Chapter 7

Metamorphism, Metamorphic Rocks, and Hydrothermal Rocks

Metamorphism

What happens to rocks that are deeply buried but are not hot enough to melt?

- They become metamorphosed! Metamorphism refers to changes to rocks that occur in the Earth's interior.
- Changes may be new textures, new mineral assemblages, or both.
- These changes occur w/o the rock melting.

Factors Controlling the Characteristics of Metamorphic Rocks

- Composition of the Parent Rock
- Temperature
- Pressure
- Fluids
- Time

CO.07

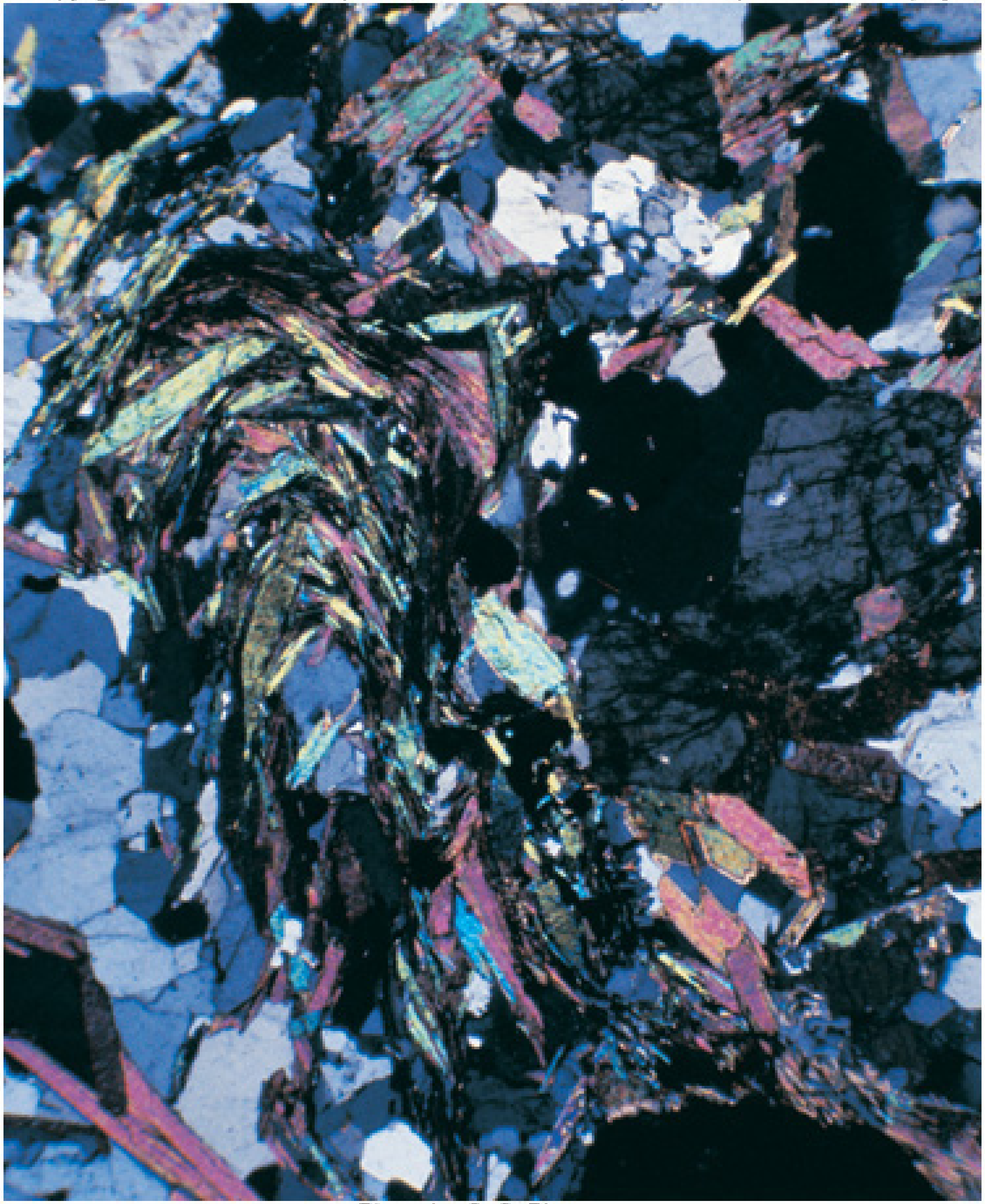


Photo by C. C. Plummer

Fig. 07.01

Photo by C. C. Plummer

Composition of the Parent Rock

- The parent rock controls the mineral content of the metamorphic rock
- A limestone composed of $CaCO_3$ cannot metamorphose into a silica-rich rock.

Temperature

- Geothermal Gradient
- The deeper a rock is beneath the surface, the hotter is will be.

Pressure

- Confining pressure - equally on all surfaces.
- Lithostatic pressure – pressure exerted on buried material that forces grains closer together and eliminates pore space.
- Pressure gradient – increase in lithostatic pressure with depth, ~1,000 atmospheres per 3.3 km.

Pressure

- Stress
- Differential Stress
- Compressive Stress
- Shearing

Fig. 07.02

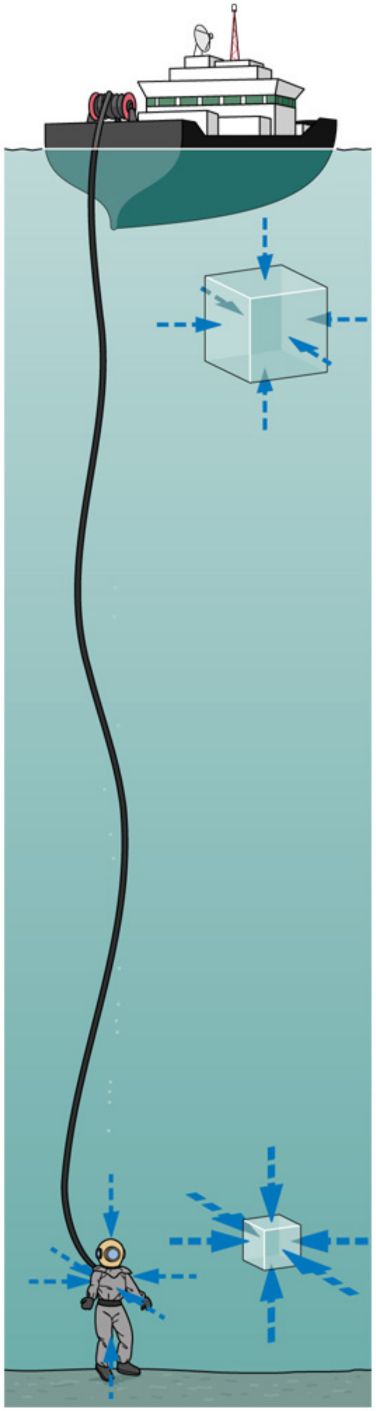
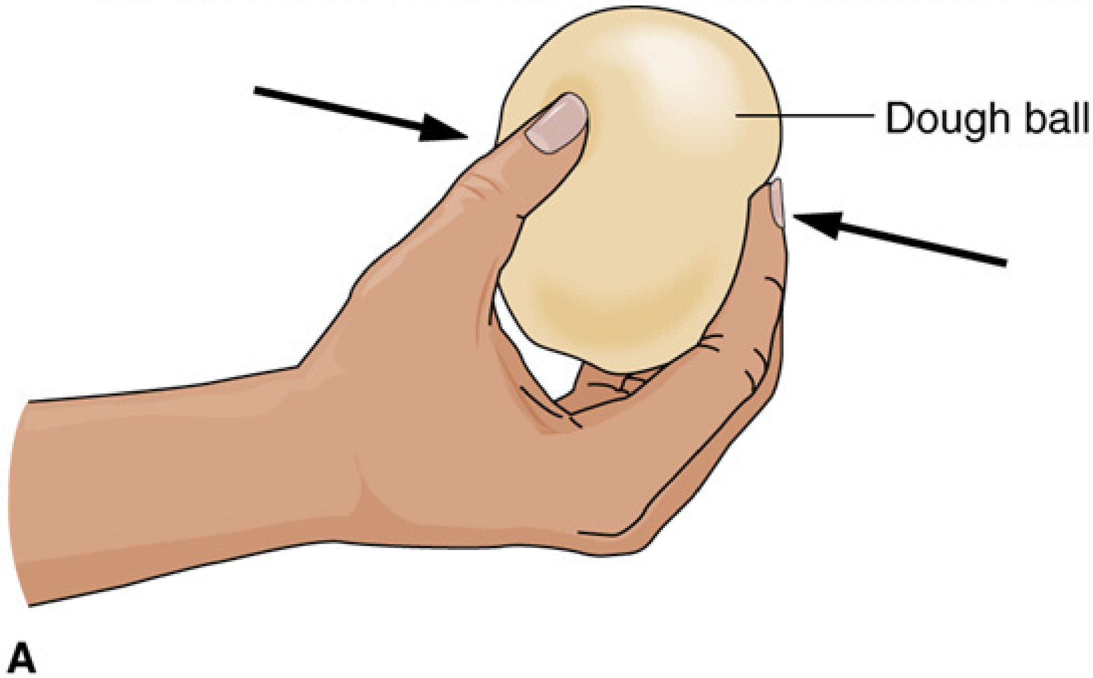


Fig. 07.03



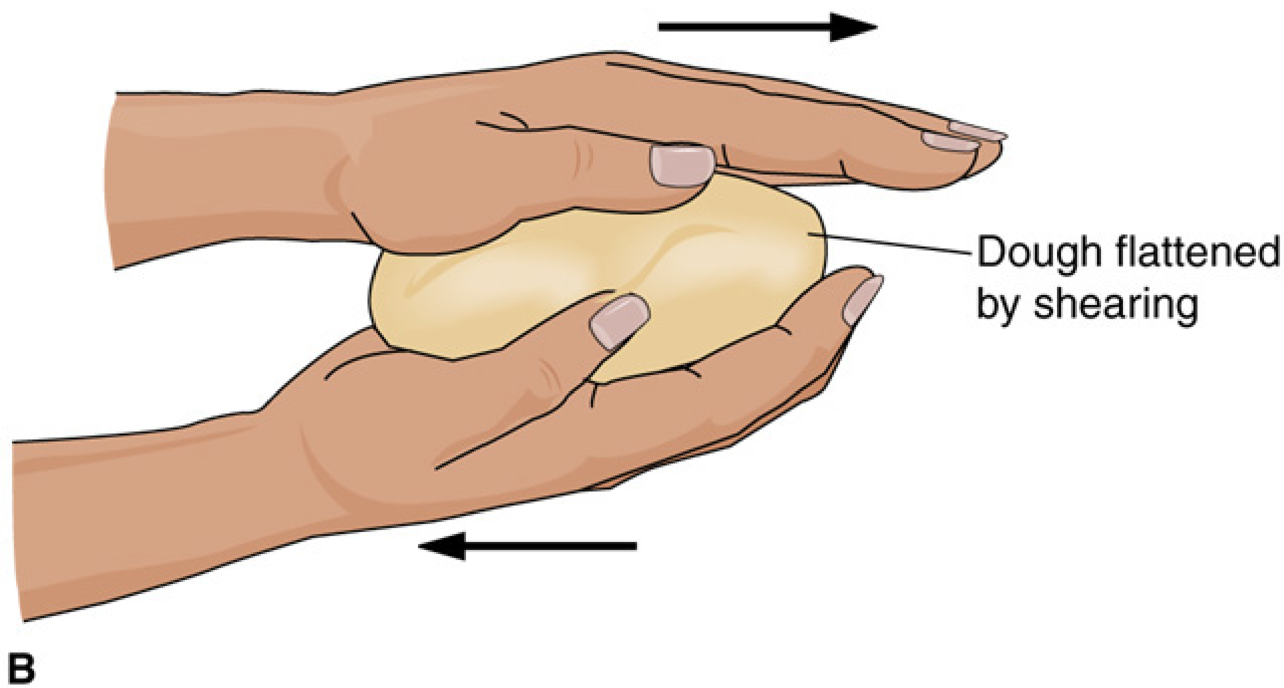


Fig. 07.04

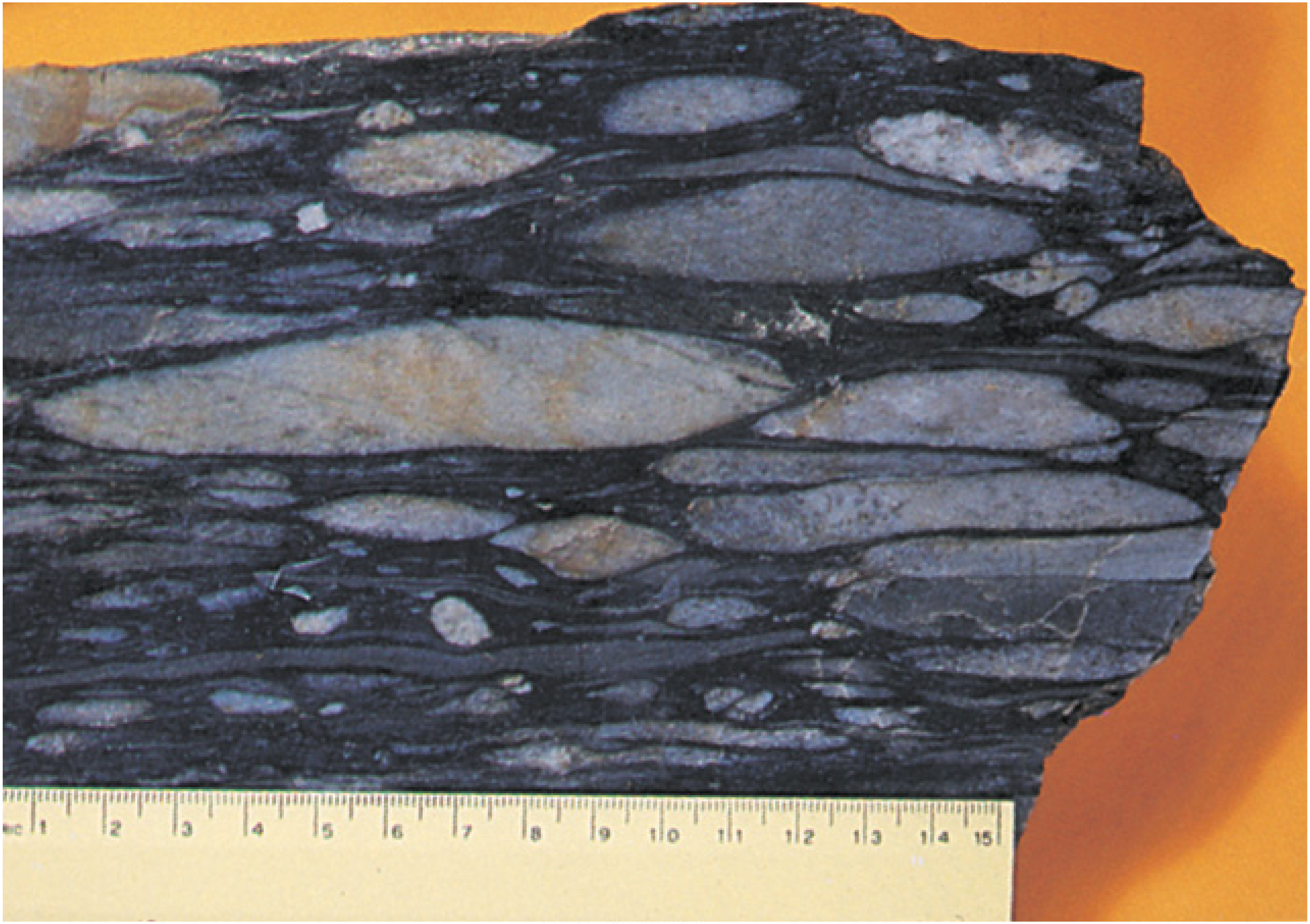


Photo by C. C. Plummer

Pressure

- Foliation– describes rock with a planar texture.
  - **Slaty** – rock splits easily along planes
  - **Schistose** – visible platy minerals in planes
  - **Gneissic** – light and dark banding of minerals

Fig. 07.05

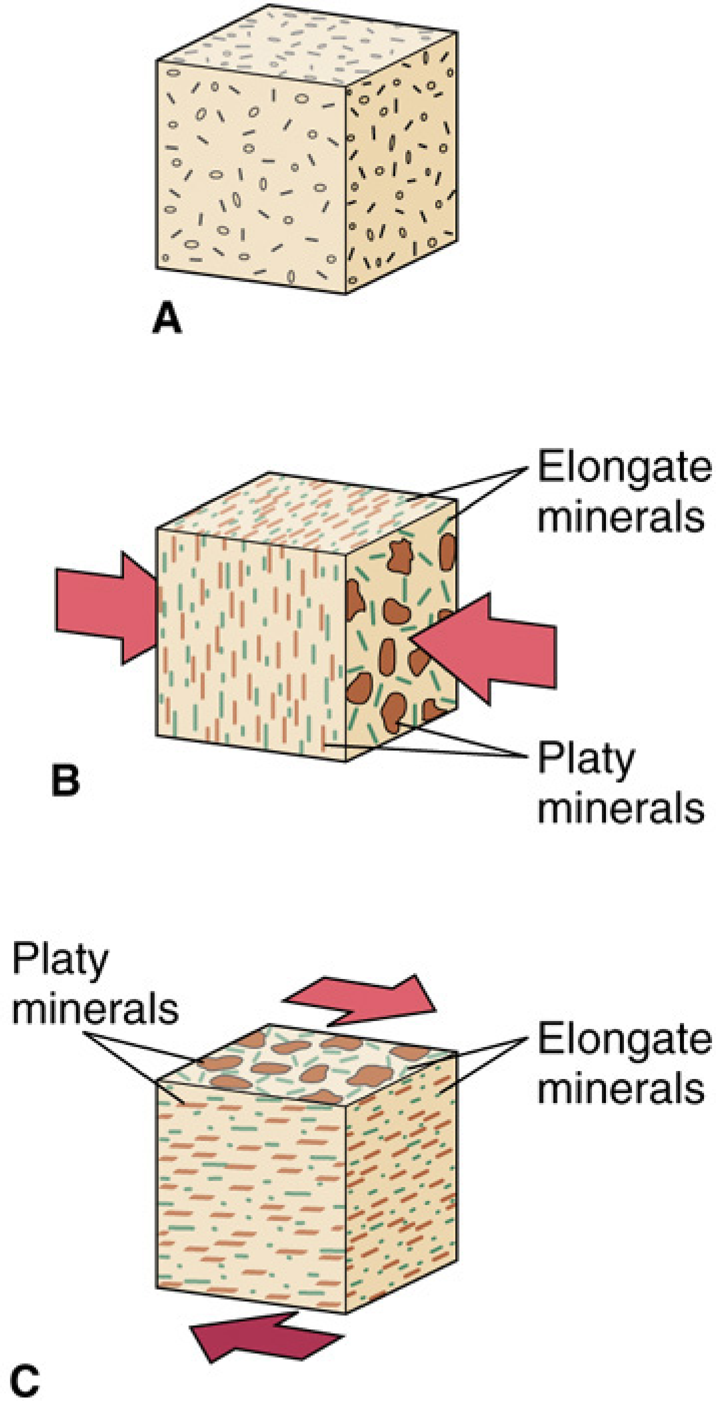

A
Elongate minerals
Platy minerals
B
Platy minerals
Elongate minerals
C

Fig. 07.06

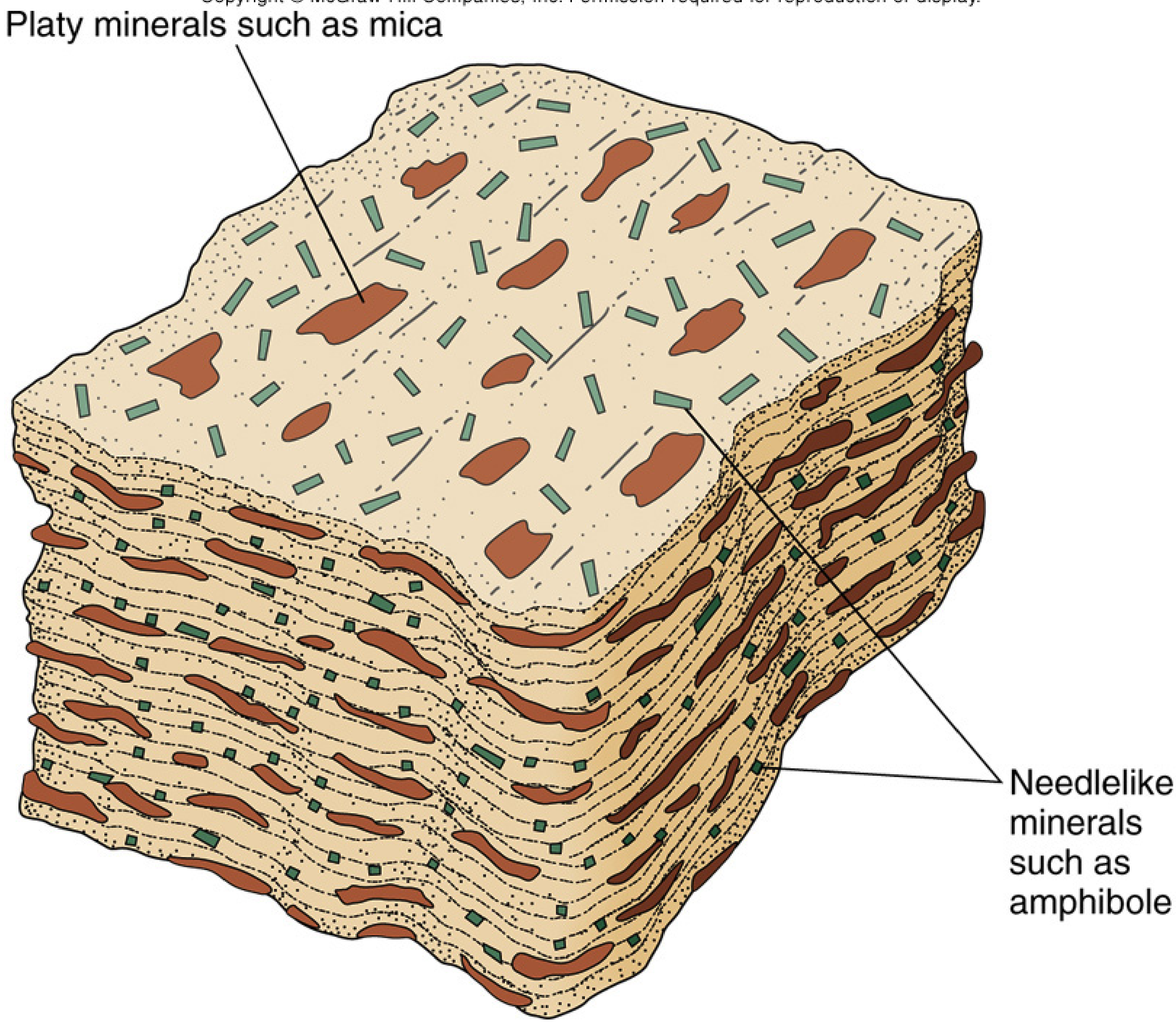

Platy minerals such as mica
Needlelike minerals such as amphibole

Fig. 07.14

Photo by C. C. Plummer

Fluids

- Water is thought to help trigger metamorphic chemical reactions

Time

- A recent calculated growth rate for garnet crystals taken from a metamorphic rock in Vermont = 1.4 mm per million years

Two most common types of Metamorphism

- Contact Metamorphism
- Regional Metamorphism

Contact Metamorphism

- High temperature is dominant factor and confining pressure usually low. Typically nonfoliated due to lack of differential stress.

  shale (mica) → hornfels

  (fine-grained, unfoliated metamorphic rock)

  basalt (amphibole) → hornfels

  quartz sandstone → quartzite

  limestone → marble

Fig. 07.08

Photo by C. C. Plummer

Regional Metamorphism

- Majority of metamorphics are produced this way by baking at considerable depth underground (>5km). Typically 300 to 800°C. Almost always foliated.

  The differential stress is due to tectonism, the constant movement and squeezing of the crust during mountain building.

  basalt → low temp → greenschist (chlorite, actinolite, and Na-rich plagioclase)

  basalt → high temp → amphibole schist (hornblende, plagioclase feldspar, and maybe garnet)

Fig. 07.09

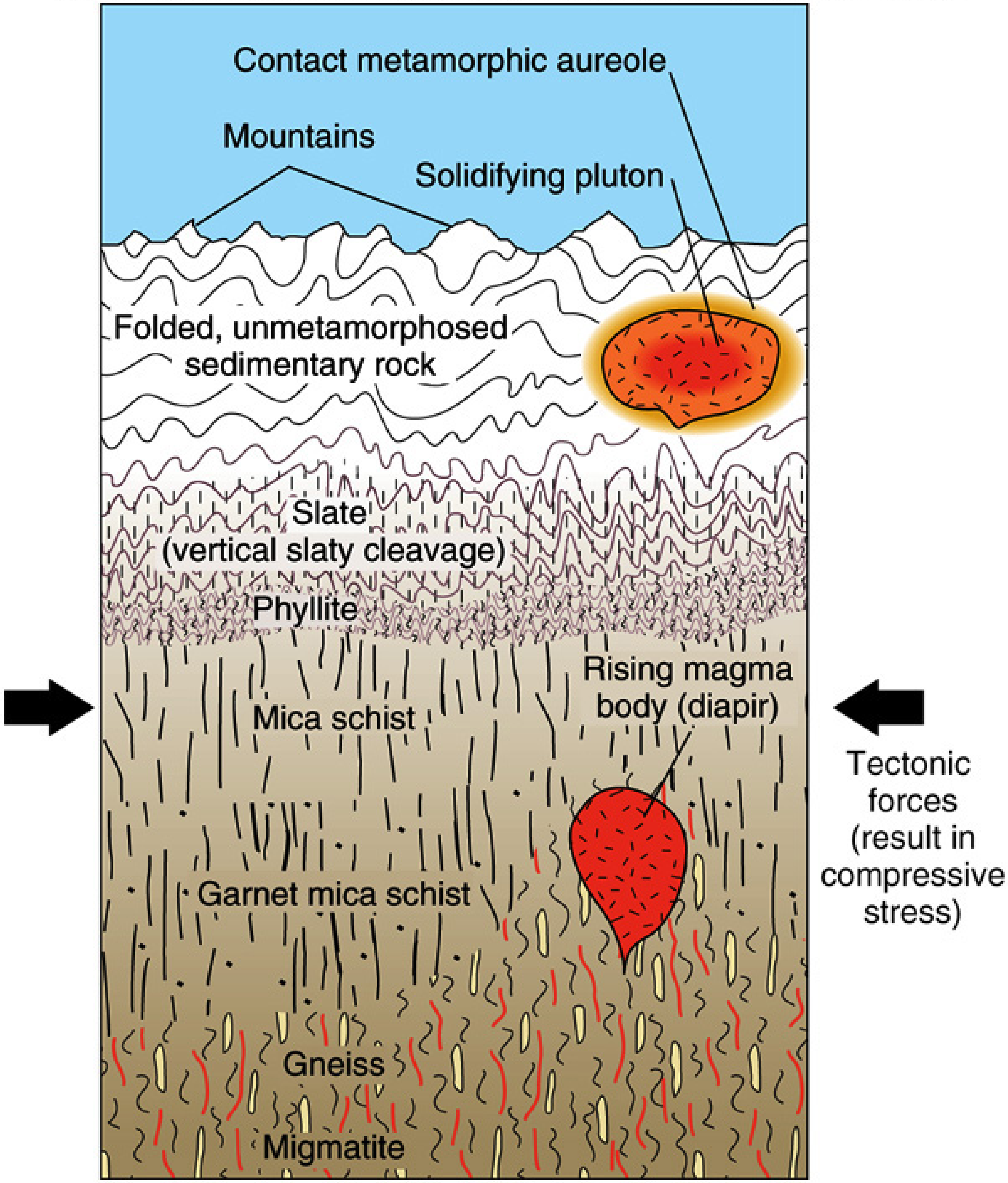

Contact metamorphic aureole
Mountains
Solidifying pluton
Folded, unmetamorphosed sedimentary rock
Slate (vertical slaty cleavage)
Phyllite
Rising magma body (diapir)
Mica schist
Garnet mica schist
Gneiss
Migmatite
Tectonic forces (result in compressive stress)

Fig. 07.10

Photo by P. D. Rowley, U.S. Geological Survey

Fig. 07.11

Photo by C. C. Plummer

Fig. 07.12

Photo by C. C. Plummer

Fig. 07.13

Photo by C. C. Plummer

Fig. 07.14

Photo by C. C. Plummer

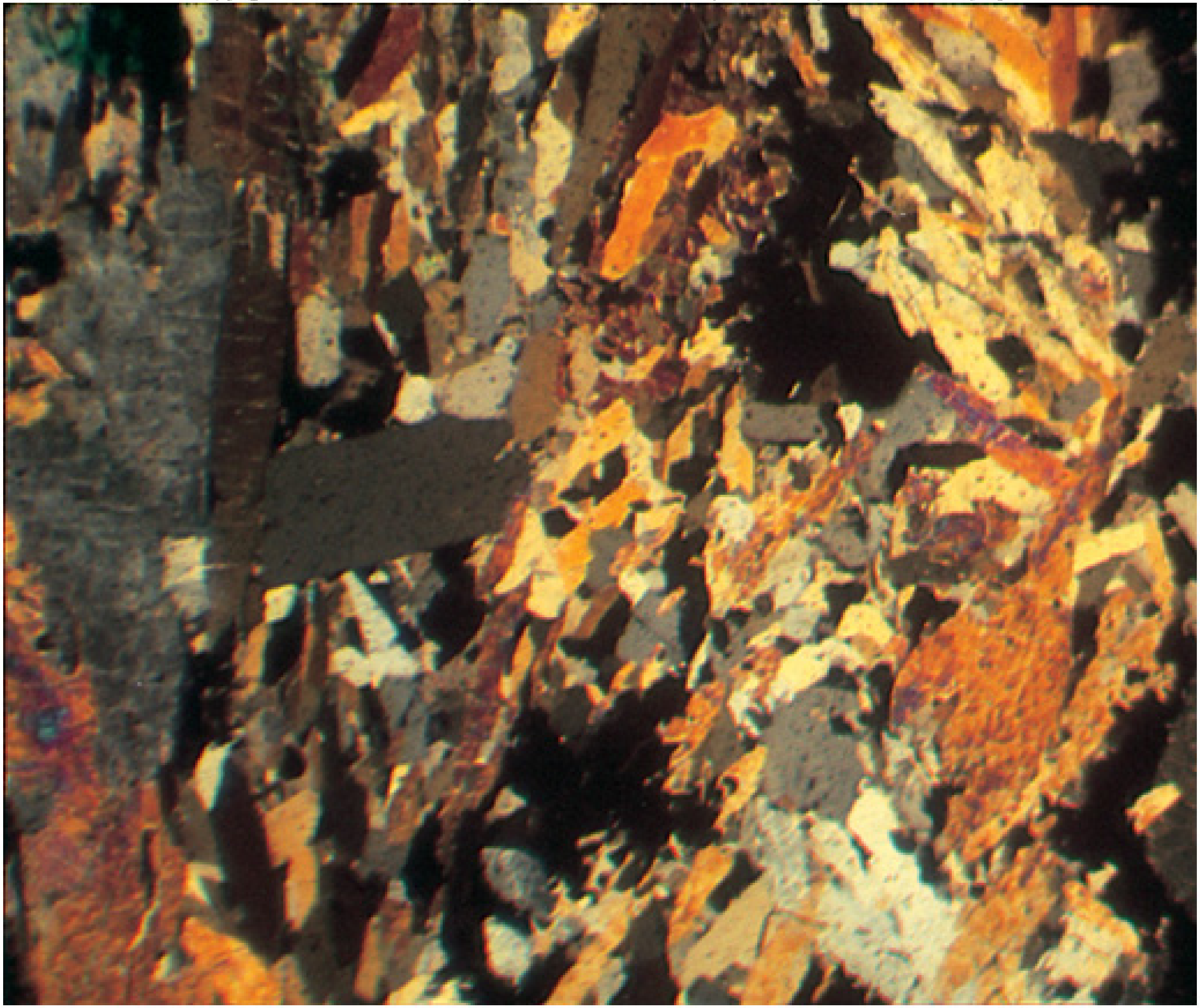
Fig. 07.15

Photo by C. C. Plummer

Classification of Metamorphic Rocks

- Foliated or not
- If not foliated, named on composition
- If foliated, determine type of foliation, then modify name based on composition

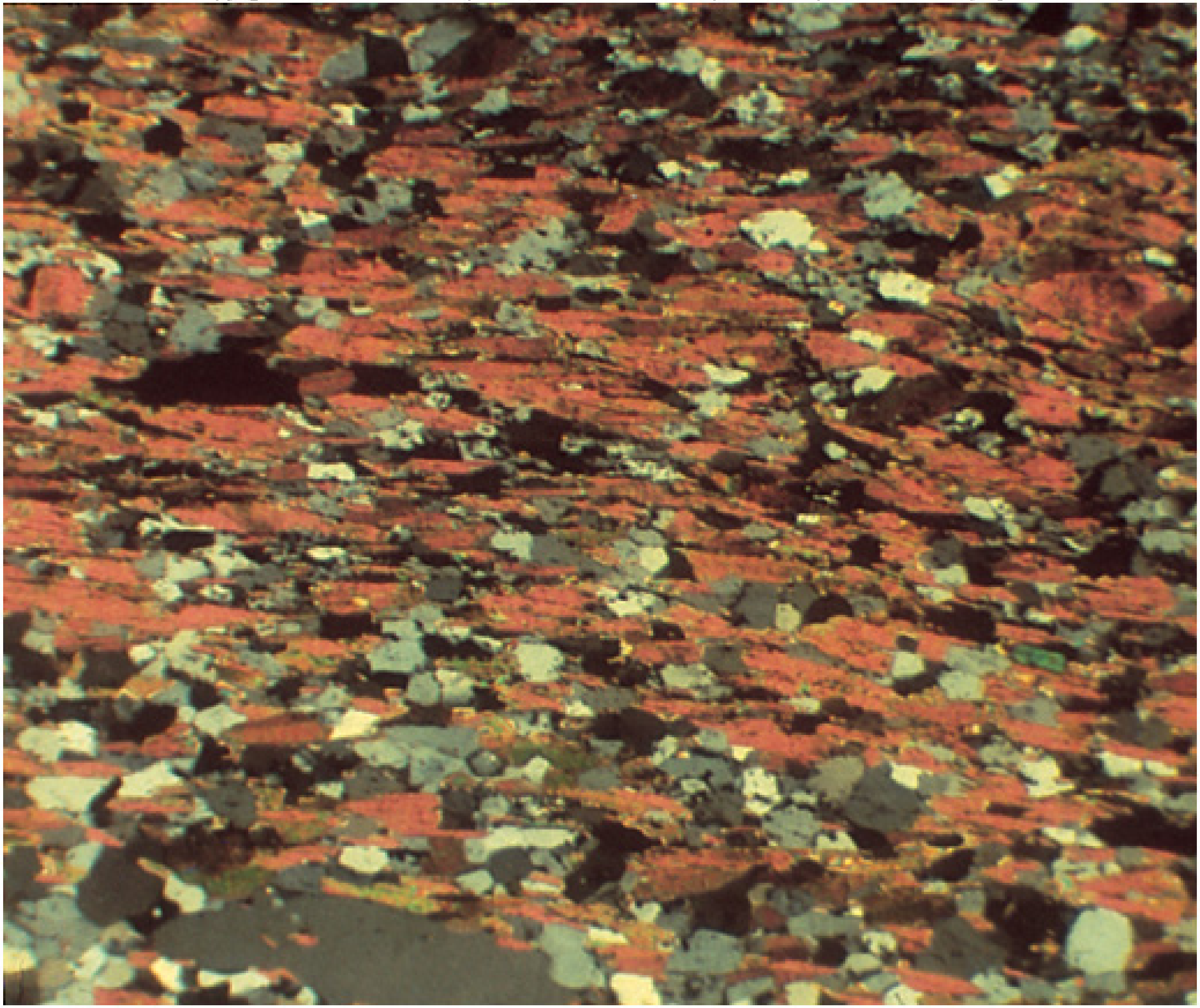
Fig. 07.07a



A

Photo by C. C. Plummer

Fig. 07.07b



B

Photo by C. C. Plummer

Table 7.1 Classification and Naming of Metamorphic Rocks (Based Primarily on Texture)

Nonfoliated

Name Based on Mineral Content of Rock

Usual Parent Rock	Rock Name	Predominant Minerals	Identifying Characteristics
Limestone Dolomite	Marble Dolomite marble	Calcite Dolomite	Coarse interlocking grains of calcite (or, less commonly, dolomite). Calcite (or dolomite) has rhombohedral cleavage; hardness intermediate between glass and fingernail. Calcite effervesces in weak acid.
Quartz sandstone	Quartzite	Quartz	Rock composed of interlocking small granules of quartz. Has a sugary appearance and vitreous luster; scratches glass.
Shale Basalt	Hornfels Hornfels	Fine-grained micas Fine-grained ferromagnesian minerals, plagioclase	A fine-grained, dark rock that generally will scratch glass. May have a few coarser minerals present.

Foliated

Name Based Principally on Kind of Foliation Regardless of Parent Rock. Adjectives Describe the Composition (e.g., biotite-garnet schist)

Texture	Rock Name	Typical Characteristic Minerals	Identifying Characteristics
Slaty	Slate	Clay and other sheet silicates	A very fine-grained rock with an earthy luster. Splits easily into thin, flat sheets.
Intermediate between slaty and schistose	Phyllite	Muscovite mica	Fine-grained rock with a silky luster. Generally splits along wavy surfaces.
Schistose	Schist	Biotite and muscovite, amphibole	Composed of visible platy or elongated minerals that show planar alignment. A wide variety of minerals can be found in various types of schist (e.g., garnet mica schist, hornblende schist, etc.).
Gneissic	Gneiss	Feldspar	Light and dark minerals are found in separate, parallel layers or lenses. Commonly, the dark layers include biotite and hornblende; the light-colored layers are composed of feldspars and quartz. The layers may be folded or appear contorted.

Table 07.02

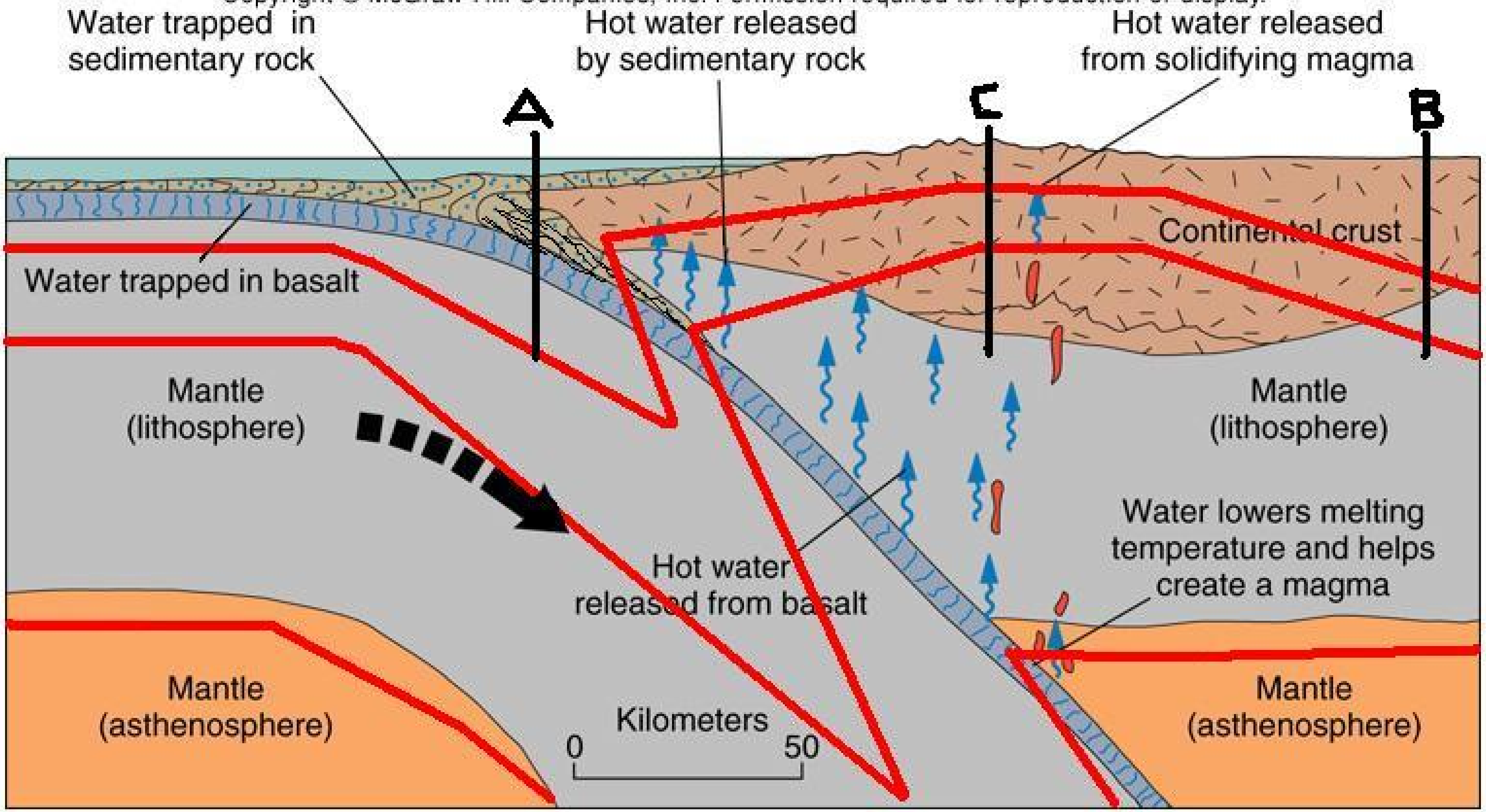
Table 7.2 Regional Metamorphic Rocks that Form under Approximately Similar Pressure and Temperature Conditions

Parent Rock	Rock Name	Predominant Minerals
Basalt	Amphibole schist (amphibolite)	Hornblende, plagioclase, garnet
Shale	Mica schist	Biotite, muscovite, quartz, garnet
Quartz sandstone	Quartzite	Quartz
Limestone or dolomite	Marble	Calcite or dolomite

Plate Tectonics and Metamorphism

- Heat is the most variable of the controlling factors of metamorphism
- In subducting environments, heat is provided by:
  1. normal overburden/geothermal gradient.
  2. friction along the collision zone.
  3. feeding of volcanic-plutonic arc complex.
- Result: study isotherms to understand why different metamorphic rocks form in two places at the same depths, and from the same parent material.

Fig. 07.16


Water trapped in sedimentary rock
Hot water released by sedimentary rock
Hot water released from solidifying magma
A
C
B
Continental crust
Water trapped in basalt
Mantle (lithosphere)
Mantle (lithosphere)
Water lowers melting temperature and helps create a magma
Hot water released from basalt
Mantle (asthenosphere)
Kilometers
0
50
Mantle (asthenosphere)

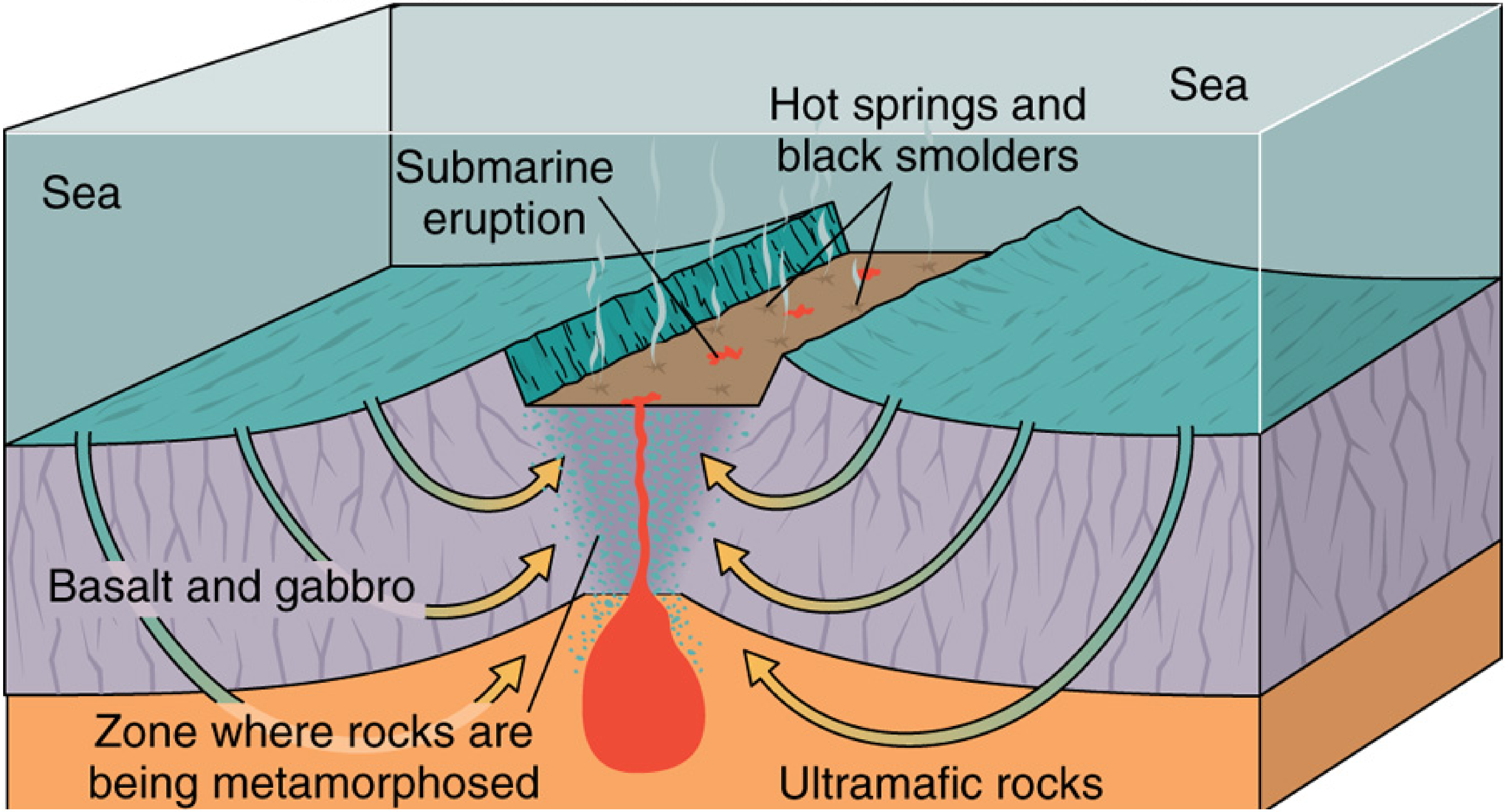
Hydrothermal Processes

- Hydrothermal Activity at Divergent Plate Boundaries – **Black Smokers**

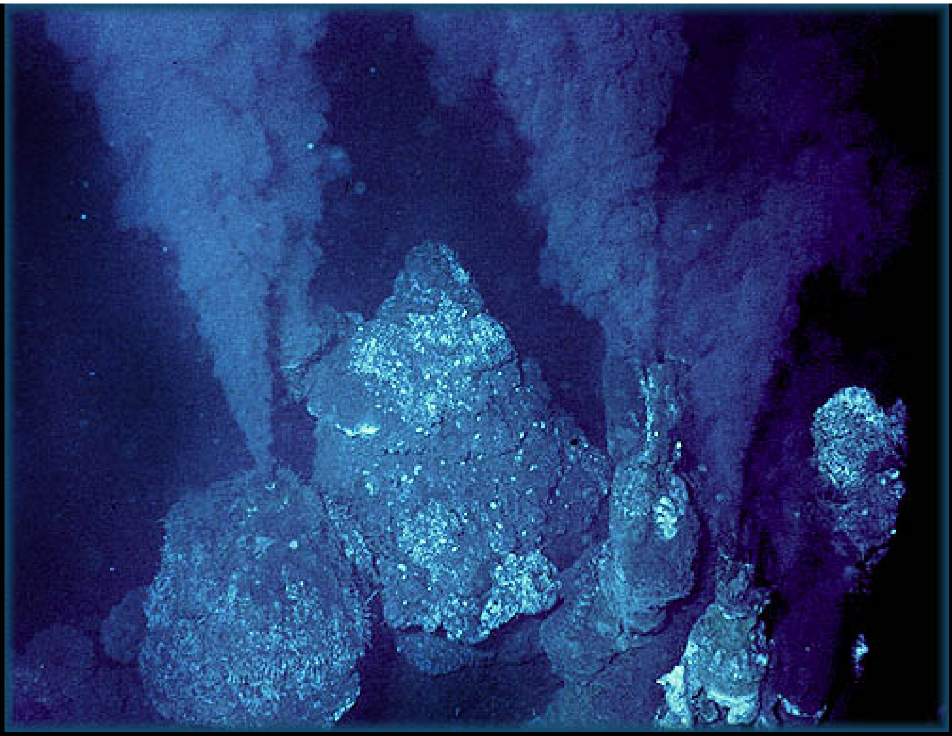
  As seawater moves through the crust, it dissolves metals and sulfur from the crustal rocks and magma. When the hot, metal-rich solutions contact seawater, metal sulfides are precipitated in a mound around the hot spring.

  Metals in these rift-valley hot springs are predominantly iron, copper, and zinc (w/ smaller amounts of manganese, gold, and silver).

Fig. 07.17


Sea
Sea
Submarine eruption
Hot springs and black smolders
Basalt and gabbro
Zone where rocks are being metamorphosed
Ultramafic rocks

Black smokers



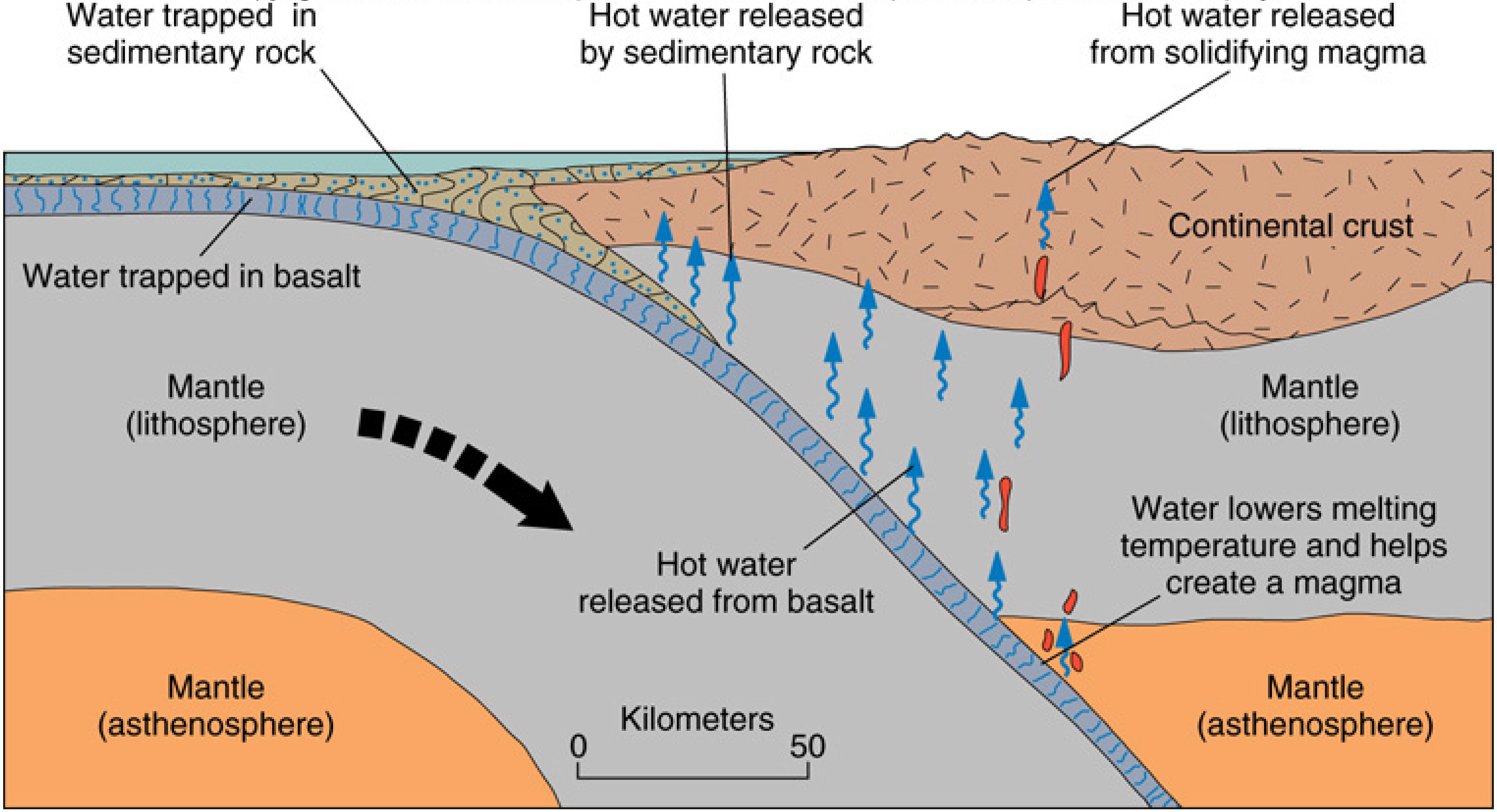
Hydrothermal Processes

- Hydrothermal Activity at Divergent Plate Boundaries

  During metamorphism the ferromagnesian igneous minerals, olivine and pyroxene, become converted to hydrous (water-bearing) minerals such as amphibole.

  The hydrous minerals may eventually contribute to magma generation at convergent boundaries. After oceanic crust is subducted the minerals are dehydrated deep in the subduction zone.

Fig. 07.22


Water trapped in
sedimentary rock
Hot water released
by sedimentary rock
Hot water released
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Continental crust
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Water lowers melting
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Hot water
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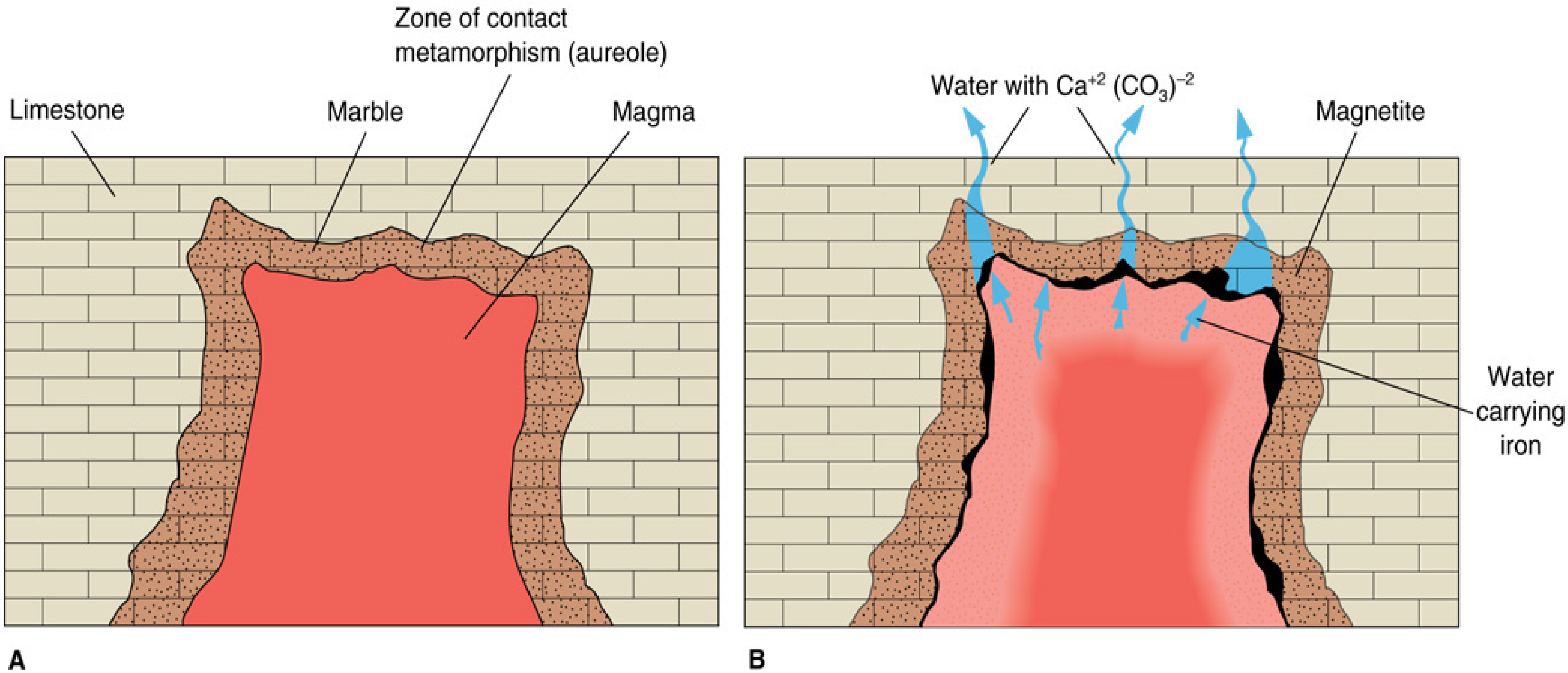
Mantle
(asthenosphere)
Kilometers
0
50
Mantle
(asthenosphere)

Hydrothermal Processes

- Metasomatism – metamorphism coupled with the introduction of ions from an external source.

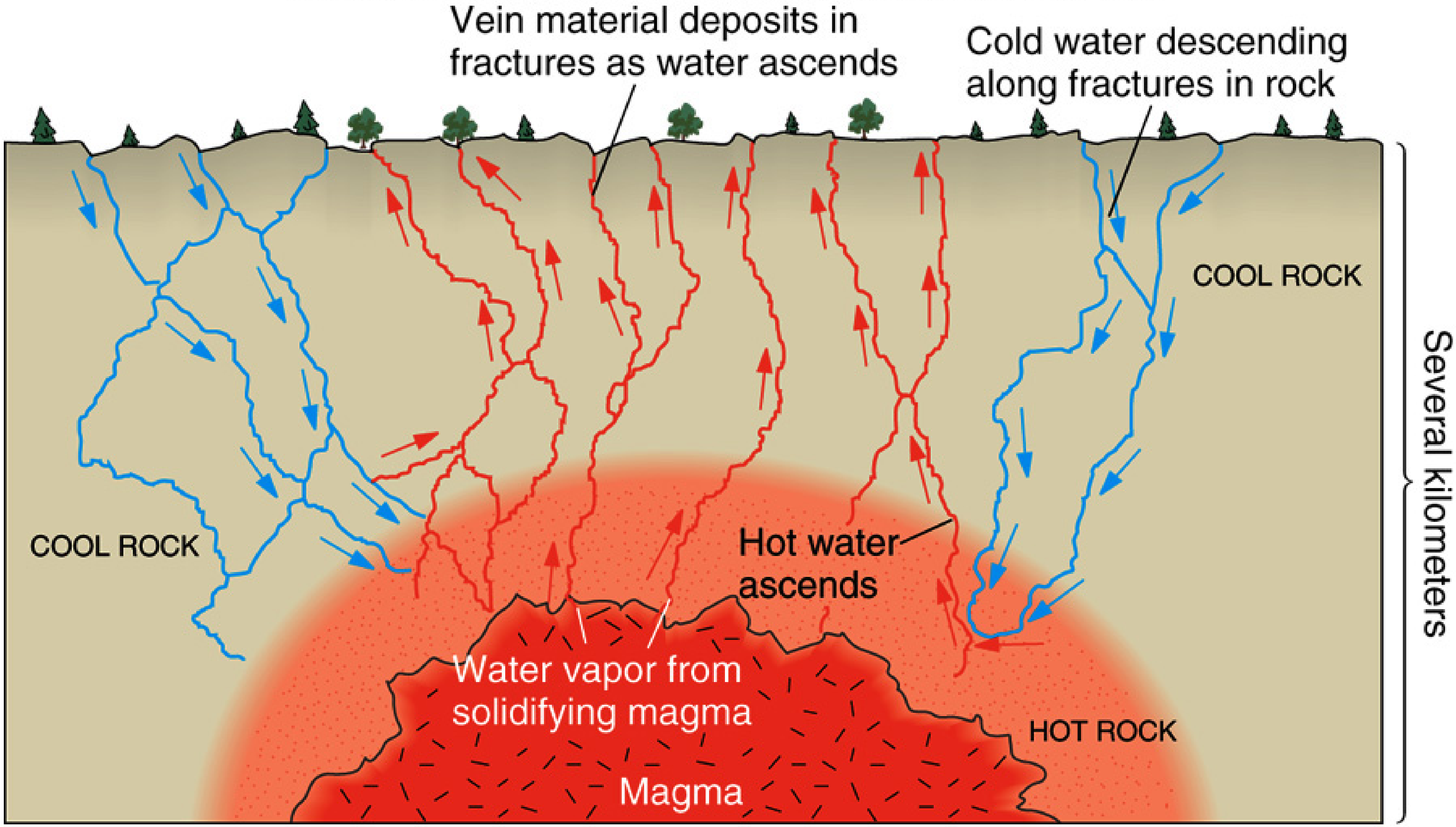
Fig. 07.19


Zone of contact
metamorphism (aureole)
Limestone
Marble
Magma
A
Water with Ca^{+2} $(CO_3)^{-2}$
Magnetite
Water
carrying
iron
B

Hydrothermal Processes

- Hydrothermal Rocks and Minerals
  1. Form from hot water given off by a cooling magma.
  2. Or, also produced by ground water heated by a pluton and circulated by convection.
- Typically form vein deposits as ions leave water and cake onto walls of fractures.
- Disseminated deposits from by depositing small grains of the ore minerals as the water percolates through the grains of the rocks.

Fig. 07.21



Vein material deposits in fractures as water ascends
Cold water descending along fractures in rock
COOL ROCK
COOL ROCK
Hot water ascends
Water vapor from solidifying magma
HOT ROCK
Magma
Several kilometers

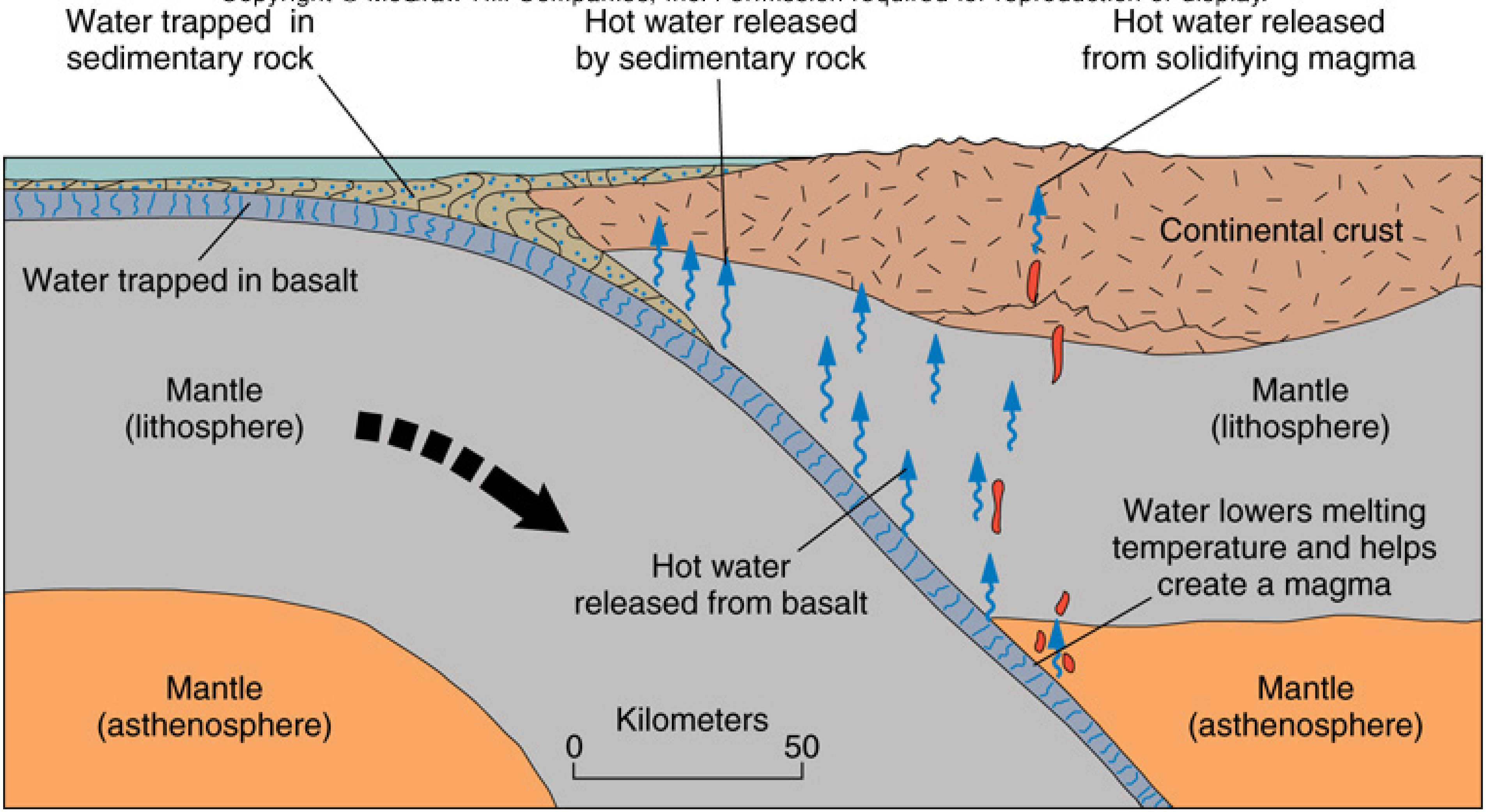
Hydrothermal Processes

- Sources of Water

  1. Surface-derived ground water can only penetrate to a limit.

  2. Plate tectonics can account for water at deeper levels in the lithosphere as seawater trapped in the oceanic crust can be carried to considerable depths through subduction. The hydrous minerals in basaltic crust provide water through recrystallization when the rocks get hot.

Fig. 07.22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Hot water released from basalt
Mantle (asthenosphere)
Kilometers
0
50
Mantle (asthenosphere)

Table 07.03

Table 7.3 Hydrothermal Processes

Role of Water	Name of Process or Product
Water transports ions between grains in a rock. Some water may be incorporated into crystal structures.	Metamorphism
Water brings ions from outside the rock, and they are added to the rock during metamorphism. Other ions may be dissolved and removed.	Metasomatism
Water passes through cracks or pore spaces in rock and precipitates minerals on the walls of cracks and within pore spaces.	Hydrothermal rocks