Economic Geology: Lecture Notes

Assembled by:

Dr. AbdelMonem Soltan

Professor of Applied Mineralogy

E-mail address: abdelmonemsoltan@gmail.com

Applied Mineralogy and Building Materials Research Group

Ain Shams University

Lecture Two: Basics

Lecture Contents

I. Types of Granitoids

II. Ophiolite sequence

III. Metamorphism

I. Types of Granitoids

Mineralogically:

✓**Essential minerals** - Quartz , Feldspar
✓**Accessory minerals** – Biotite, muscovite, amphibole.
✓Other accessories are **zircon, apatite, ilmenite, magnetite, sphene, pyrite** etc.

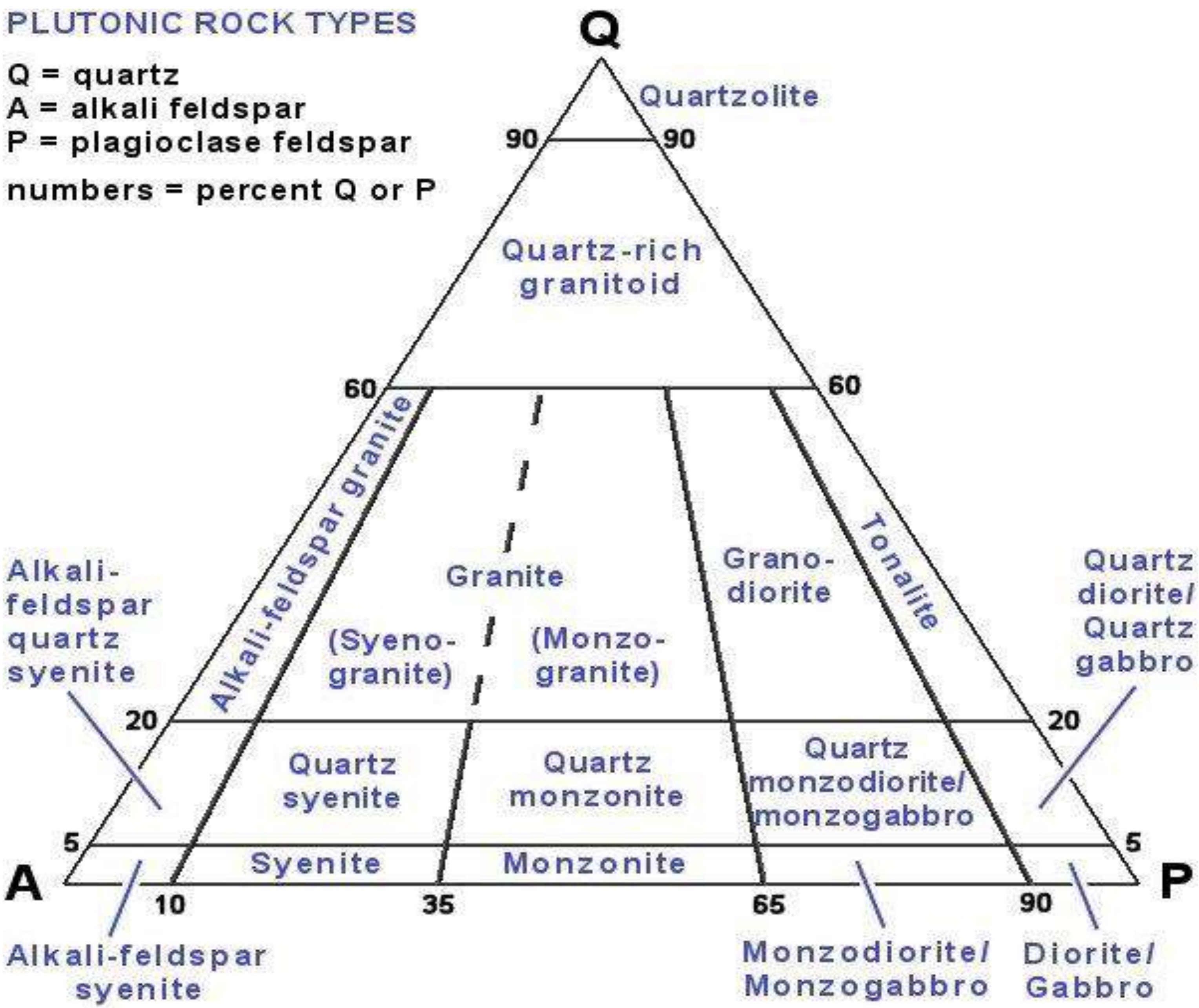
Texturally:

Medium to coarse grained crystalline rock generally exhibiting **Hypidiomorphic texture** and **Intergrowth textures** (Perthite, Antiperthite, Myrmekite, Graphic, Granophyric, Rapakivi).

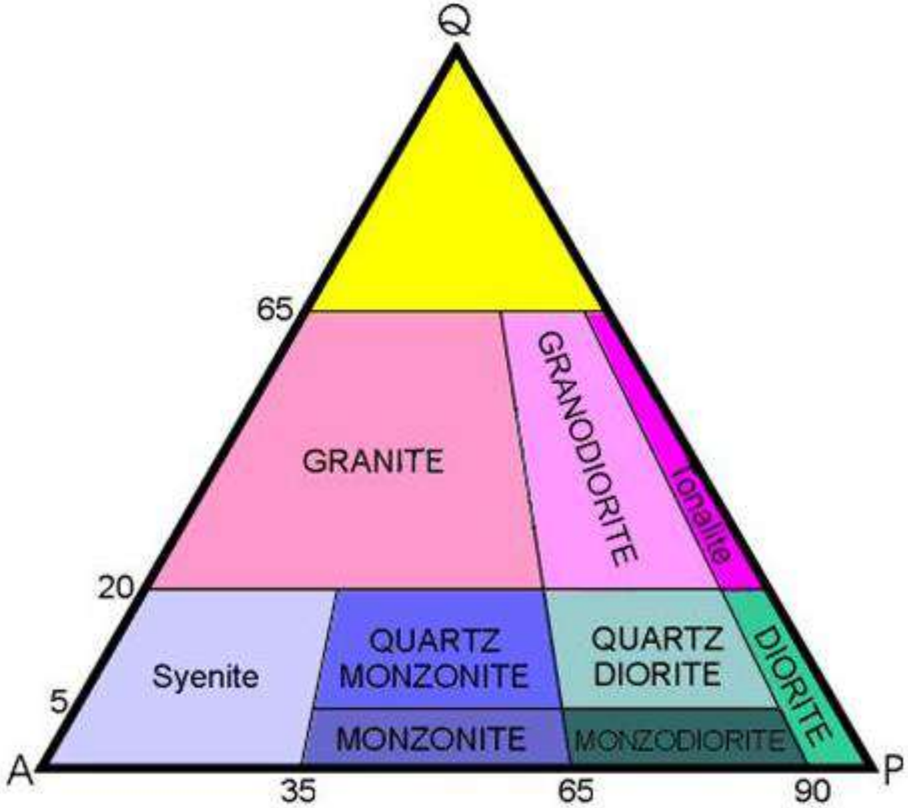
The granites could be classified based on mineralogy, geochemistry and tectonic emplacement:

✓**Mineralogical classifications** (IUGS classification)
✓**Chemical classification** (alumina saturation, S-I-A-M classification etc.)
✓**Tectonic classification** (Based on plate tectonic setting)

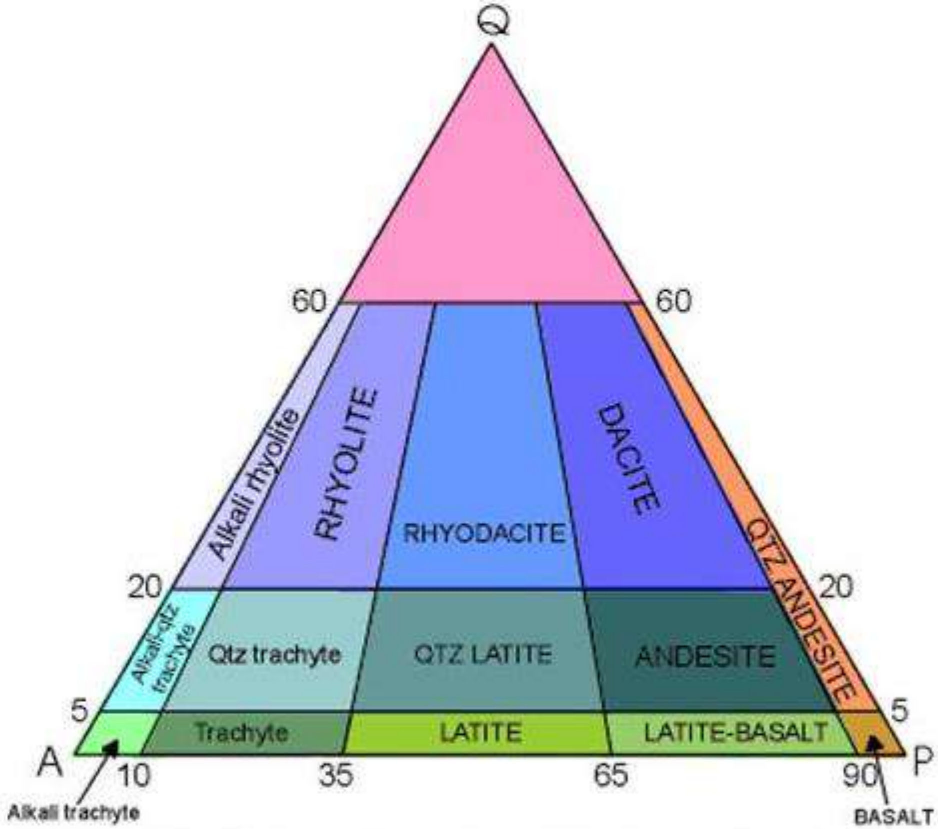
IUGS classification of Granitoids based on Mineral composition



International Union of the Geologic Sciences (modified)
Classification of igneous rocks

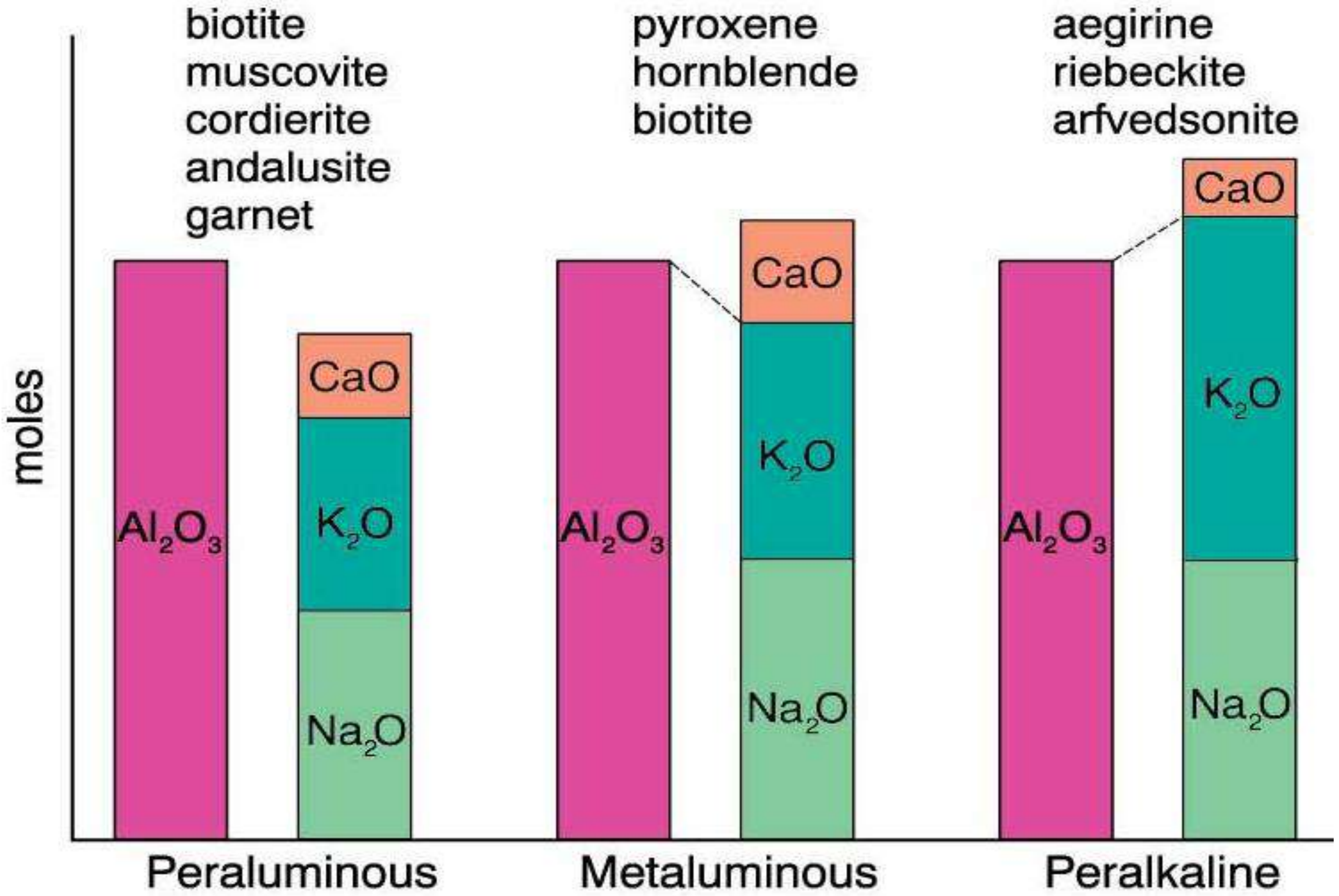


Highly Modified IUGS Classification of Phaneritic Igneous Rocks



IUGS Classification of Volcanic Rocks

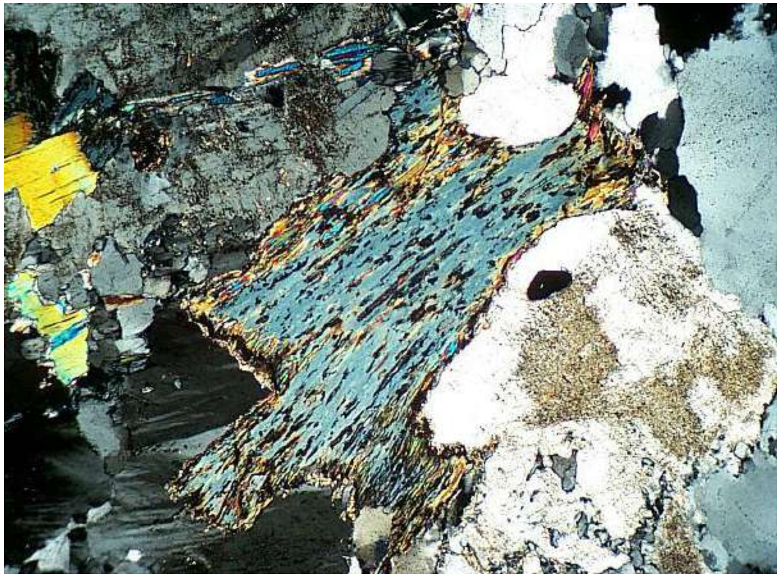
Classification of Granitoids based on Chemical composition



Alumina saturation classes based on the *molar* proportions of $Al_2O_3/(CaO+Na_2O+K_2O)$ ("A/CNK") after Shand (1927).

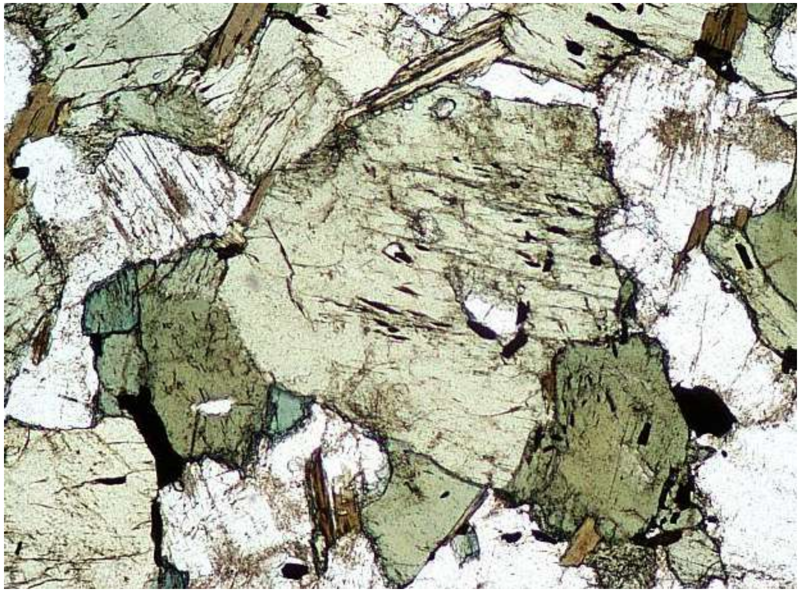
Alphabetical Classification of Granites (SIAM classification)

1. S-type Granitoid



- Derived due to partial melting of Sedimentary and meta-sedimentary rock (sedimentary protolith).
- more common in collision zones.
- Peraluminous granites [i.e., Al_2O_3 > (Na_2O + K_2O+CaO)] and have Fe_2O_3/FeO ratio < 0.3.
- characterized by muscovite, biotite and marginally higher SiO2 contents

2. I-type Granitoid



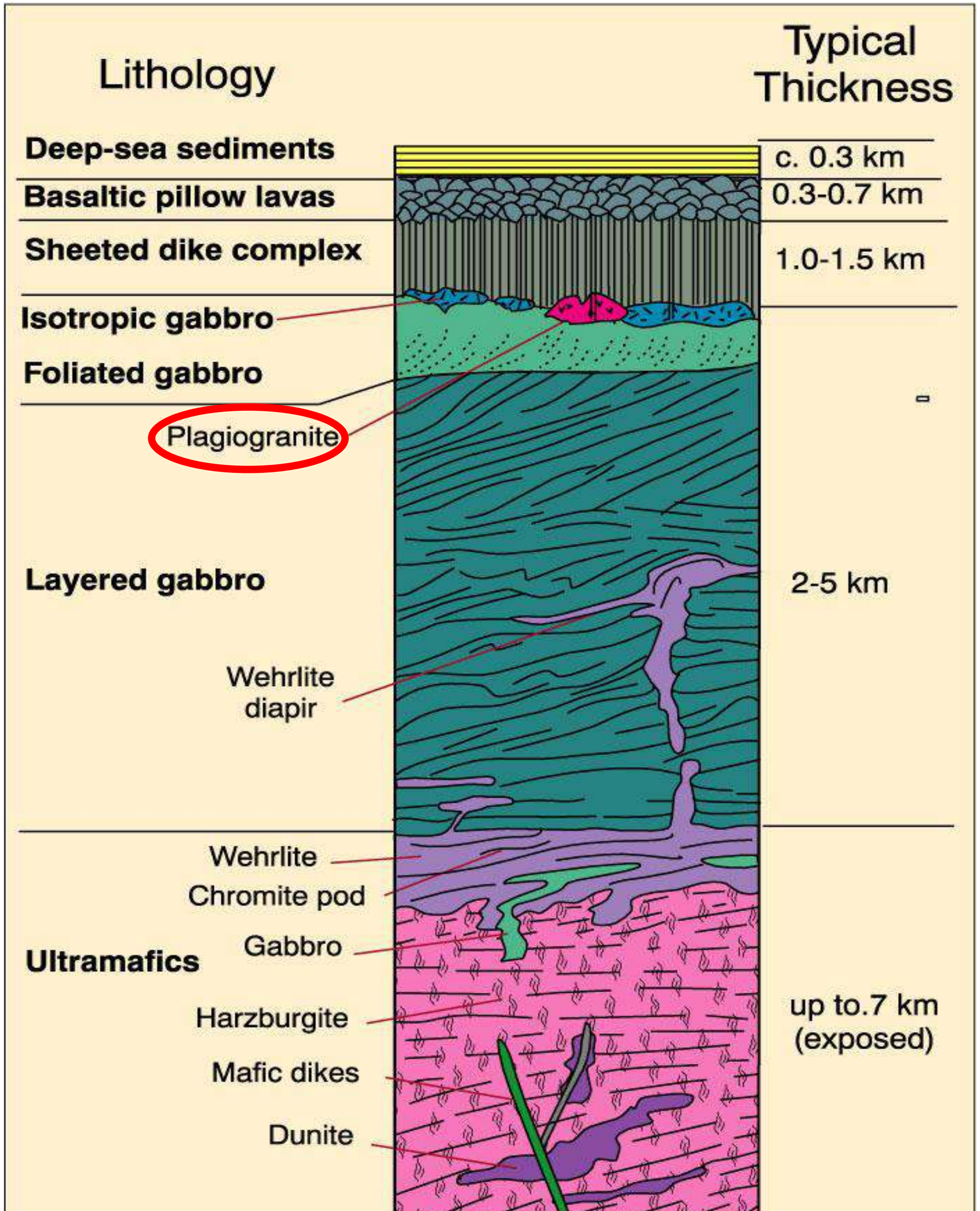
- Derived due to partial melting of Igneous protolith.
- Derived from igneous or meta-igneous rocks of lower continental crust subjected to partial melting due upwelling of mantle material to higher levels.
- Generally metaluminous granites, and have Fe_2O_3/FeO ratio > 0.3.
- characterized by presence of hornblende/alkali amphiboles ± biotite.

3. M-type Granitoid

- Derived due to fractional crystallisation of basaltic magma (direct Mantle source).
- Relatively Plagioclase rich (plagiogranite of ophiolite).
- Associated with Gabbros and Tonalites in the field.
- Formed in subduction zone.

4. A-type Granitoid (Anorogenic type)

- emplaced in either within plate anorogenic settings or in the final stages of an orogenic event.
- High SiO_2 (~73.81%)
- High F contents (6000 to 8000 ppm)
- Presence of fluorite is an important characteristic of A-type granites.



Ophiolite Sequence

SIAM Characteristics

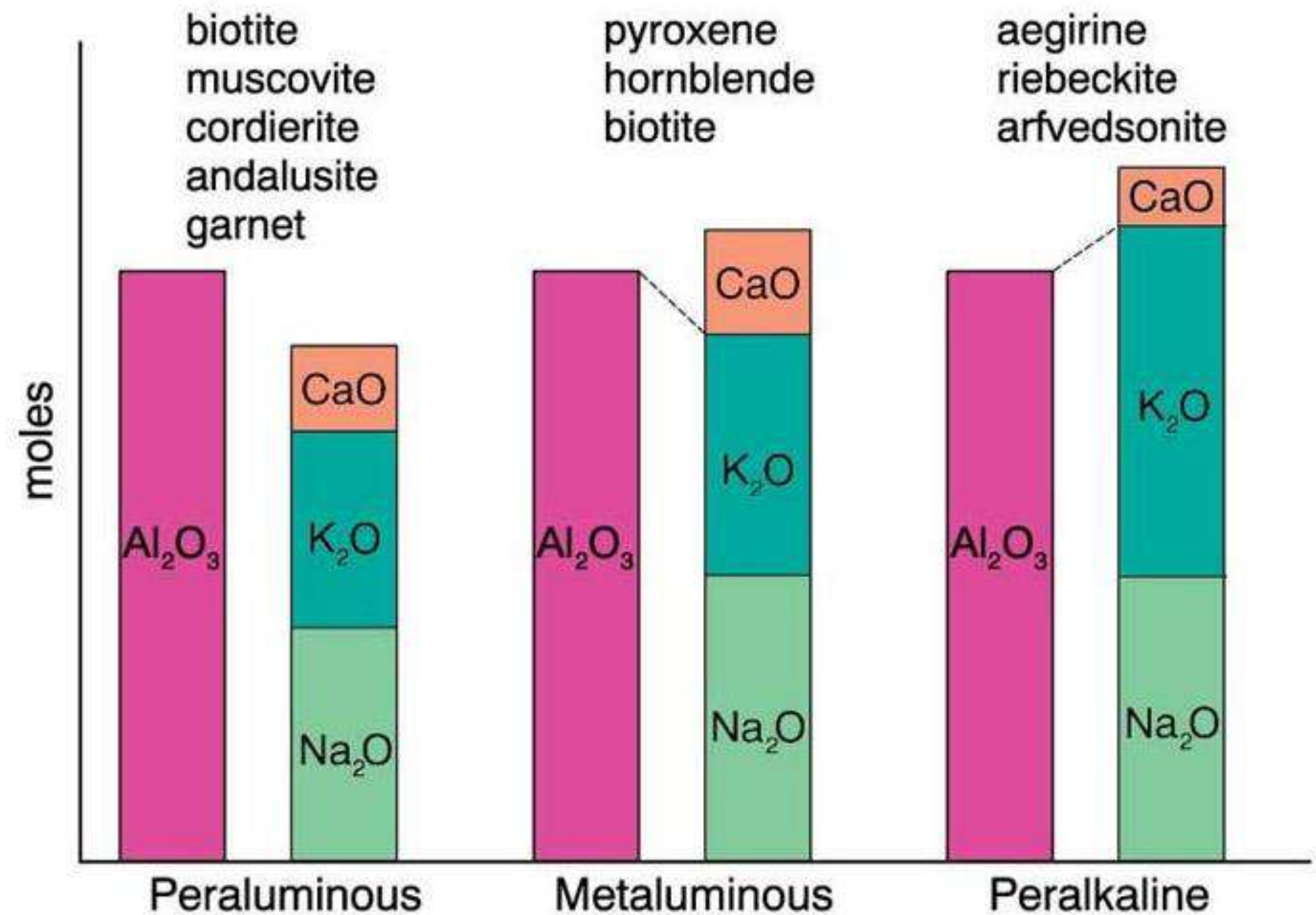
Table 18-3. The S-I-A-M Classification of Granitoids

Type	SiO_2	K_2O/Na_2O	Ca, Sr	A/(C+N+K)*	Fe^{3+}/Fe^{2+}	Cr, Ni	$\delta^{18}O$	$^{87}Sr/^{86}Sr$	Misc	Petrogenesis
M	46-70%	low	high	low	low	low	< 9‰	< 0.705	Low Rb, Th, U Low LIL and HFS	Subduction zone or ocean-intraplate Mantle-derived
I	53-76%	low	high in mafic rocks	low: metal-uminous to peraluminous	moderate	low	< 9‰	< 0.705	high LIL/HFS med. Rb, Th, U hornblende magnetite	Subduction zone Infracrustal Mafic to intermed. igneous source
S	65-74%	high	low	high metaluminous	low	high	> 9‰	> 0.707	variable LIL/HFS high Rb, Th, U biotite, cordierite Als, Grt, Ilmenite	Subduction zone Supracrustal sedimentary source
A	high $\rightarrow$ 77%	Na_2O high	low	var peralkaline	var	low	var	var	low LIL/HFS high Fe/Mg high Ga/Al High REE, Zr High F, Cl	Anorogenic Stable craton Rift zone

* *molar* $Al_2O_3/(CaO+Na_2O+K_2O)$

Data from White and Chappell (1983), Clarke (1992), Whalen (1985)

Chemical (Tectonic) Types of Granite



<u>S-type Granites</u>
high $^{87}Sr/^{86}Sr$

<u>I-type Granites</u>
low $^{87}Sr/^{86}Sr$

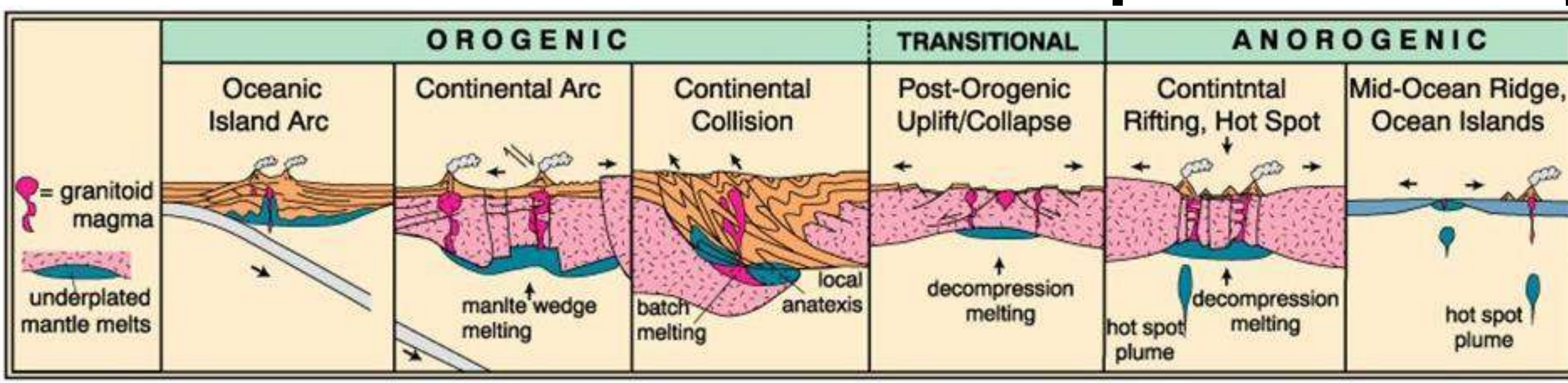
<u>A-type Granites</u>
low $^{87}Sr/^{86}Sr$

Classification based on Tectonic emplacement

Mountain building resulting from compressive stresses associated with subduction.

Magmatism takes place after the main orogenic event.

Magmatism within plate or at a spreading plate margin.

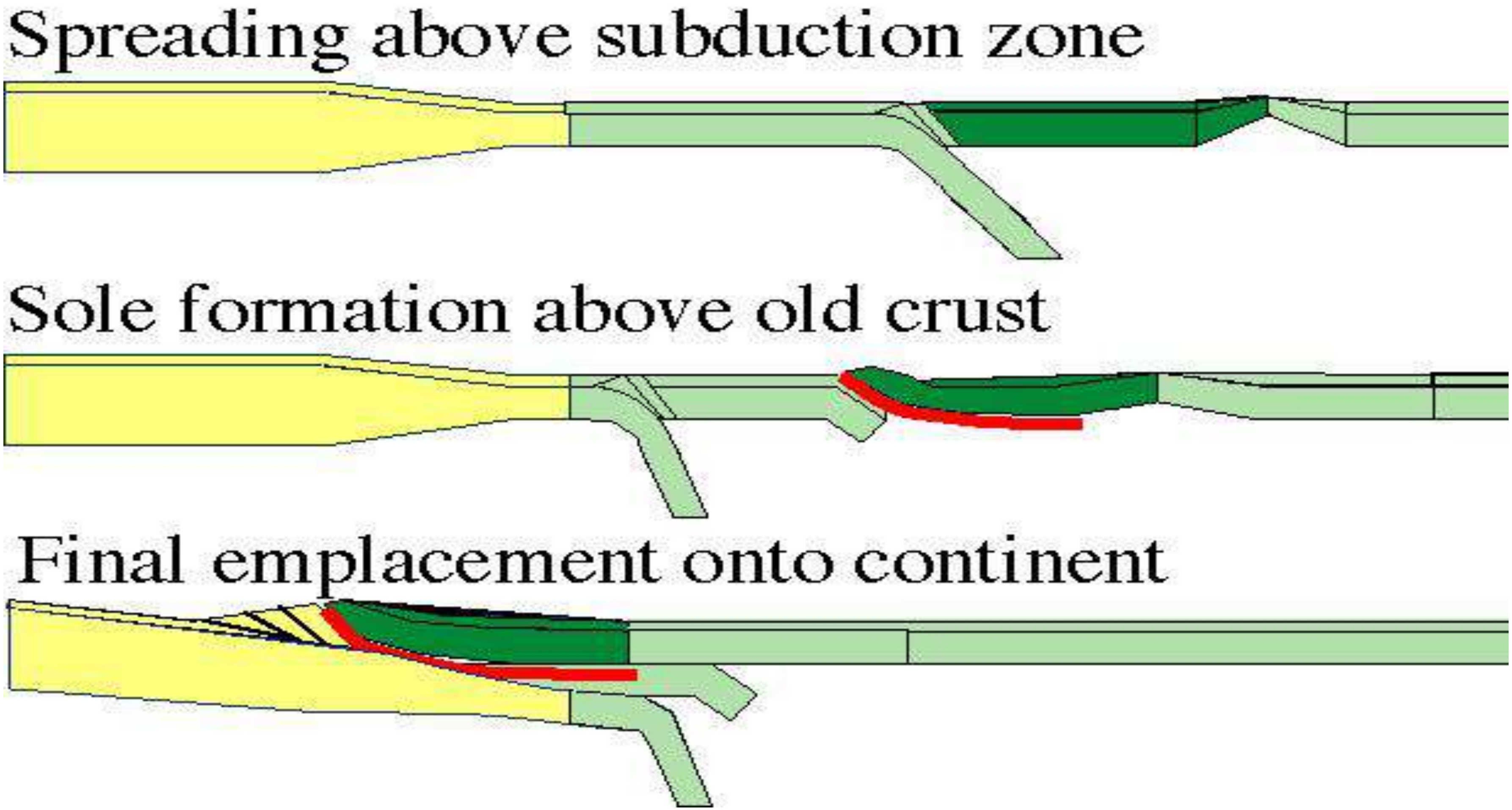


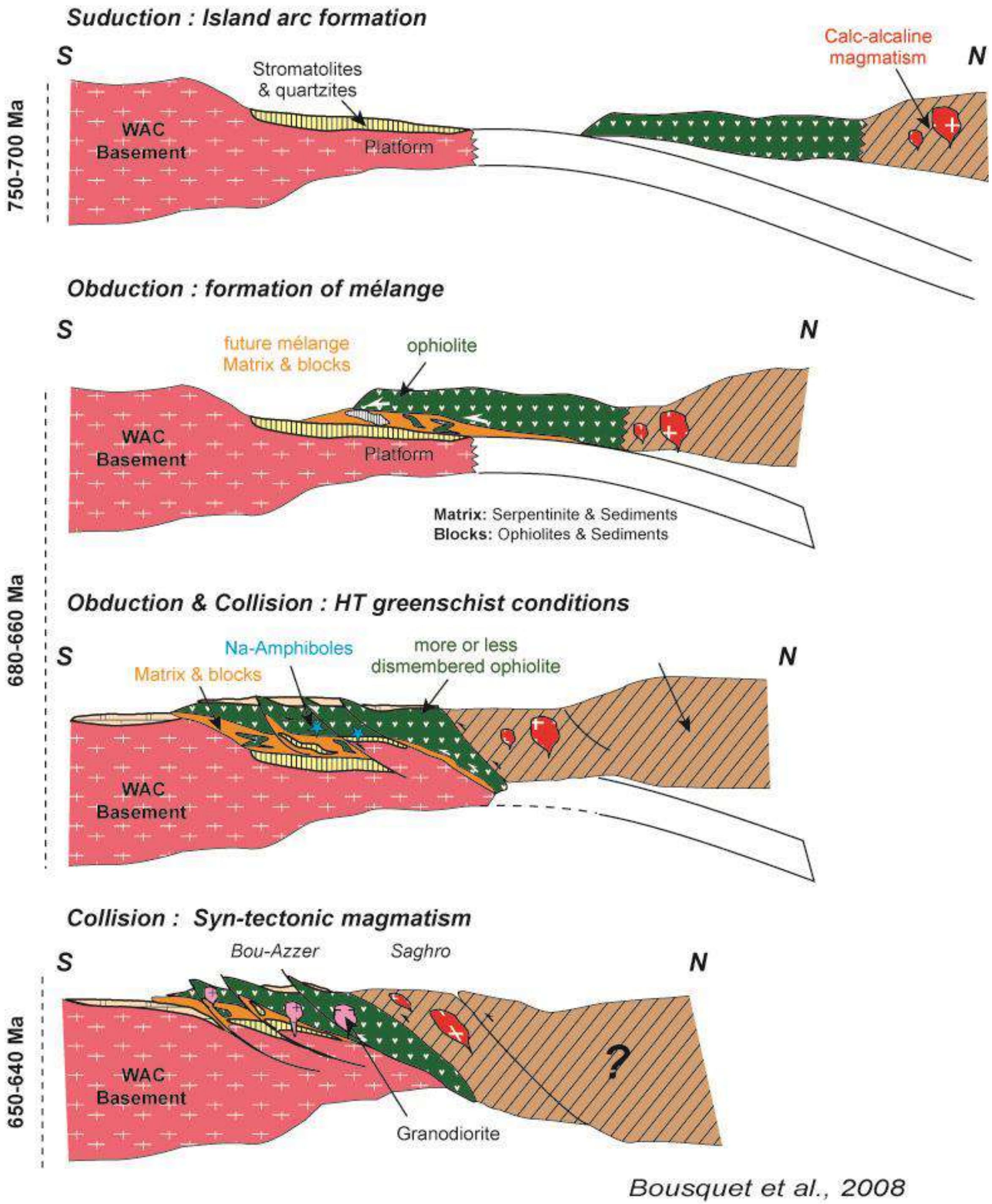
(M-Type) (S-Type) (I-Type) (A-Type)

Granitoids occur in areas where the continental crust has been thickened by orogeny, either continental arc subduction or collision. The majority of granitoids are derived by crustal anatexis, however, mantle may also be involved. The mantle contribution may range from that of a source of heat for crustal anatexis, or it may be the source of material as well.

II. Ophiolite sequence

Ophilites are fragments of oceanic crust and upper mantle that have been uplifted and emplaced on continental margins.




Suduction : Island arc formation
S
N
750-700 Ma
Stromatolites & quartzites
Calc-alcaline magmatism
WAC Basement
Platform
Obduction : formation of mélange
future mélange Matrix & blocks
ophiolite
Matrix: Serpentinite & Sediments
Blocks: Ophiolites & Sediments
680-660 Ma
Obduction & Collision : HT greenschist conditions
Na-Amphiboles
more or less dismembered ophiolite
Matrix & blocks
Collision : Syn-tectonic magmatism
650-640 Ma
Bou-Azzer
Saghro
?
Granodiorite
Bousquet et al., 2008

Ophiolites consist of five distinct layers.

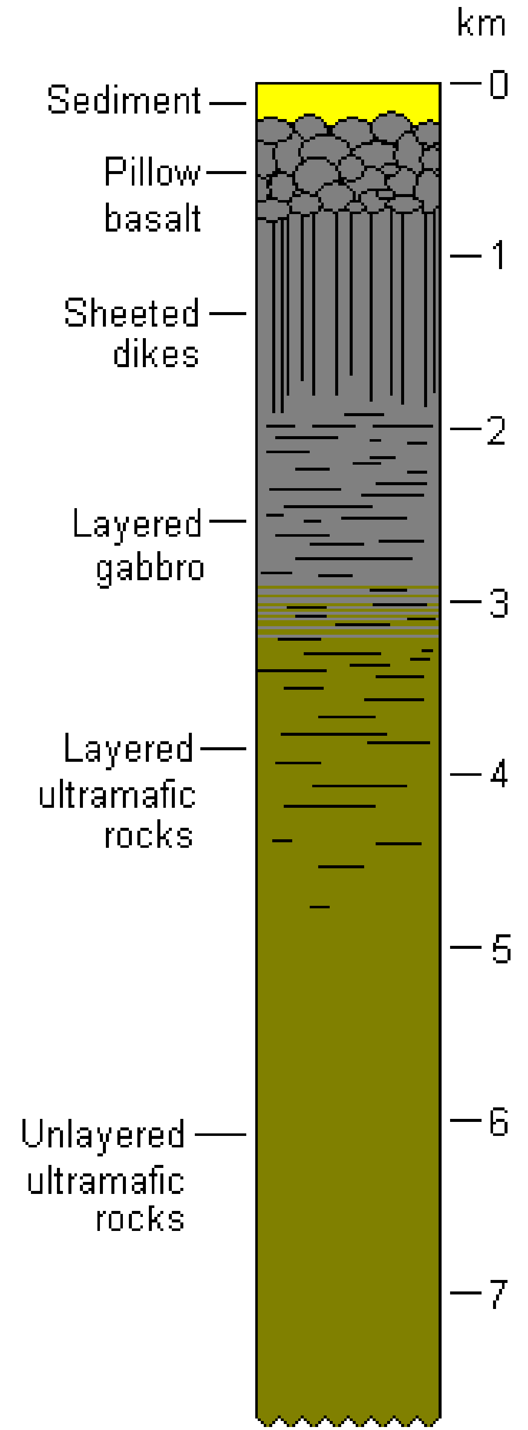
- **The first layer is the youngest and is primarily sediment that was accumulated on the seafloor.**

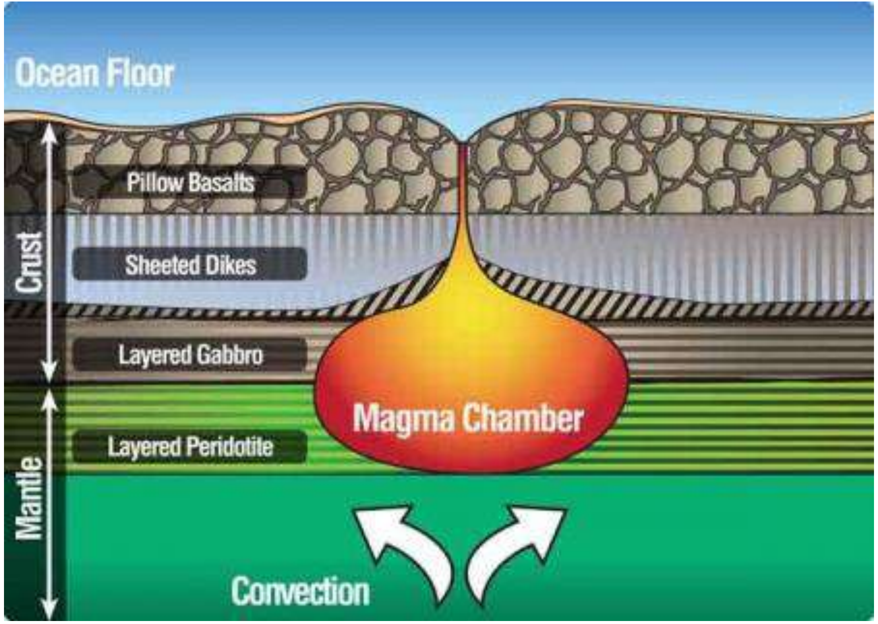
- **The second layer is pillow basalt. Pillow basalt is characterized by large pillow. When erupting lava encounters the cold sea water, the outside of the lava immediately crystallizes, forming a thick crust. The extremely hot lava still inside the blob, oozes out of the crust and instantly crystallizes again.**

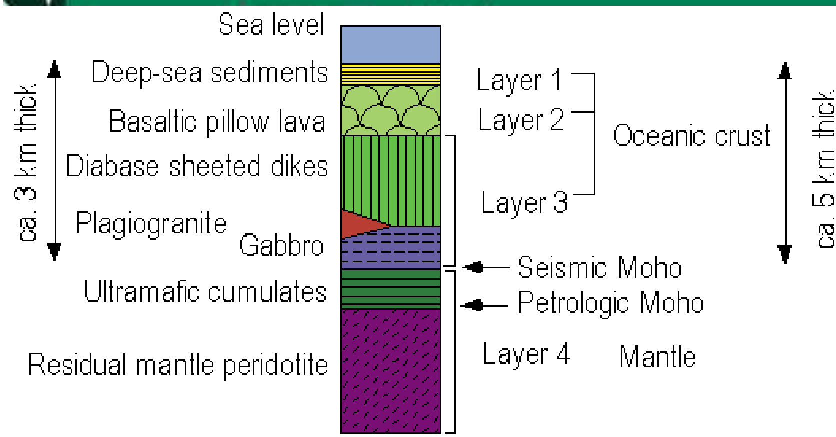
- **The third layer consists of sheeted dikes and sills. Sheeted dikes form by rising magma within the earth's crust. As the sheeted dikes cool fractures and cracks occur in the rock.**

- **The fourth layer consists of Gabbro. Isotropic (massive) gabbro, indicates fractionation of magma chamber. Layered gabbro, resulting from settling out of minerals from a magma chamber.**

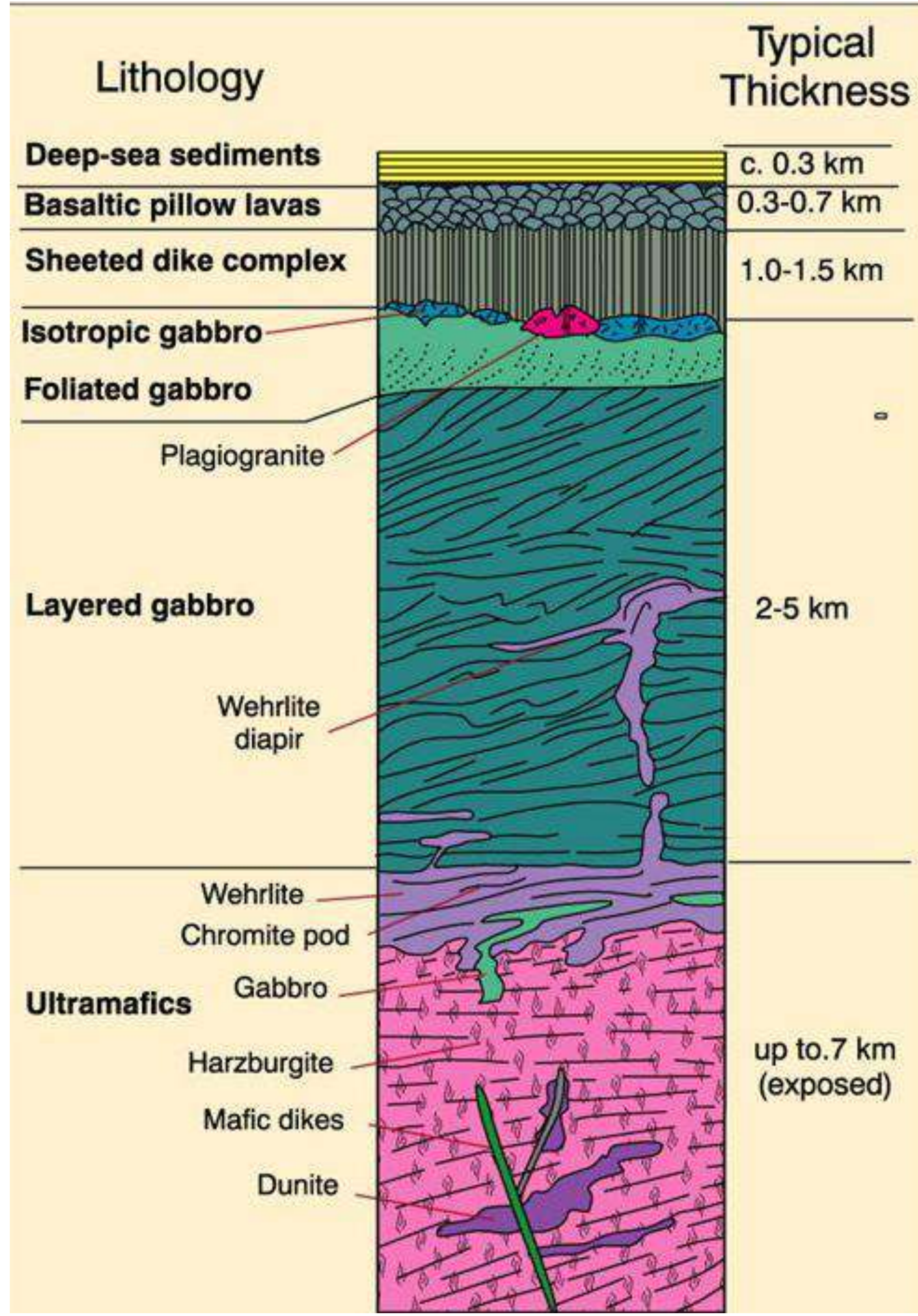
- **The bottommost layer is peridotite, which is believed to be mantle rock composition.**





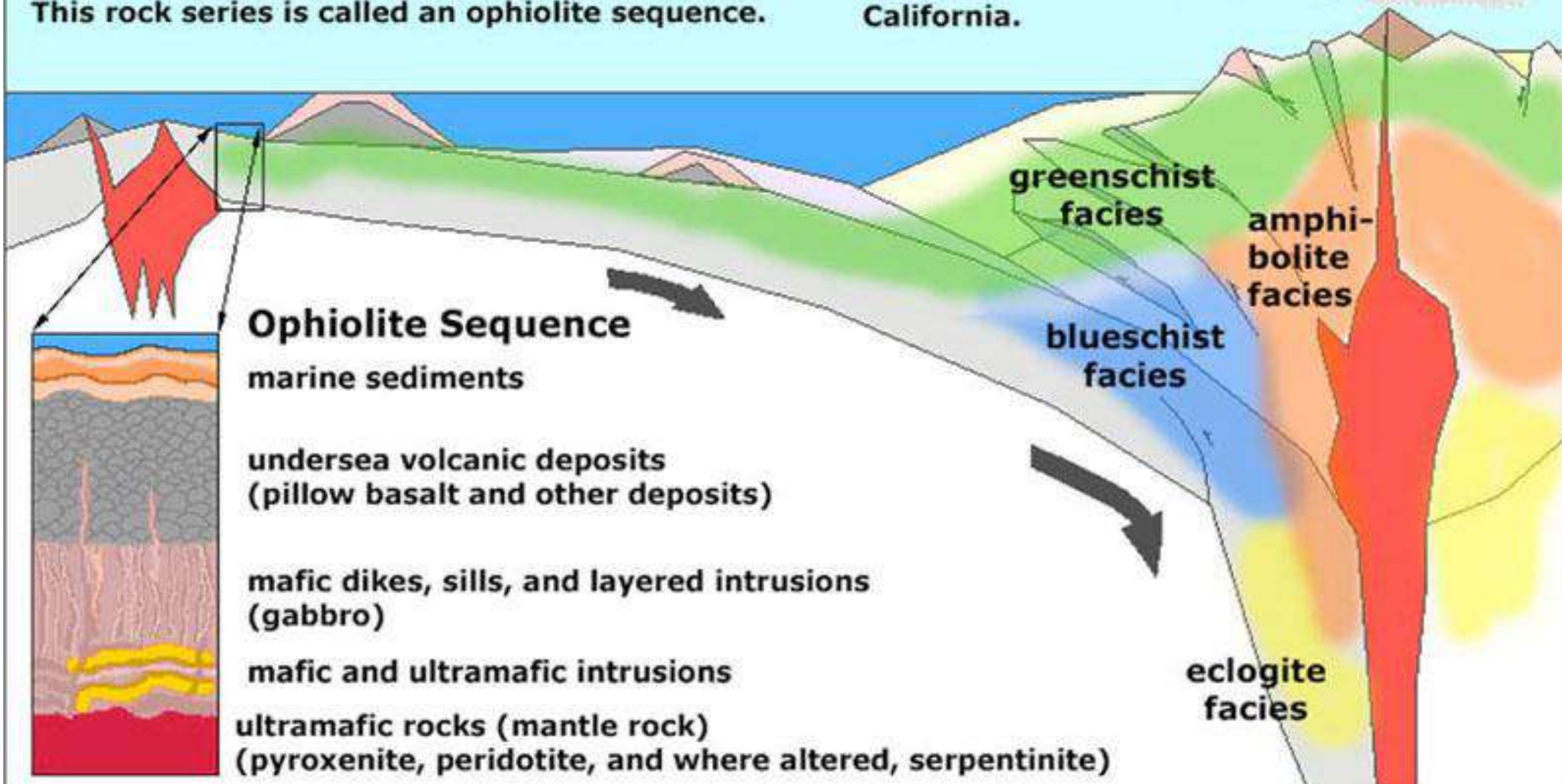


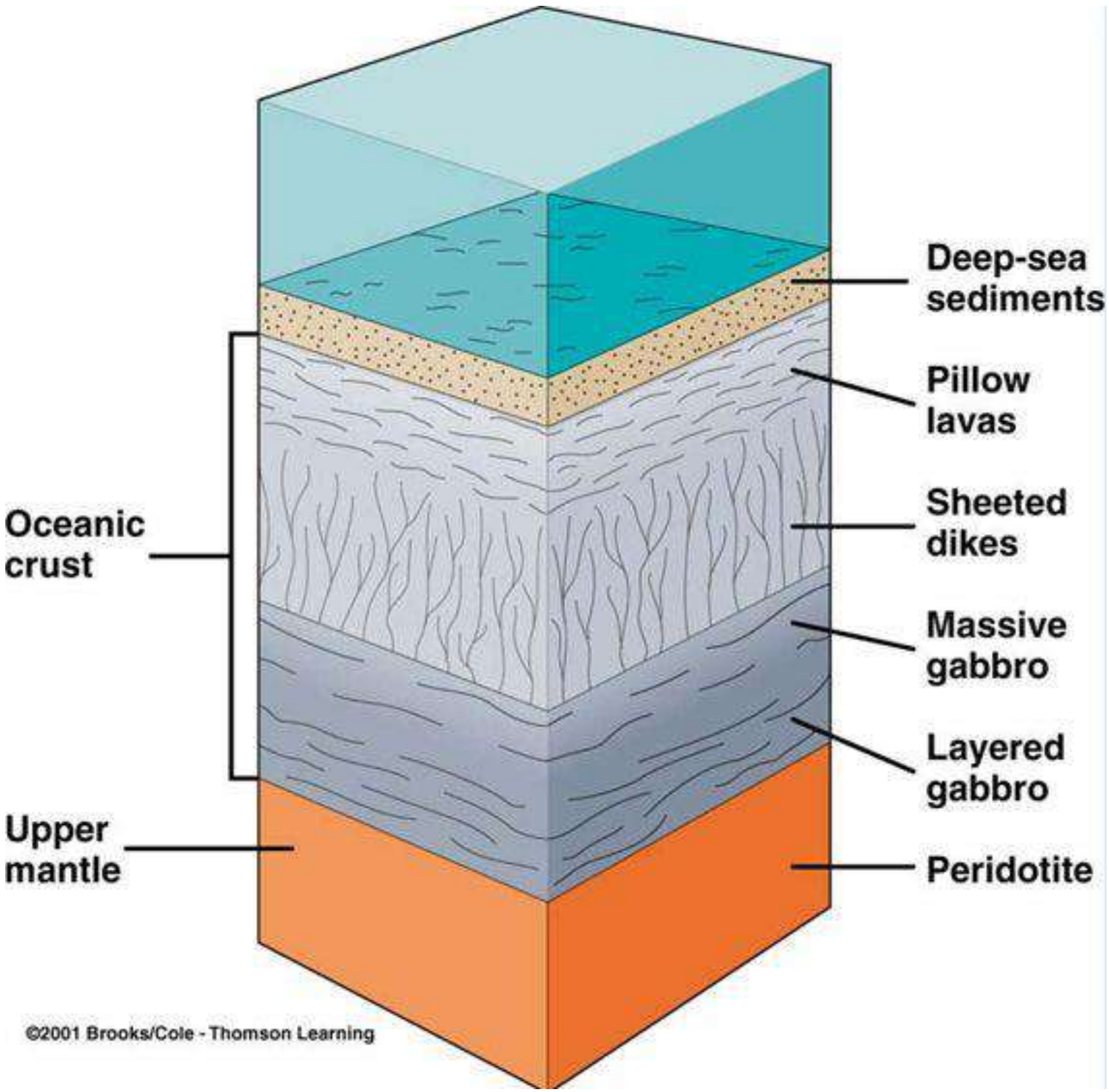
Dunite: more than 90% olivine, typically with Mg/Fe ratio of about 9:1.
Wehrlite: olivine + clinopyroxene (Augite; diopside).
Harzburgite: olivine + orthopyroxene (enstatite),
Lherzolite: olivine + enstatite + diopside

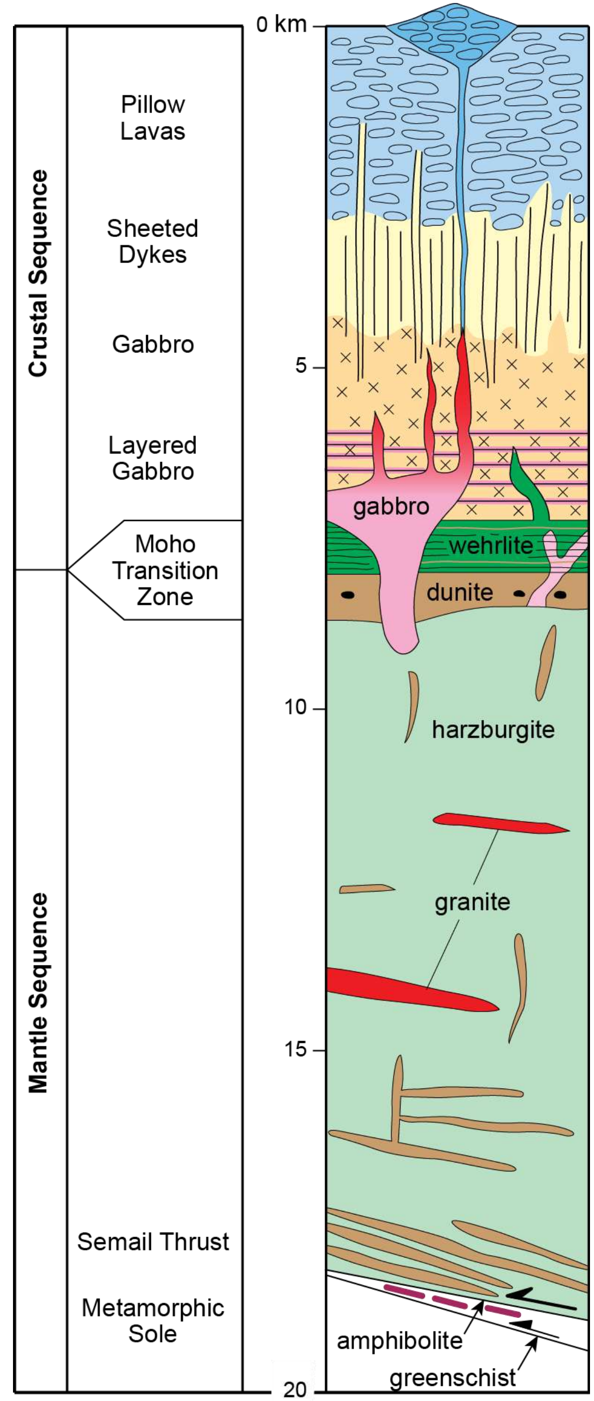


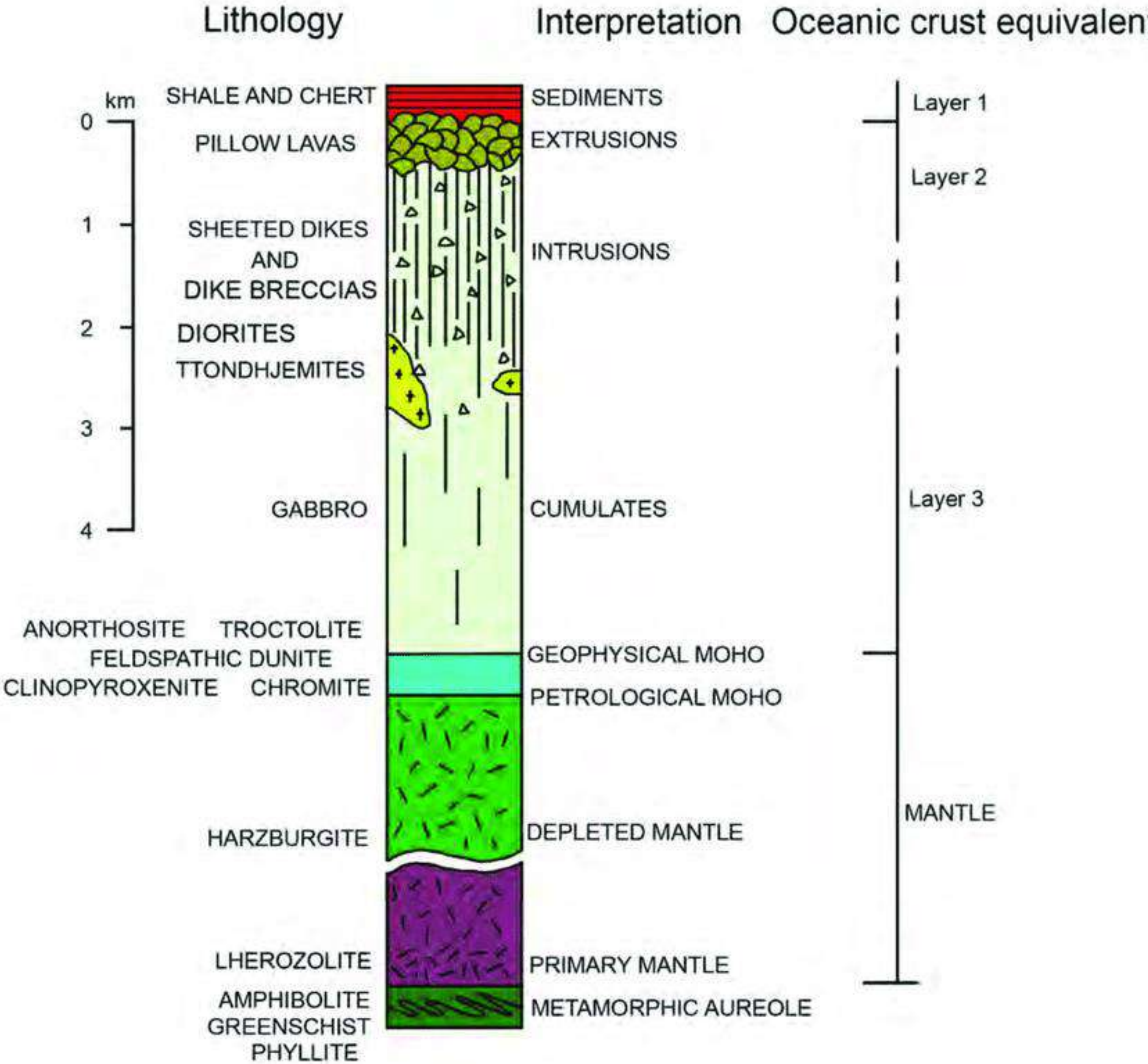
Rock in the Earth's mantle is very rich in iron and magnesium silicate minerals (ultramafic). Where hot mantle rock rises near the surface (at a spreading center) it undergoes partial melting, forming mafic rocks like gabbro and basalt. The crust under the ocean typically preserves an ordered arrangement ranging from mantle rock (at depth), intrusions, volcanic flows, and marine sediments on top. This rock series is called an ophiolite sequence.

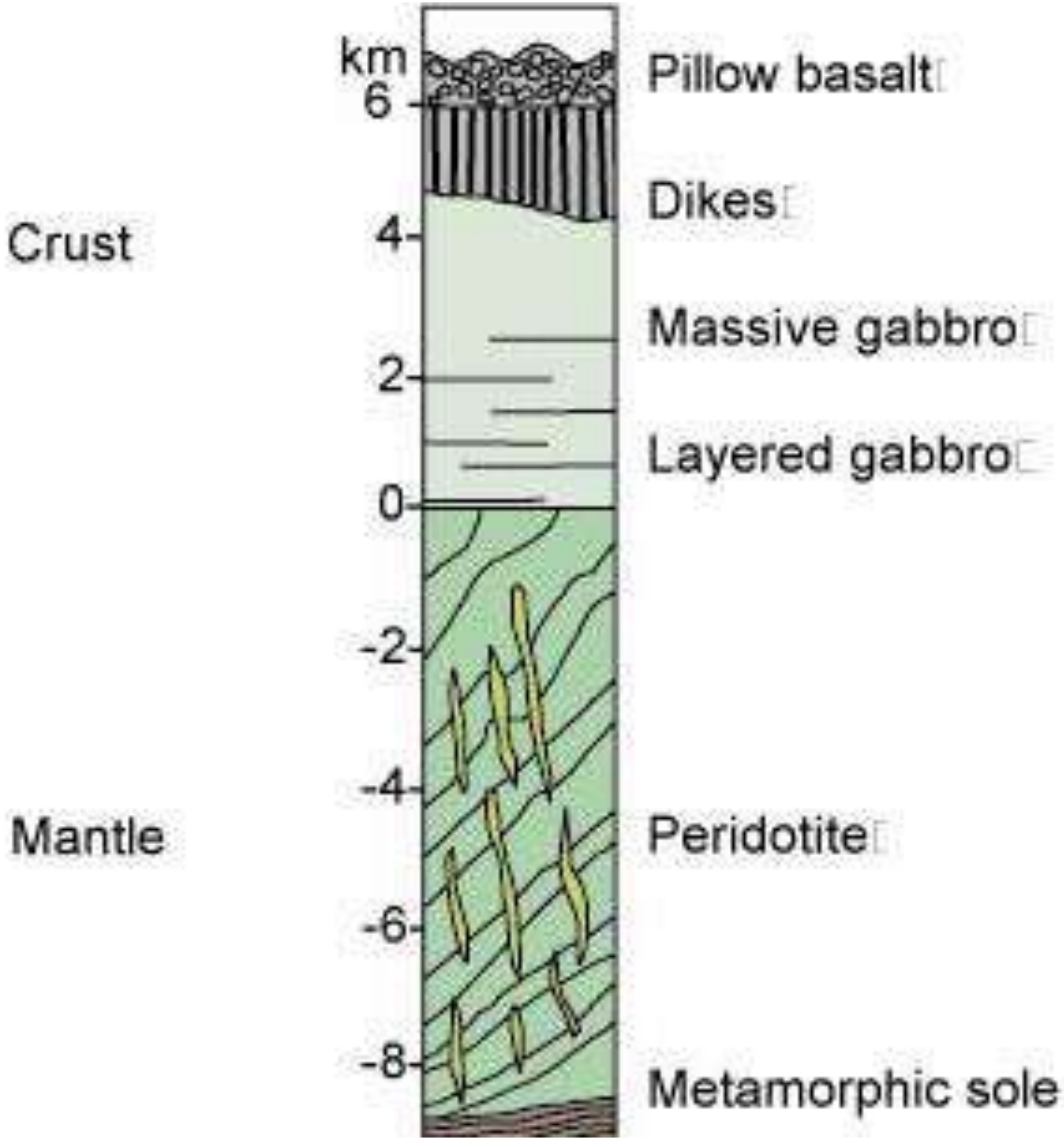
As oceanic crust is subducted and accreted onto the continental margin, its mafic and ultramafic rocks may experience a variety of physical and chemical changes. In many cases, the rock passes through multiple metamorphic conditions before being reexposed at the surface. This explains why so many mafic and ultramafic rocks occur in the coastal ranges of California.




Deep-sea sediments
Pillow lavas
Sheeted dikes
Massive gabbro
Layered gabbro
Peridotite
Oceanic crust
Upper mantle
©2001 Brooks/Cole - Thomson Learning

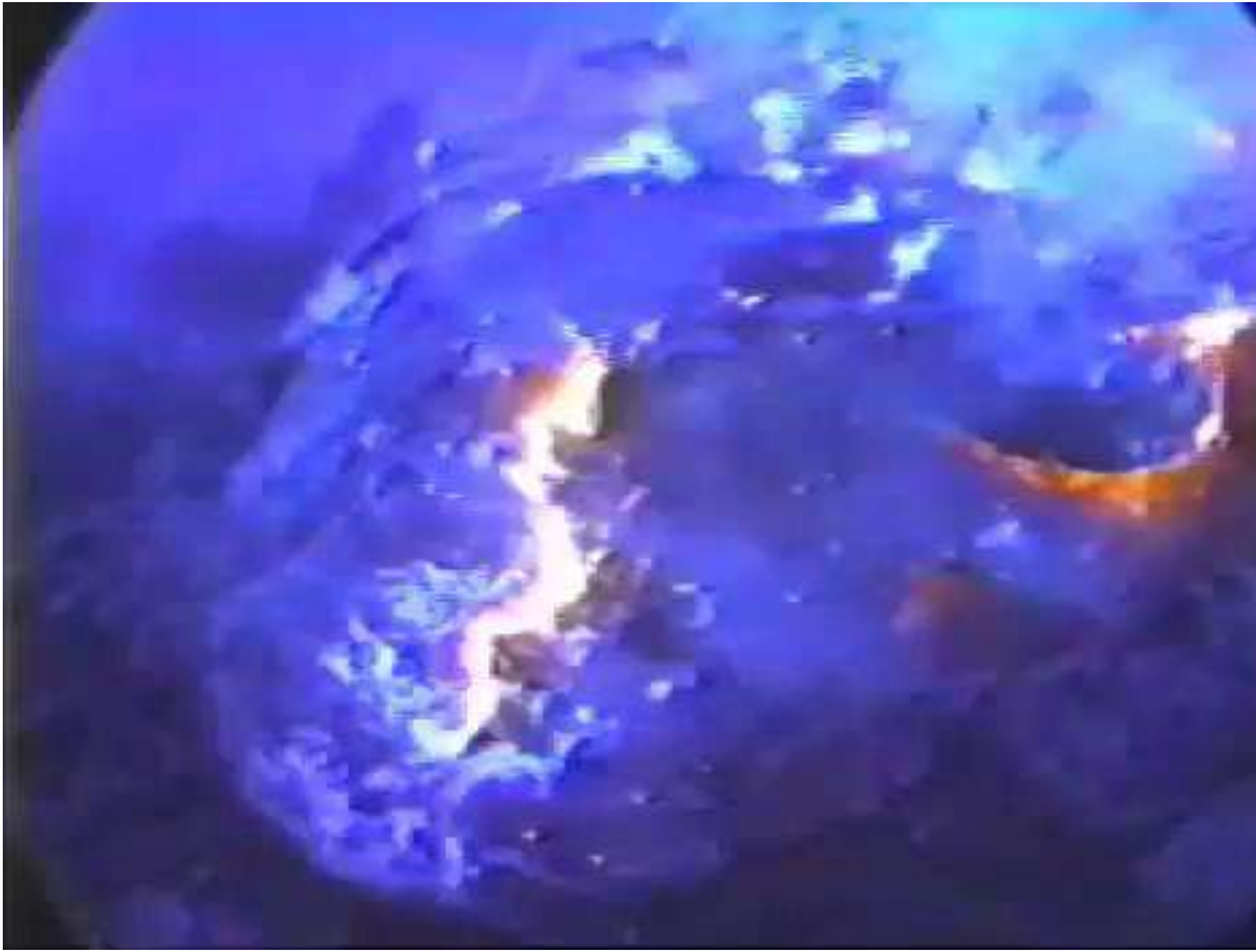

Crustal Sequence
Mantle Sequence
Pillow Lavas
Sheeted Dykes
Gabbro
Layered Gabbro
Moho Transition Zone
Semail Thrust
Metamorphic Sole
0 km
5
10
15
20
gabbro
wehrlite
dunite
harzburgite
granite
amphibolite
greenschist


Lithology
Interpretation
Oceanic crust equivalent
km
0
1
2
3
4
SHALE AND CHERT
PILLOW LAVAS
SHEETED DIKES
AND
DIKE BRECCIAS
DIORITES
TTONDHJEMITES
GABBRO
ANORTHOSITE TROCTOLITE
FELDSPATHIC DUNITE
CLINOPYROXENITE CHROMITE
HARZBURGITE
LHEROZOLITE
AMPHIBOLITE
GREENSCHIST
PHYLLITE
SEDIMENTS
EXTRUSIONS
INTRUSIONS
CUMULATES
GEOPHYSICAL MOHO
PETROLOGICAL MOHO
DEPLETED MANTLE
PRIMARY MANTLE
METAMORPHIC AUREOLE
Layer 1
Layer 2
Layer 3
MANTLE



Crust
Mantle
km
6
4
2
0
-2
-4
-6
-8
Pillow basalt
Dikes
Massive gabbro
Layered gabbro
Peridotite
Metamorphic sole

Lithology	Ocean Crustal Layers	Typical Ophiolite	Normal Ocean Crust	
		Thickness (km)		P wave vel. (km/s)
			ave.	
Deep-Sea Sediment	1	~ 0.3	0.5	1.7 -2.0
Basaltic Pillow Lavas	2A & 2B	0.5	0.5	2.0 - 5.6
Sheeted dike complex	2C	1.0 - 1.5	1.5	6.7
Gabbro	3A	2 - 5	4.7	7.1
Layered Gabbro	3B			
Layered peridotite	4	up to 7		8.1
Unlayered tectonite peridotite				

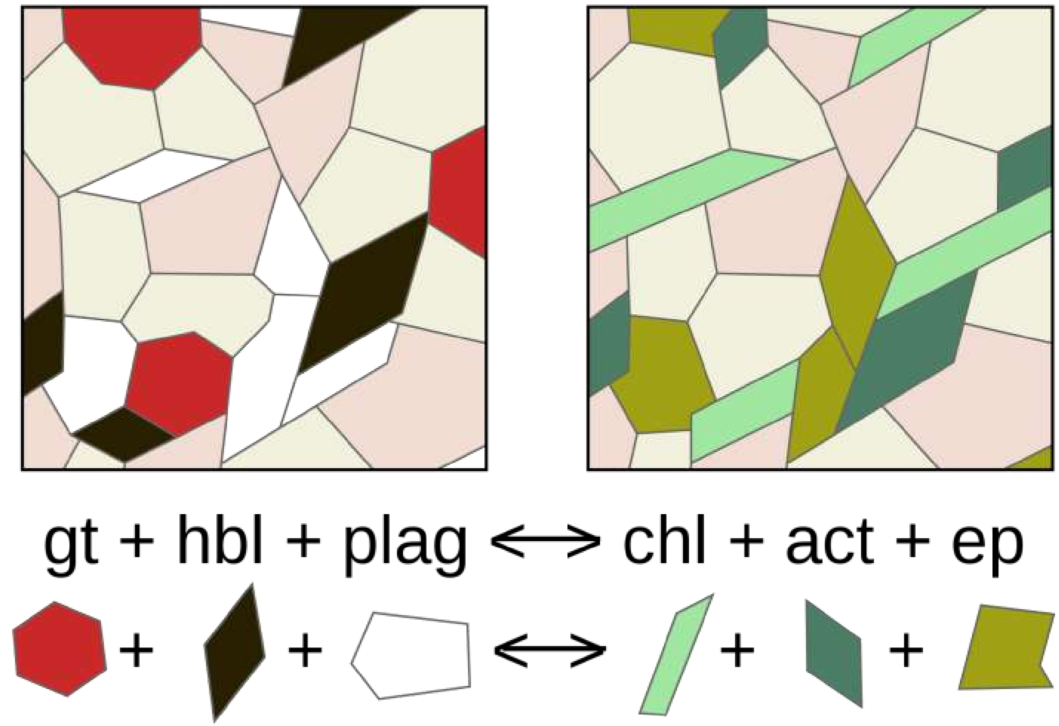


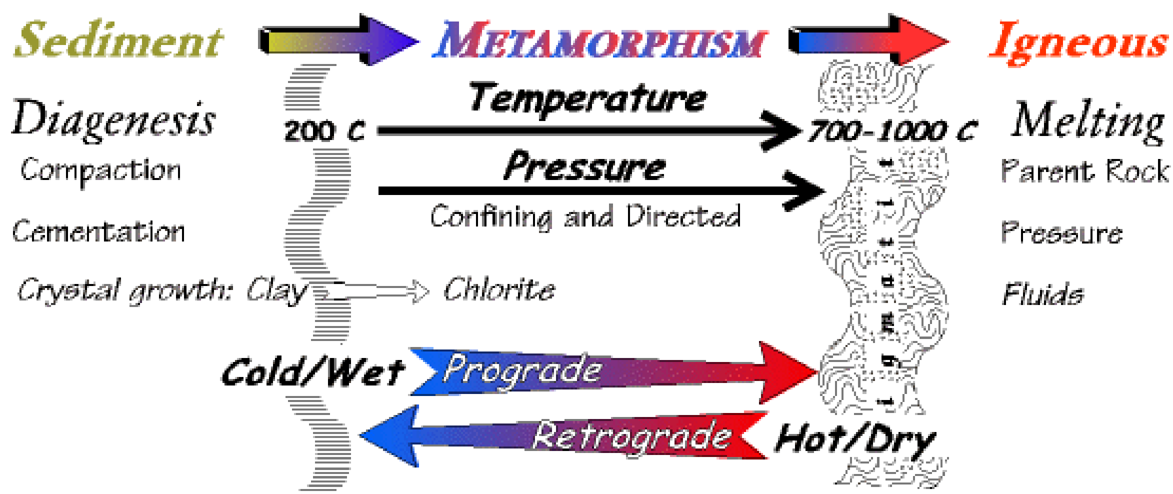
III. Metamorphism

It is a process leading to changes in mineralogy and/or texture in a rock.

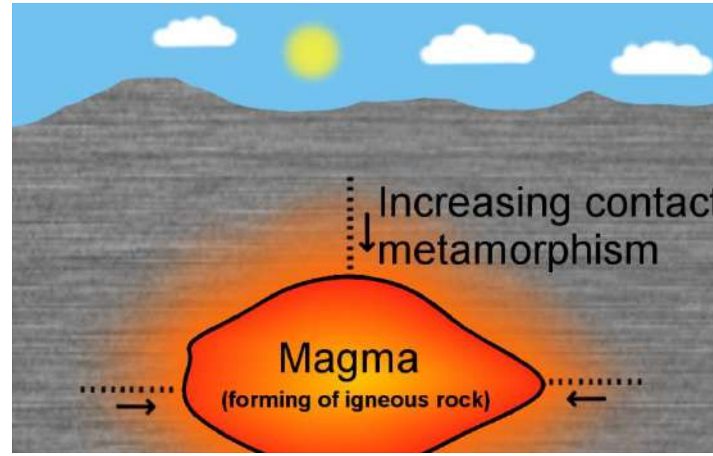
The boundary between diagenesis and metamorphism is defined by noting the first occurrence of a mineral that does not occur as a detrital or diagenetic mineral in surface sediments, (e.g. chlorite, epidote, lawsonite, laumontite, albite, zeolite,…).

Formation of some of these minerals requires a temperature of at least 150-200 °C or 1500 bars or depth of about 5 km under normal geothermal conditions. The upper limit of metamorphism is defined as the beginning of appreciable melting.

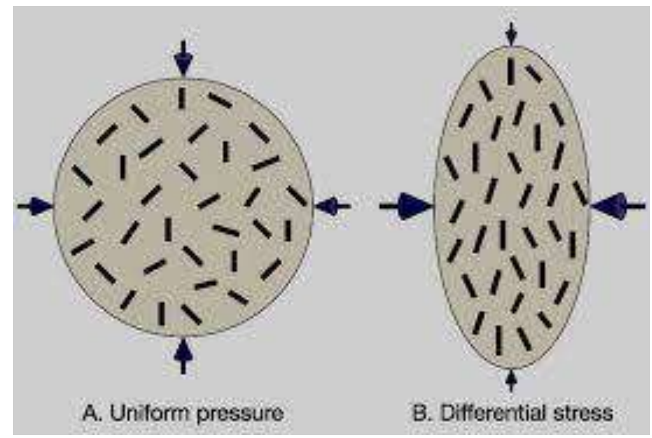




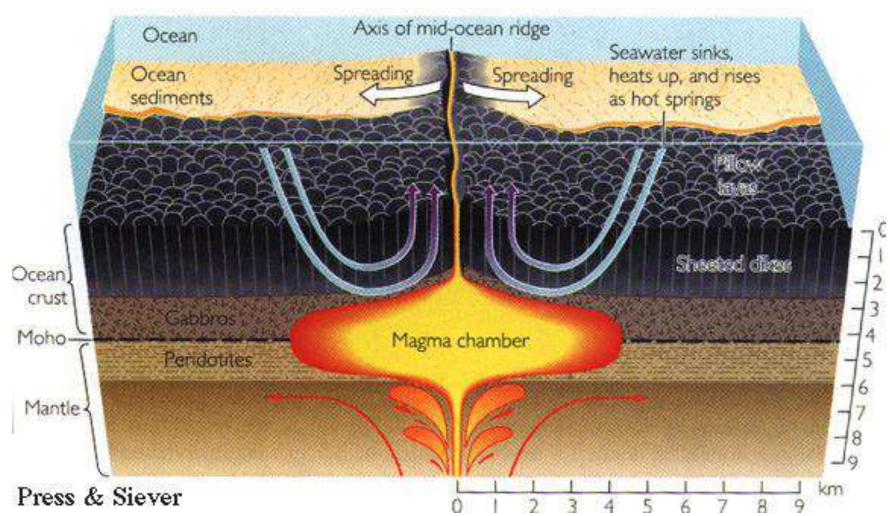
Agents of Metamorphism



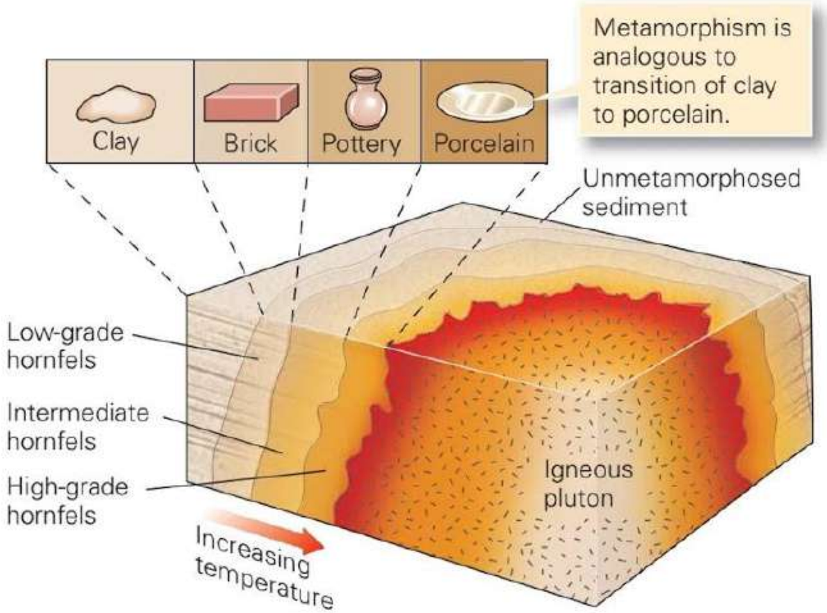
Heat is the most important source of energy allowing the formation of new and more stable mineral and textural reconstruction and recrystallization during metamorphism.



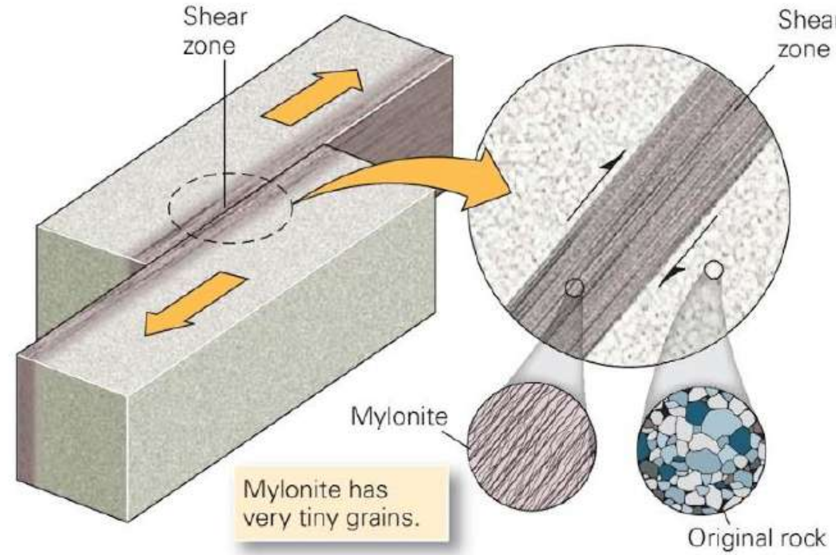
Pressure (measured in bars - 1 kb is approximately each 3 km depth). Pressure changes both a rock's mineralogy and its texture. Pressure comes in different varieties; confining pressure, directed pressure (or stress), burial pressure and fluid pressure.



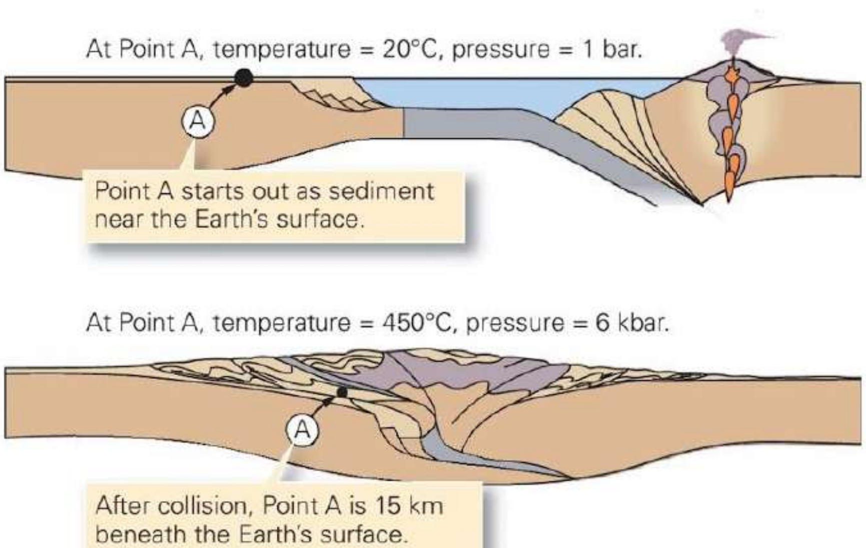
Chemically Active Fluids (ion transport): In some metamorphic settings, new materials are introduced by the action of hydrothermal solutions (hot water with dissolved ions). Many metallic ore deposits form in this way.



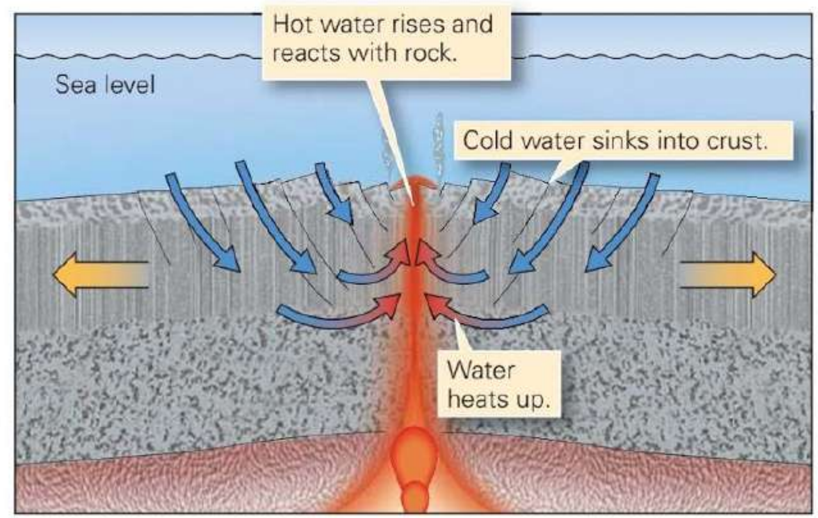
(a) Heat radiated from a large pluton can produce a metamorphic aureole, in which hornfels develops. Grade decreases progressively away from the pluton contact.



(b) Shearing of a rock under plastic conditions causes original crystals to divide into tiny crystals without breaking to form a mylonite. Mylonite has strong foliation.



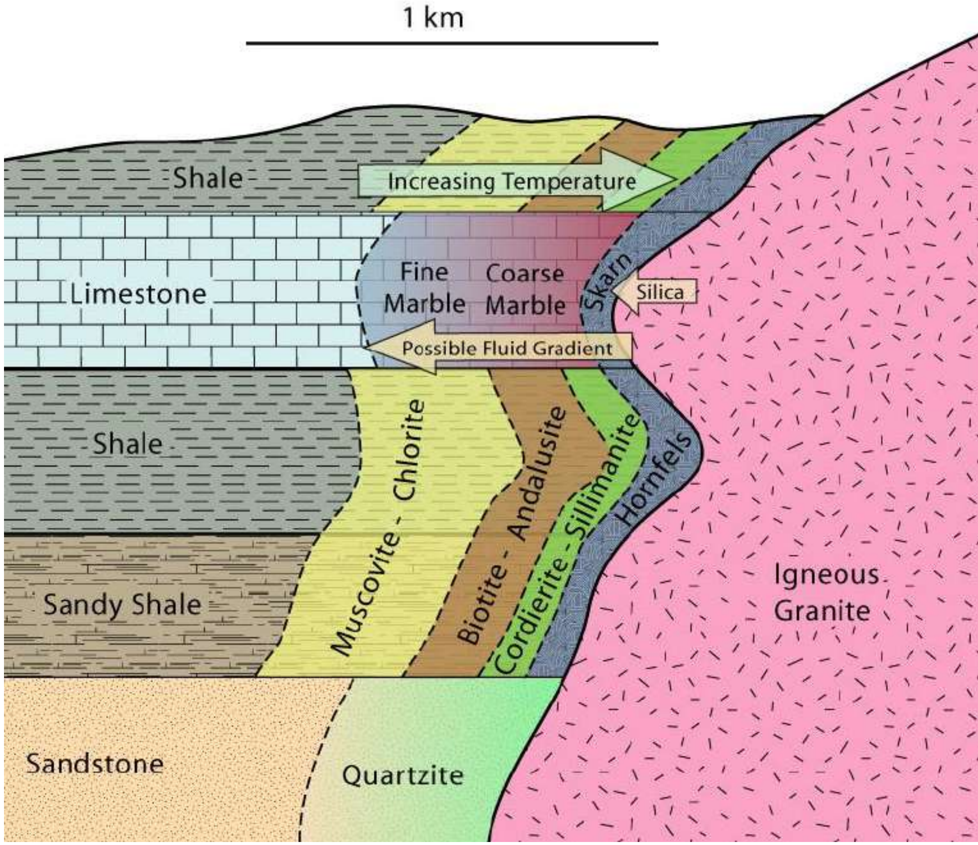
(c) Dynamothermal metamorphism happens when one part of the crust shoves over another part, so that rocks once near the surface end up at great depth.



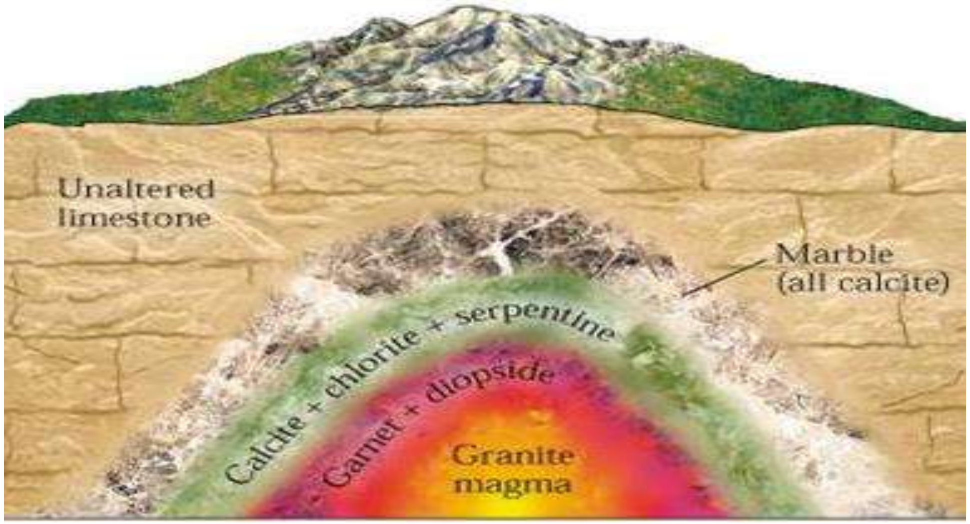
(d) The heat of rising magma at a ridge axis heats water, which then convects. The hot water reacts with the crust and forms metamorphic minerals.

Type of metamorphism

1- Contact metamorphism (Pyrometamorphism) occurs when magma invades cooler rock. Here, a zone of alteration called an aureole (or halo) forms around the emplaced magma. These large aureoles often consist of distinct zones of metamorphism. Near the magma body, high temperature minerals such as garnet may form, whereas farther away such low-grade minerals as chlorite are produced.

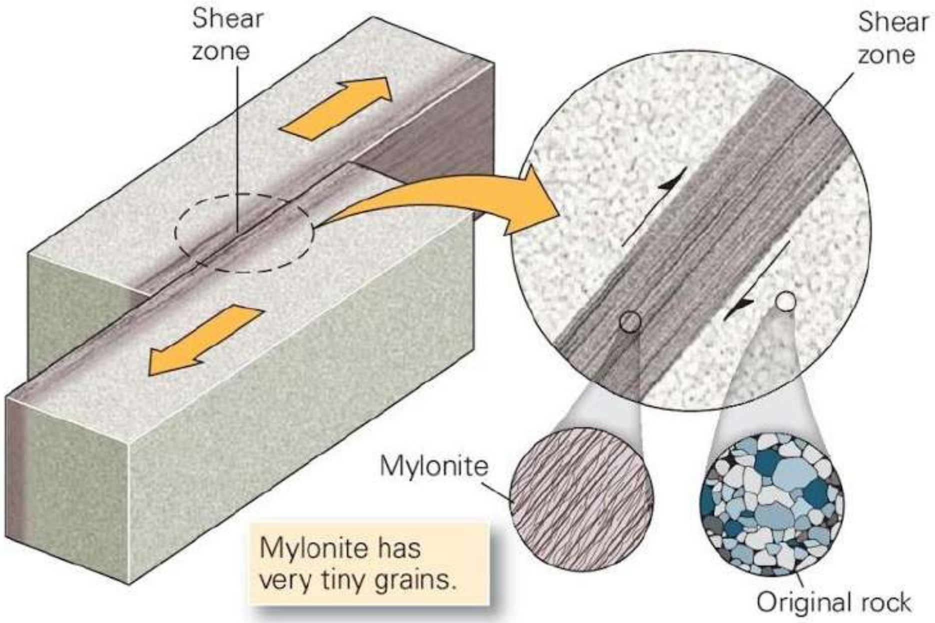


Shales baked by igneous contact form very hard fine-grained rocks called HORNFELS. Calcareous rocks (dirty limestones) when subject to contact metamorphism an alteration by hot fluids produce rocks called SKARNS.



2- Metamorphism along Fault Zones is known as dynamic metamorphism. In some cases, rock may even be milled into very fine components. The result is a loosely coherent rock called fault breccia that is composed of broken and crushed rock fragments. This type of localized metamorphism, which involves purely mechanical forces that pulverize individual mineral grains, is called cataclastic metamorphism.

Much of the intense deformation associated with fault zones occurs at great depth. In this environment the rocks deform by ductile flow, which generates elongated grains that often give the rock a foliated or lineated appearance. Rocks formed in this manner are termed mylonites.



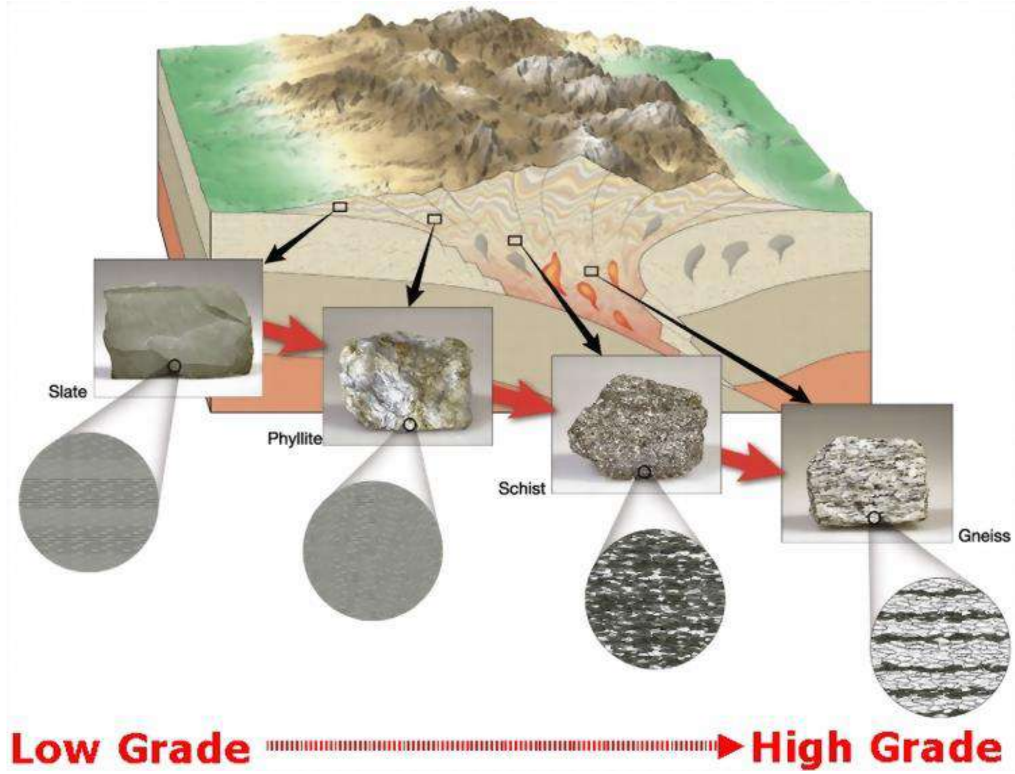
(b) Shearing of a rock under plastic conditions causes original crystals to divide into tiny crystals without breaking to form a mylonite. Mylonite has strong foliation.

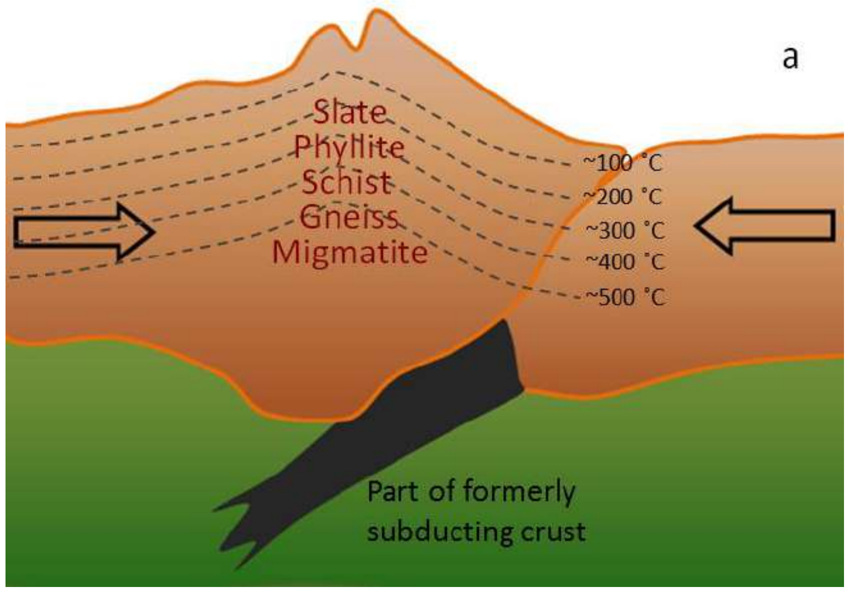
3- Regional Metamorphism.

The metamorphic rock produced during regional metamorphism are associated with mountain building (orogenic metamorphism – convergent plate boundaries). During these dynamic events, large segments of Earth's crust are intensely squeezed and become highly deformed.

As the rocks are folded and faulted, the crust is shortened and thickened, like a rumpled carpet. This general thickening of the crust results in terrains that are lifted high above sea level.

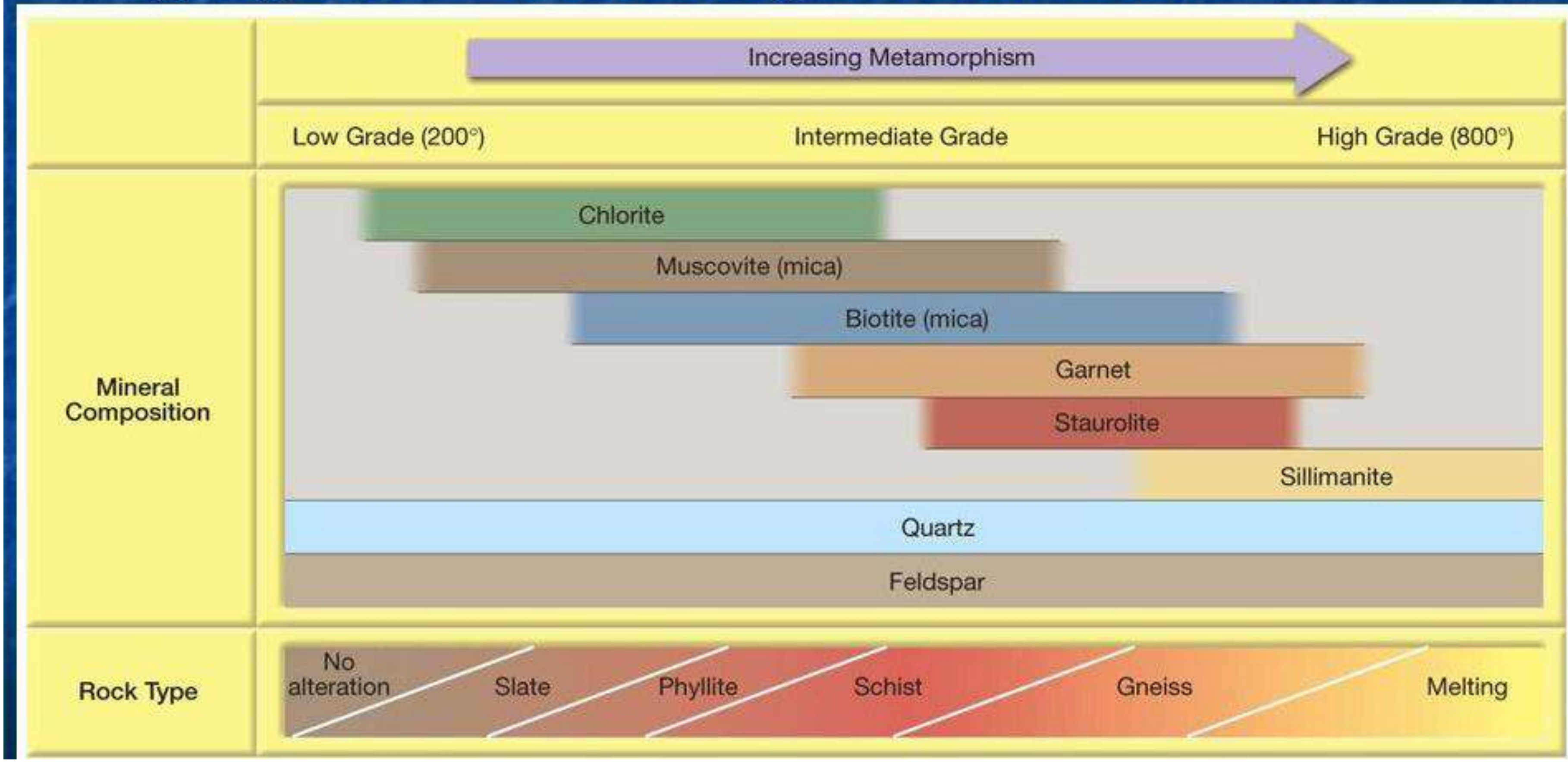
In regional metamorphism, there usually exists a gradation in intensity. As we shift from areas of low-grade metamorphism to areas of high grade metamorphism.

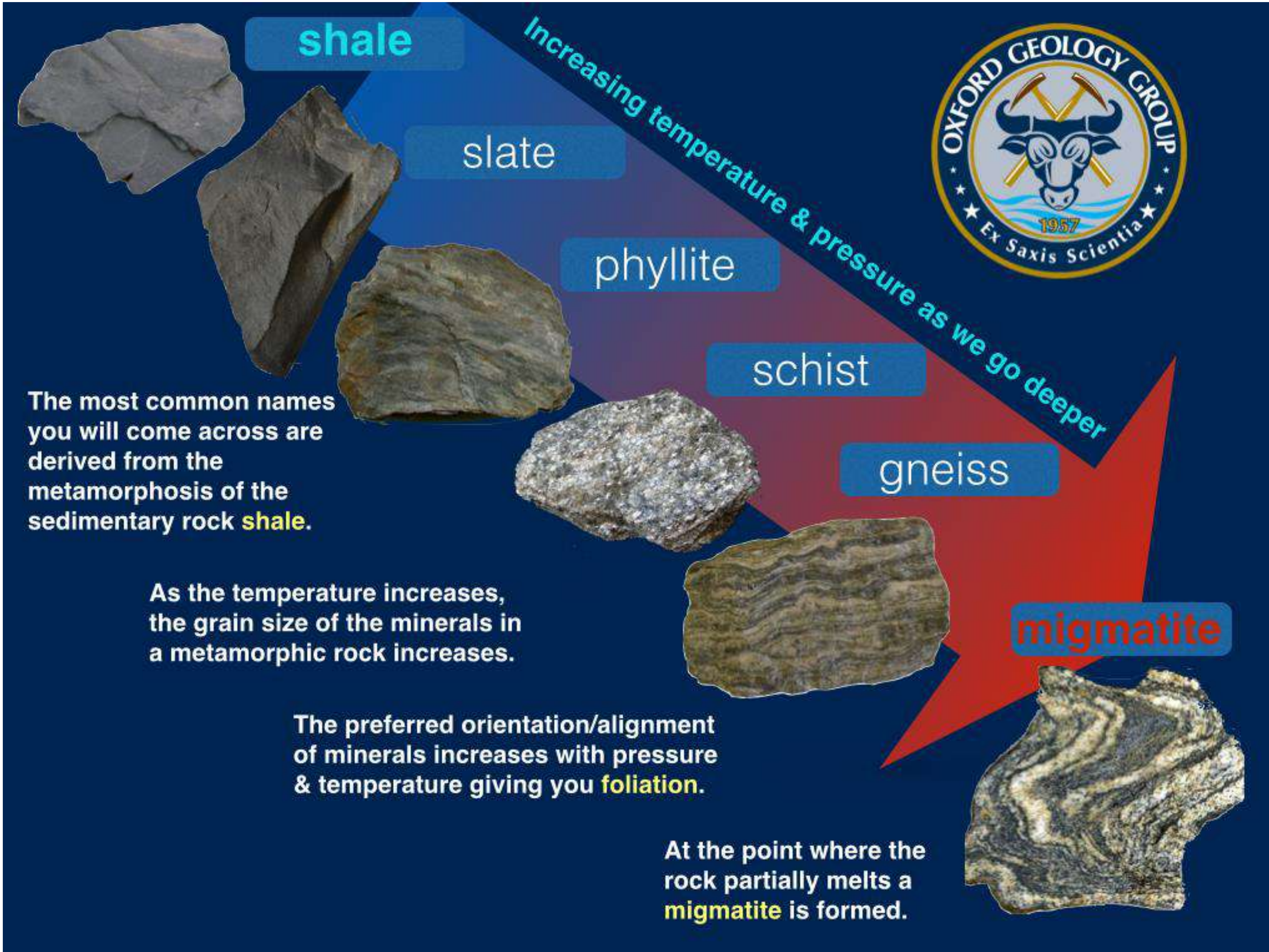


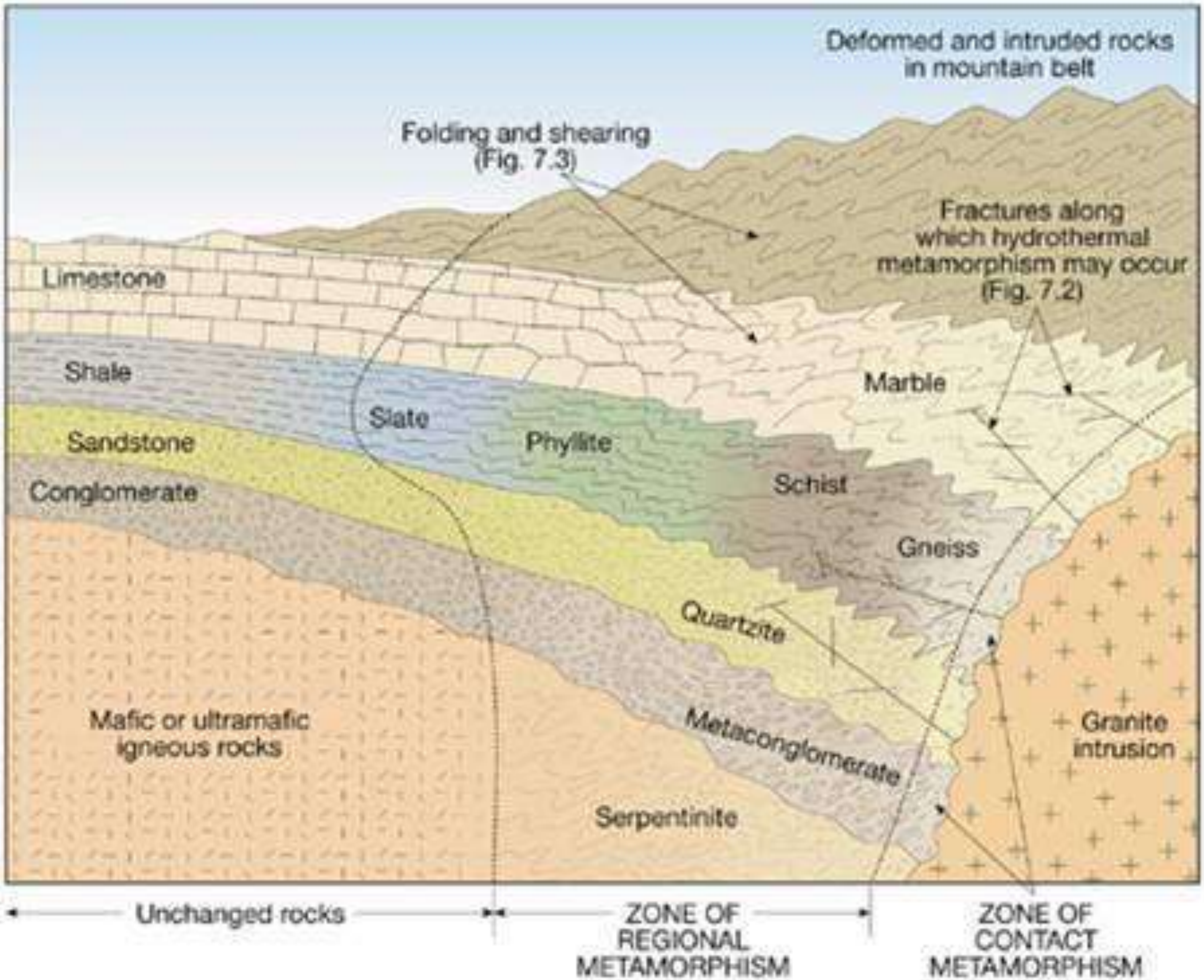


Index Minerals

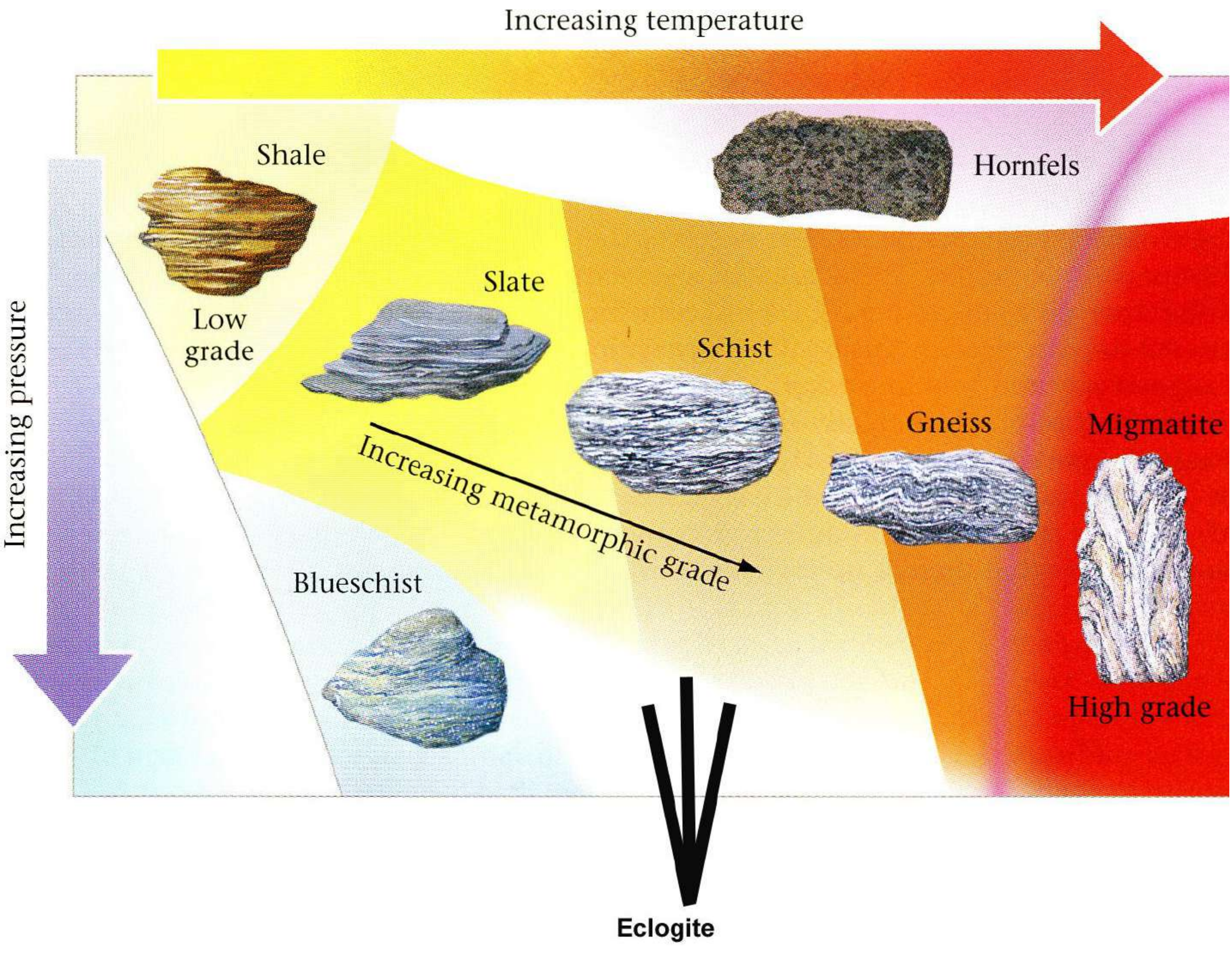
- Typical transition in mineralogy due to progressive metamorphism of shale




shale
slate
phyllite
schist
gneiss
migmatite
Increasing temperature & pressure as we go deeper
OXFORD GEOLOGY GROUP
1957
Ex Saxis Scientia
The most common names you will come across are derived from the metamorphosis of the sedimentary rock shale.
As the temperature increases, the grain size of the minerals in a metamorphic rock increases.
The preferred orientation/alignment of minerals increases with pressure & temperature giving you foliation.
At the point where the rock partially melts a migmatite is formed.


Deformed and intruded rocks in mountain belt
Folding and shearing (Fig. 7.3)
Fractures along which hydrothermal metamorphism may occur (Fig. 7.2)
Limestone
Shale
Sandstone
Conglomerate
Slate
Phyllite
Schist
Gneiss
Marble
Quartzite
Metaconglomerate
Mafic or ultramafic igneous rocks
Serpentinite
Granite intrusion
Unchanged rocks
ZONE OF REGIONAL METAMORPHISM
ZONE OF CONTACT METAMORPHISM

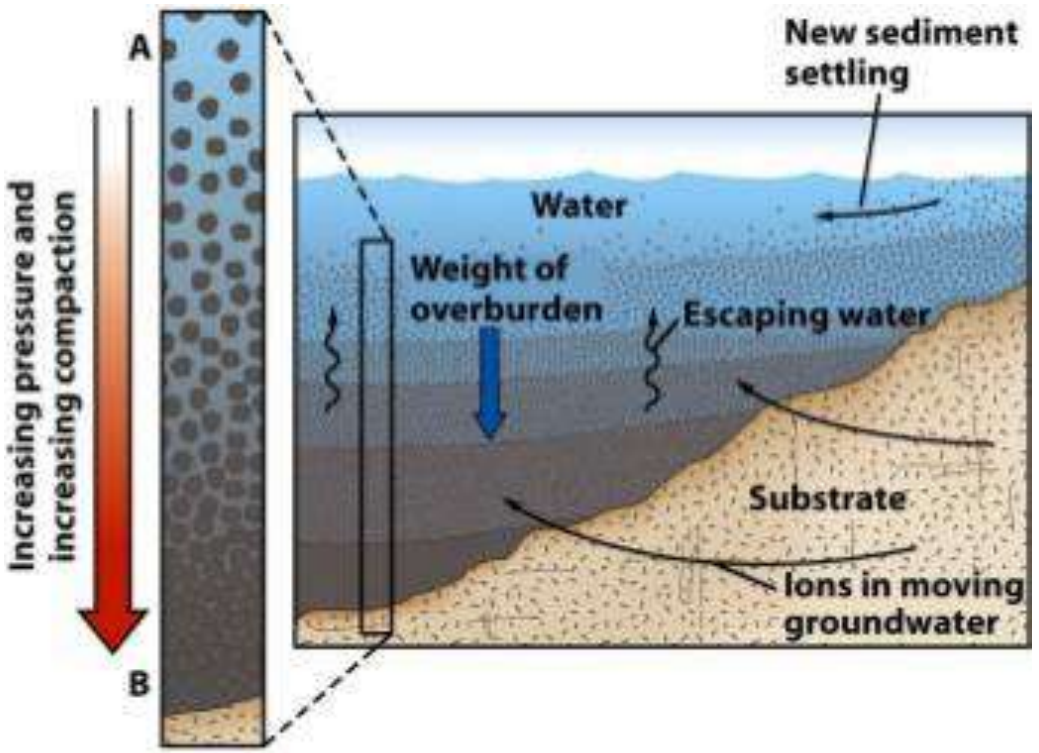
Metamorphic Environment	50-300ºC	300-450ºC	Above 450ºC
Metamorphic Grade	Low	Intermediate	High
Rock Name	**SLATE**	**SCHIST**	**GNEISS**
Rock Description	Minerals not visible with the naked eye or with a hand lens, rock shows slaty cleavage, is usually dark-colored. A product of low-grade metamorphism of shale or mudstone.	Rock is medium to coarse grained with visible grains of mica or other metamorphic minerals. Often shiny due to reflection of mica on foliation planes. Product of intermediate grade metamorphism of shale, slate, phyllite, basalt or granite.	Rock is coarse grained and usually banded with alternating layers of light and dark minerals. Foliation bands may be folded. Product of high grade metamorphism of shale, schist, granite or many other rock types.


Increasing temperature
Increasing pressure
Shale
Hornfels
Low grade
Slate
Schist
Gneiss
Migmatite
Increasing metamorphic grade
Blueschist
High grade
Eclogite

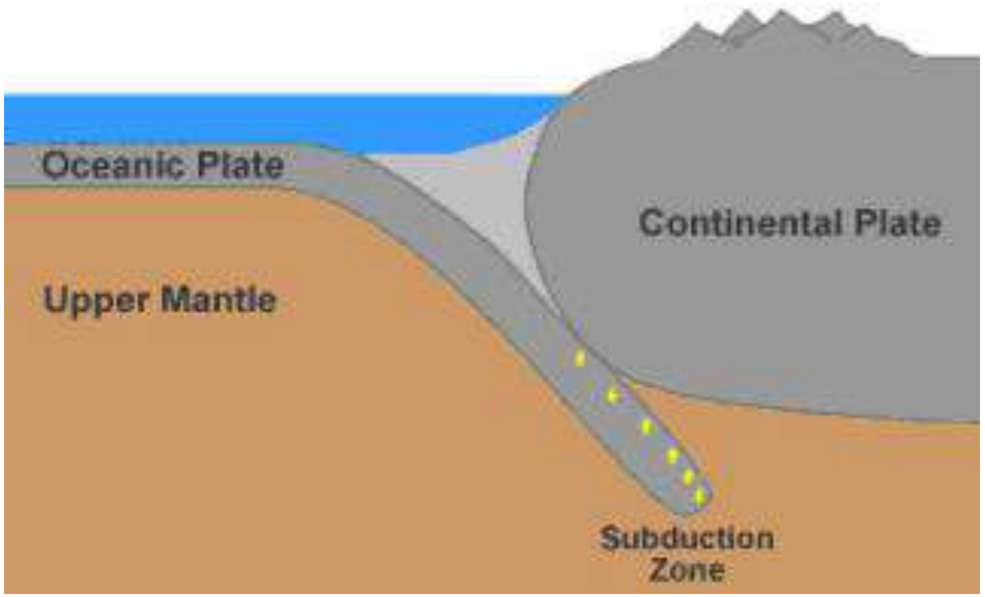
4- Burial metamorphism

Metamorphic effects attributed to increased pressure and temperature due to burial (NO TECTONICS). Range from diagenesis to the formation of zeolites, prehnite, pumpellyite, laumontite, etc.

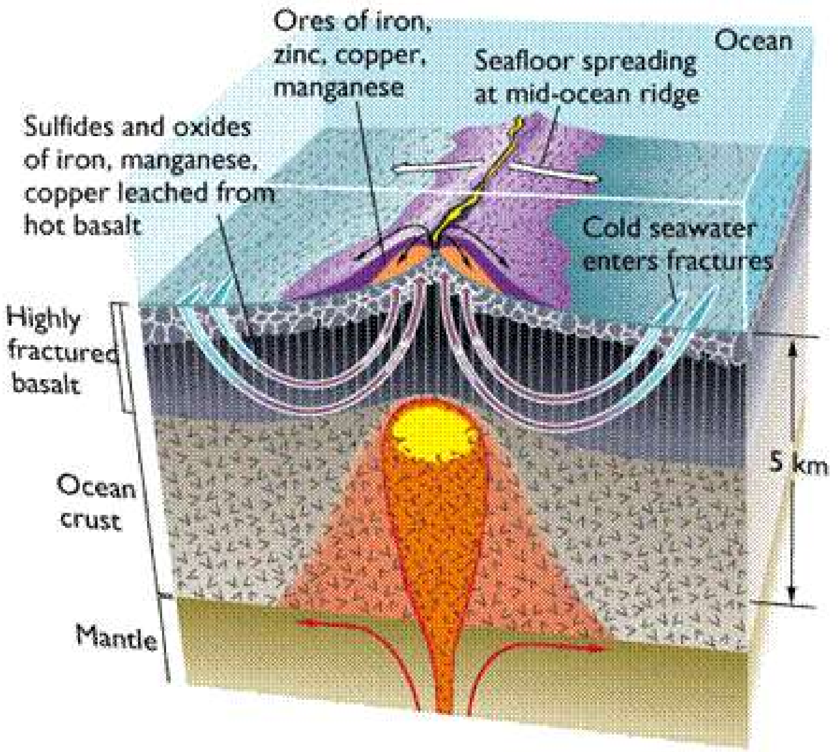
Diagenesis and lithification start when rocks reach several kilometers depth. Continued burial leads to low grade burial metamorphism. It is common for sedimentary structures in the unaltered rocks to remain in the metamorphosed rocks, indicating relatively little recrystallization. This style of metamorphism grades into regional metamorphism with increasing pressure and temperature. Burial metamorphism is found in deep sedimentary basins.



5- High-pressure low- temperature metamorphism: This metamorphism is associated with subduction zones. It is called high pressure/low temperature metamorphism where the subducting plates has been cooled by interaction with seawater.



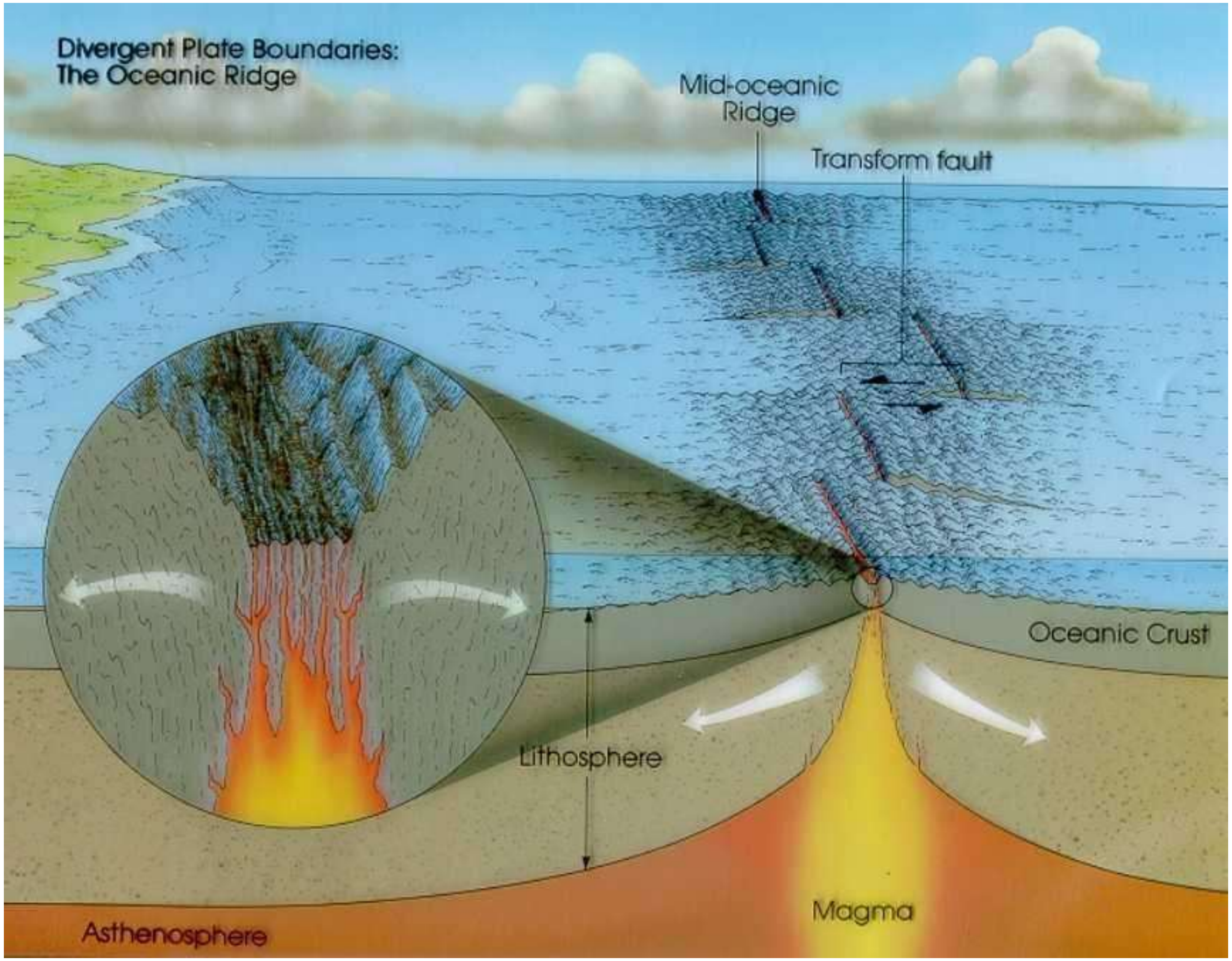
6- Hydrothermal metamorphism: (caused by hot H_2O-rich fluids and usually involving metasomatism). This style of metamorphism is distinguished by high fluid content and changes in rock composition. It occurs when hot water percolates (or convicts) through rock. This happens around plutons and in association with underwater volcanism. Pressures are usually low and temperatures moderate. By dissolving components that are least compatible within the rocks, hydrothermal metamorphism can produce very exotic deposits. Sulfides and massive ore bodies are associated with it.

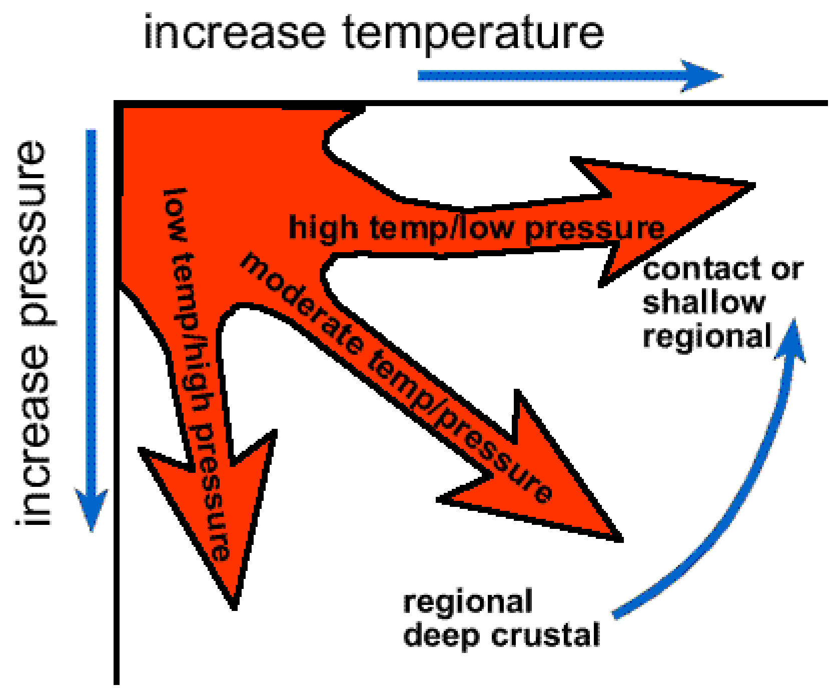


7- Ocean-Floor Metamorphism: It affects the oceanic crust **at ocean ridge spreading centers**. It is another example of hydrothermal metamorphism.

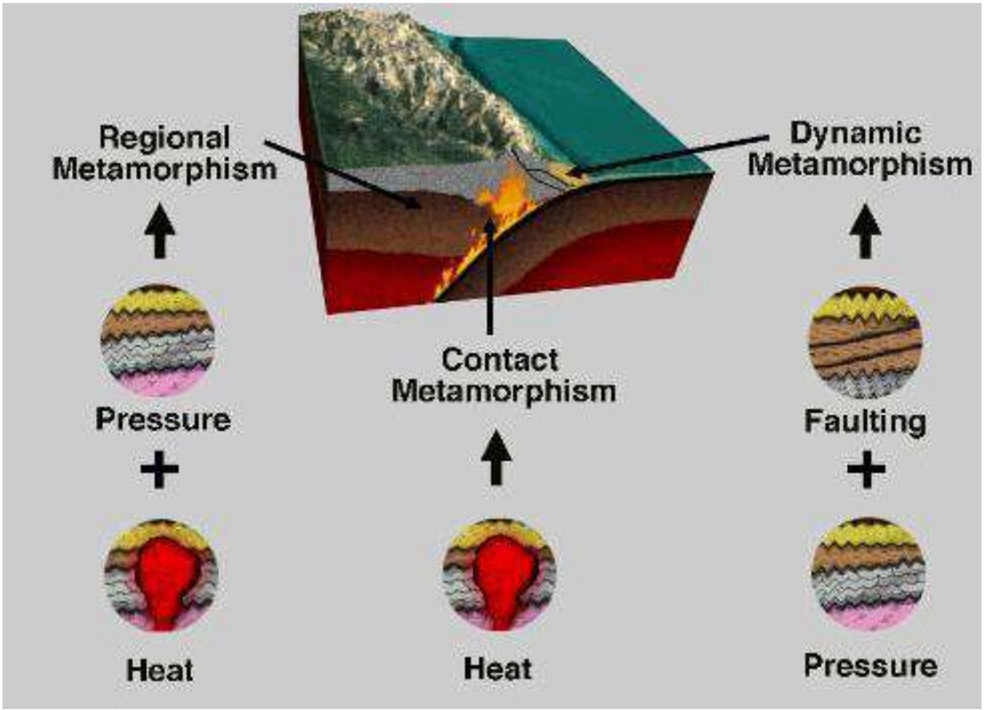
Highly altered chlorite-quartz rocks- distinctive high-Mg, low-Ca composition.

Metamorphic rocks exhibit considerable **metasomatic alteration**, notably loss of Ca and Si and gain of Mg and Na. These changes can be correlated with exchange between basalt and hot seawater

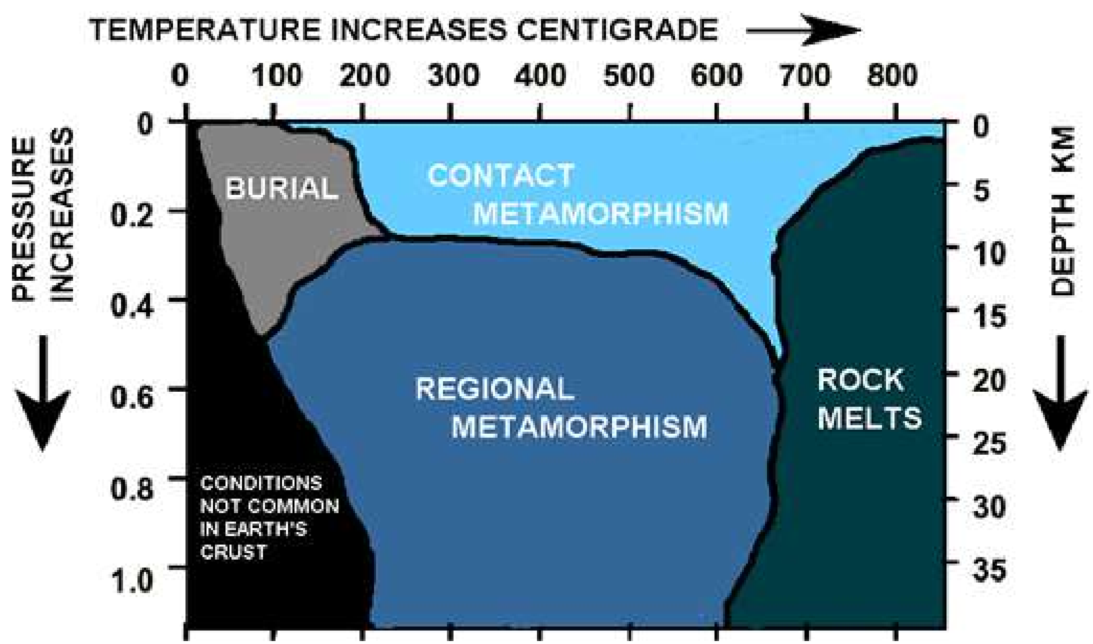




increase temperature
increase pressure
high temp/low pressure
moderate temp/pressure
low temp/high pressure
contact or
shallow
regional
regional
deep crustal

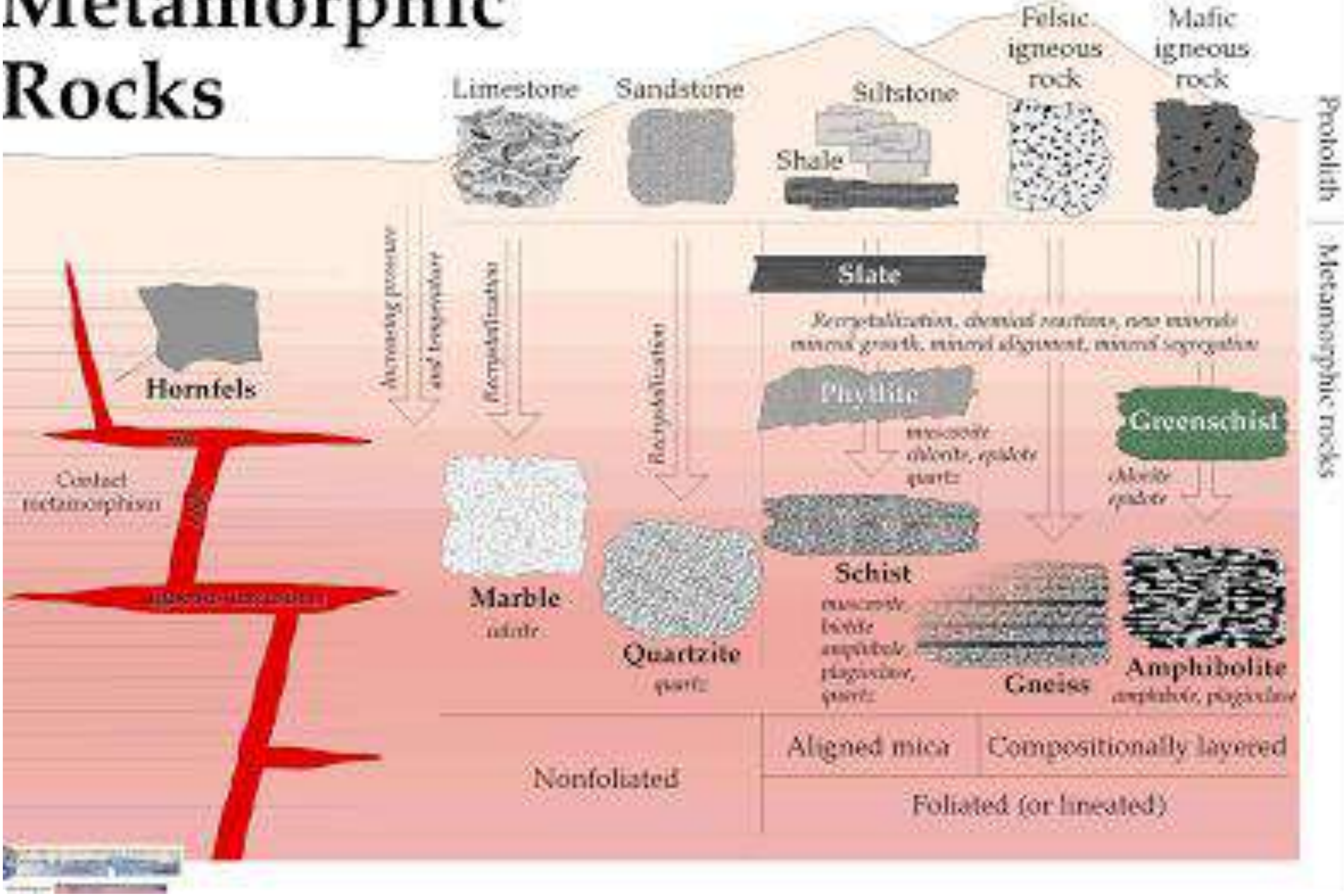


Regional
Metamorphism
Dynamic
Metamorphism
Contact
Metamorphism
Pressure
+
Heat
Heat
Faulting
+
Pressure



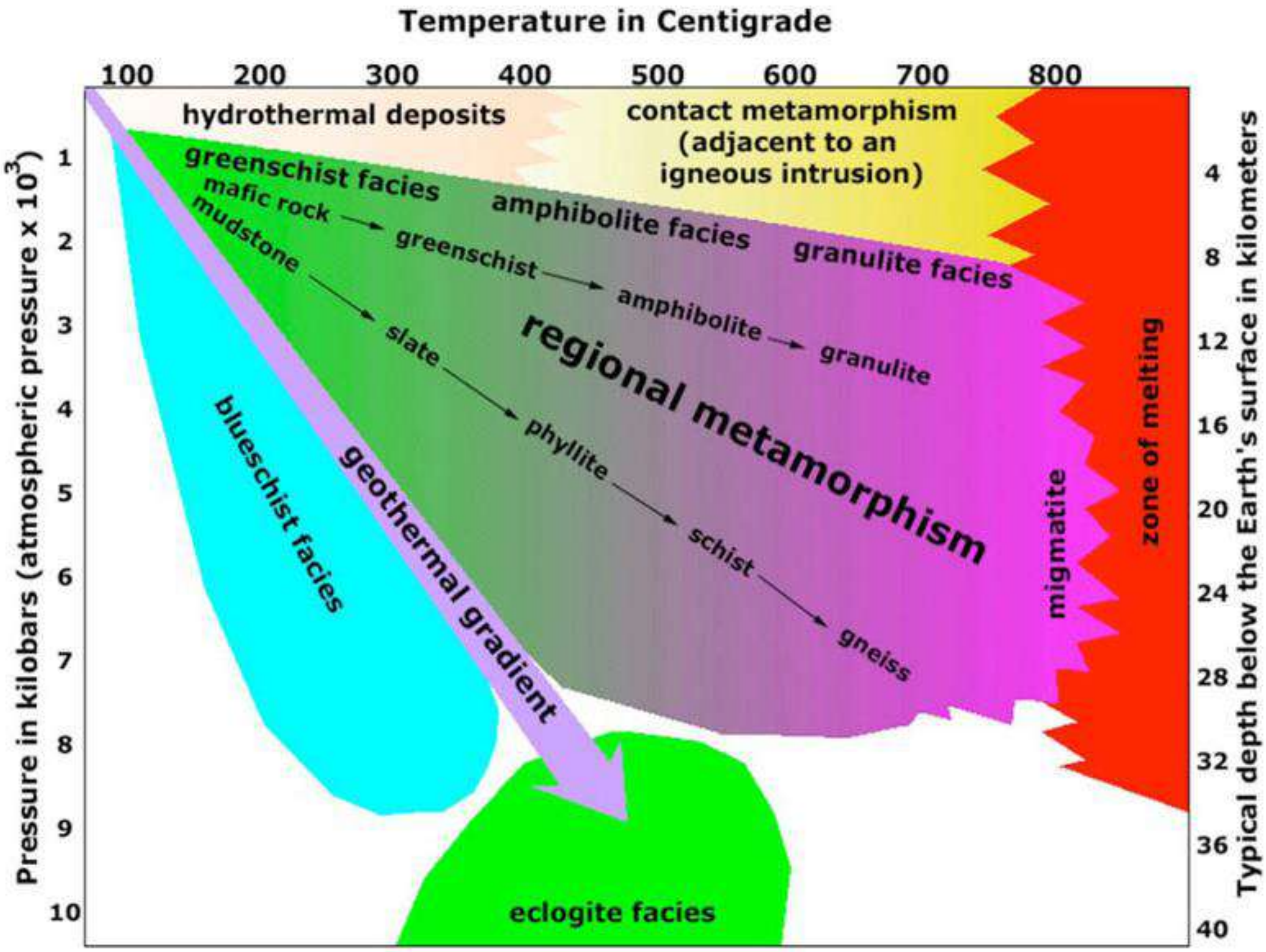
TEMPERATURE INCREASES CENTIGRADE
0
100
200
300
400
500
600
700
800
PRESSURE INCREASES
0
0.2
0.4
0.6
0.8
1.0
DEPTH KM
0
5
10
15
20
25
30
35
BURIAL
CONTACT
METAMORPHISM
REGIONAL
METAMORPHISM
ROCK
MELTS
CONDITIONS
NOT COMMON
IN EARTH'S
CRUST

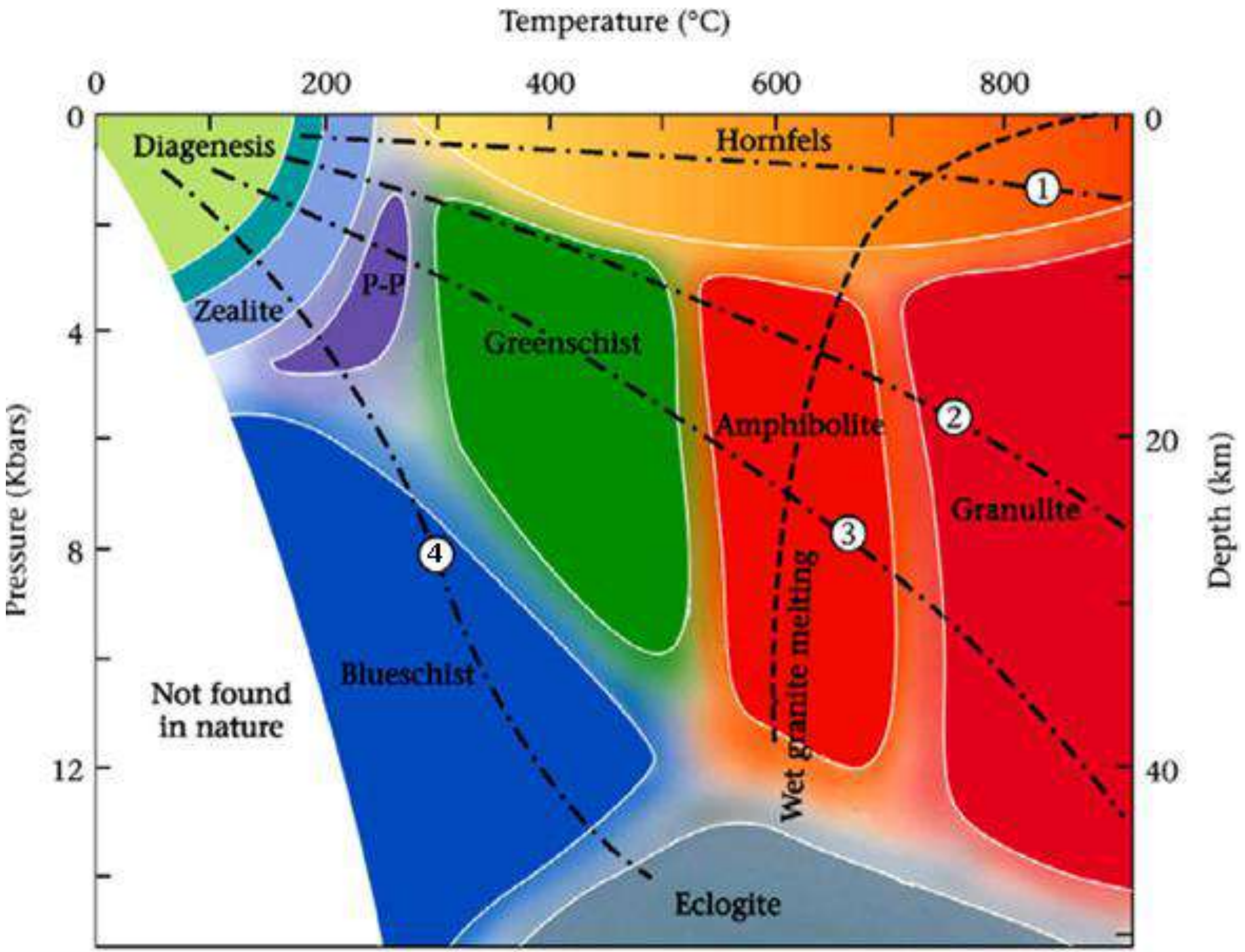
Metamorphic Rocks



Metamorphic Facies

A metamorphic facies includes rocks of any chemical composition and hence of widely varying mineralogical composition, which have reached chemical equilibrium during metamorphism under a particular set of physical conditions.





Temperature (°C)
0
200
400
600
800
0
4
8
12
Pressure (Kbars)
0
20
40
Depth (km)
Diagenesis
Hornfels
Zealite
P-P
Greenschist
Amphibolite
Granulite
Blueschist
Not found in nature
Eclogite
Wet granite melting
1
2
3
4

Facies of Low Pressure

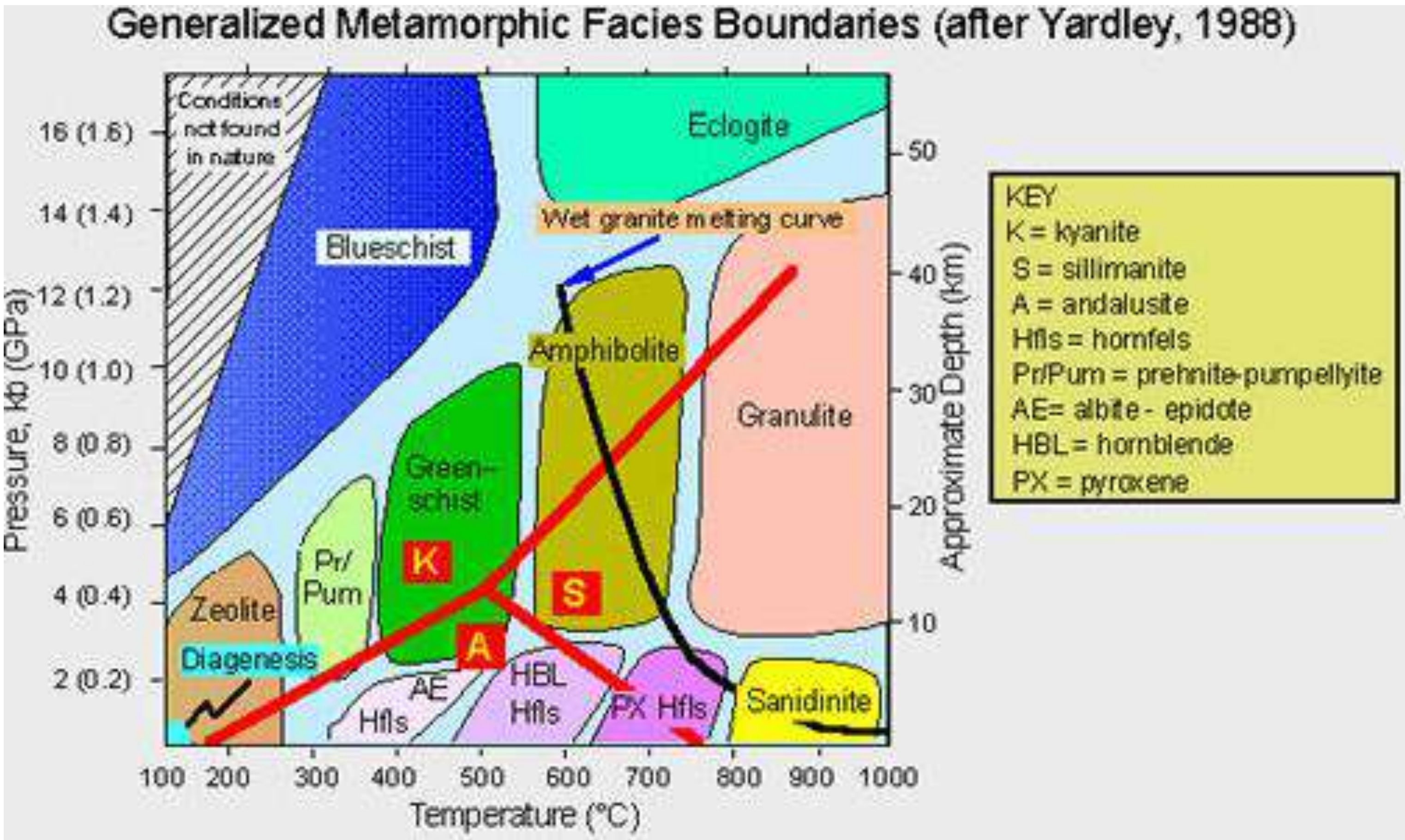
1) Albite-epidote hornfels facies,
2) Hornblende hornfels facies,
3) Pyroxene hornfels facies, and
4) Sanidinite facies.

Facies of Medium to High Pressure

1) Zeolite facies,
2) Prehnite-pumpellyite metagreywacke facies,
3) Greenschist facies,
4) Amphibolite facies, and
5) Granulite facies.

Facies of Very High Pressure

1) Glaucophane-lawsonite schist facies.
2) Eclogite facies.



Facies	Mafic rocks	Ulltramafic rocks	Mudrocks	Calcareous rocks
Zeolite	Analcime, Ca-zeolites, prehnite, zoisite, albite	Serpentine, brucite, chlorite, dolomite, magnesite	Quartz, clays, illite, albite, chlorite	Calcite, dolomite, quartz, talc, clays
Prehnite- pumpellyite	Chlorite, prehnite, albite, pumpellyite, epidote	Serpentine, talc, forsterite, tremolite, chlorite	Quartz, illite, muscovite, albite, chlorite (stilpnomelane)	Calcite, dolomite, quartz, clays, talc, muscovite
Greenschist	Chlorite, actinolite, epidote or zoisite, albite,(magnetite)	Serpentine, talc, tremolite, brucite , diopside, chlorite, pyrophyllite, (graphite)	Quartz, plagioclase, chlorite, muscovite, biotite, garnet	Calcite, dolomite, quartz, muscovite, biotite
Epidote- amphibolite	Hornblende, actinolite, epidote or zoisite,	Forsterite, tremolite, talc, serpentine, chlorite, (magnetite)	Quartz, plagioclase, chlorite, muscovite, biotite, (graphite)	Calcite, dolomite, quartz, muscovite, biotite, tremolite

Amphibolite	Hornblende, plagioclase, (sphene), (ilmenite)	Forsterite, tremolite, talc, anthophyllite, chlorite, orthopyroxene	Quartz, plagioclase, chlorite, muscovite, biotite, garnet, staurolite, kyanite, sillimanite, (graphite), (ilmenite)	Calcite, dolomite, quartz, biotite, tremolite, forsterite, diopside, plagioclase
Granulite	Hornblende, augite, orthopyroxene, plagioclase, (ilmenite)	Forsterite, orthopyroxene, augite, hornblende, garnet, Al-spinel	Quartz, plagioclase, orthoclase, biotite, garnet, cordierite, sillimanite, orthopyroxene	Calcite, quartz, forsterite, diopside , wollastonite, humite-chondrodite, Ca-garnet, plagioclase
Blueschist	Glaucophane, lawsonite, albite, aragonite, chlorite,	Forsterite, serpentine, diopside	Quartz, plagioclase, muscovite, carpholite, talc, kyanite, chloritoid	Calcite, aragonite, quartz, forsterite, diopside, tremolite zoisite
Eclogite	Mg-rich garnet, omphacite,kyanite(ruble)	Forsterite, orthopyroxene, augite, garnet	Quartz, albite, phengite, talc, kyanite, garnet	Calcite, aragonite, quartz, forsterite, diopside

Albite- epidote hornfels	Albite, epidote or zoisite, actinolite, chlorite	Serpentine, talc, tremolite, chlorite	Quartz, plagioclase, muscovite, chlorite, cordierite	Calcite, dolomite, quartz, tremolite, talc, forsterite
Hornblende hornfels	Hornblende, plagioclase, orthopyroxene, garnet	Forsterite, orthopyroxene, hornblende, chlorite, (Al-spinel), (magnetite)	Quartz, plagioclase, muscovite, biotite, cordierite, andalusite	Calcite, dolomite, quartz, tremolite, diopside, forsterite
Pyroxene hornfels	Orthopyroxene, augite, plagioclase, (garnet)	Forsterite, orthopyroxene, augite, plagioclase, Al-spinel	Quartz, plagioclase, orthoclase, andalusite, sillimanite, cordierite, orthopyroxene	Calcite, quartz, diopside, forsterite, wollastonite
Sanidinite	Orthopyroxene, augite, plagioclase, (garnet)	Forsterite, orthopyroxene, augite, plagioclase	Quartz, plagioclase, sillimanite, cordierite, orthopyroxene sapphirine, Al-spinel	Calcite, quartz, diopside, forsterite, wollastonite, monticellite, akermanite

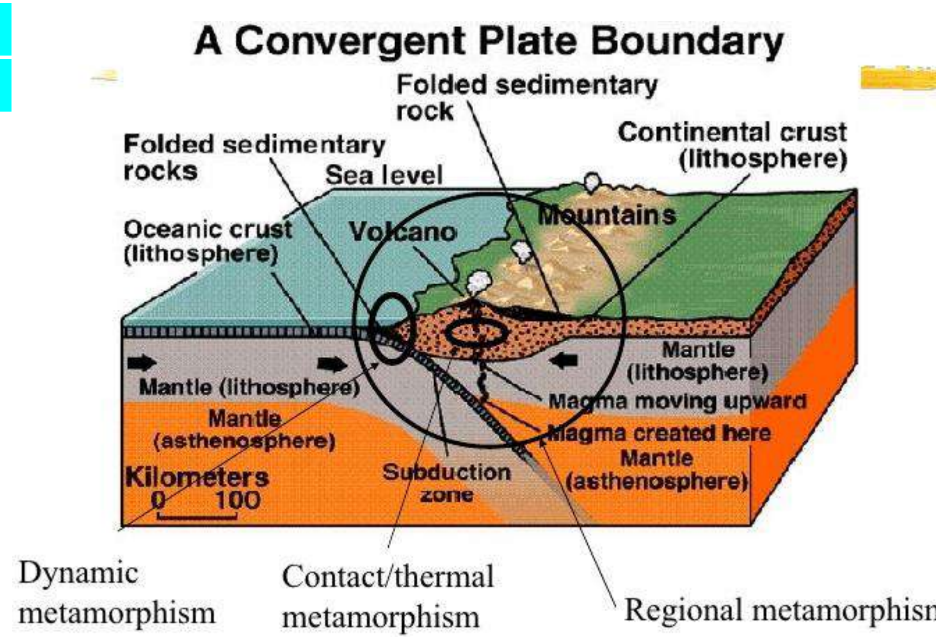
Plate Tectonic Settings of Metamorphism

Convergent Plate Margin

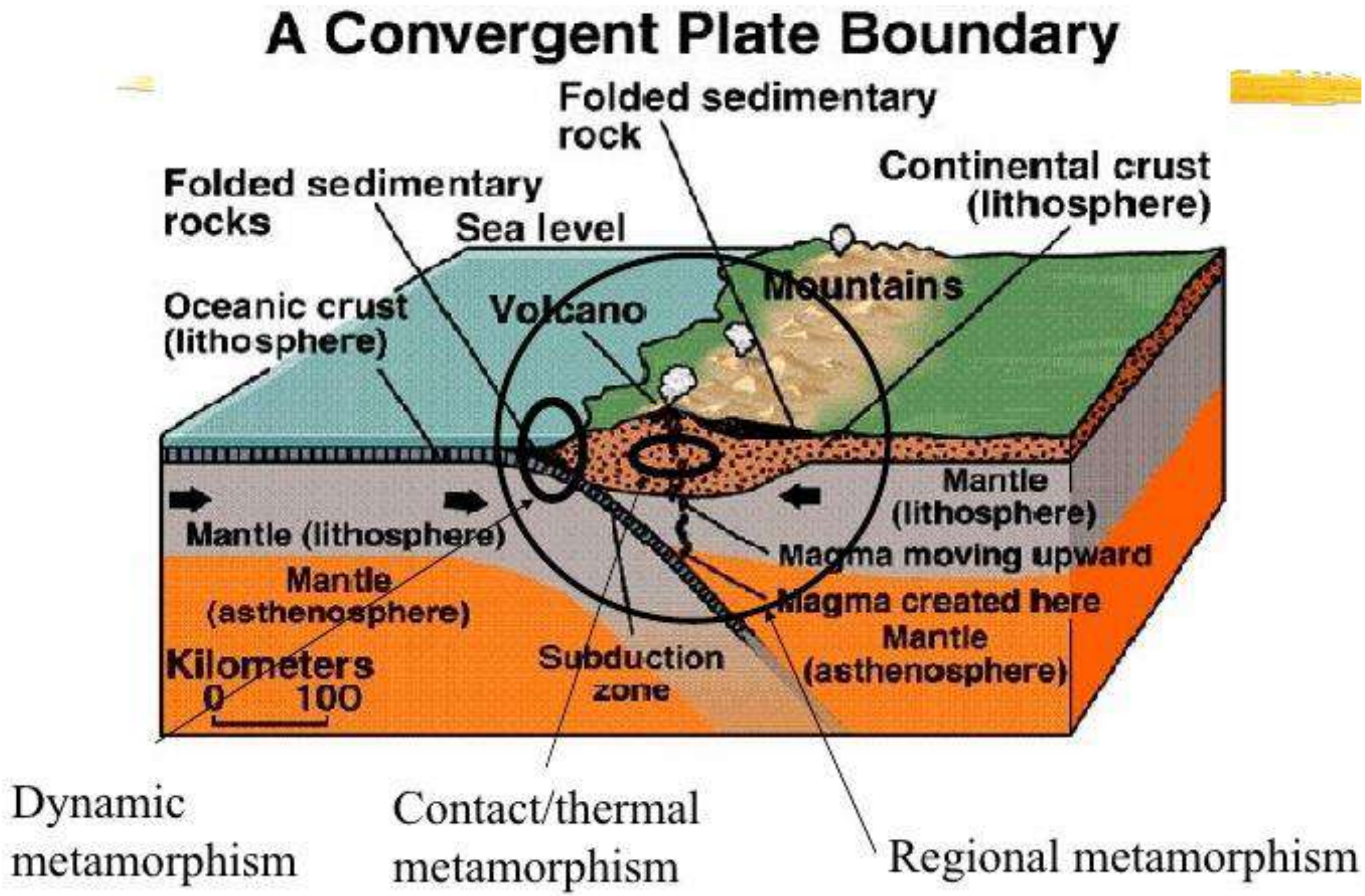
At all three types of convergent boundary (ocean-ocean, ocean-continent, continent- continent), high stresses, high deposition rates and volcanism can be found.

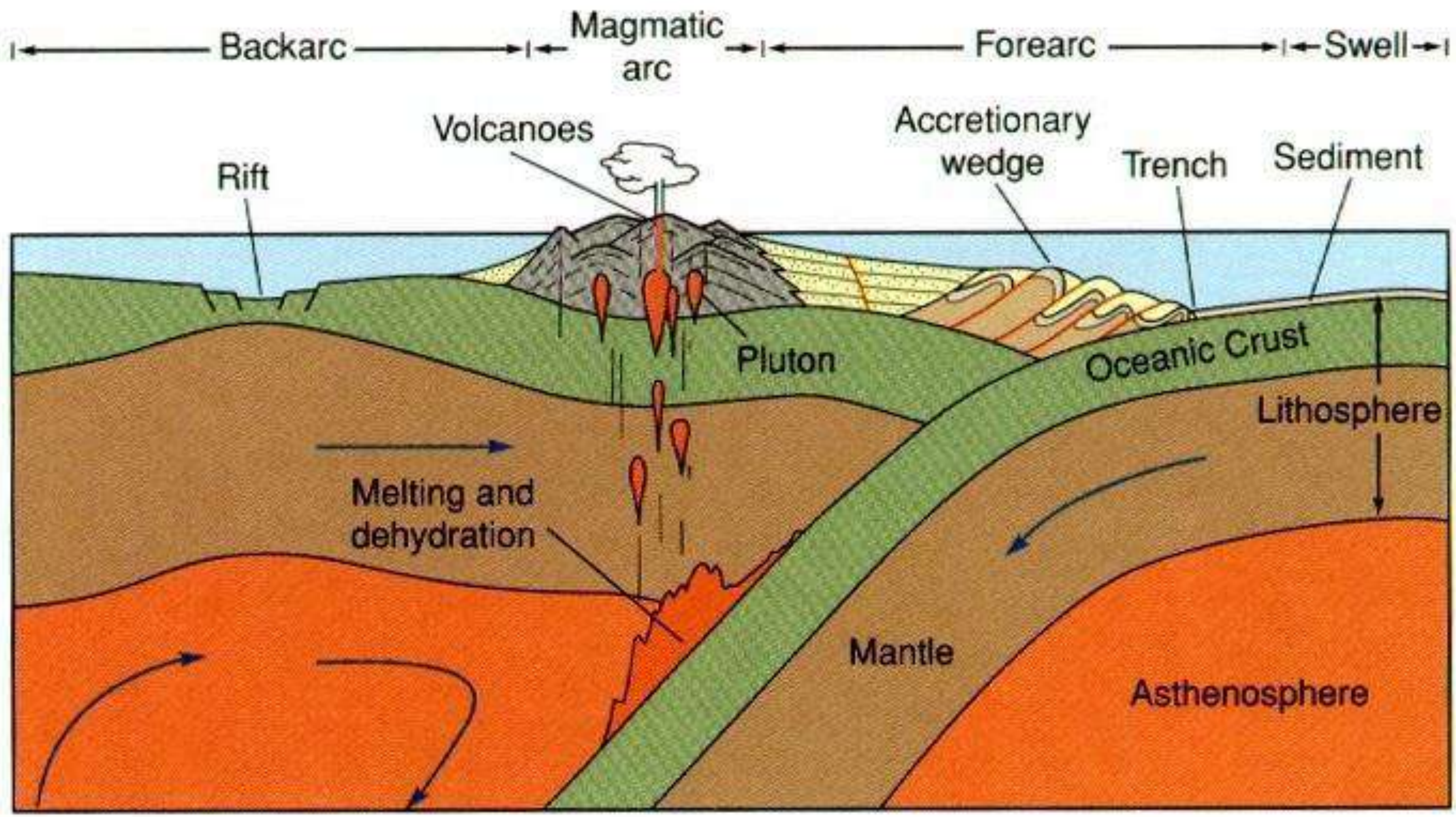
Amphibolite to granulite facies are found within the cores of mountain belts. Greenschists occur at shallower depths within the belts. Blueschists are produced by the rapid subduction of sediments and oceanic crust where high pressures can be reached before temperatures within the subducted crust can be rised.

Eclogite facies are reached within the subducting crust when it reaches depths of 20 to 25 km. Hornfels are found in contact aureoles around shallow intrusions where hot magma heats the surrounding rocks.

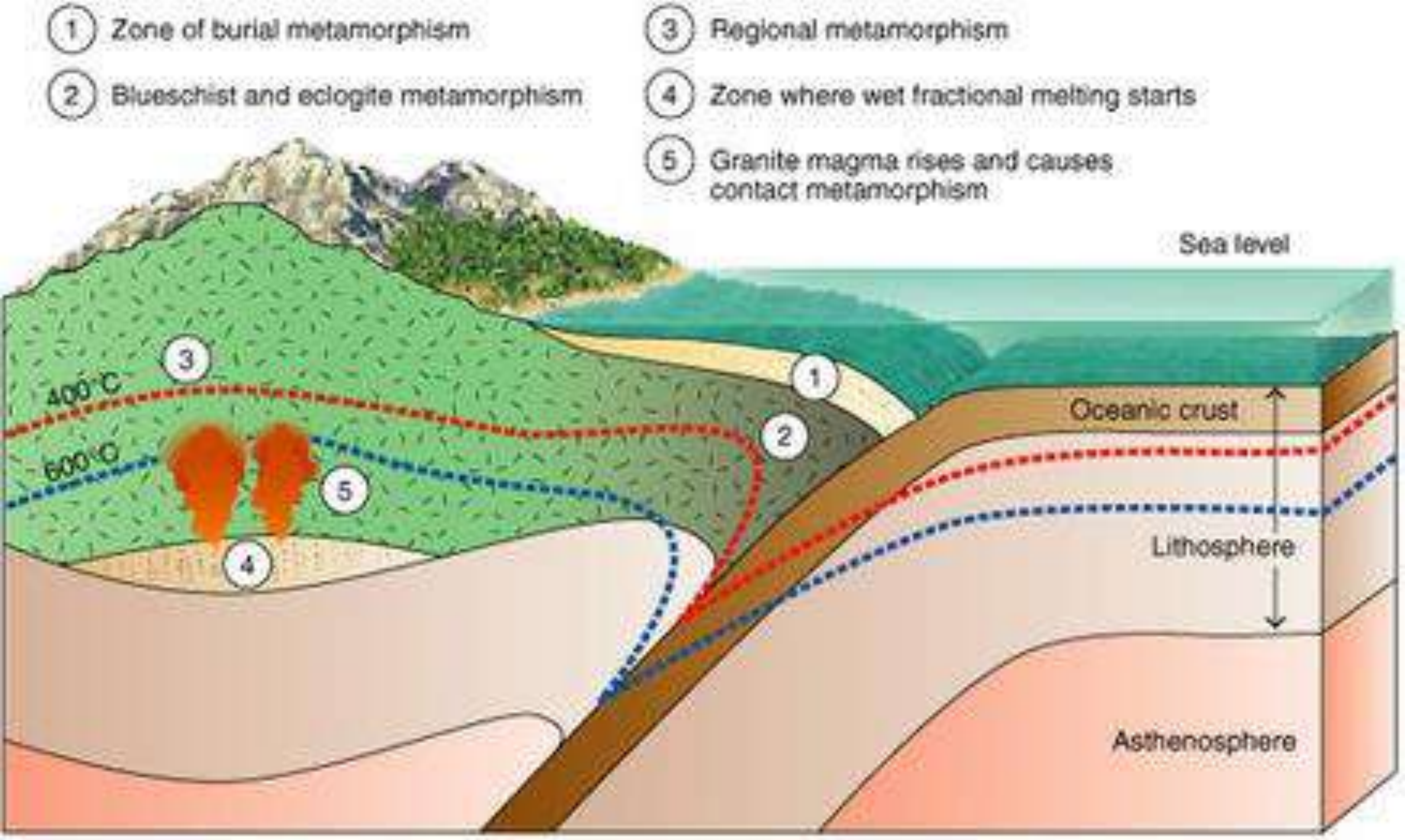


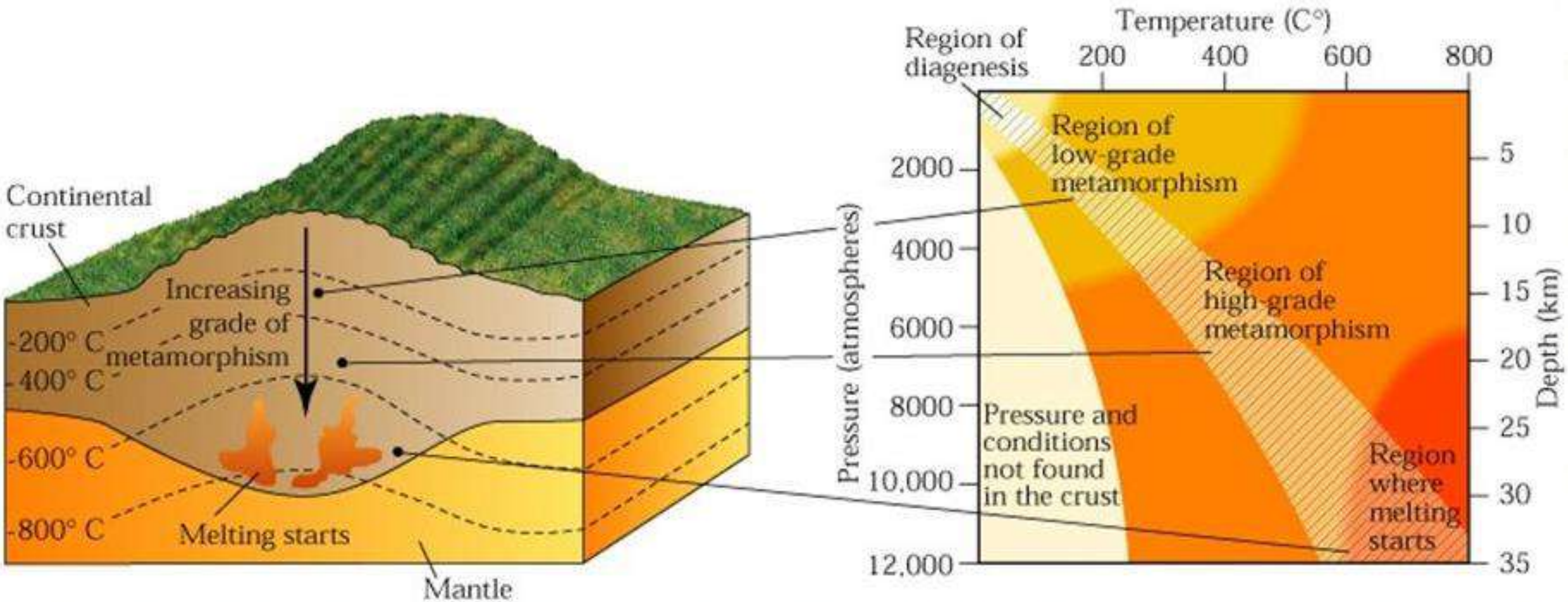
The uplift of mountains results in regional metamorphism. Baking of "country" rock by igneous intrusions produces Contact metamorphism. Faulting of highly stressed crustal rocks results in Cataclastic metamorphism. Rapid sedimentation and subsidence offshore produces Burial metamorphism. Lastly, Zeolite facies metamorphism occurs within the accretionary prism located arc ward of the trench.

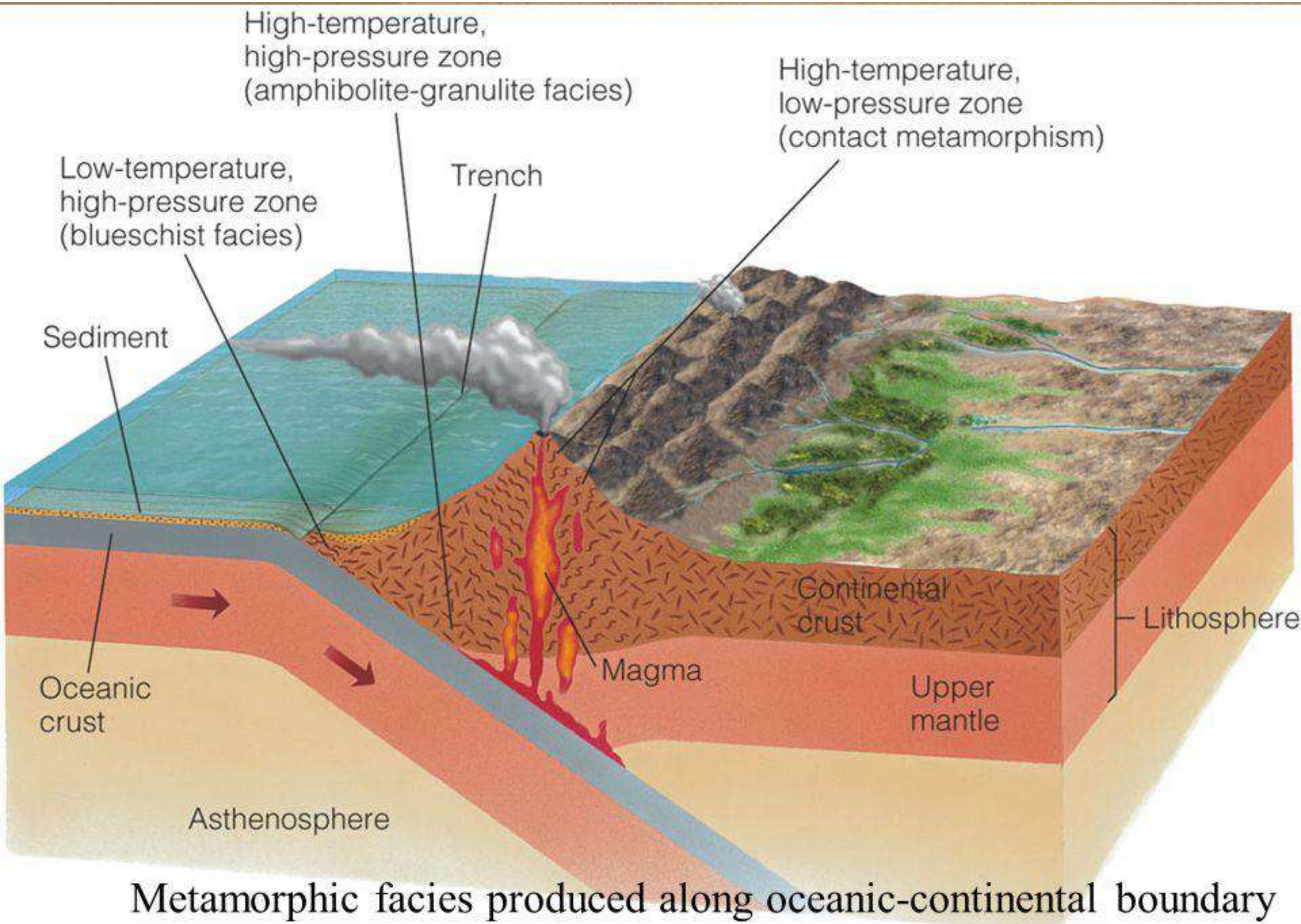




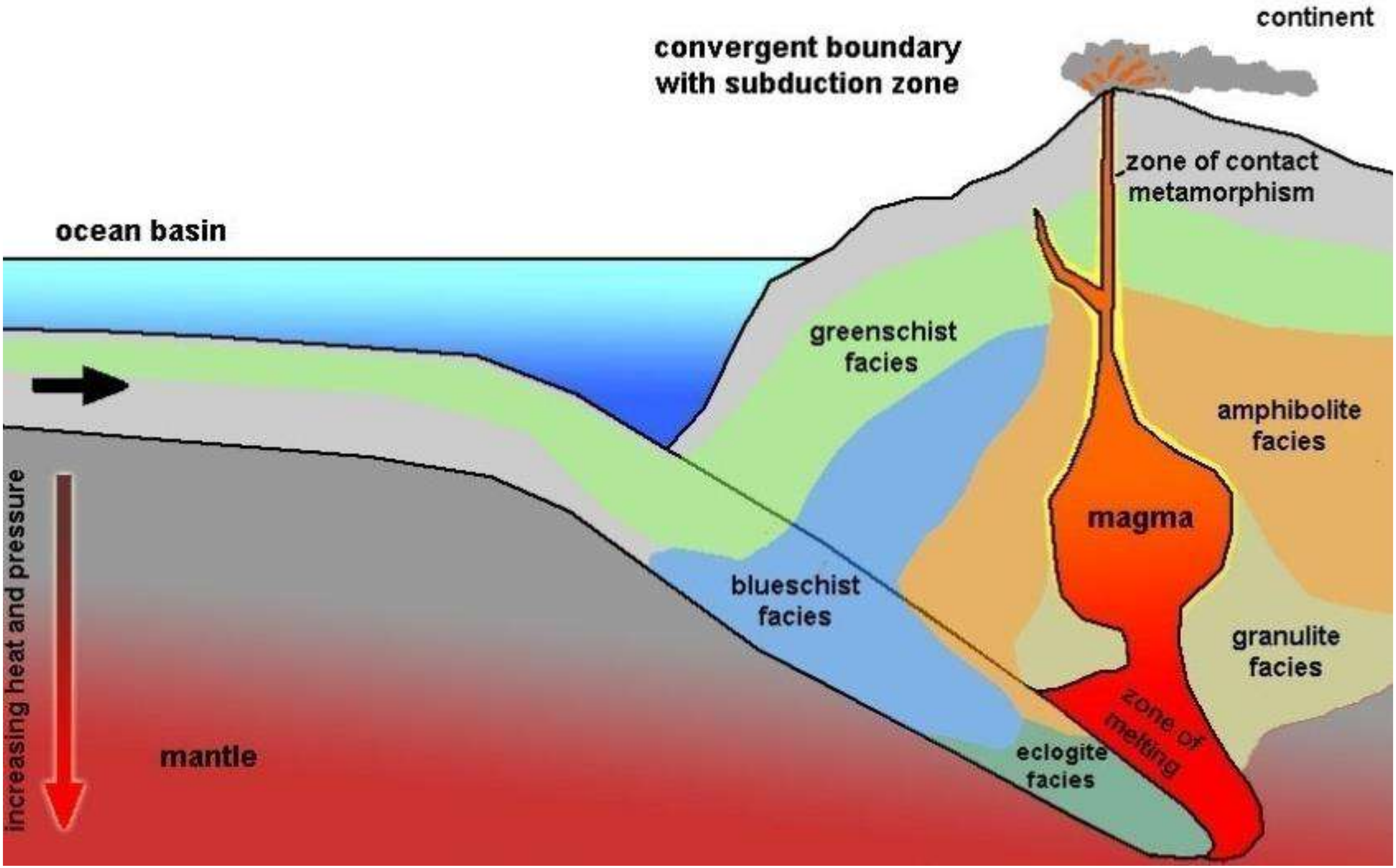
Accretinoary wedge


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
Oceanic crust
Lithosphere
Asthenosphere
400°C
600°C
1
2
3
4
5

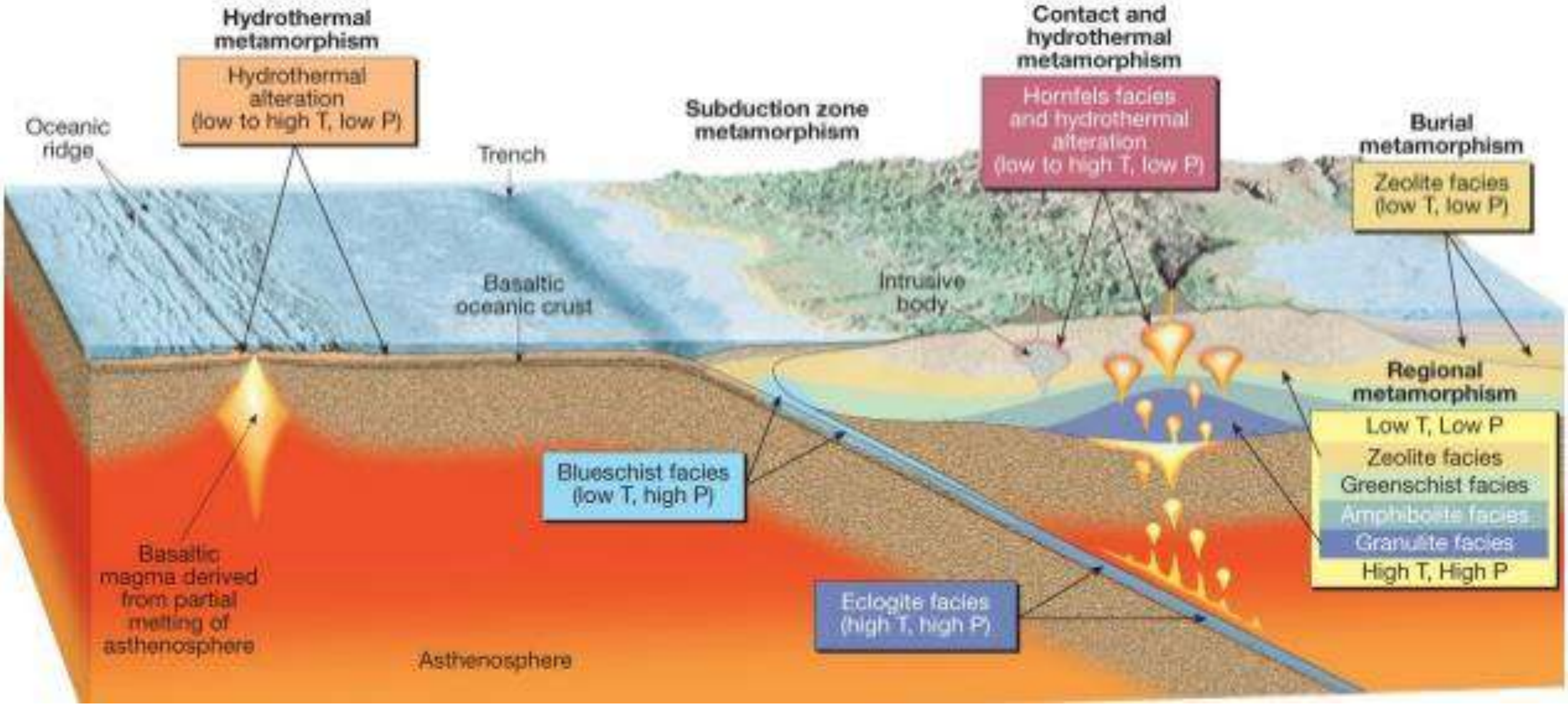

Continental crust
Increasing grade of metamorphism
-200° C
-400° C
-600° C
-800° C
Melting starts
Mantle
Temperature (C°)
200
400
600
800
Region of diagenesis
Region of low-grade metamorphism
Region of high-grade metamorphism
Pressure and conditions not found in the crust
Region where melting starts
Pressure (atmospheres)
2000
4000
6000
8000
10,000
12,000
Depth (km)
5
10
15
20
25
30
35



Metamorphic facies produced along oceanic-continental boundary

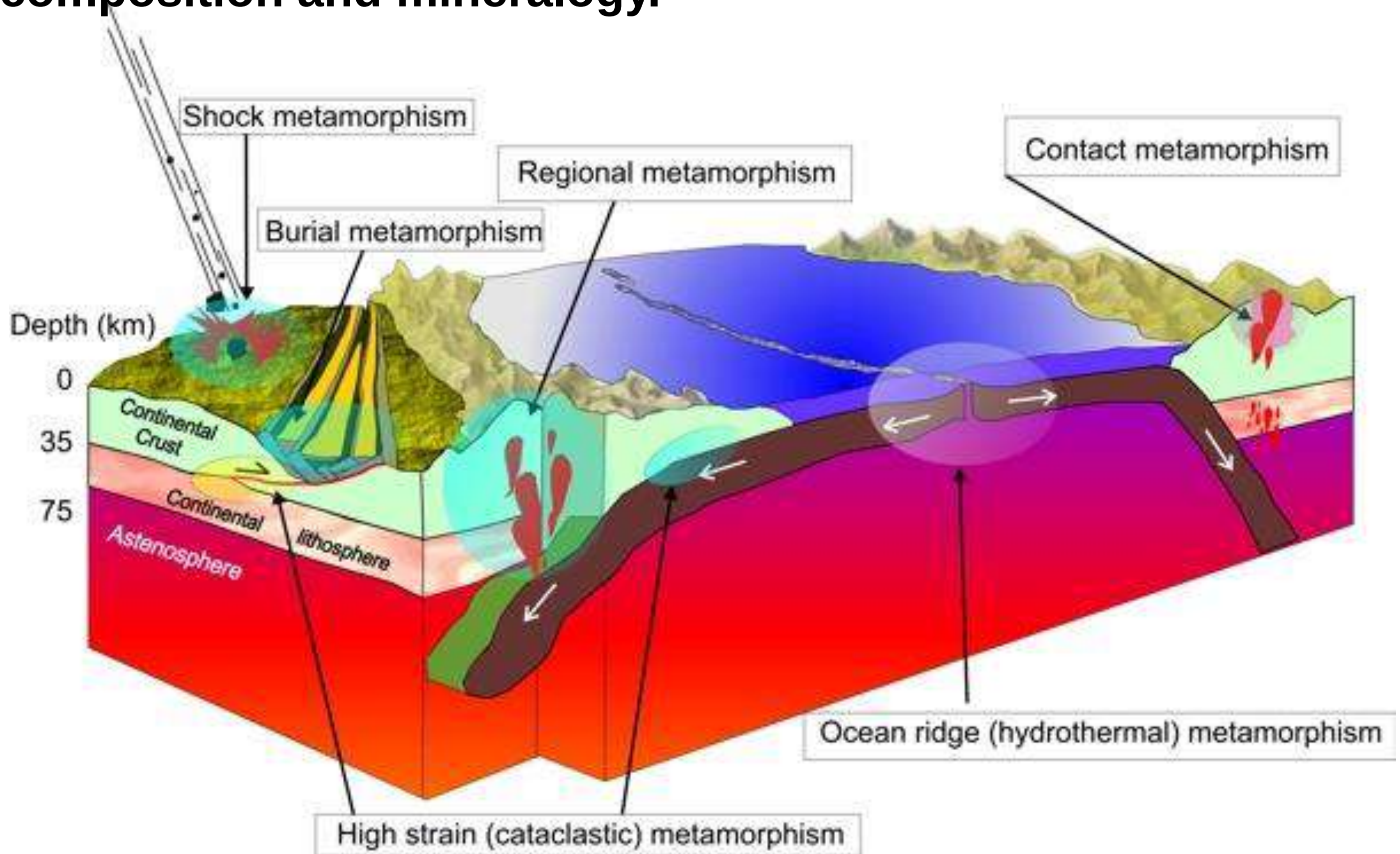


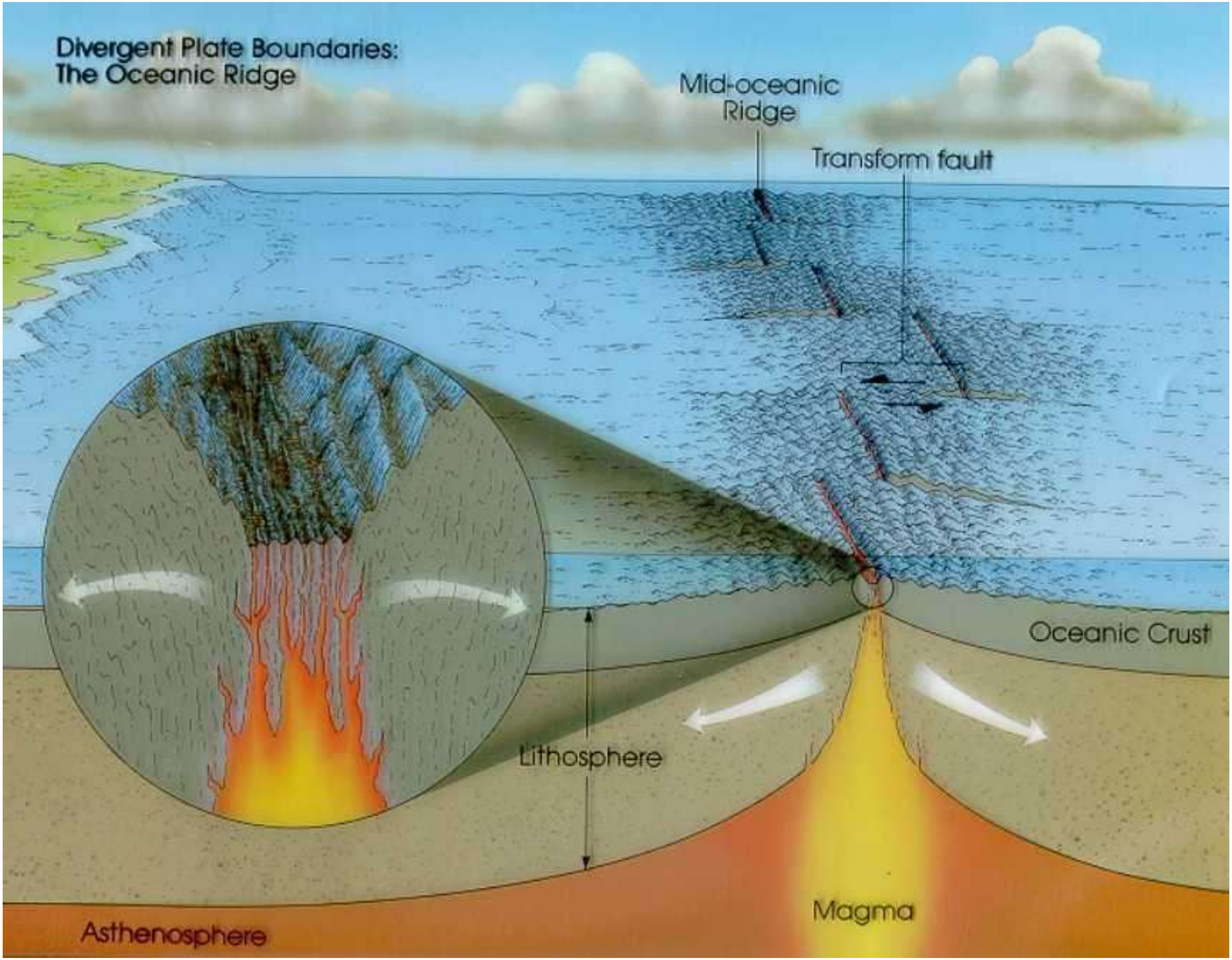
continent
convergent boundary with subduction zone
zone of contact metamorphism
ocean basin
greenschist facies
amphibolite facies
magma
blueschist facies
granulite facies
zone of melting
eclogite facies
mantle
increasing heat and pressure

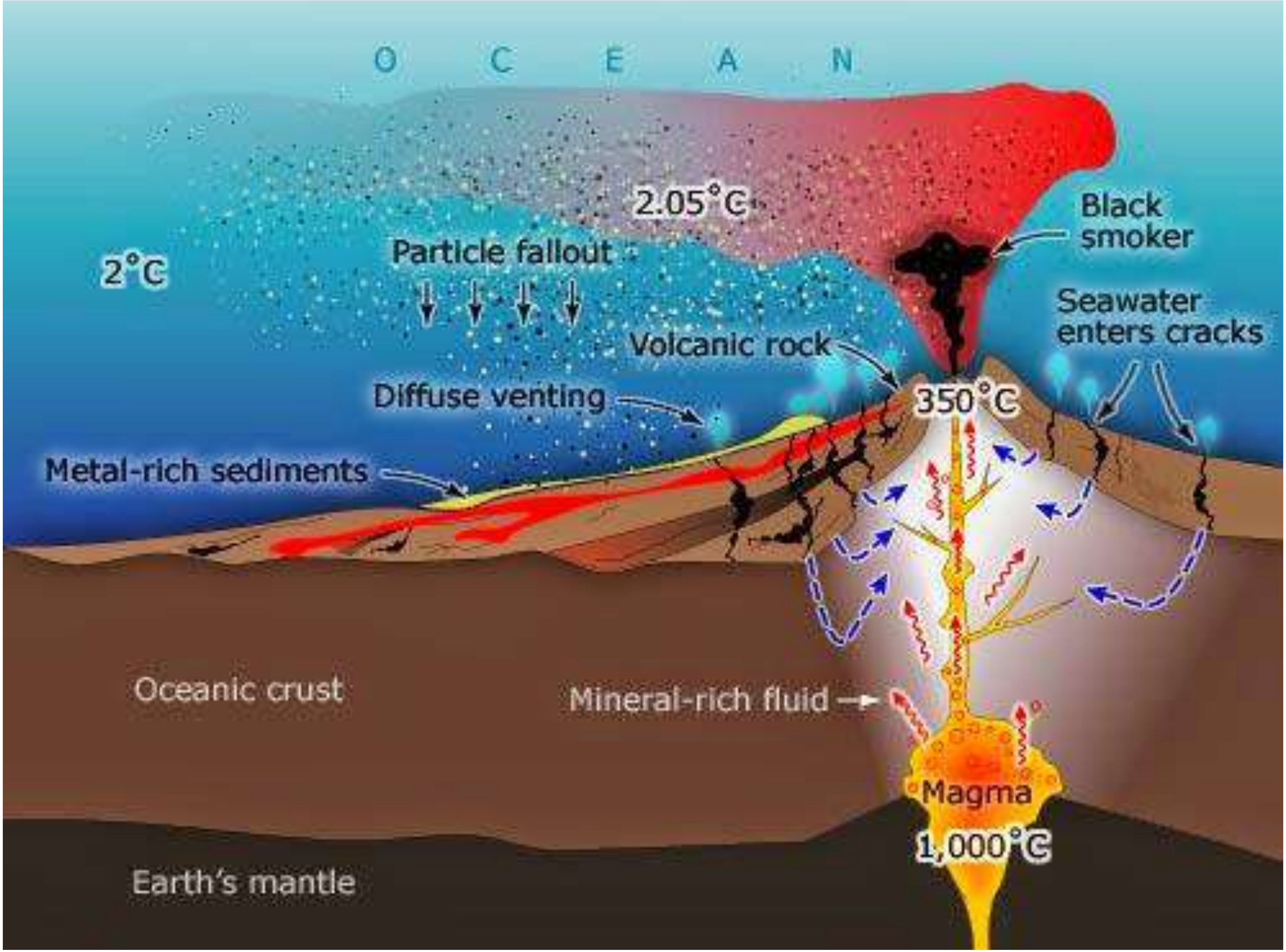

Hydrothermal metamorphism
Hydrothermal alteration (low to high T, low P)
Oceanic ridge
Trench
Subduction zone metamorphism
Contact and hydrothermal metamorphism
Hornfels facies and hydrothermal alteration (low to high T, low P)
Burial metamorphism
Zeolite facies (low T, low P)
Basaltic oceanic crust
Intrusive body
Regional metamorphism
Low T, Low P
Zeolite facies
Greenschist facies
Amphibolite facies
Granulite facies
High T, High P
Blueschist facies (low T, high P)
Eclogite facies (high T, high P)
Basaltic magma derived from partial melting of asthenosphere
Asthenosphere

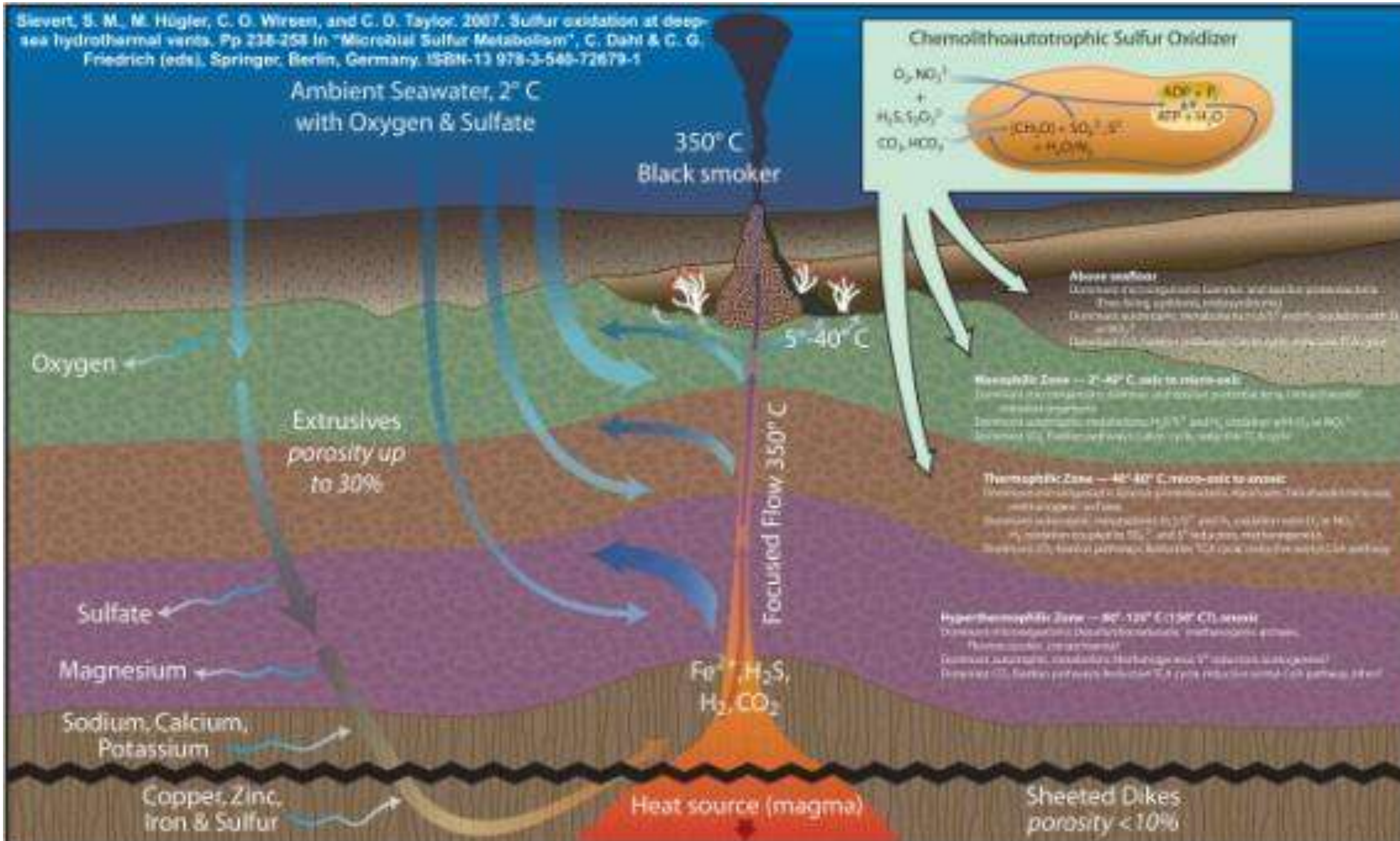
Divergent Plate Margin

A unique form of metamorphism occurs at divergent plate boundaries. New plate is created by the upwelling of hot mantle. Partial melting produces new oceanic crust through which water percolates, or convects, and is heated. Where it exits the rock, water temperatures can be as high 450 °C, and are commonly as high as 350 °C (high water pressure at the sea floor prevents boiling). As the heated water passes through the fresh basalt, it leaches out silica, iron, sulfur, manganese, copper and zinc. The basalt incorporates magnesium and sodium from the water, altering its composition and mineralogy.

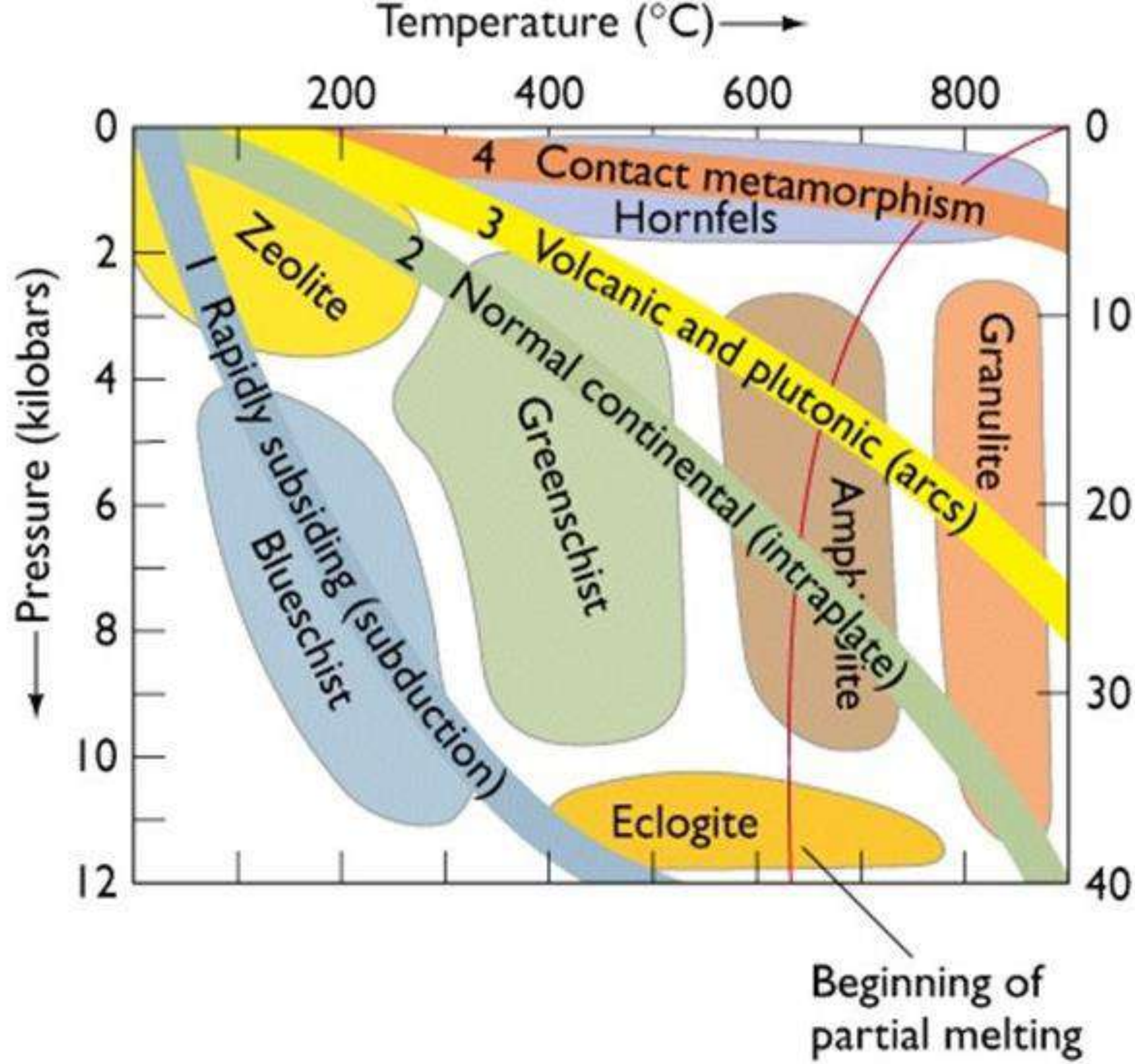



Divergent Plate Boundaries:
The Oceanic Ridge
Mid-oceanic
Ridge
Transform fault
Oceanic Crust
Lithosphere
Magma
Asthenosphere

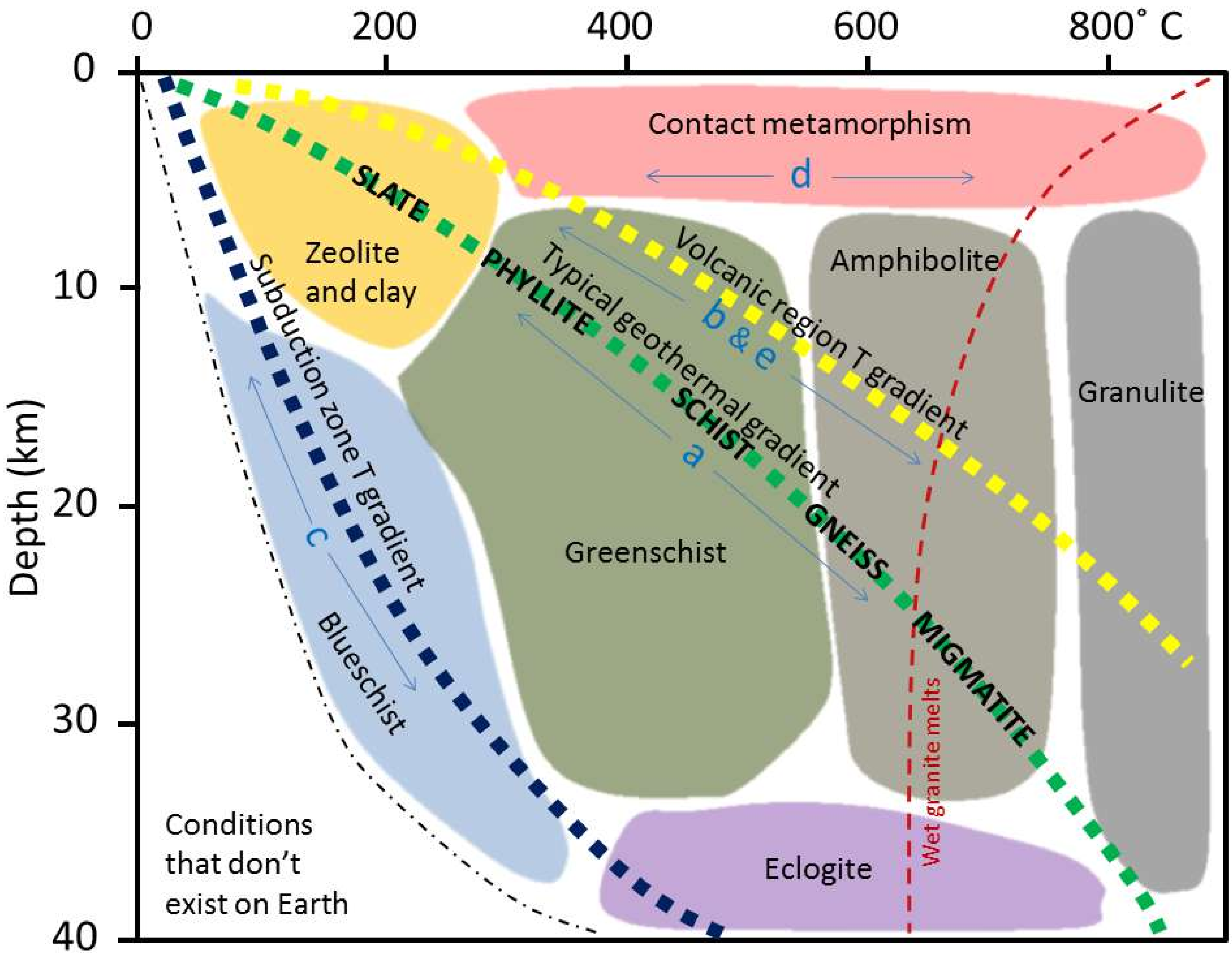

O C E A N
2.05°C
Black smoker
2°C
Particle fallout
Seawater enters cracks
Volcanic rock
Diffuse venting
350°C
Metal-rich sediments
Oceanic crust
Mineral-rich fluid
Magma
1,000°C
Earth's mantle

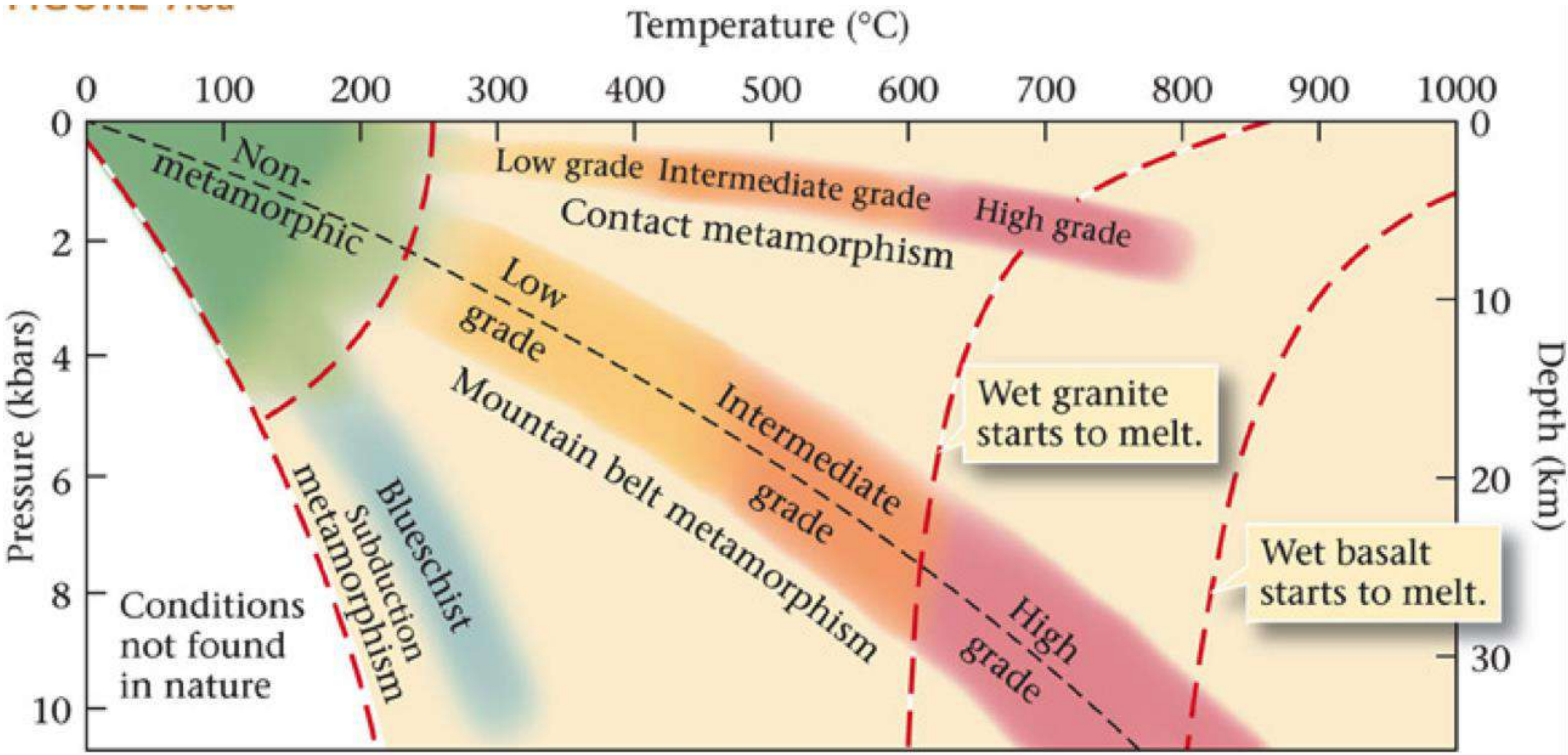


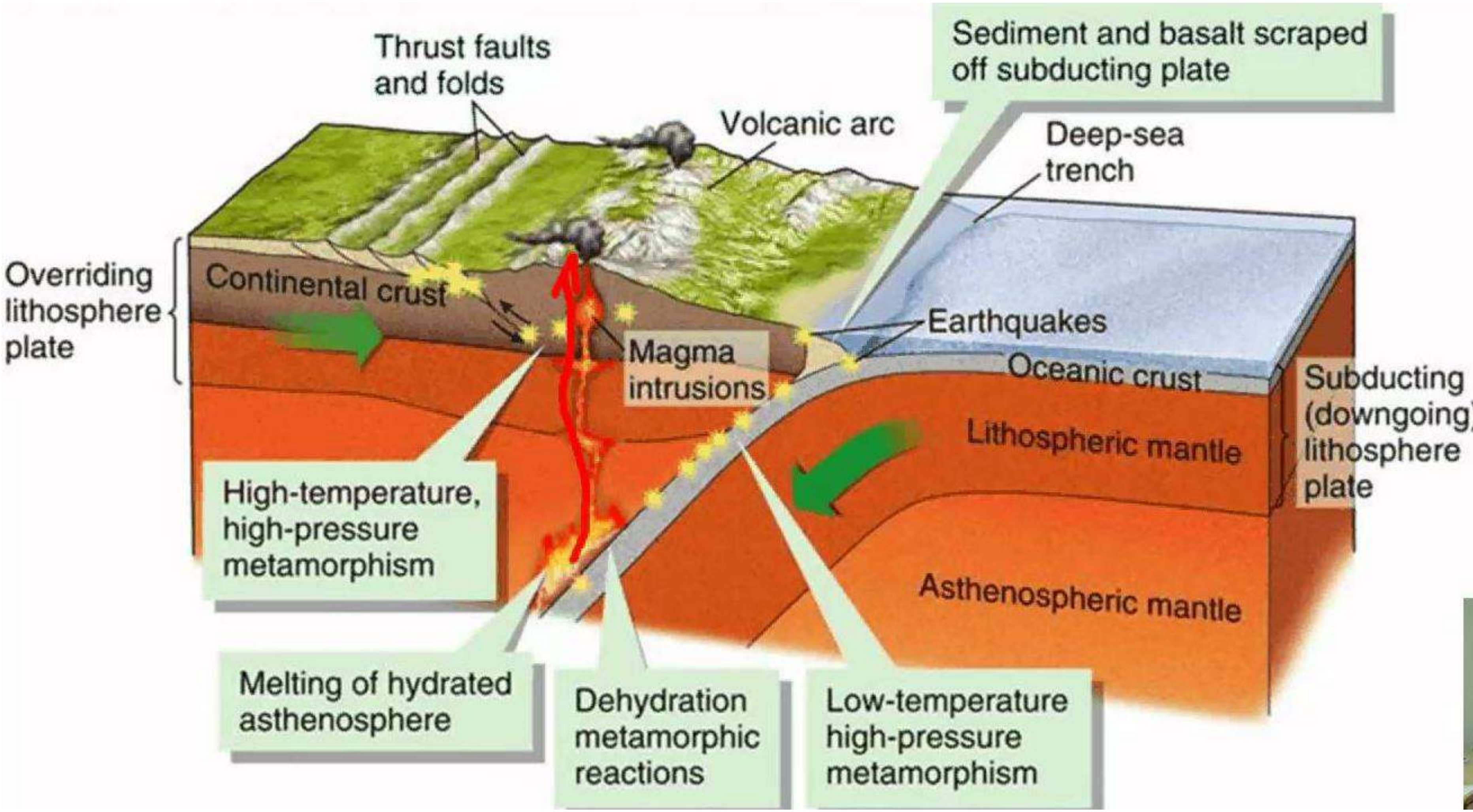
Sievert, S. M., M. Hügler, C. O. Wirsen, and C. O. Taylor. 2007. Sulfur oxidation at deep-sea hydrothermal vents. Pp 238-258 In "Microbial Sulfur Metabolism", C. Dahl & C. G. Friedrich (eds), Springer, Berlin, Germany. ISBN-13 978-3-540-72679-1
Ambient Seawater, 2° C
with Oxygen & Sulfate
350° C
Black smoker
Chemolithoautotrophic Sulfur Oxidizer
5°-40° C
Oxygen
Extrusives
porosity up to 30%
Focused Flow 350° C
Sulfate
Magnesium
Sodium, Calcium, Potassium
Copper, Zinc, Iron & Sulfur
Heat source (magma)
Sheeted Dikes
porosity <10%

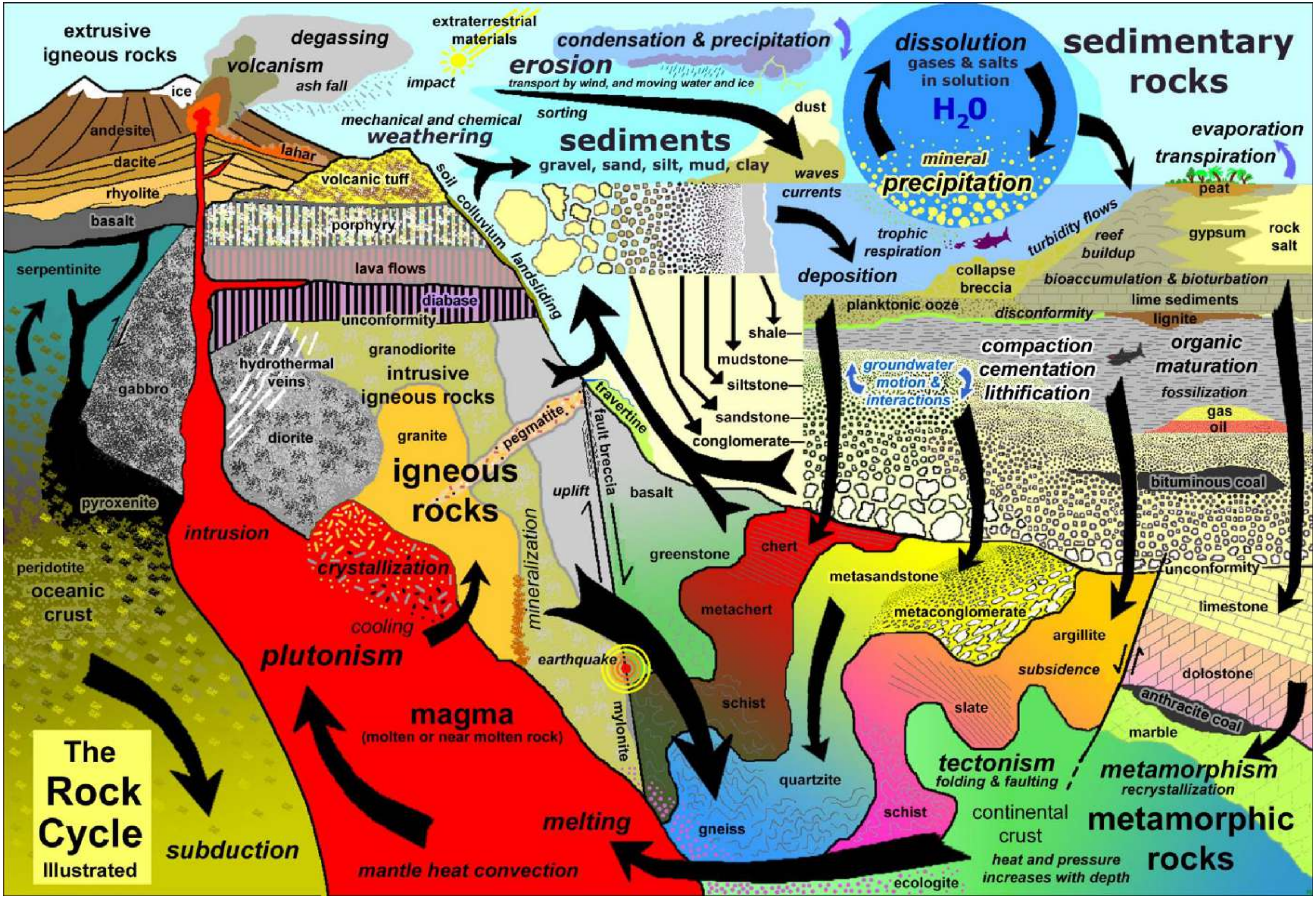

Temperature (°C)
200
400
600
800
0
2
4
6
8
10
12
Pressure (kilobars)
0
10
20
30
40
Depth (km)
4 Contact metamorphism
Hornfels
3 Volcanic and plutonic (arcs)
2 Normal continental (intraplate)
1 Rapidly subsiding (subduction)
Zeolite
Greenschist
Blueschist
Granulite
Eclogite
Beginning of
partial melting

https://opentextbc.ca/geology/chapter/7-3-plate-tectonics-and-metamorphism/




Temperature (°C)
0
100
200
300
400
500
600
700
800
900
1000
Pressure (kbars)
0
2
4
6
8
10
Depth (km)
0
10
20
30
Non-metamorphic
Low grade
Intermediate grade
High grade
Contact metamorphism
Low grade
Intermediate grade
High grade
Mountain belt metamorphism
Blueschist
Subduction metamorphism
Conditions not found in nature
Wet granite starts to melt.
Wet basalt starts to melt.


Thrust faults and folds
Volcanic arc
Sediment and basalt scraped off subducting plate
Deep-sea trench
Overriding lithosphere plate
Continental crust
Magma intrusions
Earthquakes
Oceanic crust
Subducting (downgoing) lithosphere plate
Lithospheric mantle
Asthenospheric mantle
High-temperature, high-pressure metamorphism
Melting of hydrated asthenosphere
Dehydration metamorphic reactions
Low-temperature high-pressure metamorphism



extrusive igneous rocks
degassing
volcanism
ash fall
extraterrestrial materials
impact
condensation & precipitation
erosion
transport by wind, and moving water and ice
dissolution
gases & salts in solution
H_2O
sedimentary rocks
ice
andesite
dacite
rhyolite
basalt
lahar
volcanic tuff
porphyry
lava flows
diabase
unconformity
mechanical and chemical weathering
sorting
sediments
gravel, sand, silt, mud, clay
dust
waves
currents
mineral precipitation
evaporation
transpiration
peat
soil
colluvium
landsliding
trophic respiration
turbidity flows
reef buildup
gypsum
rock salt
deposition
collapse breccia
bioaccumulation & bioturbation
planktonic ooze
lime sediments
disconformity
lignite
serpentinite
gabbro
hydrothermal veins
granodiorite
intrusive igneous rocks
diorite
granite
pegmatite
igneous rocks
shale
mudstone
siltstone
sandstone
conglomerate
groundwater motion & interactions
compaction
cementation
lithification
organic maturation
fossilization
gas
oil
travertine
fault breccia
uplift
basalt
bituminous coal
pyroxenite
intrusion
crystallization
mineralization
greenstone
chert
metasandstone
unconformity
limestone
peridotite
oceanic crust
cooling
plutonism
metachert
metaconglomerate
argillite
subsidence
earthquake
dolostone
anthracite coal
schist
slate
marble
magma
(molten or near molten rock)
mylonite
quartzite
tectonism
folding & faulting
metamorphism
recrystallization
The Rock Cycle Illustrated
subduction
melting
gneiss
schist
continental crust
metamorphic rocks
mantle heat convection
ecologite
heat and pressure increases with depth

End of Lecture