

Metamorphism and Metamorphic Rocks

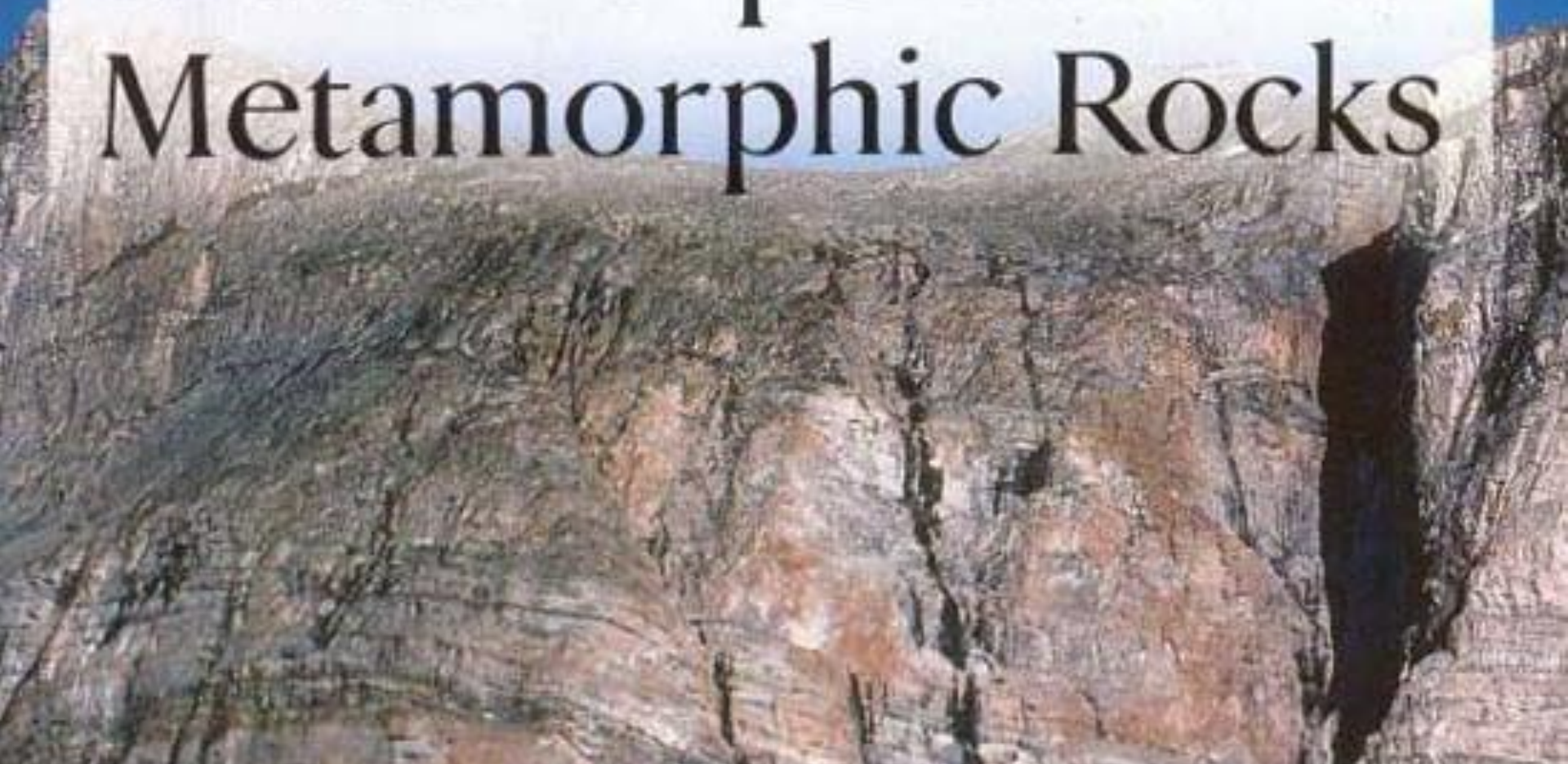


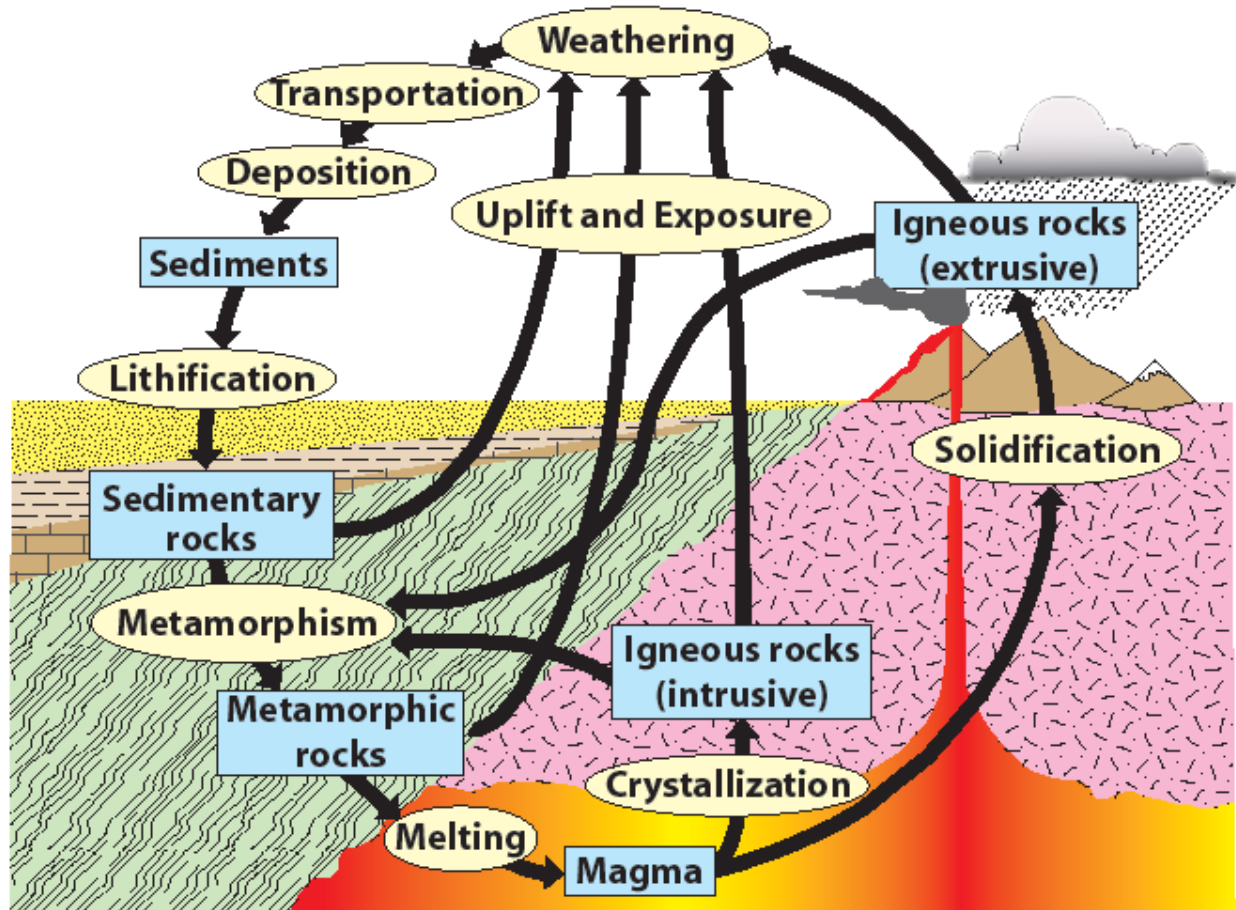


FIGURE 8.1 Deformed metamorphic rocks exposed in a road cut in the Eastern Highland of Connecticut. (Photo by Phil Dombrowski)

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The Rock Cycle



Igneous Rocks -

Rocks that form from the cooling of molten rock (magma), Example: granite and basalt

Sedimentary Rocks -

Rocks that are formed from pieces of other rocks, Example: sandstone, or that are deposited from the ocean by chemical processes, Example: limestone

Metamorphic Rocks -

Rocks that are changed by heat and pressure without melting, Example: gneiss

Introduction

Compressional forces (pressure/stress) of unimaginable magnitude and-

temperatures hundreds of degrees above surface conditions-

prevailed for perhaps thousands or millions of years in the earth to produce the deformation and metamorphism displayed by the metamorphic rocks.

Under such extreme conditions, solid rocks responds by:

- **folding,**
- **fracturing,** and often by
- **flowing.**

These conditions change appearance, mineralogy, and sometimes even in over-all chemical composition of the parent rocks.

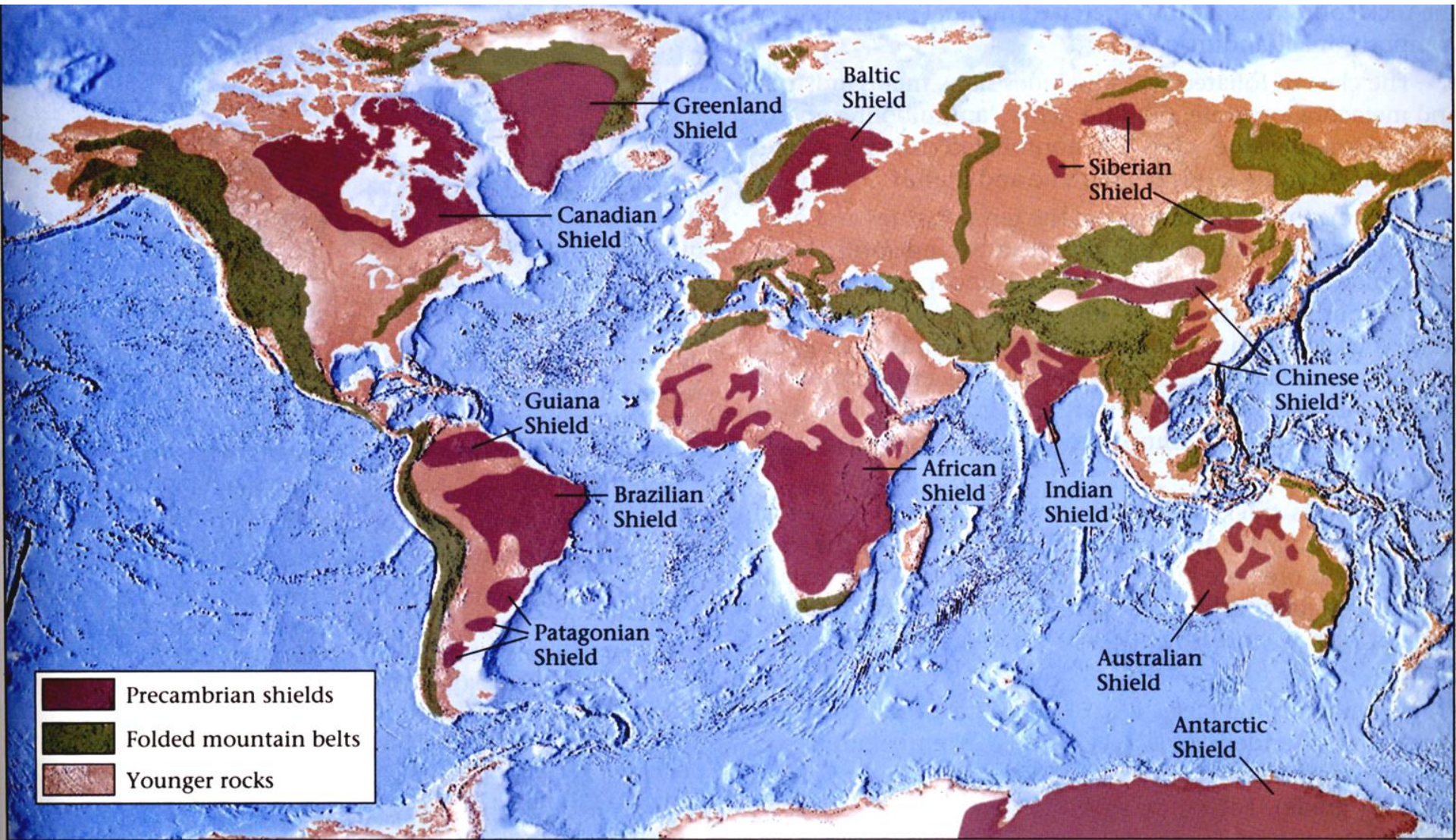
Unlike some igneous and sedimentary processes that take place in surface or near-surface environments, **metamorphism most often occurs deep within Earth**, beyond our direct observation.

The study of metamorphic rocks provides important insights into the tectonic processes that operate within Earth's crust and upper mantle.

Metamorphic rocks are found in **shield** regions such as in

- **Eastern Canada,**
- **Brazil,**
- **Africa,**
- **India,**
- **Australia, and**
- **Greenland**

Moreover, metamorphic rocks are an important component of many **mountain belts**, including **Alps**, the Appalachians and the **Himalayas**.



WHAT IS METAMORPHISM AND A METAMORPHIC ROCK ?

Metamorphism is the transformation of one rock type into another.

Metamorphic rocks are produced from **pre-existing rocks - igneous, sedimentary, or even from other metamorphic rocks.**

Thus, every metamorphic rock has a **parent rock—the rock from which it was formed.**

The **mineralogical** and **textural** change produced by increased temperature and pressure are collectively termed **Metamorphism**.

The word "Metamorphism" comes from the Greek: **meta = change**, **morph = form**, so metamorphism means to change form.

Metamorphism takes place where, **pre-existing rock** is subjected to new conditions, usually elevated temperatures pressures and and chemical environment, that are significantly different from those in which it initially formed. As a result there is changes in the **mineral assemblage and texture** in the pre-existing rock

In response to these new conditions, the rock gradually changes until a **state of equilibrium** with the new environment is achieved.

Metamorphism can thus be defined as:

“The mineralogical and structural changes or adjustment of solid rocks to physical and chemical conditions that have been imposed at depths below the near surface zones of weathering and diagenesis, and which differ from conditions under which the rocks in question originated”.

Note that Diagenesis is also a change in form that occurs in sedimentary rocks.

In geology, however, we restrict diagenetic processes to those which occur at temperatures below **200°C and pressures below about **3 kb** or **300 MPa** (MPa stands for Mega Pascals), this is equivalent to about 3 kilobars of pressure (1kb = 100 MPa).**

Metamorphism, therefore occurs at temperatures and pressures higher than 200°C and 300 MPa.

Rocks can be subjected to these higher temperatures and pressures as they are buried deeper in the Earth.

Such burial usually takes place as a result of tectonic processes such as continental collisions or subduction.

The **upper limit** of metamorphism occurs at the pressure and temperature where melting of the rock in question begins.

Once melting begins, the process changes to an igneous process rather than a metamorphic process.

Metamorphism of a rock involves three processes:

- 1. Recrystallization**
- 2. Crystallization of new minerals, and**
- 3. Rotation (re-orientation)**

Of minerals

Metamorphic rocks are produced from pre-existing igneous, sedimentary, or even from other metamorphic rocks.

Thus, every metamorphic rock has a parent rock—the rock from which it was formed.

Metamorphism, which means to "change form," is a process that leads to changes in:

- **Mineralogy,**
- **texture, and sometimes the**
- **chemical composition**

of rocks.

Metamorphism takes place where, pre-existing rock is subjected to new conditions, usually :

- I. elevated temperatures and**
- II. pressures,**

that are significantly different from those in which it initially formed.

In response to these new conditions, the rock gradually changes until a **state of equilibrium with the new environment is achieved.**

Agents of Metamorphism

WHAT DRIVES METAMORPHISM?

The agents of metamorphism include

- I. Heat,**
- II. pressure (stress), and**
- III. chemically active fluids.**

During metamorphism, rocks are usually subjected to all three metamorphic agents simultaneously.

However, the degree of metamorphism and the contribution of each agent vary from one environment to another.

Heat as a Metamorphic Agent

The most important factor driving metamorphism is heat.

Because it provides the energy needed to drive the chemical reactions that result in the **recrystallization of existing minerals and/or the formation of **new minerals**.**

Changes Caused by Heat

Low temperature environment:

When Earth materials are heated: especially those that form in **low-temperature** environments, they are affected in two ways.

(1) First, heating promotes **recrystallization** of mineral grains. This is particularly true of sedimentary and volcanic rocks that are composed of fine-grained clay and silt sized particles.

(2) Second, when rocks are heated, they eventually reach a temperature at which one or more minerals become **chemically unstable**.

When this occurs, the constituent atoms begin to arrange themselves into crystalline structures that are more stable in the new high-temperature environment.

These chemical reactions create **new minerals** with stable configurations that have an overall composition roughly equivalent to that of the original rock.

Higher temperatures environment:

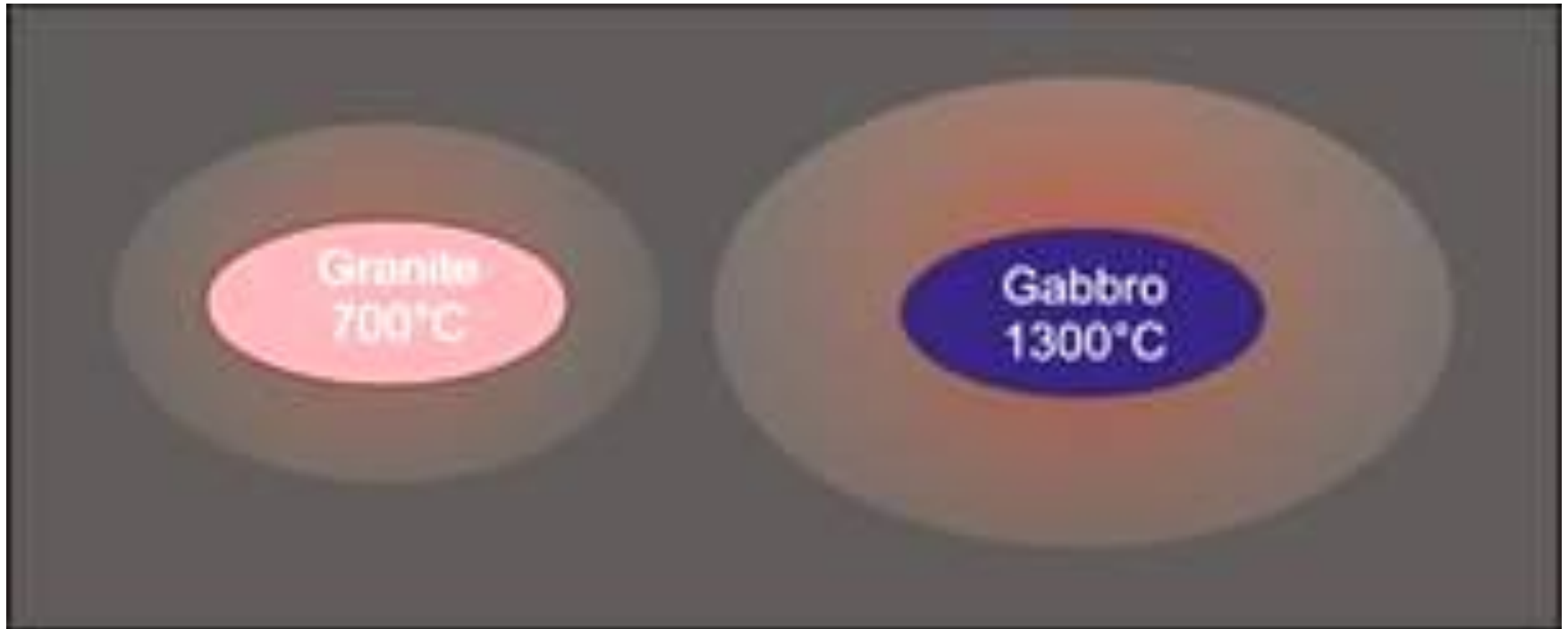
Higher temperatures promote crystal growth where fine particles join together to form larger grains of the same mineralogy.

The Source of Heat

Earth's internal heat comes mainly from:

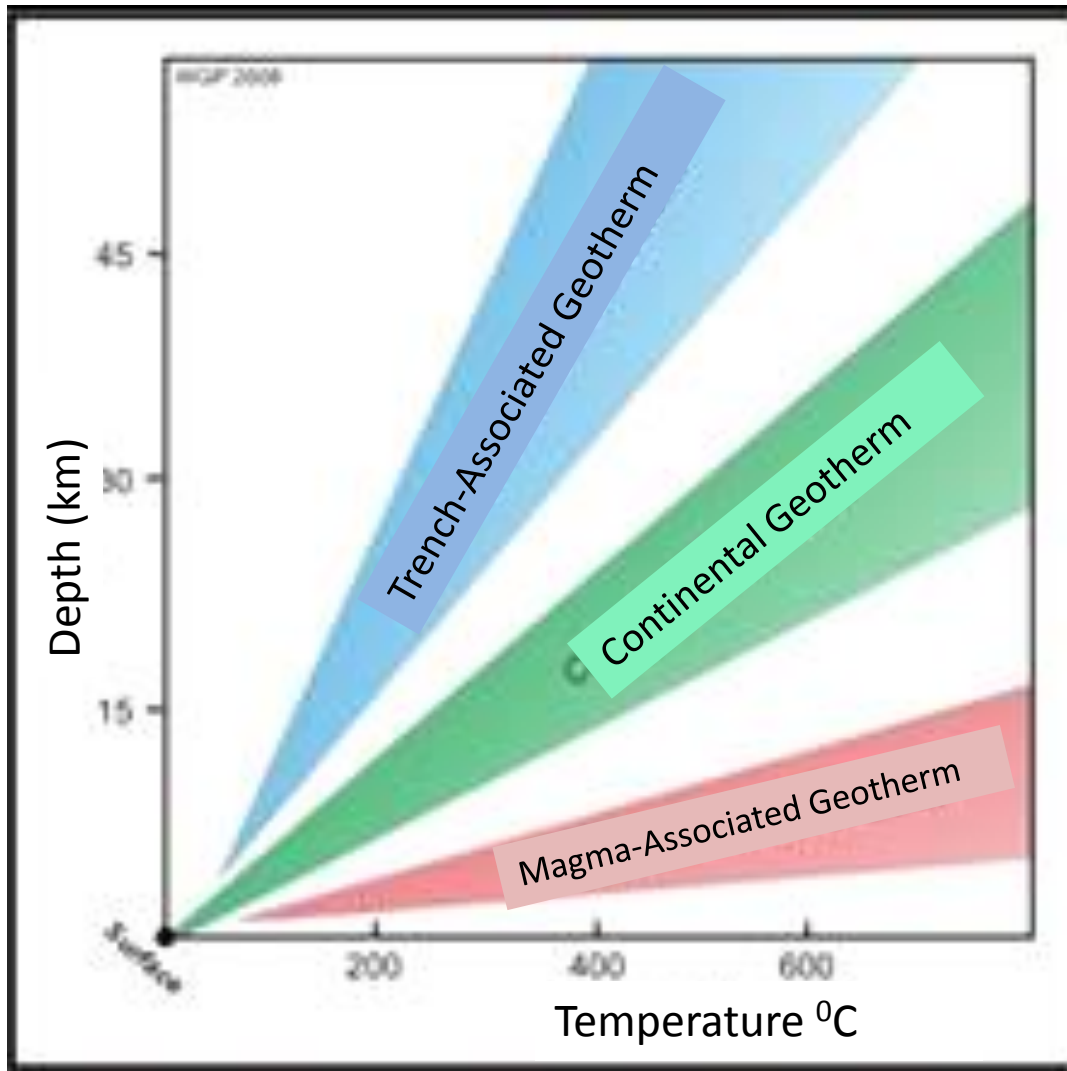
- A. energy that is continually being released by radioactive decay, and**
- B. thermal energy that remains from the time when our planet was forming.**

Sources of Heat for Metamorphism



- Heat from magma
- Emplacement of magma chambers will add heat to the immediately surrounding rock
 - Gabbroic magma ~1300°C
 - Granitic magma ~700°C

Sources of Heat for Metamorphism



- Heat from Earth's interior
- Geothermal gradient is the increase in temperature with depth
 - Typical continental geothermal gradient is 25-30°C/km
 - Volcanically active areas have geothermal gradients of 30-50°C/km
 - Oceanic trenches have geothermal gradients as low as 5-10°C/km

Temperatures increase with depth at a rate known as the geothermal gradient.

In the upper crust, this increase in temperature averages about 25°C per km (Fig 8.3).

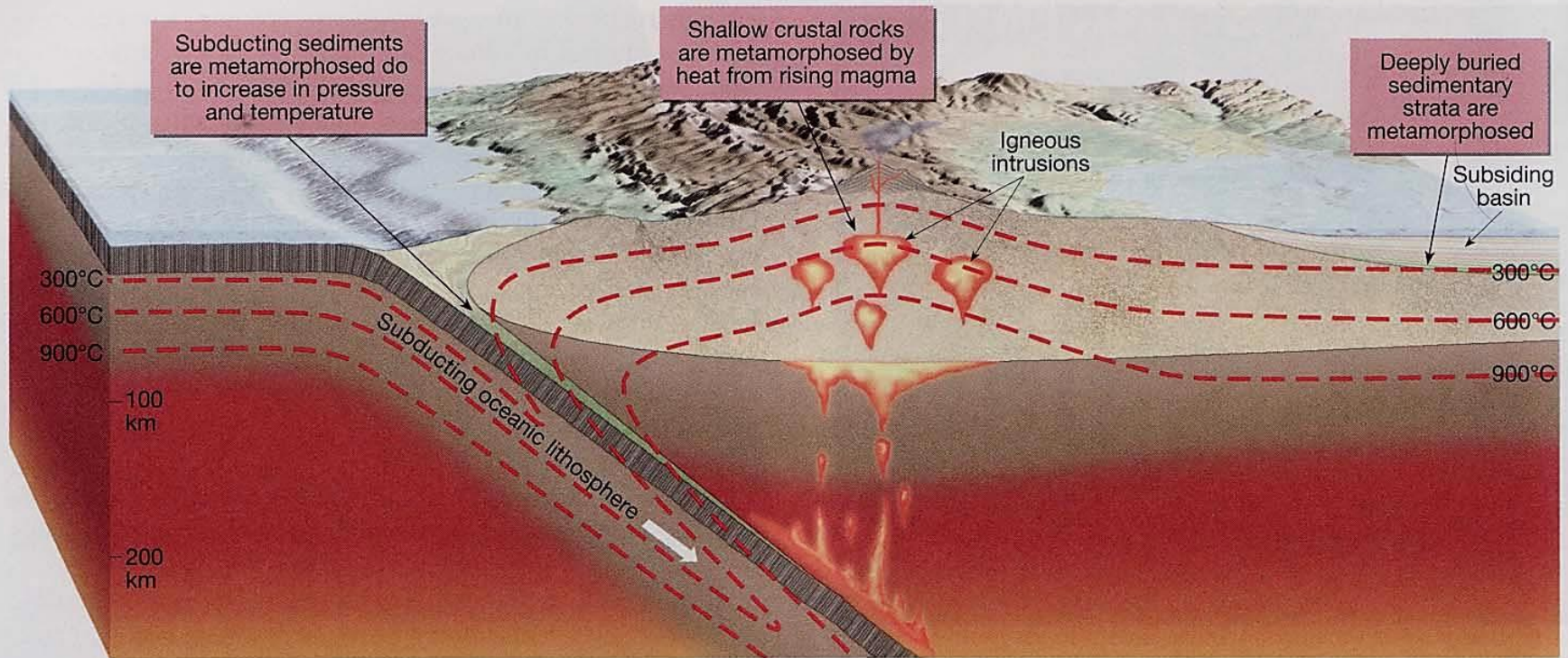


FIGURE 8.3 The geothermal gradient and its role in metamorphism. Notice how the geothermal gradient is lowered by the subduction of relatively cool oceanic lithosphere. By contrast, thermal heating is evident where magma intrudes the upper crust.

Thus, rocks that formed at Earth's surface will experience a gradual increase in temperature if they are transported to greater depths.

When buried to a depth of about 8 km, where temperatures are about **200 °C,**

clay minerals become unstable and begin to recrystallize into new minerals, such as **chlorite and muscovite**, that are stable in this environment.

Chlorite is a mica-like mineral formed by the metamorphism of dark (iron and magnesium rich) silicate minerals.

However, many silicate minerals, such as quartz and feldspar remain stable at these temperatures.

Thus, metamorphic changes in these minerals generally occur at much greater depths.

Environments where rocks may be carried to great depths and heated include:

- A. convergent plate boundaries** where slabs of sediment-laden oceanic crust are being subducted.

- B. Rocks may also become deeply buried in large basins where gradual subsidence results in very thick accumulations of sediment (see Fig 8.3).**

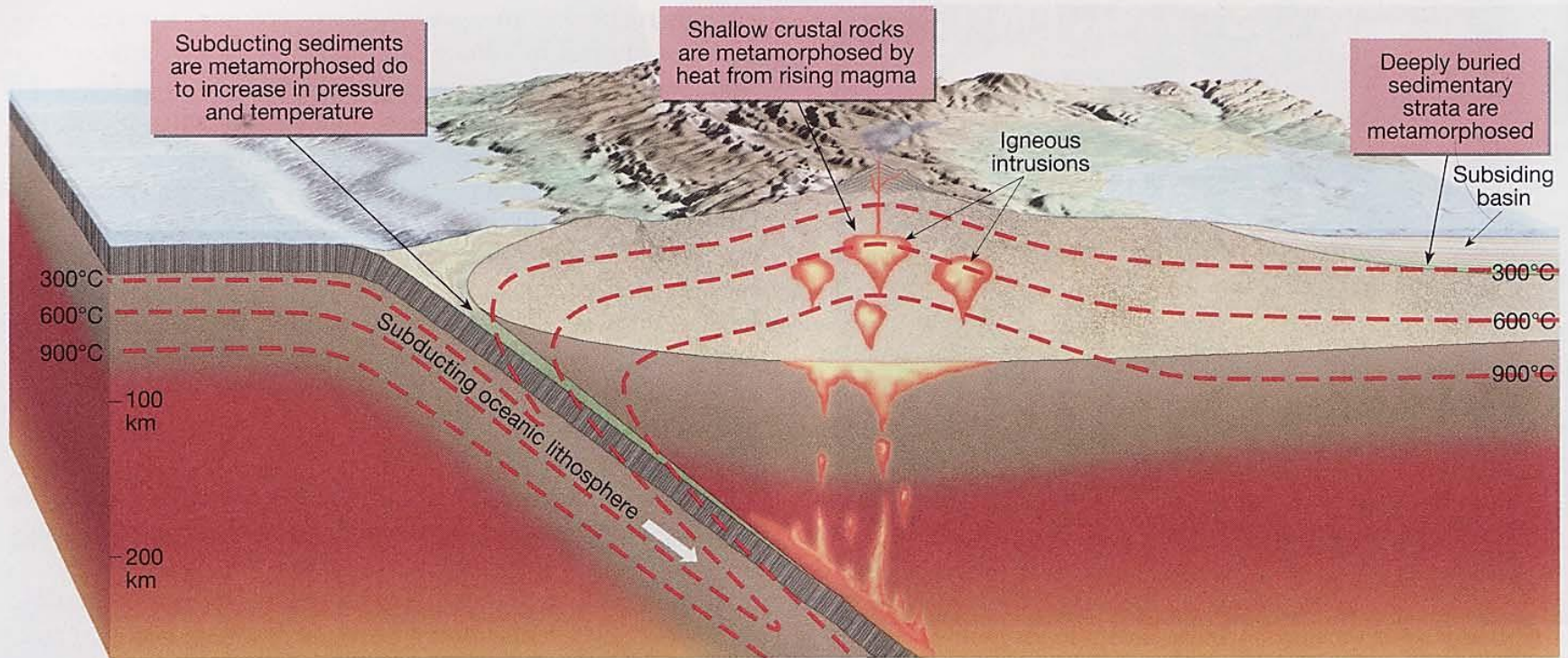


FIGURE 8.3 The geothermal gradient and its role in metamorphism. Notice how the geothermal gradient is lowered by the subduction of relatively cool oceanic lithosphere. By contrast, thermal heating is evident where magma intrudes the upper crust.

C. In addition, continental collisions, which result in crustal thickening by folding and faulting, cause some rocks to be uplifted while others are thrust downward where elevated temperature may cause metamorphism.

Heat may also be transported from the mantle into even the shallowest layers of the crust by igneous intrusions (Fig. 8.4).

Rising **mantle plumes**, upwelling at mid-ocean ridges, and magma generated by partial melting of mantle rock at subduction zones are examples.

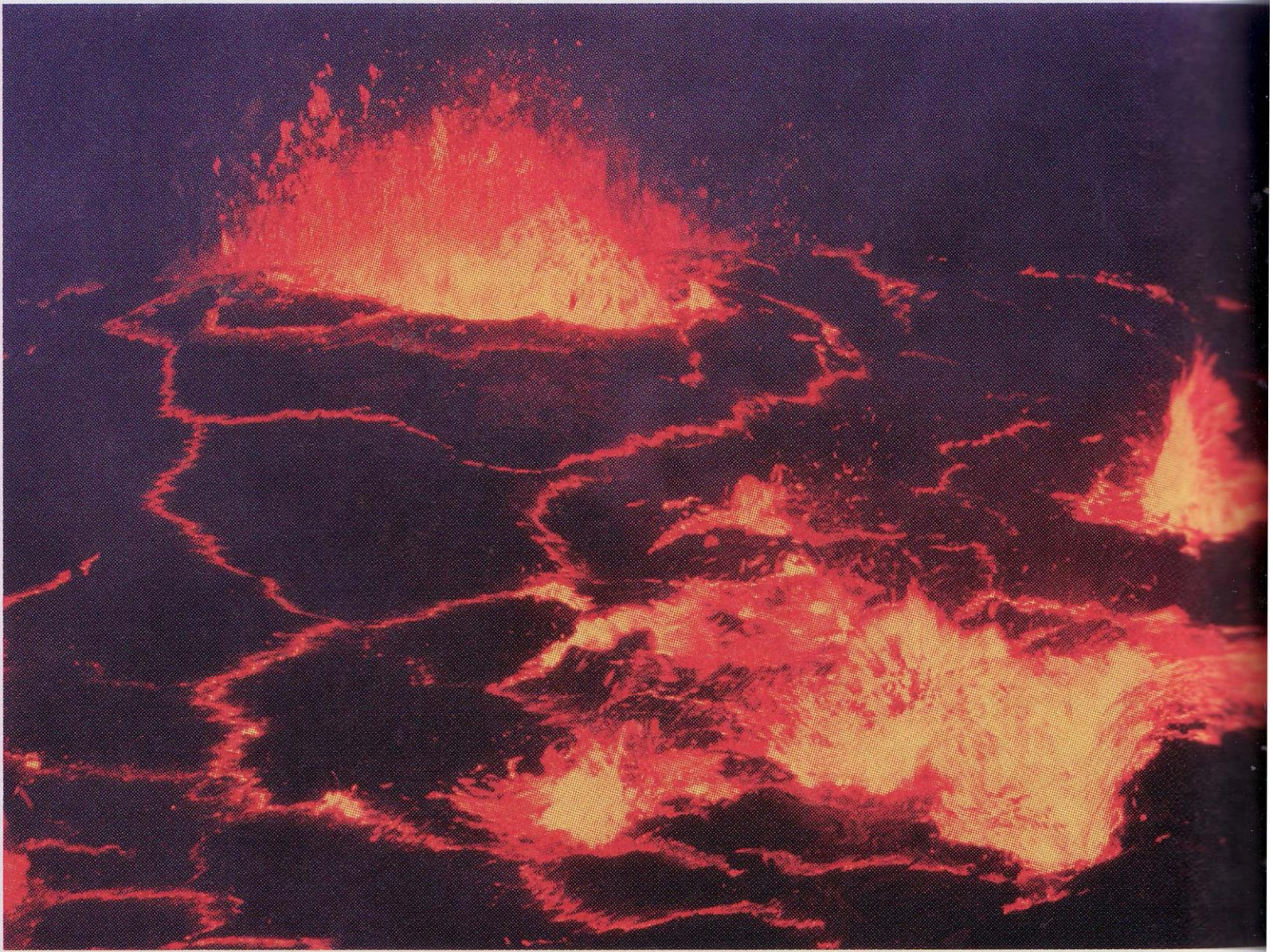


FIGURE 8.4 Earth's interior is the source of heat that drives metamorphism. Lava Lake in Pu'O'o Crater, Hawaii. (Photo by Frans Lanting/CORBIS)

When magma intrudes relatively cool rocks at shallow depths, the host rock is "baked."

This process, called **contact metamorphism**, will be considered later .

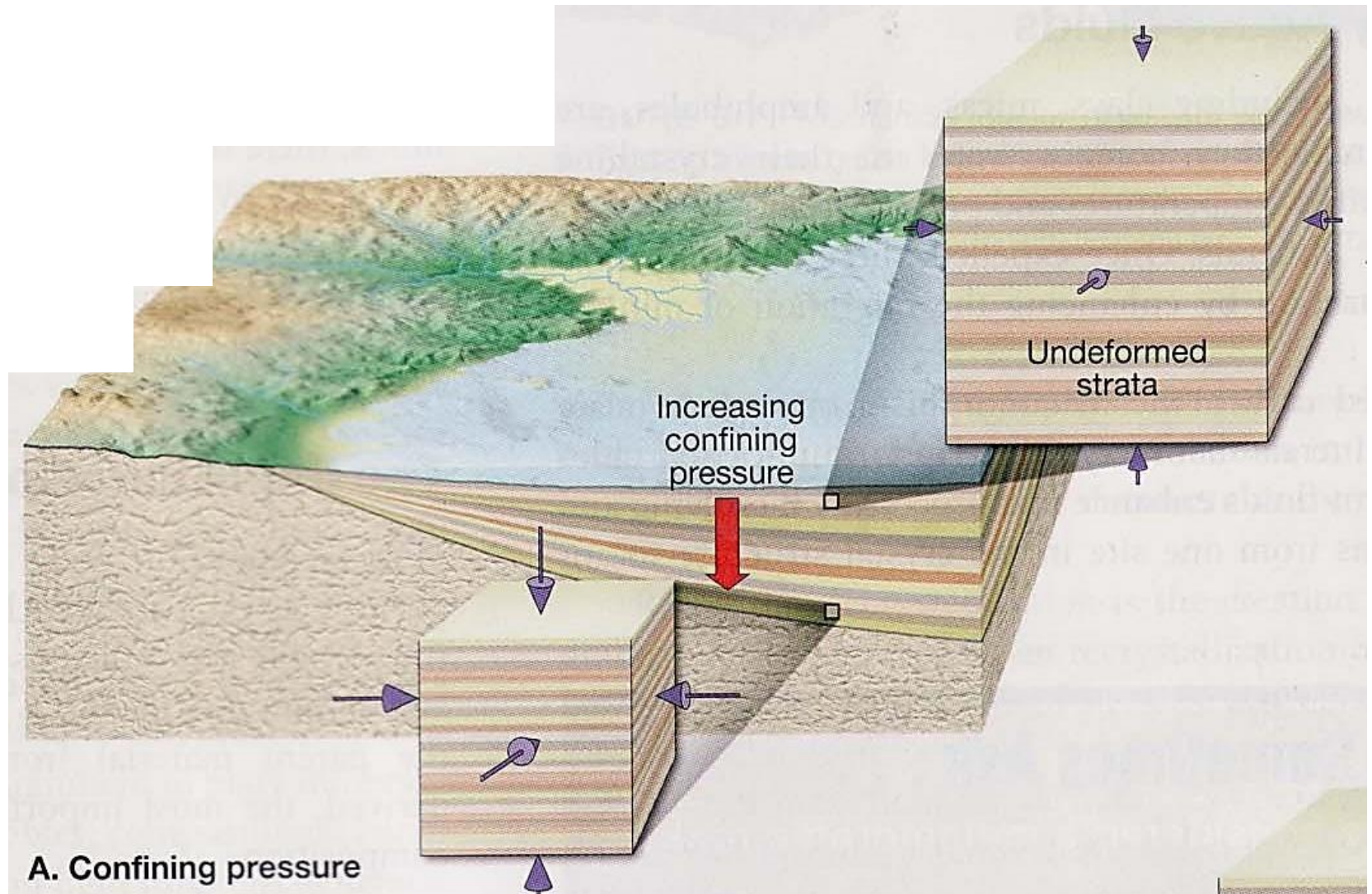
Confining Pressure and Differential Stress

Pressure, like temperature, also increases with depth as the thickness of the overlying rock increases.

Buried rock, are subjected to **confining pressure**, in which the forces are applied equally in all directions (Fig 8.5A).

The deeper we go the greater the confining pressure.

Confining pressure causes the spaces between mineral grains to close, producing a more compact rock having a greater density (Fig 8.5A).



8.5 A. In a depositional environment rocks deform by decreasing in volume

Furthermore, as confining pressure increases some minerals **recrystallize into new minerals** that have the same chemical composition but a more compact crystalline form.

In addition to **confining pressure**, rocks may be subjected to **directed pressure**.

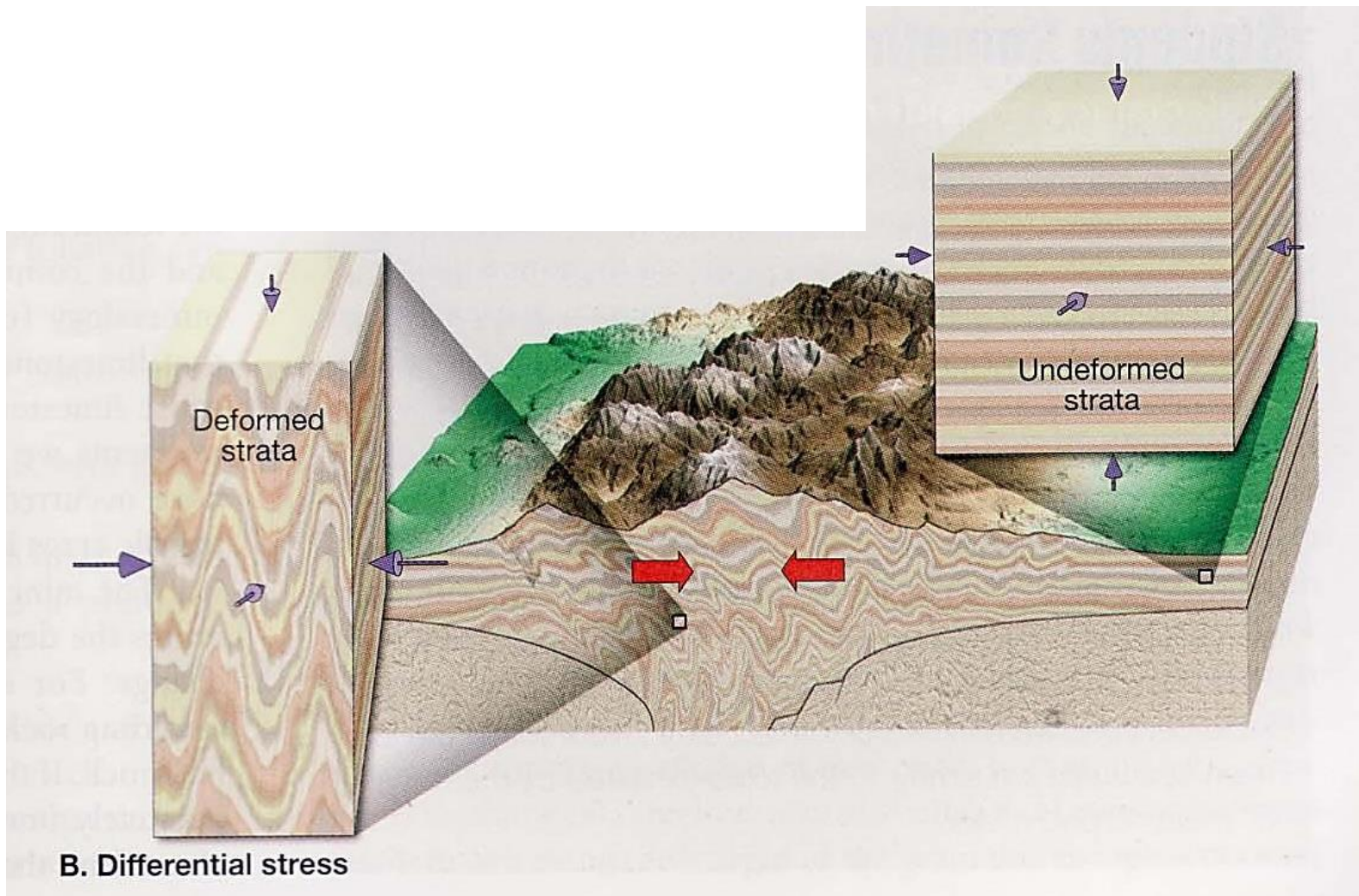
This occurs, for example, at **convergent plate boundaries** where slabs of lithosphere collide.

Here the forces that deform rock are unequal in different directions and are referred to as differential stress.

Unlike confining pressure, which "squeezes" rock equally in all directions, differential stresses are greater in one direction than in others.

Rocks subjected to differential stress are shortened in the direction of greatest stress and elongated or lengthened, in the direction perpendicular to that stress.

As a result, the rock, involved are often folded or flattened (Fig 8.5B).



8.5 B. During mountain building, rocks subjected to differential stress are shortened in the direction that pressure is applied, and lengthened in the direction perpendicular to that force.



Fig. 8.5: Metaconglomerate, also called stretched pebble conglomerate. These once nearly spherical pebble have been heated and flattered into elongated strucutre (Photo by E.J. Tarbuck)

Along convergent plate boundaries the greatest differential stress is directed roughly **horizontal in the direction of plate motion, and the least pressure is in the vertical direction.**

Consequently in these settings the crust is greatly **shortened** (horizontally) and **thickened** (vertically).

Differential stresses are important in creating the various large scale structures and textures exhibited by metamorphic rocks.

Chemically Active Fluids

Many minerals, including clays, micas, and amphiboles, are hydrated—meaning they contain water in their crystalline structures.

Elevated temperatures and pressures cause the dehydration of these minerals.

Once expelled, these hot fluids promote recrystallization by enhancing the migration of mineral matter.

The metamorphism of shale to slate involves clay minerals that recrystallize to form mica and chlorite minerals.

Hot fluids enhance this process by dissolving and transporting ions from one site in the crystal structure to another.

In increasingly hotter environments these fluids become correspondingly more reactive.

In some metamorphic environments, **hot fluids** transport mineral matter over considerable distances. This occurs, for example, when hot, mineral-rich fluids are expelled from a **magma body** as it cools and solidifies.

If the rocks that surround the pluton differ markedly in composition from the invading fluids, there may be an **exchange of ions** between the fluids and host rocks.

When this occurs, the overall chemical composition of the surrounding rock changes.

When substantial chemical change accompanies metamorphism the process is called **metasomatism.**

METAMORPHIC TEXTURES

(Textural and Mineralogical Changes)

The term texture is used to describe the size, shape, and arrangement of grains within a rock.

Most igneous and many sedimentary rocks consist of mineral grains that have a random orientation and thus appear the same when viewed from any direction.

By contrast, deformed metamorphic rocks that contain platy minerals (micas) and/or elongated minerals (amphiboles), typically display some kind of:

preferred orientation in which the mineral grains exhibit a parallel to sub-parallel alignment.

Rocks containing elongated minerals that are oriented parallel to each other will appear different when viewed from the side than when viewed head-on.

A rock that exhibits a preferred orientation of its minerals is said to possess **foliation.**

Foliation

The term foliation refers to any planar (nearly flat) arrangement of mineral grains or structural features within a rock.

It is a fundamental characteristic of regionally metamorphosed rocks.

In metamorphic environments, foliation is ultimately driven by compressional stresses that shorten rock units, causing mineral grains in preexisting rocks to develop parallel, or nearly parallel, alignments.

Examples of foliation include:

- I. the parallel alignment of platy minerals;**
- II. the parallel alignment of flattened pebbles;**
- III. compositional banding in which the separation of dark and light minerals generates a layered appearance.**

Foliation can form in many different ways, including:

- 1. Rotation** of platy and/or elongated mineral grains into a parallel or nearly parallel orientation.
- 2. Recrystallization** that produces new minerals with grains that exhibit a preferred orientation.

3. Mechanisms that change **spherically shaped grains into elongated shapes** that are aligned in a preferred orientation.

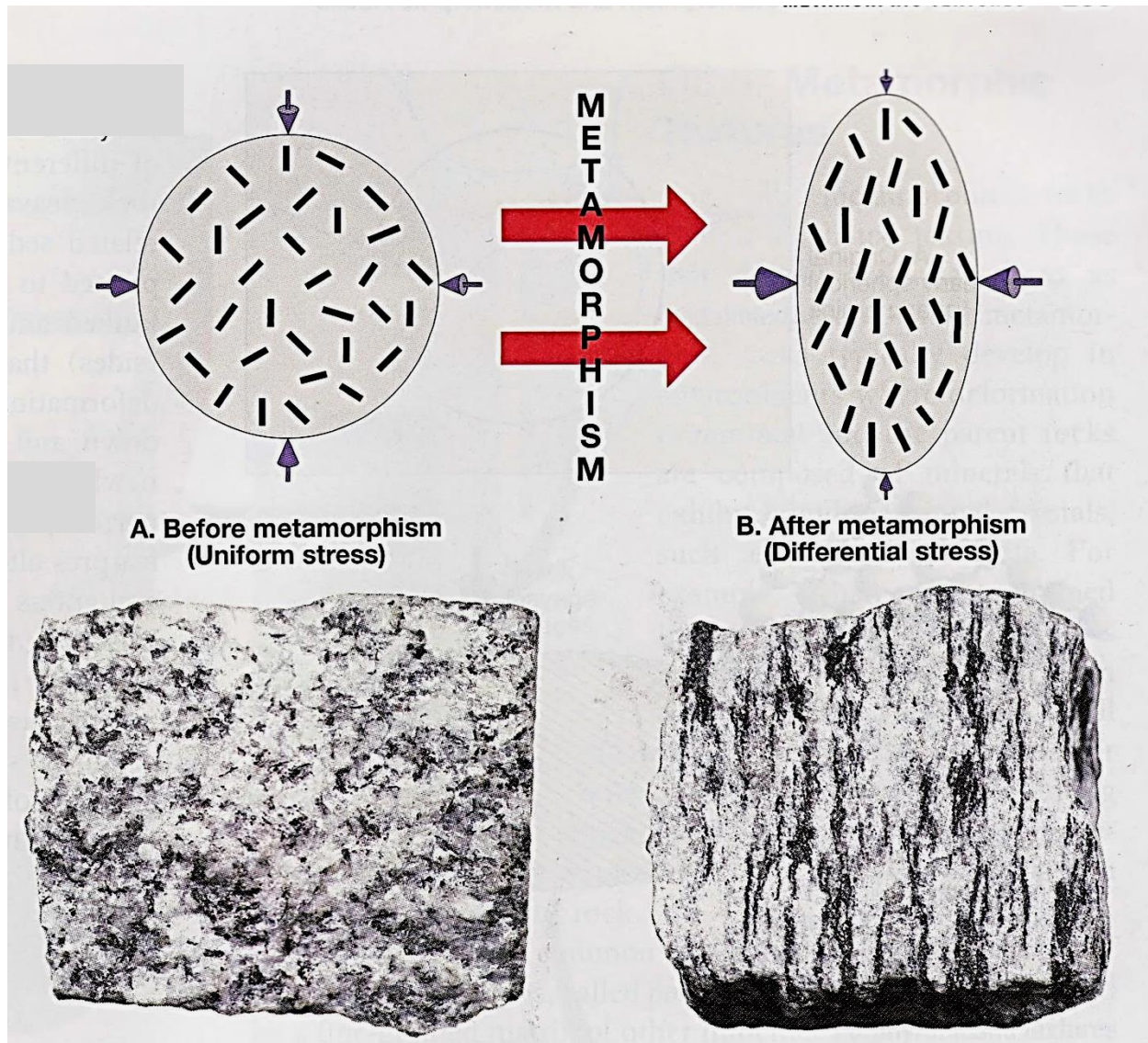


Fig. 8.7: Mechanical rotation of platy of elongated minerals grains. A. Existing mineral grains keep their random orientation if force is uniformly applied. B. As differential stress causes rocks to flatten, mineral grains rotate towards the plane of flattening. (Photos by E.J. Tarbuck)

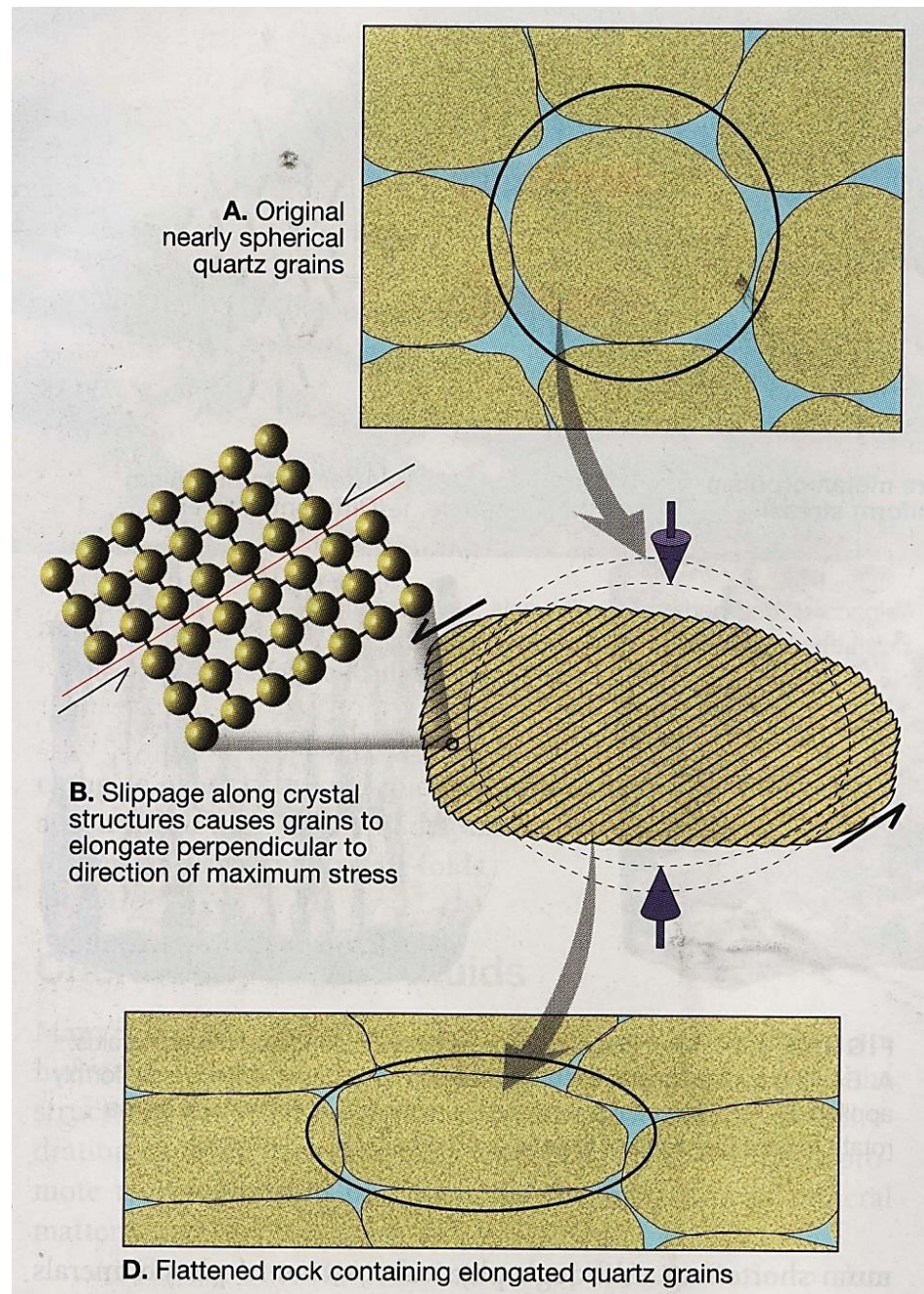


Fig. 8.8: Development of preferred orientations of minerals that have roughly spherical crystals, such as quartz, calcite, and olivine can occur in one of two ways. The first mechanism, shown in this illustration, occurs as units of a mineral's crystalline structure slide relative to one another. The other mechanism is shown in Fig. 8.9.

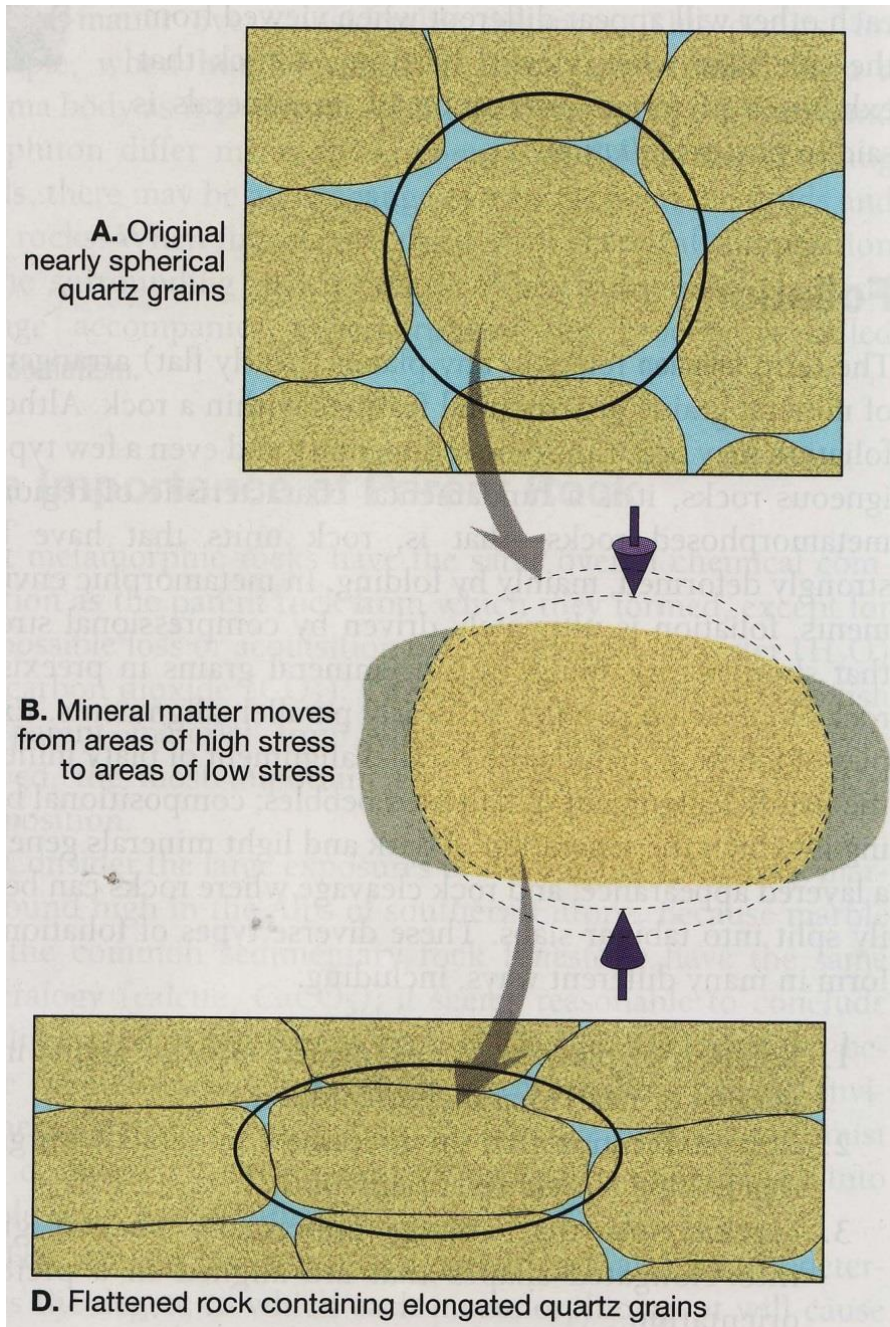
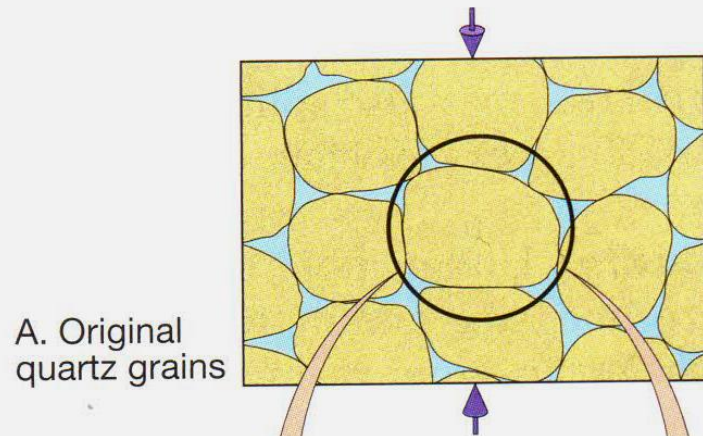
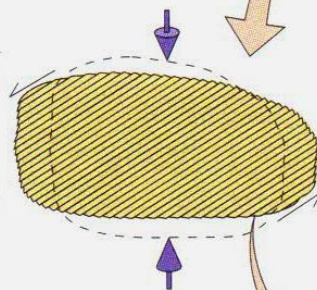


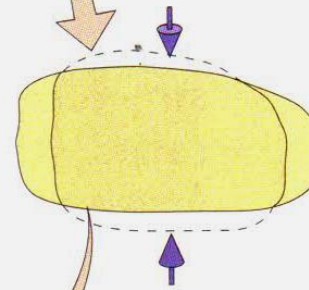
Fig. 8.9: This mechanism for changing the shape of mineral grains involves dissolving material from areas of high stress and depositing that material in locations of low stress. This mechanism, as well as the one shown in Fig. 8.8, changes the shape of mineral grains, but not their volume and composition.



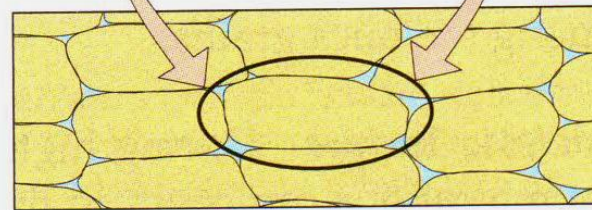
A. Original quartz grains



B. Grains deformed by slippage along planes within the crystalline structure



C. Grains distorted as ions move from more stressed to less stressed sites



D. Flattened rock exhibiting distorted quartz grains

Foliated Textures

Various types of foliation exist, depending largely upon the grade of metamorphism and the mineralogy of the parent rock.

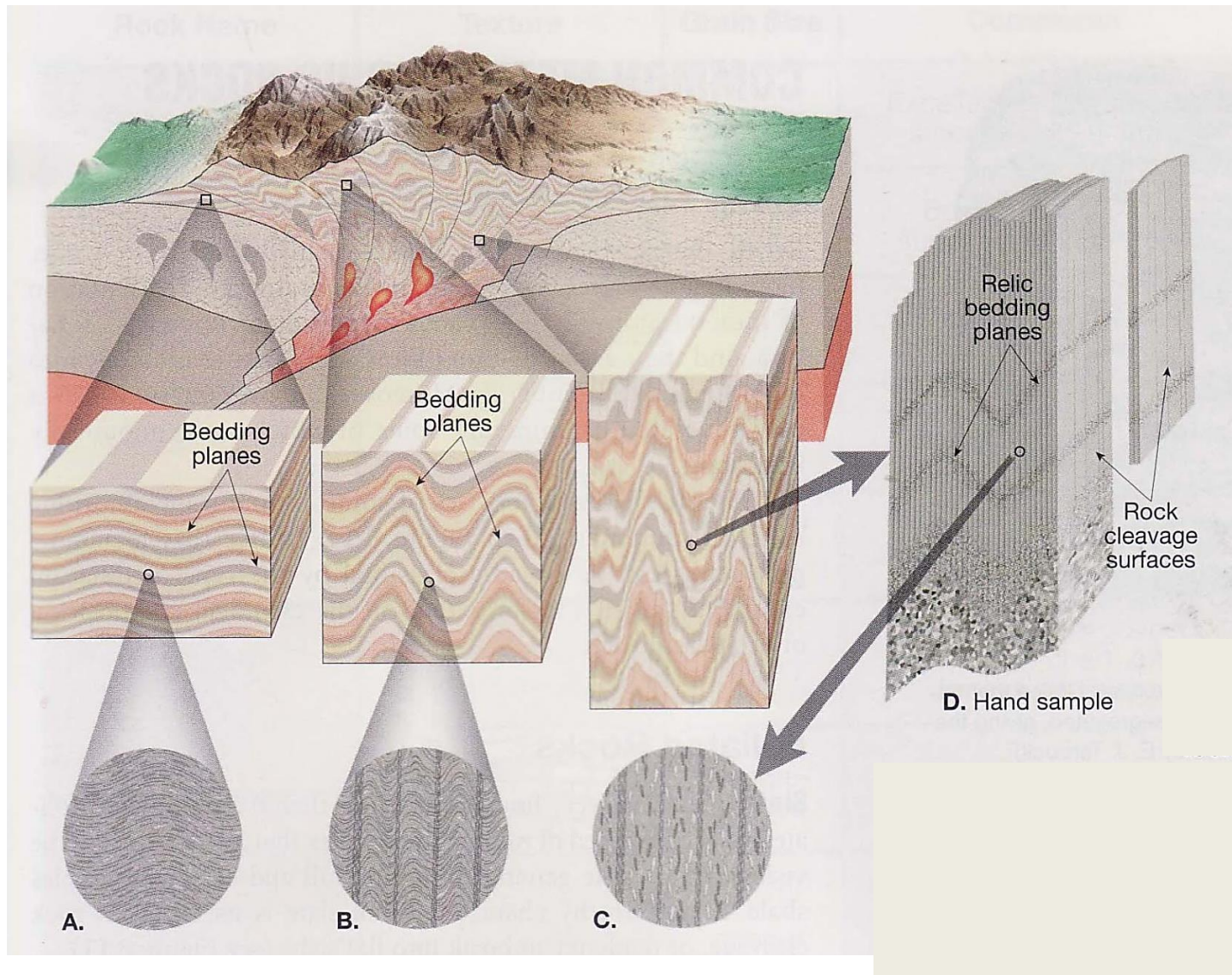
We will look at three:

- 1. Rock cleavage or Slaty cleavage,**
- 2. Schistosity, and**
- 3. Gneissic texture.**

Rock or Slaty Cleavage

Rock cleavage refers to closely spaced surfaces along which rocks split into thin slabs when hit with a hammer.

Rock cleavage develops in various metamorphic rocks but is best displayed in slates that exhibit an excellent splitting property called **slaty cleavage.**



▲ FIGURE 8.8 Development of one type of rock cleavage. As shale is strongly folded (A, B) and metamorphosed to form slate, the developing mica flakes are bent into microfolds. C. Further metamorphism results in the recrystallization of mica grains along the limbs of these folds to enhance the foliation. D. Hand sample of slate illustrates rock cleavage and its orientation to relic bedding surfaces.



FIGURE 8.9 Excellent slaty cleavage is exhibited by the rock in this slate quarry near Alta, Norway. The parallel mineral alignment in this rock allows it to split easily into the flat slabs visible in the photo. (Photo by Fred Bruemmer/ DRK Photo).



Fig. 8.11. Excellent slaty cleavage is exhibited by the rock in this slate quarry in Tanzania. Because slate breaks into flat slabs, it has many uses (Photo by Randy Olson/NGS image Collection).



Use of slate for the roof of this house in Switzerland (Photo by E.J. Tarbuck)



Schistosity

Under higher temperature-pressure regimes, the minute mica and chlorite crystals in slate begin to grow.

When these platy minerals are large enough to be discernible with the unaided eye and exhibit a planar or layered structure, the rock is said to exhibit a type of foliation called **schistosity.**

Rocks having this texture are referred to as **schist**.

In addition to platy minerals, schist often contains **deformed quartz and feldspar** crystals that appear flat or **lens-shaped** and hidden among the mica grains.

Schist is formed by regional metamorphism and has schistose structure and has coarse mineral grains and is fissile, splitting in thin layers.

Its main characteristic is hinted at in its name: *schist* comes from the ancient Greek for "split," through Latin and French.



▲ **FIGURE 8.15** Mica schist. This sample of schist is composed mostly of muscovite and biotite. (Photo by E. J. Tarbuck)

High temperatures and high pressures aligns the grains of mica, hornblende and other flat or elongated minerals into thin layers, or foliation.

At least 50 percent of the mineral grains in schist are aligned this way.

Gneissic Texture

During high-grade metamorphism, ion migration can result in the segregation of minerals as shown in Fig 8.12.

Notice that the dark biotite crystals and light silicate minerals (quartz and feldspar) have separated, giving the rock a banded appearance called gneissic texture.

A metamorphic rock with this texture is called **gneiss (pronounced "nice").**



▲ FIGURE 8.10 This rock displays a gneissic texture. Notice that the dark biotite flakes and light silicate minerals are segregated, giving the rock a banded or layered appearance. (Photo by E. J. Tarbuck)

Other Metamorphic Textures

Not all metamorphic rocks, exhibit a foliated texture. Those, that do not are referred to as **nonfoliated**.

Nonfoliated metamorphic rocks typically develop in environments where deformation is minimal and the parent rocks are composed of minerals that exhibit **equidimensional** crystals, such as quartz or calcite

(For example, when a fine-grained **limestone** (made of calcite) is metamorphosed to **marble**).

Porphyroblastic texture

Another texture common to metamorphic rocks consists unusually large grains, called **porphyroblasts**, that are surrounded by a fine-grained matrix of other minerals.

Porphyroblastic texture develops in a wide range of rock types and metamorphic environments when minerals in the parent rock recrystallize to form new minerals (Figure 8.13).

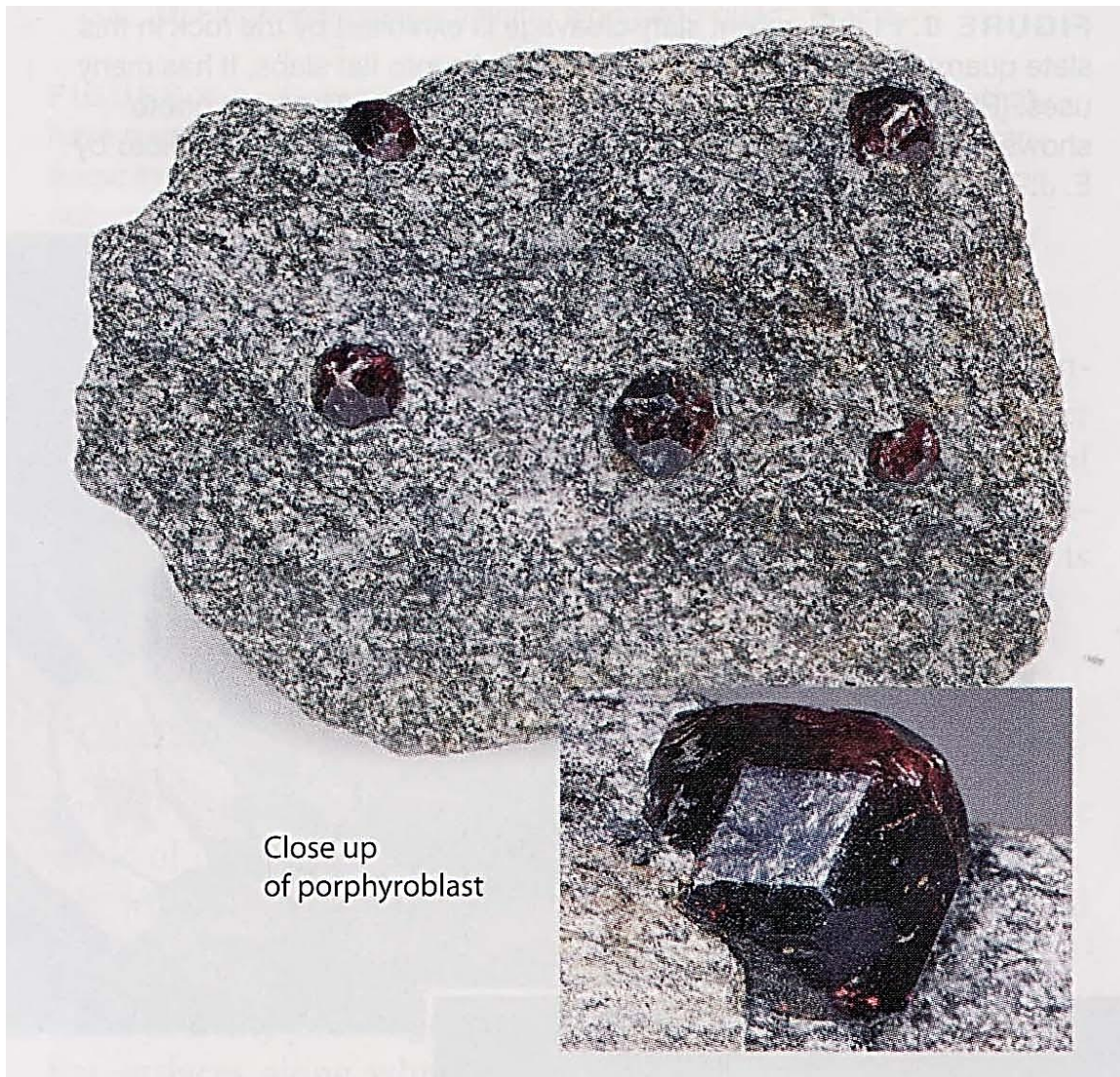


FIGURE 8.11 Garnet-mica schist. The dark red garnet crystals (porphyroblasts) are embedded in a matrix of fine-grained micas. (Photo by E. J. Tarbuck)

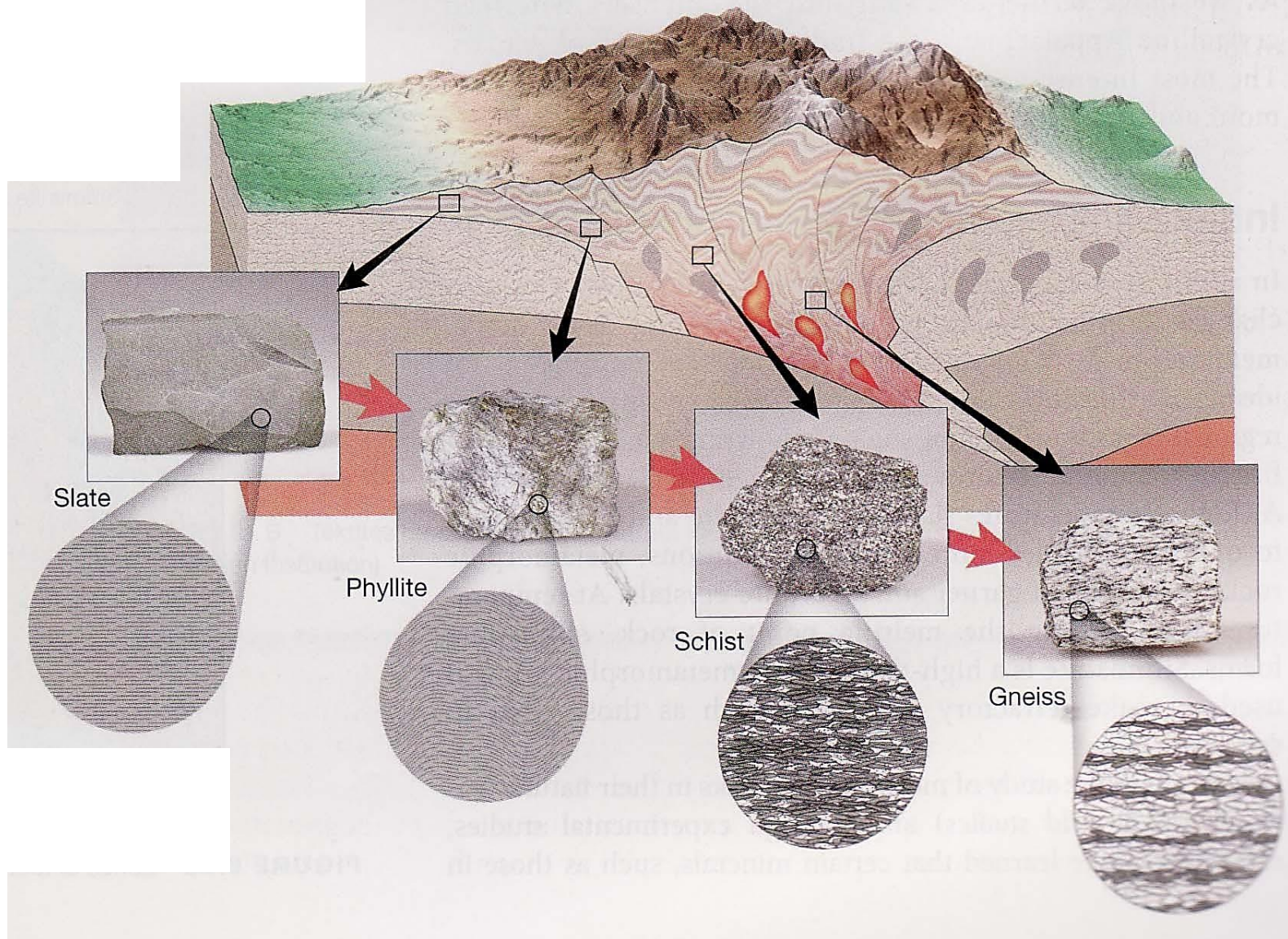
Textural Variations

When we begin with a clay-rich sedimentary rock such as shale or mudstone, a gradual increase in metamorphic intensity is accompanied by a general coarsening of the grain size.

Thus, we observe shale changing to a fine-grained slate, which then forms phyllite and, through continued recrystallization, generates a coarse-grained schist (Fig 8.26).

Under more intense conditions a gneissic texture that exhibits layers of dark and light minerals may develop.

FIGURE 8.26 Idealized illustration of progressive regional metamorphism. From left to right, we progress from low-grade metamorphism (slate) to high-grade metamorphism (gneiss). (Photos by E. J. Tarbuck)



Types of metamorphism

METAMORPHIC ENVIRONMENTS

(Types of metamorphism)

There are many environments in which metamorphism occurs. Most are in the vicinity of plate margins, and several are associated with igneous activity.

With the exception of impact metamorphism, there is considerable overlap among the other types.

Agents of metamorphism

Metamorphism is due to the operation of the three factors. The different kinds of metamorphism are thus due to various combinations of these factors.

1. Heat (Temperature)

2. Pressure

A. uniform pressure (like hydrostatic pressure)

B. directed pressure

3. Chemically active fluids

Metamorphism can be:

- 1. Heat Predominant (Thermal metamorphism including hydrothermal)**
- 2. Directed Pressure Metamorphism (Cataclastic metamorphism)**
- 3. Directed pressure and Heat (Dynamothermal metamorphism)**
- 4. Hydrostatic (lithostatic) pressure dominant (Static metamorphism)**
- 5. Uniform pressure and temperature dominant Plutonic metamorphism)**

We will consider following types of metamorphism:

- 1. Thermal or Contact metamorphism (Heat predominant)**
- 2. Hydrothermal metamorphism**
- 3. Burial and subduction Zone metamorphism**
- 4. Regional metamorphism**
- 5. Impact metamorphism; and**
- 6. Directed Pressure Metamorphism (Cataclastic metamorphism, e.g. along faults)**

Contact or Thermal Metamorphism

It occurs when rocks immediately surrounding a molten igneous body are "baked" and therefore altered from their original state.

Thus, Contact metamorphism occurs adjacent to igneous intrusions and results from high temperatures associated with the igneous intrusion.

Since only a small area surrounding the intrusion is heated by the magma,

metamorphism is restricted to the zone surrounding the intrusion, called a **metamorphic or contact aureole.**

Small intrusions such as dikes and sills typically form aureoles only a few centimeters thick.

While large plutons like batholiths can produce aureoles that extend outward for several kilometers.

The rock produced is often a rock that shows no foliation, called a **hornfels. It is a very hard, fine-grained metamorphic rock produced.**

The large aureoles often consist of distinct zones of metamorphism.

Near the magma body, high-temperature minerals such as **garnet may form, whereas farther away low- grade minerals such as **chlorite** are produced.**

Rocks within the metamorphic aureole are usually **not foliated.**

Outside of the contact aureole, the rocks are not affected by the intrusive event.

The grade of metamorphism increases in all directions toward the intrusion.

Because the temperature contrast between the surrounding rock and the intruded magma is larger at shallow levels in the crust where pressure is low, contact metamorphism is often referred to as high temperature, low pressure metamorphism.

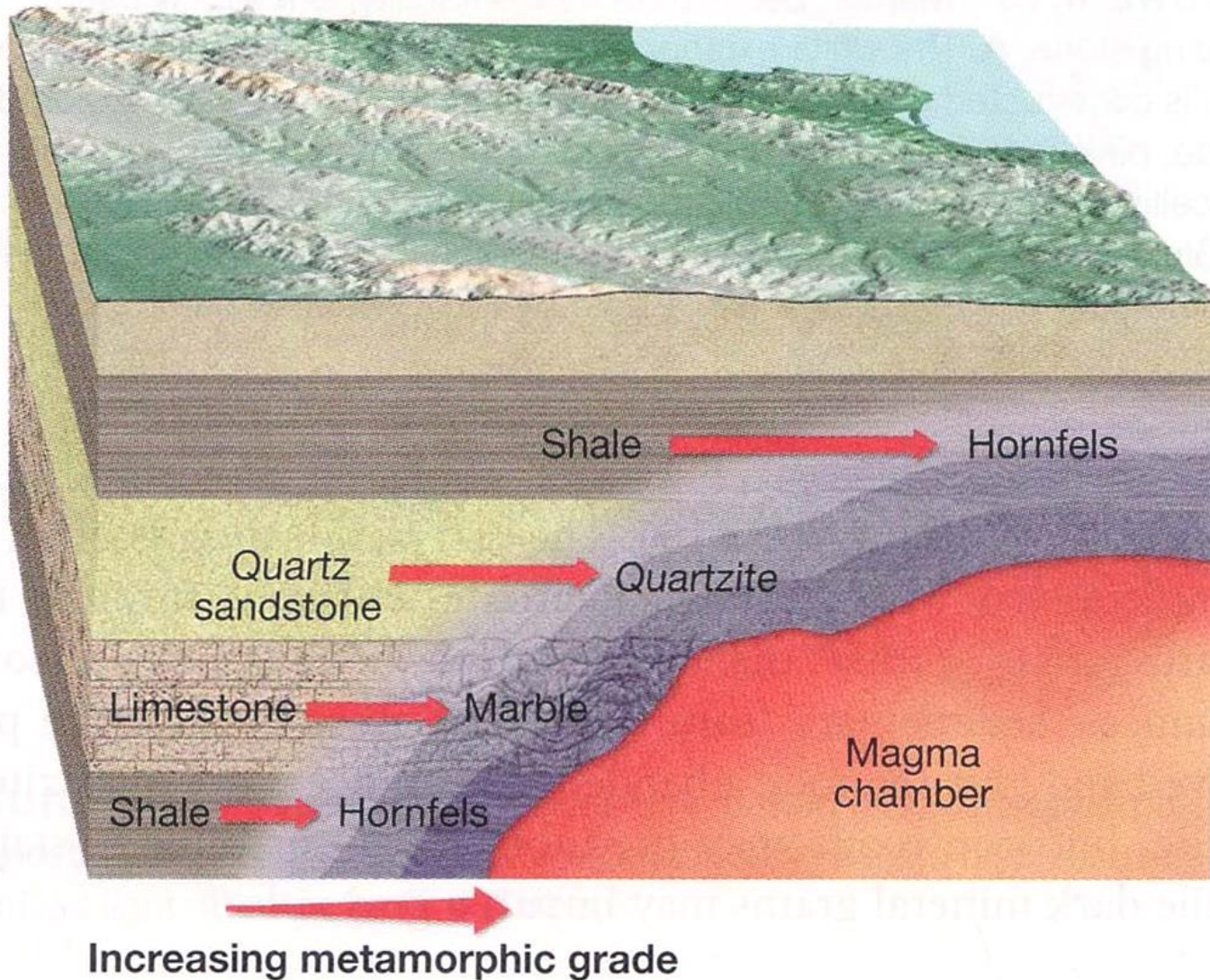
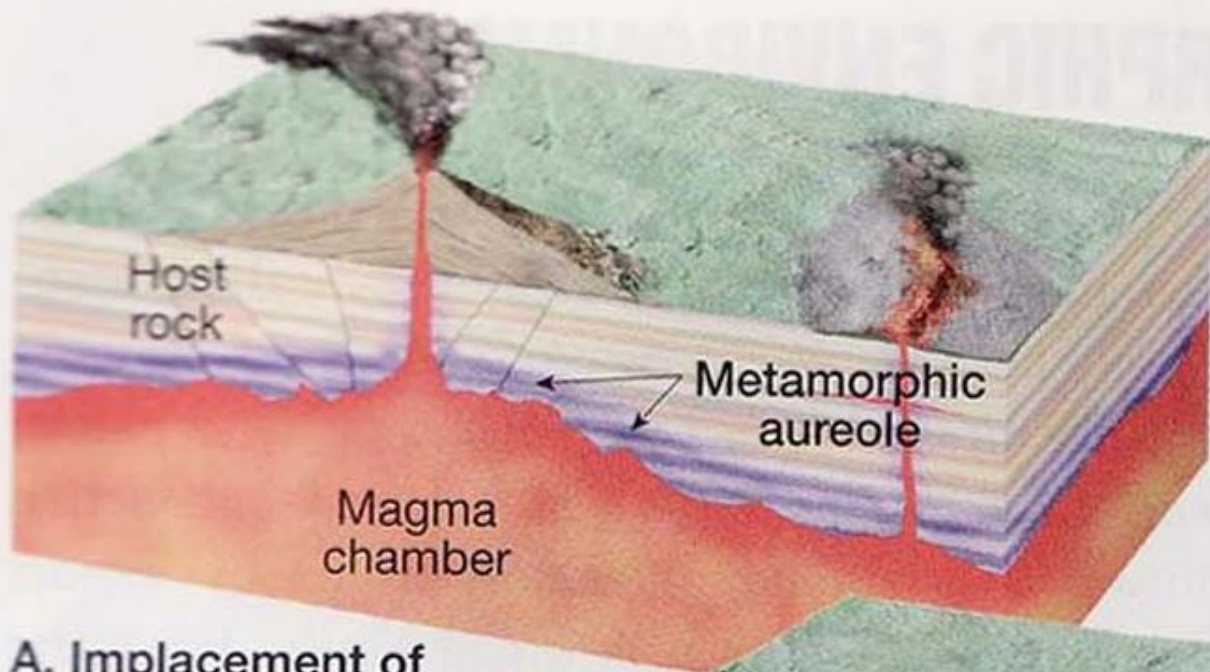
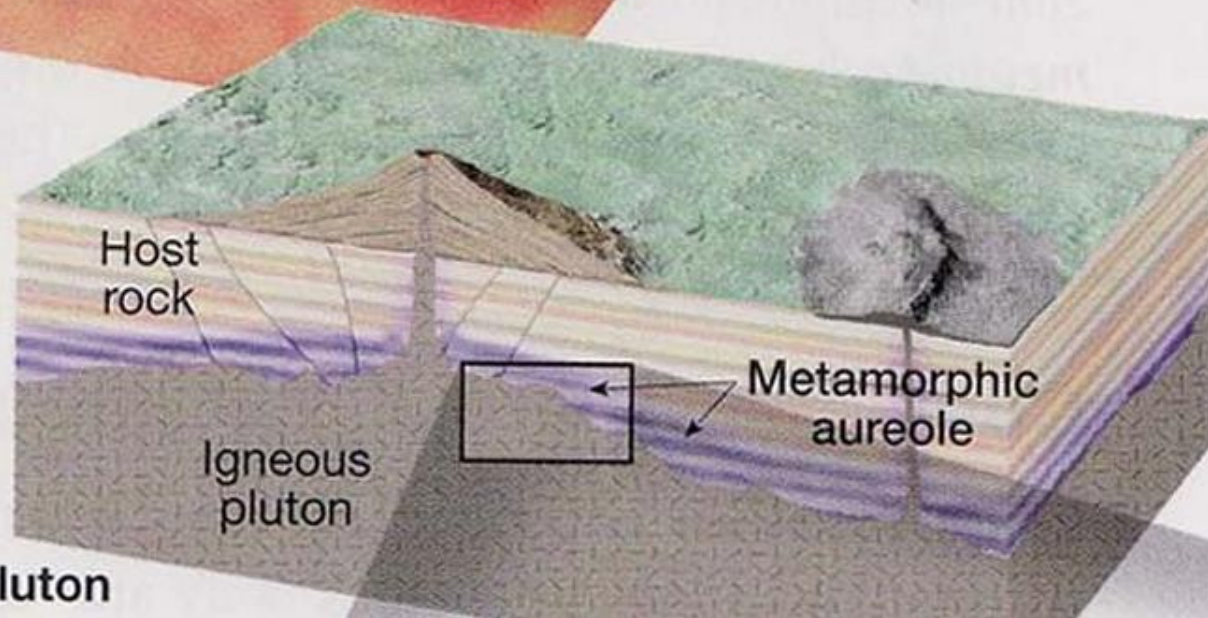


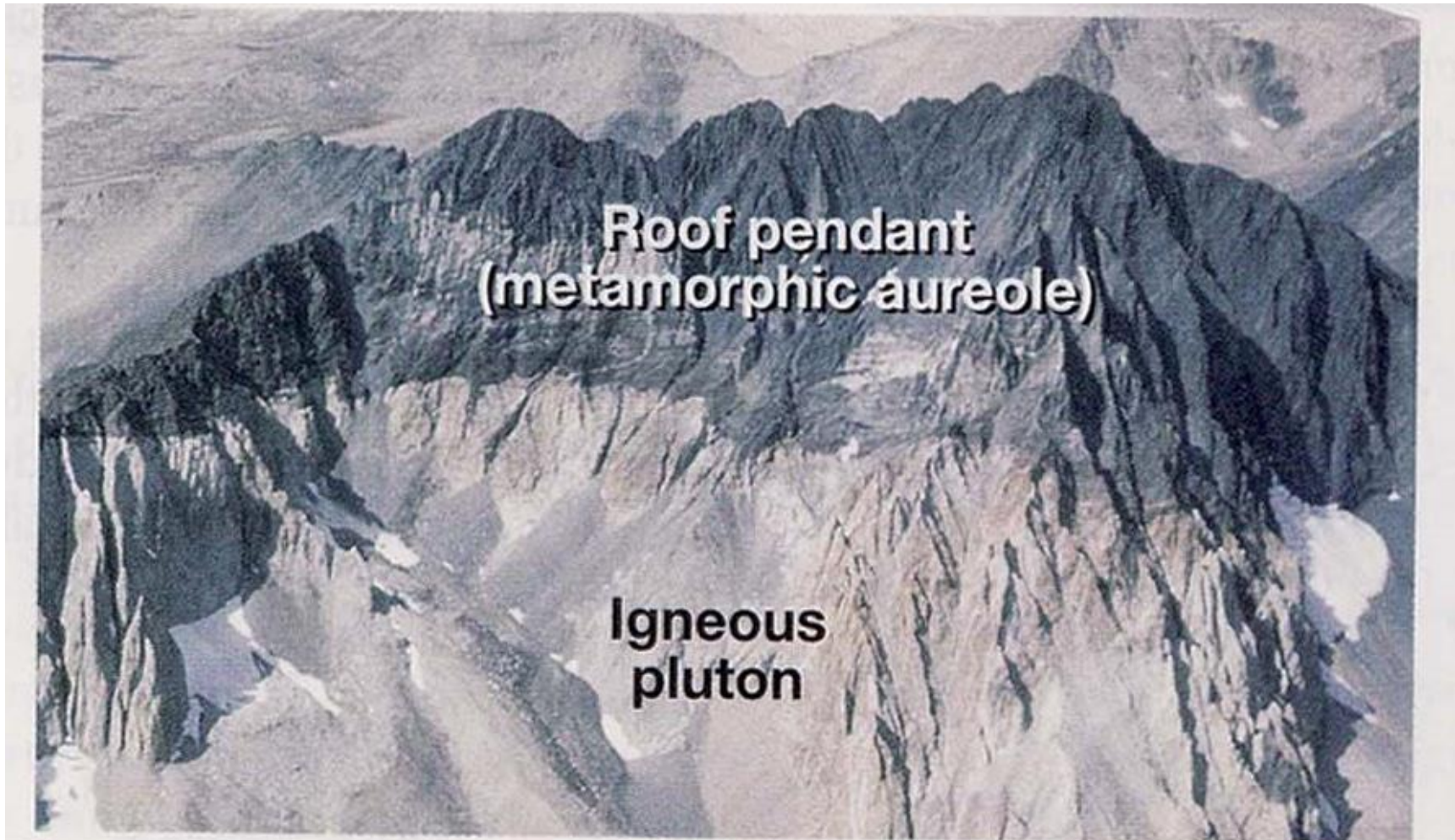
Fig. 8.21: Contact metamorphism of shale yields hornfels, while contact metamorphism of quartz sandstone and limestone produces quartzite and marble, respectively.



A. Implication of igneous body and metamorphism

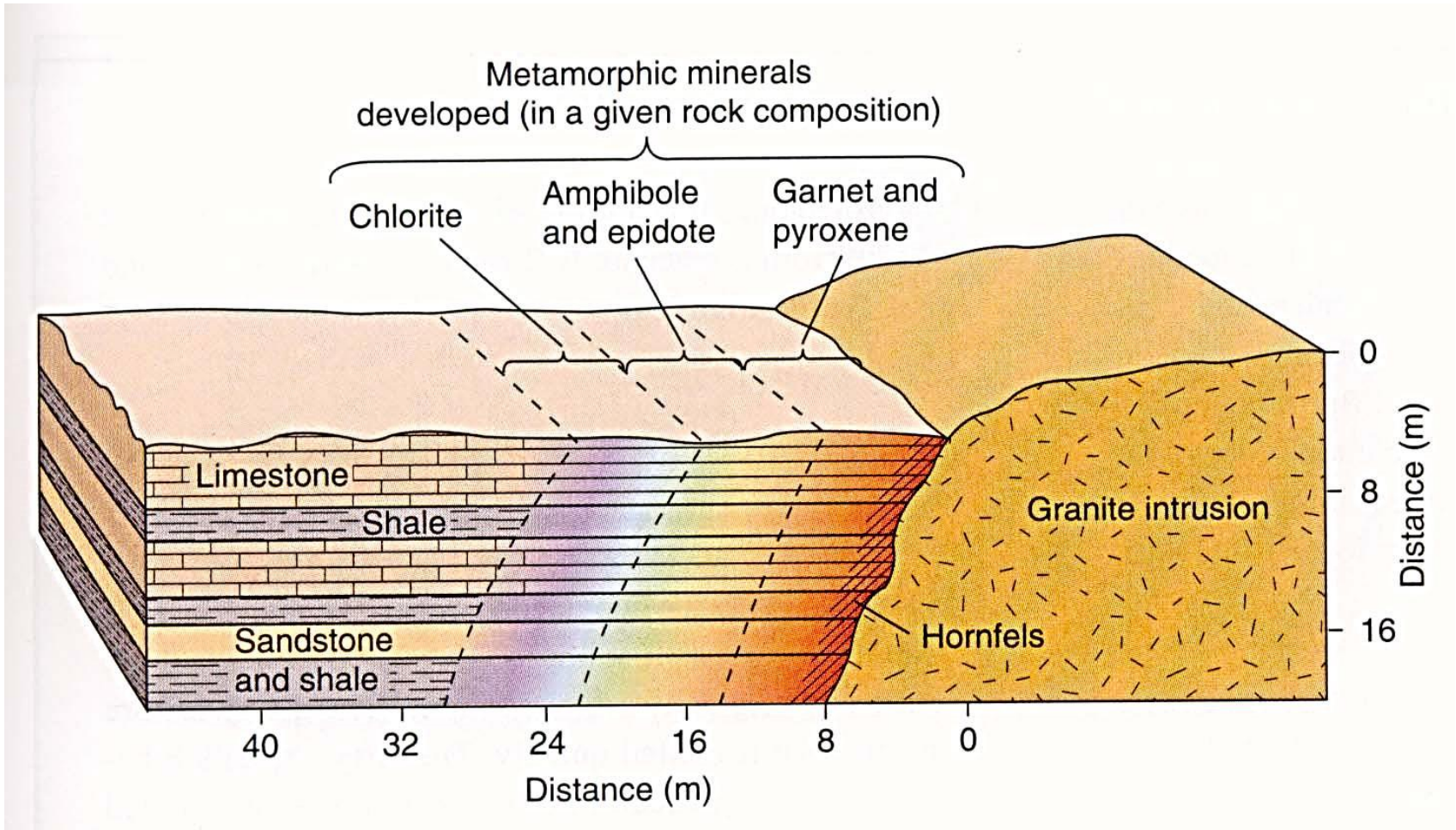


B. Crystallization of pluton



C. Uplift and erosion expose pluton and metamorphic cap rock

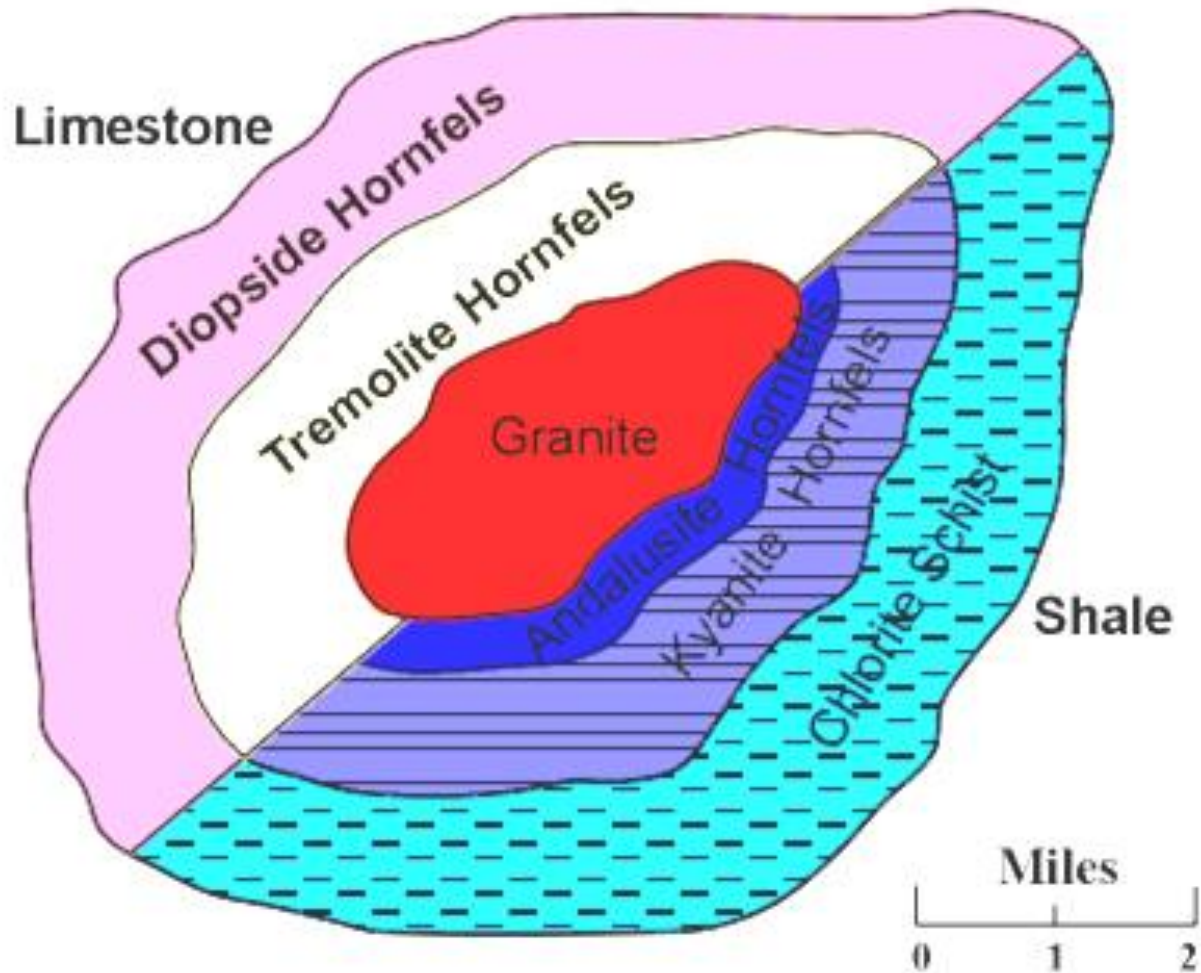
Contact metamorphism produces a zone of alteration called an *aureole* around an intrusive igneous body. In the photo, the dark layer, called a *roof pendant* (*suspended or hanging*), consists of metamorphosed host rock adjacent to the upper part of the light-colored igneous pluton. The term roof pendant implies that the rock was once the roof of a magma chamber. Sierra Nevada, California USA).

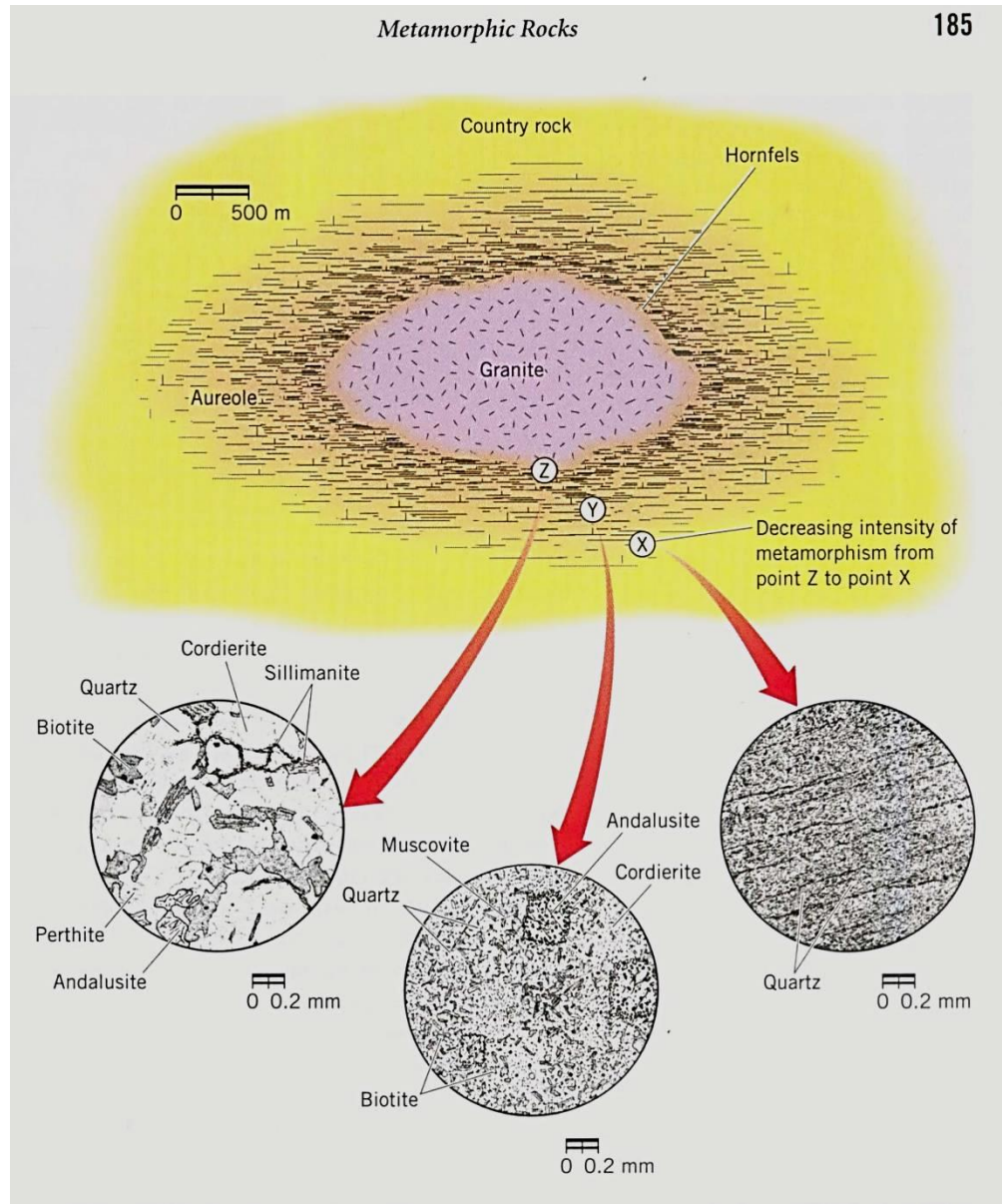


Metamorphic effects adjacent to a hot intrusion: contact metamorphism. Metamorphic minerals are developed depending on the protolith composition.

Contact Metamorphism

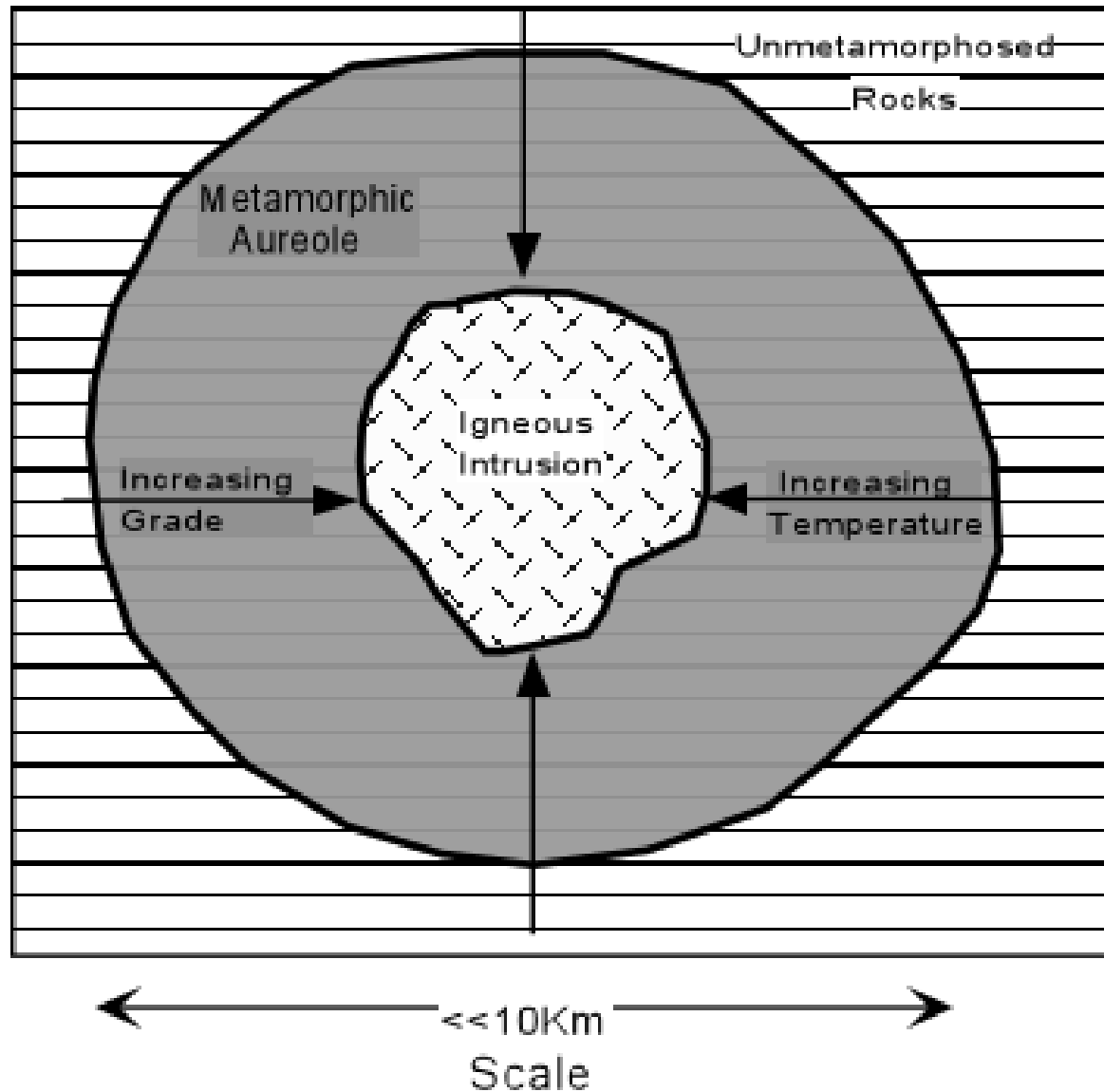
Marysville Pluton





Contact or Thermal metamorphism

Contact Metamorphism



Any rock may be affected by Contact metamorphisms but intrusive igneous rocks and previously metamorphosed rocks are less susceptible to metamorphic change as they form originally in high P/T conditions.

Hydrothermal Metamorphism

When hot, ion-rich fluids circulate through fissures (openings) and cracks in rock, a **chemical alteration** called hydrothermal metamorphism occurs (Fig 8.22).

This type of metamorphism is often closely associated with the **emplacement** (intrusion) **of magma**.

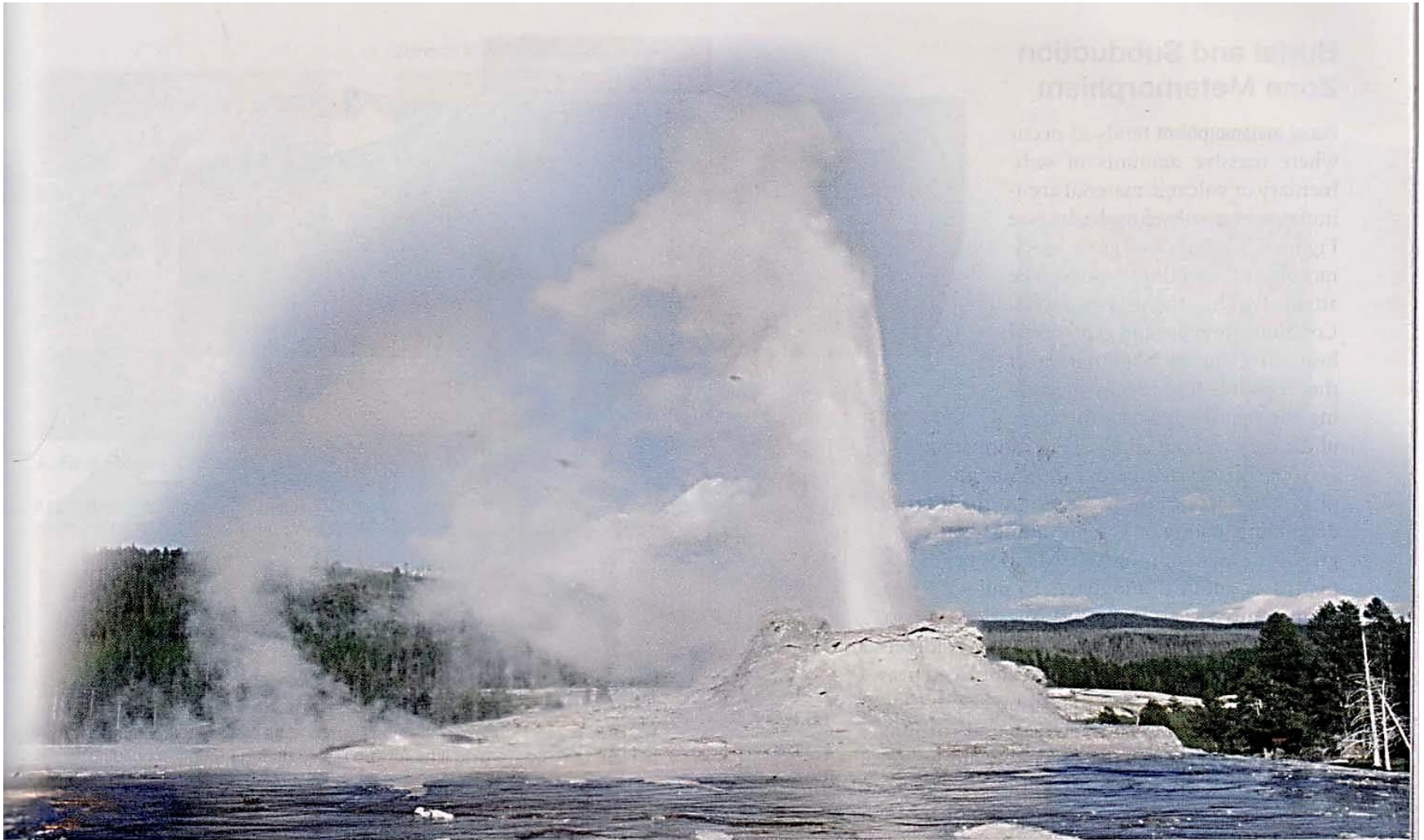


FIGURE 8.22 Hydrothermal metamorphism can occur at shallow crustal depths in regions where hot springs and geysers are active. (Photo by Philippe Clement/Nature Picture Library)

As large magma bodies cool and solidify, **silica-rich fluids (mainly water)** are driven into the **host rocks**.

When the host rock is highly fractured mineral matter contained in these **hydrothermal solutions** may precipitate to form a variety of minerals, some of which are economically important.

Burial metamorphism

Burial metamorphism tends to occur where massive amounts of sedimentary or volcanic material accumulates in a subsiding basin (Fig 8.3).

Here, low-grade metamorphic conditions may be attained within the deepest layers.

Confining pressure and geothermal heat drive the recrystallization of the constituent minerals - changing the texture and/or mineralogy of the rock without appreciable deformation.

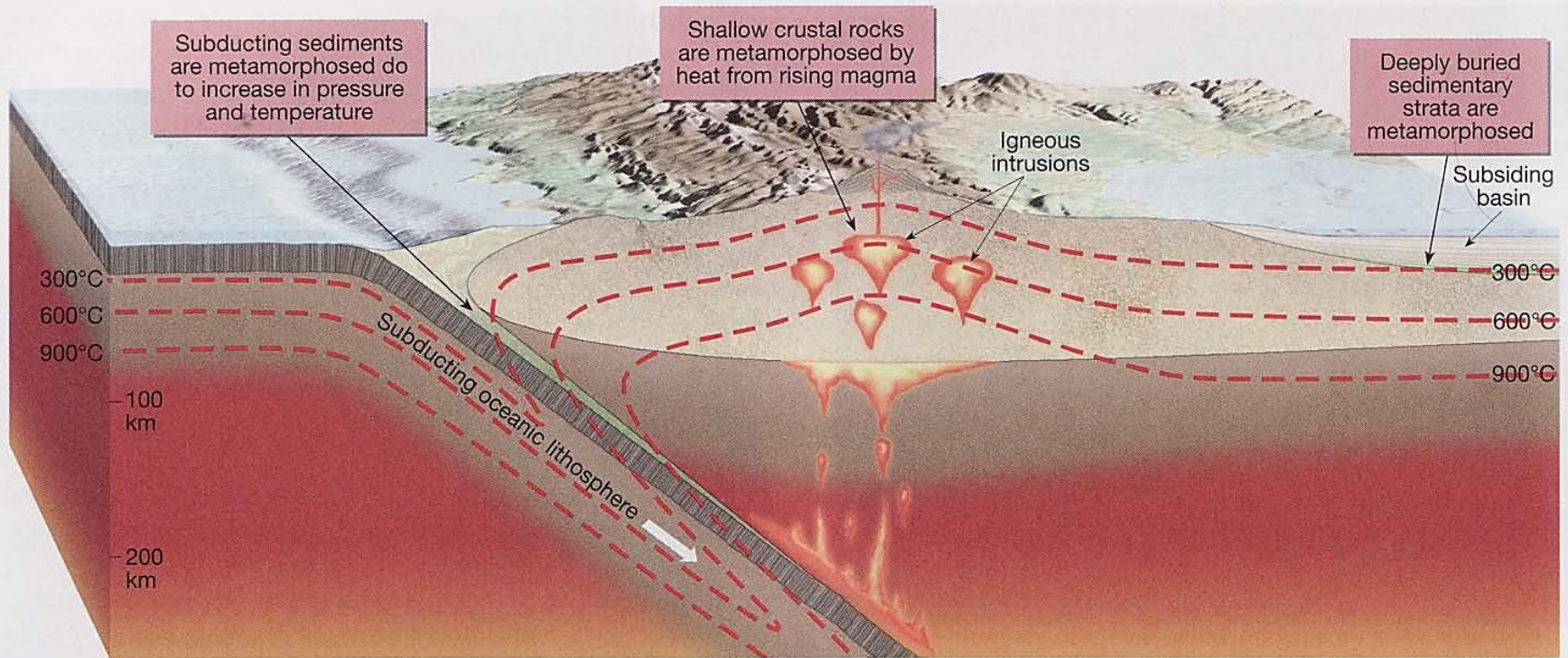


FIGURE 8.3 The geothermal gradient and its role in metamorphism. Notice how the geothermal gradient is lowered by the subduction of relatively cool oceanic lithosphere. By contrast, thermal heating is evident where magma intrudes the upper crust.

The depth required for burial metamorphism varies from one location to another, depending mainly on the prevailing geothermal gradient.

Metamorphism typically begins at depths of about 8 km, where temperatures are about 200°C.

However, in areas that exhibit large geothermal gradients and where molten rock has been emplaced near the surface, metamorphism can occur at depths of only a few km.

Rocks and sediments can also be carried to great depths along convergent boundaries where oceanic lithosphere is being subducted.

This phenomenon, called **subduction zone metamorphism, differs from burial metamorphism in that differential stresses play a major role in deforming rock as it is metamorphosed.**

Regional Metamorphism

Most metamorphic rock is produced by regional metamorphism during **mountain building** when large segments of Earth's crust are intensely deformed along **convergent plate boundaries** (Fig 8.24).

This activity occurs often during continental collisions.

Sediments and crustal rocks that form the margins of the colliding continental blocks are folded and faulted, causing them to shorten and thicken like a rumpled carpet.

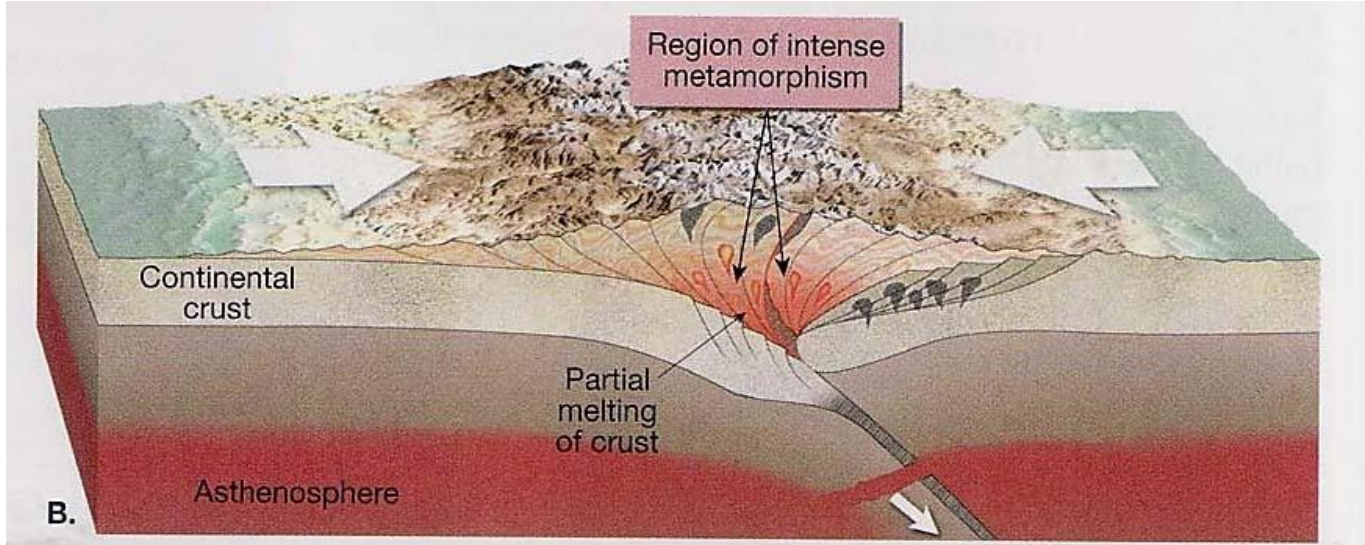
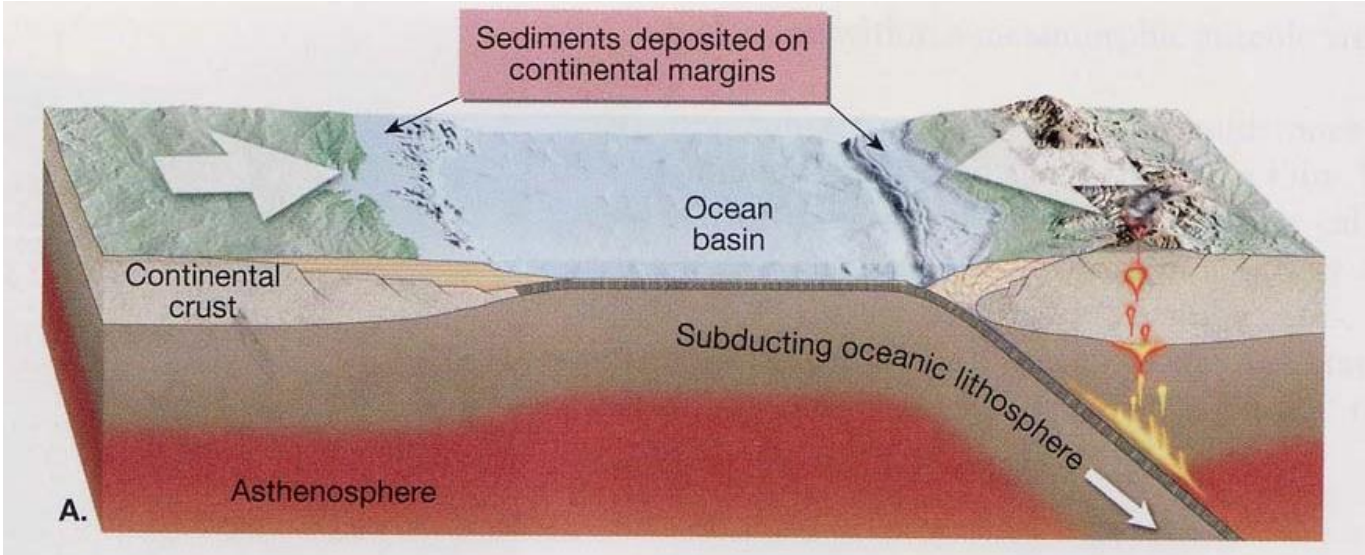


FIGURE 8.24 Regional metamorphism occurs where rocks are squeezed between two converging lithospheric plates during mountain building.

Often, these deeply buried rocks become heated to their melting point. As a result, magma collects until it forms bodies large enough to buoyantly rise and intrude the overlying metamorphic and sedimentary rocks (see Fig 8.24).

Consequently, the cores of many mountain ranges consist of folded and faulted metamorphic rocks, often intertwined with igneous bodies.

Other Metamorphic Environments

Other types of metamorphism that generate relatively small amounts of metamorphic rock tend to be localized.

Directed Pressure (Cataclastic) Metamorphism

Cataclastic metamorphism occurs as a result of **mechanical deformation, like when two bodies of rock slide past one another along a fault zone.**

Metamorphism along Fault Zones Near the surface, rock behaves like a brittle solid.

Heat is generated by the friction of sliding along such a shear zone, and the rocks tend to be mechanically deformed, being crushed and pulverized, due to the shearing.

The result is a loosely coherent rock called **fault breccia** that is composed of broken and crushed rock fragments (Fig 8.25A).

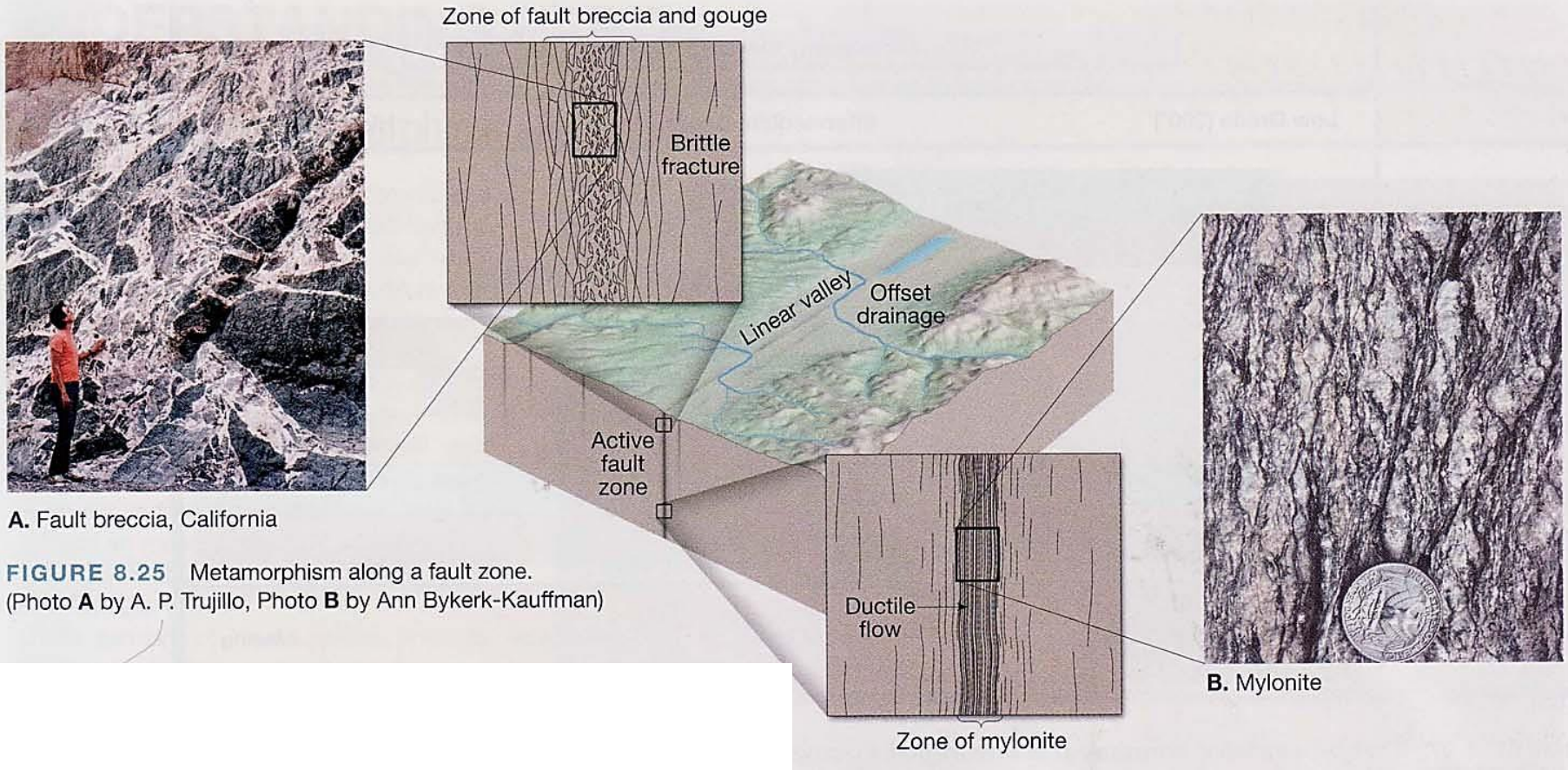
In some shallow fault zones a soft, uncemented claylike material called **fault gouge** is also produced.

Much of the deformation associated with fault zones occurs at great depth and thus at high temperatures.

In this environment preexisting minerals deform by ductile flow (Fig 8.25B).

As large slabs of rock move in opposite directions, the minerals in the fault zone between them tend to form elongated grains that give the rock a foliated or lineated appearance.

Rocks formed in these zones of intense ductile deformation are termed **mylonites (mylo — a mill, **ite**— a stone).**



A. Fault breccia, California

FIGURE 8.25 Metamorphism along a fault zone.
 (Photo A by A. P. Trujillo, Photo B by Ann Bykerk-Kauffman)

B. Mylonite

Impact Metamorphism

Impact (or **shock**) metamorphism occurs when high-speed projectiles called meteorites (fragments of comets or asteroids) strike Earth's surface.

Upon impact the energy of the once rapidly moving meteorite is transformed into **heat energy** and **shock waves** that pass through the surrounding rocks. The result is pulverized, shattered, and sometimes melted rock.

The products of these impacts, called **impactites**, include mixtures of fused fragmented rock plus glass-rich ejecta that resemble volcanic bombs.

In some cases, a very dense form of quartz (coesite) and minute diamonds are found.

These high-pressure minerals provide convincing evidence that pressures and temperatures as great as those existing in the upper mantle must have been attained for at least a brief moment.

Thank you

Granite intrusion in the metamorphic rock, Nepal Himalaya



Granite intrusion (light coloured rocks) into the sedimentary rocks (dark rocks at the top) in the Nepal Himalaya, Everest area





Augen gneiss in the Himalaya



Thinly banded biotite gneiss of pelite and quartz sandstone origin

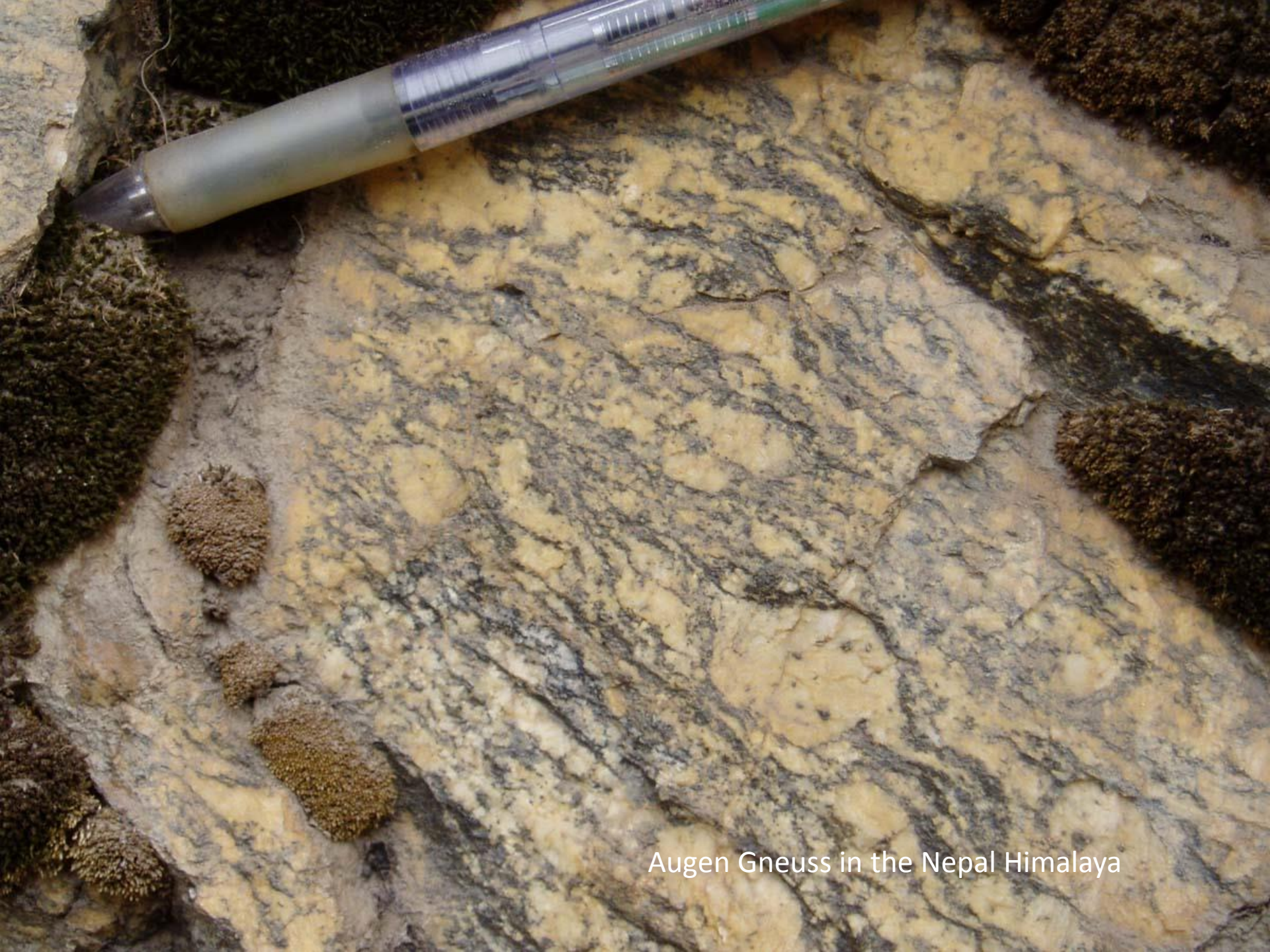
Thinly banded meta pelite

Thinly banded quartzite





Gneissic rock
of the Nepal
Himalaya
(Everest area)



Augen Gneuss in the Nepal Himalaya

