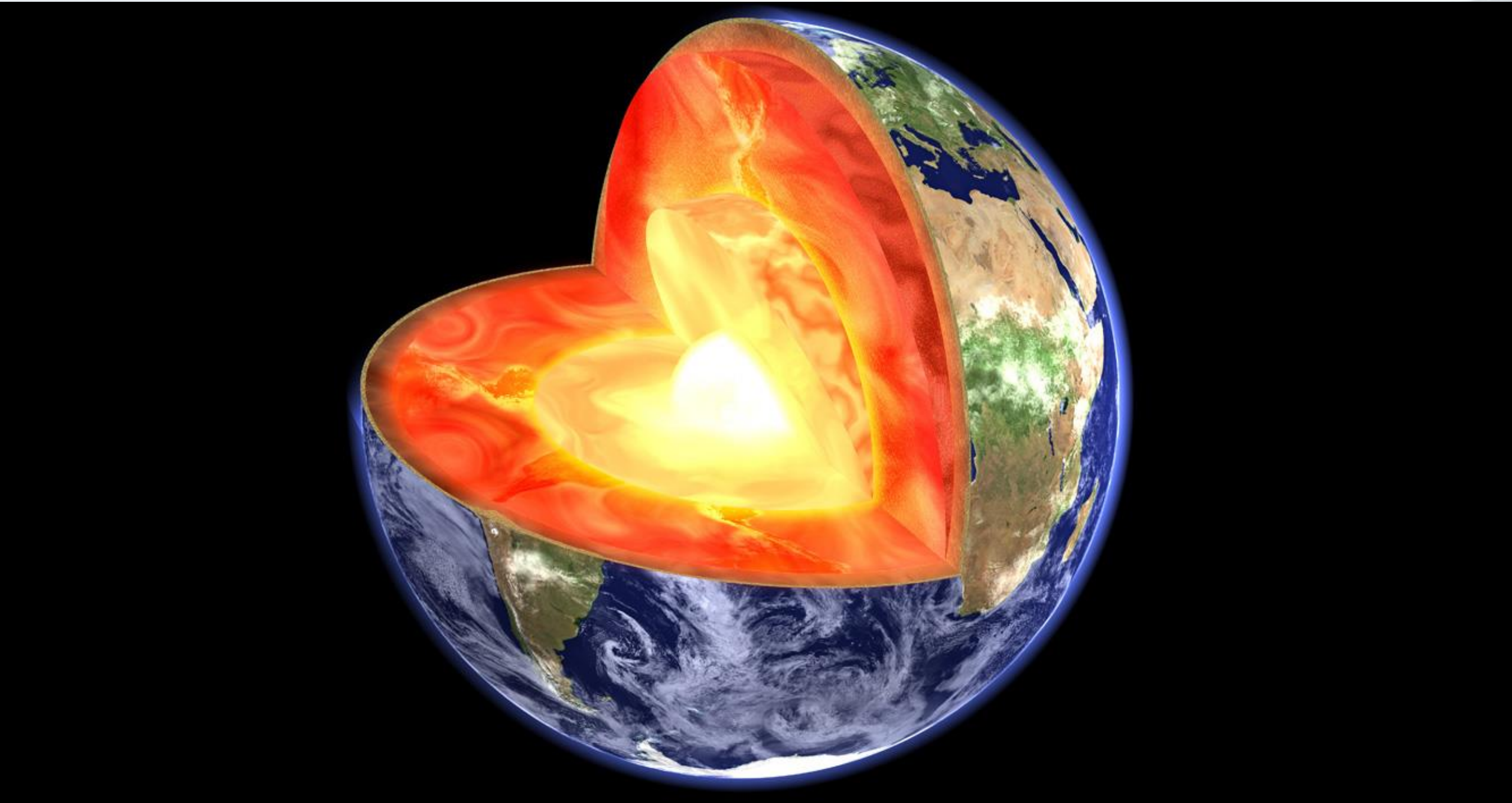
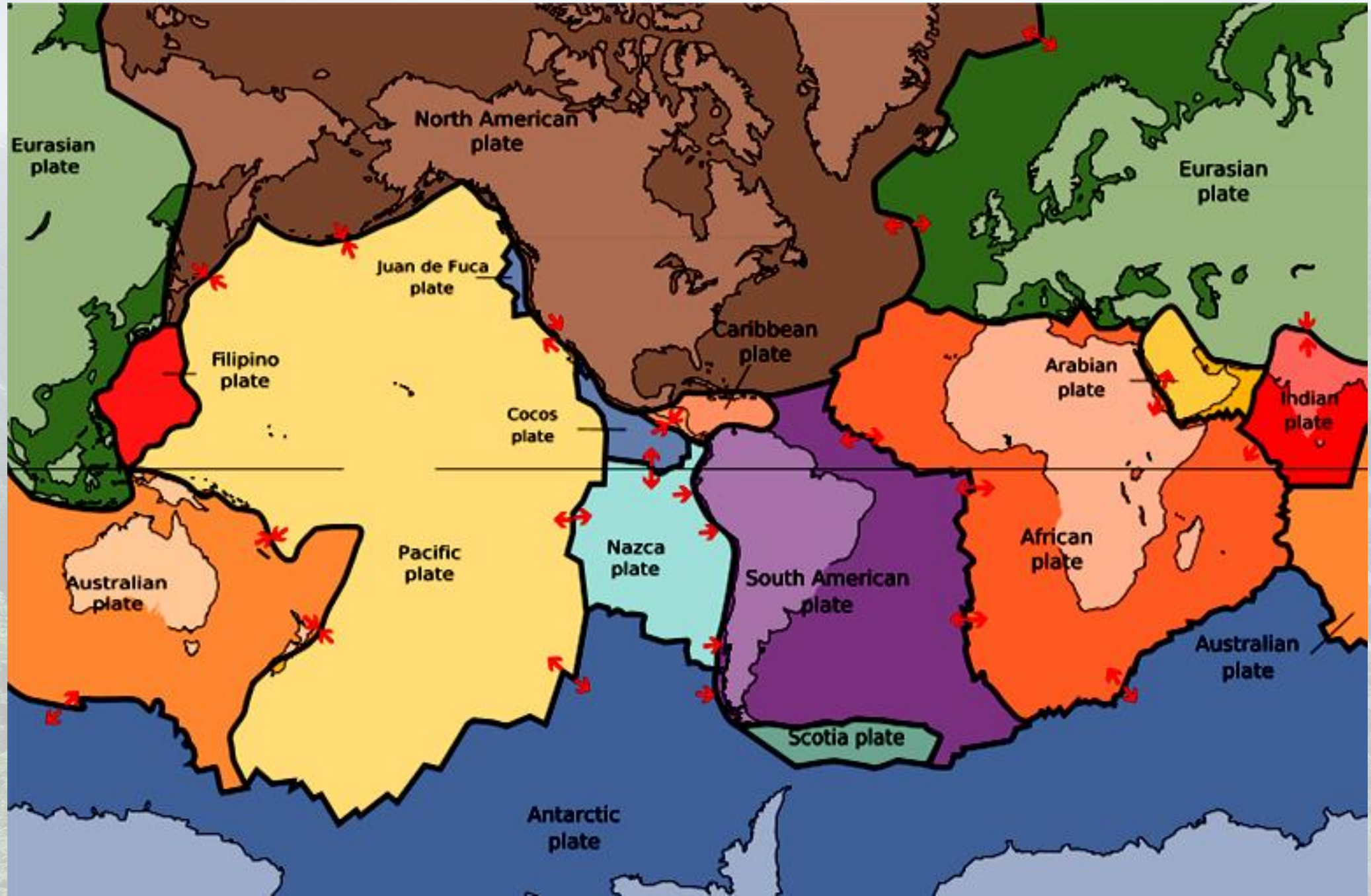
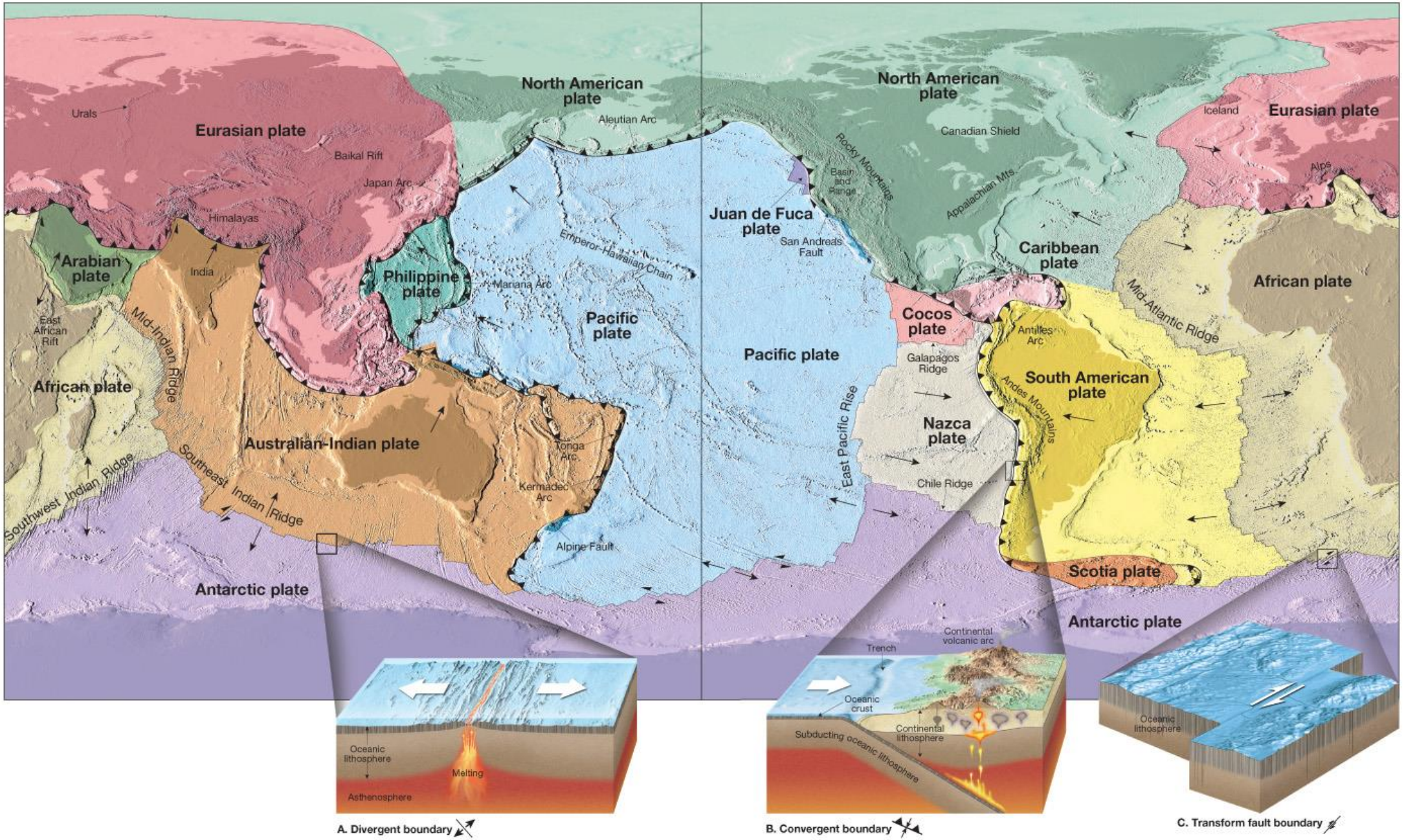
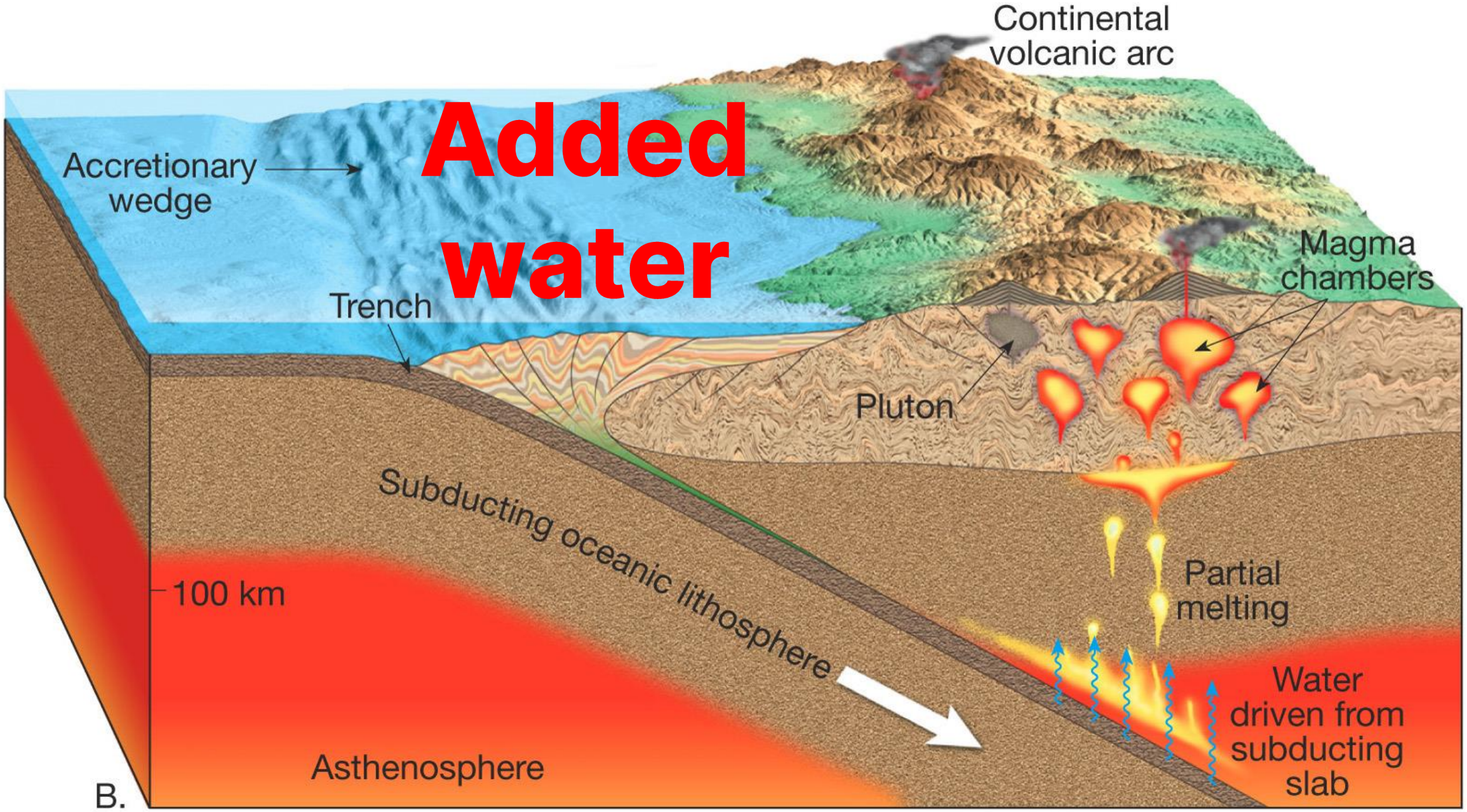
GY4051 Earth Science and Society

Metamorphism

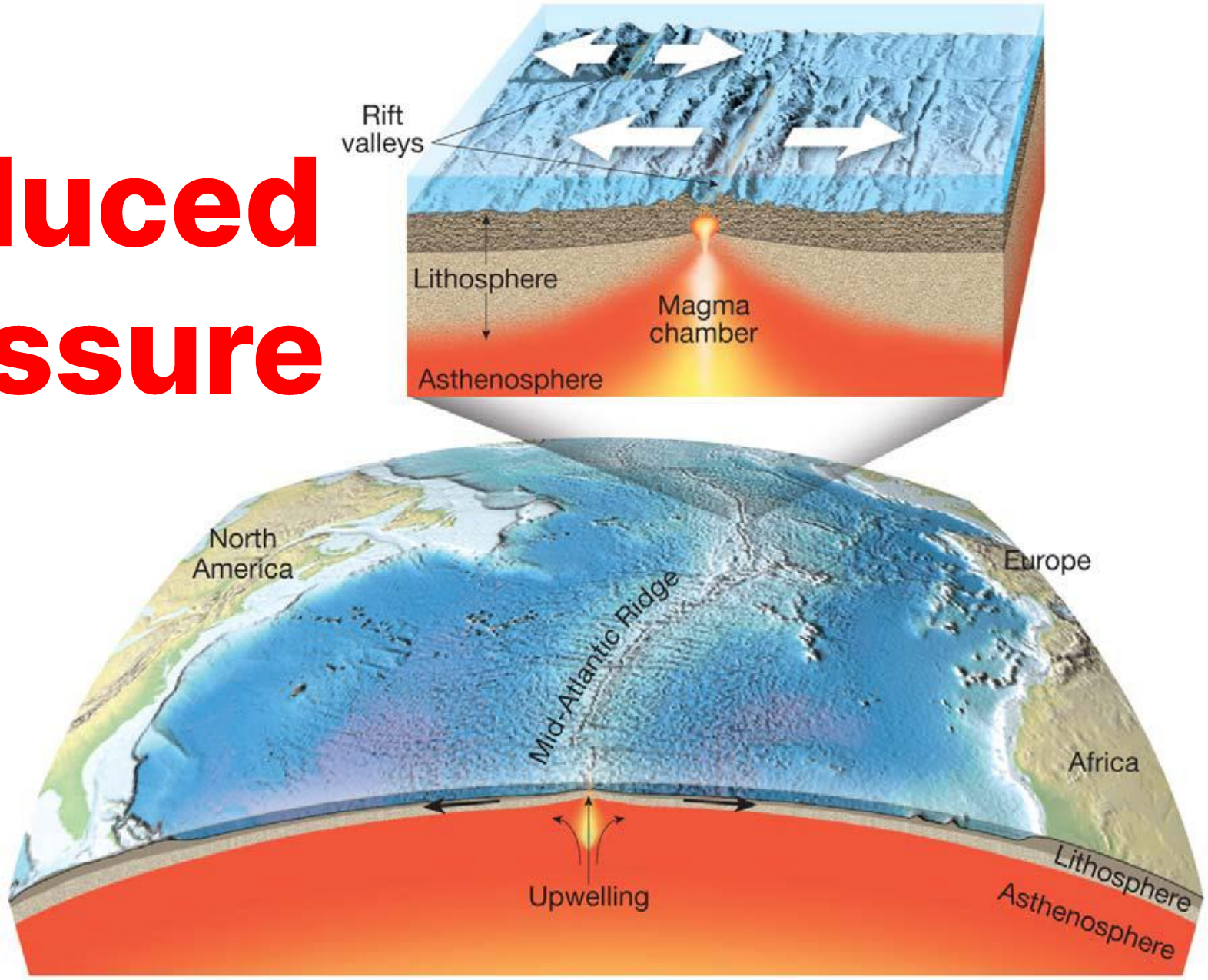



Eurasian plate
North American plate
Eurasian plate
Juan de Fuca plate
Caribbean plate
Filipino plate
Arabian plate
Indian plate
Cocos plate
Pacific plate
Nazca plate
South American plate
African plate
Australian plate
Australian plate
Scotia plate
Antarctic plate

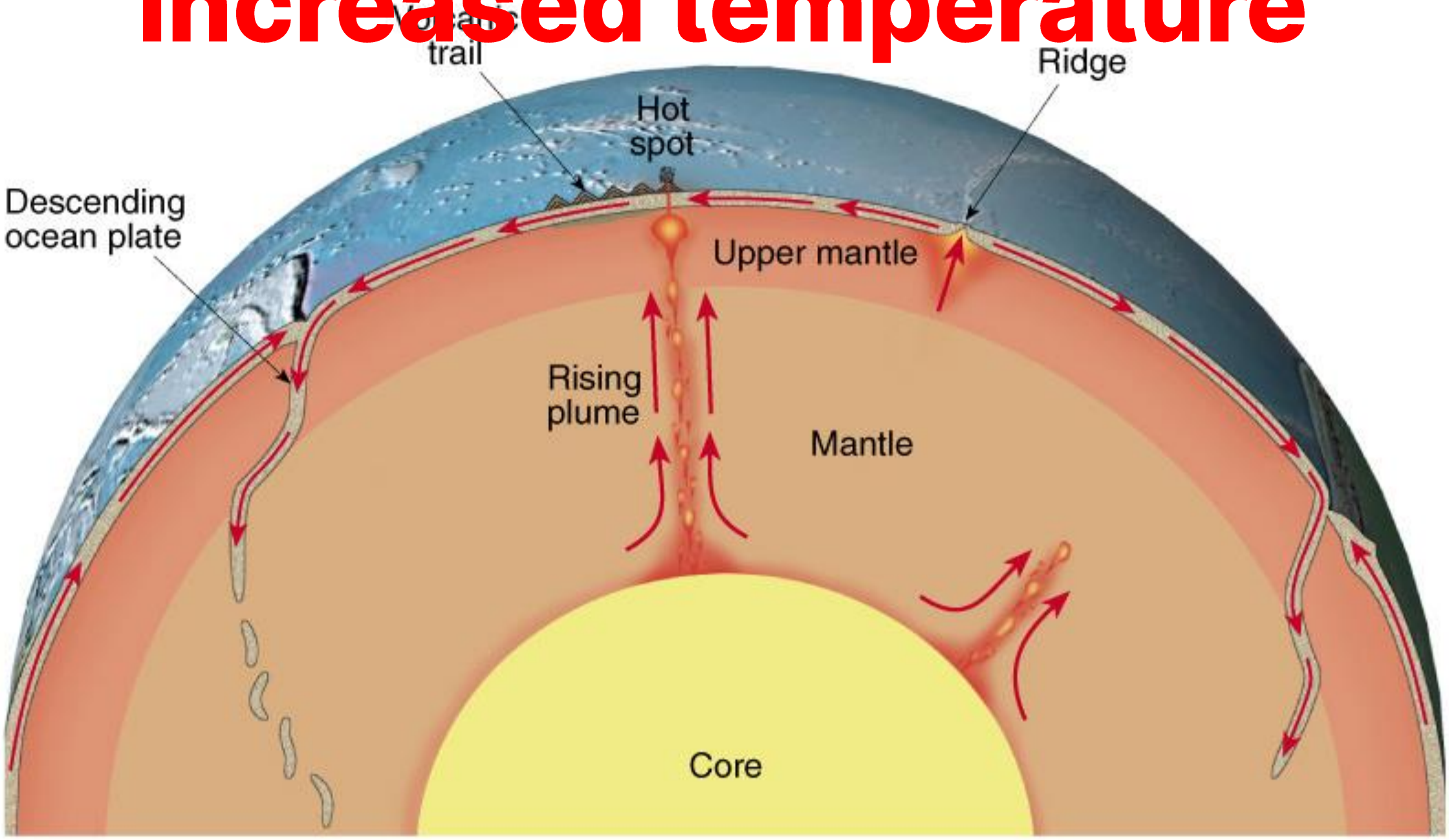




Reduced pressure

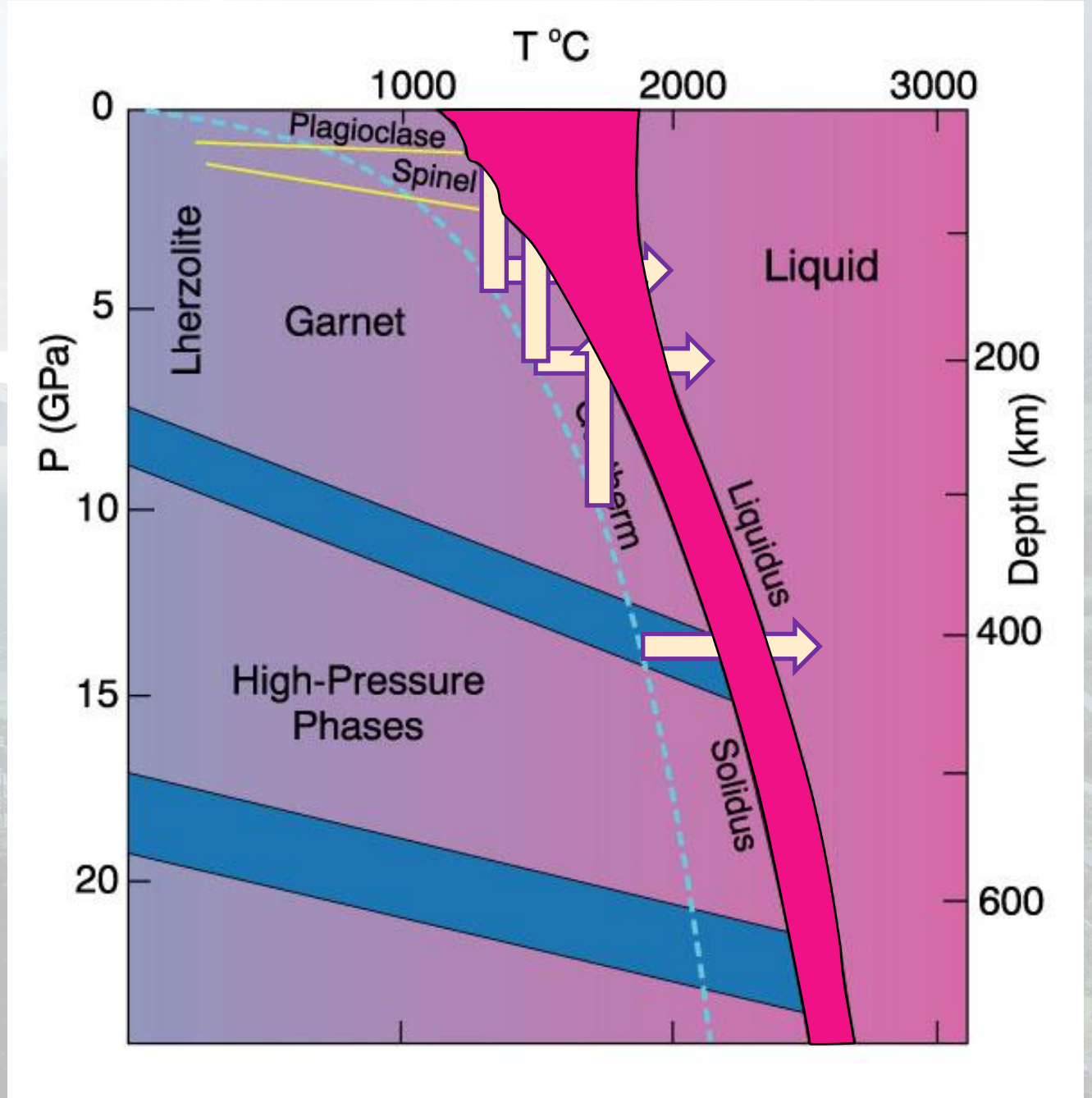


Increased temperature



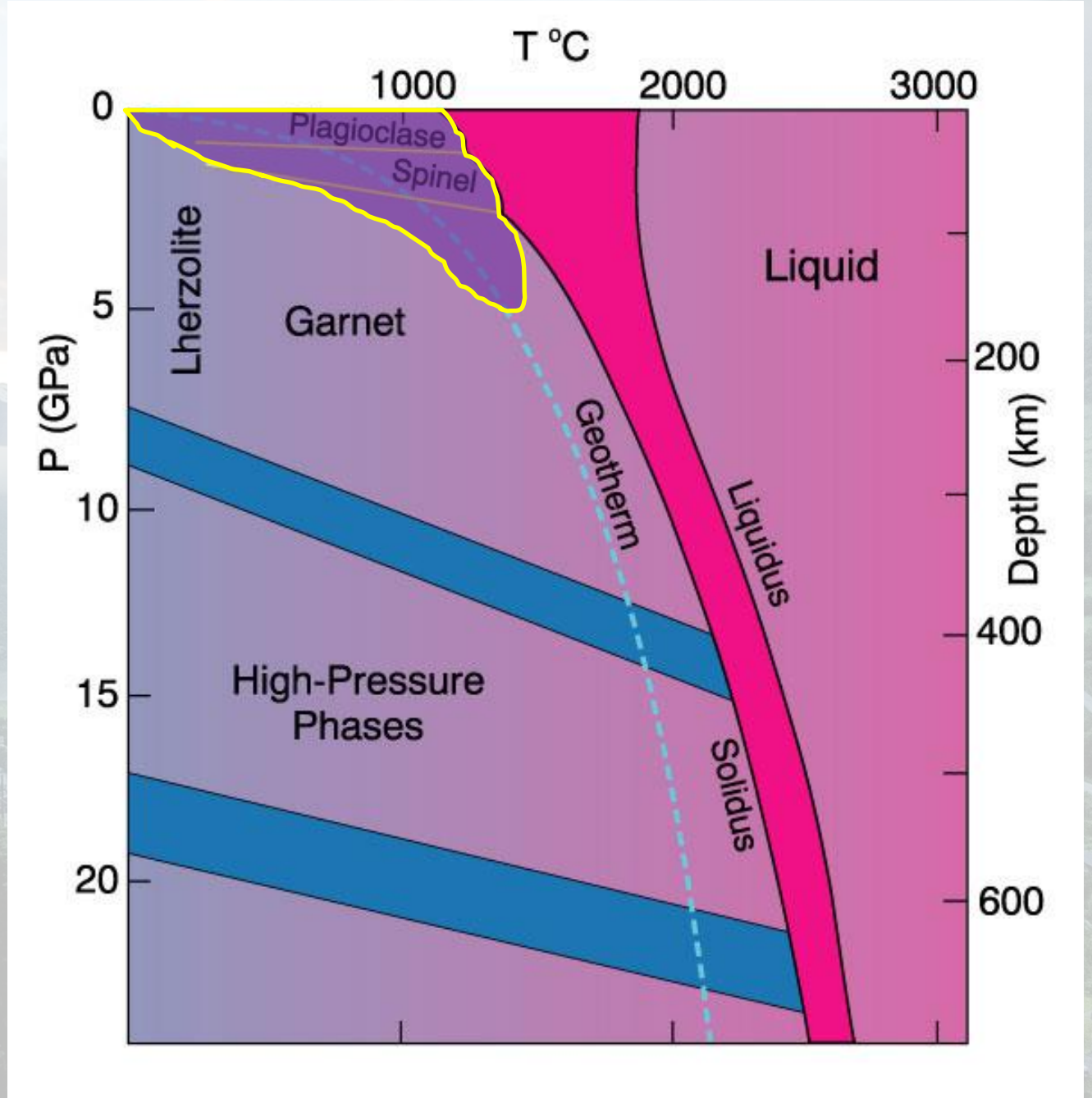
Three ways:

- Increase the temperature
- Lower the pressure
- Add water



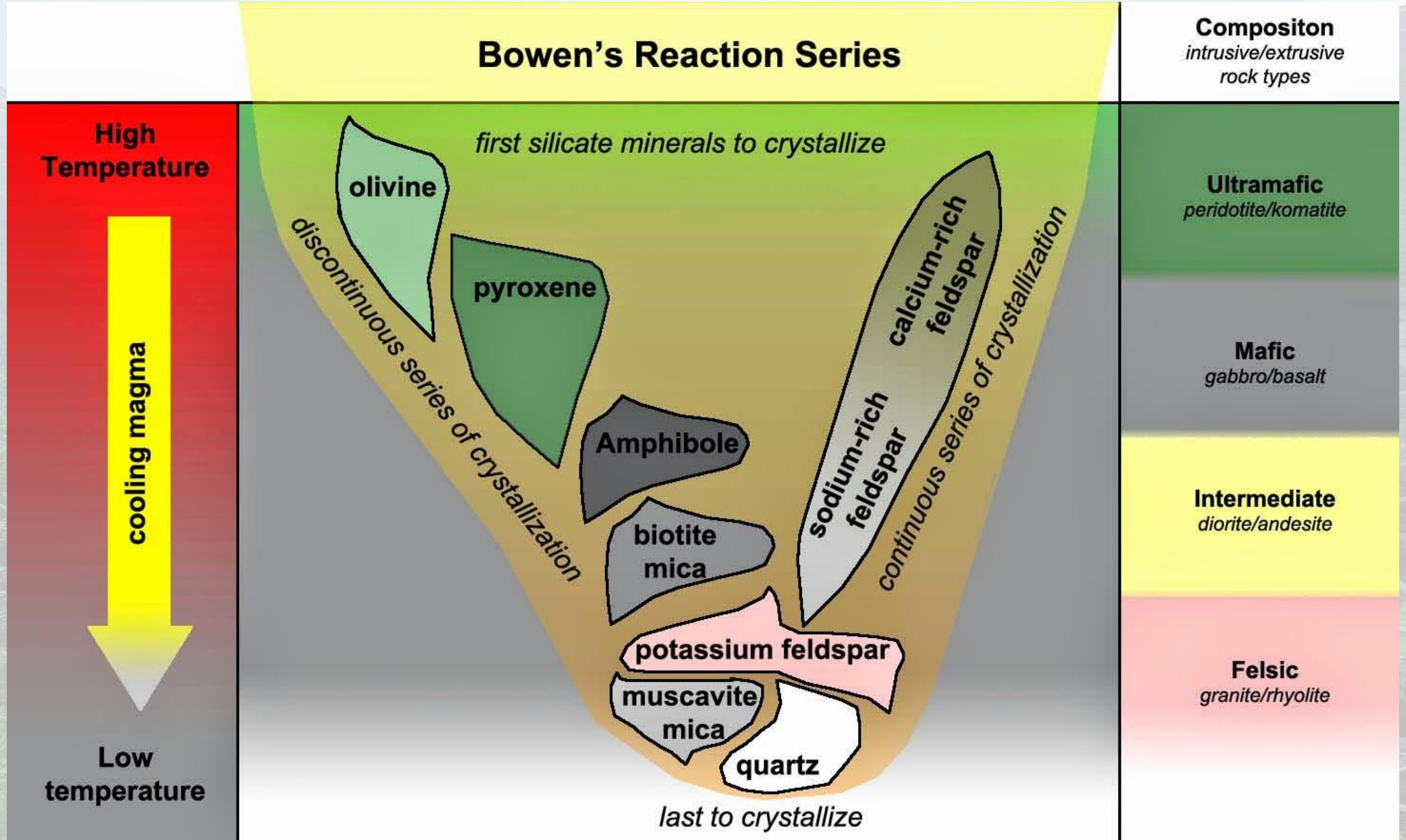
Metamorphic conditions

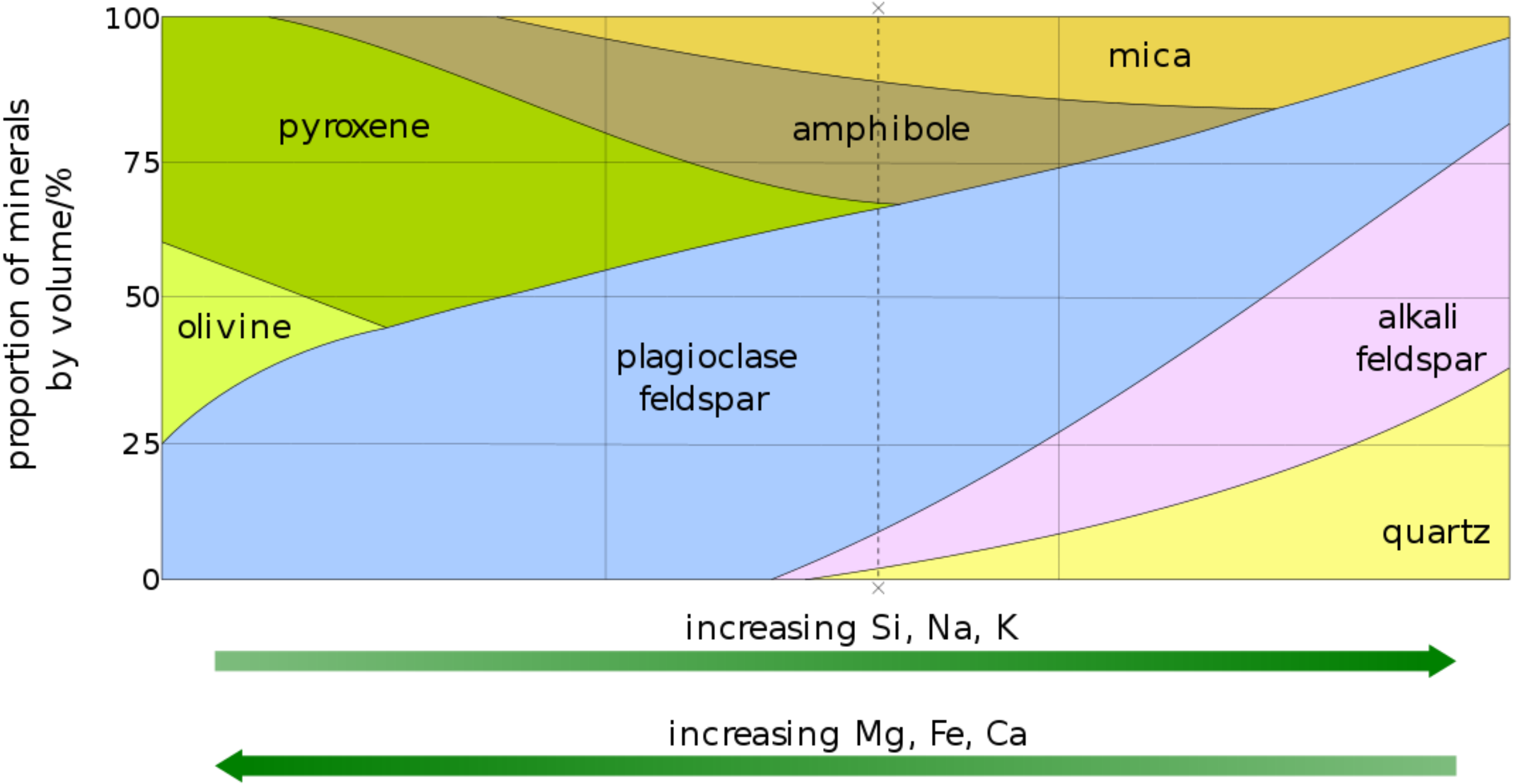
- Higher temperature
- Higher pressure
- But not enough to cause melting

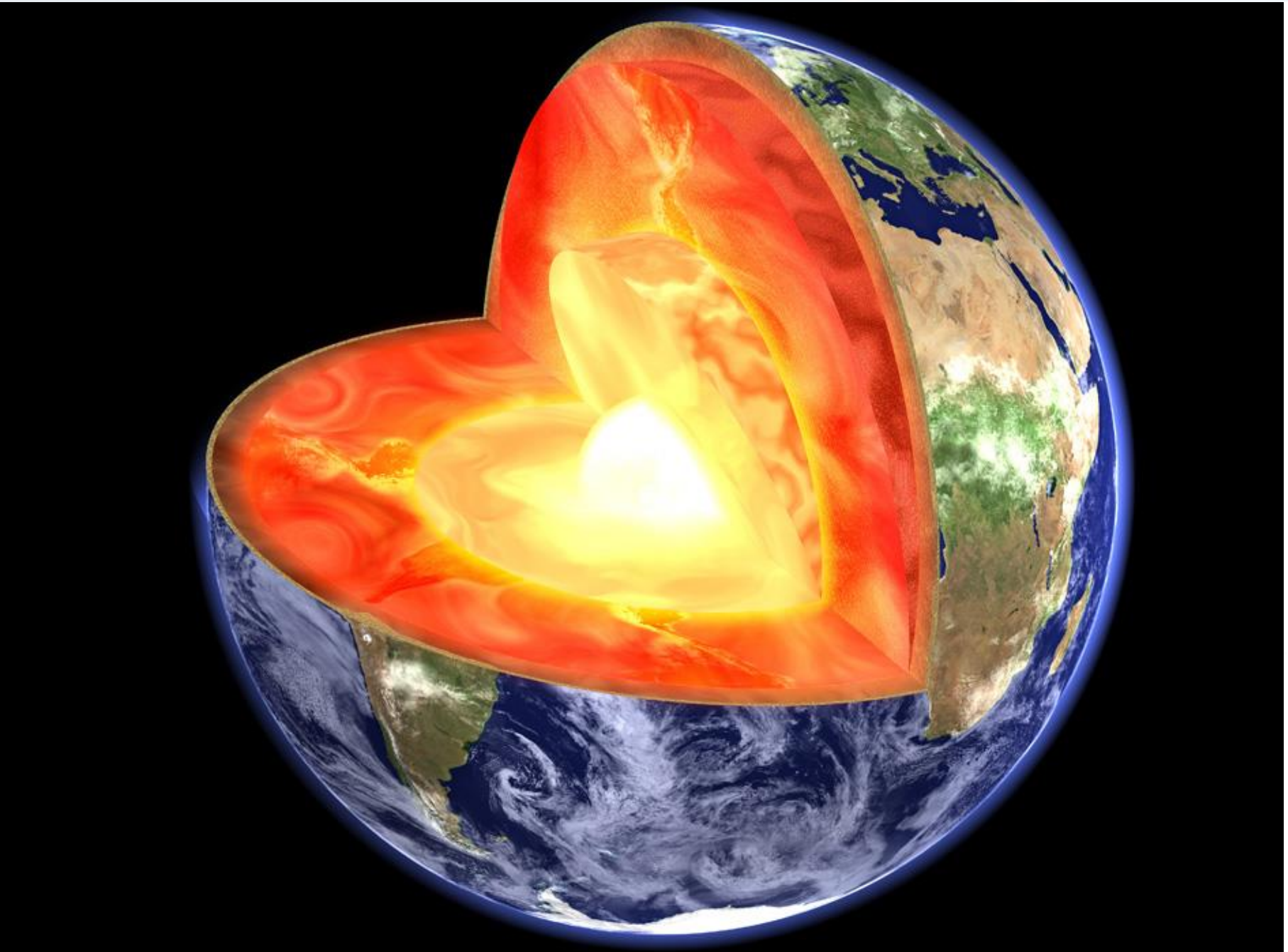


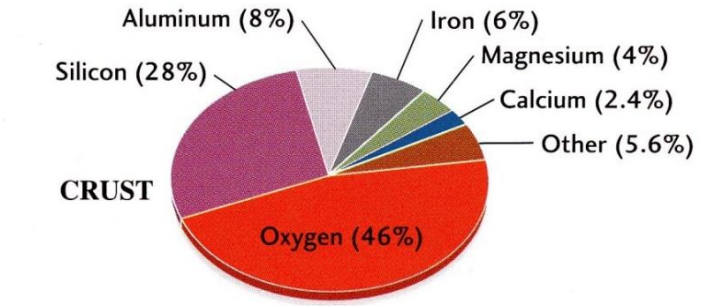
Three things can change with metamorphism

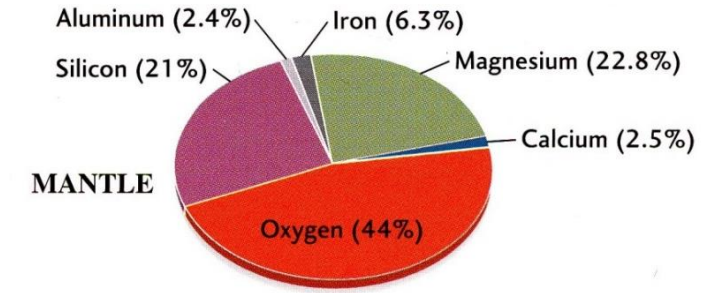
1. Which minerals make up the rock

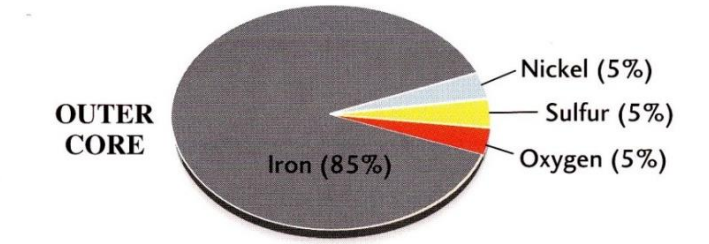

Bowen's Reaction Series
High Temperature
cooling magma
Low temperature
first silicate minerals to crystallize
olivine
pyroxene
Amphibole
biotite mica
potassium feldspar
muscavite mica
quartz
last to crystallize
discontinuous series of crystallization
continuous series of crystallization
calcium-rich feldspar
sodium-rich feldspar
Compositon
intrusive/extrusive rock types
Ultramafic
peridotite/komatite
Mafic
gabbro/basalt
Intermediate
diorite/andesite
Felsic
granite/rhyolite

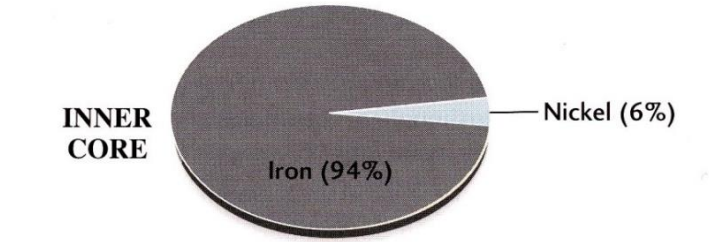

100
75
50
25
0
proportion of minerals by volume/%
pyroxene
amphibole
mica
olivine
plagioclase feldspar
alkali feldspar
quartz
increasing Si, Na, K
increasing Mg, Fe, Ca




Aluminum (8%)
Iron (6%)
Magnesium (4%)
Silicon (28%)
Calcium (2.4%)
Other (5.6%)
CRUST
Oxygen (46%)

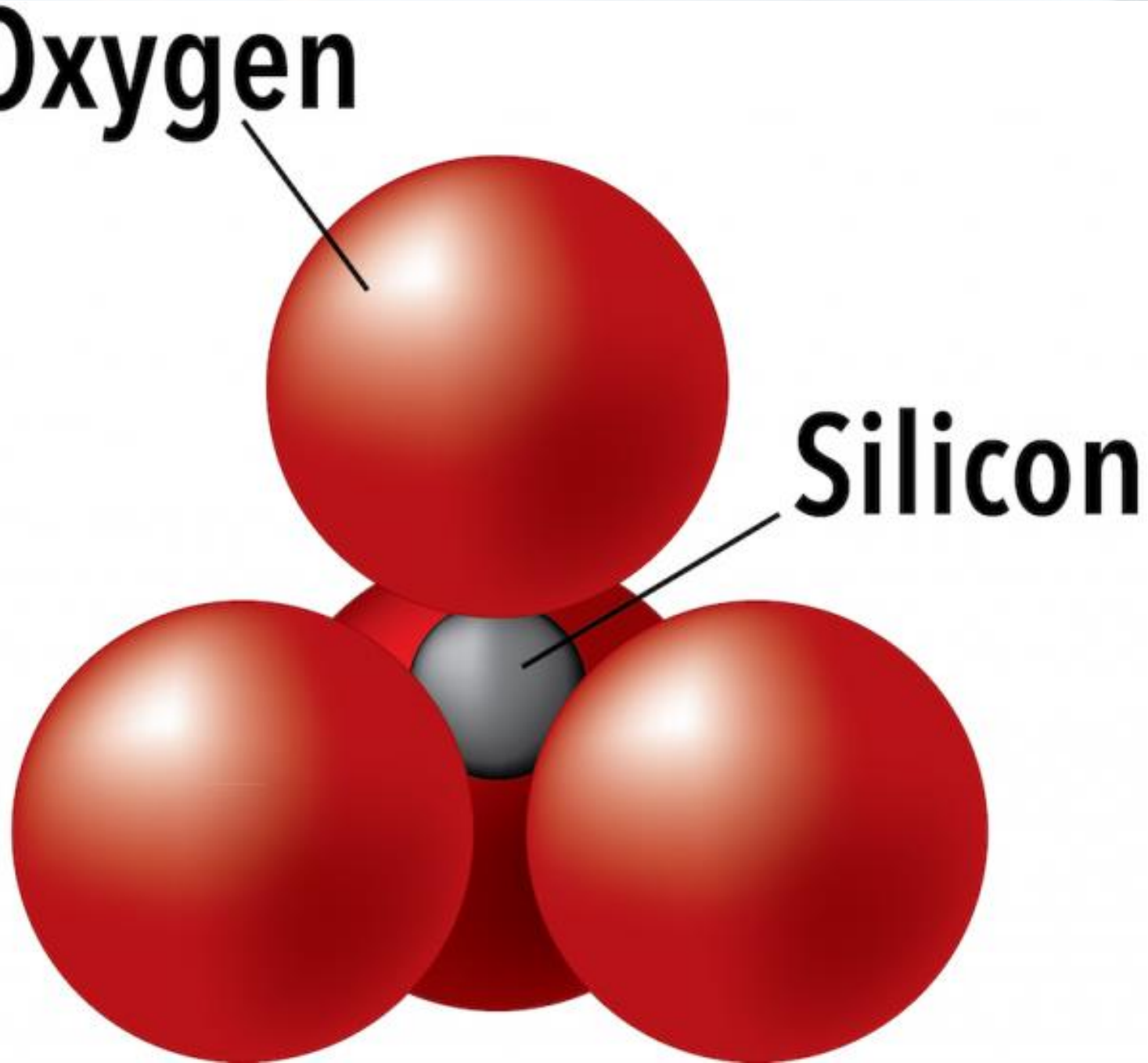

Aluminum (2.4%)
Iron (6.3%)
Silicon (21%)
Magnesium (22.8%)
Calcium (2.5%)
MANTLE
Oxygen (44%)


Nickel (5%)
Sulfur (5%)
OUTER CORE
Iron (85%)
Oxygen (5%)


INNER CORE
Nickel (6%)
Iron (94%)

SiO_4^{4-}

Silicate tetrahedron

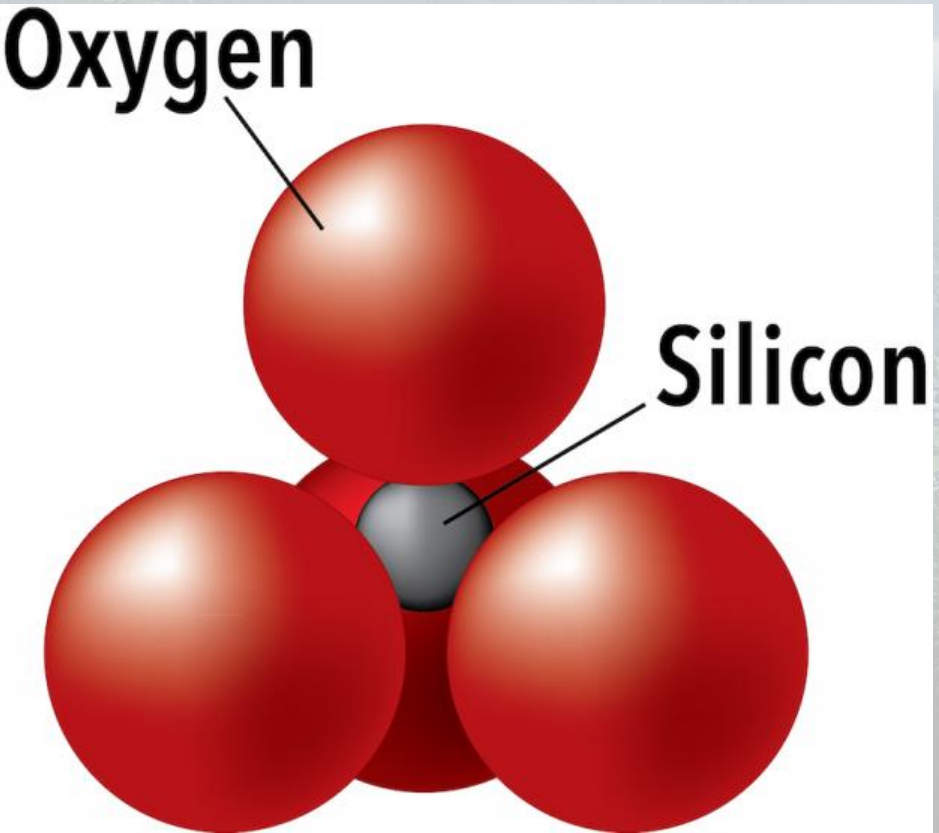


Orthosilicates

Single SiO_4 units

4- balanced by 2 x 2+

e.g. Fe^{2+}, Mg^{2+}, Ca^{2+}



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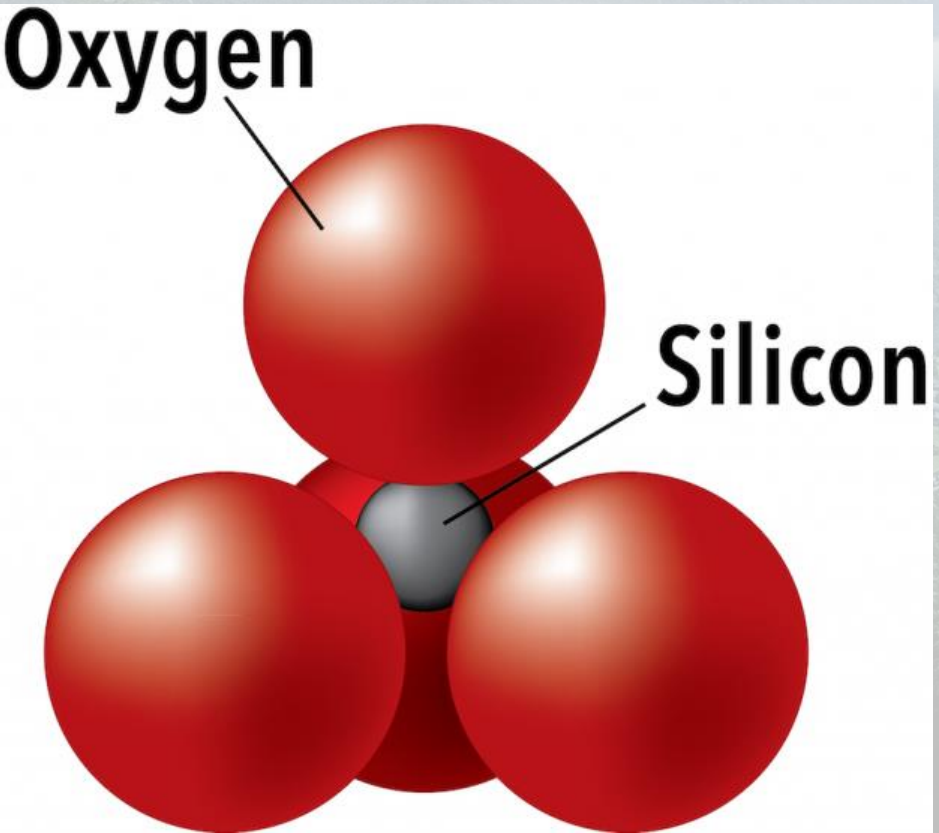
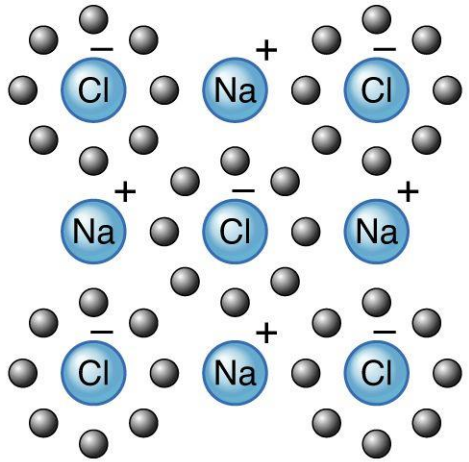
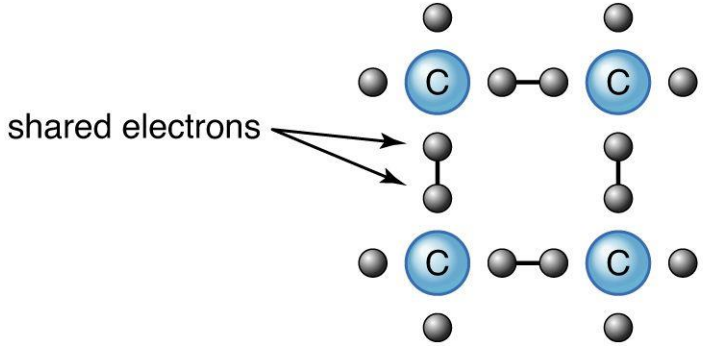
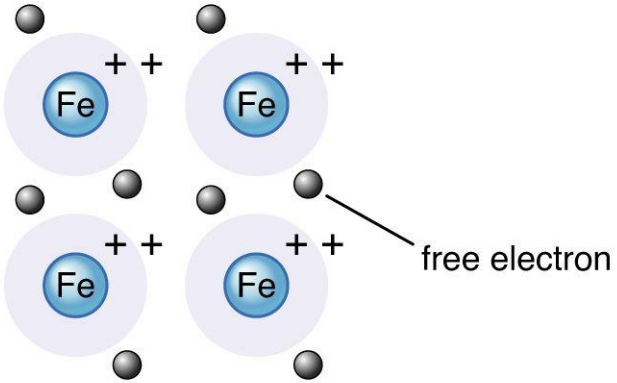




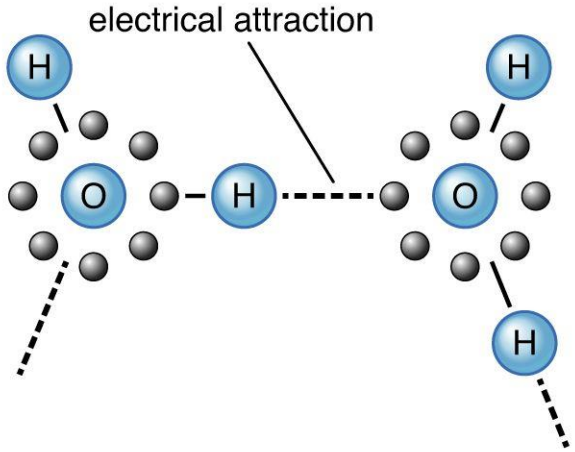
ionic bonding
electron transferred from Na to Cl



covalent bonding
atoms share electrons



metallic bonding
ions surrounded by free electrons



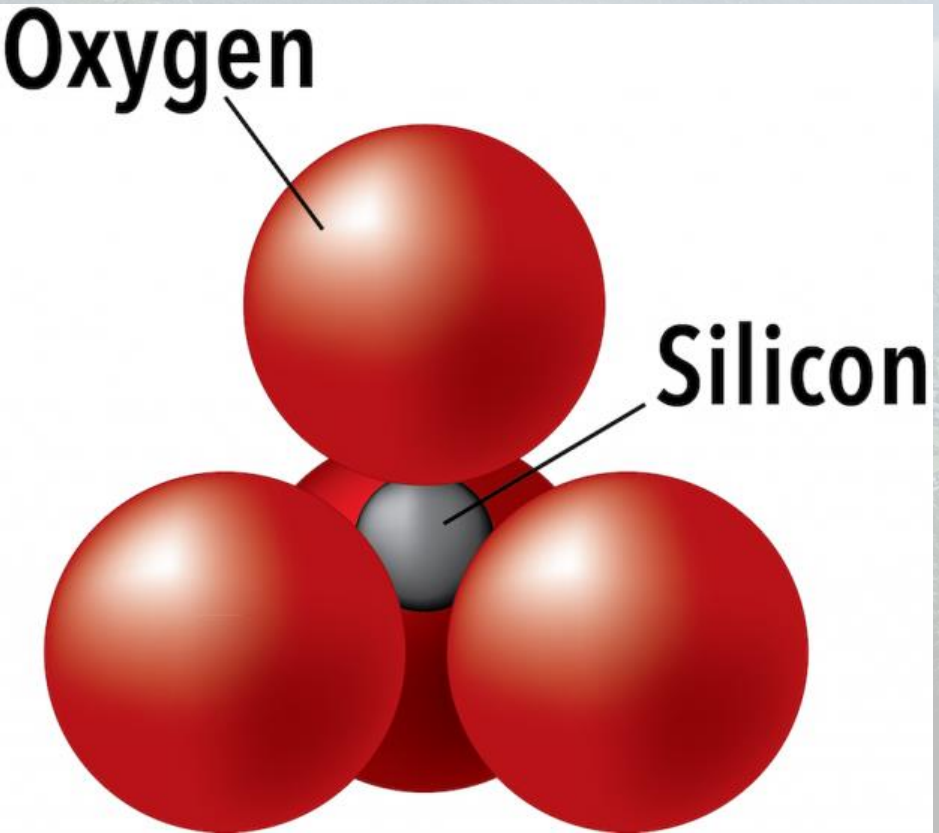
molecular bonding
weak electrical attraction binds molecules

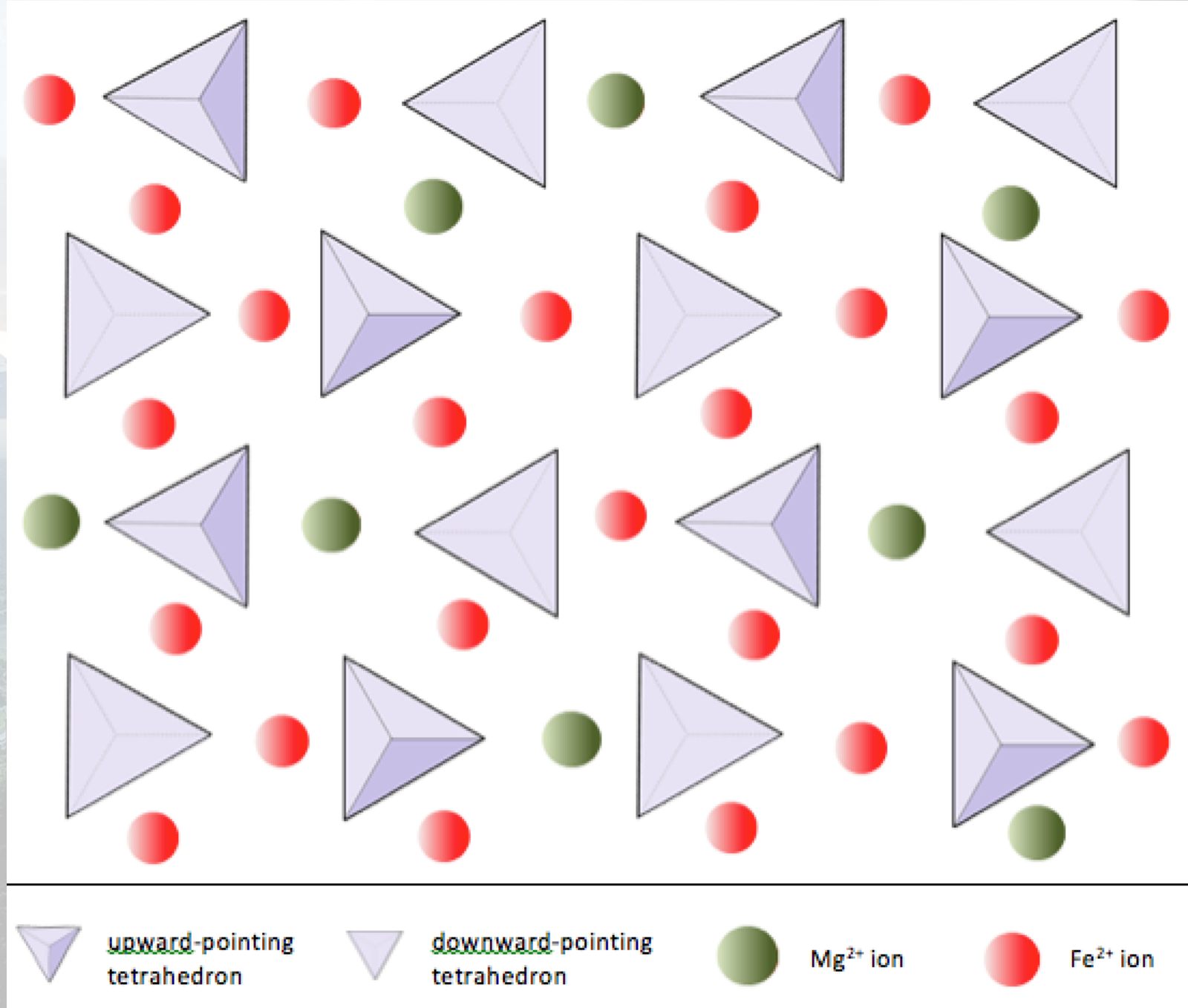
Orthosilicates

Single SiO_4 units

4- balanced by 2 x 2+

e.g. olivine, $(Mg,Fe)_2SiO_4$





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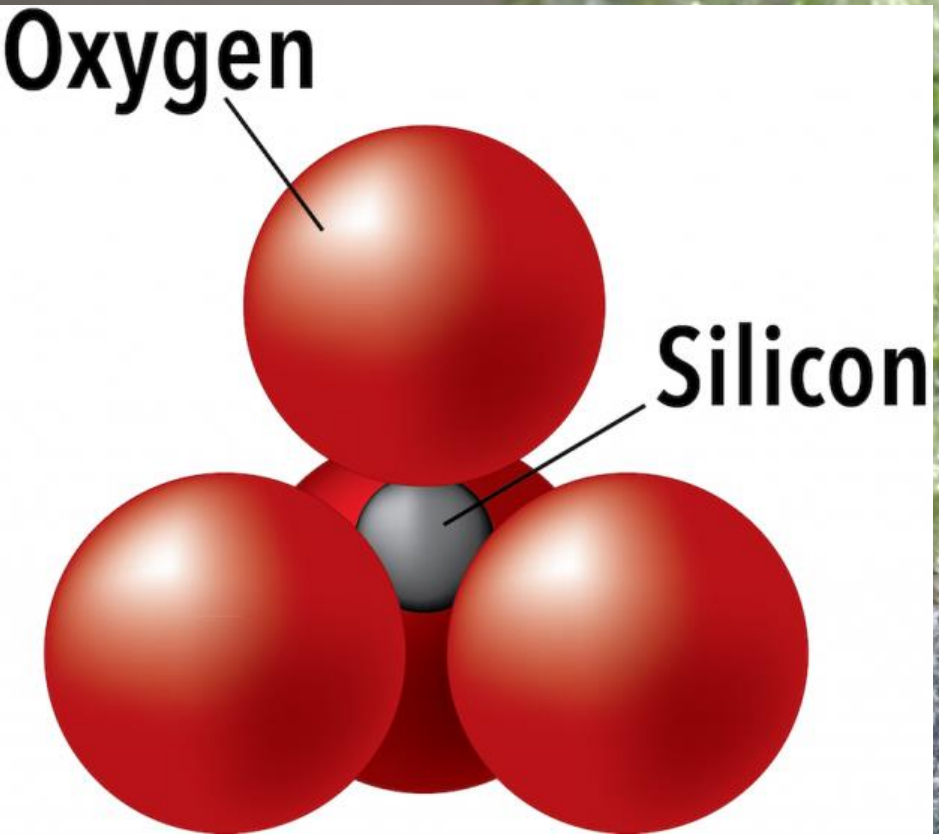
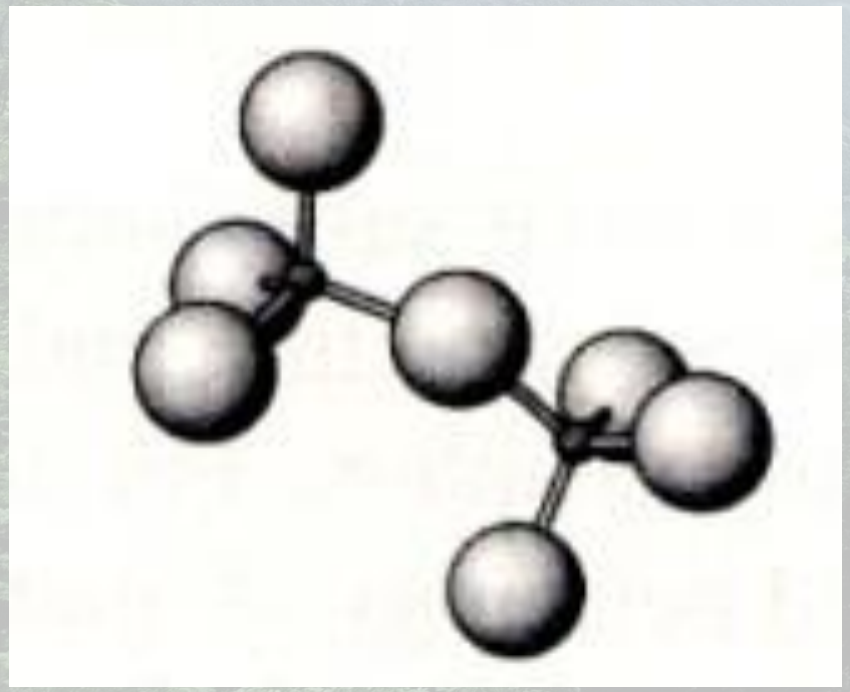


Orthosilicates

Double SiO_4 units sharing one O

$2 \times Si^{4+} + 7 \times O^{2-} = \underline{6-}$

e.g. Epidote

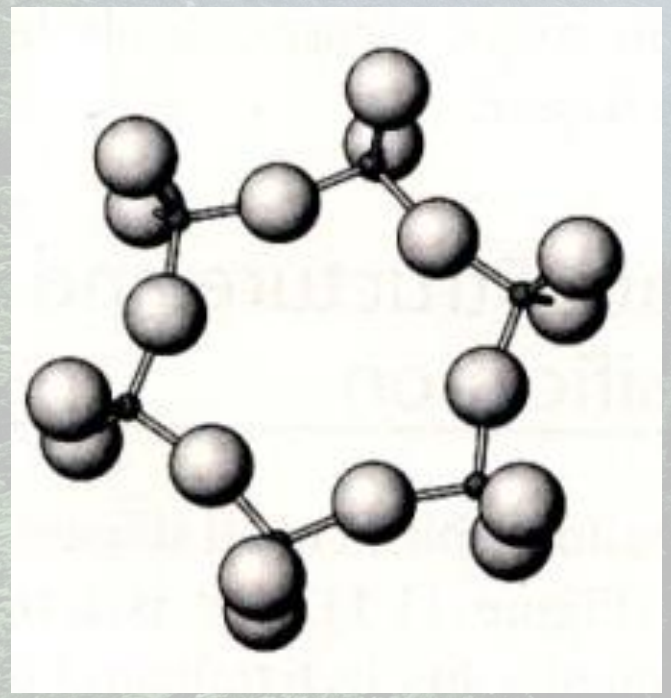


Ring silicates

Six SiO_4 units sharing 2 O's each

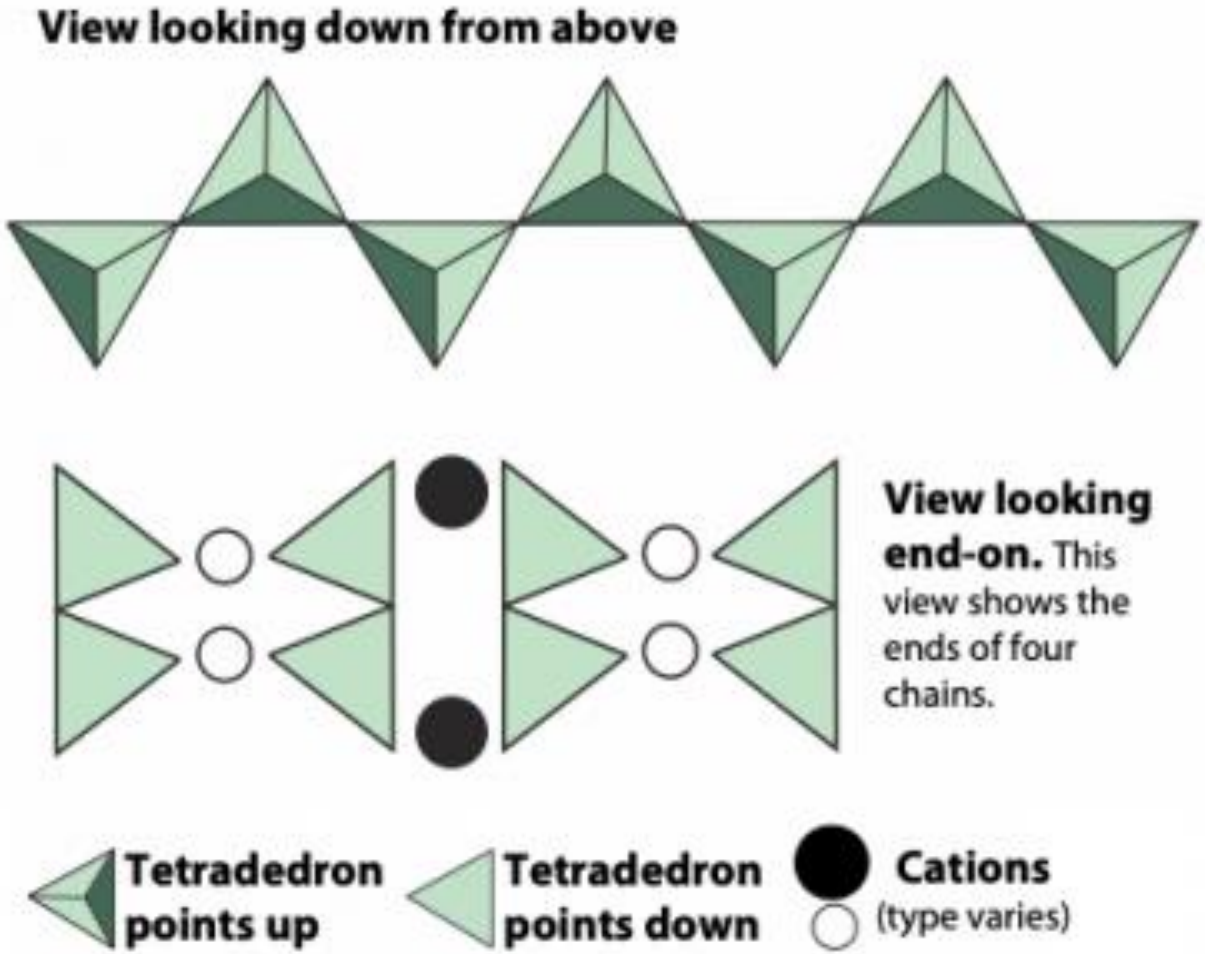
$6 \times Si^{4+} + 18 \times O^{2-} = \underline{12-}$

e.g. Beryl (inc. aquamarine, emerald)



Chain silicates

SINGLE CHAIN



Aegirine variety

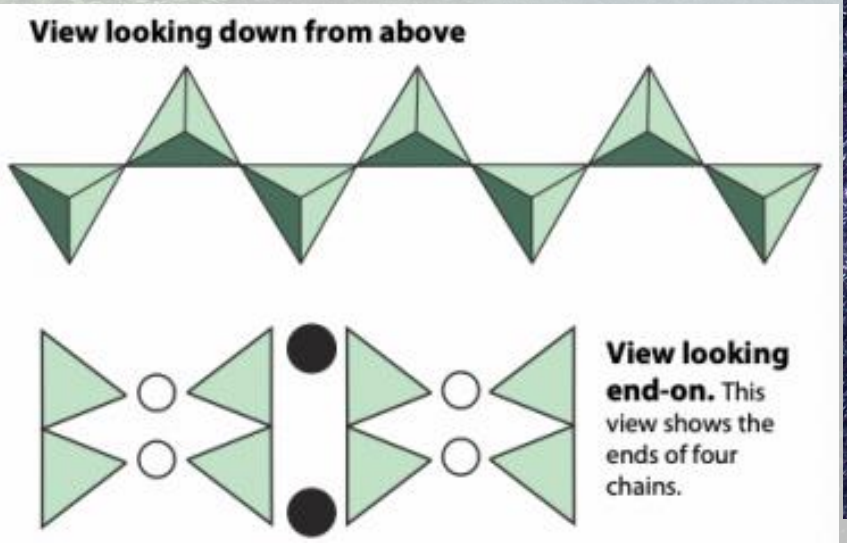
R. Weller/ Cochise College

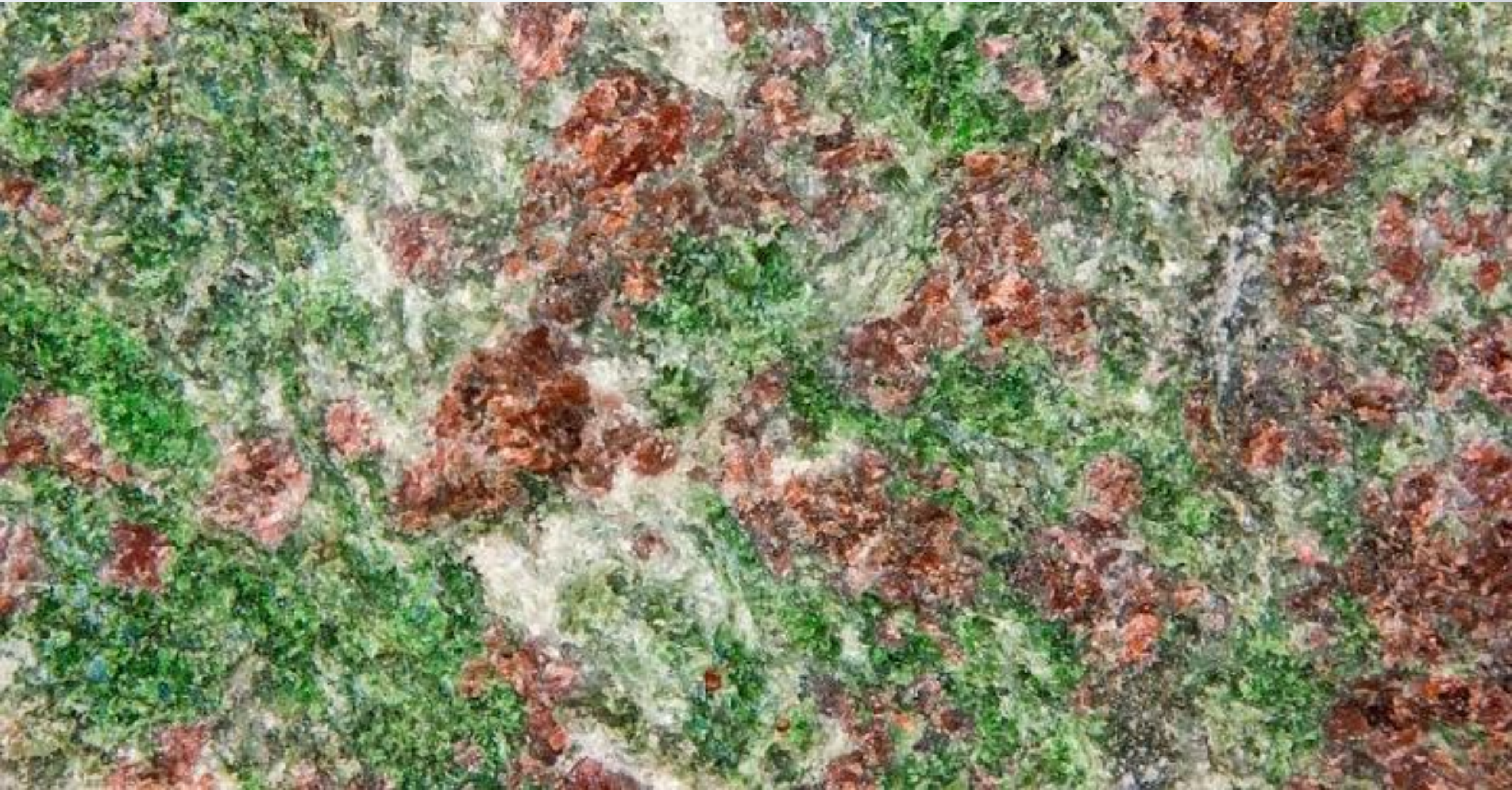
Chain silicates

Continuous chains of SiO_4 units sharing 2 x O

$Si^{4+} + 2 \times O^{2-} + 2 \times \frac{1}{2}O^{2-}$
$= \underline{2-}$

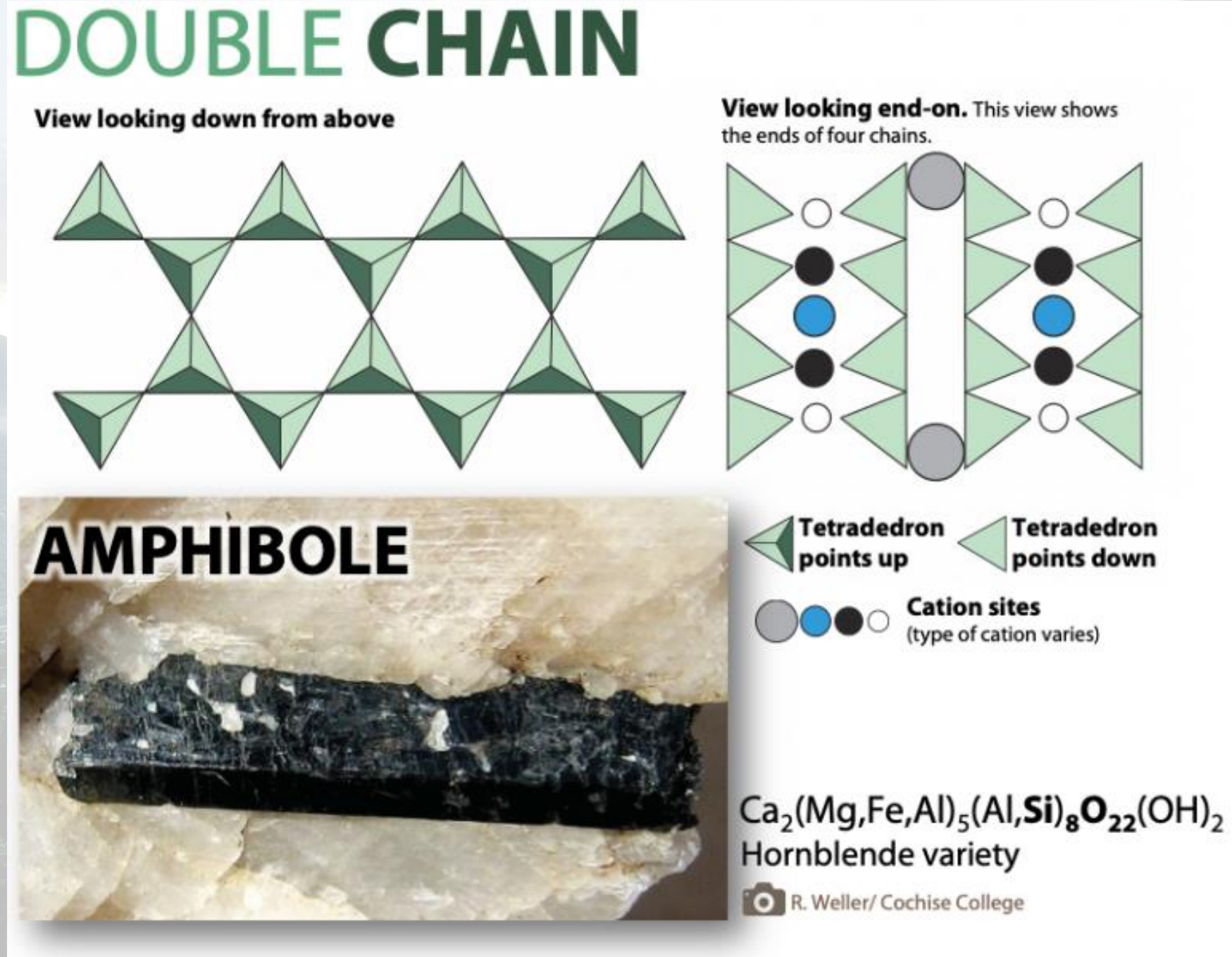
e.g. Pyroxene





Double Chain silicates

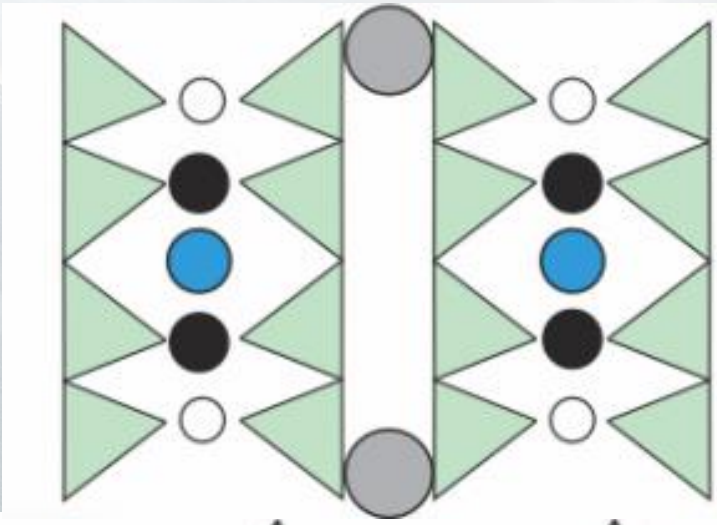
Continuous double chains of SiO_4 units

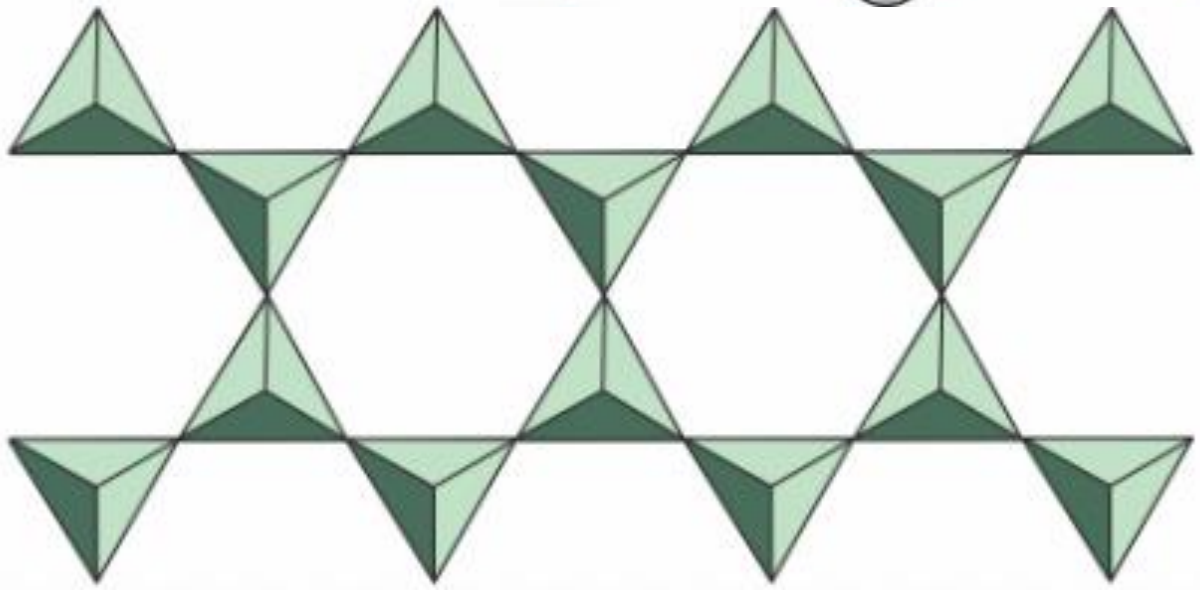


Double Chain silicates

Continuous double chains of SiO_4 units

e.g. Amphibole

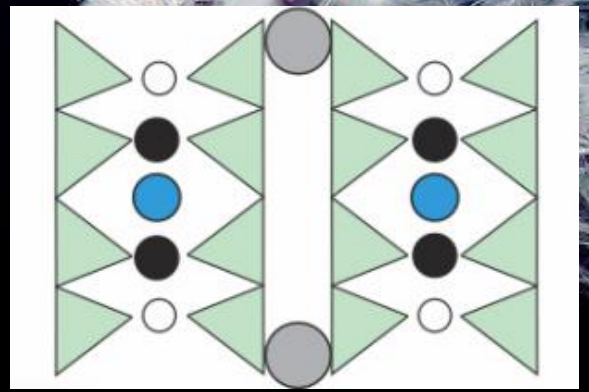




Double Chain silicates

Continuous double chains of SiO_4 units

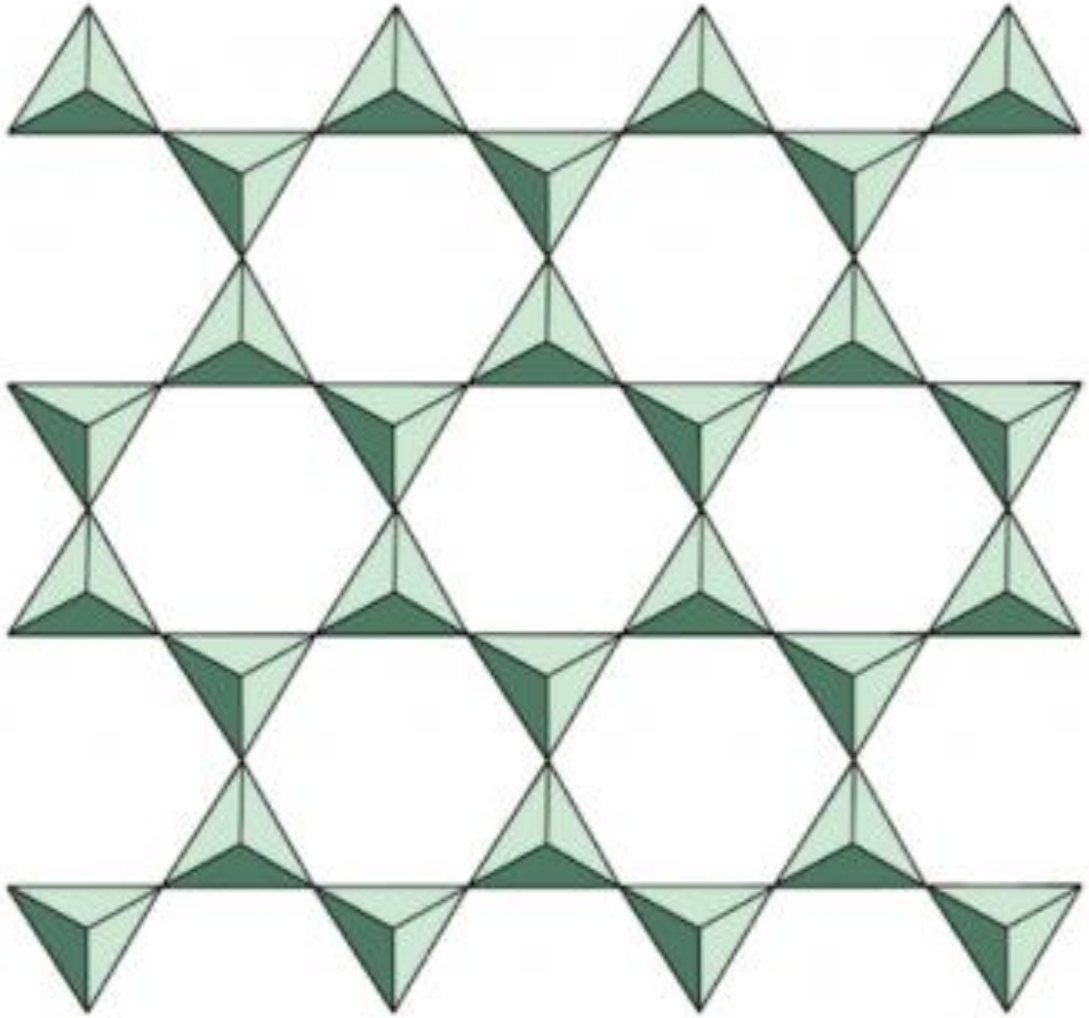
e.g. Asbestos



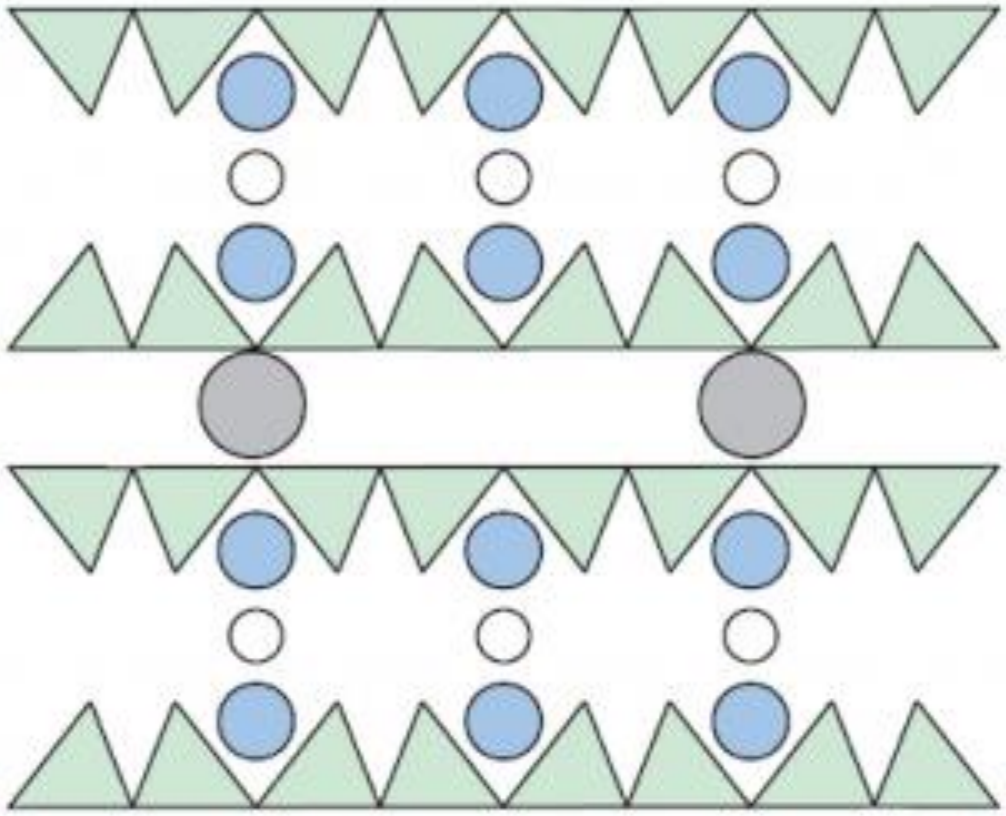
Sheet Silicates

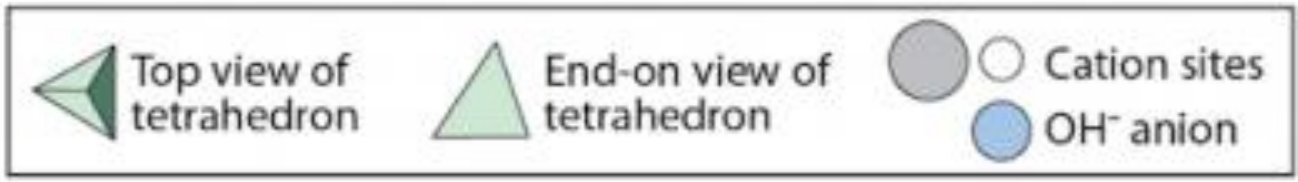
Continuous sheets of SiO_4 units sharing 3 O's each, e.g. mica

View looking down on the sheet of tetrahedra



View looking end-on at sheets of tetrahedra





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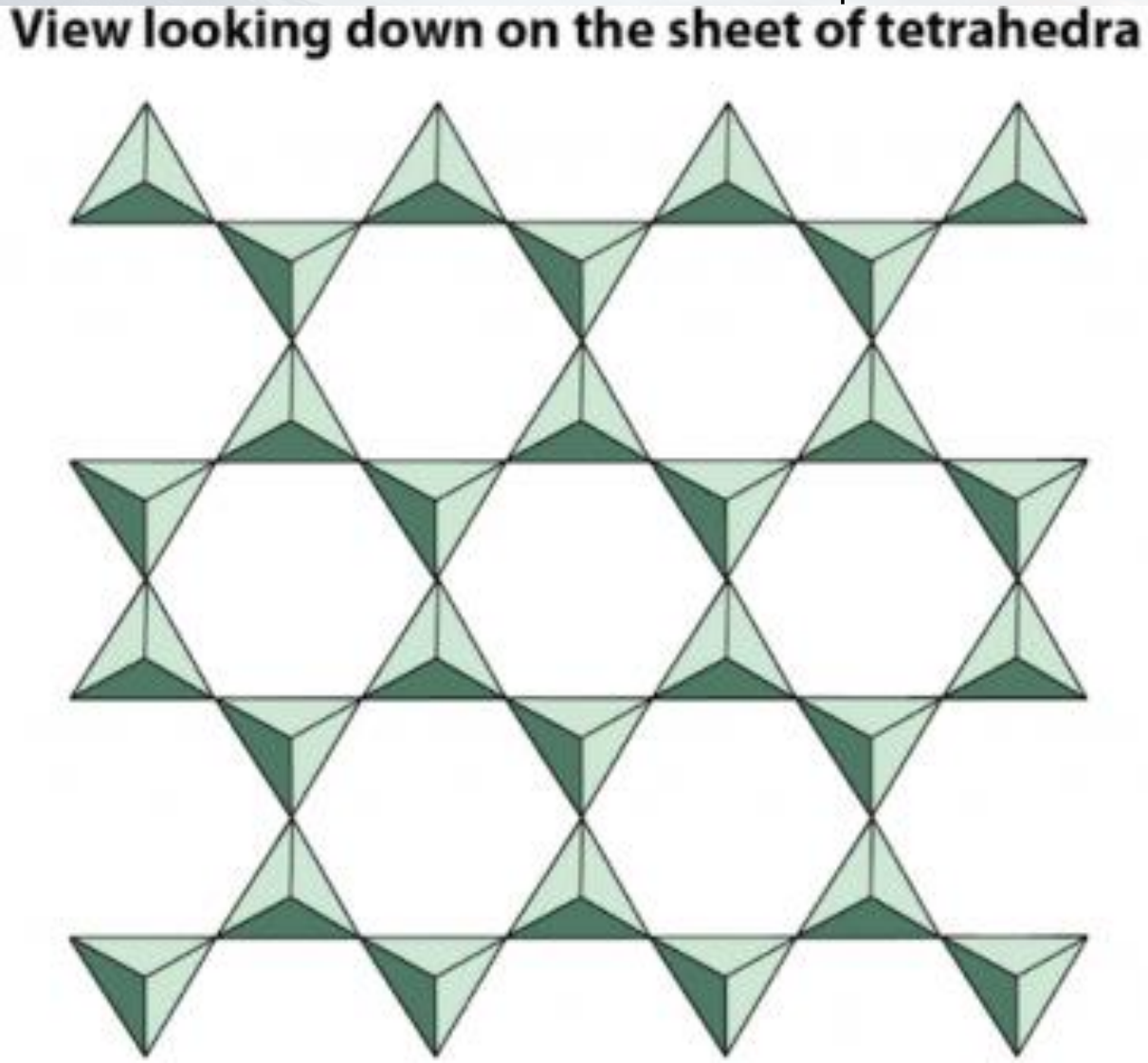

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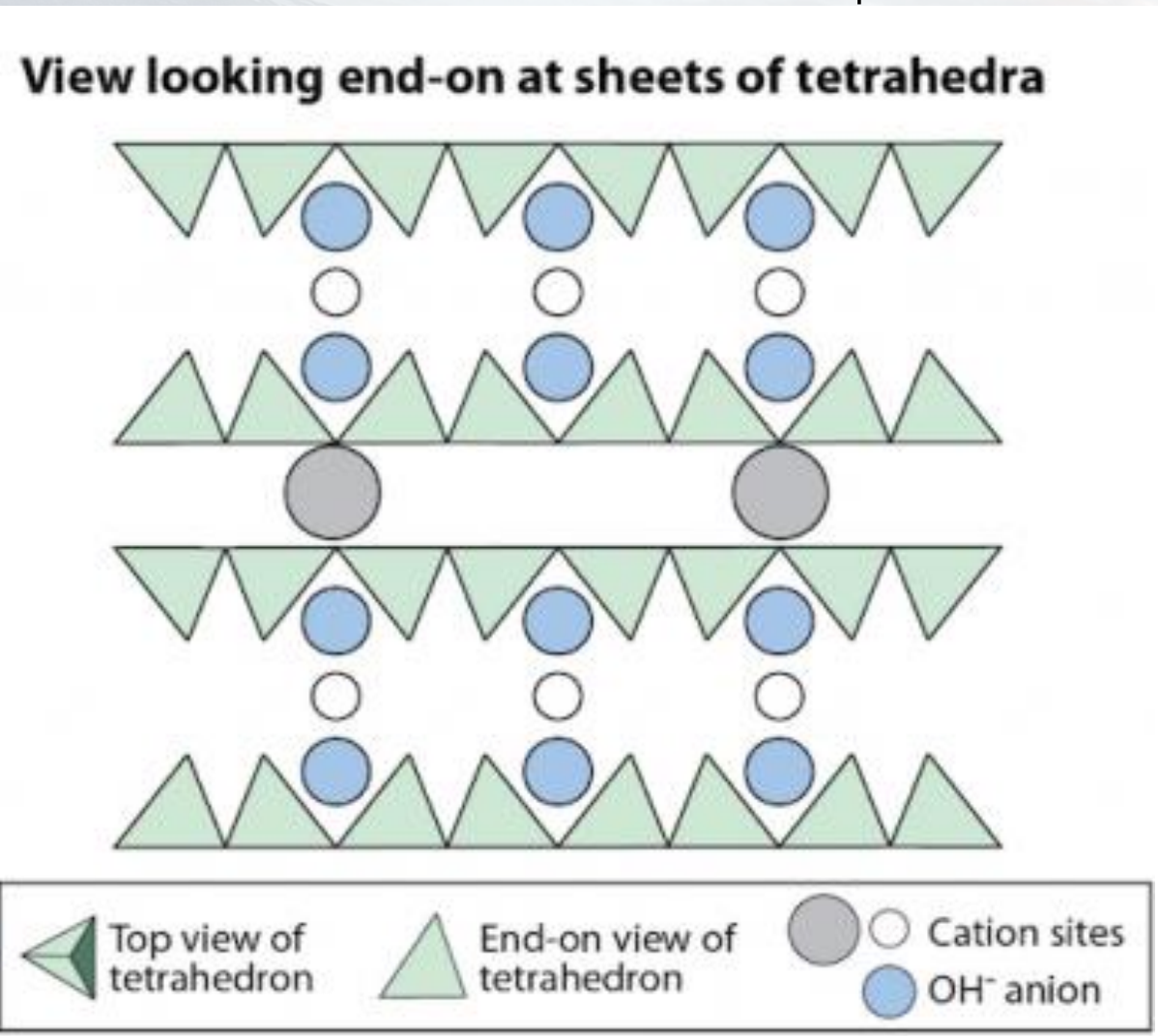
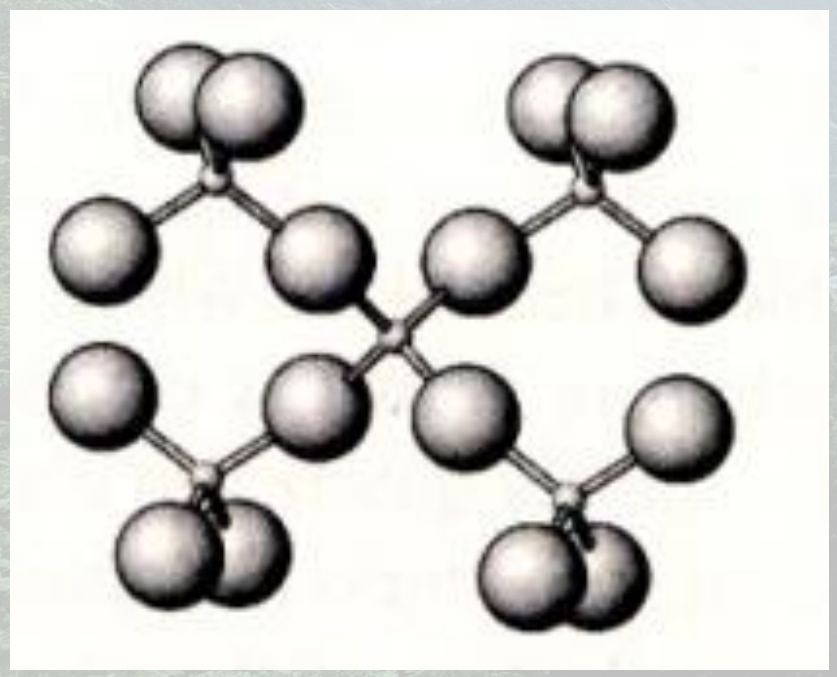


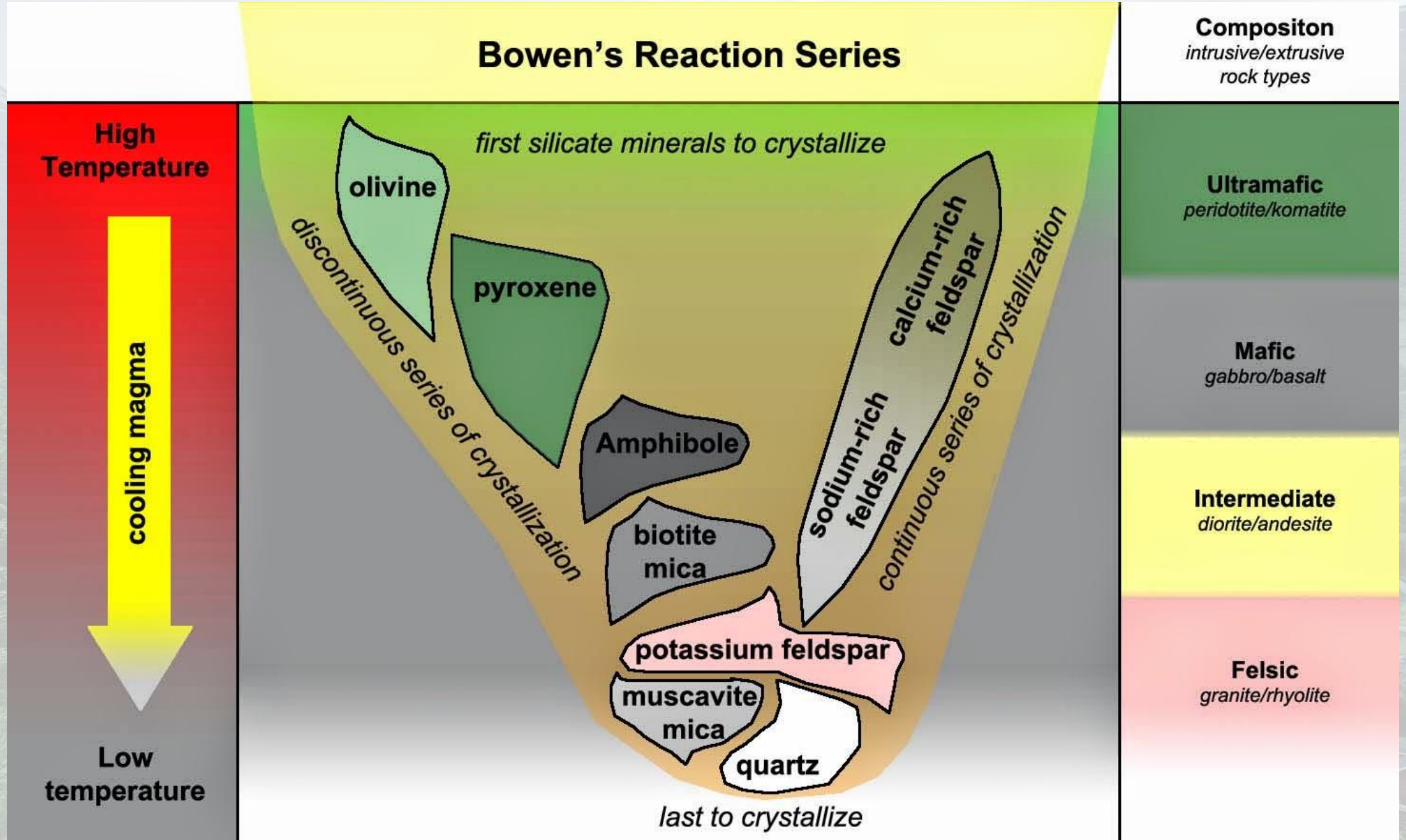
Framework silicates

Continuous 3D framework of SiO_4 units sharing all 4 O's

$Si^{4+} + 4 \times ½O^{2-} = SiO_2$

e.g. Quartz, feldspar




Bowen's Reaction Series
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cooling magma
Low temperature
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olivine
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quartz
last to crystallize
discontinuous series of crystallization
continuous series of crystallization
calcium-rich feldspar
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intrusive/extrusive rock types
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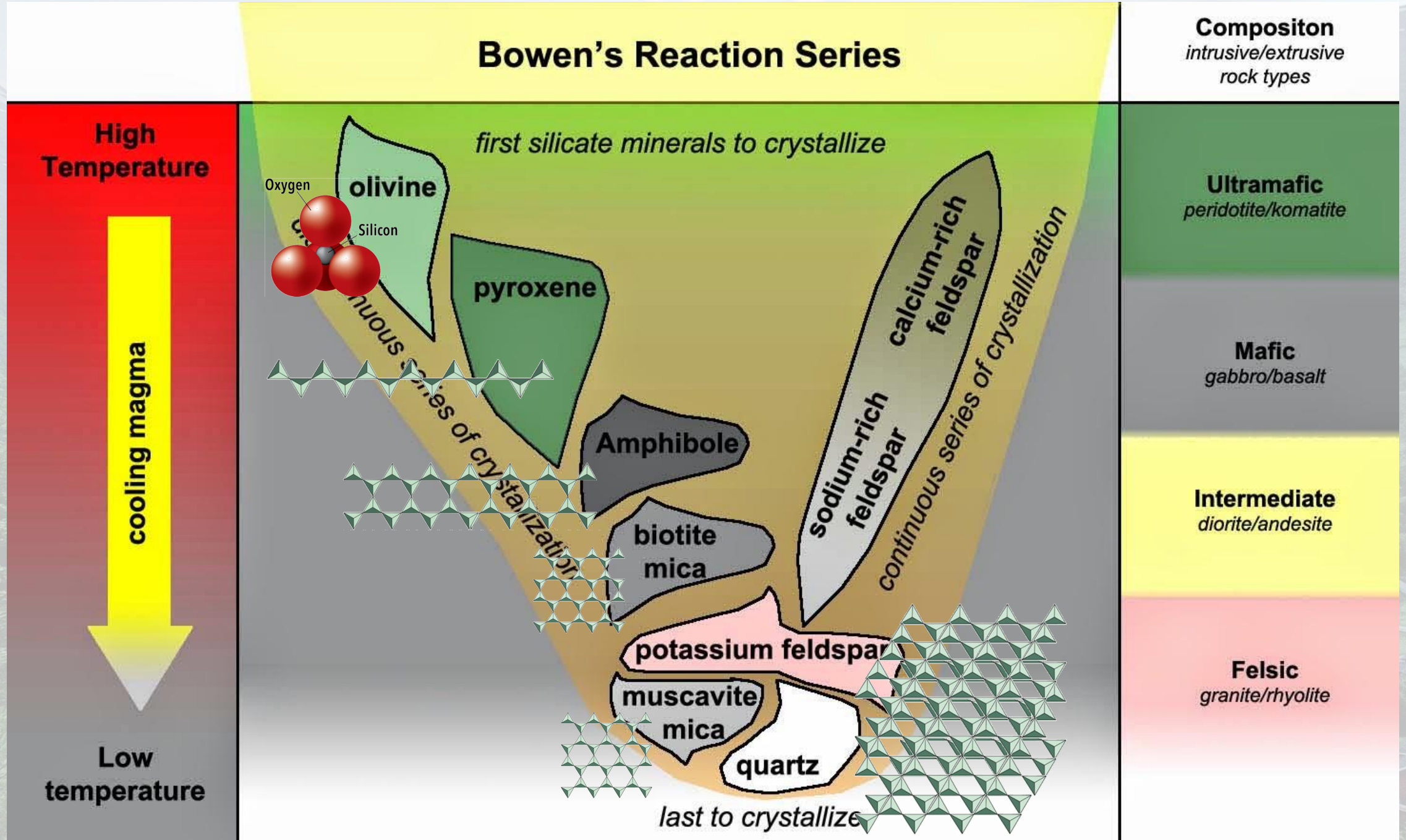
Bowen's Reaction Series
High Temperature
cooling magma
Low temperature
first silicate minerals to crystallize
Oxygen
Silicon
olivine
pyroxene
Amphibole
biotite mica
potassium feldspar
muscavite mica
quartz
last to crystallize
continuous series of crystallization
sodium-rich feldspar
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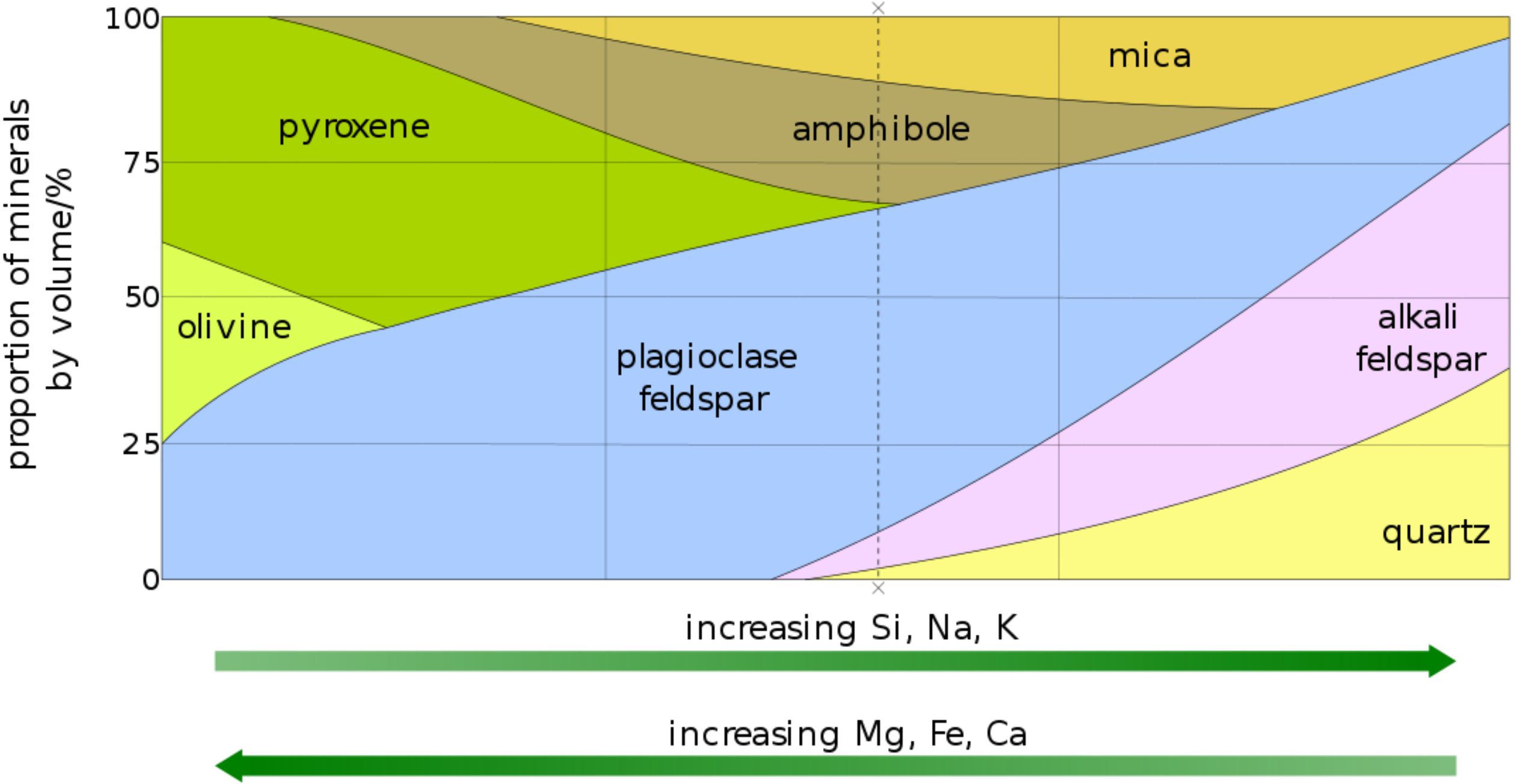
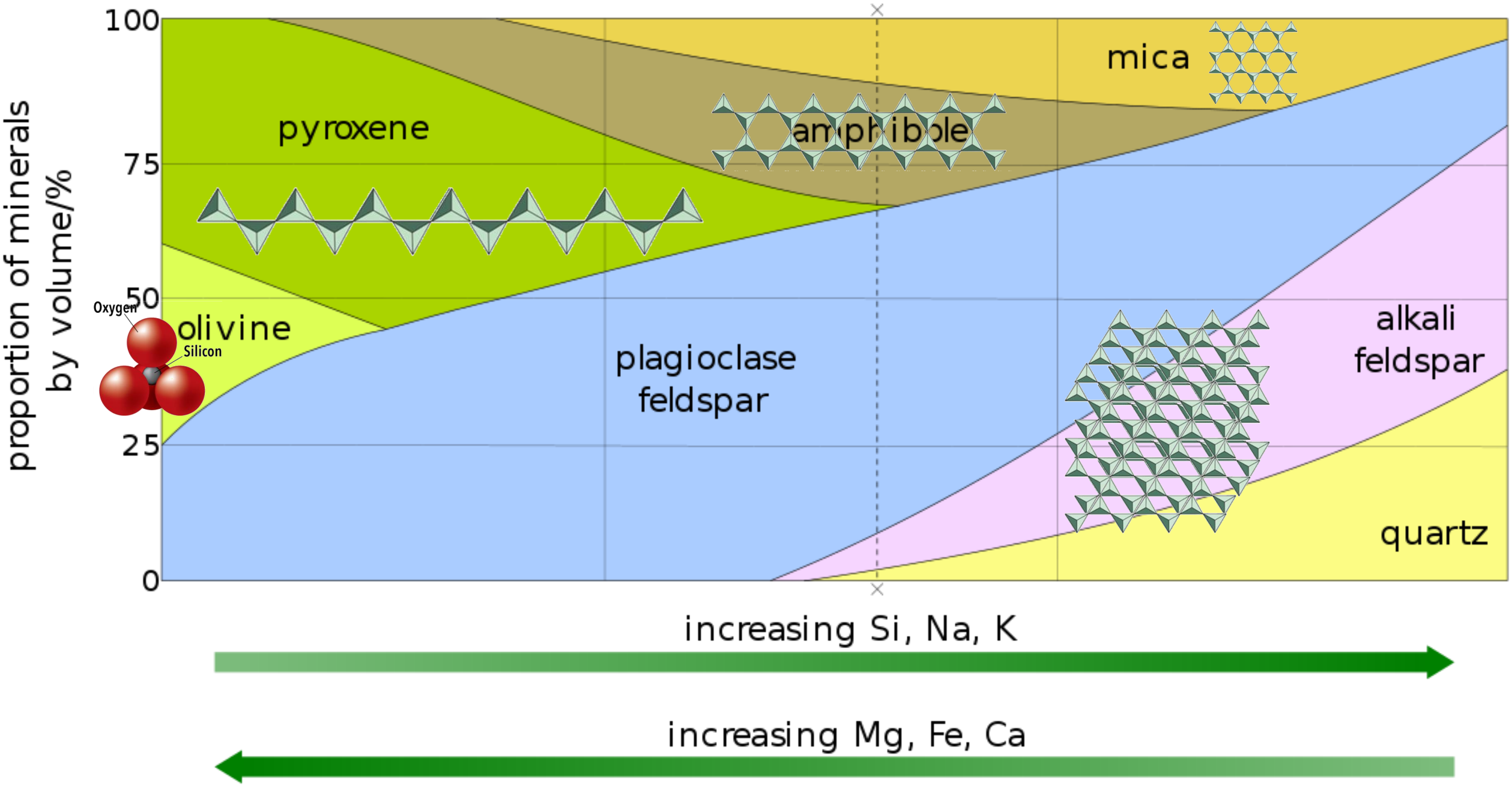
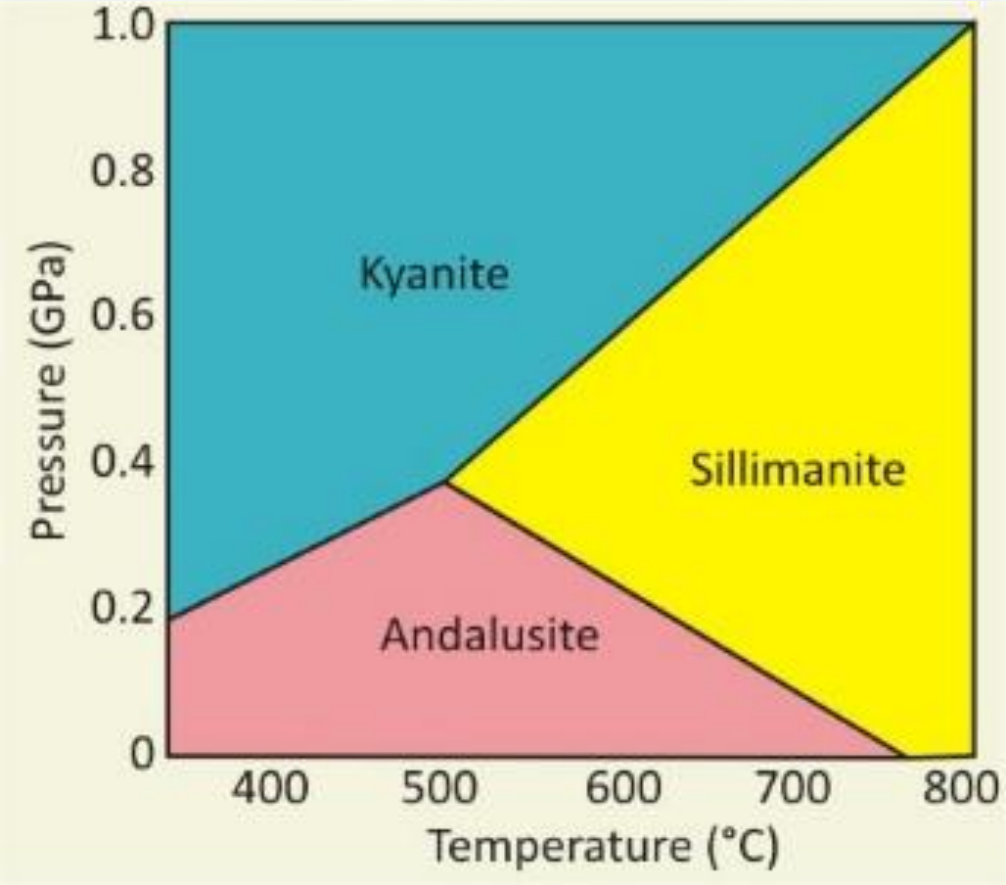

100
75
50
25
0
proportion of minerals by volume/%
pyroxene
amphibole
mica
olivine
plagioclase feldspar
alkali feldspar
quartz
increasing Si, Na, K
increasing Mg, Fe, Ca


proportion of minerals by volume/%
100
75
50
25
0
pyroxene
amphibole
mica
olivine
Oxygen
Silicon
plagioclase feldspar
alkali feldspar
quartz
increasing Si, Na, K
increasing Mg, Fe, Ca

Al_2SiO_5



Al_2SiO_5

Al_2SiO_5


On the Earth's surface, this is called *chemical weathering*


Obviously not at mantle P/T conditions
Metastable at Earth surface
Piece of mantle

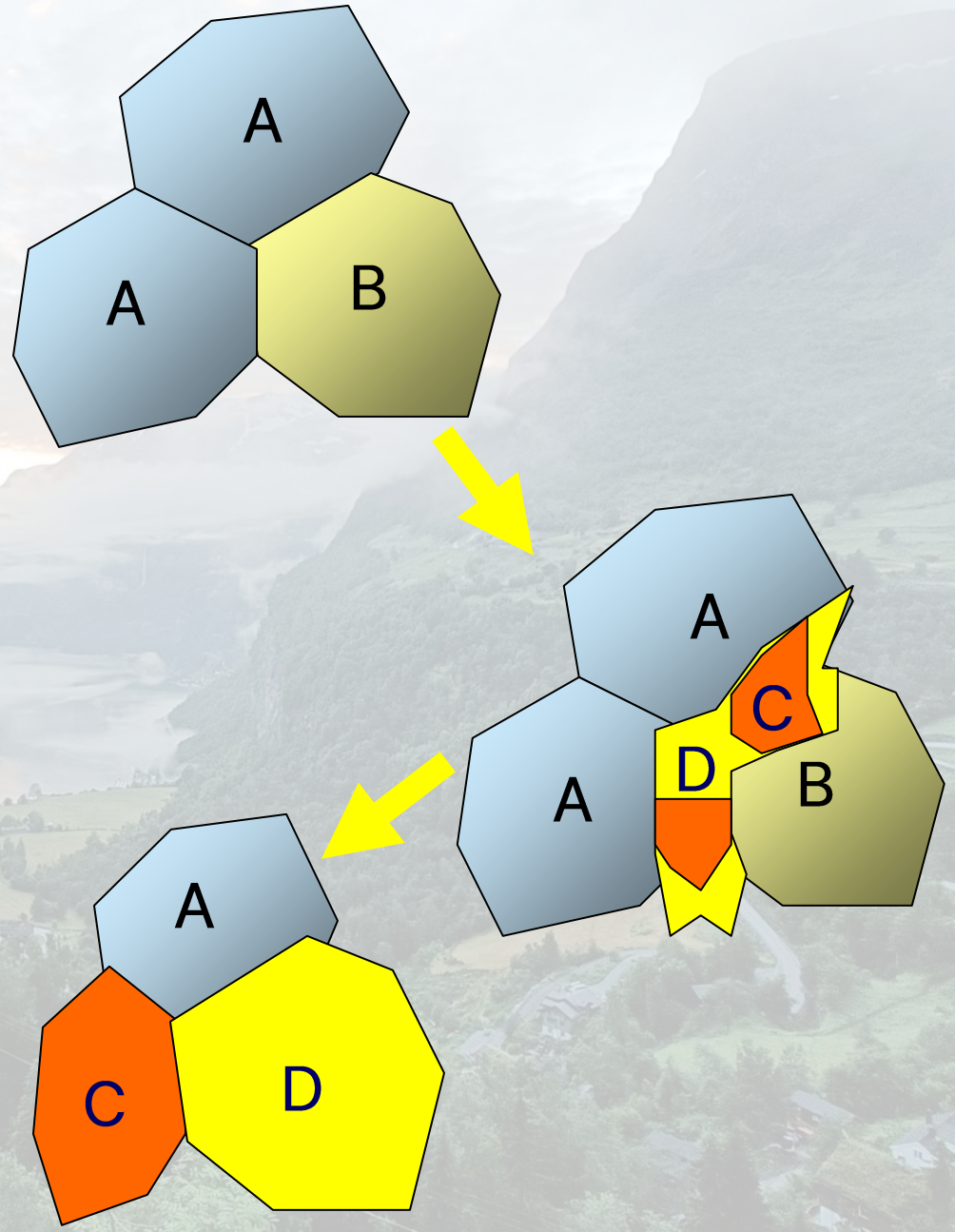
Set of minerals A + B **stable** at initial pressure and temperature

Pressure and temperature change – A + B are now **unstable**

Minerals A + B start to recrystallize, bit by bit

New minerals start to grow which *are* stable at this pressure and temperature: C + D

New minerals will eventually replace most or all of the earlier ones



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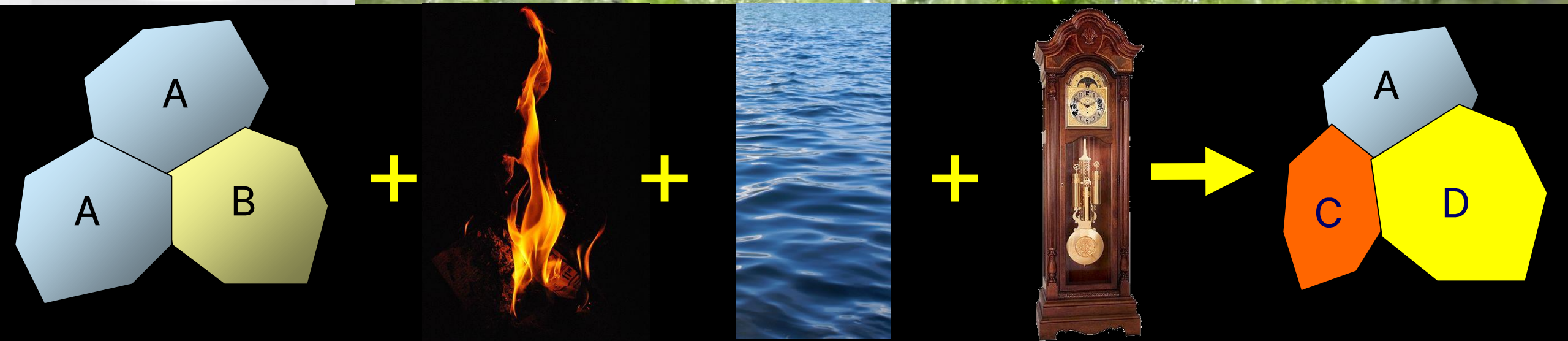
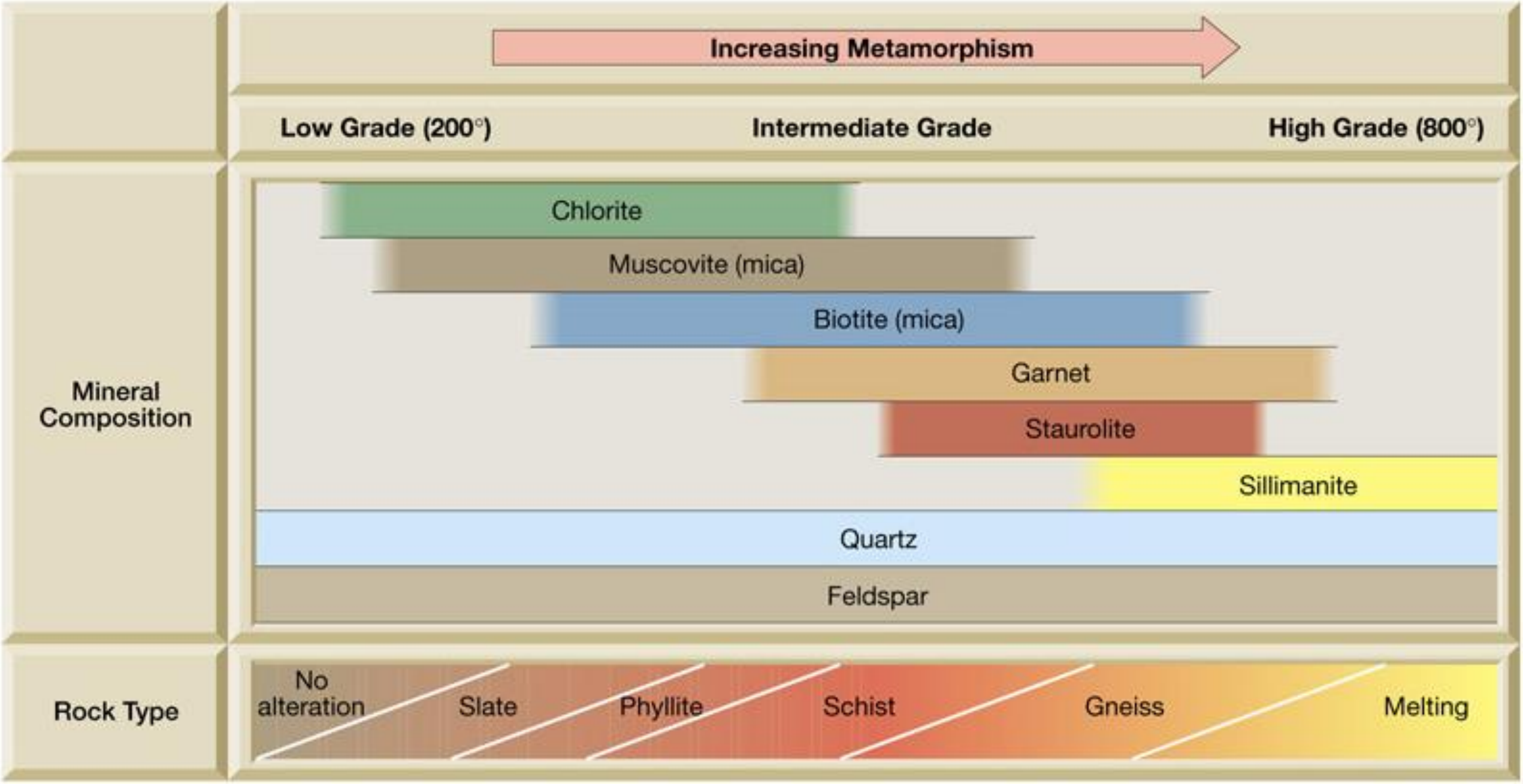
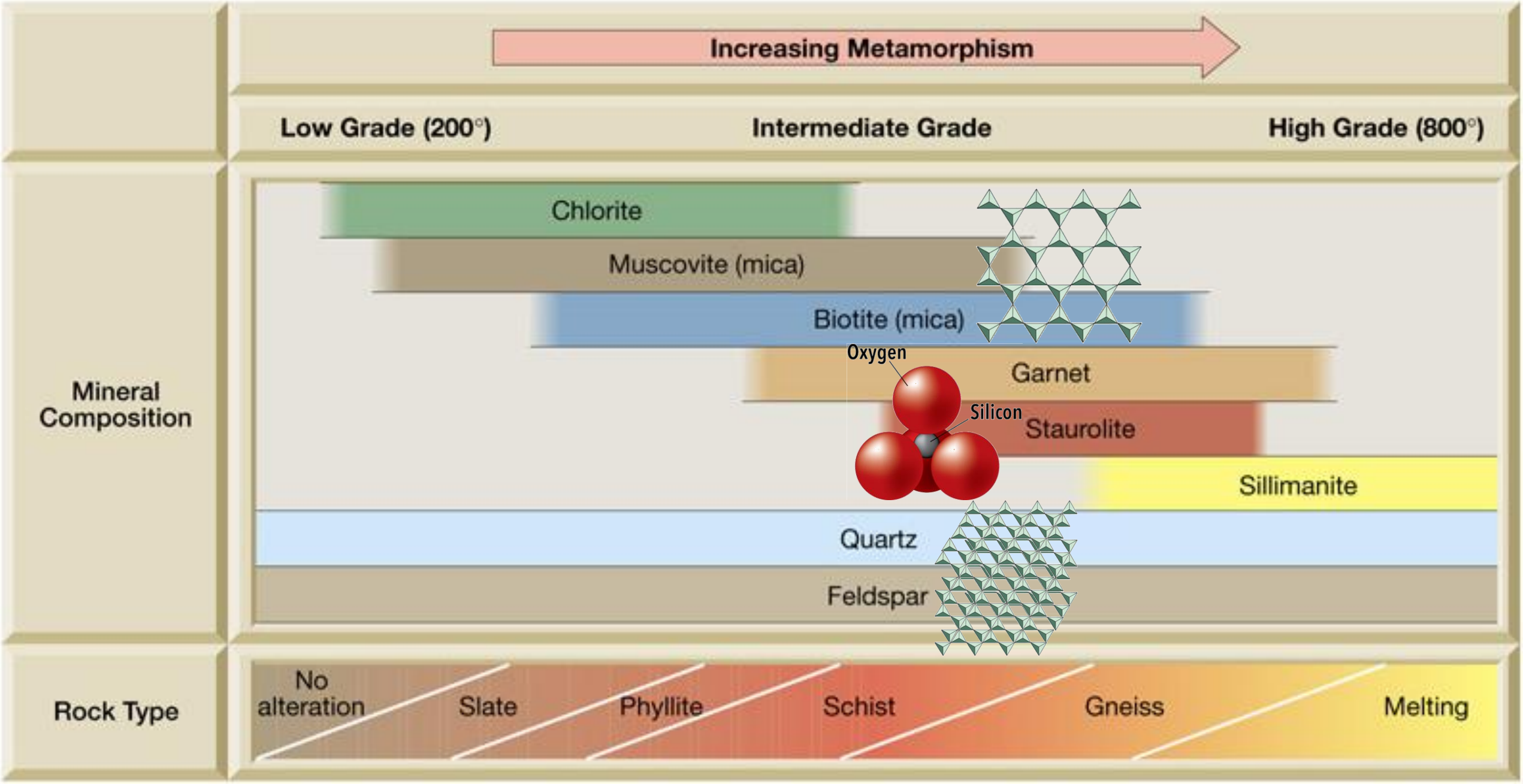
Metastable at Earth surface

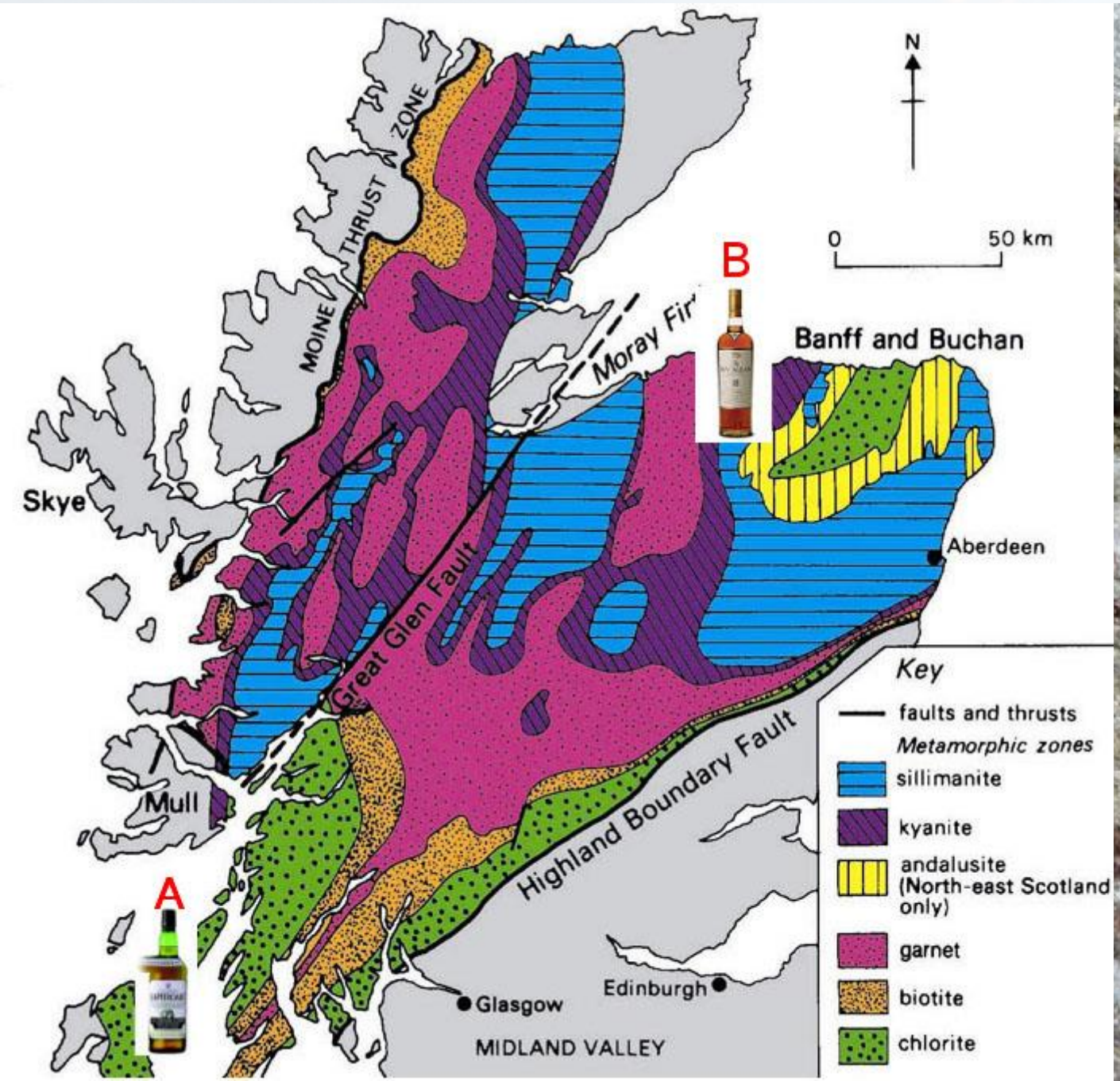
Piece of mantle




Increasing Metamorphism
Low Grade (200°)
Intermediate Grade
High Grade (800°)
Mineral Composition
Chlorite
Muscovite (mica)
Biotite (mica)
Garnet
Staurolite
Sillimanite
Quartz
Feldspar
Rock Type
No alteration
Slate
Phyllite
Schist
Gneiss
Melting


Increasing Metamorphism
Low Grade (200°)
Intermediate Grade
High Grade (800°)
Mineral Composition
Chlorite
Muscovite (mica)
Biotite (mica)
Garnet
Staurolite
Sillimanite
Quartz
Feldspar
Oxygen
Silicon
Rock Type
No alteration
Slate
Phyllite
Schist
Gneiss
Melting


Oxygen
Silicon


N
0
50 km
MOINE THRUST ZONE
Moray Firth
B
Banff and Buchan
Skye
Aberdeen
Great Glen Fault
Mull
Highland Boundary Fault
A
Glasgow
Edinburgh
MIDLAND VALLEY
Key
faults and thrusts
Metamorphic zones
sillimanite
kyanite
andalusite (North-east Scotland only)
garnet
biotite
chlorite

Three things can change with metamorphism

1. Which minerals make up the rock
2. What crystal size the minerals are

Crystal size grows with higher pressure and temperature

Shale
(parent rock)

Slate

Phyllite

Schist

Gneiss

Migmatite

Three things can change with metamorphism

1. Which minerals make up the rock
2. What crystal size the minerals are
3. How thick the layers are

Slate — Cleavage

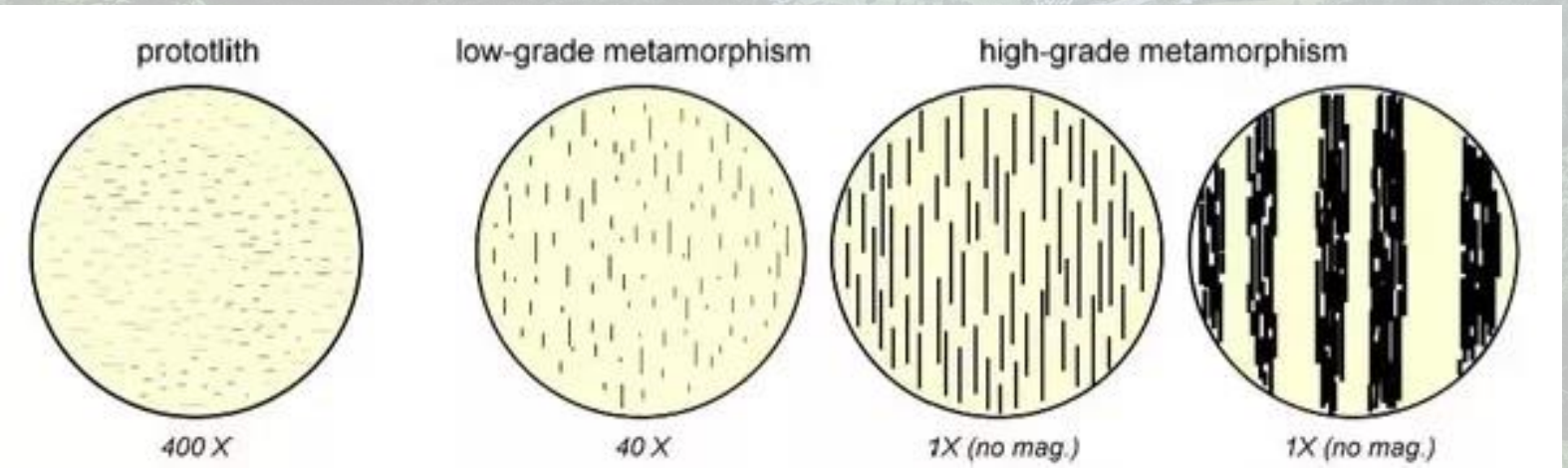
Phyllite — Foliation

Schist — Schistosity

Gneiss — Banding

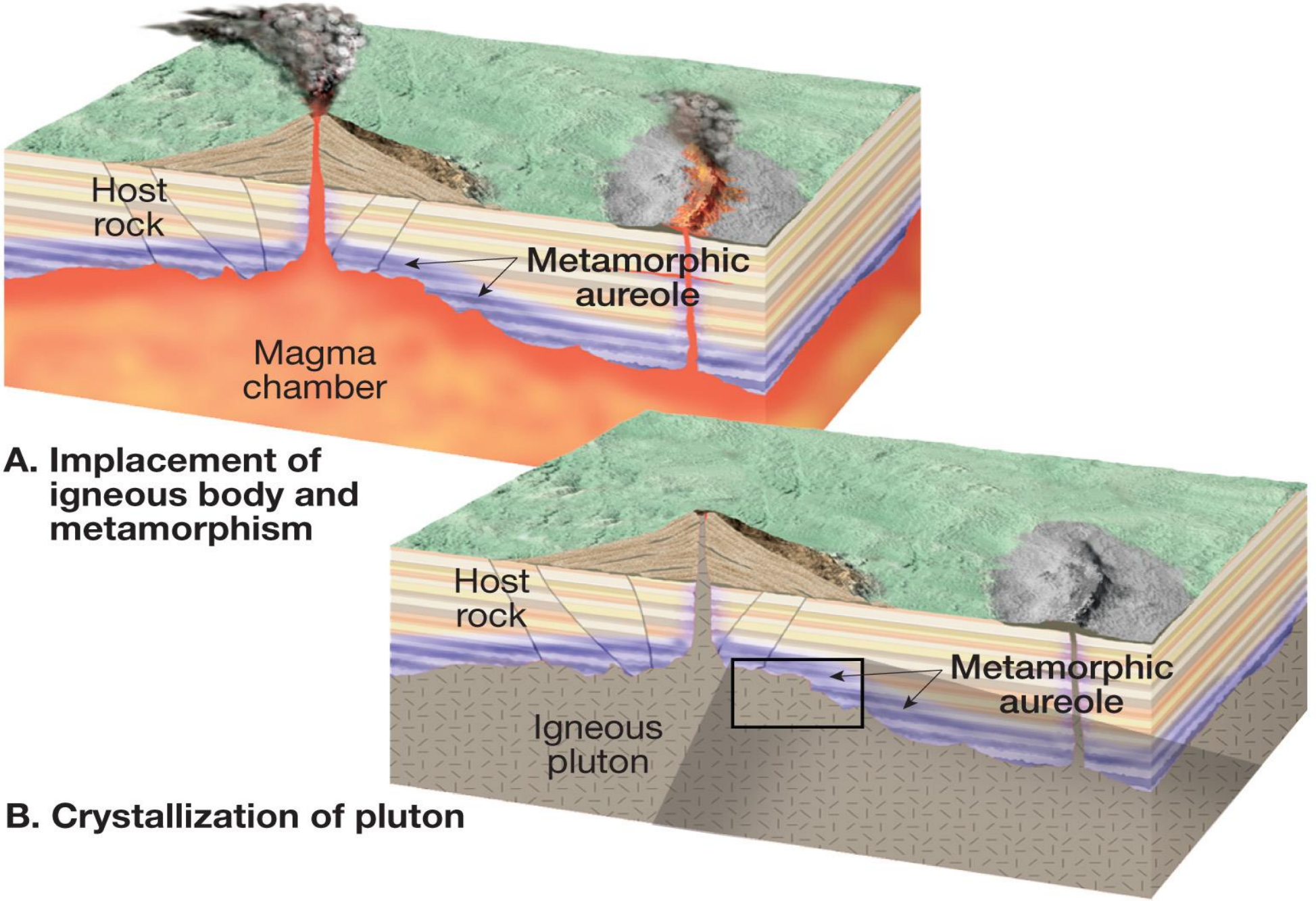
++ layer thickness

++ mineral size



So, how does metamorphism happen?

Heat

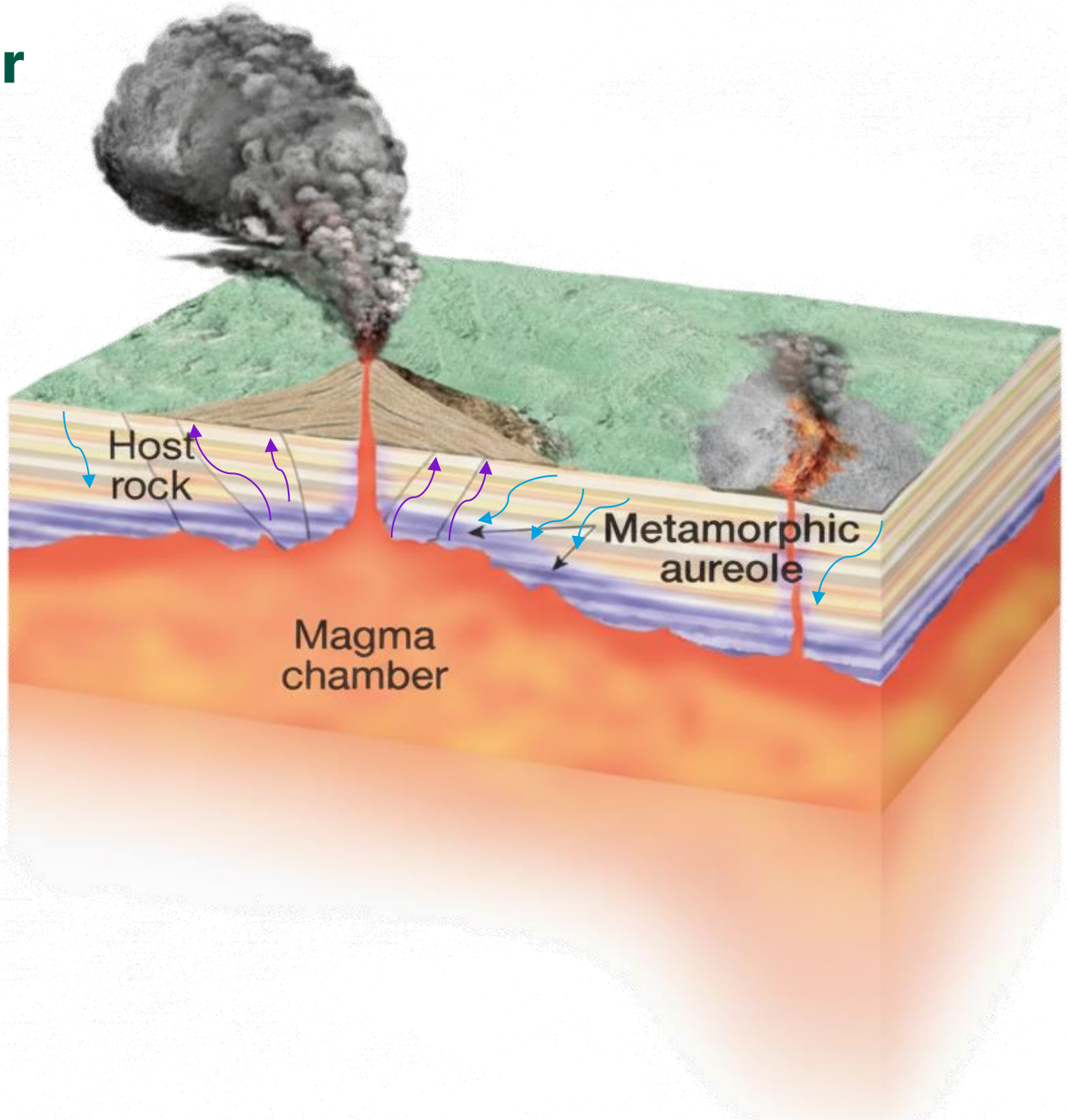

Host rock
Metamorphic aureole
Magma chamber
A. Implacement of igneous body and metamorphism
Host rock
Metamorphic aureole
Igneous pluton
B. Crystallization of pluton

Heat and water

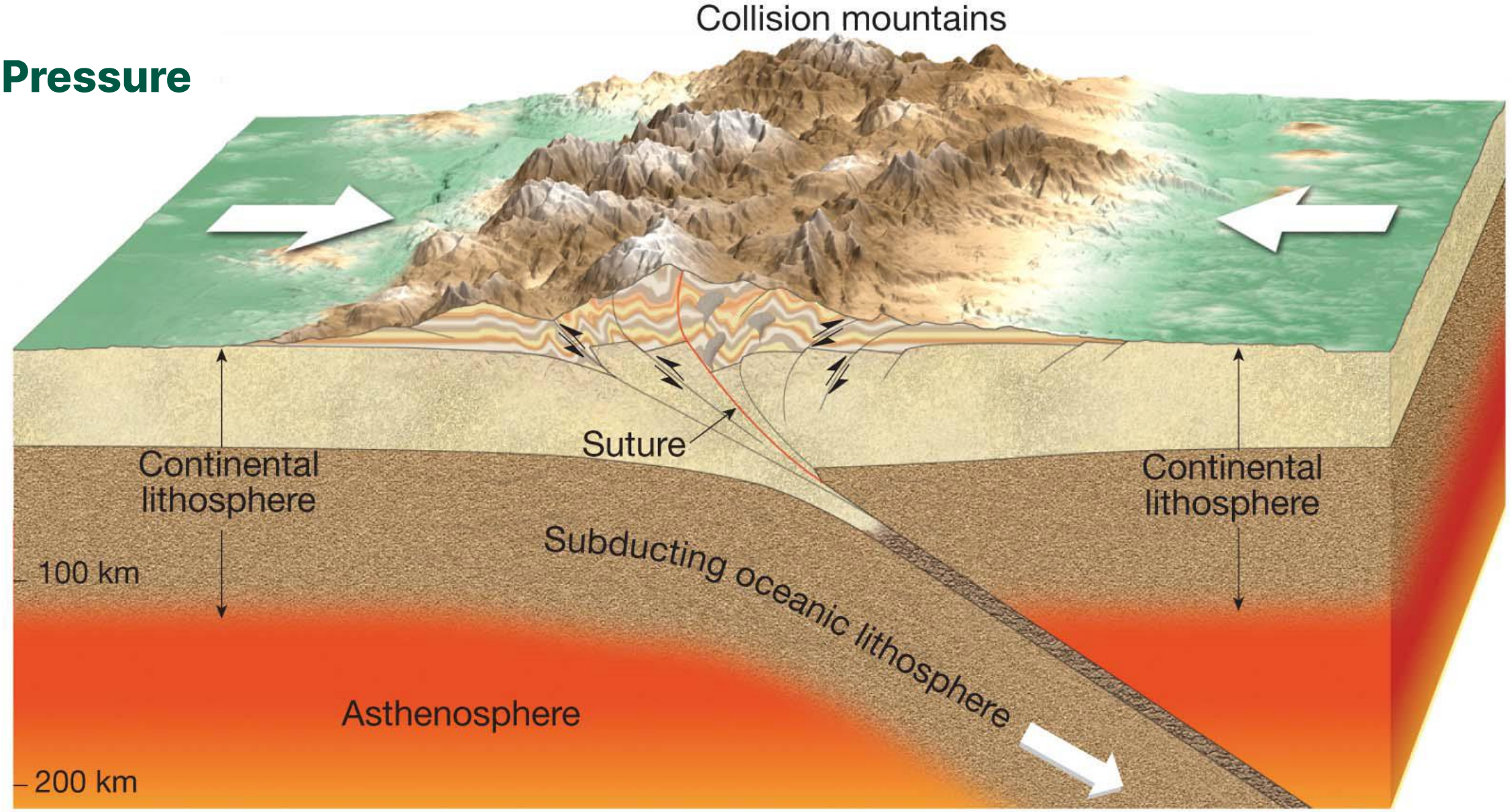
Cold water seeps down through rock...

...is heated, dissolves minerals, and rises...

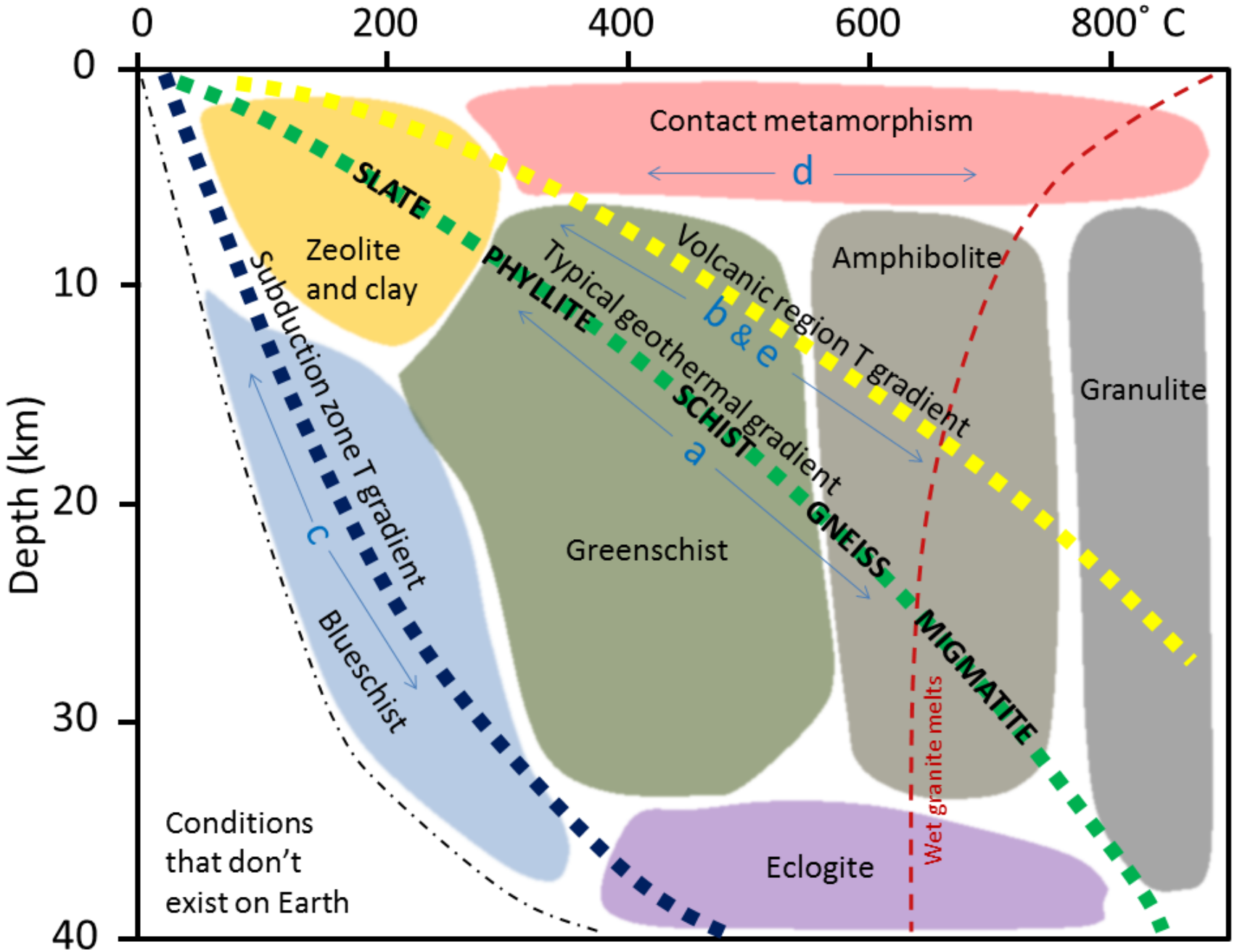
...cools and deposits minerals

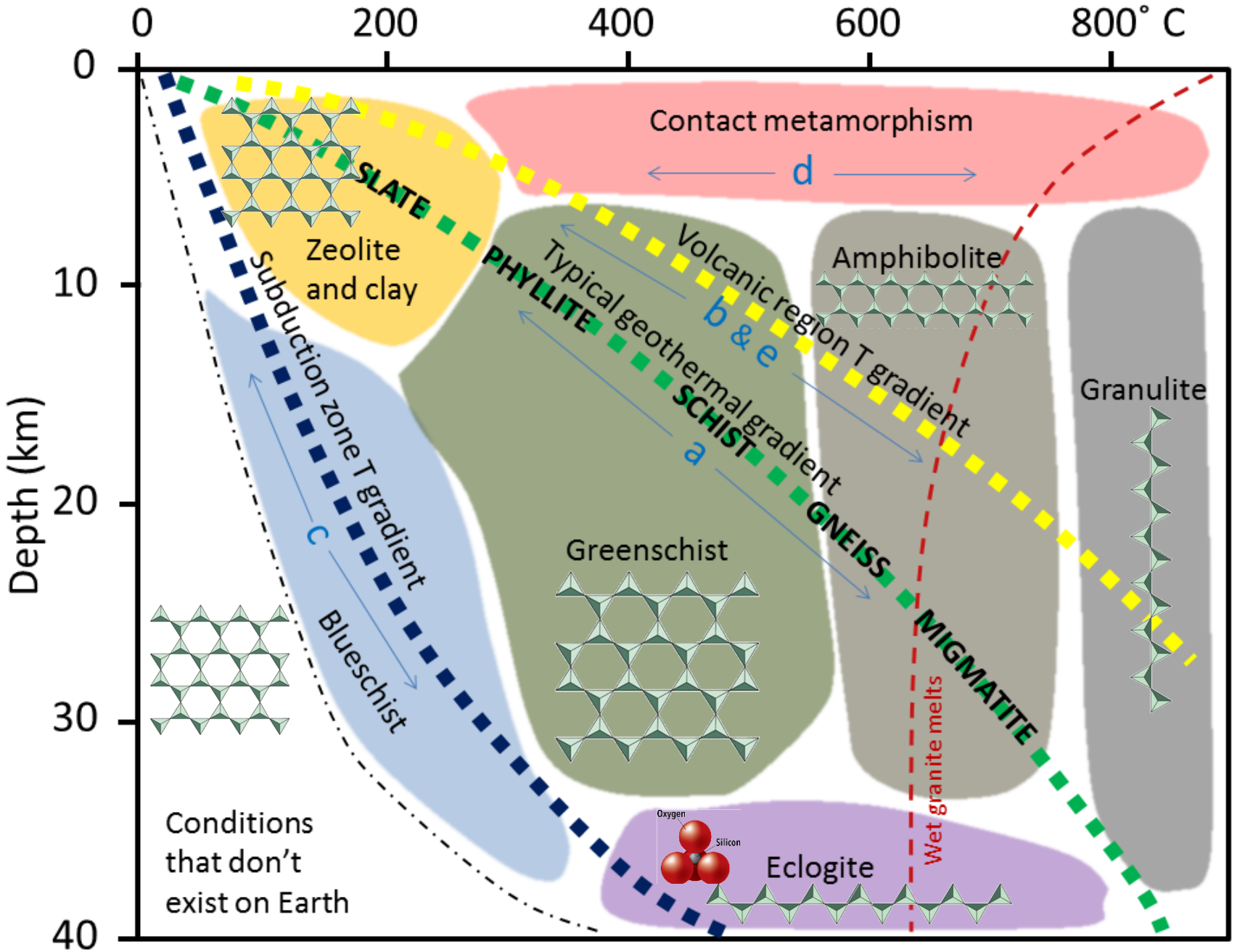


Pressure



C.


0
200
400
600
800˚ C
0
10
20
30
40
Depth (km)
Contact metamorphism
d
SLATE
Zeolite and clay
Volcanic region T gradient
Typical geothermal gradient
PHYLLITE
b & e
Amphibolite
Granulite
SCHIST
a
GNEISS
MIGMATITE
Greenschist
Subduction zone T gradient
c
Blueschist
Wet granite melts
Conditions that don't exist on Earth
Eclogite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800˚ C
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Depth (km)
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Zeolite
and clay
Volcanic region T gradient
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Typical geothermal gradient
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GNEISS
MIGMATITE
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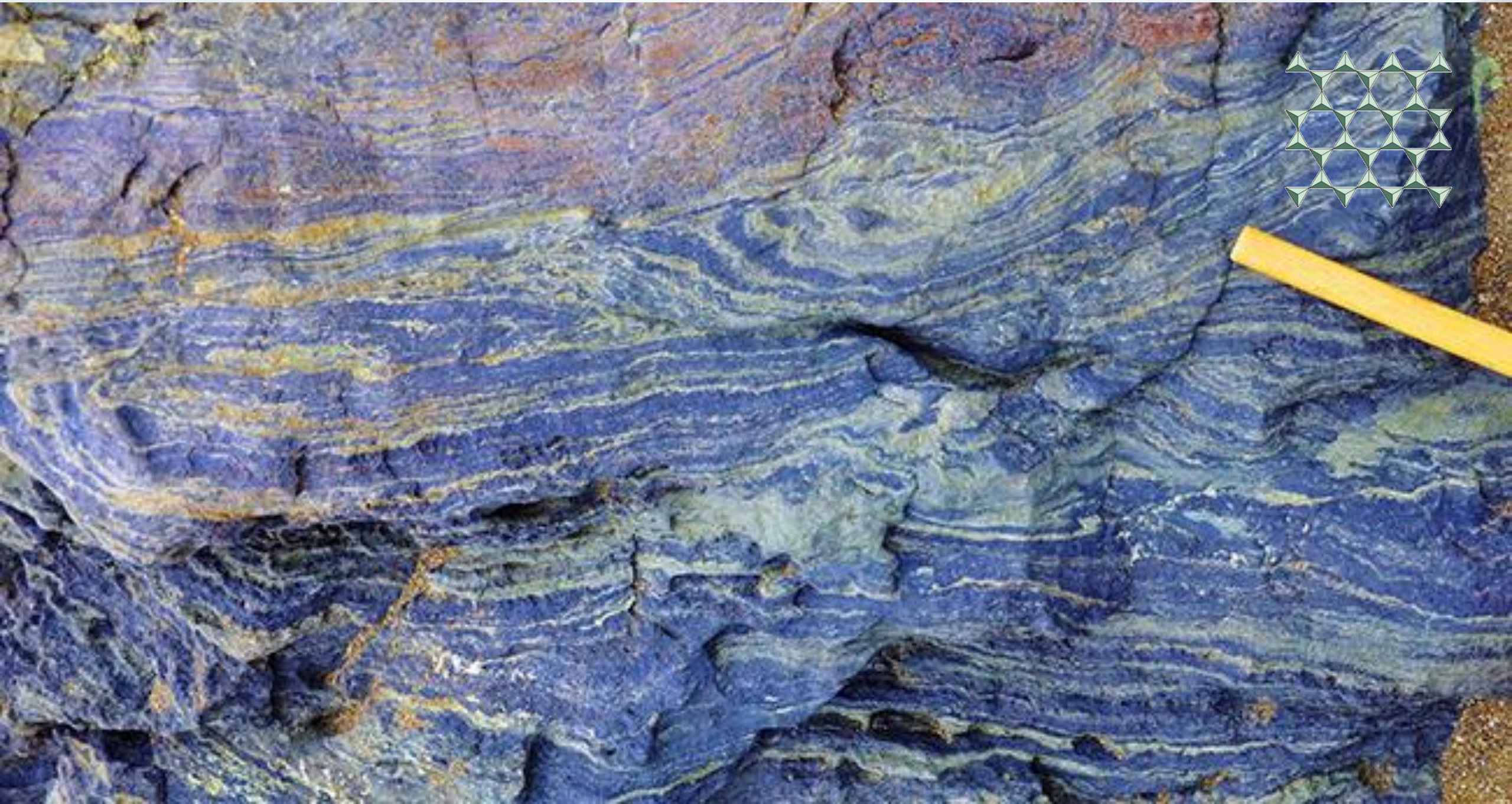
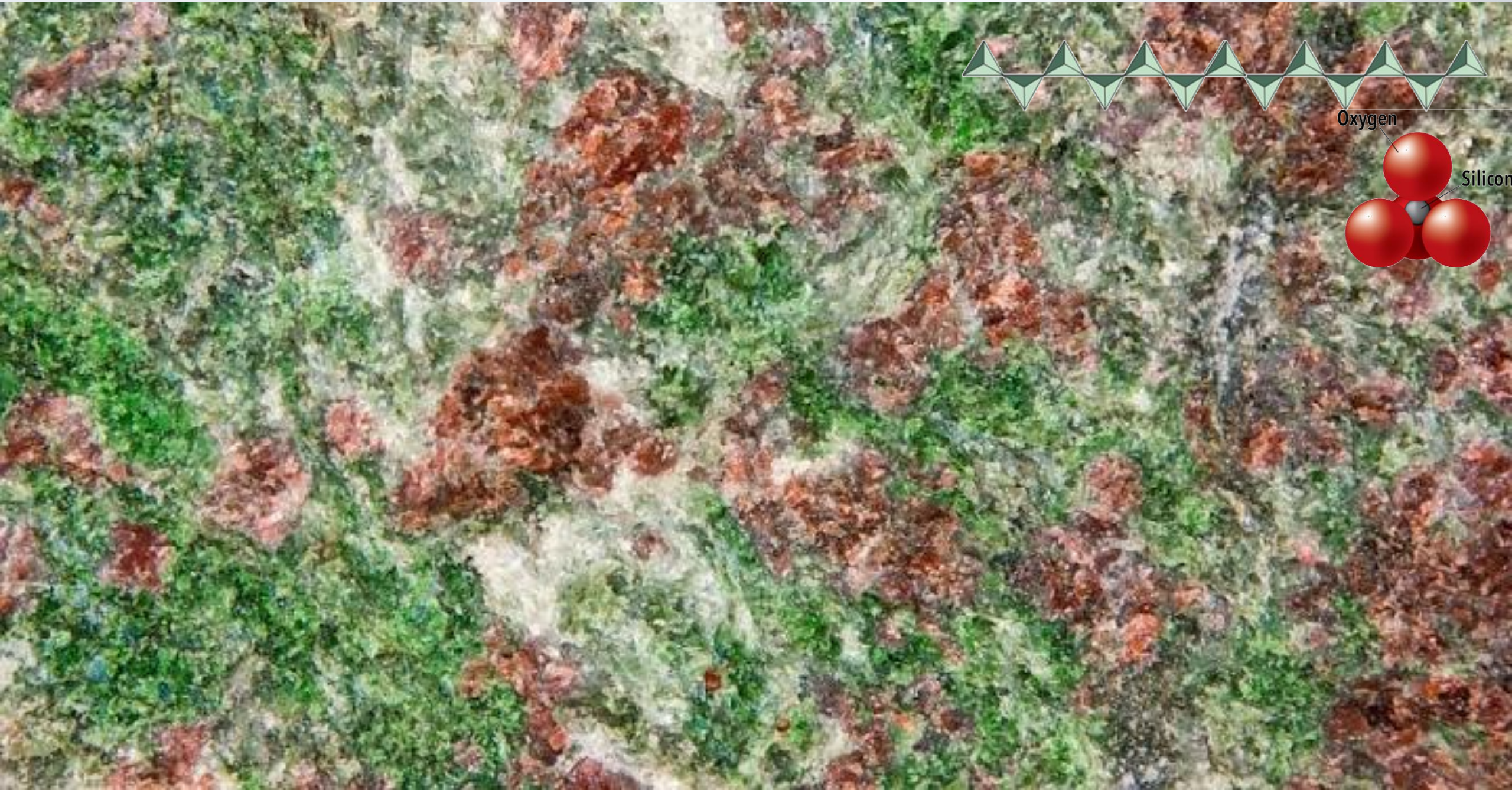
Greenschist
Subduction zone T gradient
c
Blueschist
Wet granite melts
Oxygen
Silicon
Eclogite
Conditions
that don't
exist on Earth




Oxygen
Silicon

Shale
(parent rock)

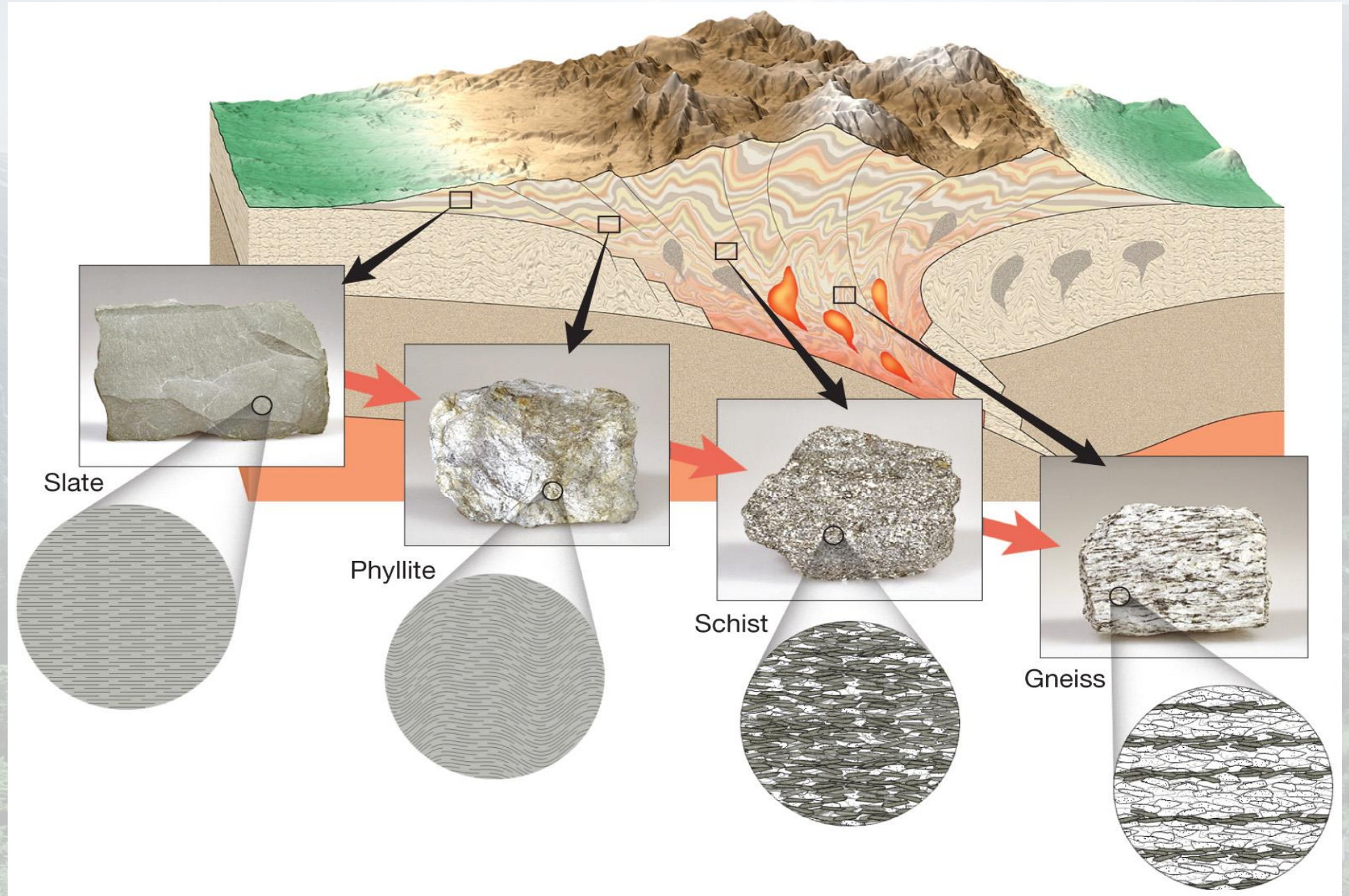
Slate

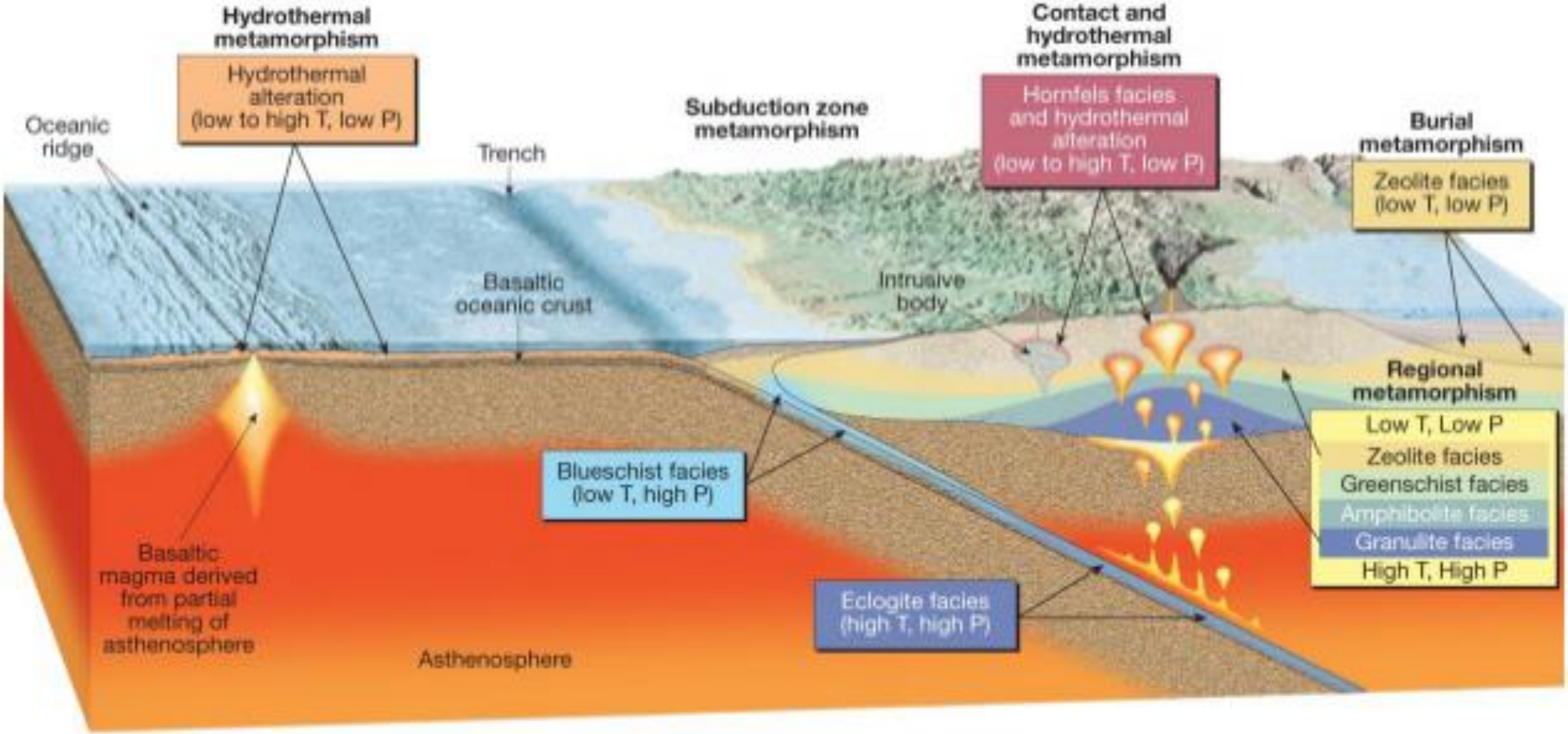
Phyllite

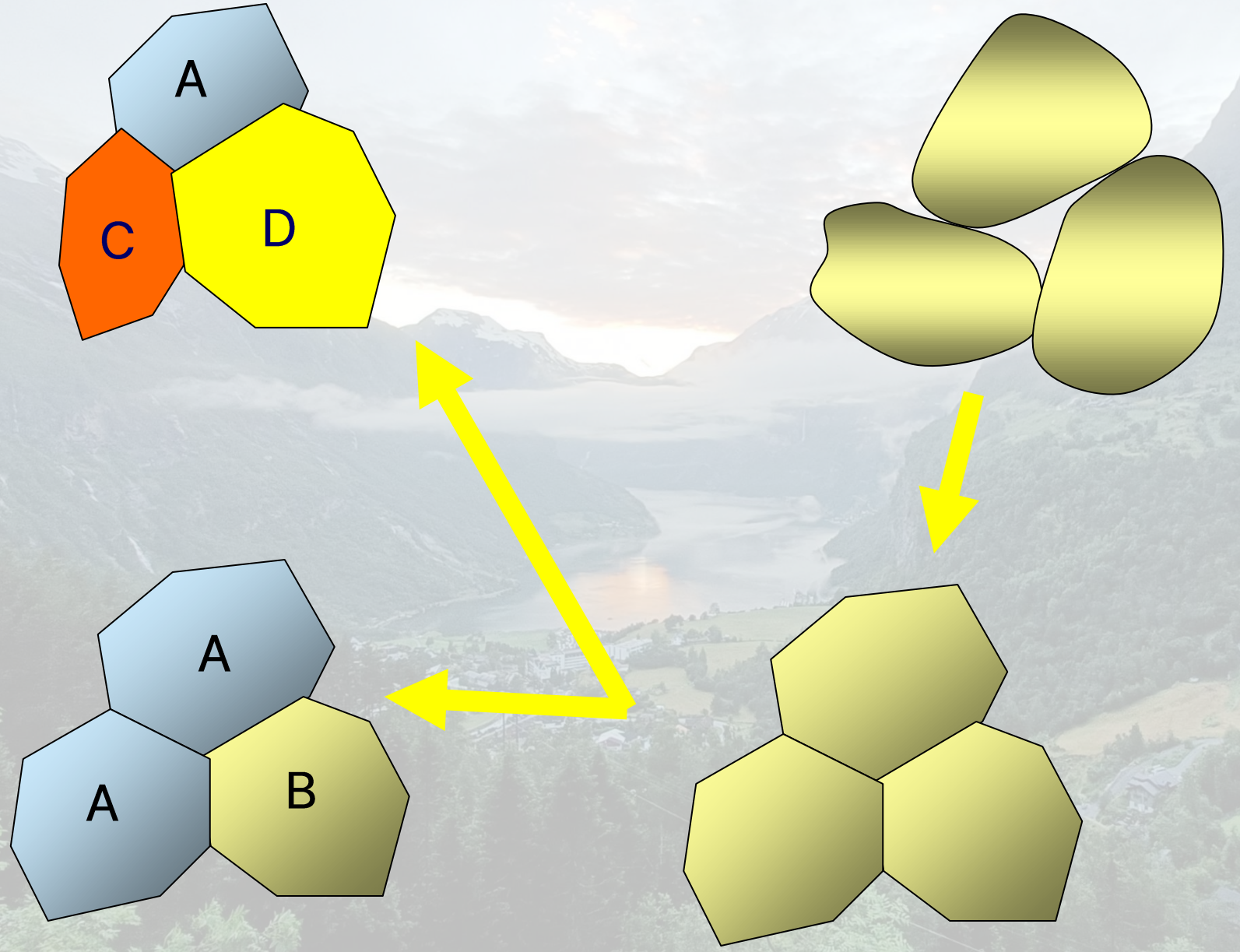
Schist

Gneiss

Migmatite






A
C
D
A
A
B

Slate Mine, Llanberis, Wales


Assynt, Scotland


Connemara, Galway

‘Lazy Beds’ – old pre-’famine’ potato farms on metamorphic rocks of Tully Mountain, Galway

(ridges in the grass)