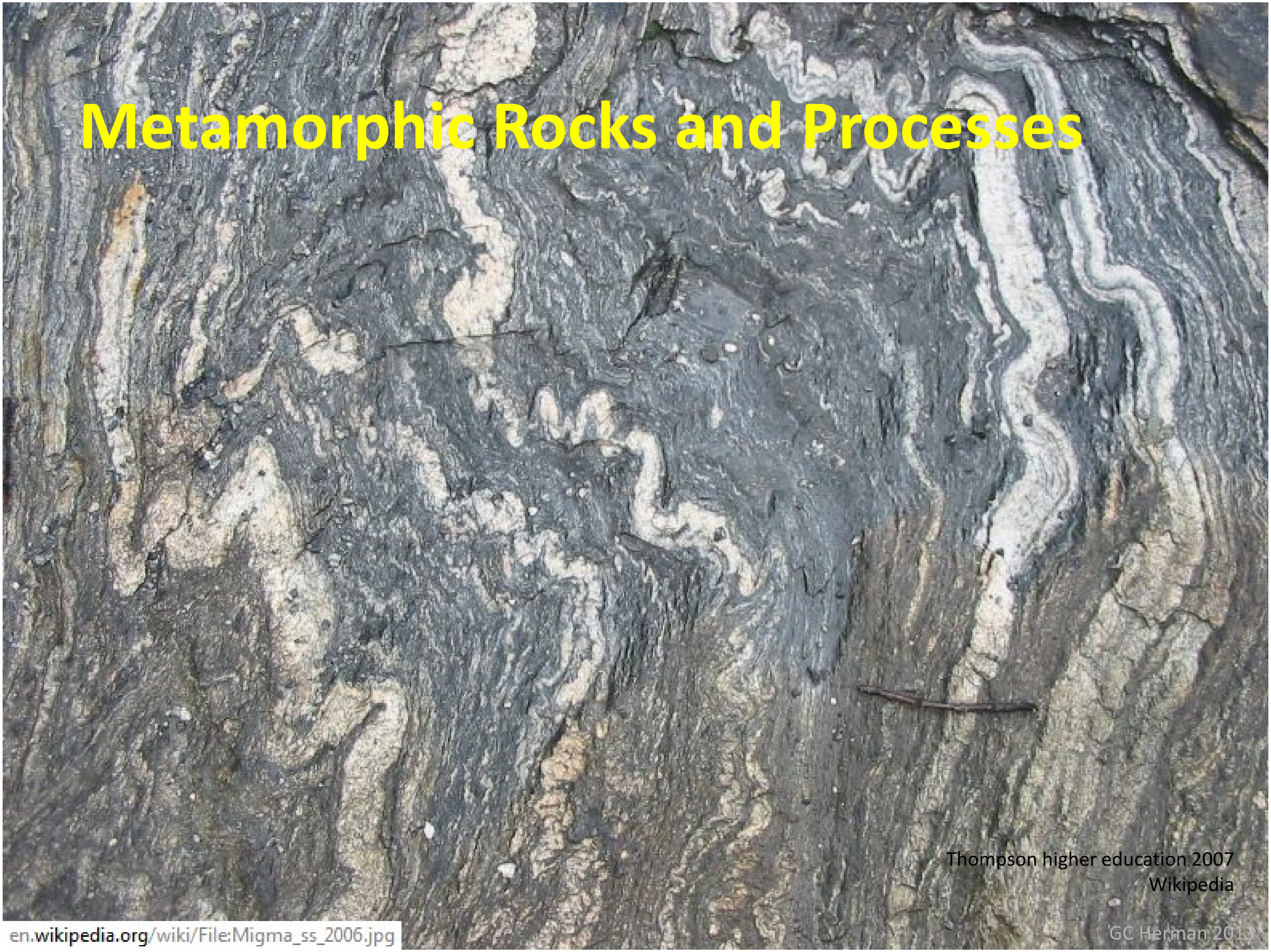
# Metamorphic Rocks and Processes




Thompson higher education 2007
Wikipedia

# What is metamorphism?

•The transformation or ***recrystallization*** of rocks, usually beneath Earth's surface, as the result of heat, pressure, and/or fluid activity, produces metamorphic rocks.

•Intrusive magmas or deep burial provide the heat which causes metamorphism.

•Pressure is produced by overlying rocks (lithostatic) or is differential pressure produced by various stresses (like at convergent tectonic-plate boundaries).

•The principal types of metamorphism are ***contact, dynamic and regional****.*

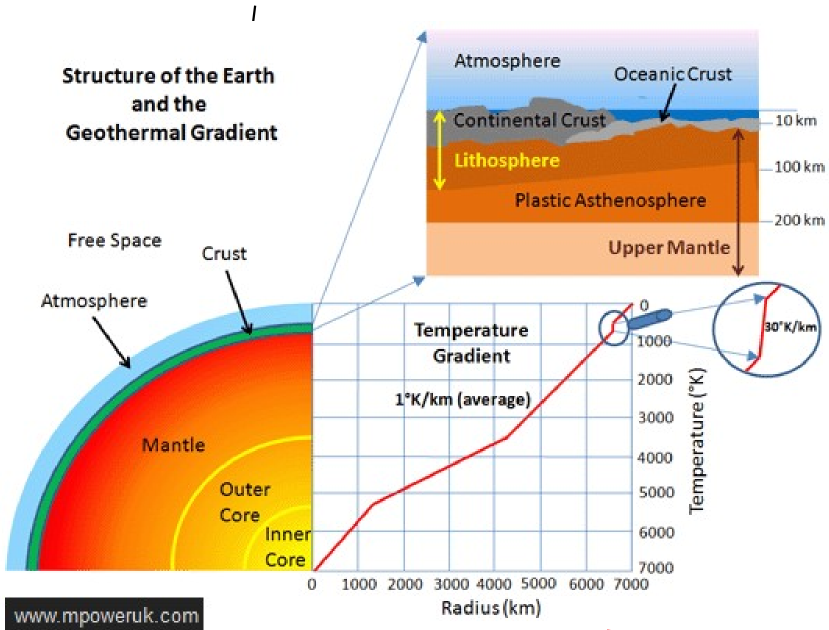
•Metamorphic rocks are classified principally according to texture.

•The process is vital for the making of continental crust, and perhaps, for help making the Earth’s climate warm and habitable.

# 3 Principal Agents of Metamorphism

## 1) HEAT

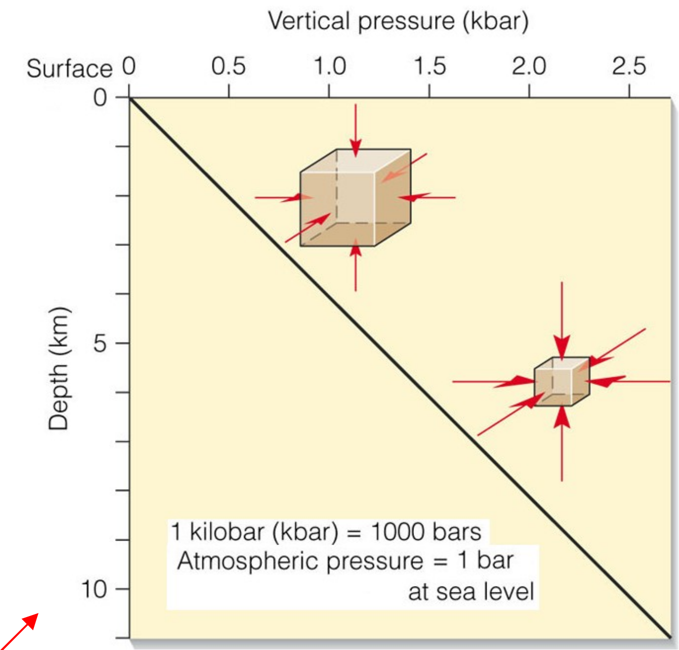
Near surface: **25°C per km of depth** in most of the world (1°F per 70 ft)




**Geothermal gradient**

**T & Ps**

## 2) PRESSURE




**Lithostatic pressure**

**3) FLUID ACTIVITY** – Fluids within sedimentary rocks or issuing from magmas can accelerate chemical changes which occur during metamorphism and can cause new minerals to form.

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# Metamorphic Fluid Activity

## 3) FLUID ACTIVITY

the presence or absence of fluids is vital for  three reasons:

a) *The presence and breakdown of $H_2O$ supplies the $OH^-$ (the hydroxyl ion) for the creation of certain metamorphic minerals.*

b) The loss of fluids during metamorphism affects crystallization processes and as new metamorphic minerals grow and evolve.

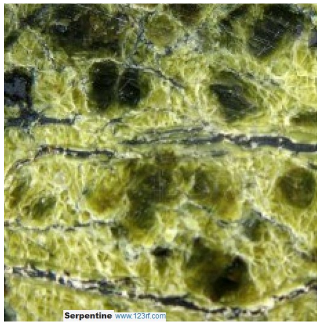
c) The presence of excess fluids after metamorphic equilibrium is reached may help *retrograde metamorphic* processes when the newly recrystallized rocks are uplifted, eroded, and subject to new equilibrium conditions

# Metamorphic Fluid Activity

**3a)** Fluids are essential to help form new minerals, seeking to adjust to changing conditions (equilibrate) in ways to maximize their stability.


$$2MgSiO_4 + H_2O \rightarrow Mg_3SiO_5(OH)_4 + MgO$$

olivine + water → serpentine + MgO





+


$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$$

Calcite + Quartz → Wollastonite + Carbon Dioxide

# Metamorphic Fluid Activity

**3b)** The presence of excess fluids after metamorphic equilibrium is reached also helps *retrograde metamorphism to occur.*


$$CaCO_3 + SiO_2 \longleftrightarrow CaSiO_3 + CO_2$$

Calcite + Quartz $\longleftrightarrow$ Wollastonite + $CO_2$

•If the level of $CO_2$ in the fluid permeating the limestone has reached saturation, that is, no more $CO_2$ can be dissolved by the fluid, then the reaction can no longer occur.

•Ordinarily, quartz and calcite are 'unhappy together' and can coexist at higher T & Ps than they ordinarily would if $CO_2$ could escape the system, thereby allowing the fluid to become unsaturated, and the mineralization process to continue, or renew.

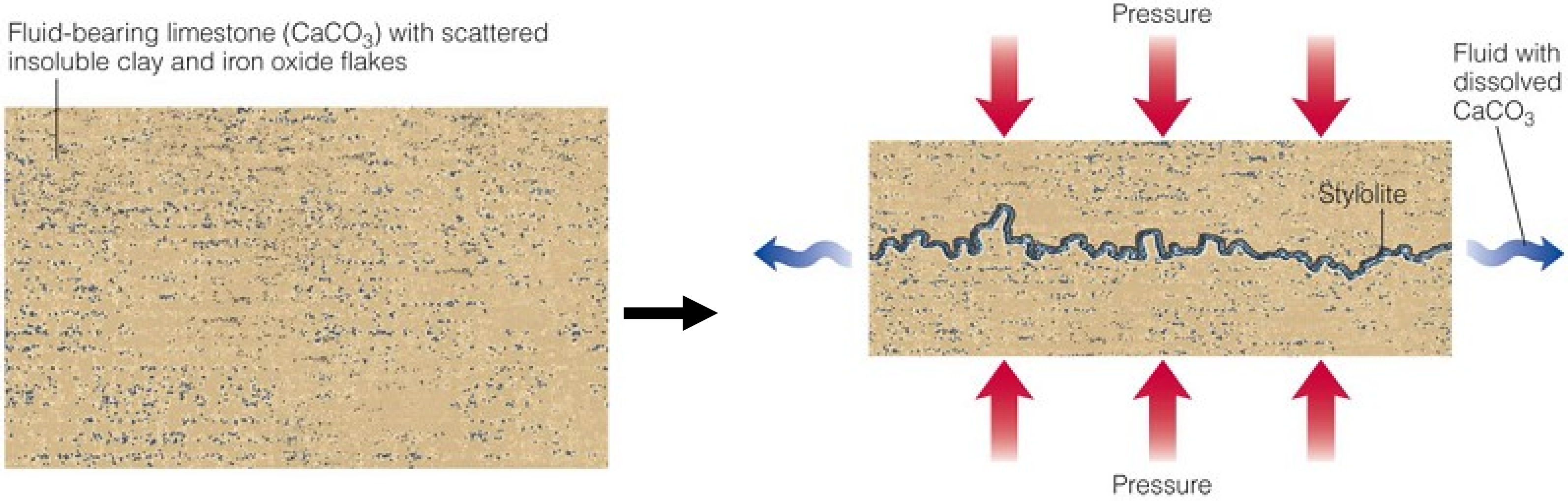
# Metamorphic Fluid Activity

**3c)** The general absence of fluids after peak metamorphism is reached (recrystallization is complete) helps preserve the metamorphic rocks during cooling and uplift for exposure at the surface today.

- *Remember that metamorphism commonly results in loss of fluids such as $OH^-$ and $CO_2$, resulting in the inability to reconstruct the original (pre-metamorphic) minerals upon uplift and erosion (T&P decreases).*
- In some cases though, heat loss is slow and the necessary fluids are present so that the metamorphic process can run in reverse (*retrograde metamorphism*)

# Fluid loss, dissolution seams, and *stylolites*

a) Fluids can escape along dissolution seams, when certain rocks dissolve at high T & Ps.




# Metamorphic Rocks and Processes

- *Heat, pressure, fluid activity, and <u>time</u>* all play determining roles in the metamorphism or rocks

- Rock become metamorphosed because the physical conditions to which they are exposed change inside Earth.

- Minerals seek to adjust to changing conditions in ways that maximize their stability. These may involve chemical reactions that change the mineral composition of the rock.

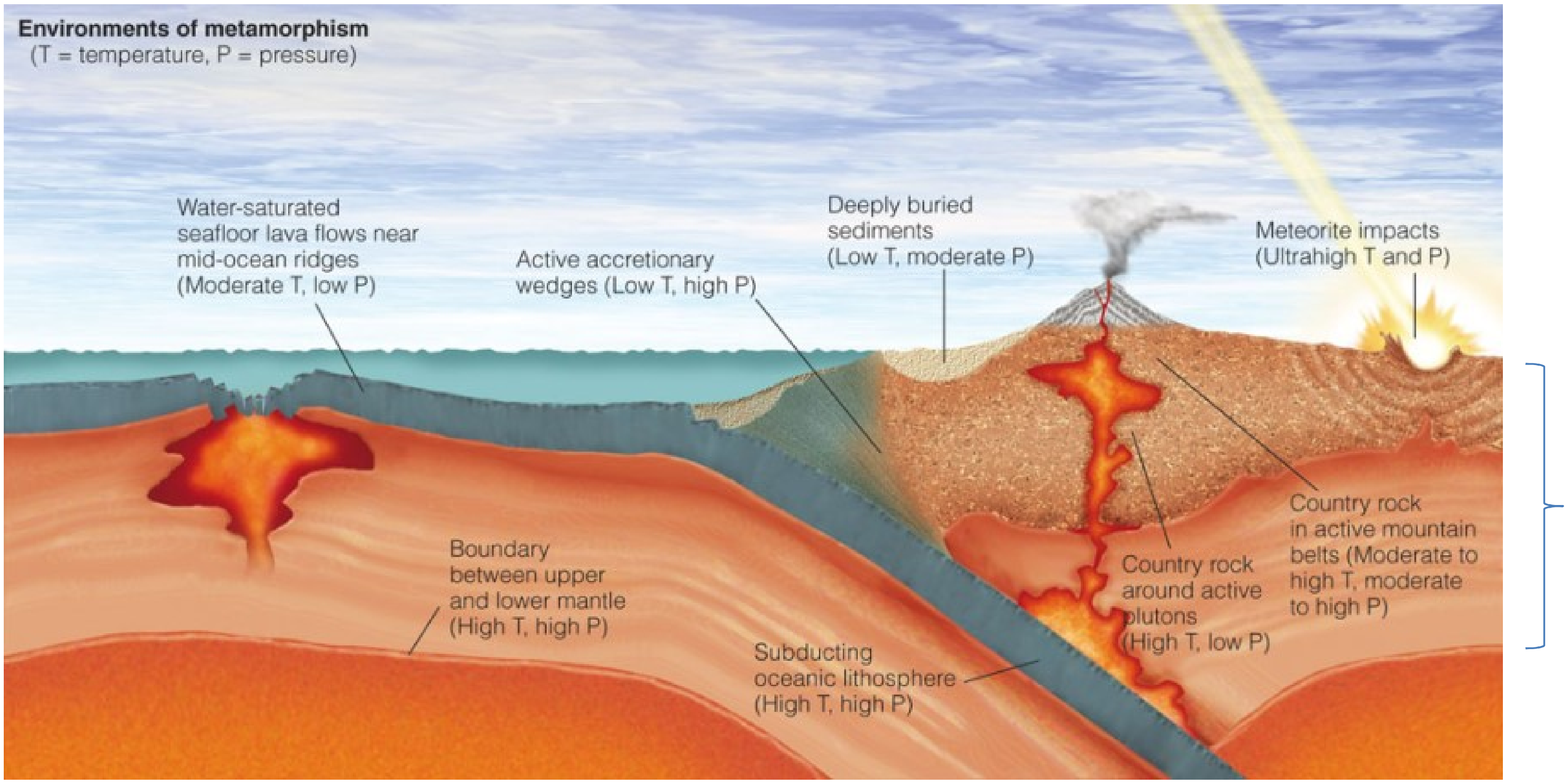
- Metamorphic fluids, which are very active in the Earth's crust, greatly influence the ease with which certain mineral reactions take place.

- The absence of fluids and the loss of heat prevent retrograde metamorphism reactions from undoing metamorphic effects when erosion exposes these rocks to surface conditions.

# Metamorphic Rocks and Processes

- The principal types of metamorphism are:

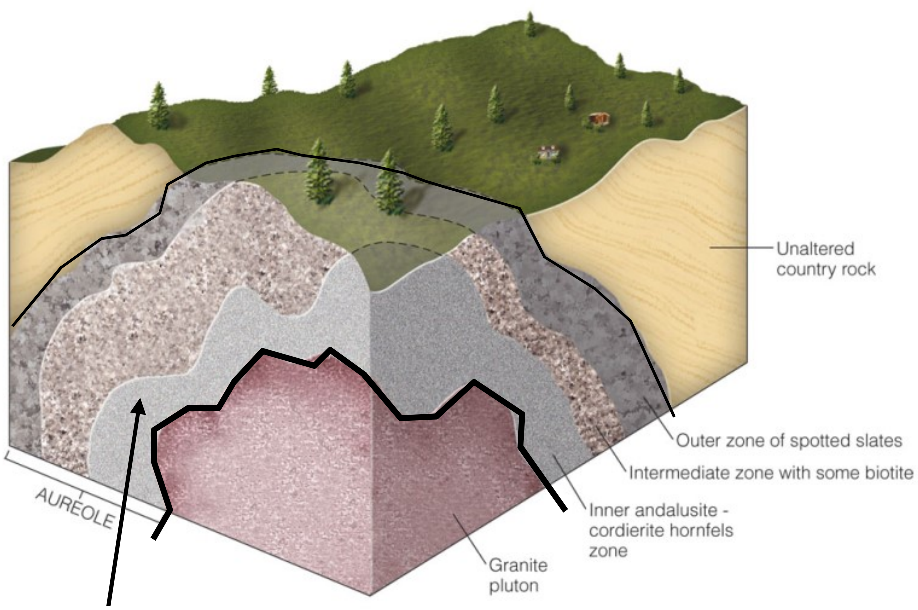
***1) contact, 2) dynamic, and 3) regional***



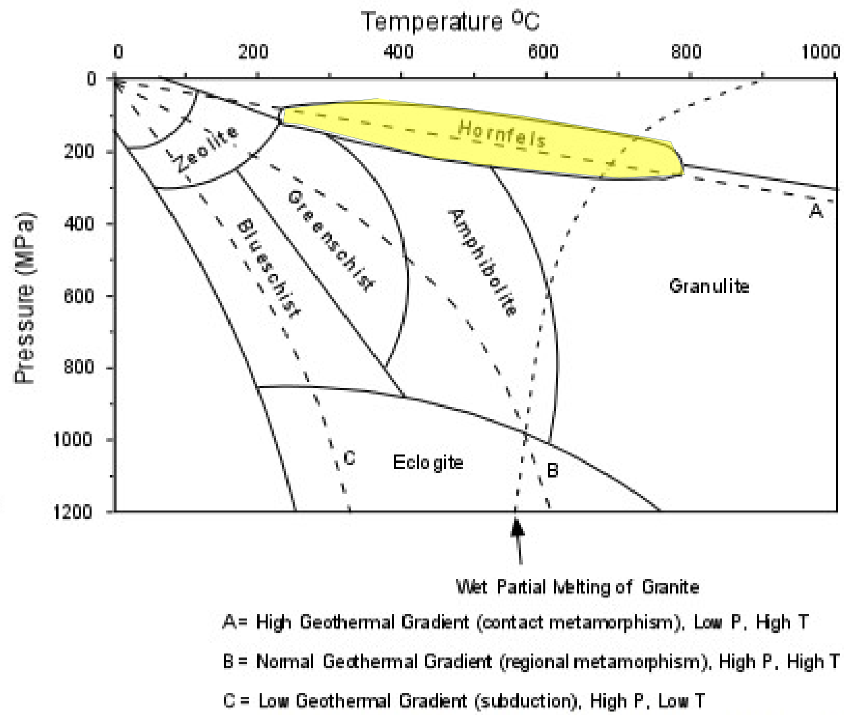
# **Contact Metamophism** is when a body of magma alters the surrounding country rock

•Increased temperature causes thermal alteration

•Hydrothermal fluids either by release from the magma or from thermal excitation of meteoric groundwater




**Contact aureole –** area of metamorphism surrounding an intrusion




www.tulane.edu/~sanelson/images/metafacies.gif

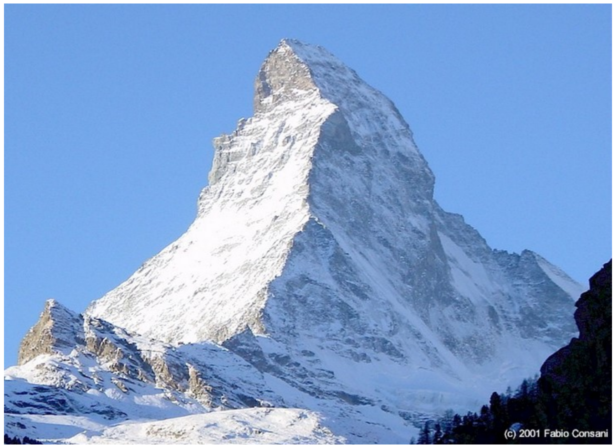
# Contact Metamophism

• The degree of metamorphic change diminishes outward from the contact reflecting decreasing temperature changes away from the heat source

• Composition of the country rock is important as shale, mudstone, and impure carbonate sedimentary rocks are particularly susceptible to the formation of new minerals whereas pure sandstone and limestone are not.

•Contact metamorphism of fine-grained rocks often results in hard, fine-grained **hornfels** with a porcelain texture.

(German, meaning "hornstone", after its frequent association with glacial "horn peaks" in the Alps, being a very hard rock and thus more likely to resist glacial action and form horn-shaped peaks such as Matterhorn) is the group designation for a series of contact metamorphic rocks that have been baked and indurated by the heat of intrusive igneous masses and have been rendered massive, hard, splintery, and in some cases exceedingly tough and durable (Wikipedia)



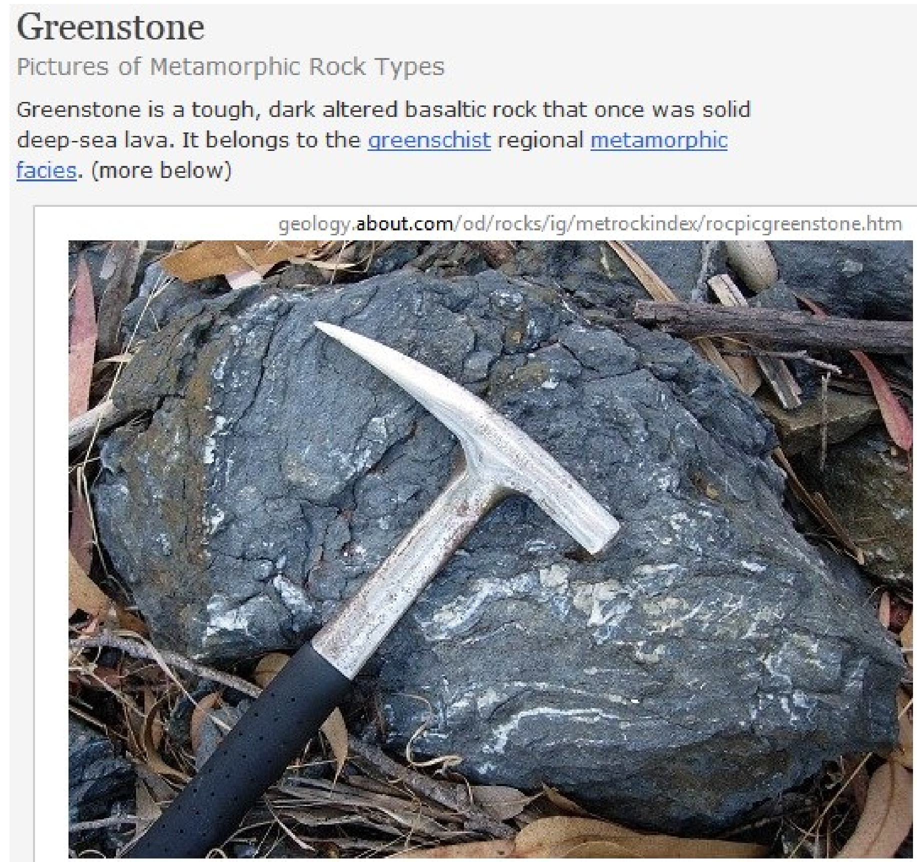
# Common Nonfoliated Metamorphic Rocks

## • Hornfels

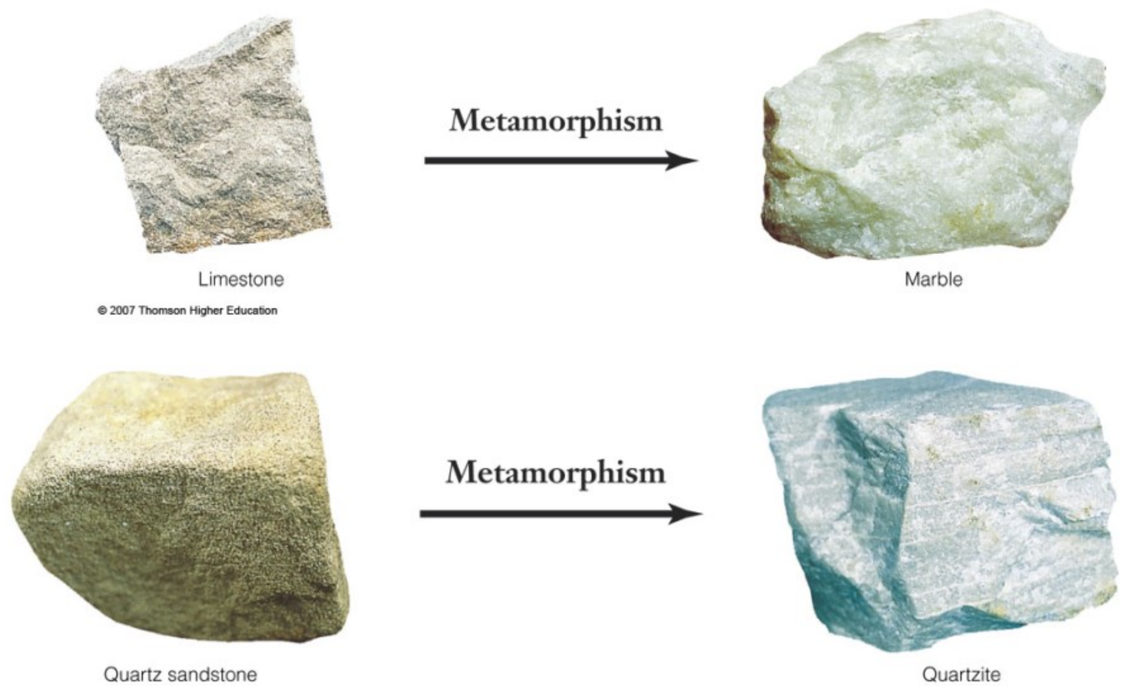
German for 'Hornstone' because it's exceptionally tough with texture likened to animal horns. These properties occur because  of new, fine grained, non-aligned growth platy or prismatic crystals.

Hornfels is the group designation for a series of contact metamorphic rocks that have been baked and *indurated* by the heat of intrusive igneous masses and have been rendered massive, hard, splintery, and in some cases exceedingly tough and durable.

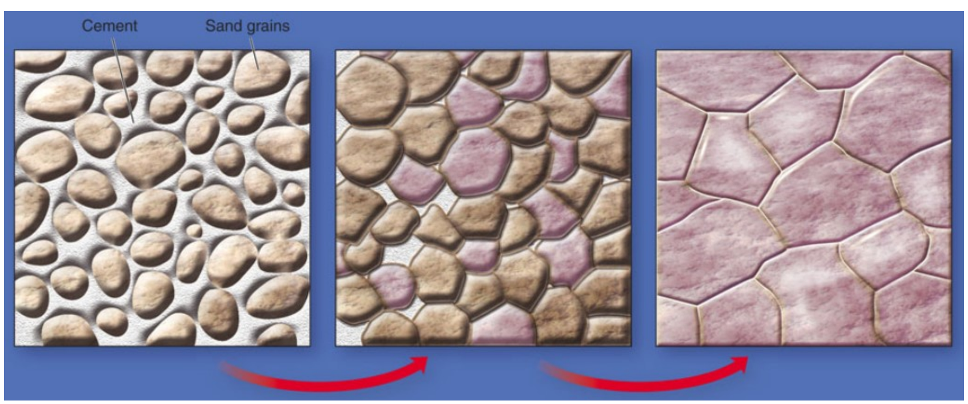
## • Greenstone



# Common Nonfoliated Metamorphic Rocks



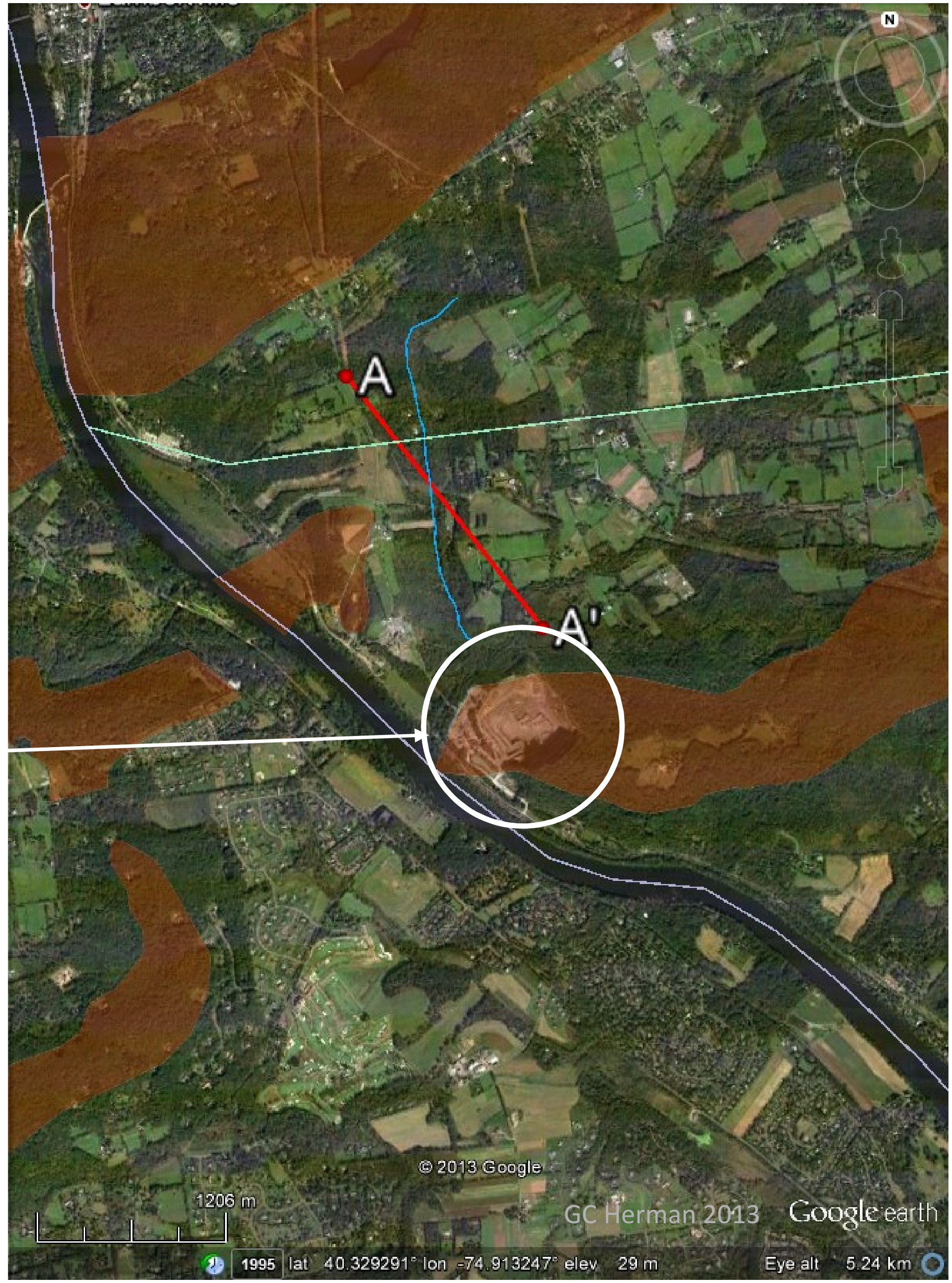

- **Marble**
- **Quartzite**



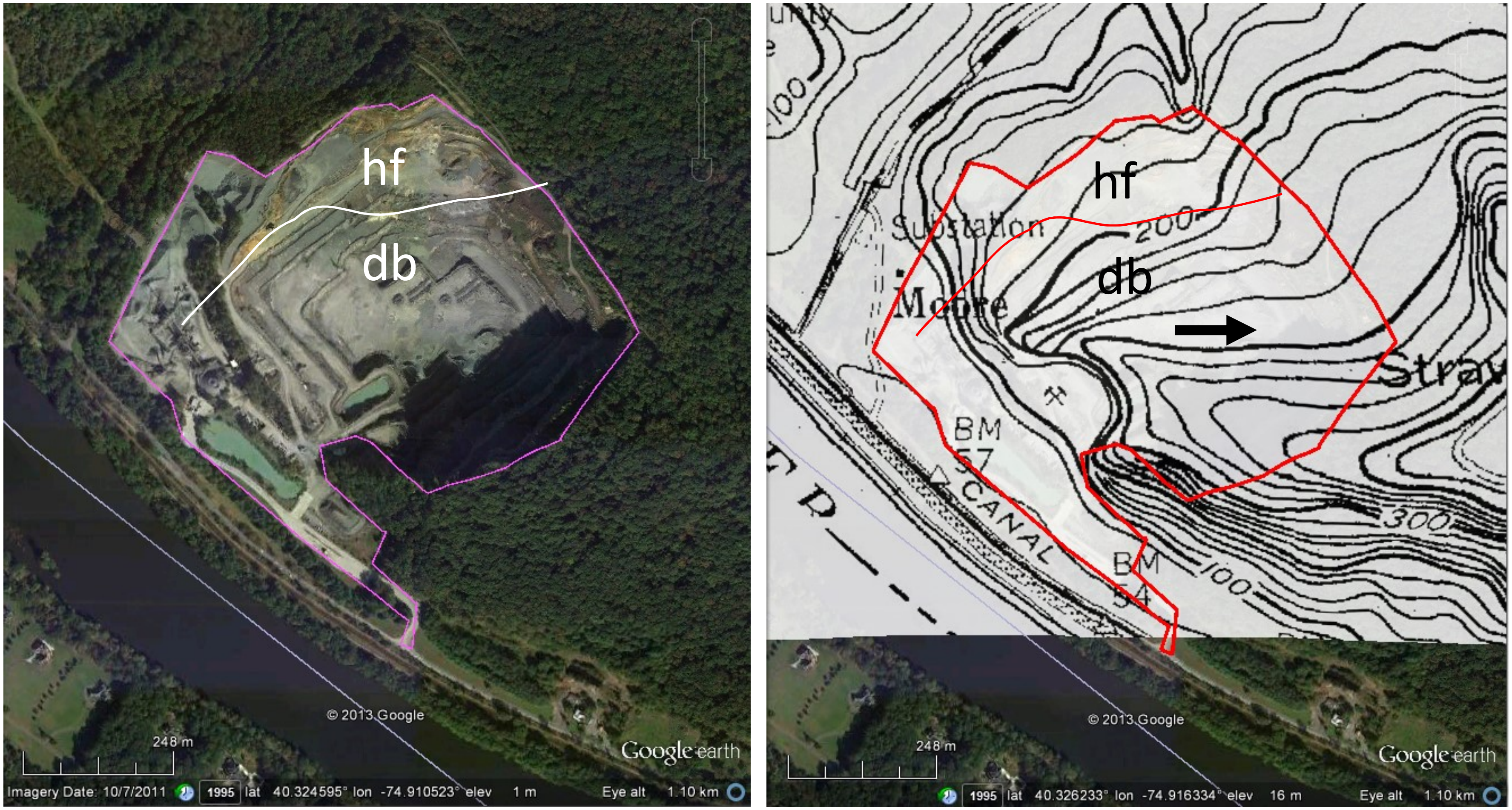

Changes in quartz sandstone as metamorphic progression to quartzite – note the length of grain and crystal boundaries decrease with increasing metamorphsim

• **Local Hornfels Example**

Moore's Station Trap Rock Industries, Mercer County, NJ 2013

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

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# Moore's Station Trap Rock Industries, Mercer County, NJ 2013 east view diabase

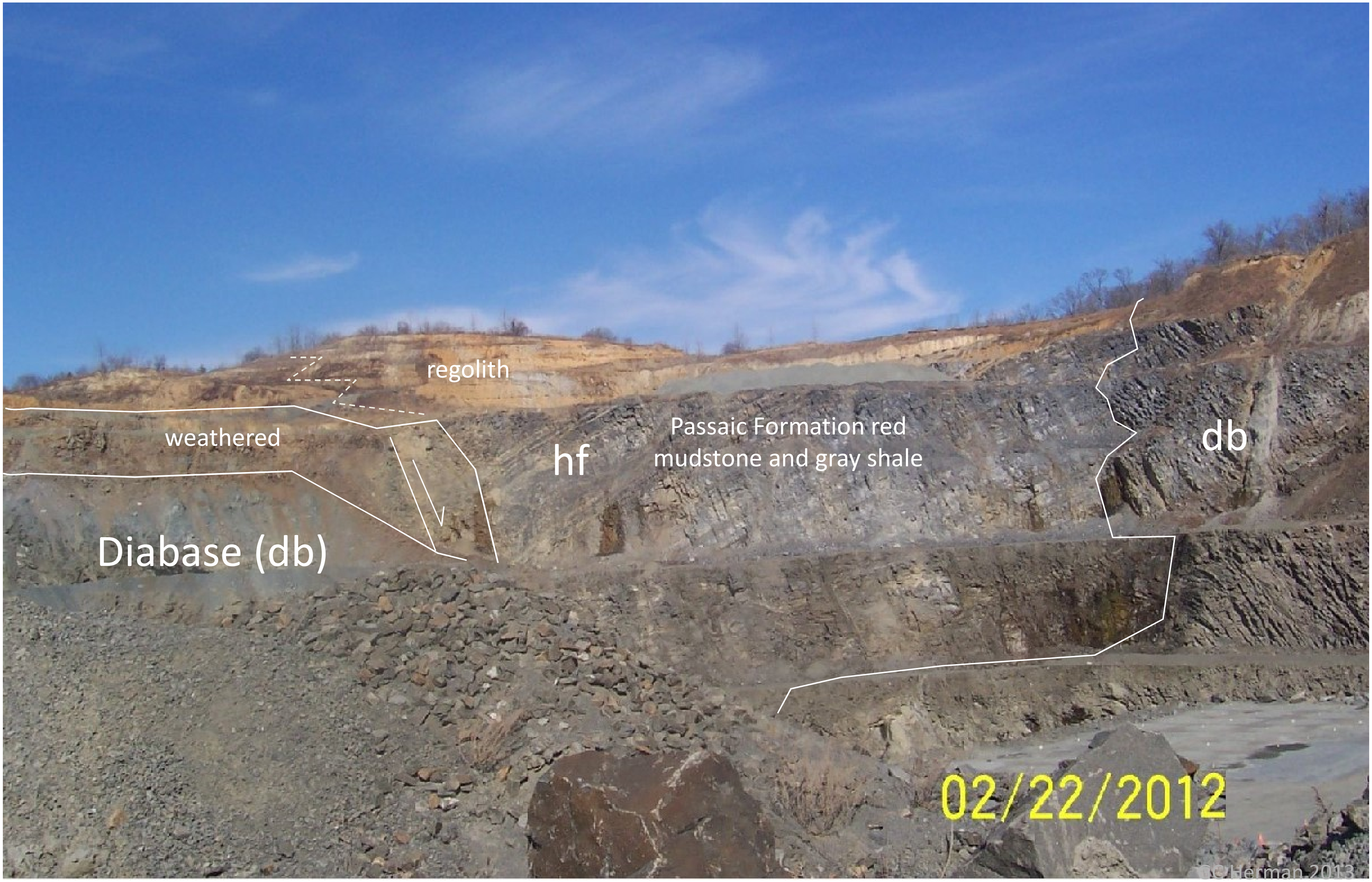
# Moore's Station Trap Rock Industries, Mercer County, NJ 2013 diabase

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013


Faulting with weathering and quart-calcite-veining with sulfides in diabase

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

North view



# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

Passaic Fm mudstone hornfels

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

weathered contact on west

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

Supergene? weathered west contact

# Moore's Station Trap Rock Industries, Mercer County, NJ 2013

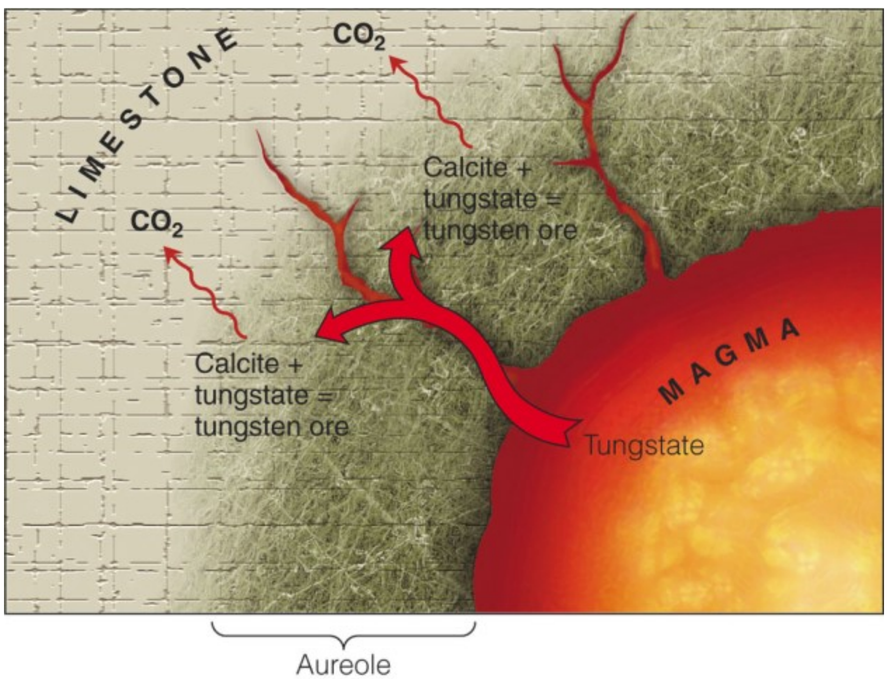
weathered contact on west

## *The Main Ore Deposits Resulting from Contact Metamorphism*

| Ore Deposit | Major Mineral | Formula | Use |
|---|---|---|---|
| Copper | Bornite<br>Chalcopyrite | $Cu_5FeS_4$<br>$CuFeS_2$ | Important sources of copper, which is used in various aspects of manufacturing, transportation, communications, and construction |
| Iron | Hematite<br>Magnetite | $Fe_2O_3$<br>$Fe_3O_4$ | Major sources of iron for manufacture of steel, which is used in nearly every form of construction, manufacturing, transporation, and communications |
| Lead | Galena | PbS | Chief source of lead, which is used in batteries, pipes, solder, and elsewhere where resistance to corrosion is required |
| Tin | Cassiterite | $SnO_2$ | Principal source of tin, which is used for tin plating, solder, alloys, and chemicals |
| Tungsten | Scheelite<br>Wolframite | $CaWO_4$<br>$(Fe, Mn)WO_4$ | Chief sources of tungsten, which is used in hardening metals and manufacturing carbides |
| Zinc | Sphalerite | (Zn, Fe)S | Major source of zinc, which is used in batteries and in galvanizing iron and making brass |

# Metasomatism

When secondary veins and late-stage dikes crisscross and cut bedrock and as driven by, or carrying along mineral-enriched fluids that interact with the country rock during cooling and crystallization to produce a bulk compositional change in bedrock (different from regional metamorphism)




**Metasomatism along a quartz and calcite complex vein, Trap Rock Industries, Pennington NJ**

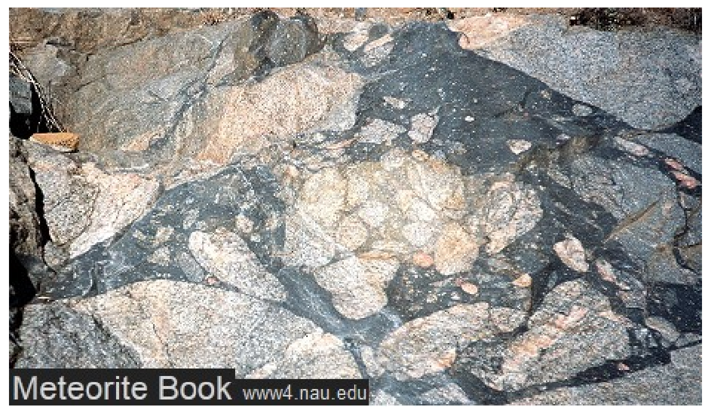
# **Dynamic Metamorphism** is one type of pressure-dominated metmorphism.

• Occurs in fault zones in the shallow crust subjected to large *differential pressures* resulting from tectonic processes like continental collisions where horizontal pressures (stresses) exceed *lithostatic pressures* associated with burial.

•Mineral recrystallization occurs in fault zones where the rocks are crushed and sheared from differential pressures to produce *mylonite* and *pseudotachylite.*

mylonite

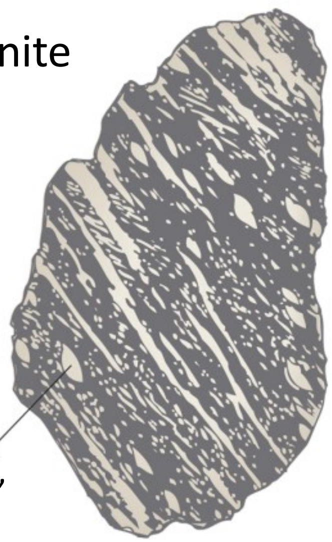

pseudotachylite



# Dynamic Metamorphism

Is one type of pressure-dominated metmorphism.

mylonite

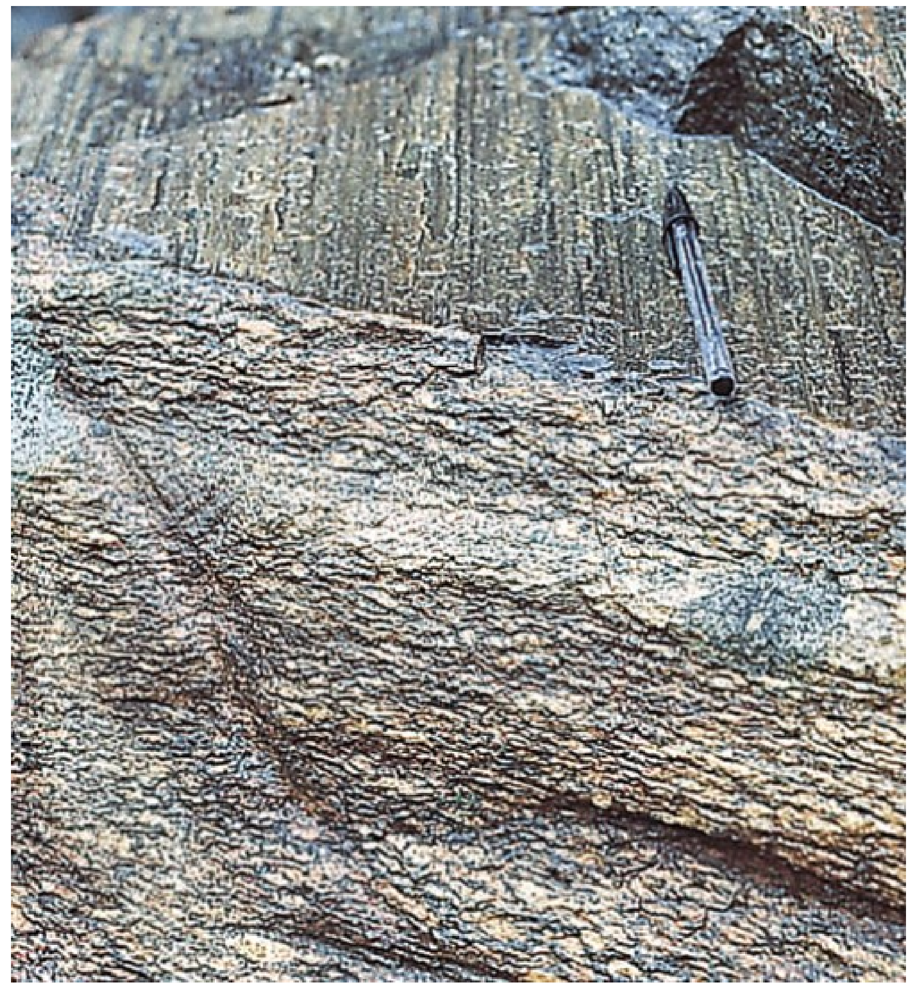



"eye"

There are many different mechanisms that accommodate crystal-plastic deformation.

In crustal rocks the most important processes are dislocation creep and diffusion creep (Wikipedia)

Mylonite from the AdirondackHighlands, New York



# Dynamic Metamorphism

## Tectonite

From Wikipedia, the free encyclopedia

**Tectonites** are metamorphic or tectonically deformed rocks whose fabric reflects the history of their deformation, or rocks with fabric that clearly displays coordinated geometric features that indicate continuous solid (ductile) flow during formation. *Planar foliation* results from a parallel orientation of platey mineral phases such as the phyllosilicates or graphite. Slender prismatic crystals such as amphibole produce a *lineation* in which these prisms or columnar crystals become aligned.[1]

### Classification

- *S-tectonites* (from the German, *Schiefer* for schist) have a dominant planar fabric and may indicate a flattening type of strain. This may also be due to a lack of minerals capable of giving a lineation e.g. in a phyllonite.[1]
- *L-tectonites* have a dominant linear fabric and generally indicate a constrictional type of strain. This may be due to a lack of platey phases.[1]
- *L-S tectonites* have equally developed linear and planar fabric elements and may indicate a plane strain deformation. Many mylonites are L-S tectonites consistent with a simple shear deformation.

L-S tectonite viewed in the plane of the S fabric

L-S tectonite viewed perpendicular to the plane of the S fabric

### References

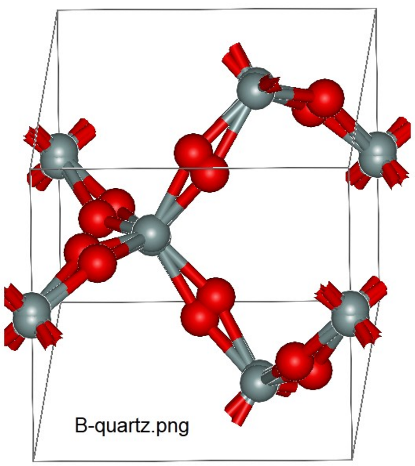

1. ^ a b c Best, Myron G., *Igneous and Metamorphic Petrology*, Wiley-Blackwell, 2nd ed. 2002, p. 448

# **Shock Metamorphism** another type of pressure-dominated metamorphism caused by bolide (asteroid, comet, and meteor) impacts

• Shock waves emanate outward from an impact with pressure waves reaching 20 to 500 kilobars (lithostatic pressure from 3 km burial = 1 kb).

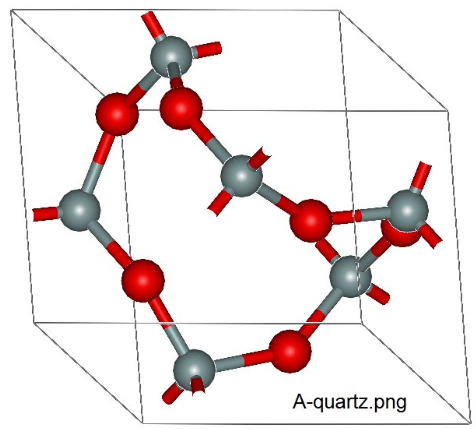
•Instantaneous polymorphism of quartz into stishovite, an ultradense form of $SiO_2$

High T



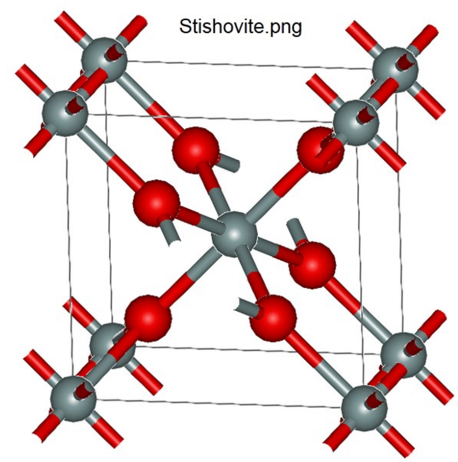

2.53 g/cm$^3$

Atmospheric




2.65 g/cm$^3$

High P




4.29 g/cm$^3$

**Density** →

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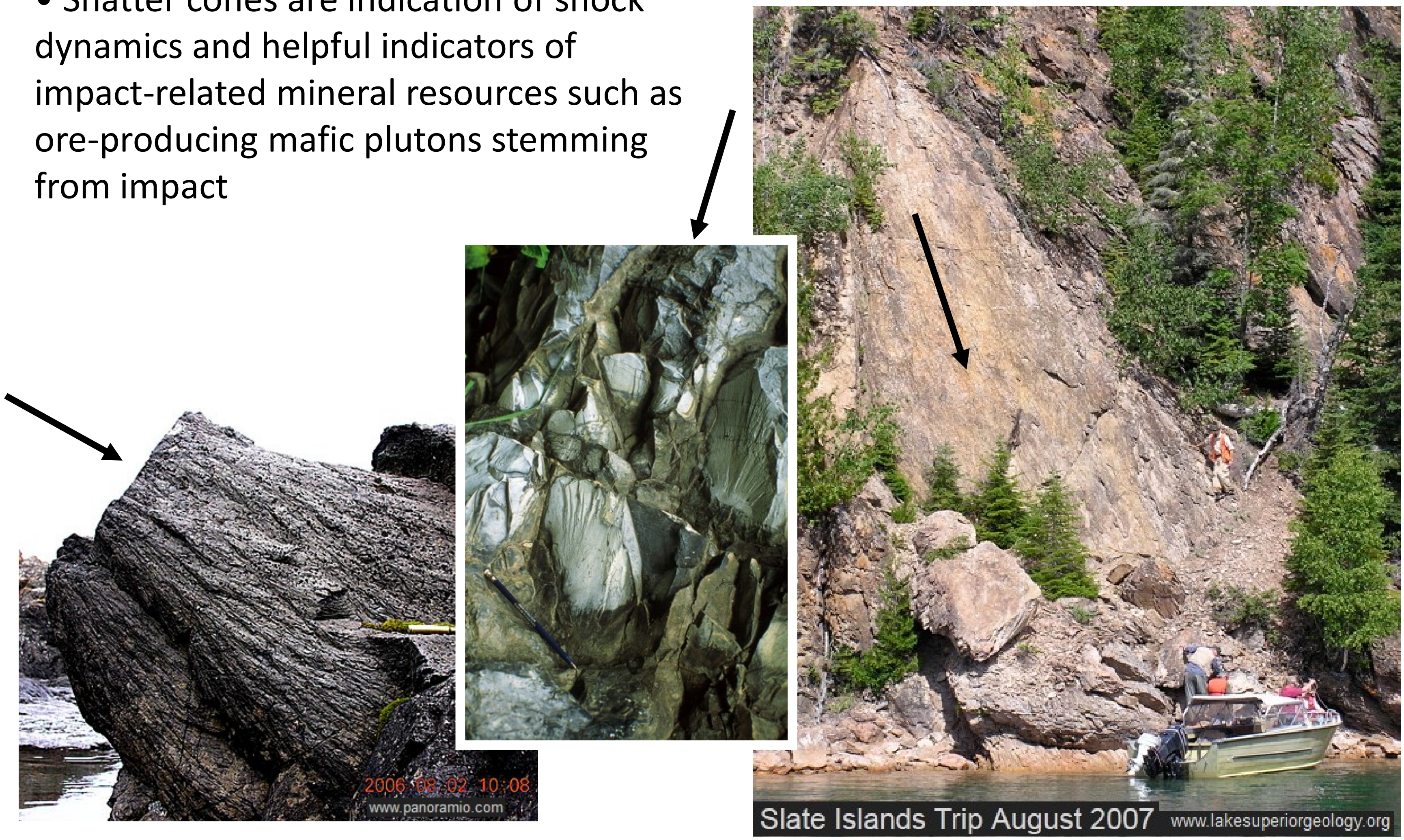
**Shock Metamorphism** another type of pressure-dominated metamorphism caused by bolide (asteroid, comet, and meteor) impacts

- Shatter cones are indication of shock dynamics and helpful indicators of impact-related mineral resources such as ore-producing mafic plutons stemming from impact



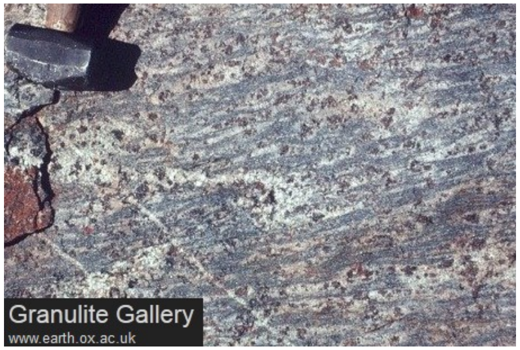
# Regional (Dynamothermal) Metamorphism

• Most common type of metamorphism that occurs over large areas from tremendous pressures and temperatures in the deep crust to produce foliated rocks.

• Metamorphic grade is used to characterize the degree to which rocks have undergone change.


1) Low (greenschist) with the appearance of chlorite (group of minerals) around 200°C
   - $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$


2) Medium – Biotite and garnet schist >200°C < 550°C




•$Al_2OSiO_4$

3) High – Silliminite forms, gneisses and granulites > 550°C

# Foliated Metamorphic Rocks

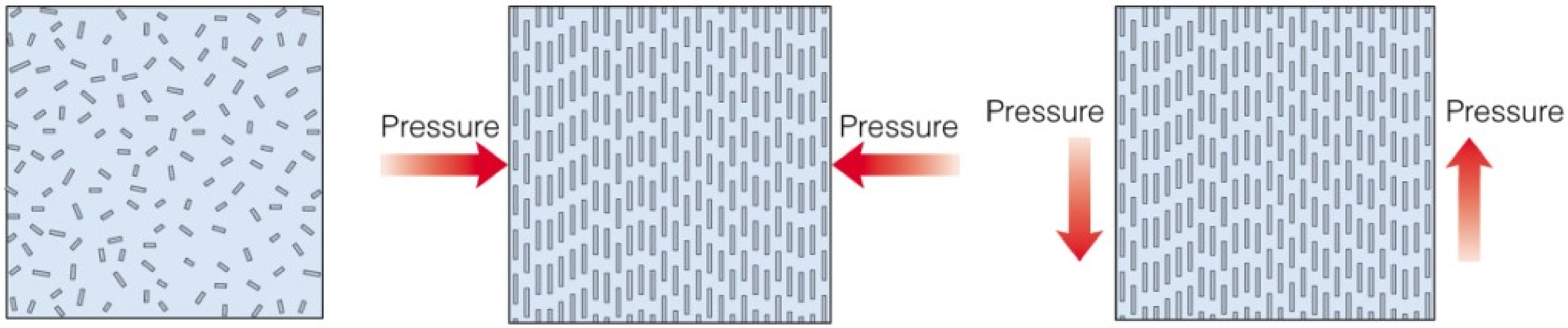
•Foliated metamorphic rocks form a graded series of grain size and/or development of foliation, from fine grained ***slate***, to ***phyllite*** and coarser grained ***schist***, to ***gneiss***, with segregated bands of minerals.

*Classification of Common Metamorphic Rocks*

| Metamorphic Rock | Typical Minerals | Metamorphic Grade | Characteristics of Rocks | Parent Rock |
|---|---|---|---|---|
| Slate | Clays, micas, chlorite | Low | Fine-grained, splits easily into flat pieces | Mudrocks, volcanic ash |
| Phyllite | Fine-grained quartz, micas, chlorite | Low to medium | Fine-grained, glossy or lustrous sheen | Mudrocks |
| Schist | Micas, chlorite, quartz, talc, hornblende, garnet, staurolite, graphite | Low to high | Distinct foliation, minerals visible | Mudrocks, carbonates, mafic igneous rocks |
| Gneiss | Quartz, feldspars, hornblende, micas | High | Segregated light and dark bands visible | Mudrocks, sandstones, felsic igneous rocks |
| Amphibolite | Hornblende, plagioclase | Medium to high | Dark, weakly foliated | Mafic igneous rocks |
| Migmatite | Quartz, feldspars, hornblende, micas | High | Streaks or lenses of granite intermixed with gneiss | Felsic igneous rocks mixed with sedimentary rocks |

• ***Amphibolite*** is another fairly common coarse grained foliated metamorphic rock.

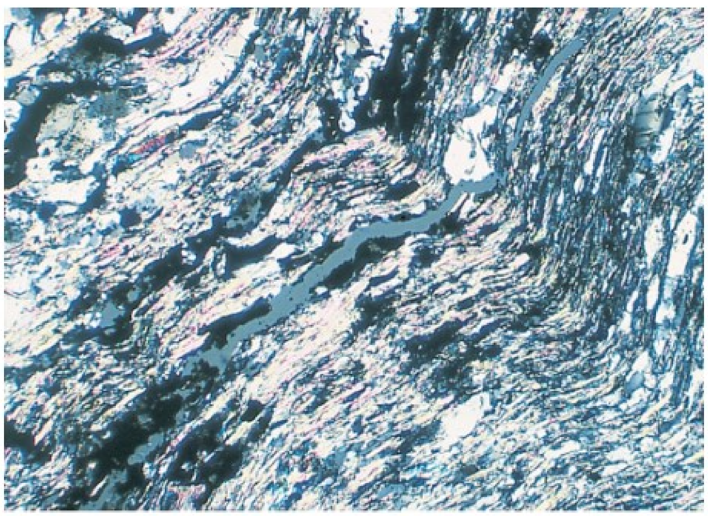
# Foliated Metamorphic Rocks




Random arrangement of elongated minerals before pressure is applied to two sides

Elongated minerals arranged in a parallel fashion as a result of pressure applied to two sides

Elongated minerals arranged in a parallel fashion as a result of shear



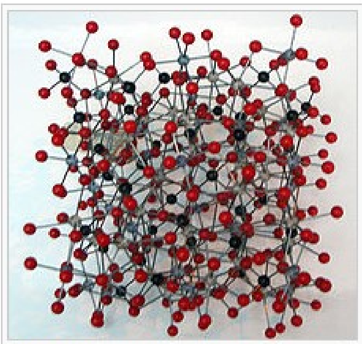
Folded foliation in a metamorphic rock from near Geirangerfjord, Norway

# The origin of rotated garnets in foliated metamorphic rocks involves tectonic shear strains operating at medium- to high-metamorphic grades

**Garnet**

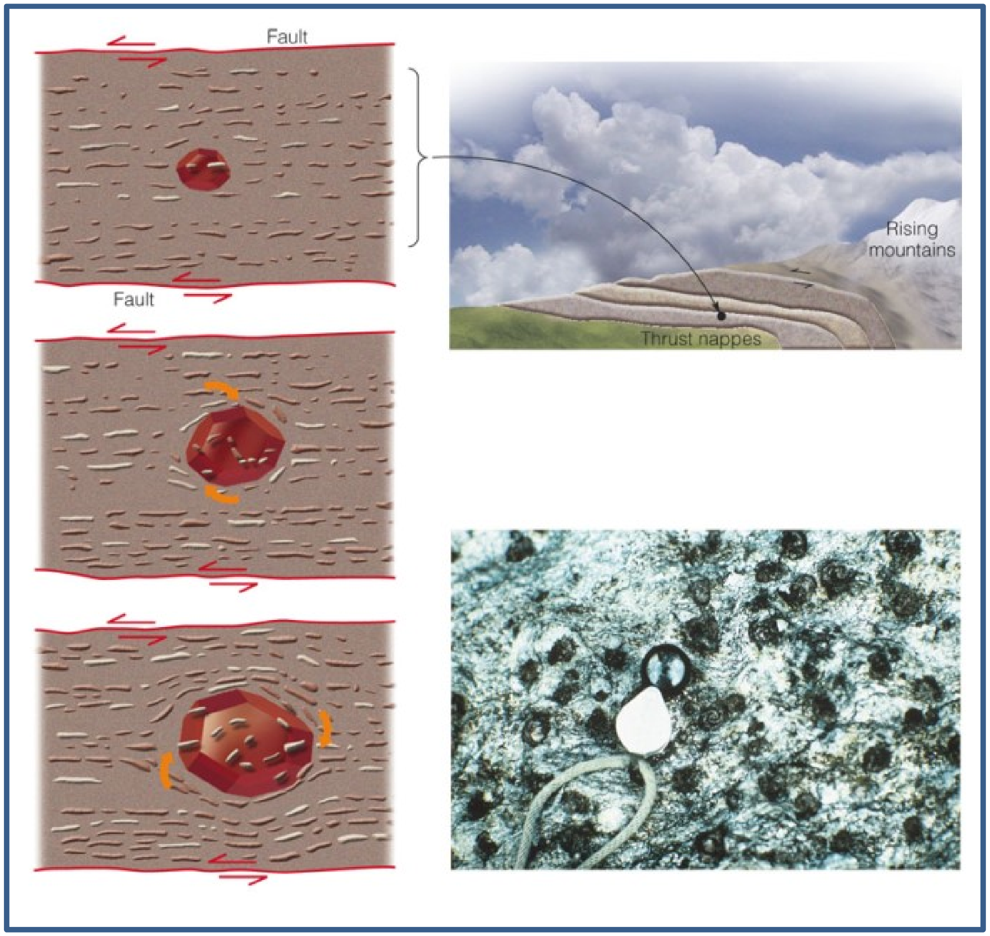
| General | |
|---|---|
| Category | Nesosilicate |
| Formula (repeating unit) | The general formula $X_3Y_2(SiO_4)_3$ |
| **Identification** | |
| Color | virtually all colors |
| Crystal habit | Rhombic dodecahedron or cubic |
| Crystal system | Cubic rhombic dodecahedron, icositetrahedron |
| Cleavage | Indistinct |
| Fracture | conchoidal to uneven |
| Mohs scale hardness | 6.5–7.5 |
| Luster | vitreous to resinous |
| Streak | White |
| Specific gravity | 3.1–4.3 |
| Polish luster | vitreous to subadamantine[1] |
| Optical properties | Single refractive, often anomalous double refractive[1] |

A sample showing the deep red color garnet can exhibit.



Crystal structure model of garnet

en.wikipedia.org/wiki/Garnet

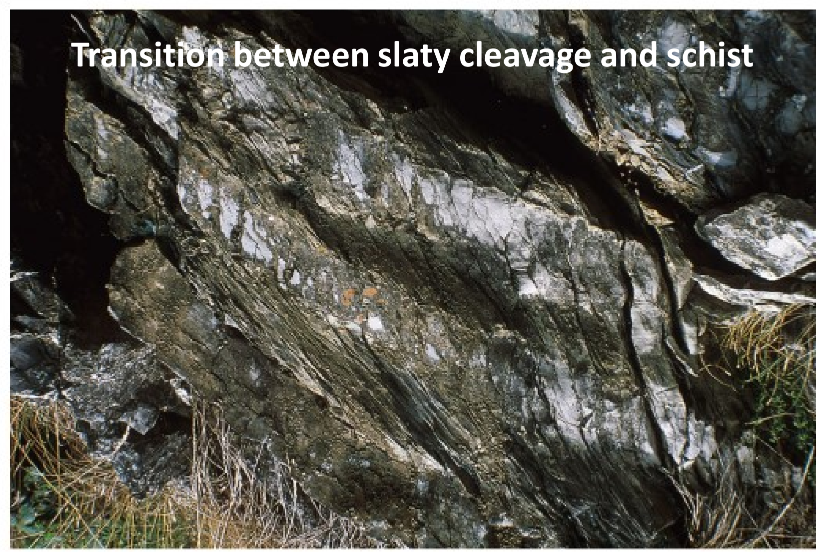



- Almandine: $Fe_3Al_2(SiO_4)_3$
- Pyrope: $Mg_3Al_2(SiO_4)_3$
- Spessartine: $Mn_3Al_2(SiO_4)_3$
- Andradite: $Ca_3Fe_2(SiO_4)_3$
- Grossular: $Ca_3Al_2(SiO_4)_3$
- Uvarovite: $Ca_3Cr_2(SiO_4)_3$

# Foliated Metamorphic Rocks  Slate and slaty cleavage





# Foliated Metamorphic Rocks Schist

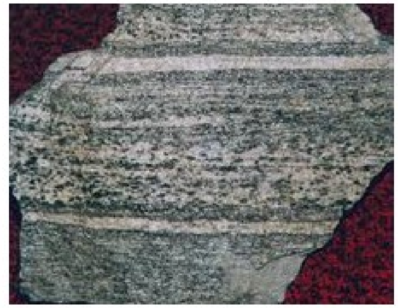




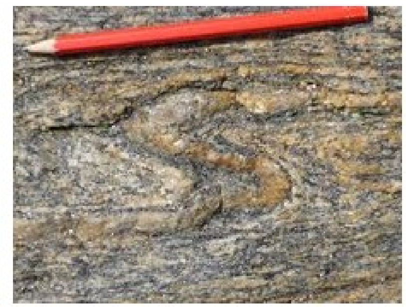


# Foliated Metamorphic Rocks **Gneiss**



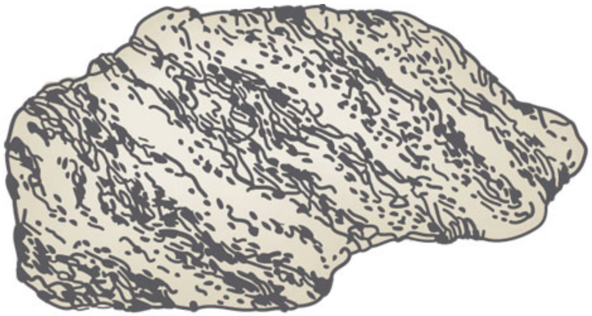




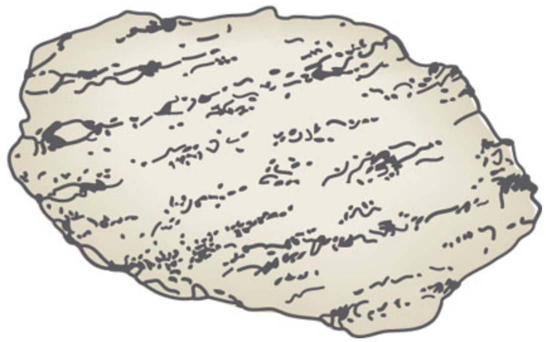





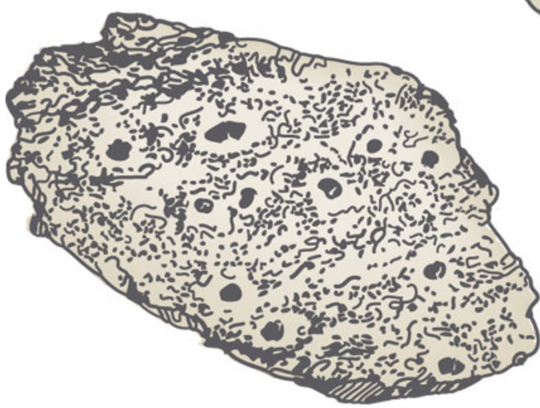
# Foliated Metamorphic Rocks Gneiss



**Paragneiss - metamorphic product of silicate sedimentary rocks**



**Orthogneiss – metamorphic product of felsic igneous rocks**





**Spotted gneiss – Spots are magnetite porphyroblasts formed from reheating and breakdown of biotite**

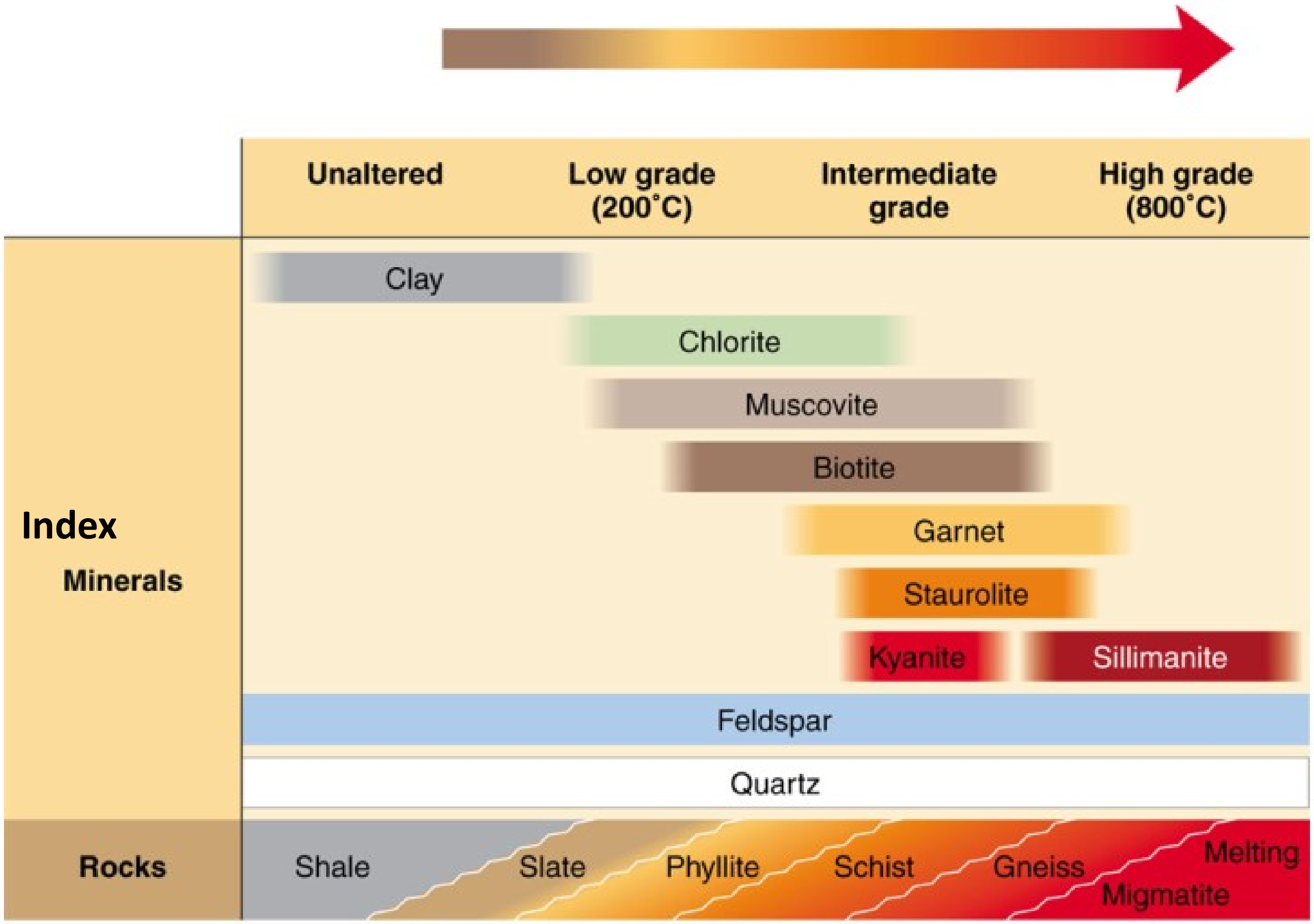
# Foliated Metamorphic Rocks

**Mimatite –** Mixed-mode crystalline rocks having both igneous and metamorphic characteristics (i.e. melt and layering aspects)

**Stretched-pebble conglomerate**

# Metamorphic Zones

•Metamorphic rocks often can be arranged in metamorphic zones which reflect the pressure and temperature conditions of metamorphism using *index minerals*

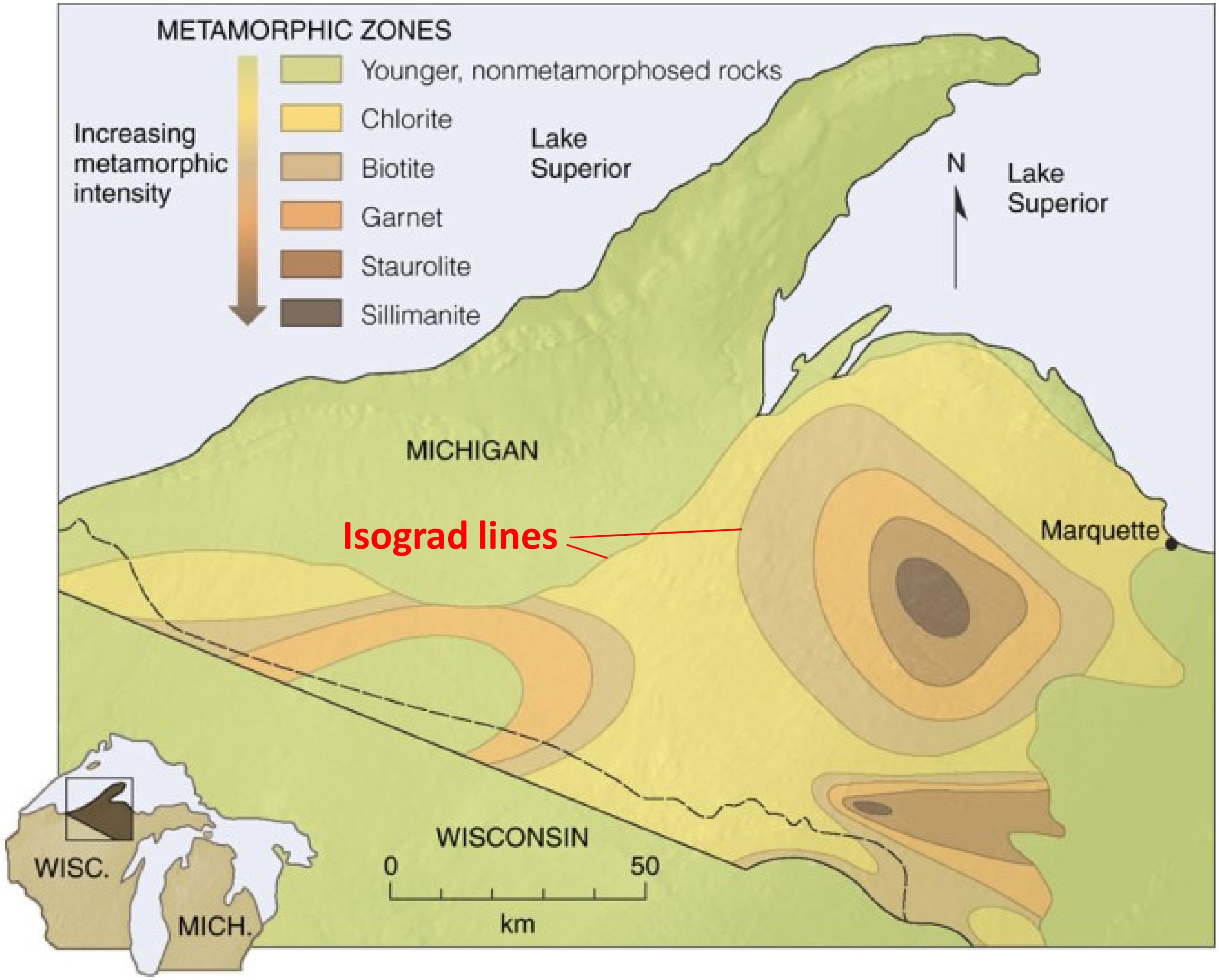


# **Metamorphic Zones** in the upper peninsula of Michigan

- **Isograd lines are used to trace lines of equal metamorphic grade**

**•Zones are identifed on the basis of key index minerals**

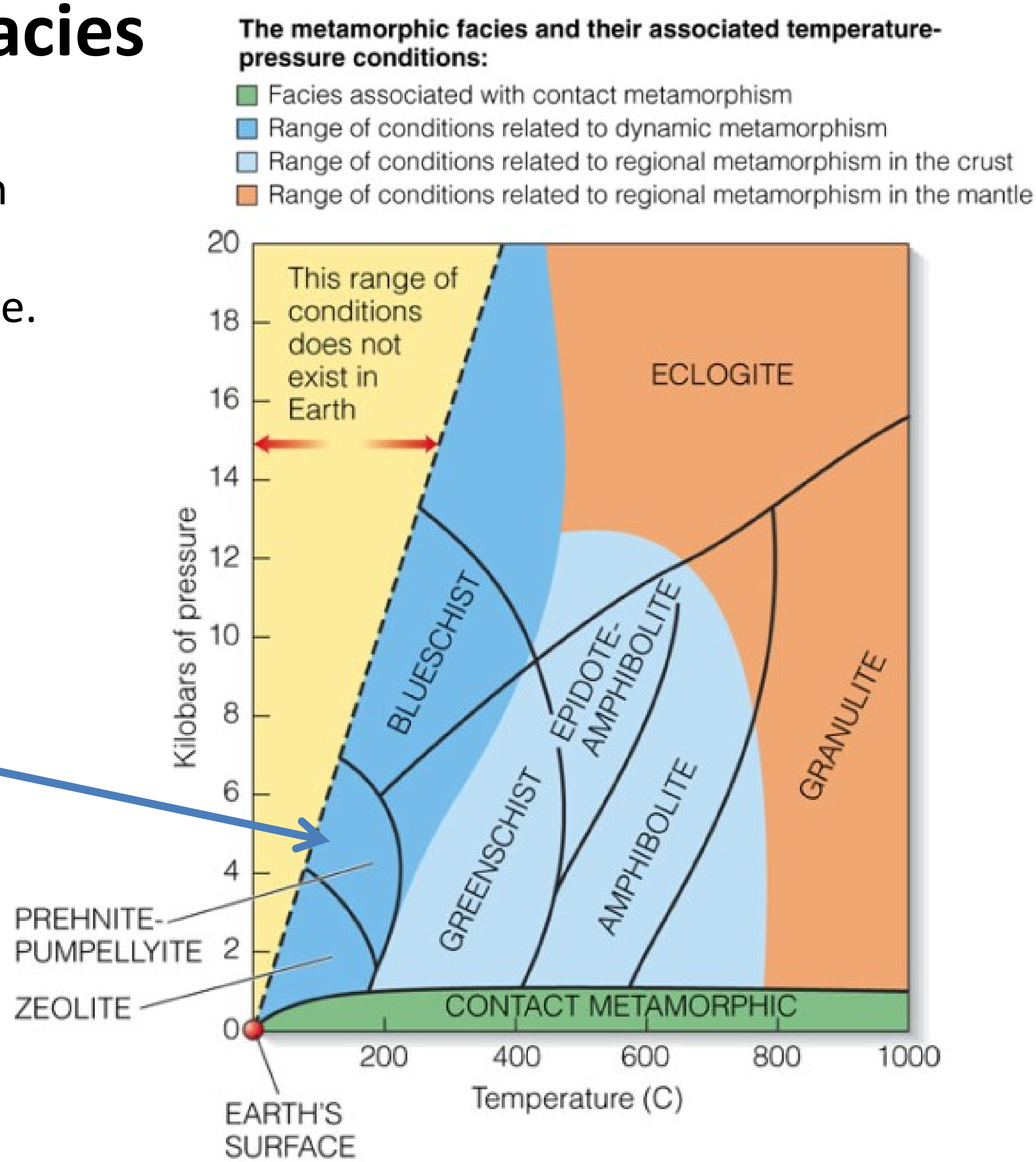
**•Differ from *metamorphic facies* that are identified by the T & P conditions**



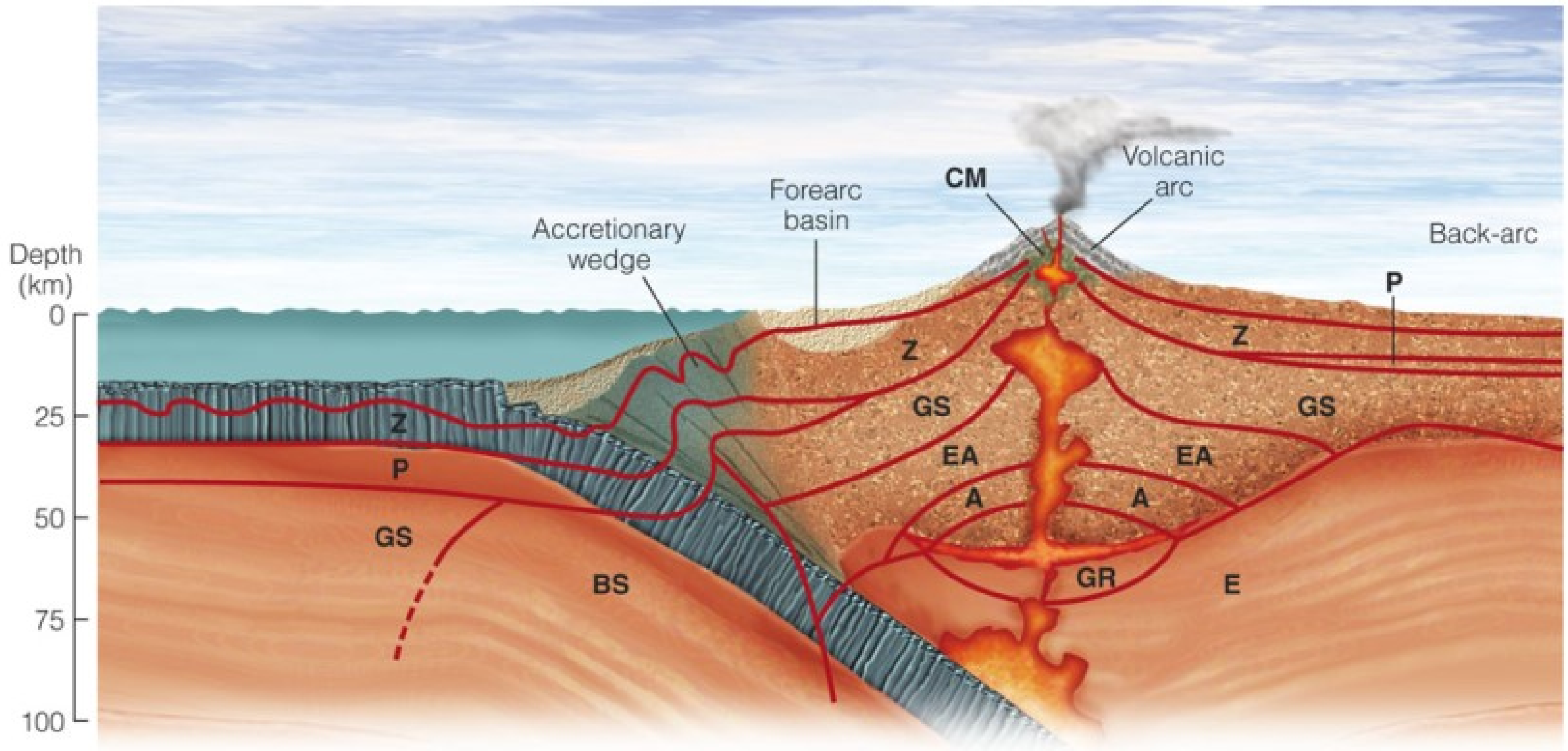
# Metamorphic Facies

are characterized by particular minerals which reflect specific ranges of temperature and pressure.

Metamorphic rocks formed near the surface and within an oceanic-continental convergent plate boundary zone result from low temperature and high pressure conditions.



Metamorphism can occur along all types of plate boundaries, but is most common and extensive along convergent boundaries.

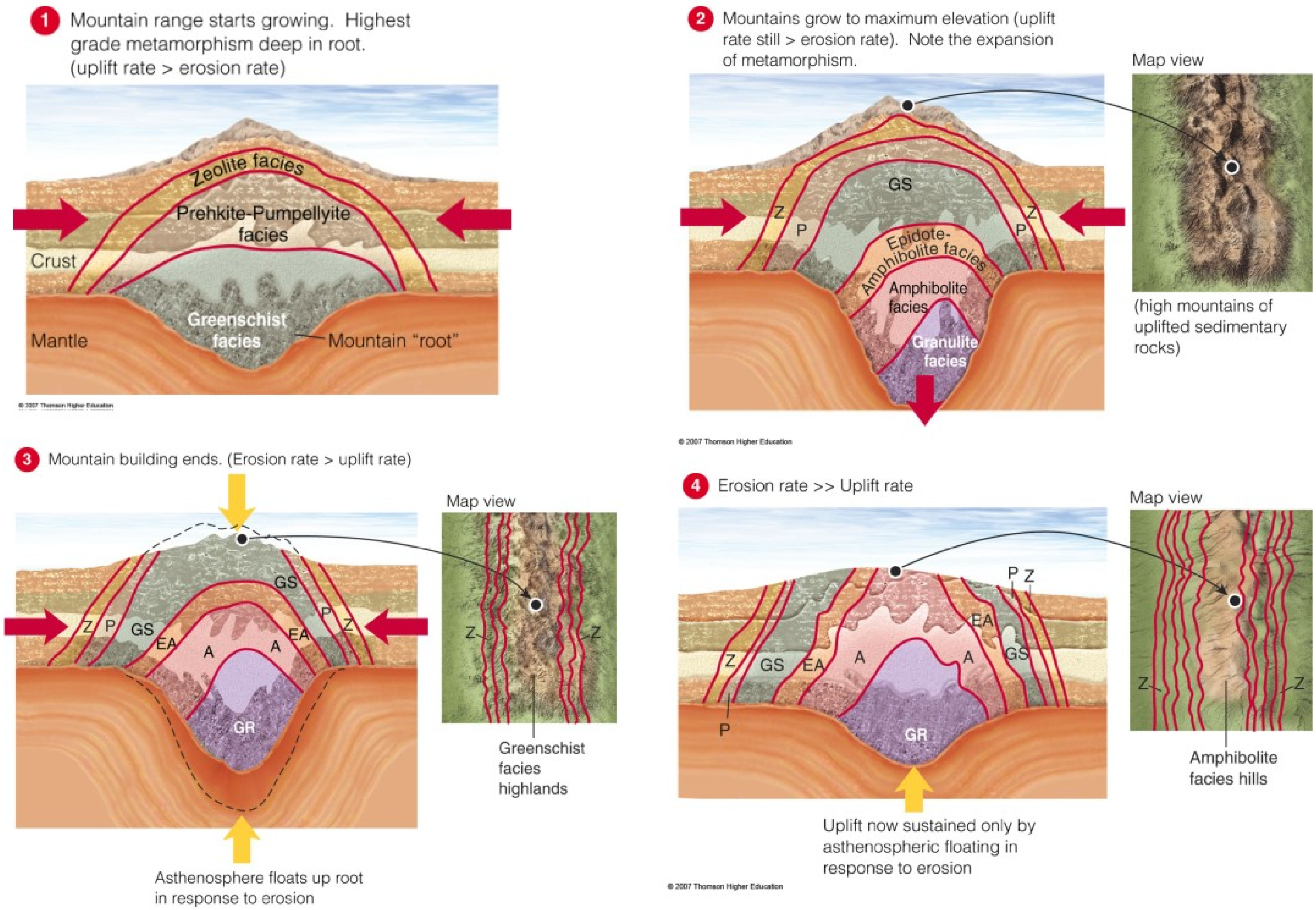



Relationship of facies to major tectonic features at a convergent plate boundary
Abbreviations:

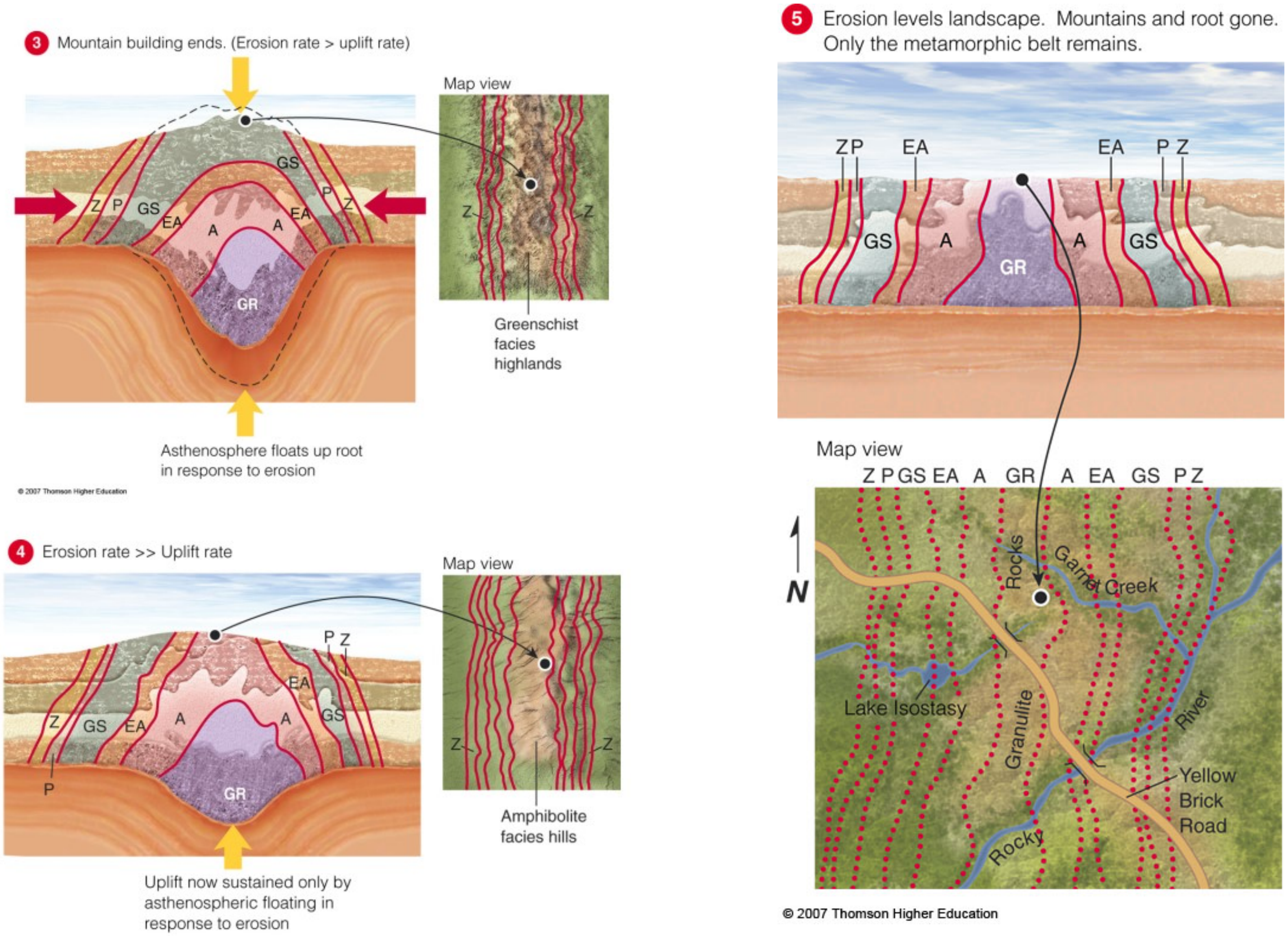
**A** = amphibolite facies
**BS** = blueschist facies
**CM** = contact metamorphic zone shown in green
**E** = eclogite facies
**EA** = epidote-amphibolite facies
**GR** = granulite facies
**GS** = greenschist facies
**P** = prehnite-pumpellyite facies
**Z** = zeolite facies

Higher temperatures and pressures exist at depth in convergent plate boundaries and produce higher grades of metamorphism in a descending oceanic plate.

# Development of a metamorphic rock belt during mountain growth and evolution

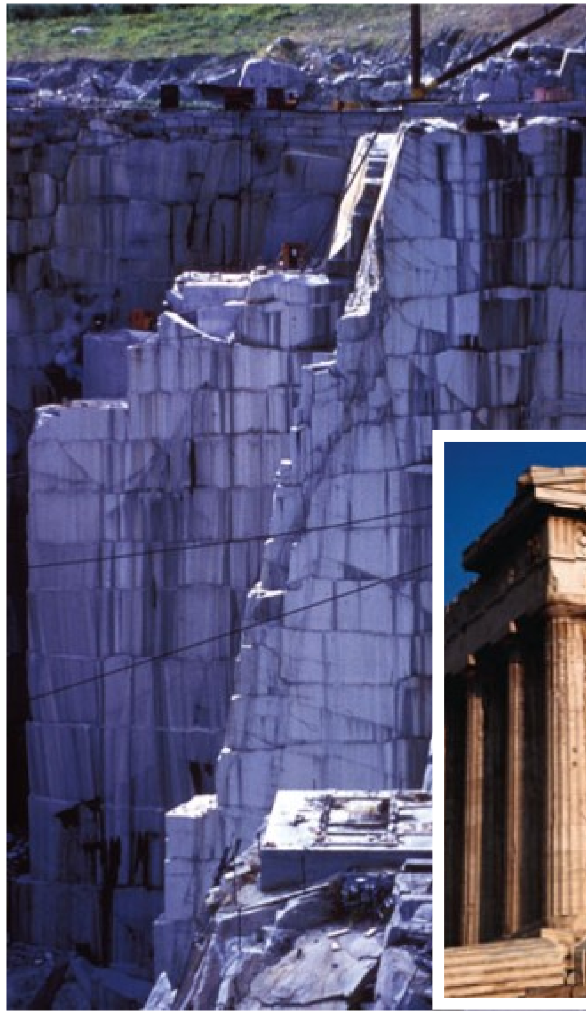


# Development of a metamorphic rock belt during mountain growth and evolution



# Metamorphic Rocks Resources and Uses

- Mineral resources which are metamorphic rocks include marble, slate, graphite, talc, and asbestos



# Metamorphic Rocks Resources and Uses

- Talc and asbestos mineral resources

garnet

asbestos

Red garnets were the most commonly used gemstones in the Late Antique Roman world