METAMORPHIC ROCKS & PROCESSES

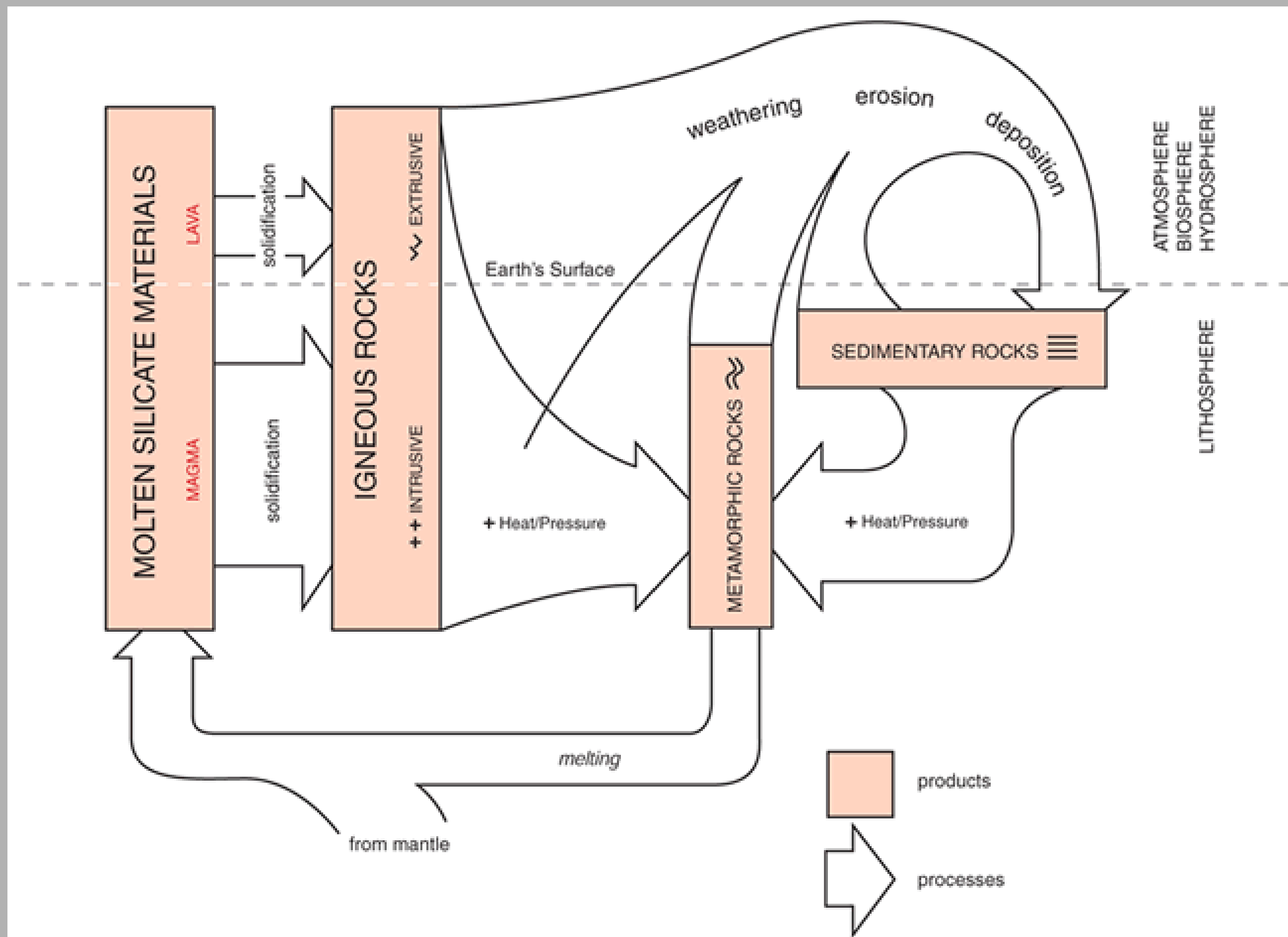
Lava flow (above) bakes mud layer (below) into a brick red shale during the process of CONTACT metamorphism

Metamorphic rocks and processes

- Metamorphism comes from the Greek words

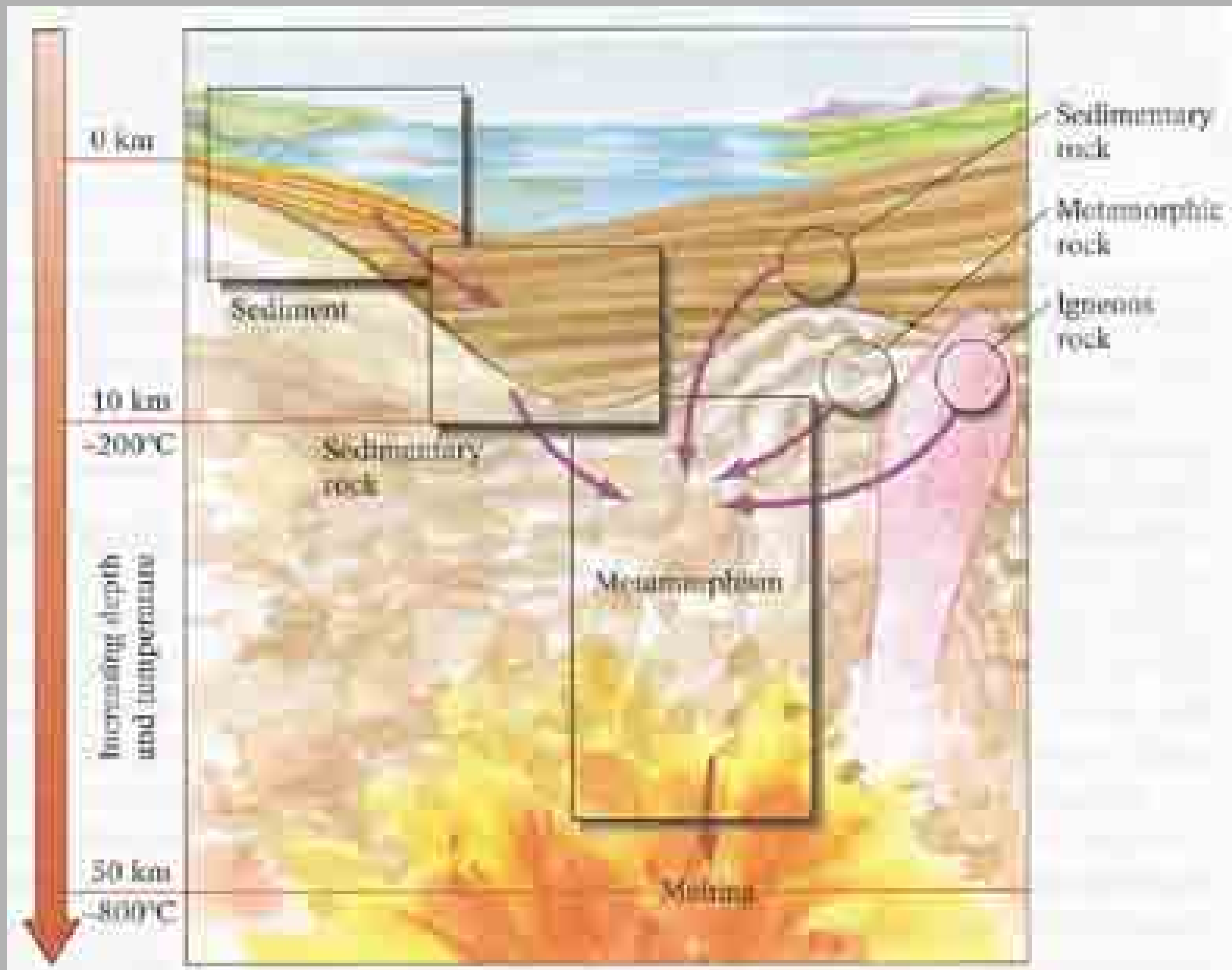
  "Meta" - change

  "Morphe" - form
- Metamorphic rocks form by solid-state (no melting) transformation of preexisting rock by processes that take place beneath Earth's surface.
- Chemical, mineralogical and structural adjustments of solid rocks to physical and chemical changes at depths below the region of sedimentation



http://amonline.net.au/geoscience/images/earth_diagrams/rock_cycle.gif

Any rock can be metamorphosed



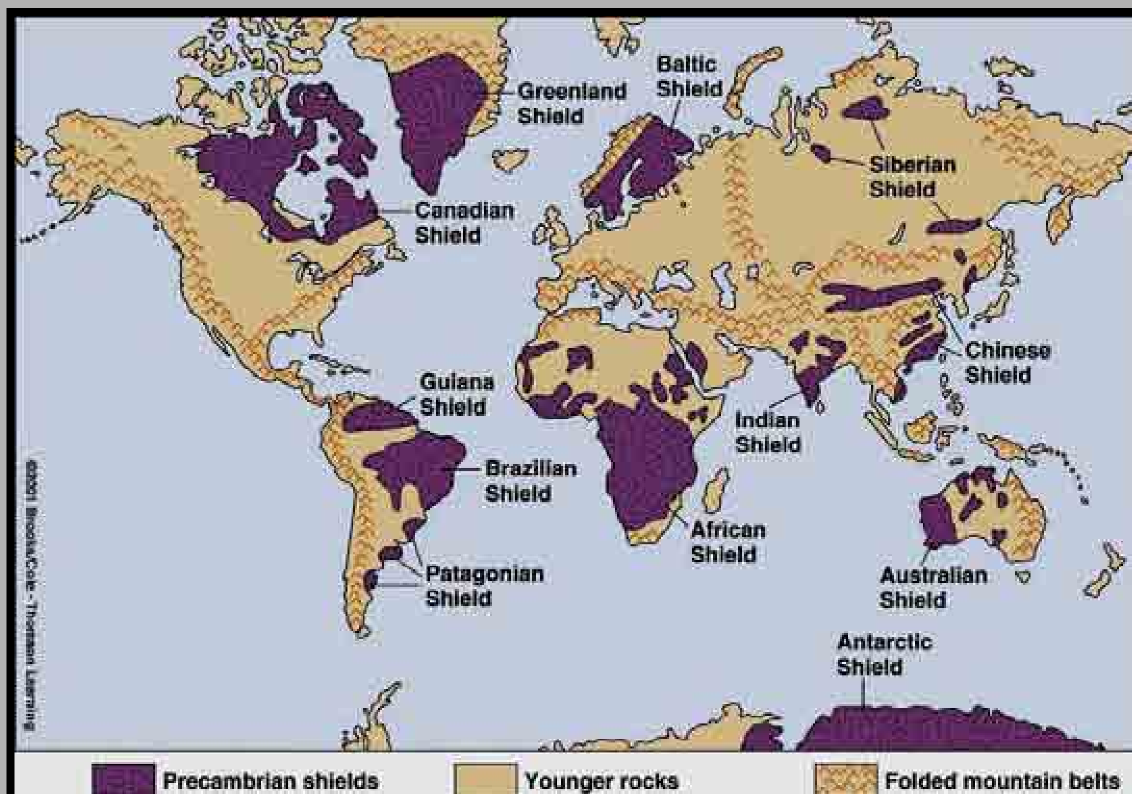
Chernicoff and Whitney (2002)

Why Study Metamorphic Rocks?

- Studies of metamorphic rocks provide insights into the physical and chemical changes that take place deep within Earth. The presence of index minerals in metamorphic rocks allows geologists to assess the temperatures and pressures the parent rock encountered.
- Knowledge of metamorphic processes and rocks is valuable, because metamorphic minerals and rocks have economic value. For example, slate and marble are building materials, garnets are used as gemstones and abrasives, talc is used in cosmetics, paints, and lubricants, and asbestos is used for insulation and fireproofing.

Why Study Metamorphic Rocks?

Metamorphic rocks are some of the oldest on Earth, are widely exposed in the core areas, known as shields, of continents, and make up a large portion of the roots of mountain ranges.



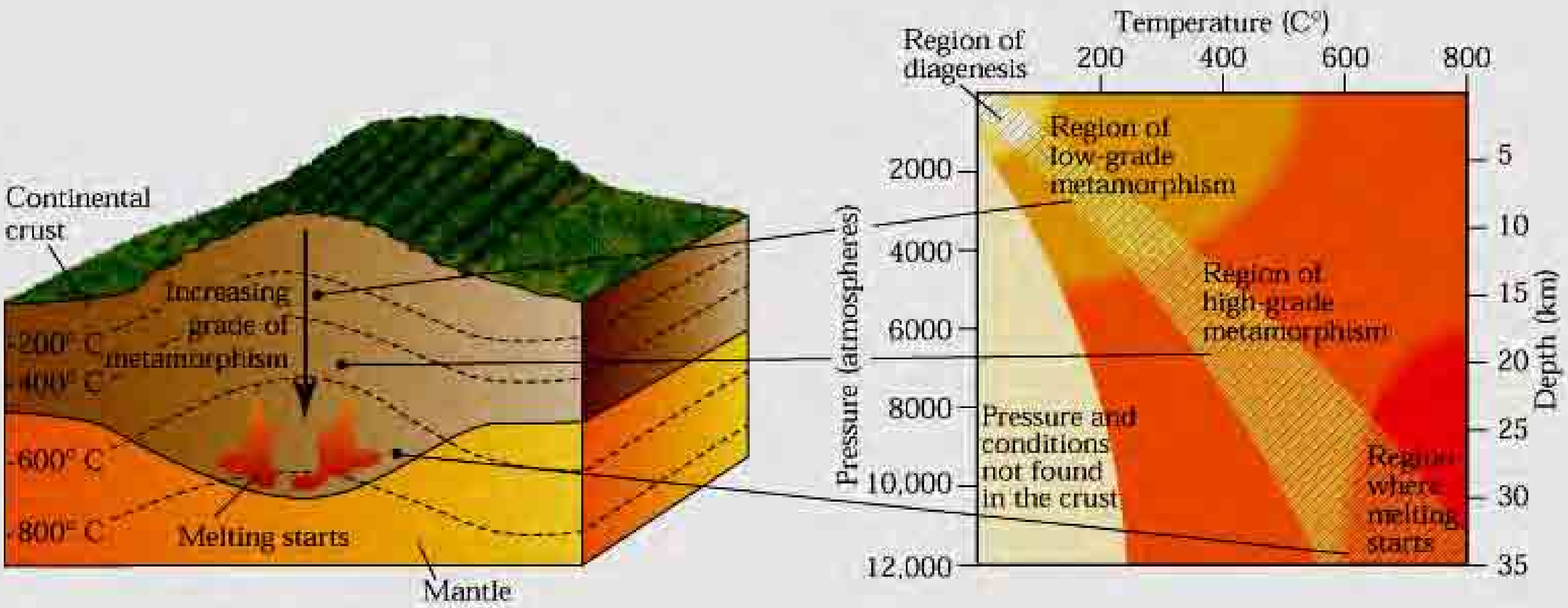
Wicander and Monroe (2002)

Why Study Metamorphic Rocks?

Chernicoff and Whitney (2002)

Limits of metamorphism

- Metamorphism is a response to the Earths geothermal gradient (~30°C/km)
- At ~5km the temperature is ~150°C this is the point at which diagenesis ends and metamorphism begins

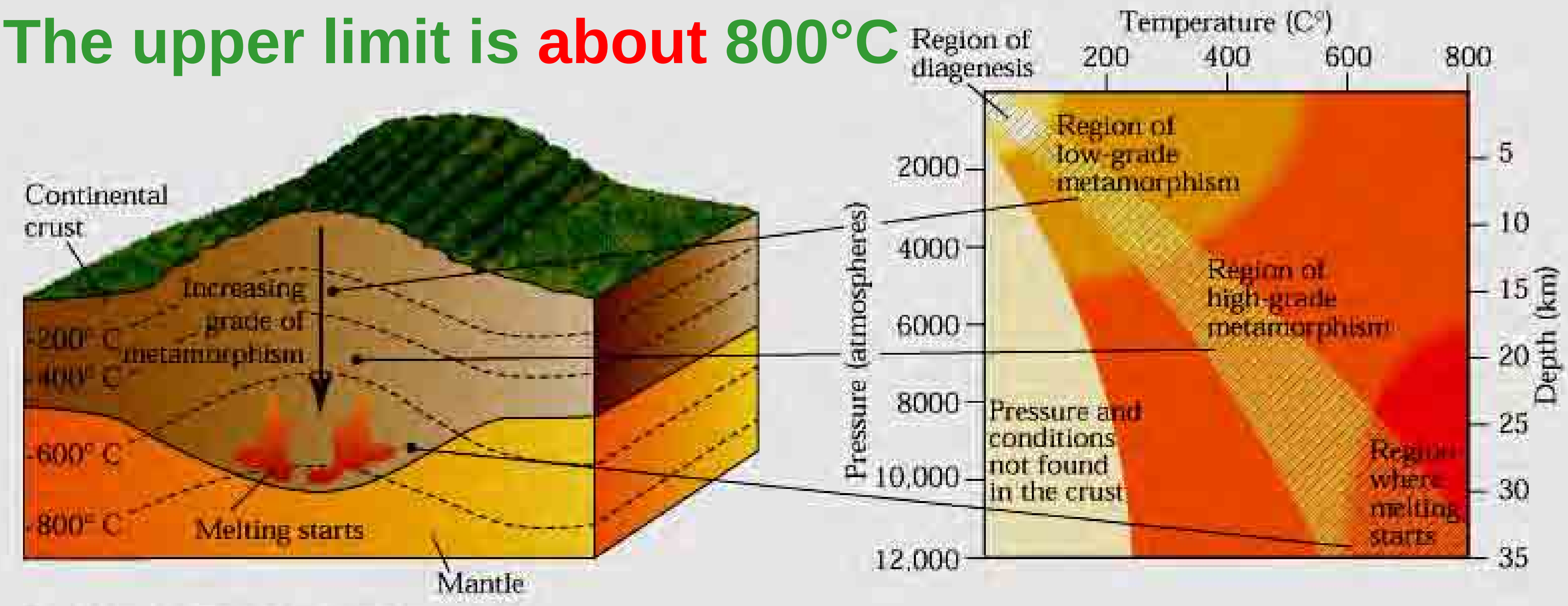


Murck and Skinner (1999)

Limits of metamorphism

- 5 km is also the point at which pressure is high enough for recrystallisation and new mineral growth (1500 times atmosphere)

The upper limit is about 800°C



Murck and Skinner (1999)

Agents of Metamorphism

There are three main sources of chemically active fluids:

- pore waters of sedimentary rocks,
- fluids from cooling magma,
- water from dehydration of water-bearing minerals like gypsum ($CaSO_4 . 2H_2O$)

Pore fluids

- As well as transporting material pore fluids act as a reservoir
- As pressure and temperature increase material is transferred from the fluid to the minerals and vice versa
- In this way fluids serve to catalyse the reactions
- Metamorphism will drive fluids out of hydrous minerals forming veins

The Role of Fluids

- An example of metamorphism by fluid activity is seawater moving through the hot basalt of the oceanic crust. Olivine in the basalt is transformed to the mineral serpentine.

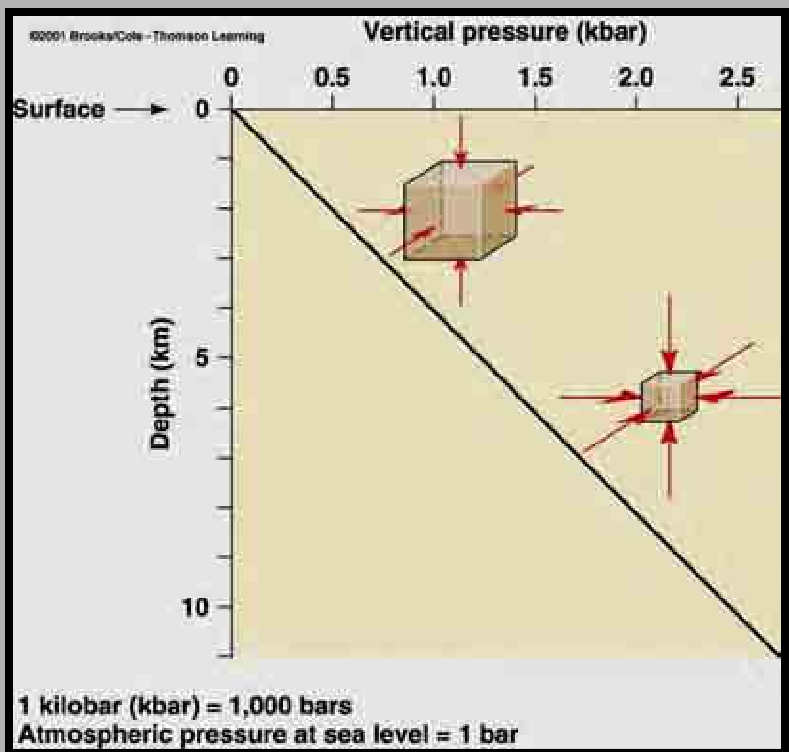
$$2Mg_2SiO_4 + 2H_2O \rightarrow Mg_3Si_5O_5(OH)_4 + MgO$$

olivine	water		serpentine	carried away in solution

olivine **water** **serpentine** **carried away in solution**

Pressure

Lithostatic pressure results from the weight of overlying rocks, is applied equally in all directions, and increases with depth of burial.



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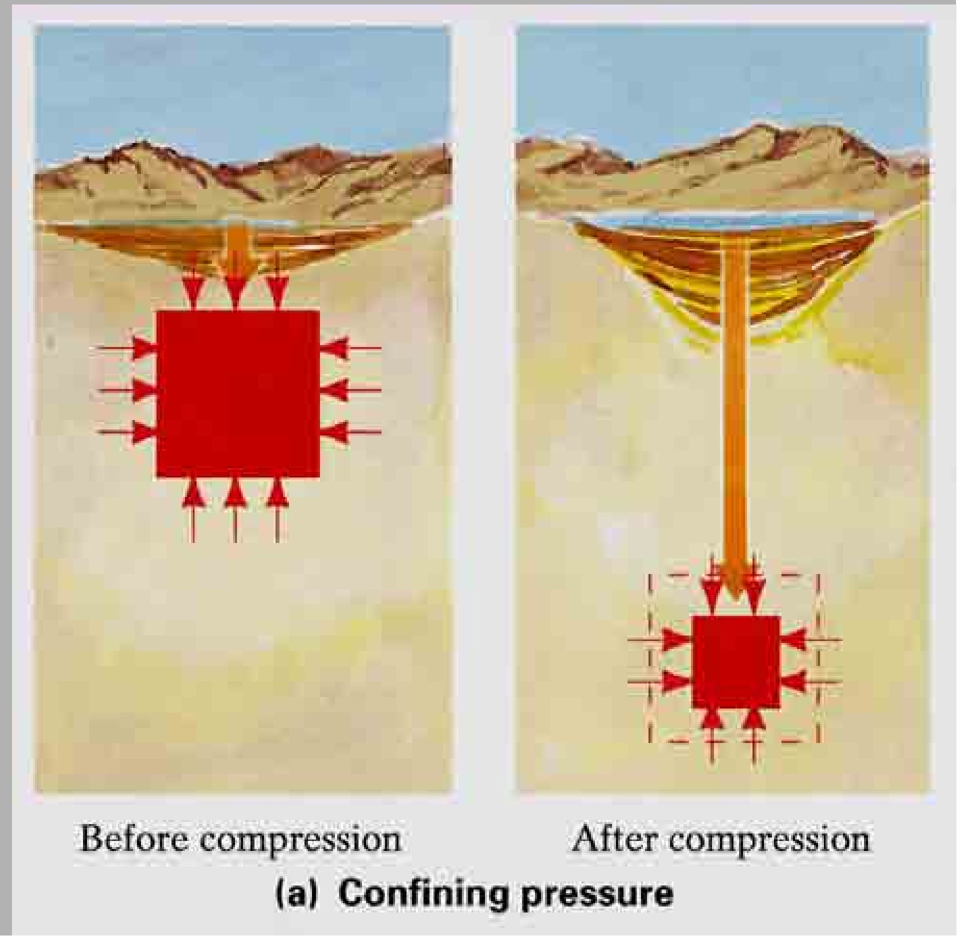

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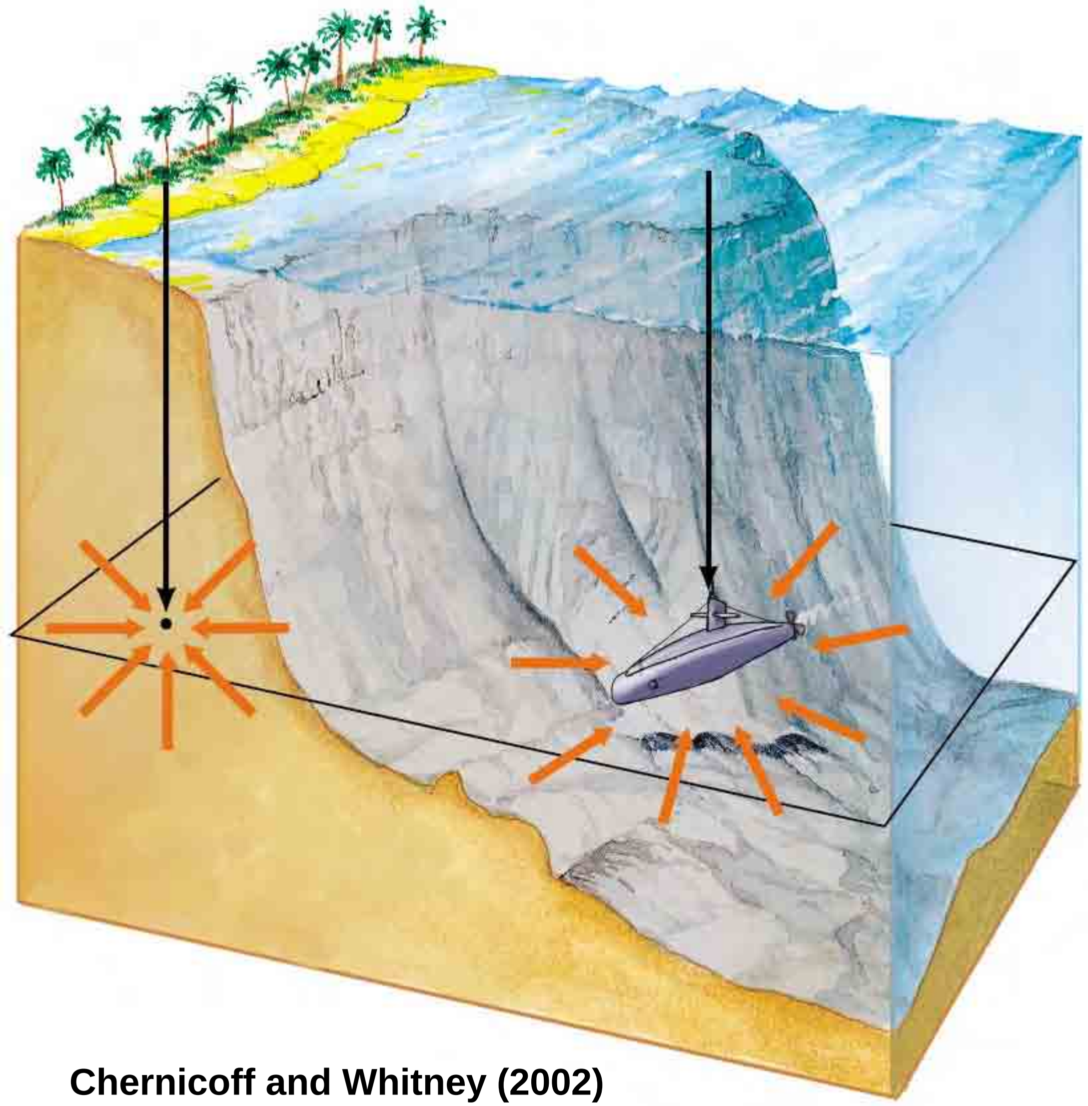
Pressure

The minerals of parent rocks subjected to increasing lithostatic pressure recrystallize as smaller and denser minerals. The pressure increase with depth in the ocean is similar to lithostatic pressure.



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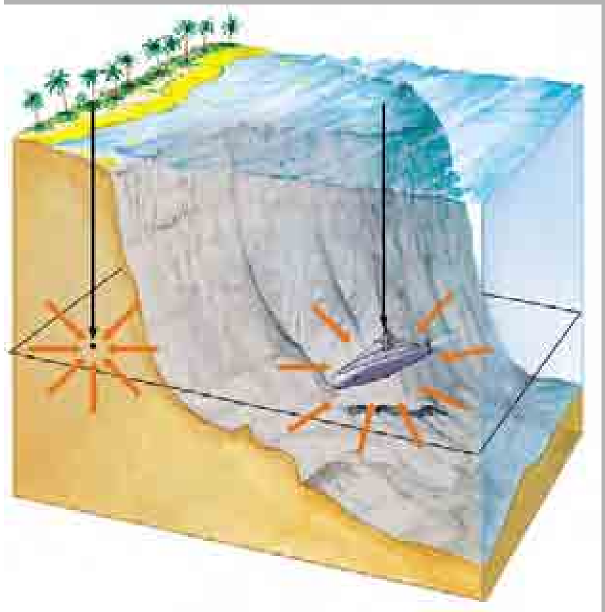
Pressure

Styrofoam cups lowered to great depths in the ocean decrease in volume, but keep their general shape.



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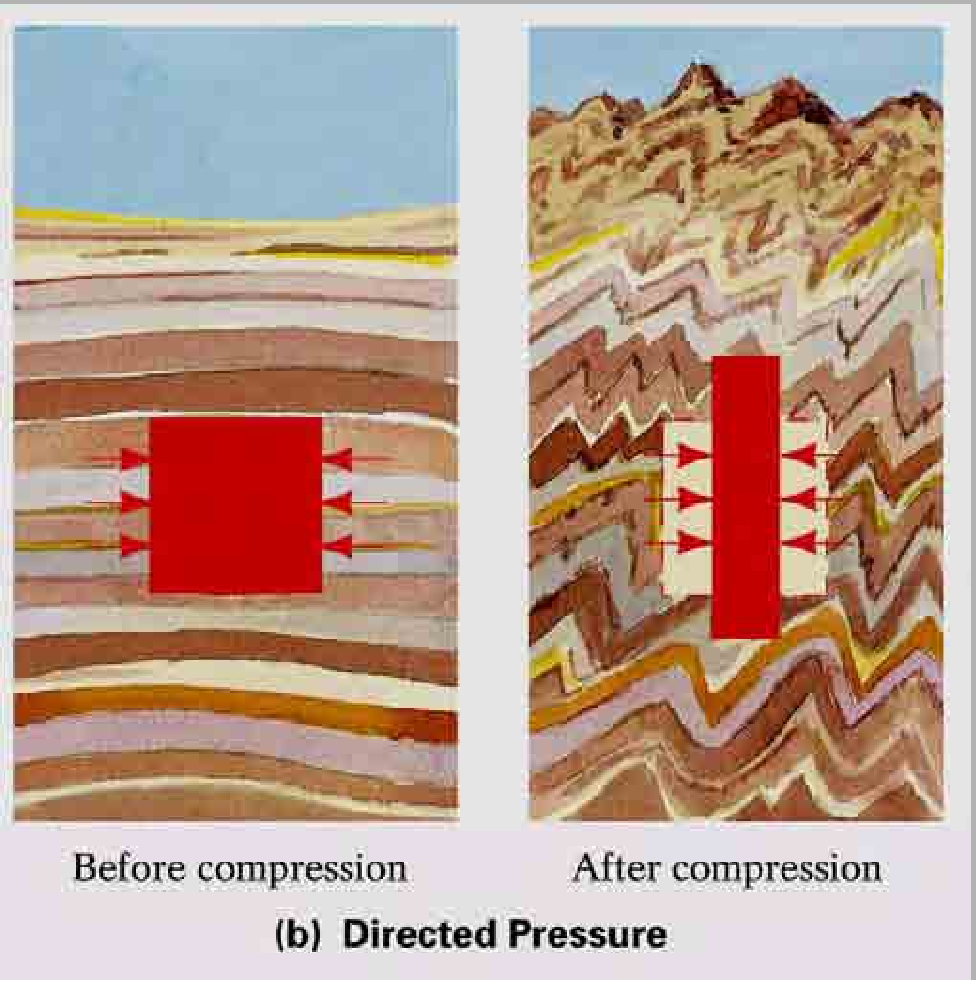
Directed pressure

Most metamorphic rocks form under conditions of differential stress



Chernicoff and Whitney (2002)

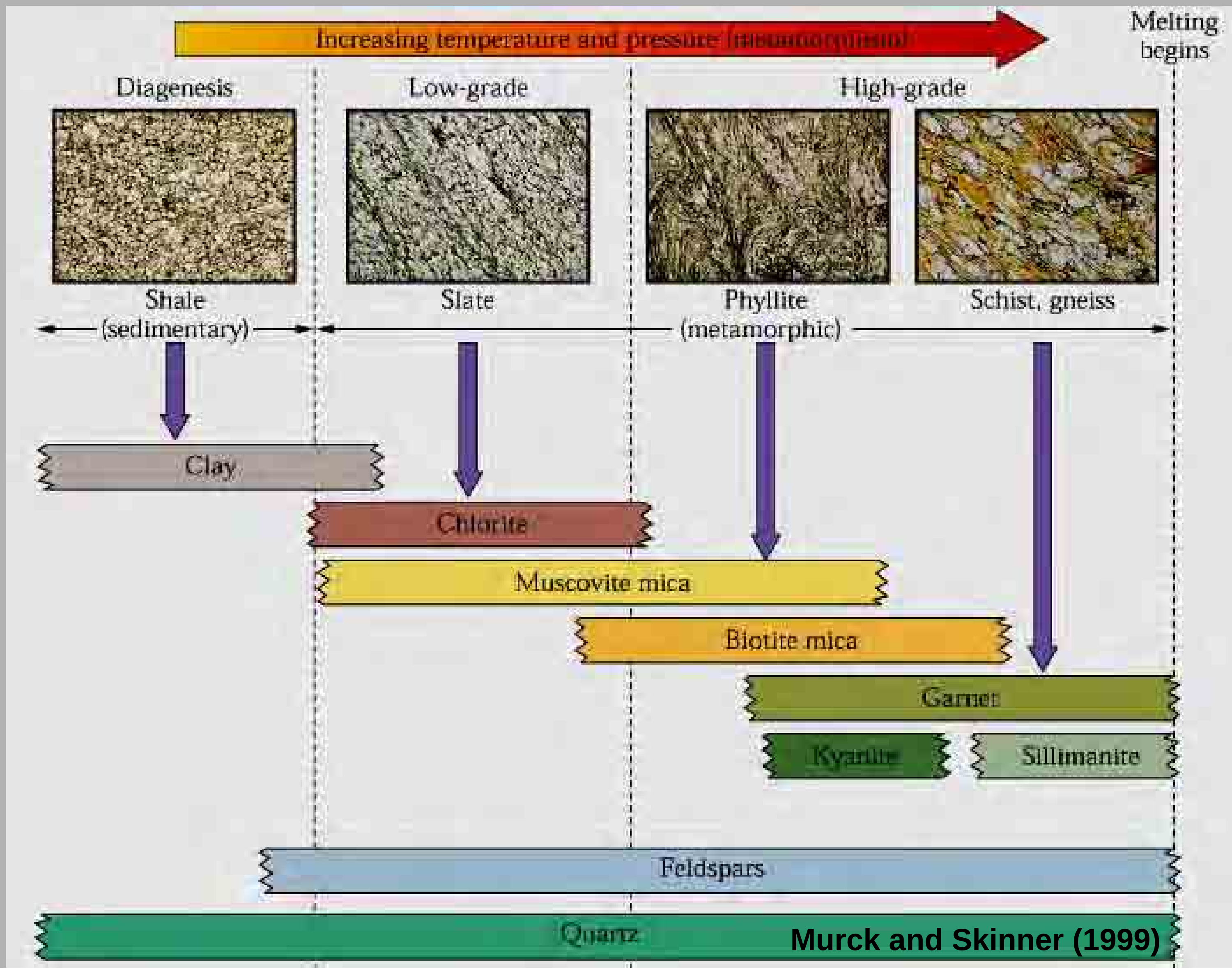
Pressure

Differential pressure refers to the conditions where pressure is greater in one direction than in another. It is associated with deformation and mountain building and produces distinctive metamorphic textures and features. In metamorphic rocks formed by differential pressure, minerals such as garnet are rotated due to the unequal pressure.

Temperature

- Heat increases the rate of the chemical reactions that yield new minerals as parent rocks are metamorphosed.
- The heat may come from magma intrusion or deep burial via subduction at convergent boundaries.
- In country rock surrounding a magma body, heat’s effect decreases with distance from the magma body.

Heat



Murck and Skinner (1999)

Time

- The chemical reactions involved in metamorphism are relatively slow
- The longer the metamorphic event lasts the larger the grain size
- It is thought that coarse grained metamorphic rocks took millions of years to form
- But temperature, pressure and fluid content are more important

Causes of metamorphism

The processes that cause metamorphism are

- Mechanical deformation
- Chemical recrystallisation

Mechanical processes include grinding, crushing & fracturing

Deformed conglomerate
Murck and Skinner (1999)

Three types of metamorphism

Chemical recrystallisation includes changes in composition, growth of new minerals, recrystallisation and changes in pore fluid compositions

Murck and Skinner (1999)

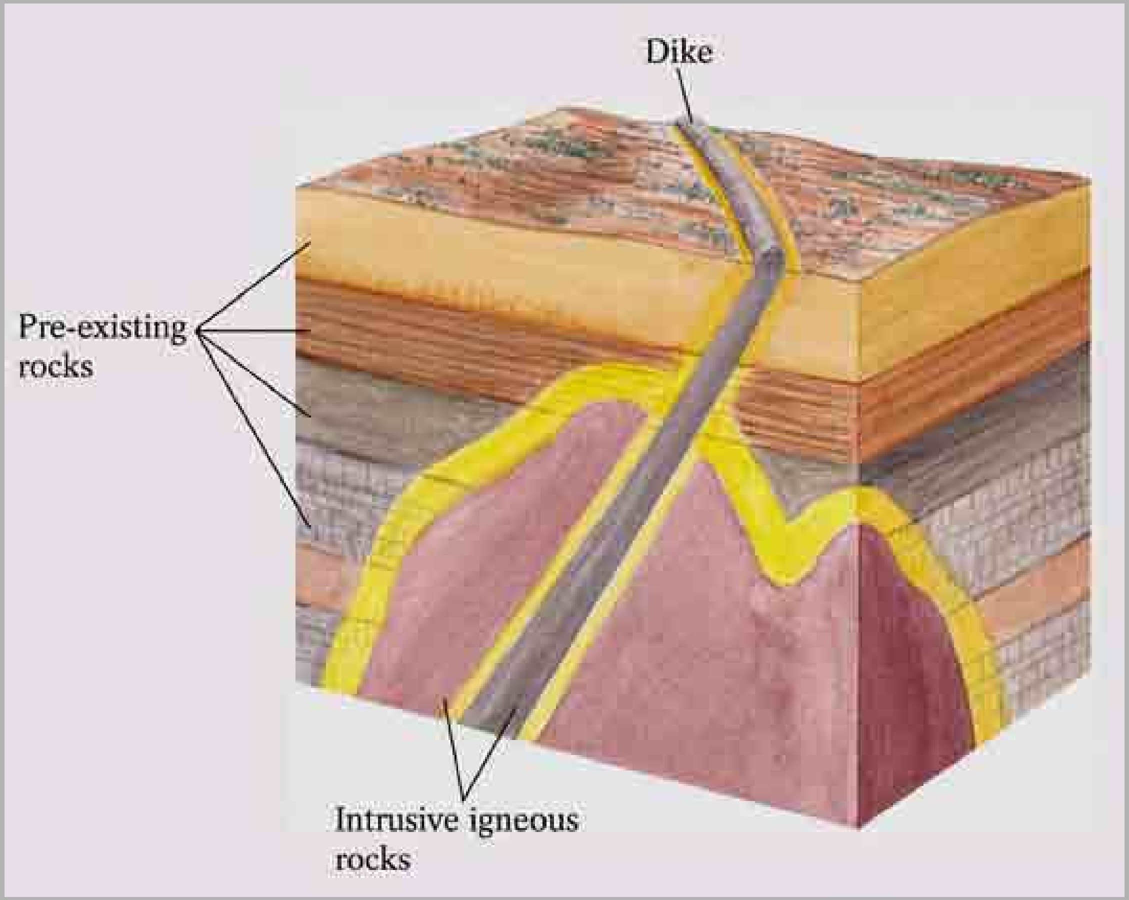
Metamorphism involves both chemical and mechanical changes but in varying proportions

Three types of metamorphism

- There are basically three types of metamorphism
  - Contact metamorphism (heat)
  - Dynamic metamorphism (pressure)
  - Regional metamorphism (heat & pressure)

Contact Metamorphism

Contact metamorphism occurs when heat or release of chemically active fluids from a magma or lava body alter the adjacent country rock.



Chernicoff and Whitney (2002)

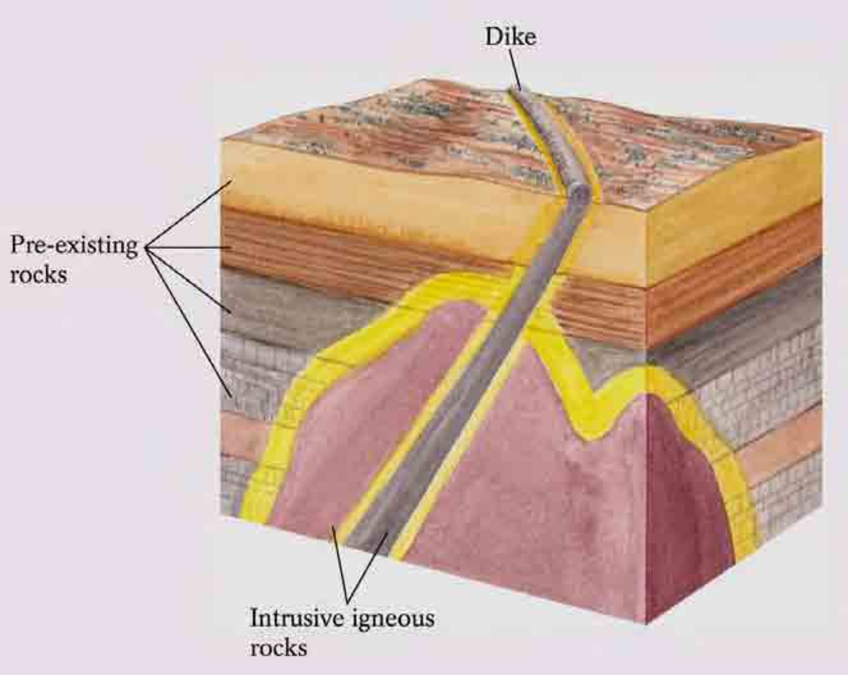
Contact metamorphism

Chernicoff and Whitney (2002)

Contact Metamorphism

- Two types of contact metamorphism are recognized:
  - alteration due to baking of country rock
  - alteration due to hot chemically active solutions, known as hydrothermal alteration.

Many rocks produced by baking are hard and fine-grained with a porcelain-like texture.



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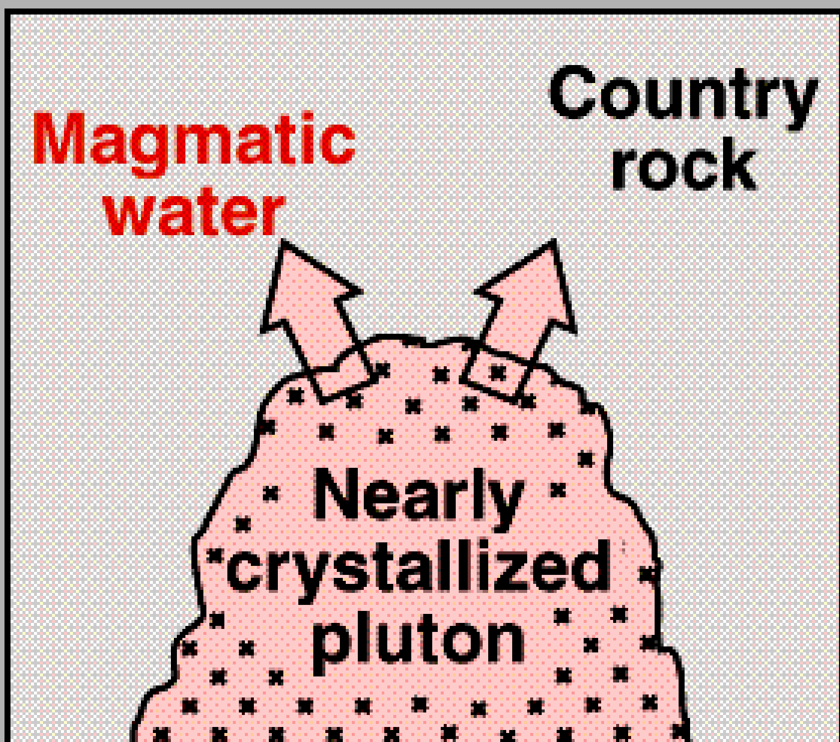
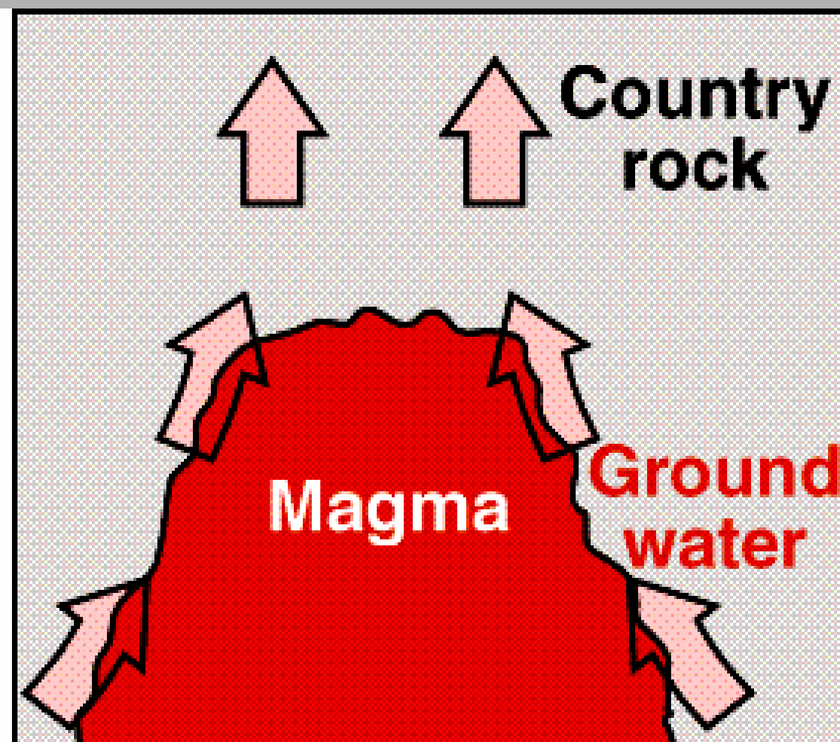
Contact Metamorphism

Hydrothermal alteration

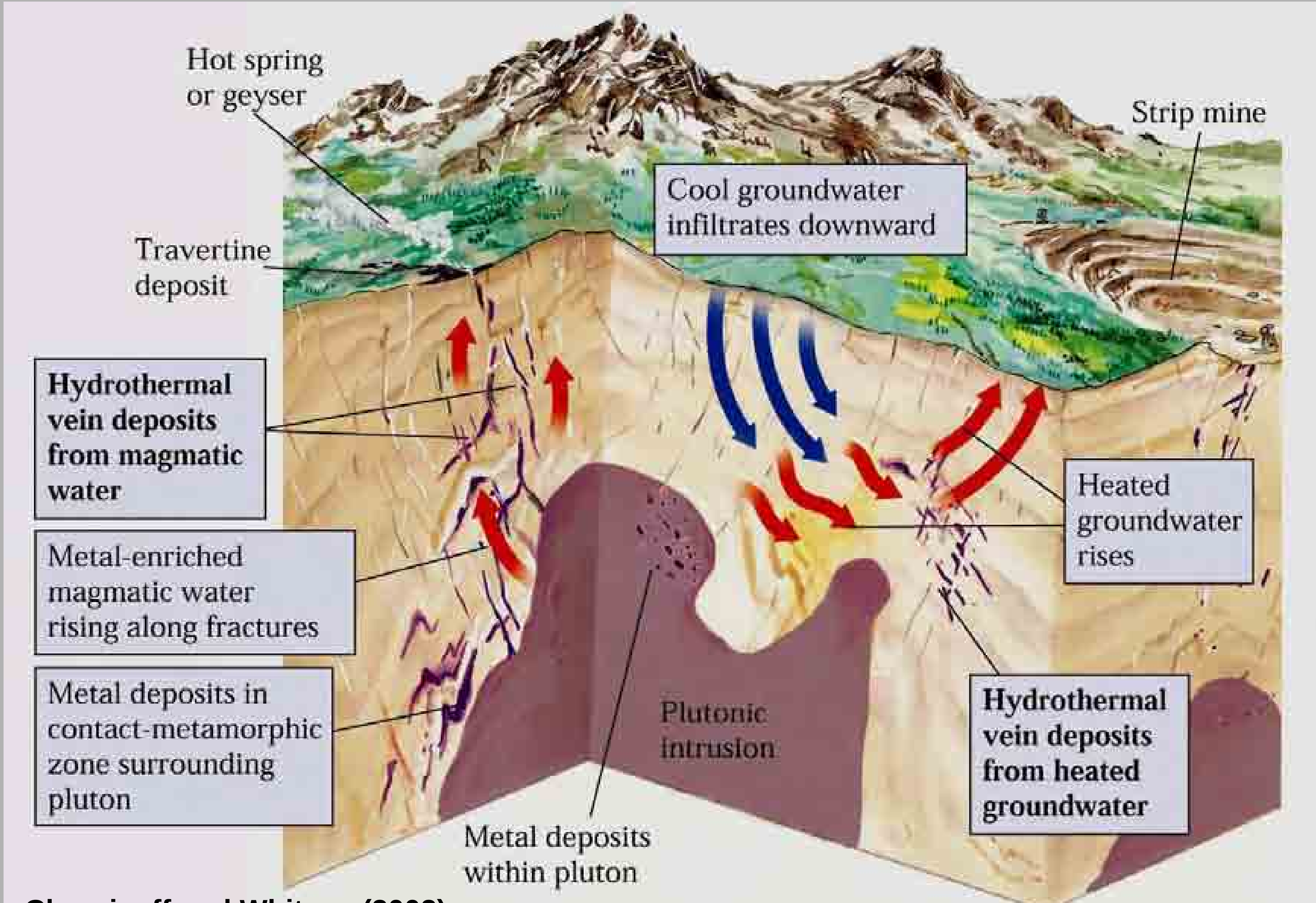
In the final stages of cooling, magma releases large volumes of hot, mineral-charged solutions into the surrounding country rock, which causes hydrothermal alteration.





Plummer et al. (2001)

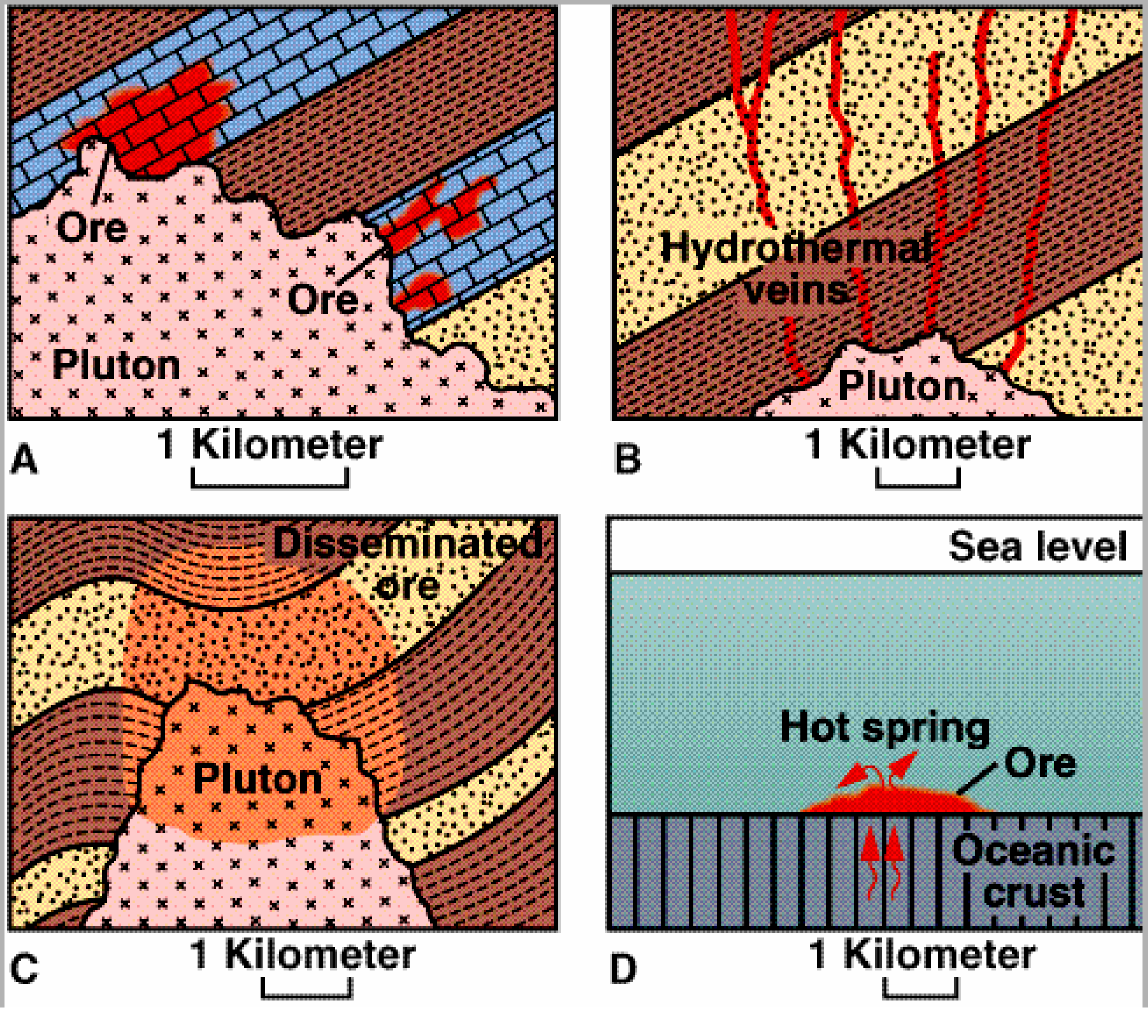
Hydrothermal processes



Chernicoff and Whitney (2002)

Hydrothermal ore deposits

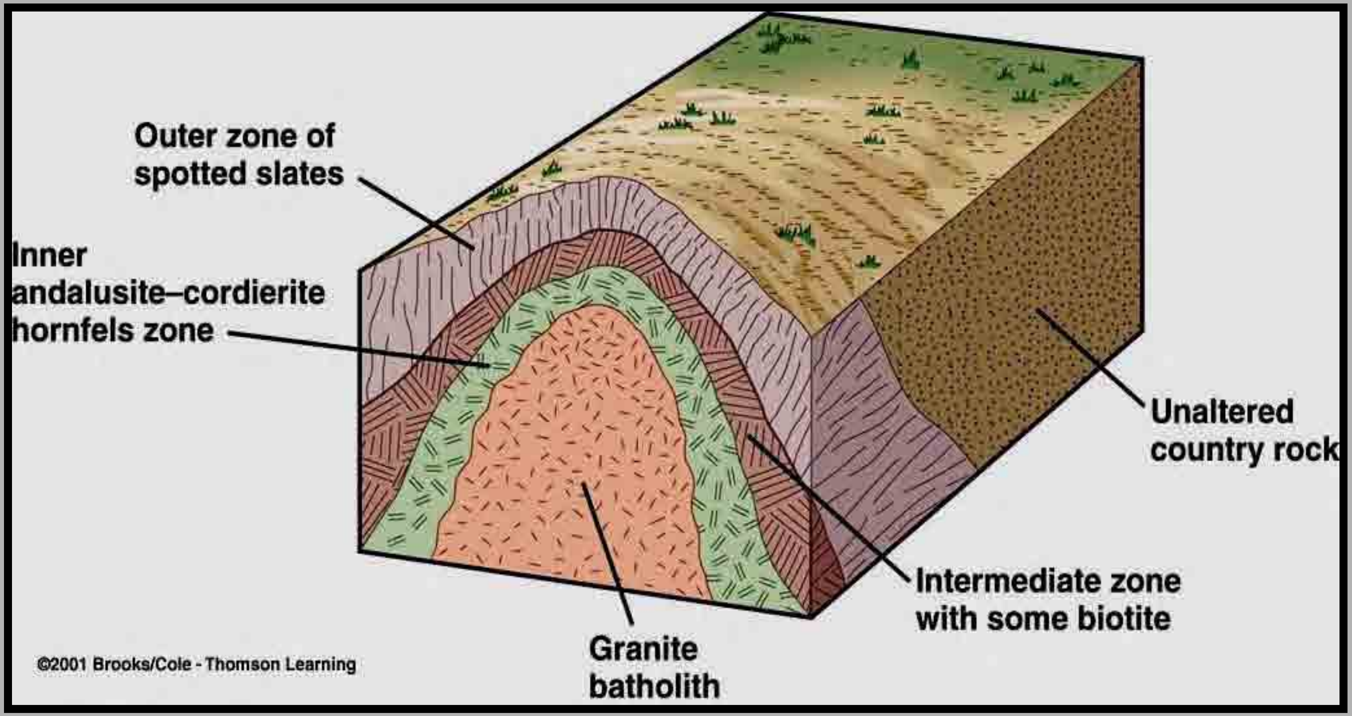
Many of Earth's deposits of copper, gold, tin, zinc. etc., formed by the migration of metallic ions in solutions.



Plummer et al. (2001)

Contact Metamorphism

Concentric zones of alteration surrounding a magma body comprise an aureole. The zone closest to the intrusion contains higher temperature metamorphic minerals whereas more distant zones contain lower temperature minerals. The size, temperature, and magma composition of an intrusion as well as the mineralogy of the country rock controls the width of the metamorphic aureole.



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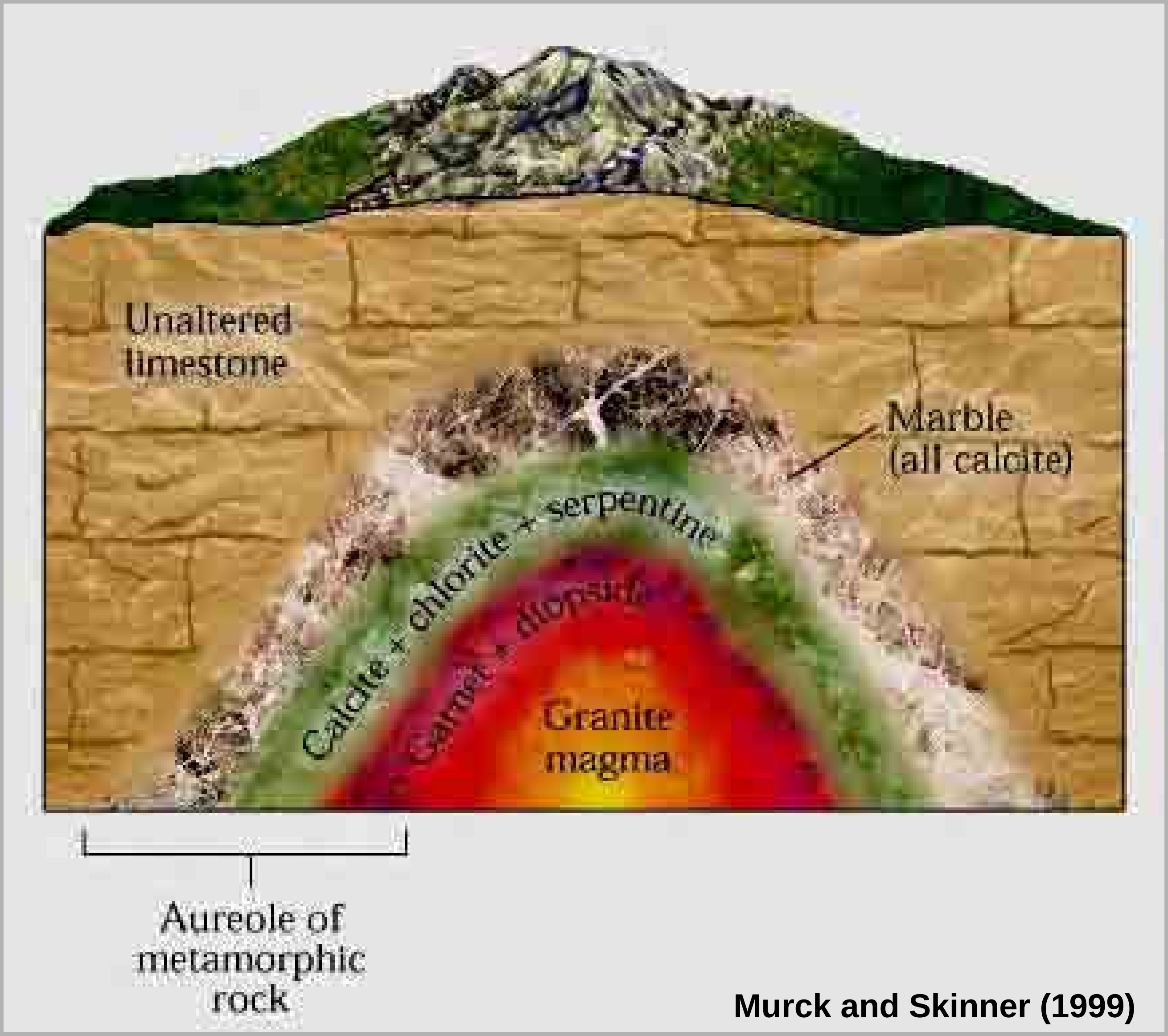
Contact Metamorphism



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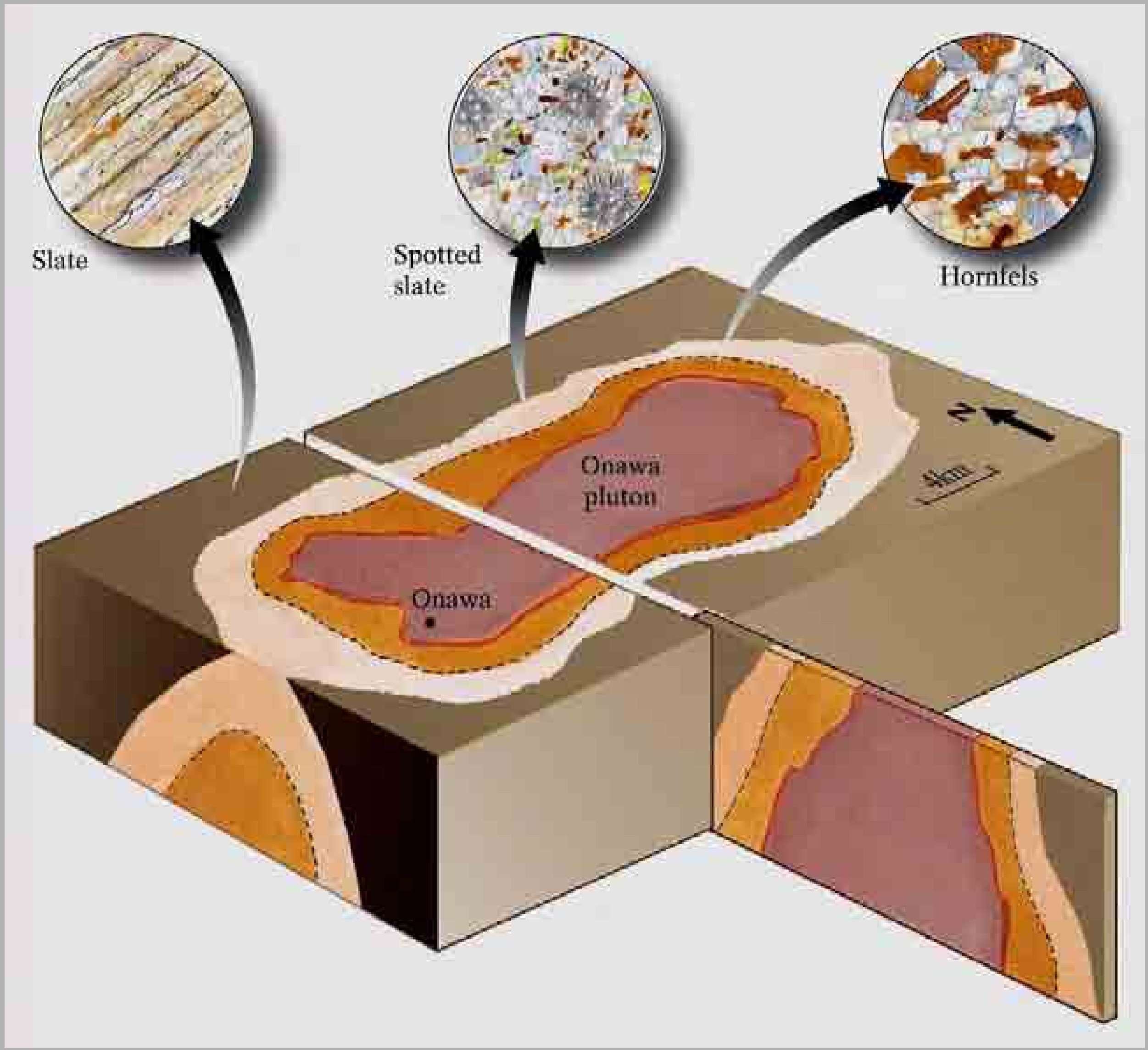
Heat from the Onawa pluton



Chernicoff and Whitney (2002)

Contact Metamorphism

The boundary between an igneous intrusion and the surrounding metamorphic aureole can be sharp or transitional. The boundary shown in the figure below is well-defined and sharp.

Wicander and Monroe (2002)

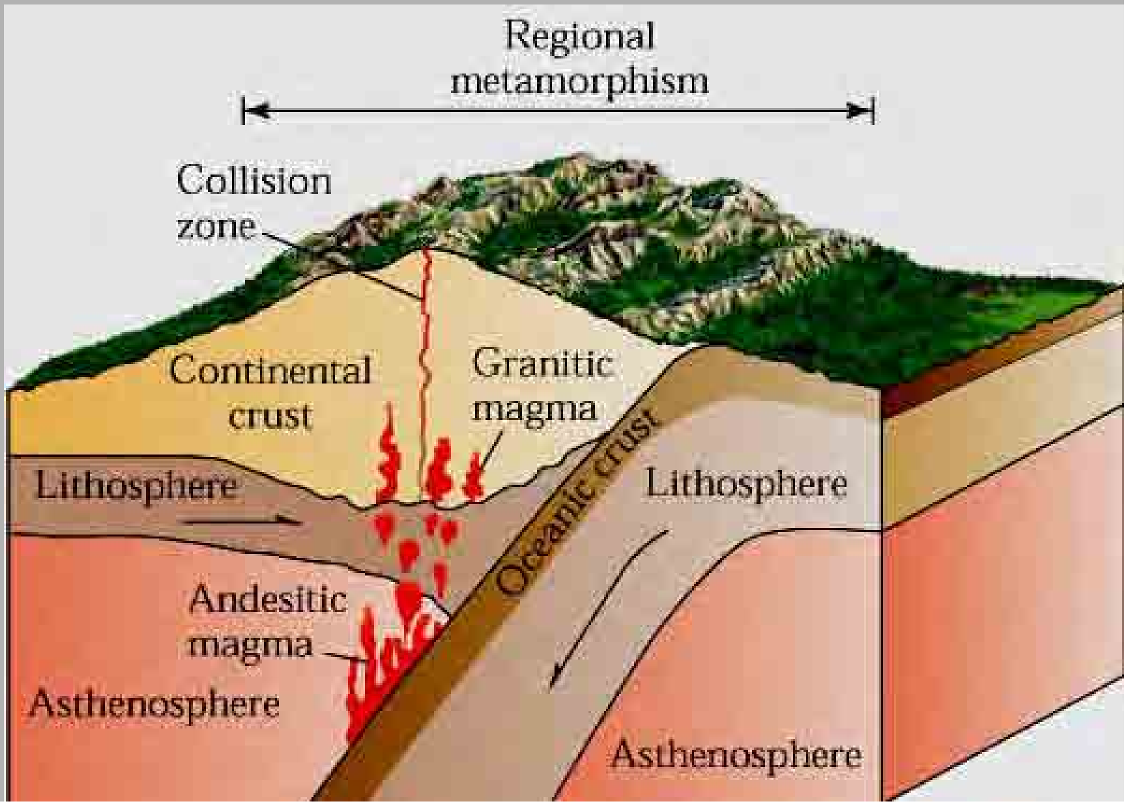
Dynamic Metamorphism

Dynamic metamorphism occurs along fault zones where rocks have been altered by high differential pressure. Rocks formed by dynamic metamorphism are restricted to narrow zones adjacent to faults and are known as mylonites. Mylonites are commonly hard, dense, fine-grained, and contain thin laminations. Such rocks are found along the famous San Andreas Fault of California.

Wicander and Monroe (2002)

Regional Metamorphism

- Regional metamorphism occurs over broad areas, is cause by high pressure and temperature, and deformation in deeper portions of the crust. It is most obvious along convergent plate boundaries
- This is the most common form of metamorphism



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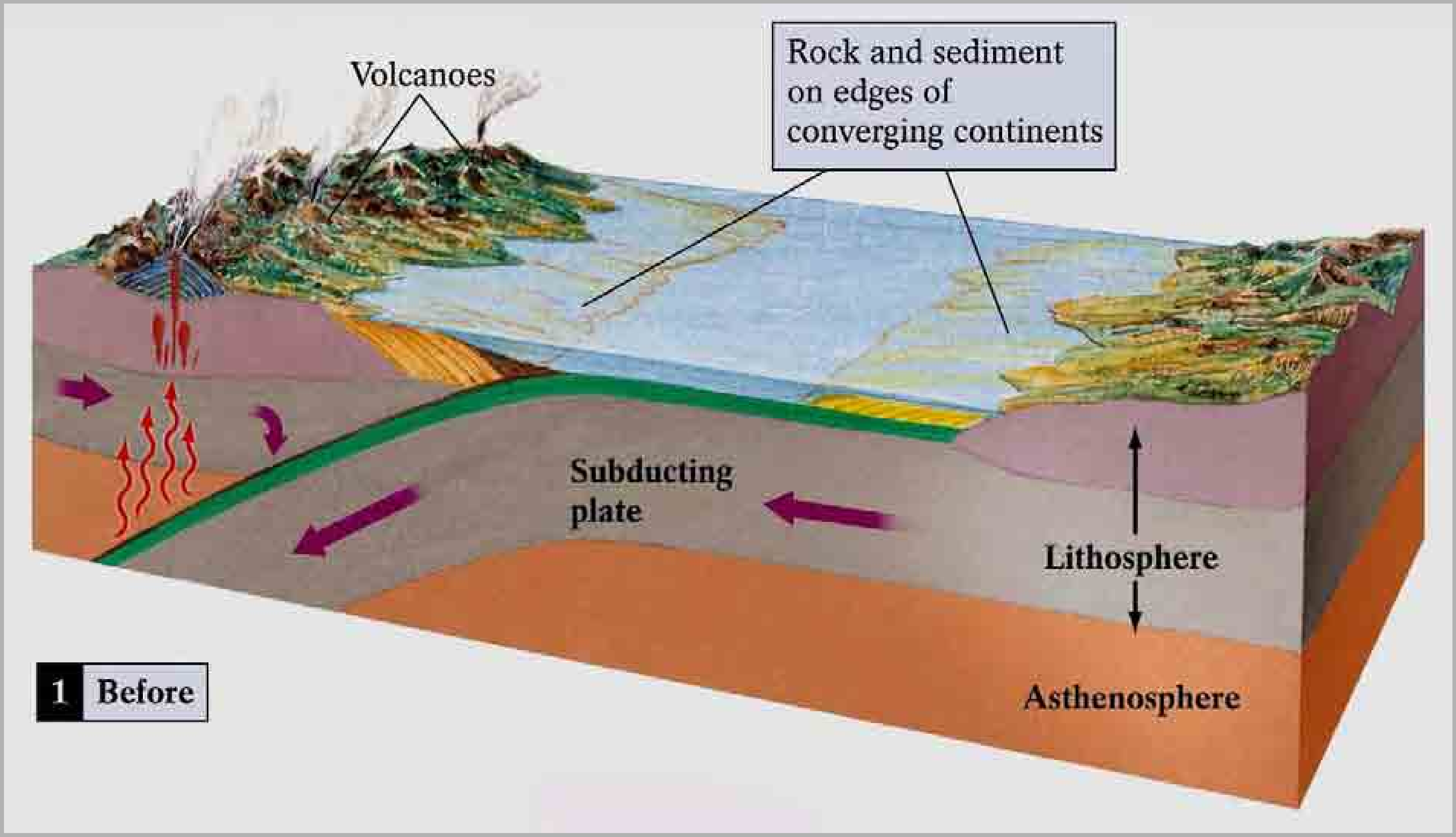
Regional metamorphism



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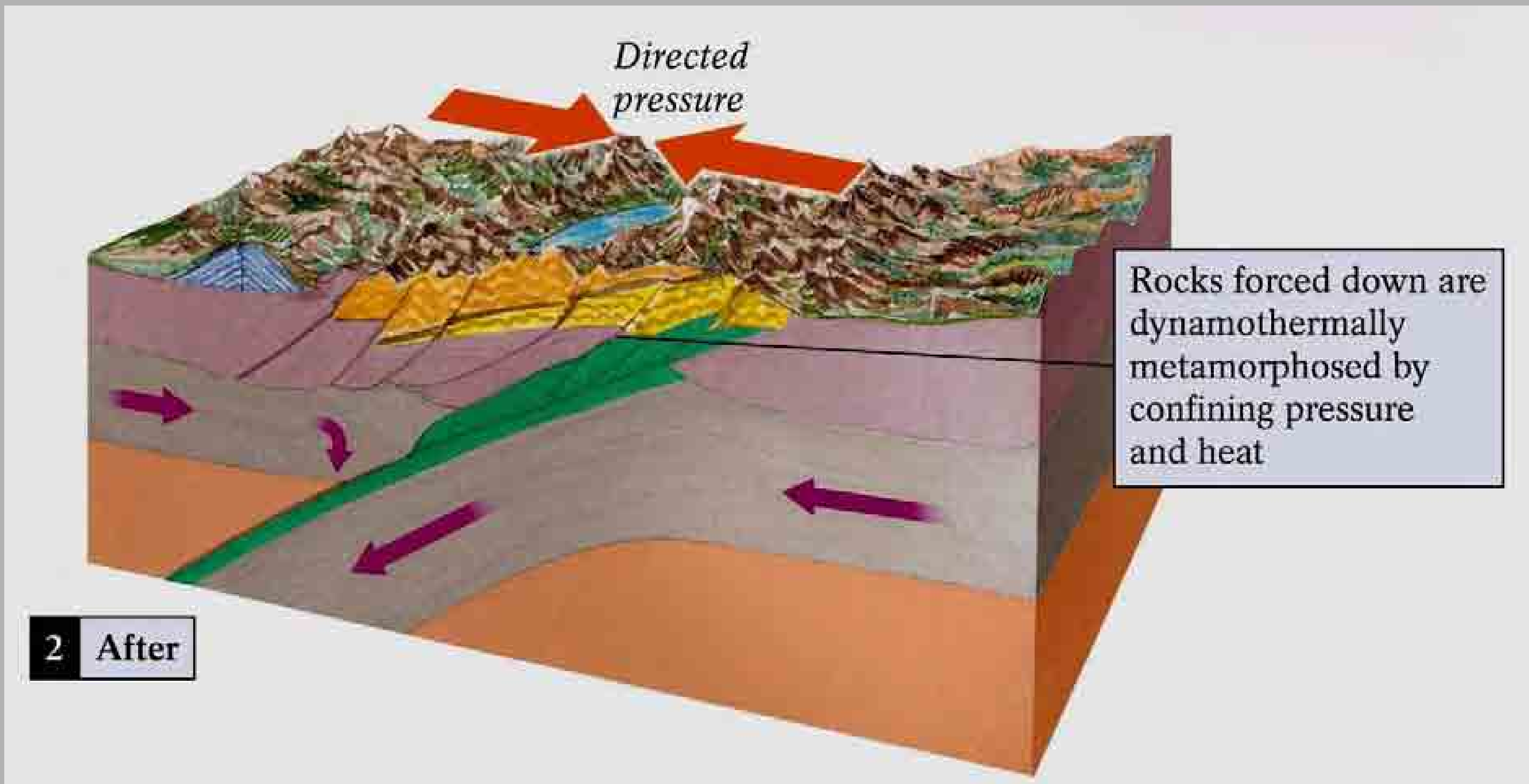
Regional metamorphism



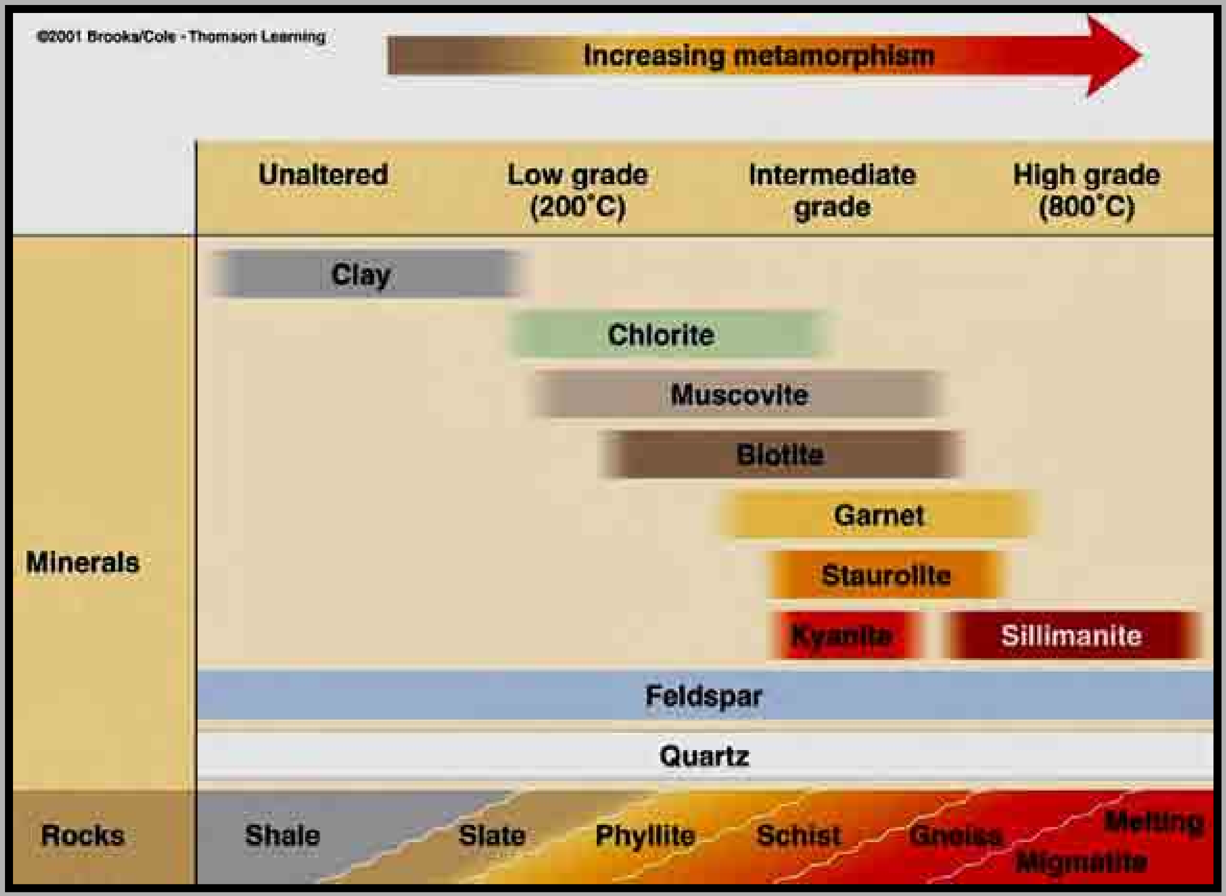
Chernicoff and Whitney (2002)

Regional metamorphism

- As crustal thickening progresses material at the bottom of the pile is subjected to increased temperature and pressure
- If the burial is slow then heat and pressure build equally
- If the burial is fast the the poor conductivity of rocks means that pressure builds quicker than temperature

Regional Metamorphism

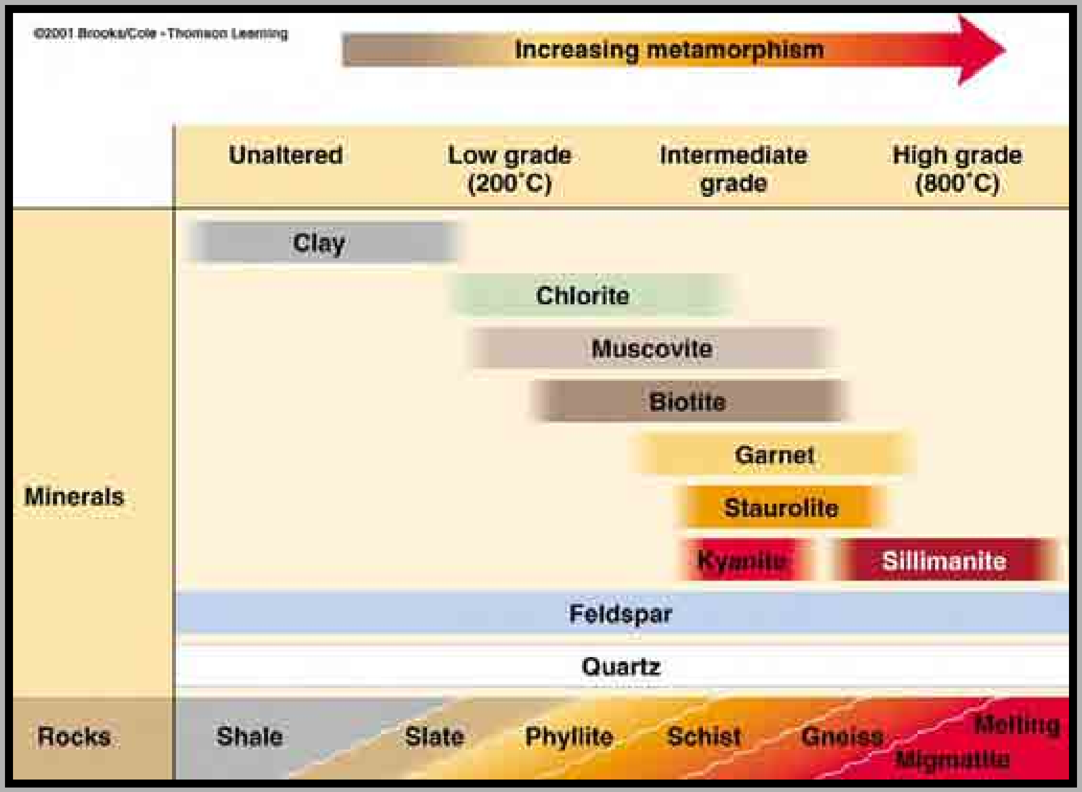
Geologists recognize low, medium, and high grade regional metamorphism based on index minerals that form at specific pressure-temperature conditions.



Wicander and Monroe (2002)

Regional Metamorphism

Beginning with a clay-rich parent rock such as shale and tracking its subjection to ever more intense pressure and heat illustrates the sequence of index minerals formed by low- to high-grade regional metamorphism. For example, chlorite forms under low-grade conditions, staurolite and kyanite under intermediate-grade, and sillimanite under high-grade conditions.



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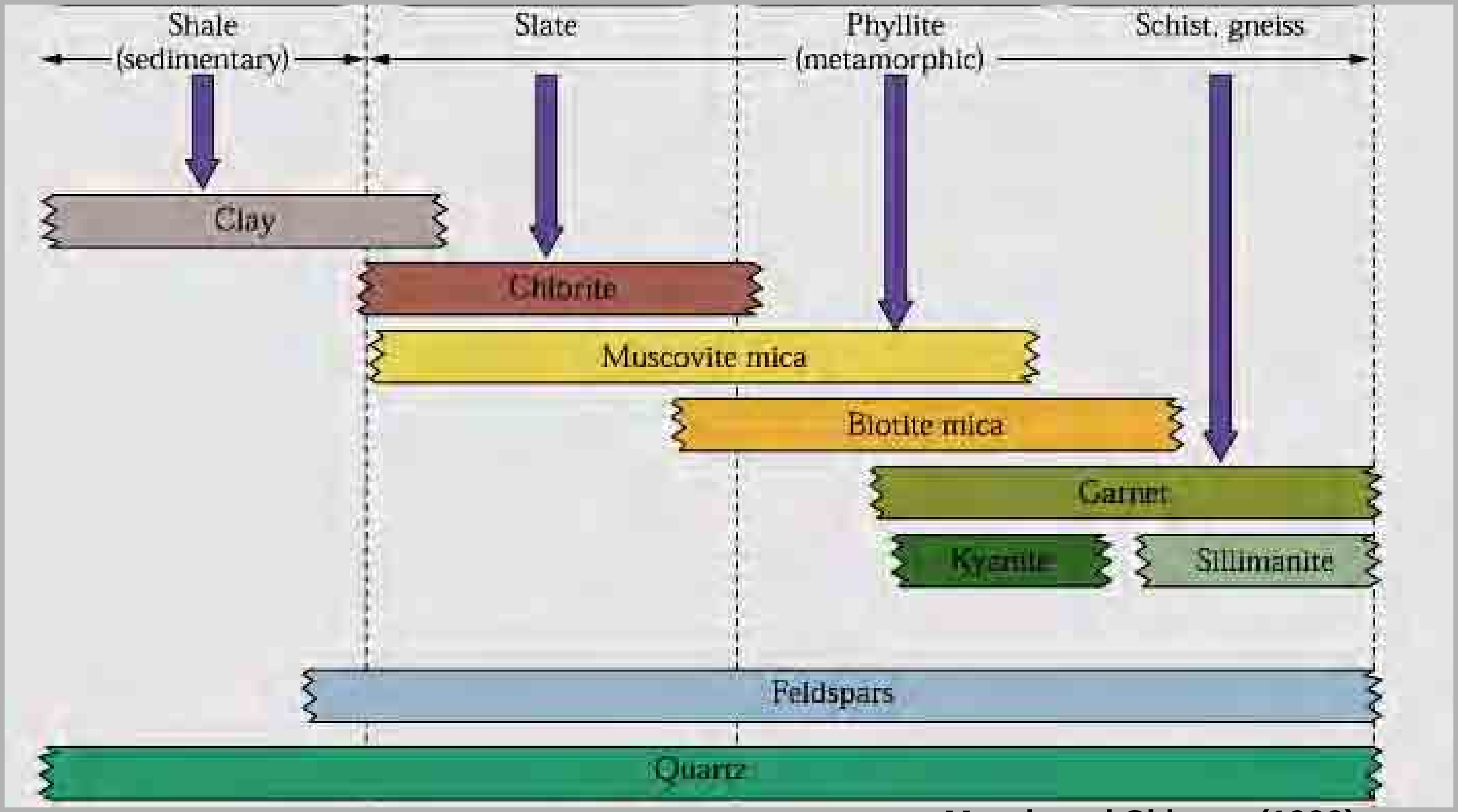
Index minerals

Index minerals were identified that could define metamorphic grade

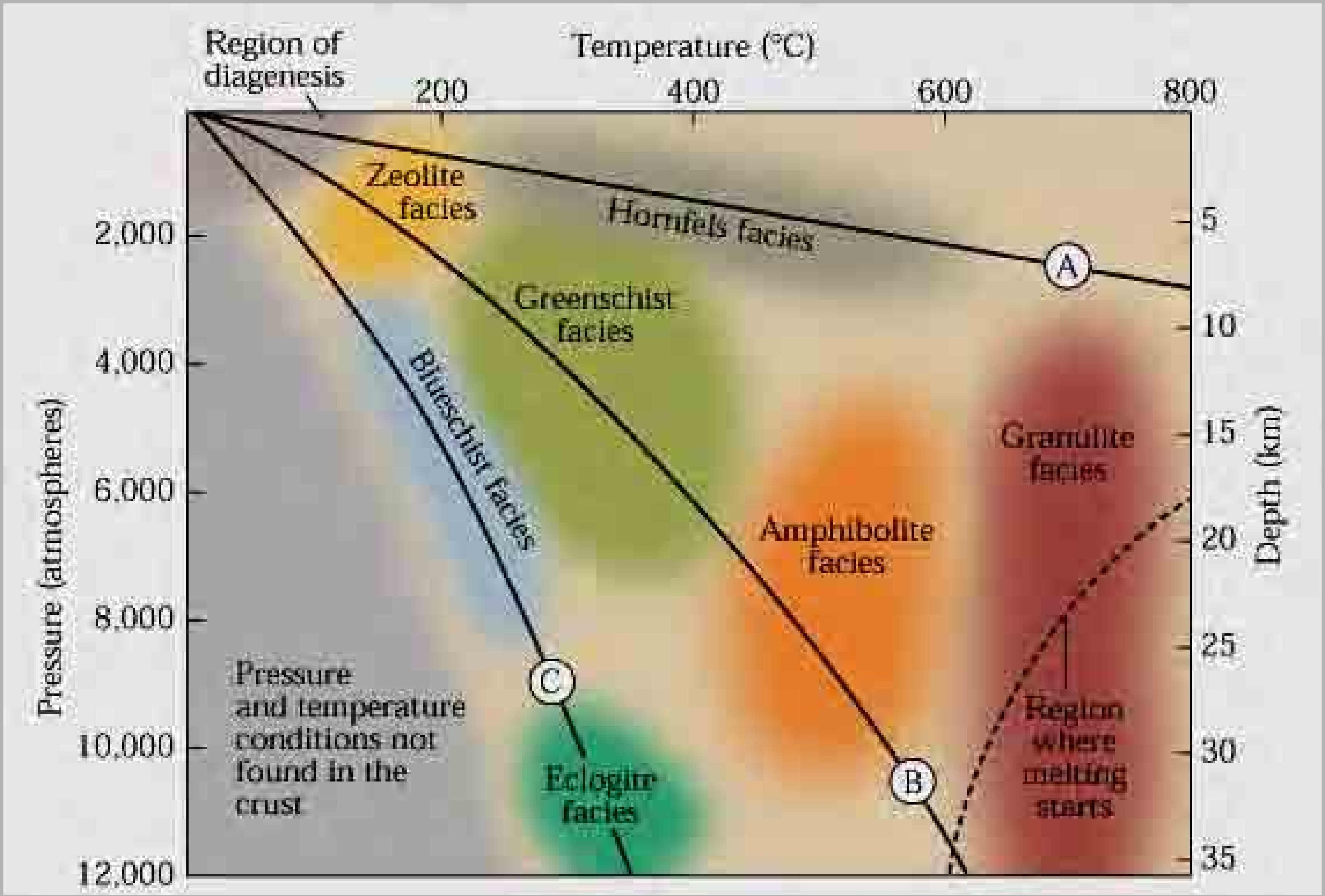


Murck and Skinner (1999)

Metamorphic facies

- We know that the chemical composition of metamorphosed rocks does not change
- Metamorphism is isochemical
- Elements are redistributed but not lost
- Consequently any changes are the result of temperature and pressure
- This has led to the concept of metamorphic facies

Metamorphic facies



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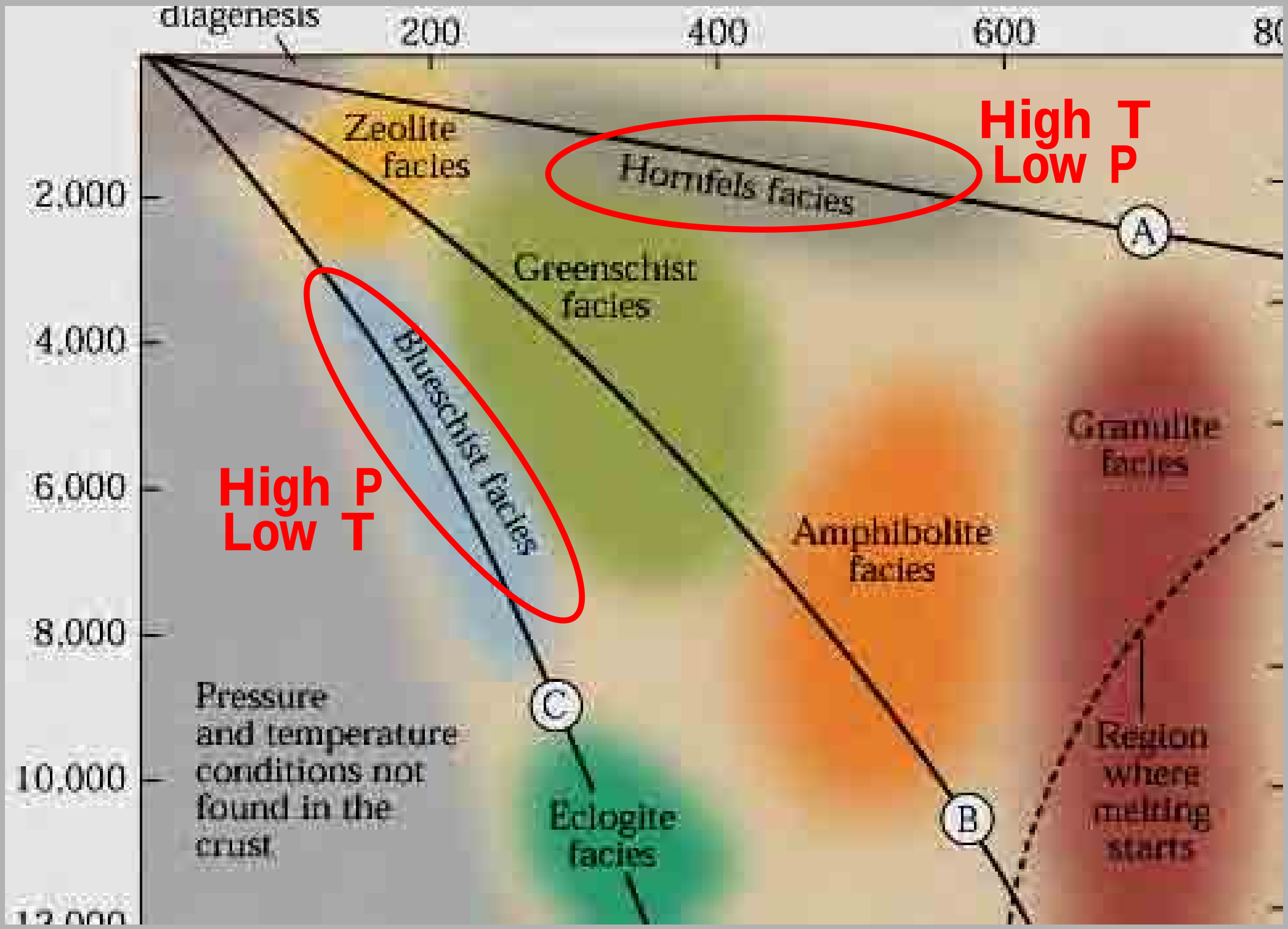
Metamorphic facies

Each facies represents a characteristic range of temperature and pressure



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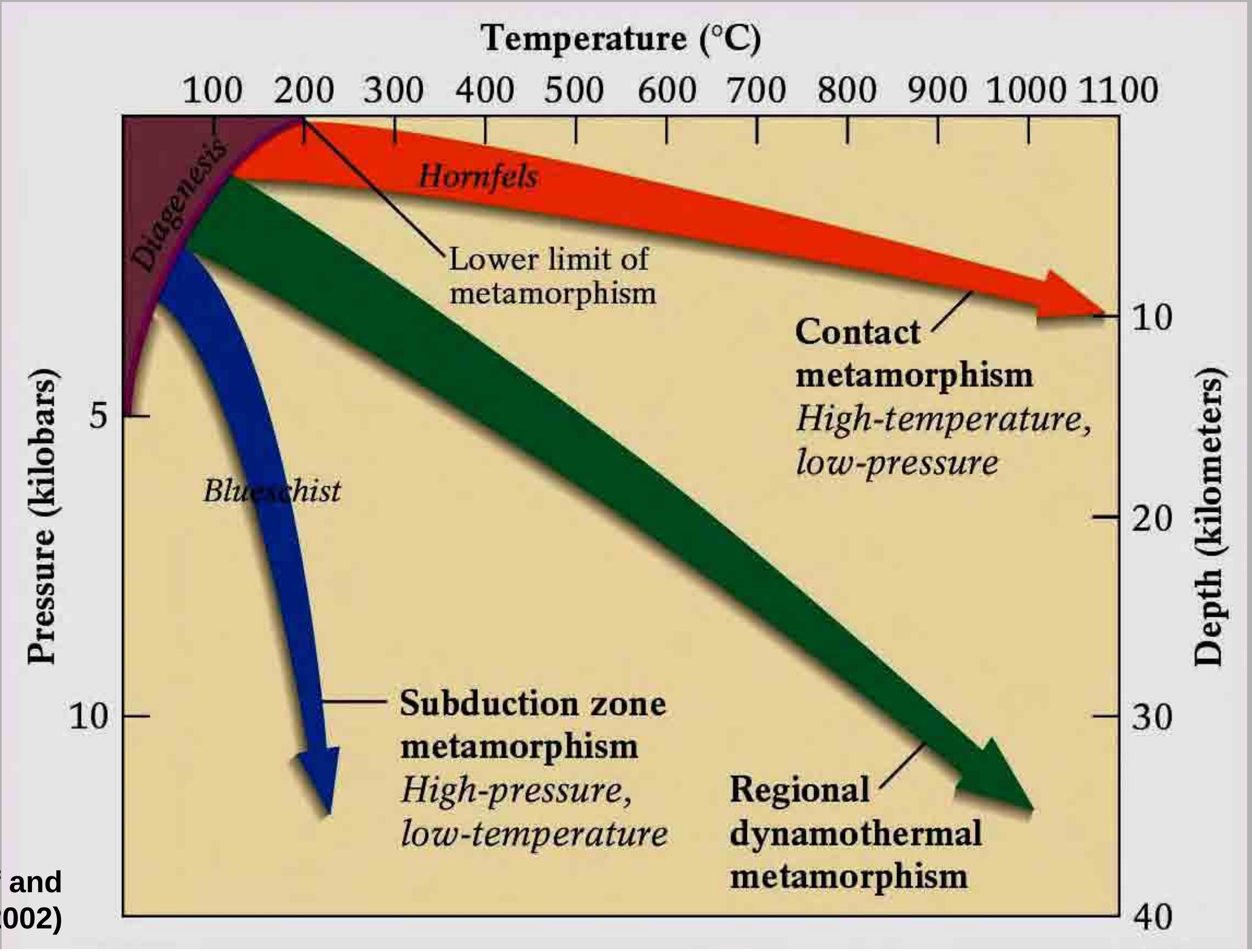
Metamorphic facies



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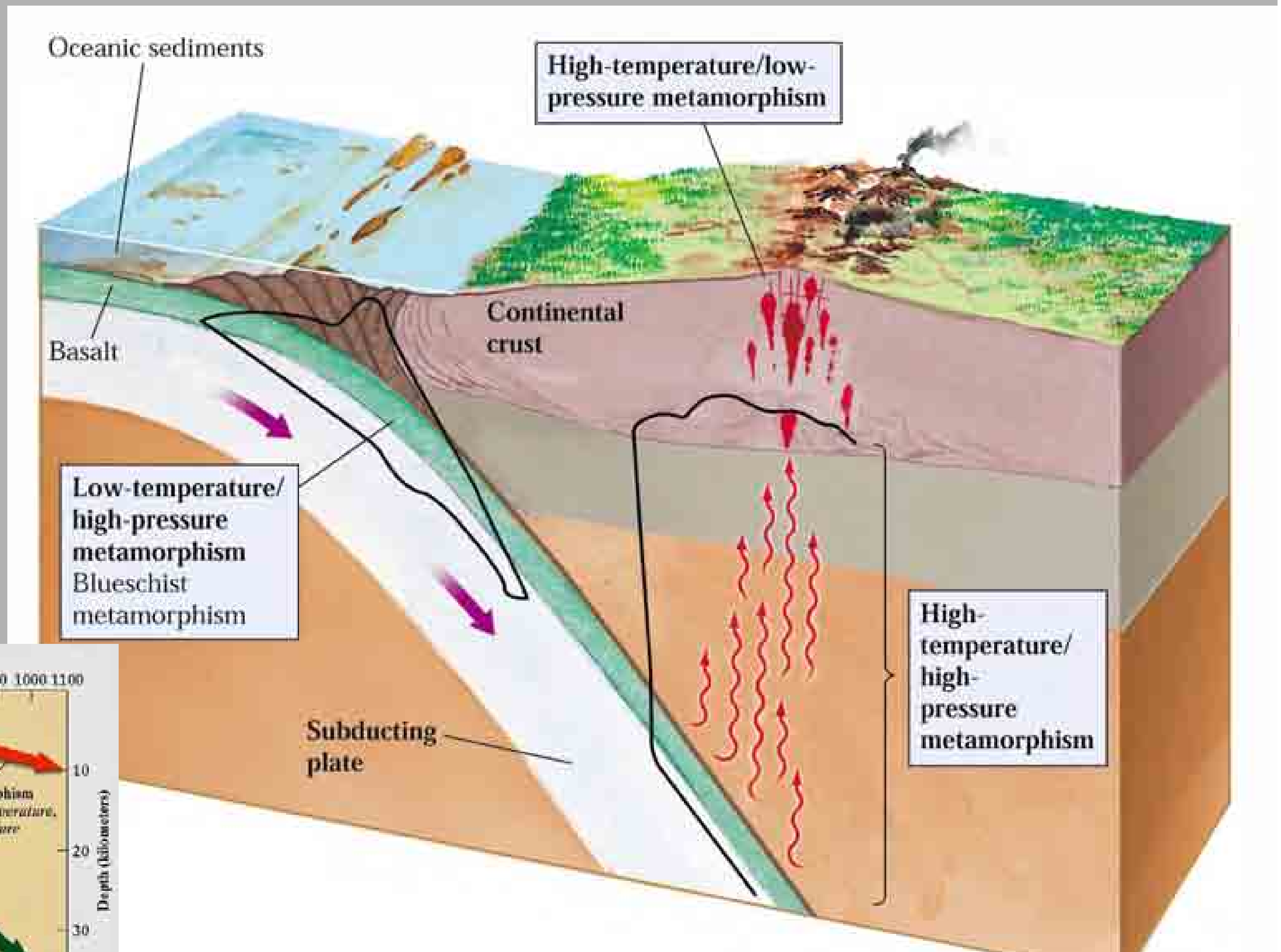
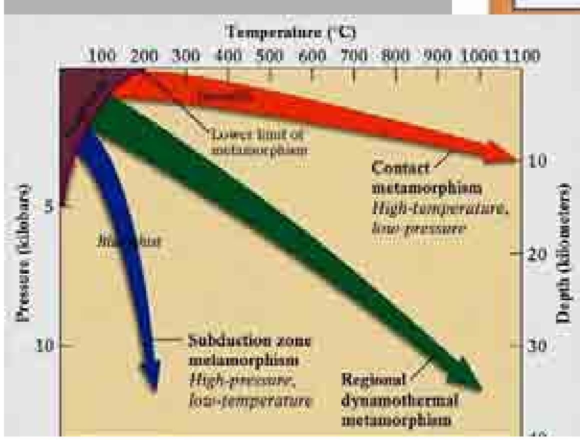
Metamorphism





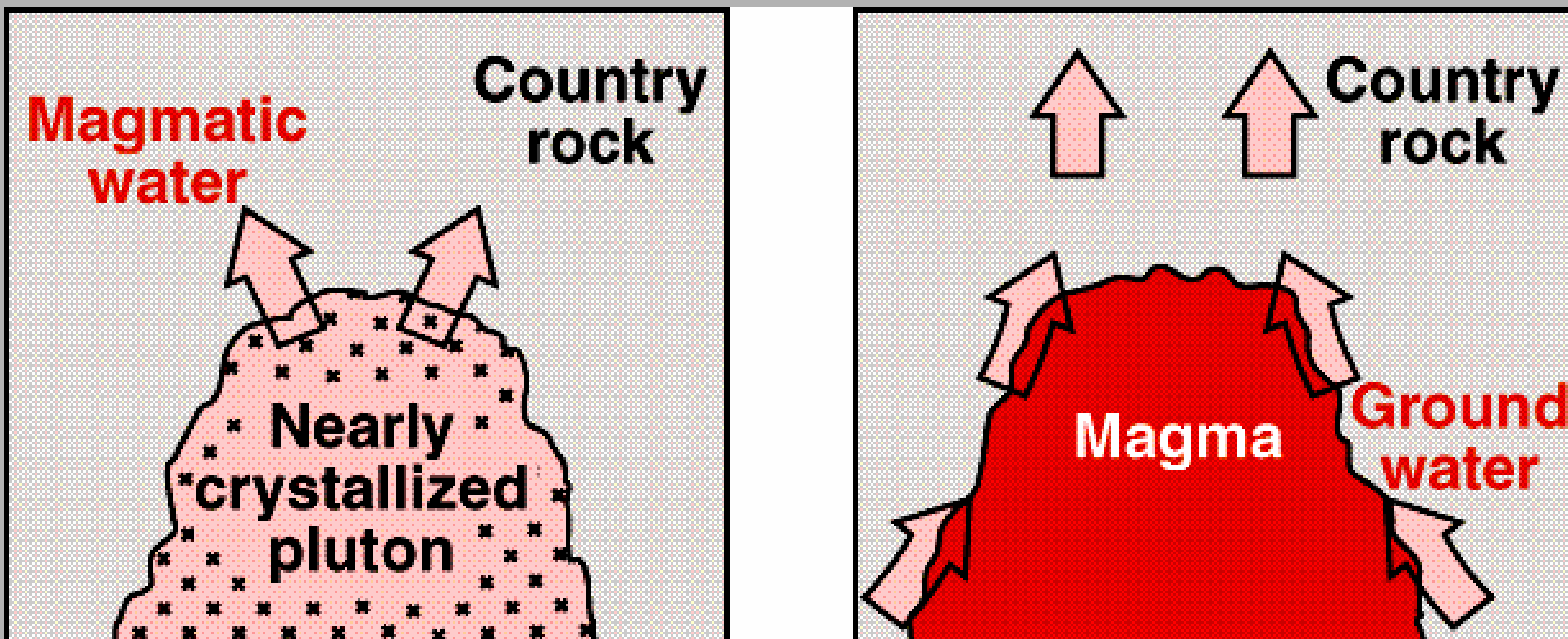
Chernicoff and Whitney (2002)

Metasomatism

- Geologists consider metamorphism to be a low water-rock ratio process (1:10)
- Processes with a high water-rock ratio of 10:1 or even 100:1 are metasomatic
- An area where this readily occurs is in open fractures
- Metasomatism removes and adds material from the walls of the fracture (unlike metamorphism)

Metasomatism

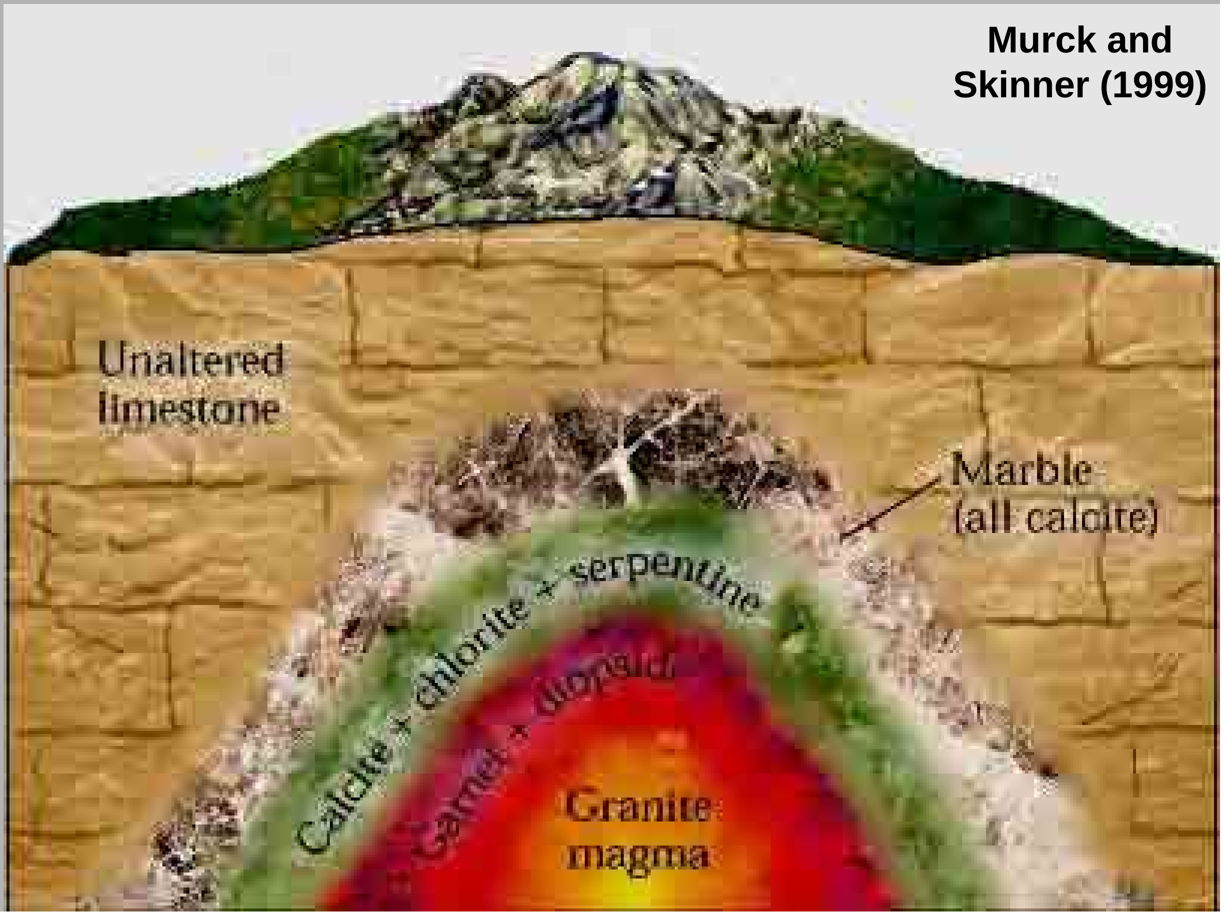
- Because of the large amounts of fluids required metasomatism is generally associated with contact metamorphism



Plummer et al. (2001)

Metasomatism

The effects are most pronounced when the intrusion is emplaced in limestone



Murck and Skinner (1999)

Metamorphic ores - skarns

- The term has been used to describe limestones and dolomites into which large amounts of Si, Al, Fe & Mg were metasomatically introduced on the margins of a pluton
- The majority are barren but some may be ores of Fe, Cu, W, Zn, Mo, Pb
- Exoskarns form in the country rock and endoskarns in the host rock

Ore Deposits Resulting from Contact Metamorphism

Hydrothermal contact metamorphism produces many metal ore minerals.

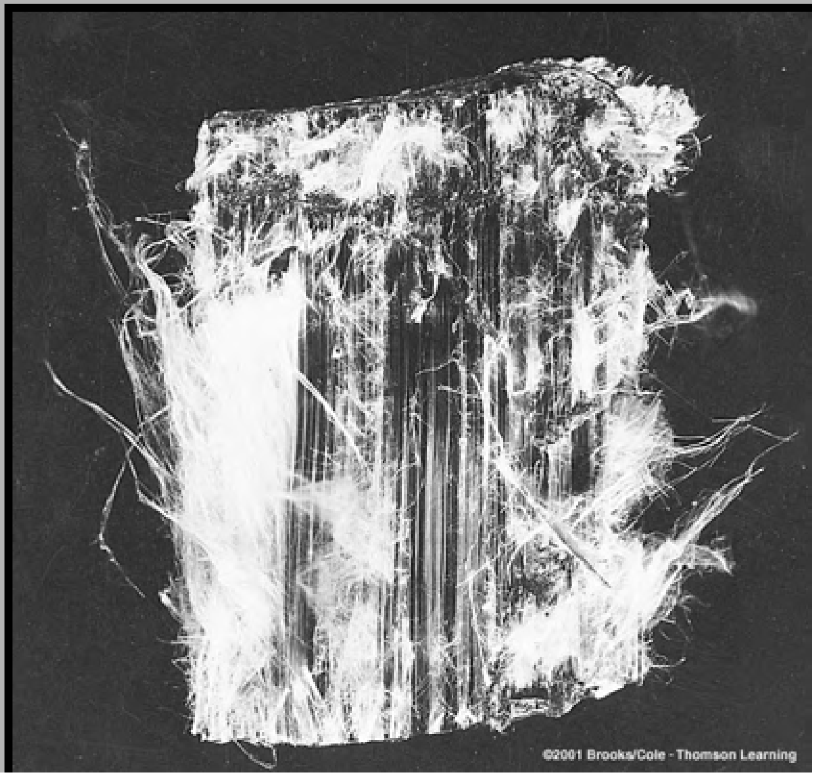
Ore	Mineral	Formula	Use
Copper	Bornite	Cu_5FeS_4	manufacturing, transportation, communications
Iron	Hematite	Fe_2O_3	steel manufacturing
	Magnetite	Fe_3O_4	
Lead	Galena	PbS	batteries, pipes, solder
Tin	Cassiterite	SnO_2	plating, solder, alloys
Tungsten	Scheelite Wolframite	$CaWO_4$ $(Fe,Mn)WO_4$	metal hardening, carbide manufacturing
Zinc	Sphalerite	(Zn,Fe)S	batteries, galvanizing iron, brass making

Metamorphism & Natural Resources

- Metamorphic minerals and rocks provide many valuable resources, marble and slate the two most widely used.
- Economically valuable metamorphic minerals include: talc to talcum powder, graphite for pencils and dry lubricant, garnet and corundum for abrasive and gemstones, kyanite for high-temperature porcelain.

Metamorphism and Natural Resources

Asbestos has had broad use as insulation and fireproofing. Chrysotile asbestos consists of silky fibers and makes up 95% of all asbestos used in the U.S. Crocidolite asbestos has long, straight fibers. Research shows it is this variety that presents a health risk. Yet, EPA policies treat all asbestos the same.



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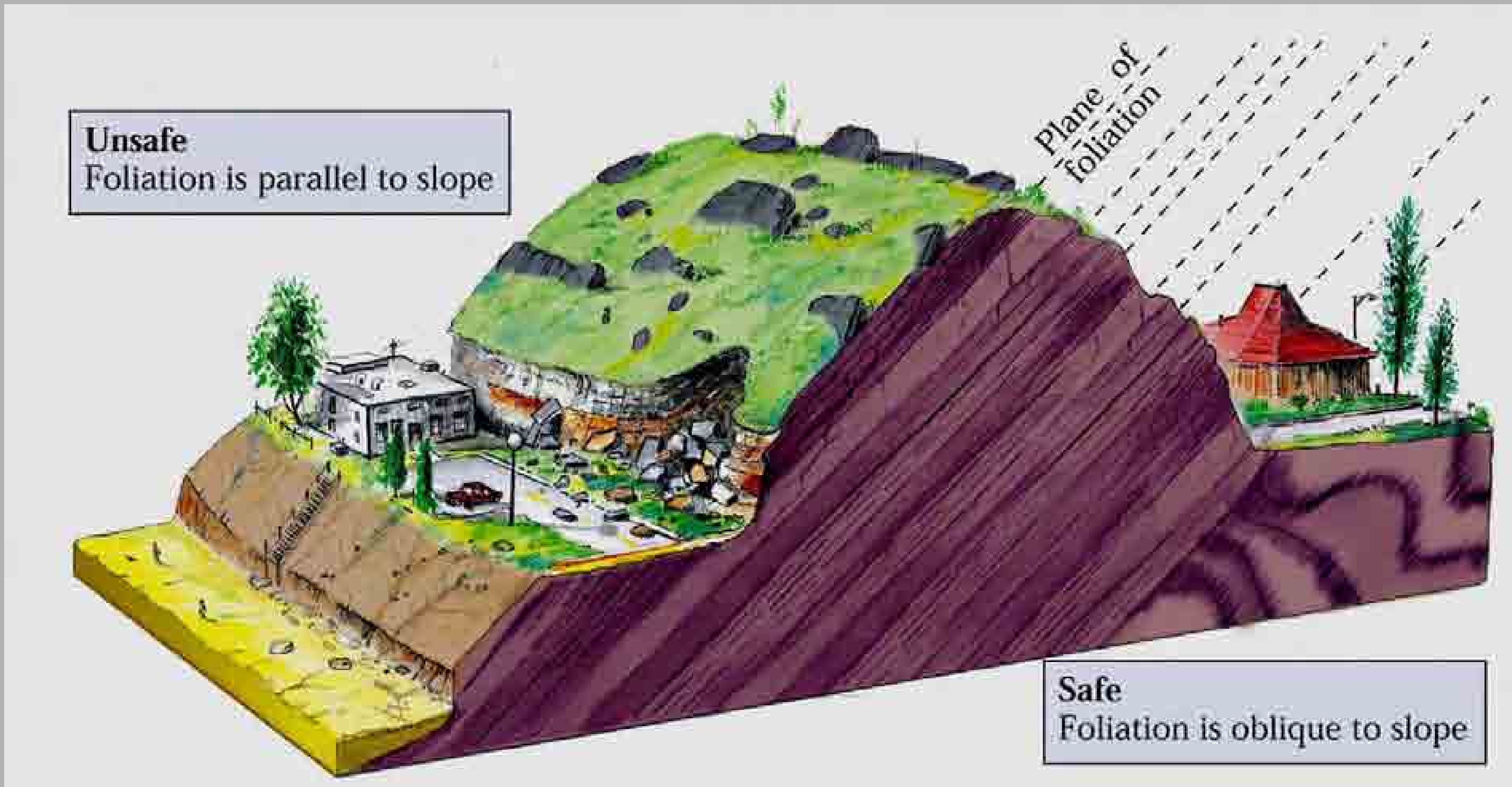
Metamorphism & man



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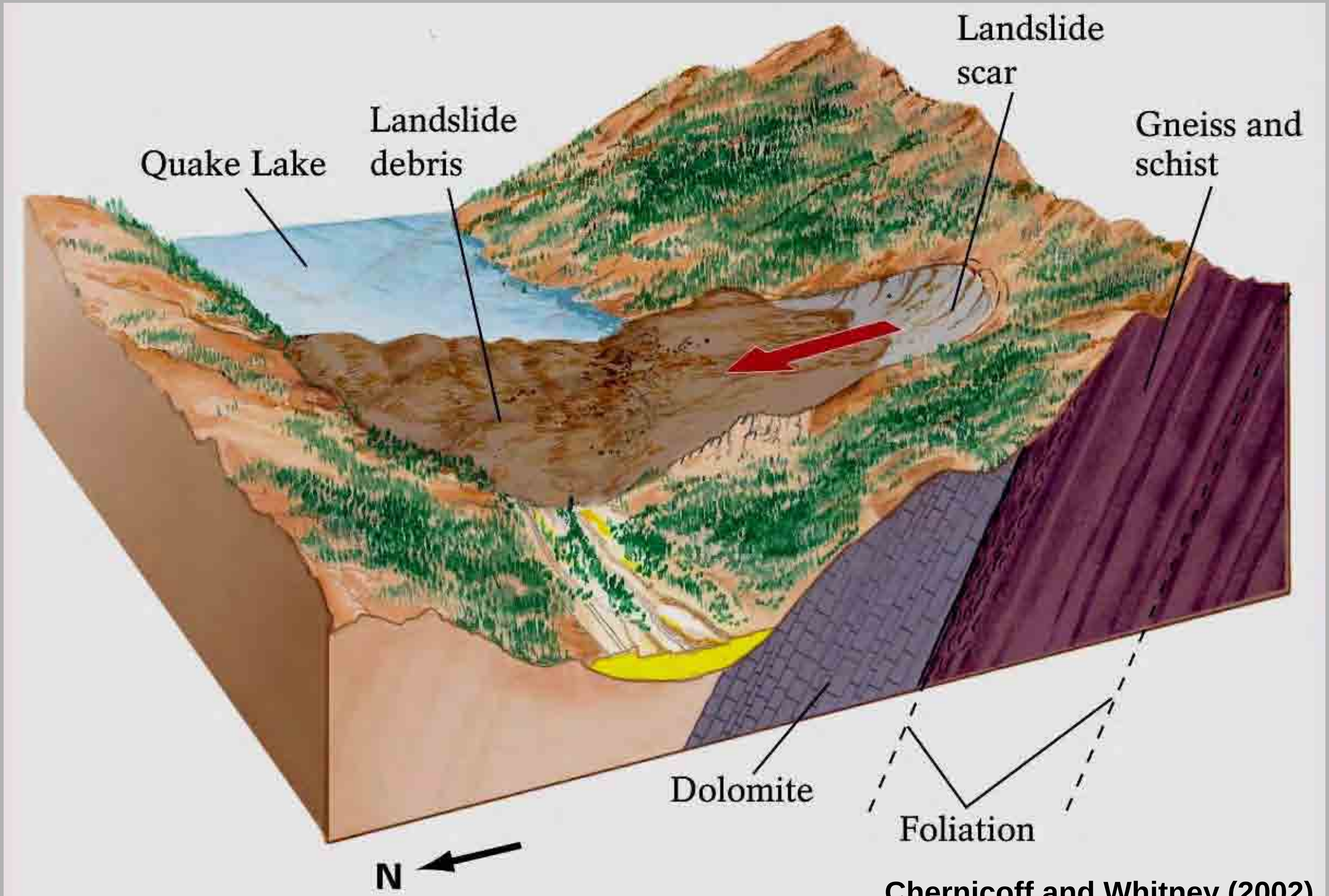
Metamorphism and man



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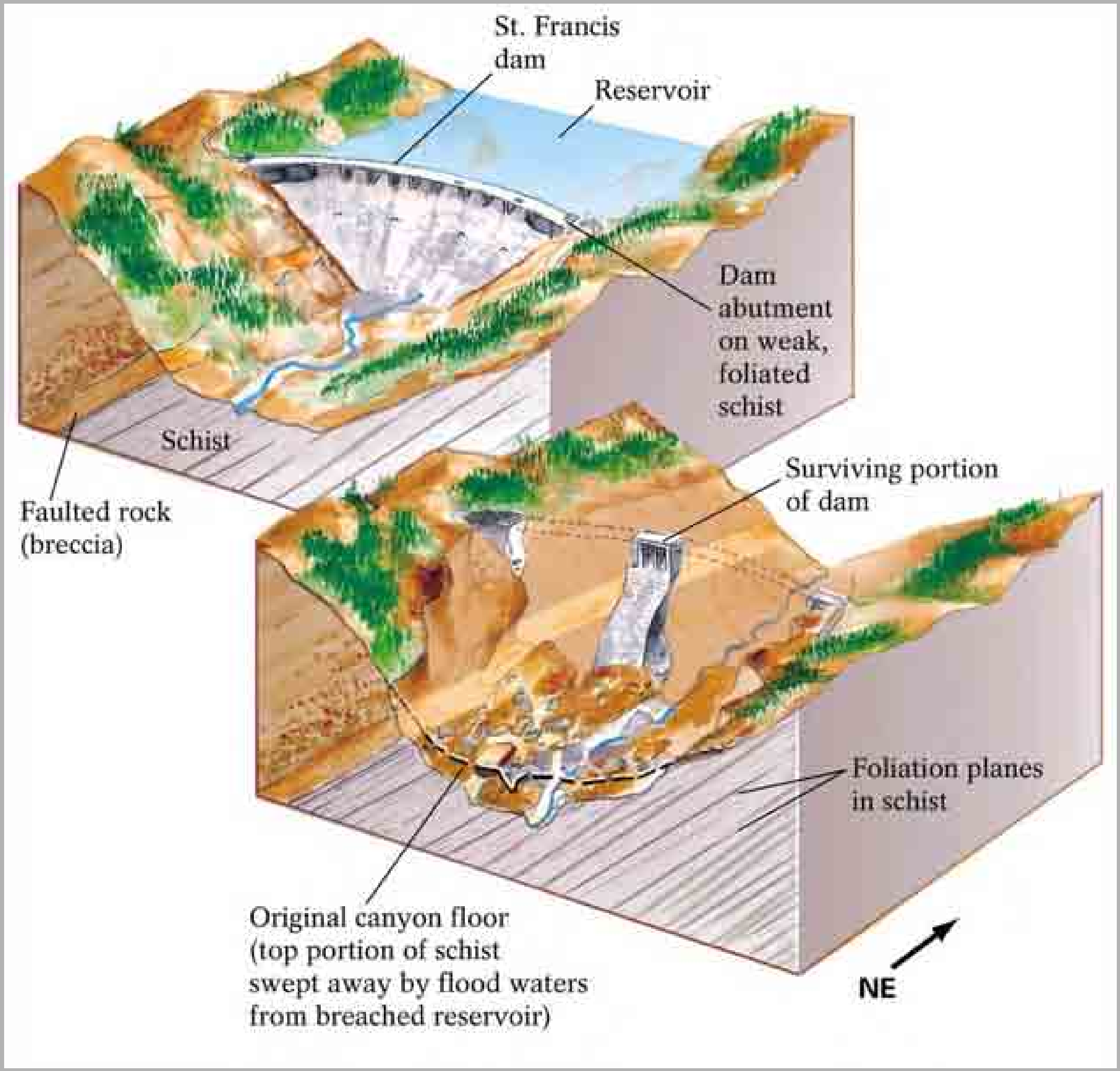
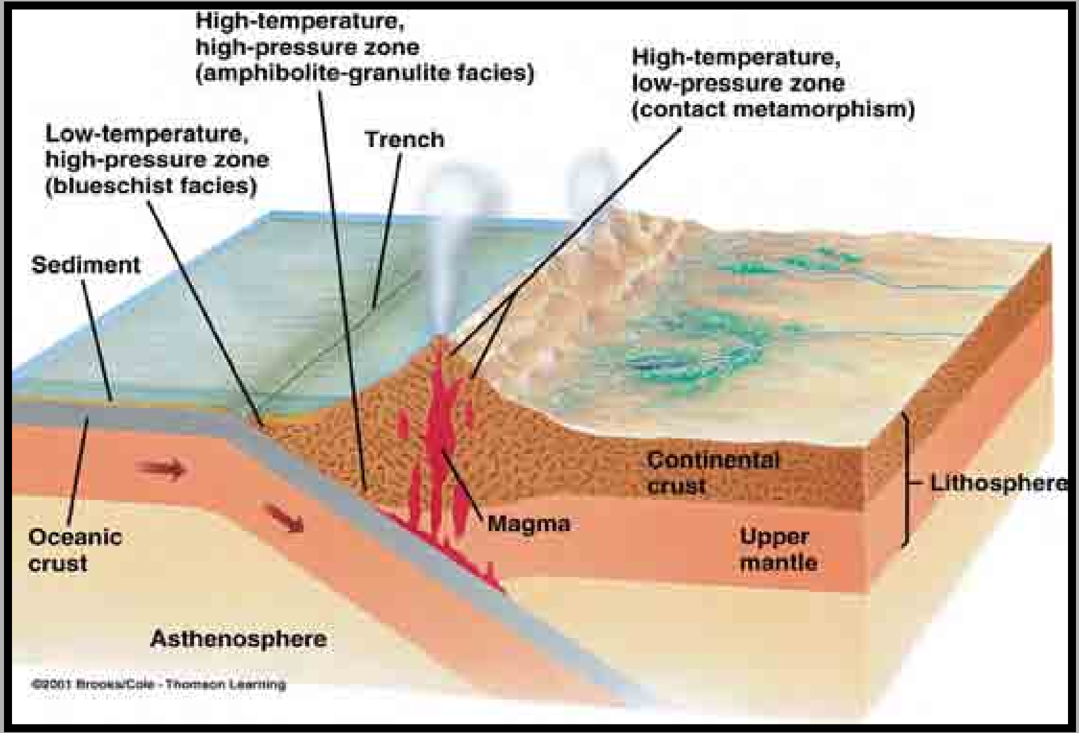
St. Francis Dam



Chernicoff and Whitney (2002)

Metamorphism & Plate Tectonics

Metamorphism is most common along convergent plate boundaries where temperature and pressure increase as a result of plate collisions. Low-temperature, high-pressure metamorphism occurs in the higher parts of subducting oceanic crust, but high-temperature, high-pressure affects the deeper reaches of the subducting plate. High-temperature, low-pressure contact metamorphism follows the rising magma from the melting plate.

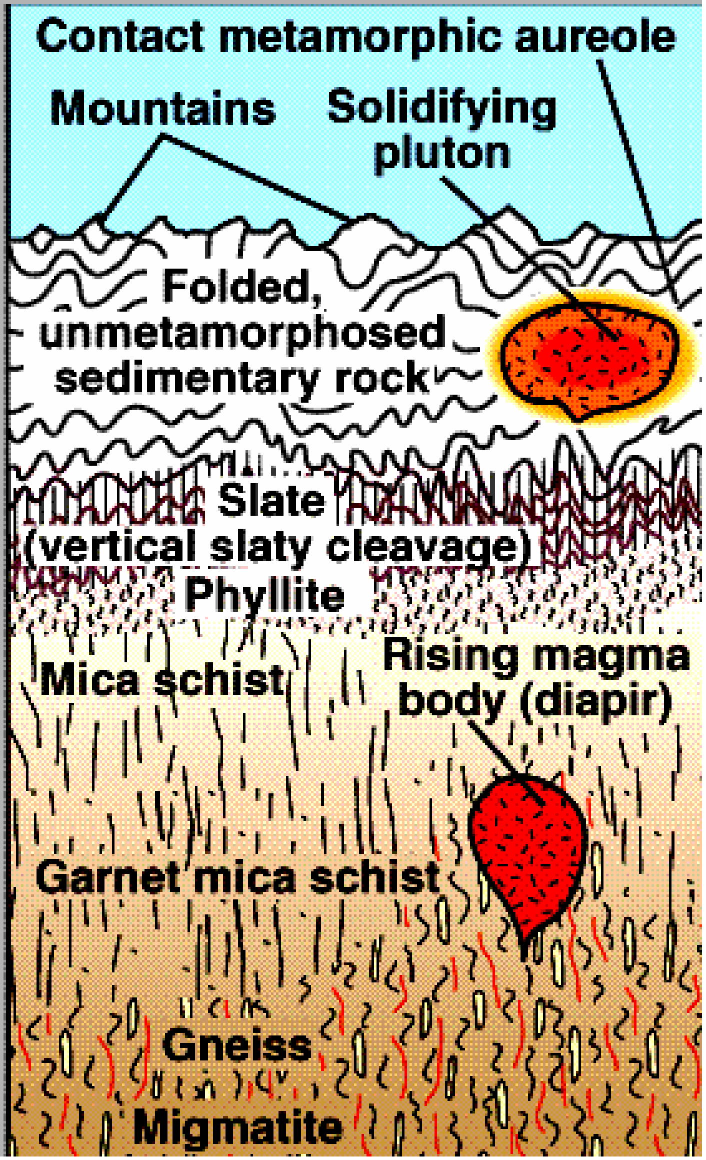


Wicander and Monroe (2002)

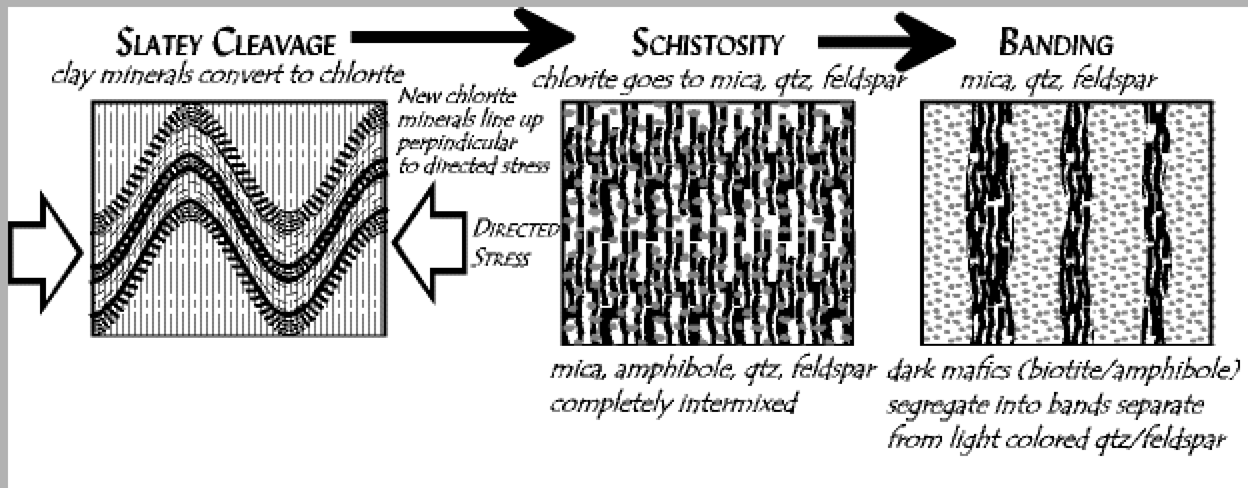
Summary

- Metamorphism is a response to changes in temperature and pressure
- The protolith, chemical composition and time are also important factors

Plummer et al. (2001)



The Metamorphic Rocks



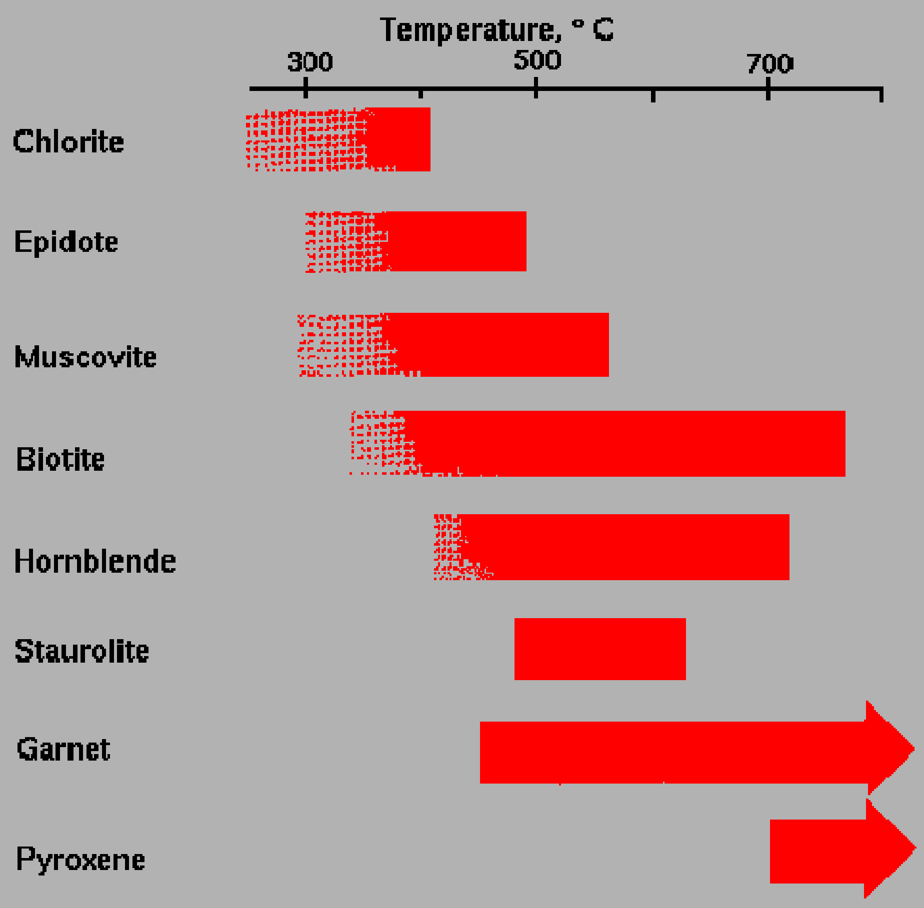
Foliation: layering or banded appearance produced by exposure to heat and directed pressure

Protolith: parent rock

http://csmres.jmu.edu/geollab/Fichter/MetaRx/metkeyvrysp.html

Lab Manual: pg 47

Metamorphic Index Minerals



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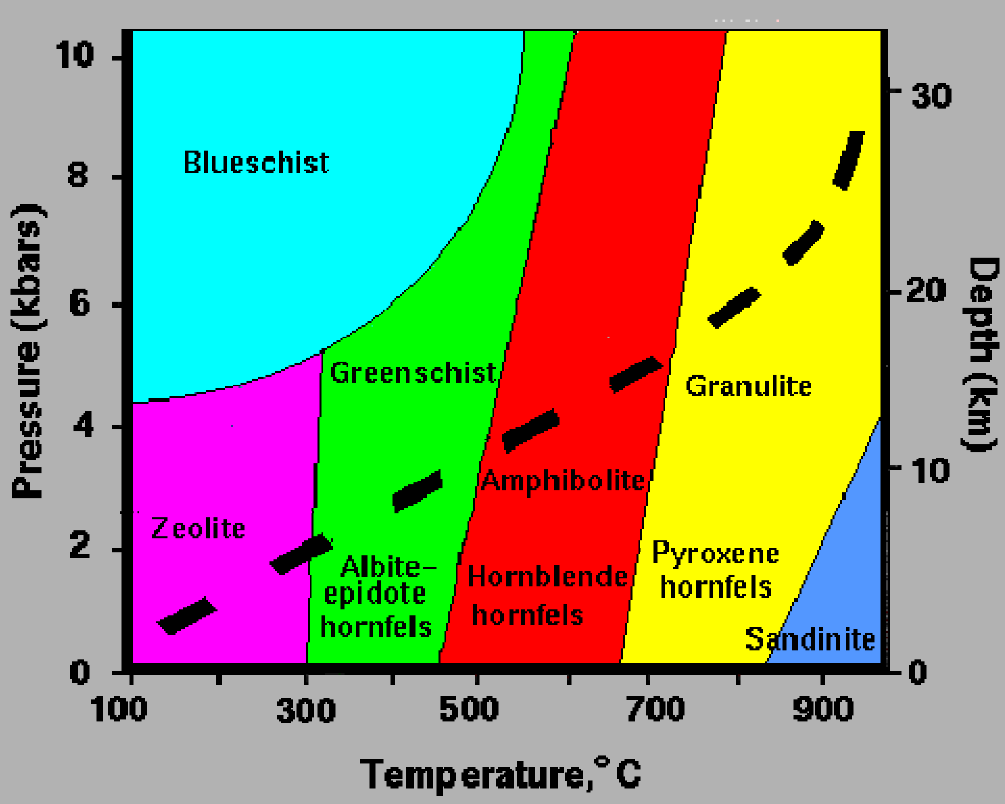


http://homepage.usask.ca/~mjr347//prog/geoe118/geoe118.029.html

Foliated: Slate

- Parallel orientation of grains
- Low grade metamorphic, slaty texture
- Protolith: shale/mudstone

Foliated: Phyllite

- Very fine grained mica
- Barely macroscopic
- Crenulated parallelism, sheen

Foliated: Chlorite Schist

- Mid-grade metamorphic rock
- Schistose texture

Foliated: Muscovite Schist

Foliated: Garnet Schist

Foliated: Gneiss

- High grade metamorphic
- Gneissic banding: 1mm to cm's scale
- Protolith: Shale, mudstone, igneous rock

Non-Foliated and Foliated: Amphibolite

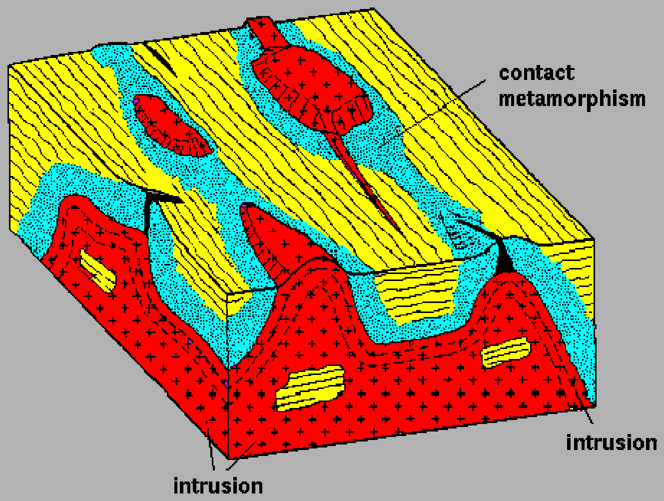
- Coarse grained, high grade
- Protolith: Mafic and Ultramafic igneous rocks

Non-Foliated: Marble

- $CaCO_3$
- Metamorphosed limestone!
- Beware of colours

Non-Foliated: Quartzite

- Metamorphism of sandstone



http://www.geol.ucsb.edu/faculty/hacker/geo102C/lectures/islandArc.jpg

Non-foliated: Hornfels

Protolith: anything

Heat sources: magma chambers, dikes, sills

High Pressure Metamorphic Rocks: Blueschist and Greenschist

Eclogites: Subductions zones!

http://www.britannica.com/EBchecked/topic/178181/eclogite

Anthracite

- Protolith: Bituminous coal
- Conchoidal fractures

http://wiki.ggc.usg.edu/mediawiki/images/7/72/Coal_anthracite.jpg


Kyanite
Pamela Gore, 1996


Pamela Gore, 1996


Garnet
Staurolite
Pamela Gore, 1996