Dikes, Antarctica

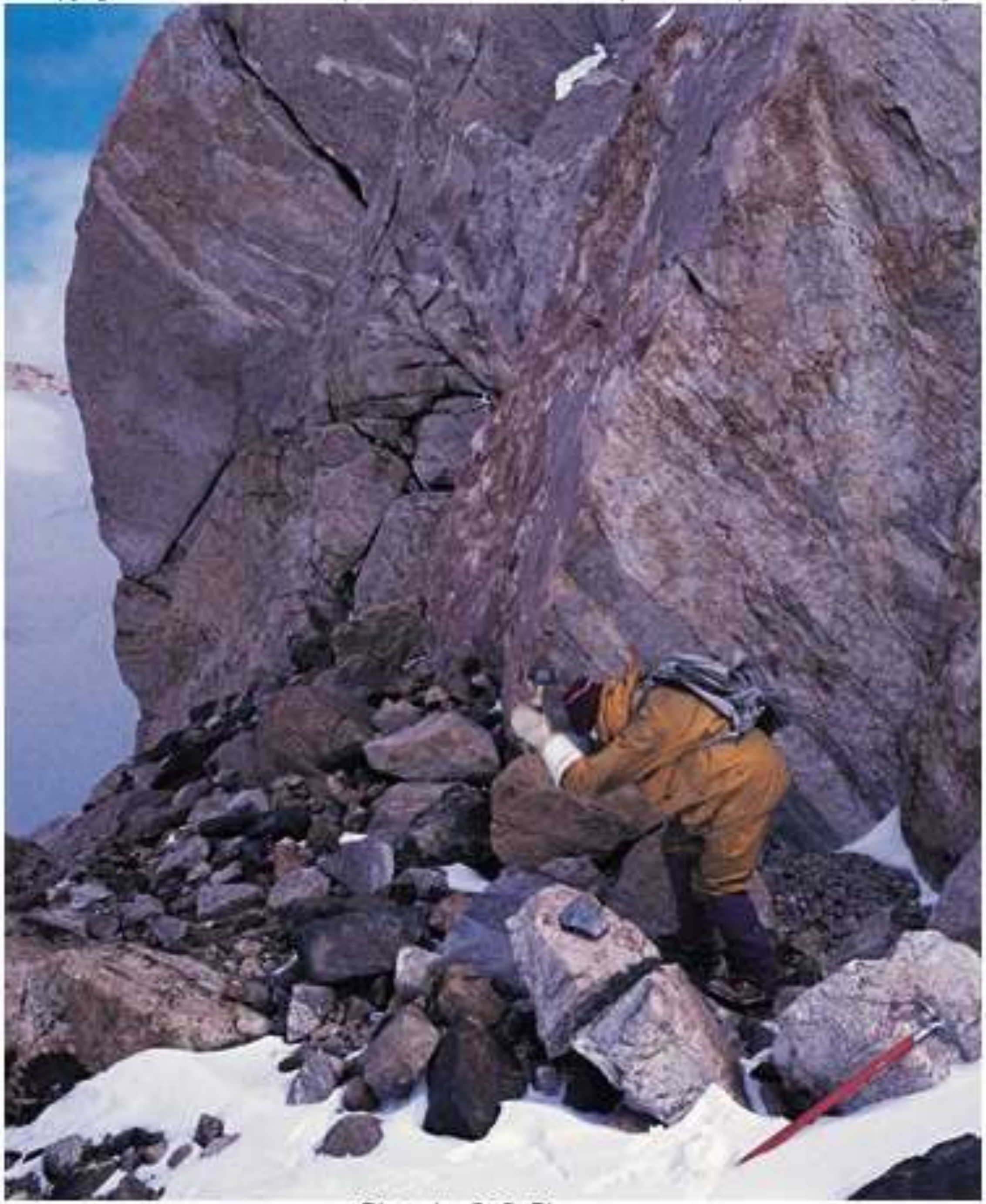
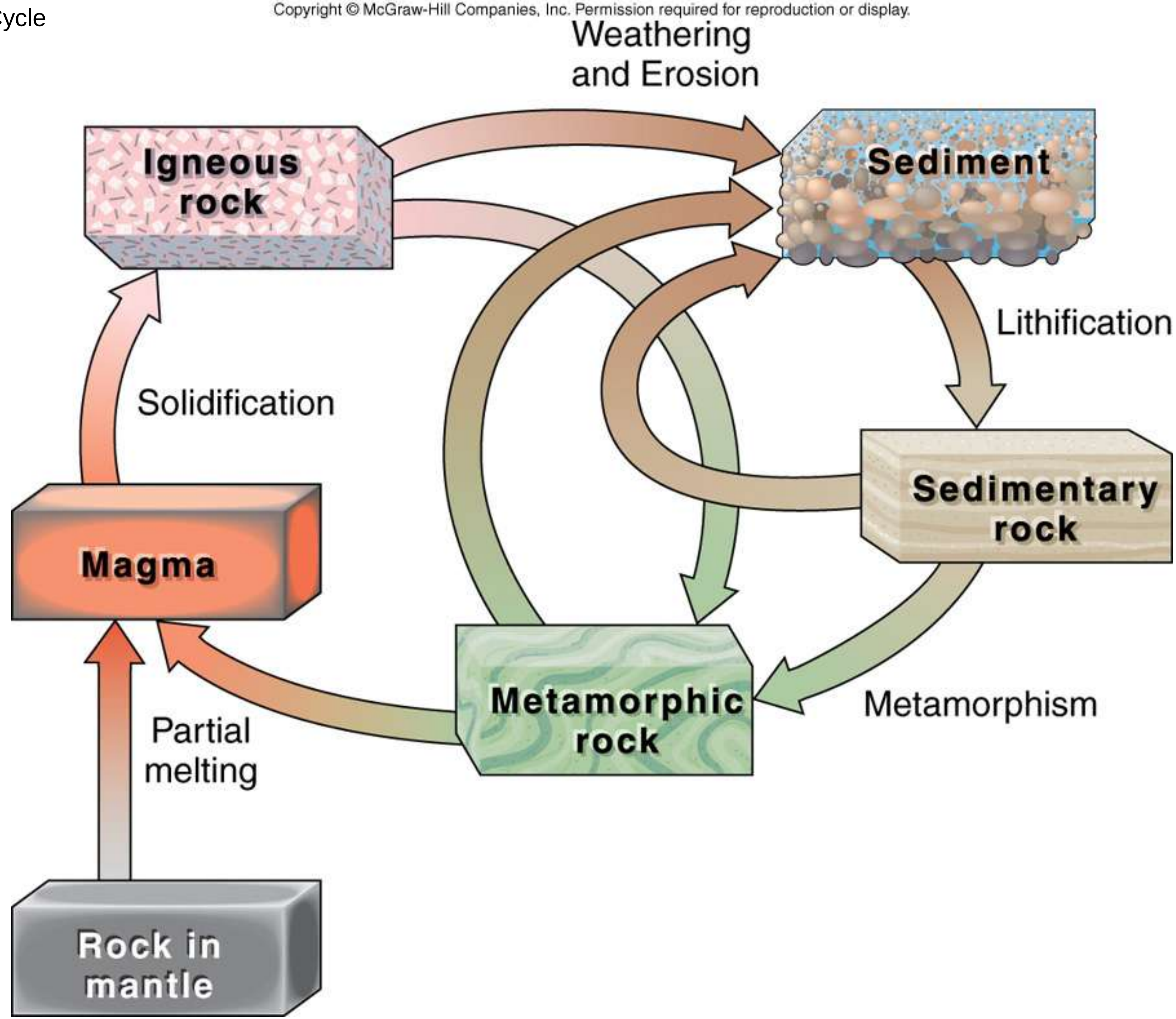


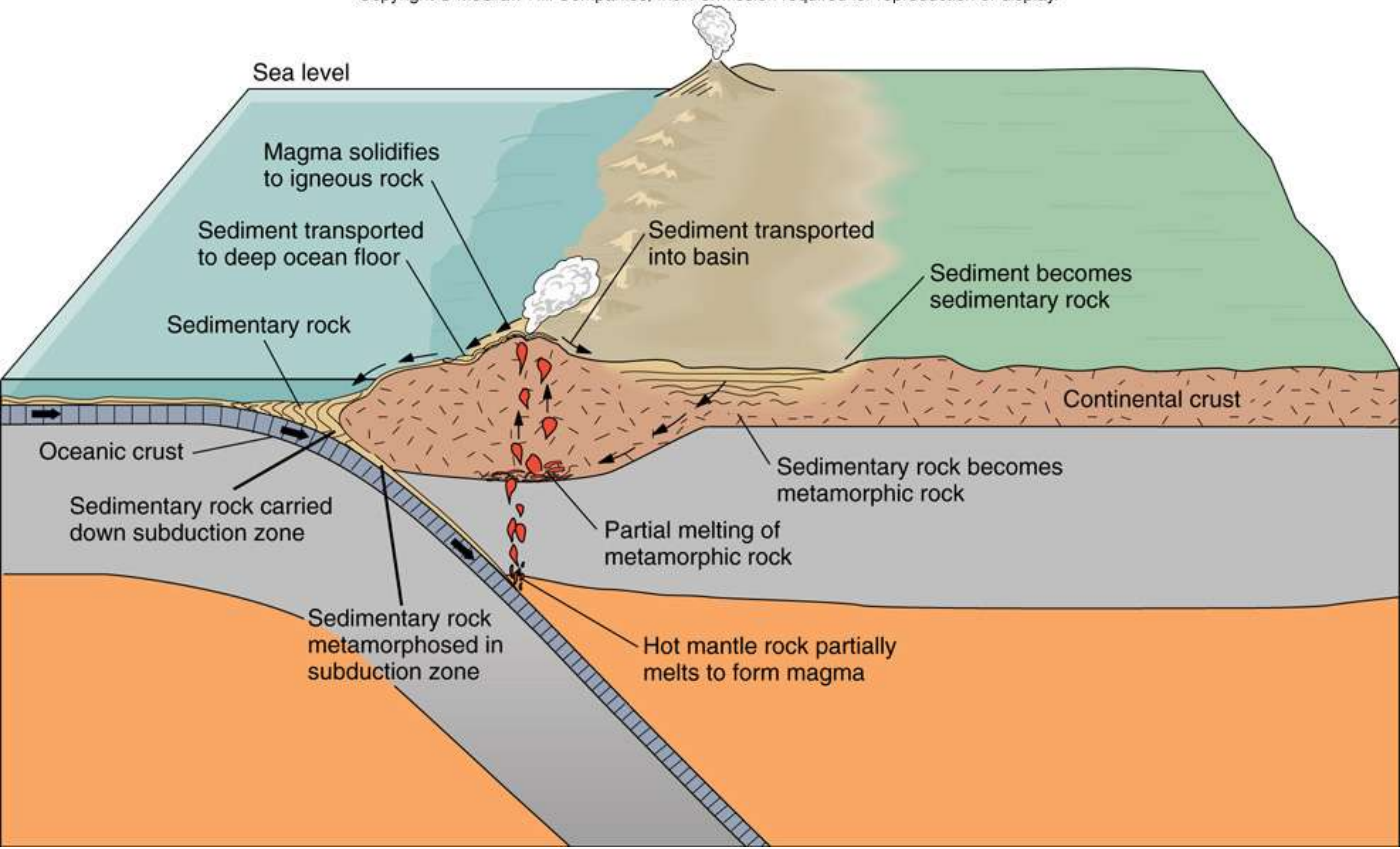
Photo by C. C. Plummer

Rock Cycle



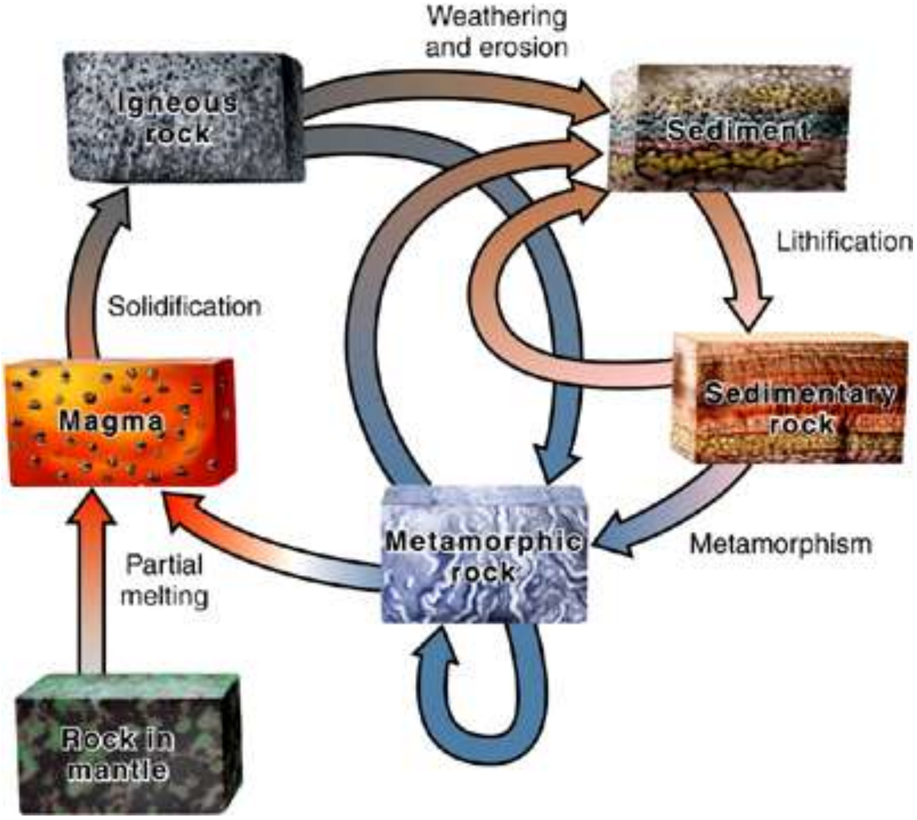
Copyright © McGraw-Hill Companies, Inc. Permission required for reproduction or display.
Weathering and Erosion
Igneous rock
Sediment
Lithification
Solidification
Sedimentary rock
Magma
Metamorphic rock
Metamorphism
Partial melting
Rock in mantle

Plate tectonics, rock cycle



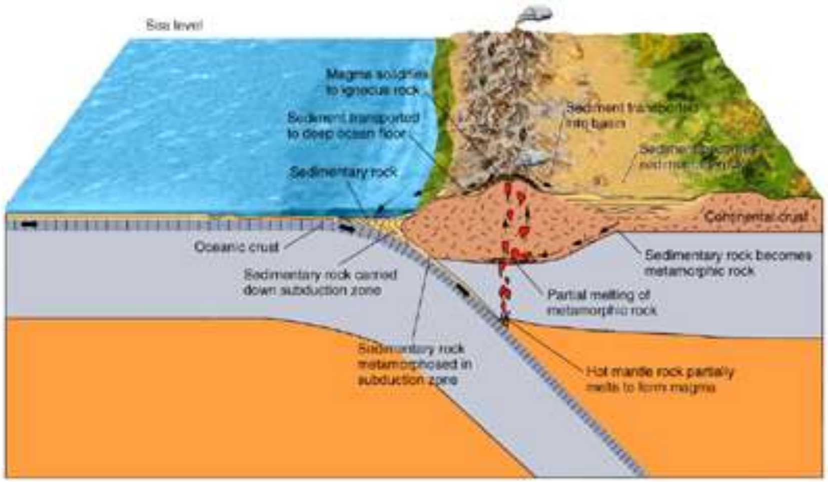
The Rock Cycle

- A *rock* is a naturally formed, consolidated material usually composed of grains of one or more minerals
- The *rock cycle* shows how one type of rocky material gets transformed into another
  - Representation of how rocks are formed, broken down, and processed in the geosphere
  - Arrows indicate possible process paths within the cycle



The Rock Cycle and Plate Tectonics

- *Magma* is created by melting of rock above a subduction zone
- Less dense magma rises and cools to form *igneous rock*
- Igneous rock exposed at surface gets weathered into *sediment*
- Sediments transported to low areas, buried and hardened into *sedimentary rock*
- Sedimentary rock heated and squeezed at depth to form *metamorphic rock*
- Metamorphic rock may heat up and melt to form *magma*

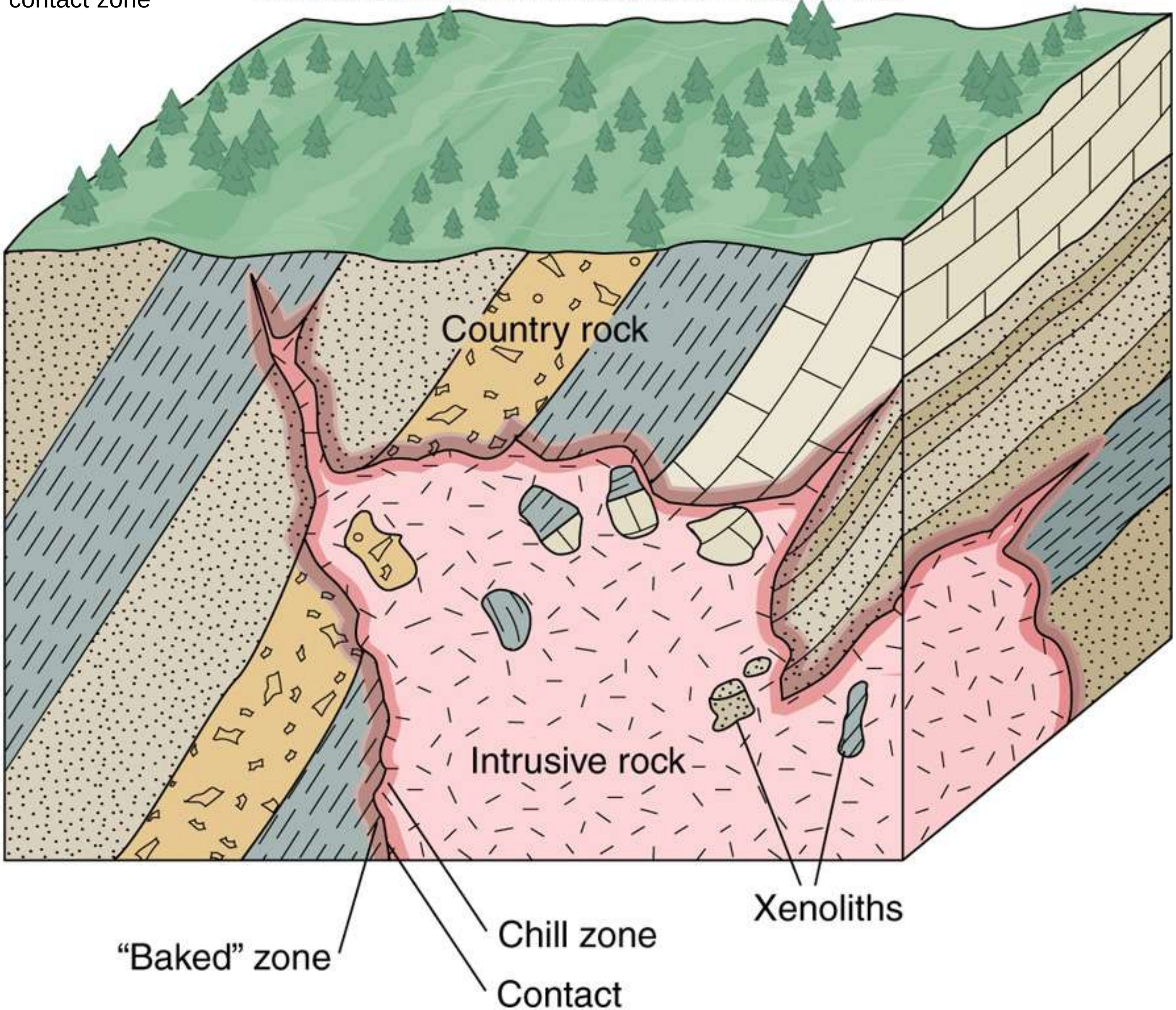


Convergent plate boundary

Granite intruding shale

Photo by Kay Kepler

Intrusion/ contact zone



Igneous Rocks

- *Magma* is molten rock
- *Igneous rocks* form when magma cools and solidifies
  - *Intrusive* igneous rocks form when magma solidifies underground
    - Granite is a common example
  - *Extrusive* igneous rocks form when magma solidifies at the Earth's surface (lava)
    - Basalt is a common example

Granite

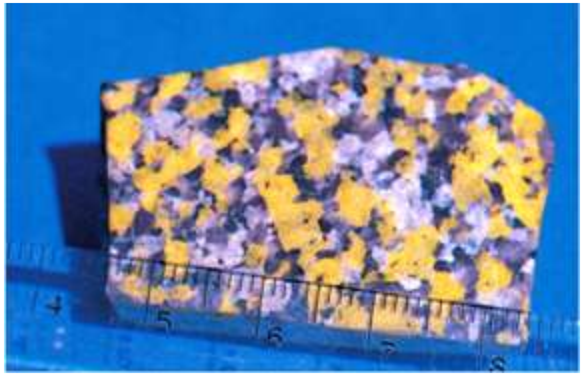
Basalt

Igneous Rock Identification

- Igneous rock names are based on *texture* (grain size) and mineralogic *composition*
- *Textural classification*
  - *Plutonic* rocks (gabbro-diorite-granite) are coarse-grained and cooled slowly at depth
  - *Volcanic* rocks (basalt-andesite-rhyolite) are typically fine-grained and cooled rapidly at the Earth's surface
- *Compositional classification*
  - *Mafic* rocks (gabbro-basalt) contain abundant dark-colored ferromagnesian minerals
  - *Intermediate* rocks (diorite-andesite) contain roughly equal amounts of dark- and light-colored minerals
  - *Felsic* rocks (granite-rhyolite) contain abundant light-colored minerals

Igneous Rock Textures

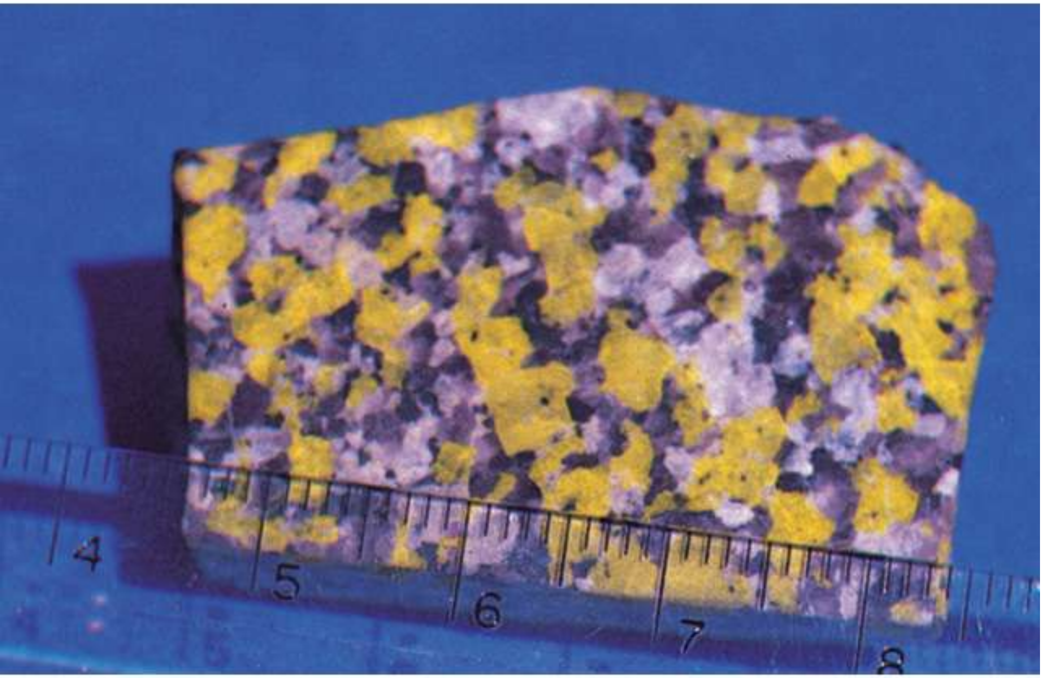
- *Texture* refers to the size, shape and arrangement of grains or other constituents within a rock
- Texture of igneous rocks is primarily controlled by *cooling rate*
- Extrusive igneous rocks cool quickly at or near Earth's surface and are typically *fine-grained* (most crystals <1 mm)
- Intrusive igneous rocks cool slowly deep beneath Earth's surface and are typically *coarse-grained* (most crystals >1 mm)



Coarse-grained igneous rock

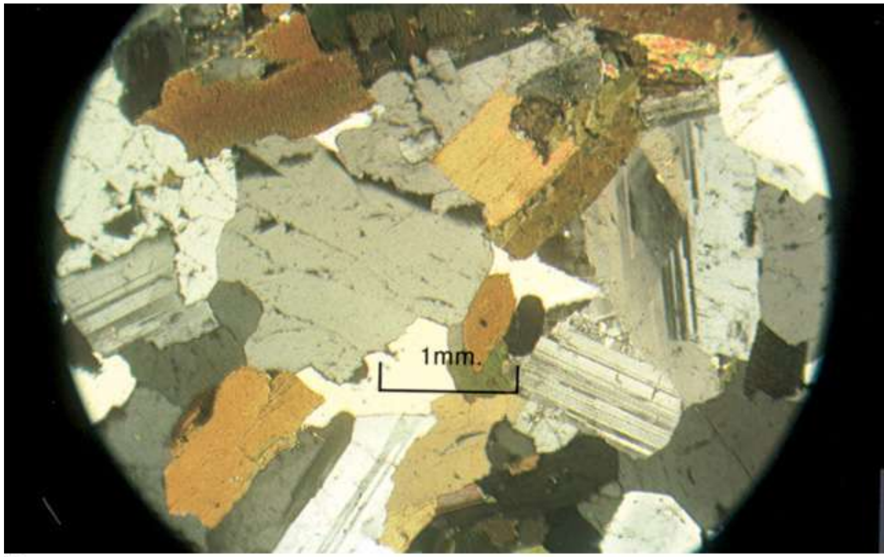
Fine-grained igneous rock

Phaneritic – coarse grained - plutonic



A

Photo by C. C. Plummer

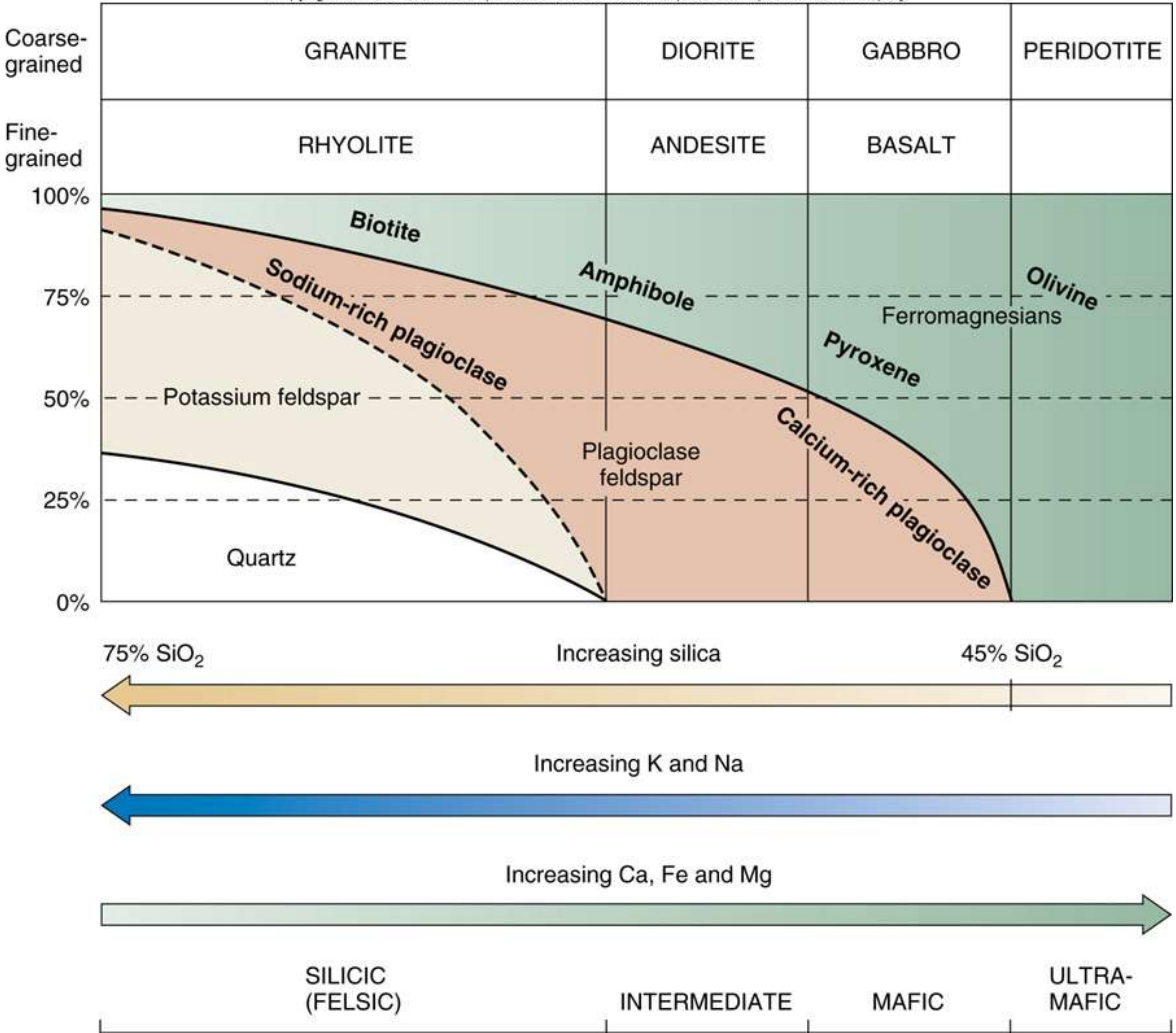


B

Photo by C. C. Plummer

Igneous Rock Identification

i.d. chart



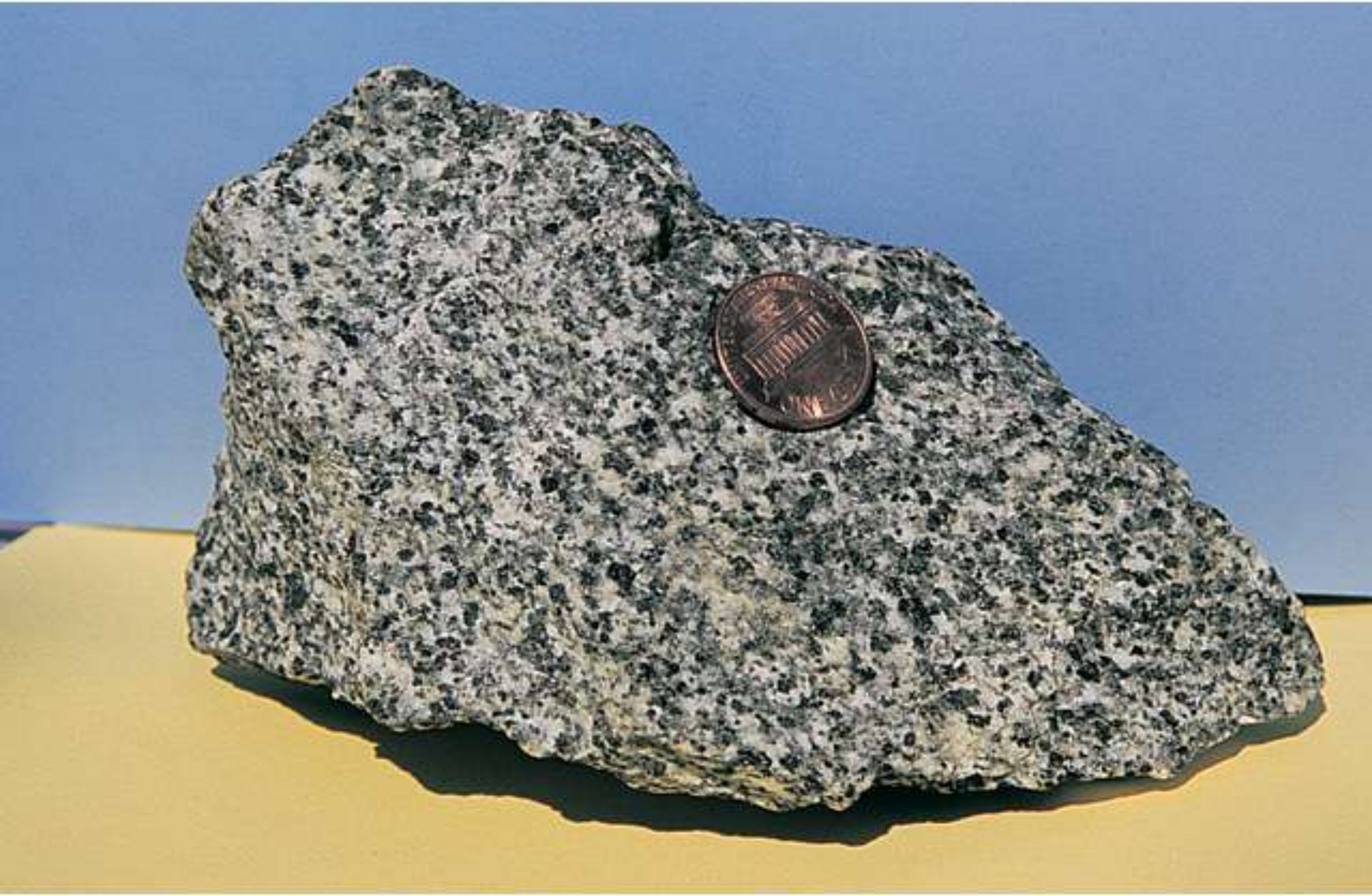
Coarse-grained
GRANITE
DIORITE
GABBRO
PERIDOTITE
Fine-grained
RHYOLITE
ANDESITE
BASALT
100%
75%
50%
25%
0%
Biotite
Amphibole
Olivine
Ferromagnesians
Sodium-rich plagioclase
Pyroxene
Potassium feldspar
Plagioclase feldspar
Calcium-rich plagioclase
Quartz
75% SiO_2
Increasing silica
45% SiO_2
Increasing K and Na
Increasing Ca, Fe and Mg
SILICIC (FELSIC)
INTERMEDIATE
MAFIC
ULTRA-MAFIC

granite

Granite

Photo by C. C. Plummer

diorite



Diorite

Photo by C. C. Plummer

gabbro

Gabbro

Photo by Larry Davis

Fig. 03.07d

Ryolite

Photo by C. C. Plummer

Fig. 03.07e

Andesite (porphyritic)

Photo by C. C. Plummer

Fig. 03.07f

Basalt

Photo by C. C. Plummer

Igneous Rock Identification

granite

rhyolite

diorite

andesite

gabbro

basalt

Igneous rock id table

Table 3.1 **Identification of Igneous Rocks**

Coarse-Grained	Granite	Diorite	Gabbro	Peridotite
Fine-Grained	Rhyolite	Andesite	Basalt	—
Mineral Content	Quartz, feldspars (white, light gray, or pink). Minor ferromagnesian minerals.	Feldspars (white or gray) and about 35–50% ferromagnesian minerals. No quartz.	Predominance of ferromagnesian minerals. Rest of rock is plagioclase feldspar (medium to dark gray).	Entirely ferromagnesian minerals (olivine and pyroxene).
Color of Rock (most commonly)	Light-colored	Medium-gray or medium-green	Dark gray to black	Green to black

Special Igneous Textures

- A *pegmatite* is an extremely coarse-grained igneous rock (most crystals >5 cm) formed when magma cools *very slowly* at depth

- A *glassy* texture contains no crystals at all, and is formed by extremely rapid cooling

- A *porphyritic* texture includes two distinct crystal sizes, with the larger having formed first during slow cooling underground and the small forming during more rapid cooling at the Earth's surface

Pegmatitic igneous rock

glassy

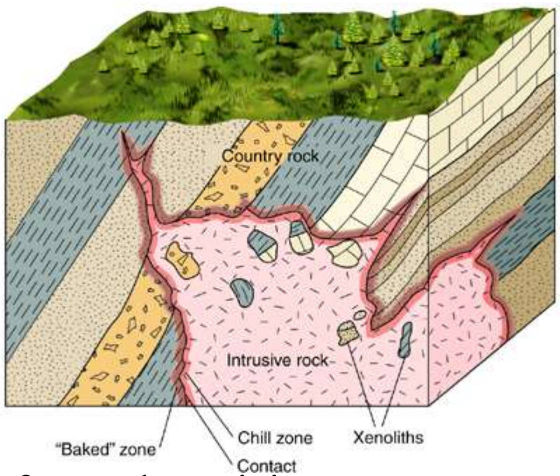
Porphyritic igneous rock

pegmatite

Photo by C. C. Plummer

Intrusive Rock Bodies

- Intrusive rocks exist in bodies or structures that penetrate or cut through pre-existing *country rock*
- *Intrusive bodies* are given names based on their size, shape and relationship to country rock
  - Shallow intrusions
    - Form <2 km beneath Earth's surface
    - Chill and solidify fairly quickly in cool country rock
    - Generally composed of fine-grained rocks
  - Deep intrusions: *Plutons*
    - Form at considerable depth beneath Earth's surface when rising blobs of magma (*diapirs*) get trapped within the crust
    - Crystallize slowly in warm country rock
    - Generally composed of coarse-grained rocks



Intrusive Rock Bodies

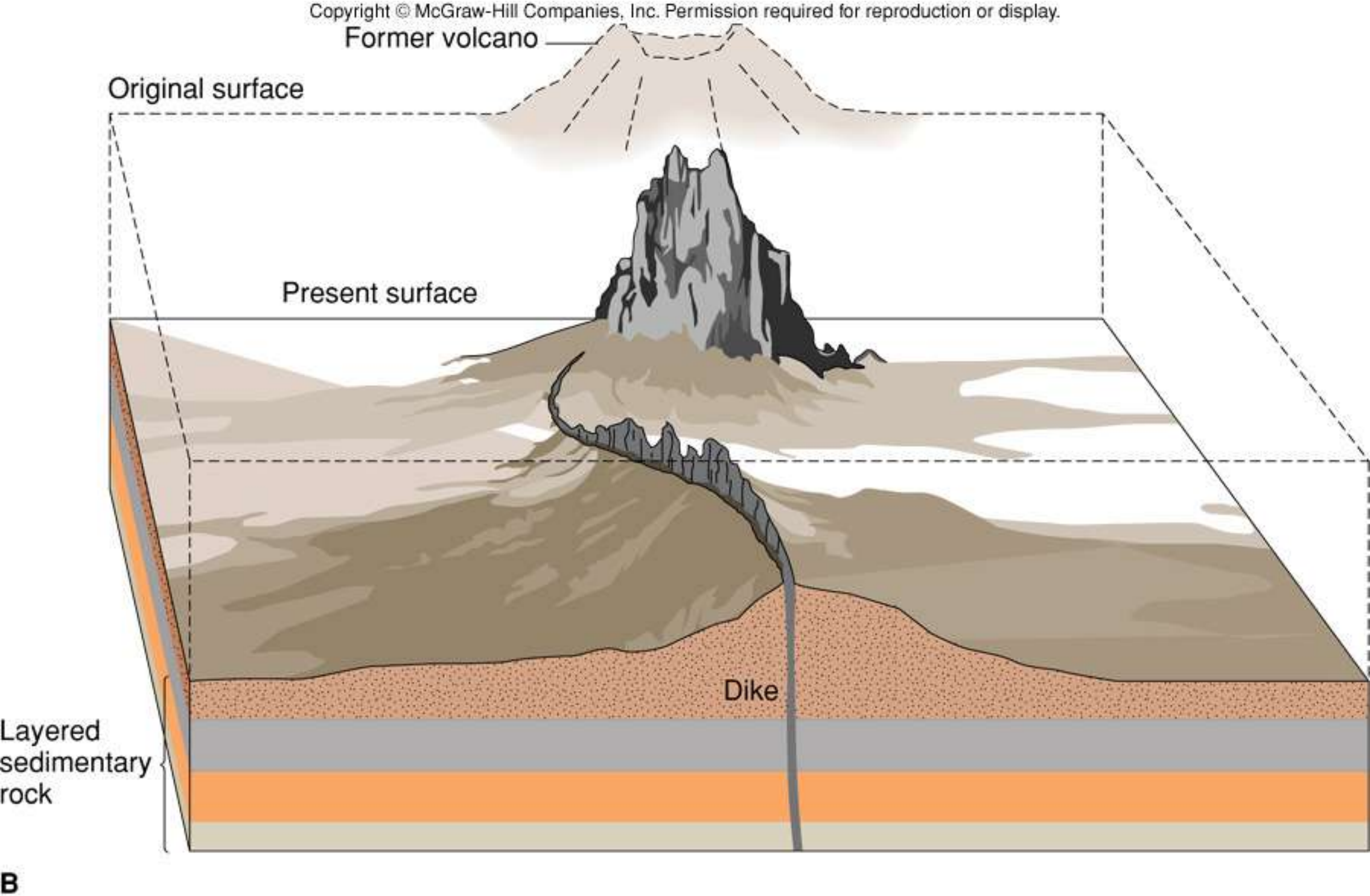
- *Volcanic necks*
  - Shallow intrusion formed when magma solidifies in throat of volcano
- *Dikes*
  - Tabular intrusive structure that cuts across any layering in country rock
- *Sills*
  - Tabular intrusive structure that parallels layering in country rock
- *Plutons*
  - Large, blob-shaped intrusive body formed of coarse-grained igneous rock, commonly granitic
  - Small plutons (exposed over <100 km^2) are called *stocks*, large plutons (exposed over >100 km^2) are called *batholiths*

Light-colored dikes

Basaltic sill

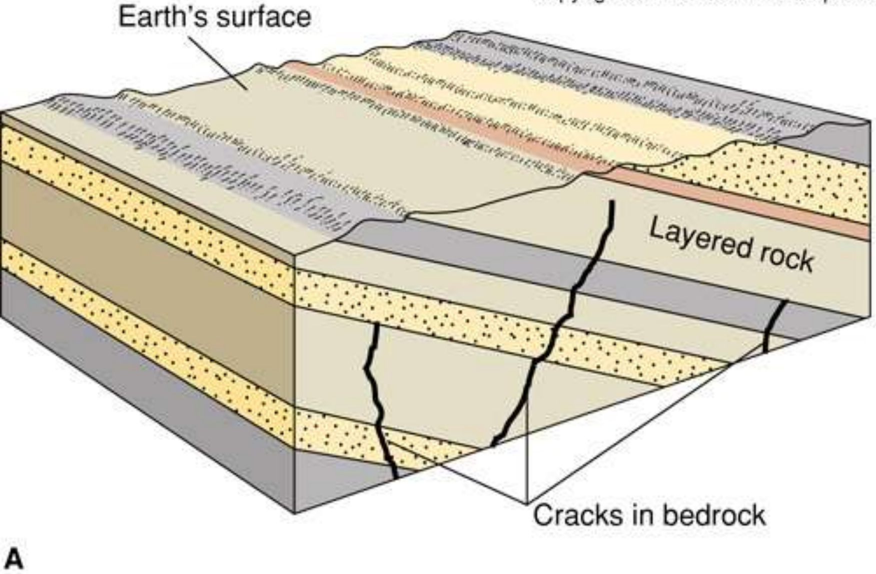
Sierra Nevada batholith

dikes

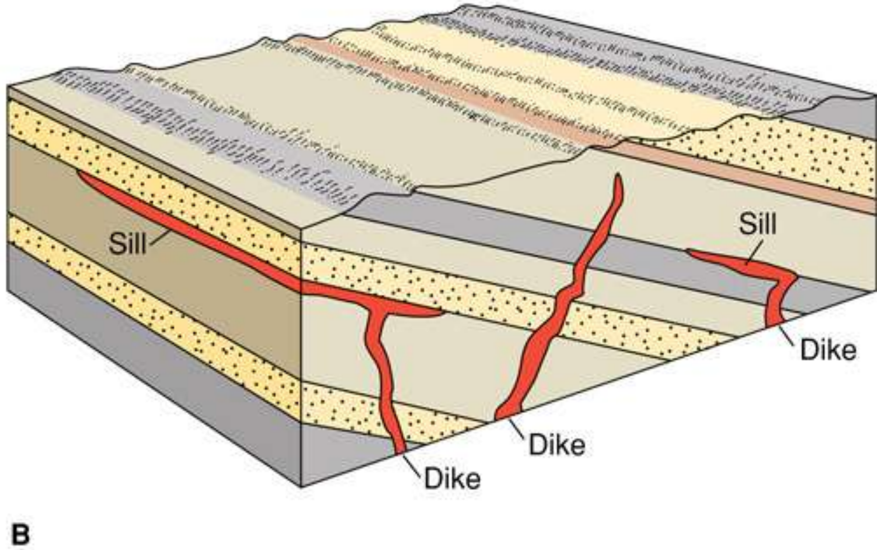


Copyright © McGraw-Hill Companies, Inc. Permission required for reproduction or display.
Former volcano
Original surface
Present surface
Dike
Layered sedimentary rock
B

Dikes, sills



Earth's surface
Layered rock
Cracks in bedrock
A



Sill
Sill
Dike
Dike
Dike
B

Dikes, sills, antarctica

Photo by C. C. Plummer

Igneous Rock Chemistry

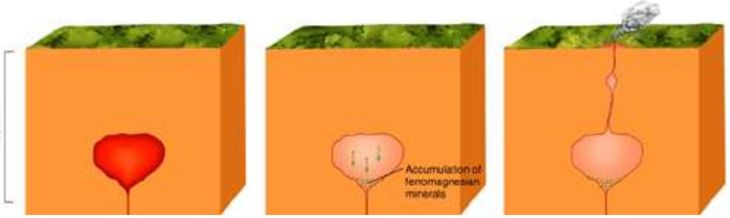
- Rock chemistry, particularly *silica* (SiO_2) content, determines mineral content and general color of igneous rocks
  - *Mafic* rocks have ~50% silica, by weight, and contain dark-colored minerals that are abundant in iron, magnesium and calcium
    - Intrusive/extrusive mafic rocks - gabbro/basalt
  - *Felsic (silicic)* rocks have >65% silica, by weight, and contain light-colored minerals that are abundant in silica, aluminum, sodium and potassium
    - Intrusive/extrusive felsic rocks - granite/rhyolite
  - *Intermediate* rocks have silica contents between those of mafic and felsic rocks
    - Intrusive/extrusive intermediate rocks - diorite/andesite
  - *Ultramafic* rocks have <45% silica, by weight, and are composed almost entirely of dark-colored ferromagnesian minerals
    - Most common ultramafic rock is peridotite (intrusive)

Lessons from Bowen's

- Large variety of igneous rocks is produced by large variety of *magma compositions*
- *Mafic magmas* will crystallize into *basalt* or *gabbro* if early-formed minerals are not removed from the magma
- *Intermediate magmas* will similarly crystallize into *diorite* or *andesite* if minerals are not removed
- Separation of early-formed ferromagnesian minerals from a magma body increases the silica content of the remaining magma
- Minerals melt in the reverse order of that in which they crystallize from a magma

Magma Evolution

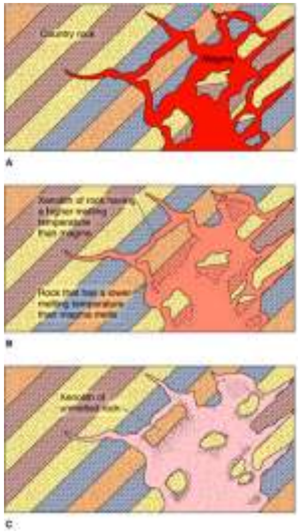
- A change in the composition of a magma body is known as *magma evolution*
- Magma evolution can occur by *differentiation*, *partial melting*, *assi*
  or *magma mixing*

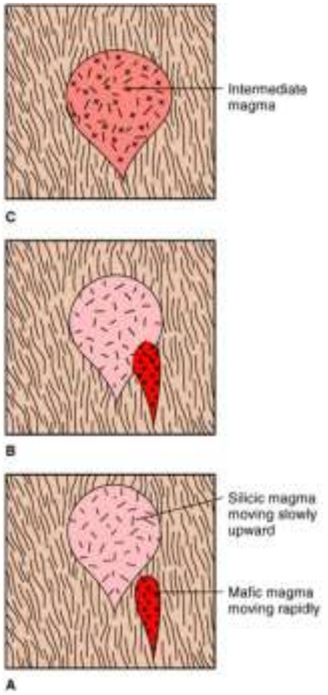


- *Differentiation* involves the changing of magma composition by the removal of denser early-formed ferromagnesian minerals by *crystal settling*
- *Partial melting* produces magmas less mafic than their source rocks, because lower melting point minerals are more felsic in composition

- *Assimilation* occurs when a hot magma melts and incorporates more felsic surrounding country rock

- *Magma mixing* involves the mixing of more and less mafic magmas to produce one of intermediate composition





pluton

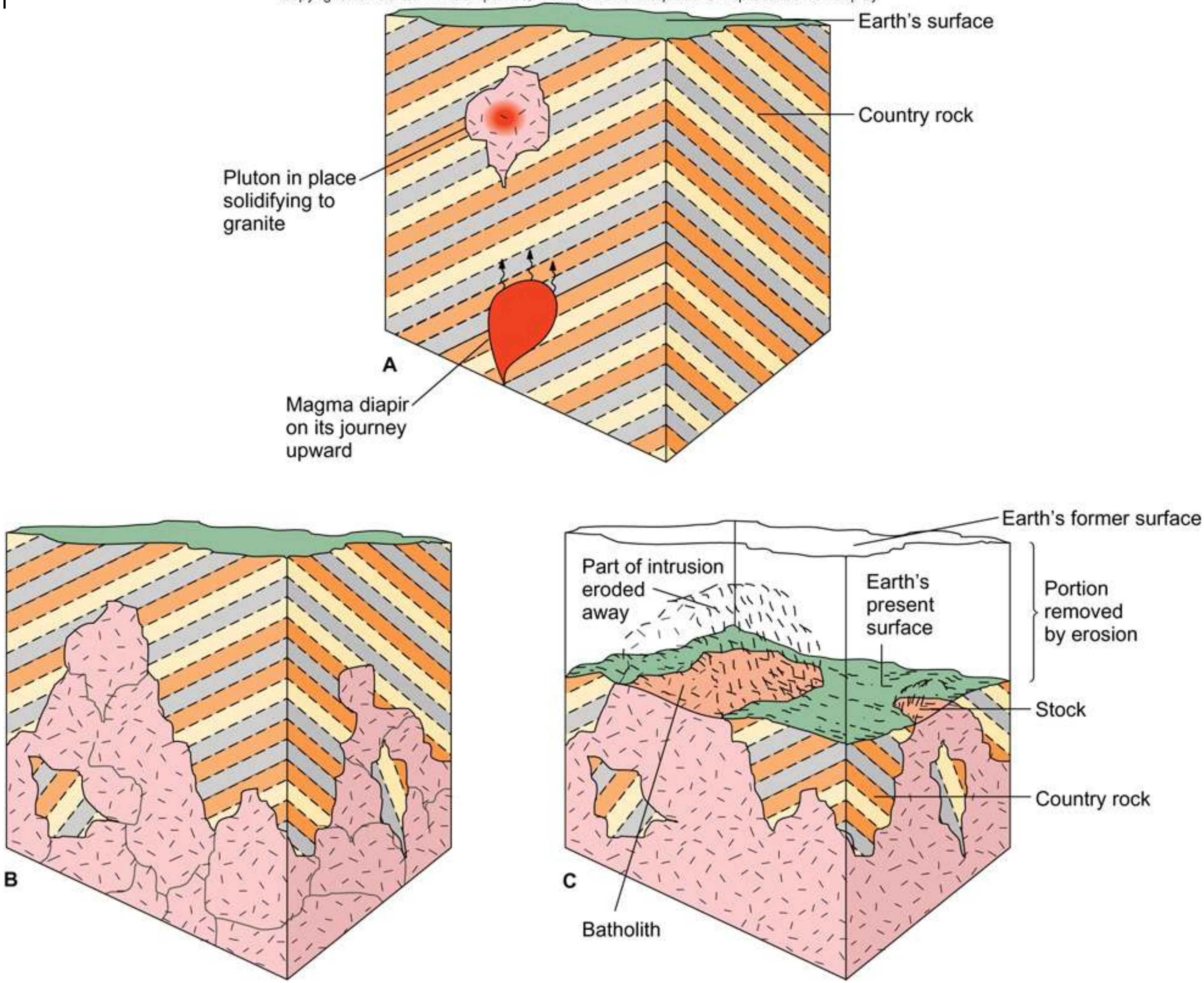

Earth's surface
Country rock
Pluton in place solidifying to granite
A
Magma diapir on its journey upward
B
Earth's former surface
Part of intrusion eroded away
Earth's present surface
Portion removed by erosion
Stock
Country rock
C
Batholith

Fig. 03.13

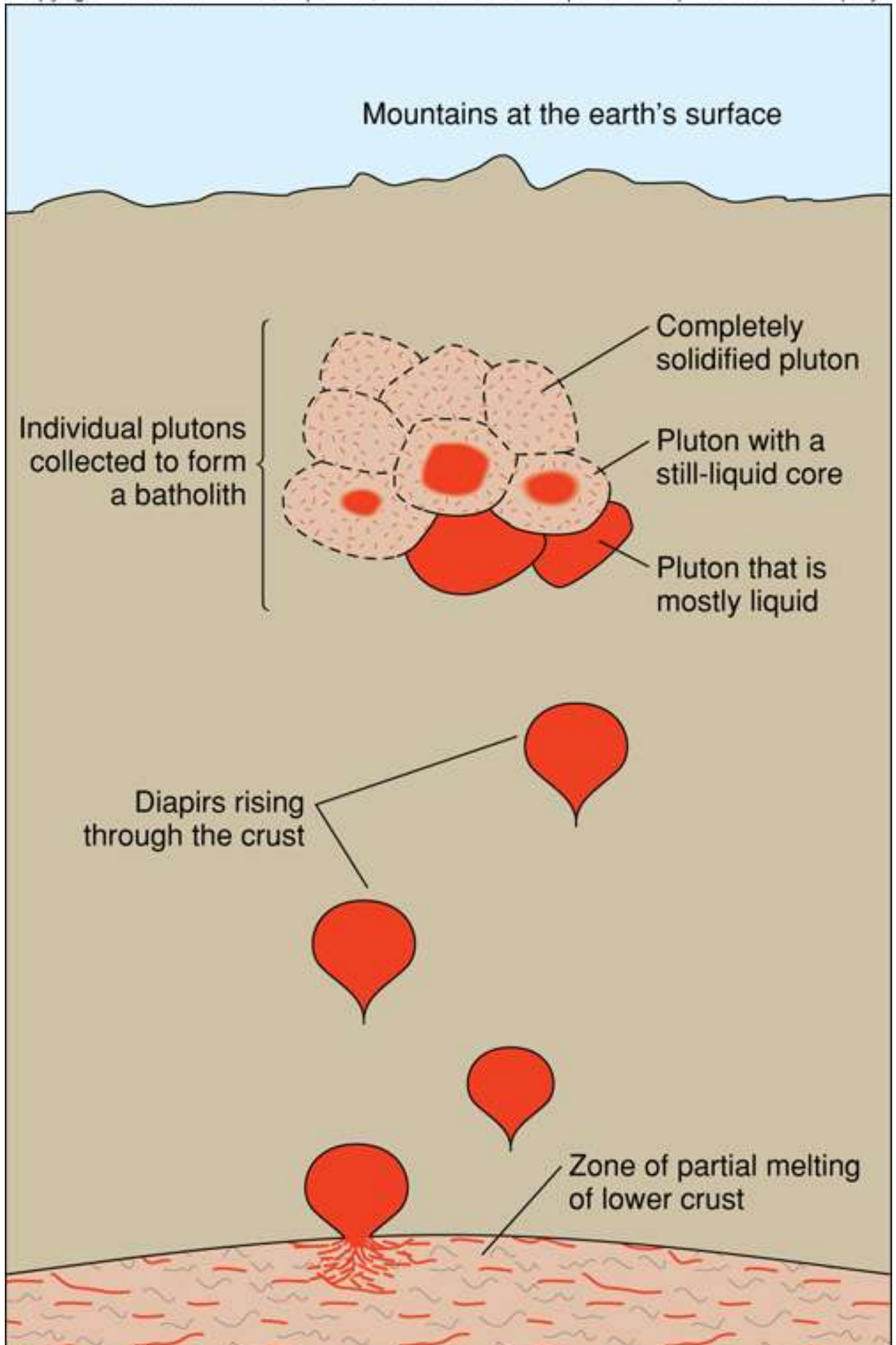

Mountains at the earth's surface
Completely solidified pluton
Individual plutons collected to form a batholith
Pluton with a still-liquid core
Pluton that is mostly liquid
Diapirs rising through the crust
Zone of partial melting of lower crust

Fig. 03.14

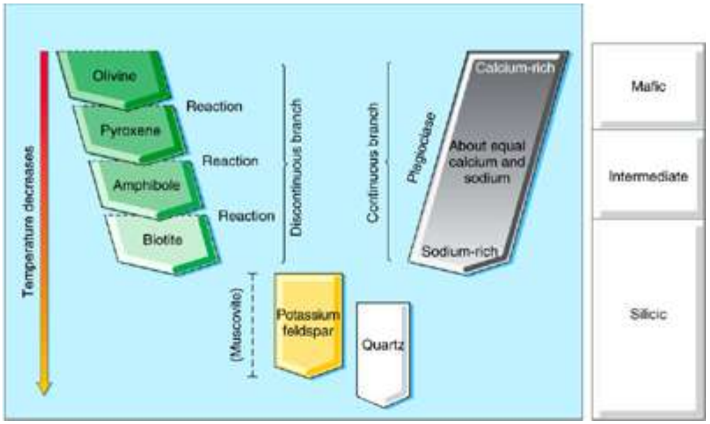
Photo by C. C. Plummer

How Magma Forms

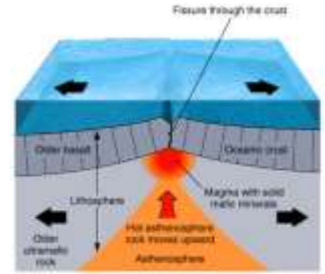
- *Heat from below*
  - Heat upward (by conduction and convection) from the very hot (>5000°C) core through the mantle and crust
- *Heat vs. pressure*
  - Melting point of minerals increases with increasing pressure
  - In the hottest regions within the upper mantle and crust, pressure can be low enough for melting to occur
- *Hot water under pressure*
  - Water becomes increasingly reactive at higher temperatures
  - At sufficient pressures and temperatures, highly reactive water vapor can reduce the melting point of rocks by over 200°C
- *Mineral mixtures*
  - Mixtures of minerals, such as quartz and potassium feldspar, can result in the melting of both at temperatures hundreds of degrees lower than either mineral would melt on its own

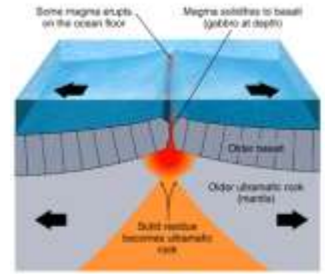
Bowen's Reaction Series

- Minerals crystallize in a predictable order, over a large temperature range
- *Discontinuous branch*
  - Ferromagnesian minerals (olivine, pyroxene, amphibole, biotite) crystallize in sequence with decreasing temperature
  - As one mineral becomes chemically unstable in the remaining magma, another begins to form
- *Continuous branch*
  - Plagioclase feldspar forms with a chemical composition that evolves (from Ca-rich to Na-rich) with decreasing temperature



Igneous Activity and Plate Tectonics





- Igneous activity occurs primarily at or near tectonic plate boundaries
- Mafic igneous rocks are commonly formed at *divergent boundaries*
  - Increased heat flow and decreased overburden pressure produce mafic magmas from partial melting of the asthenosphere
- Intermediate igneous rocks are commonly formed at *convergent boundaries*
  - Partial melting of basaltic oceanic crust produces intermediate magmas

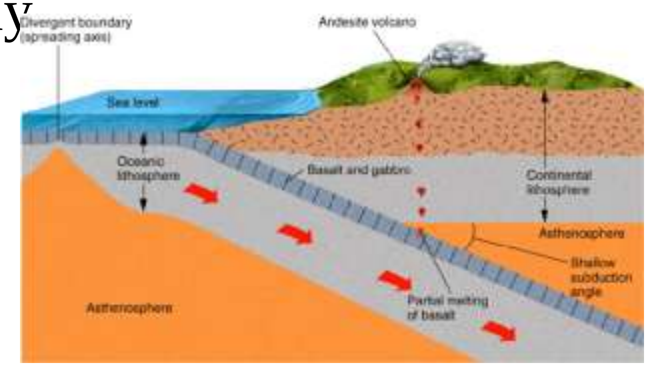
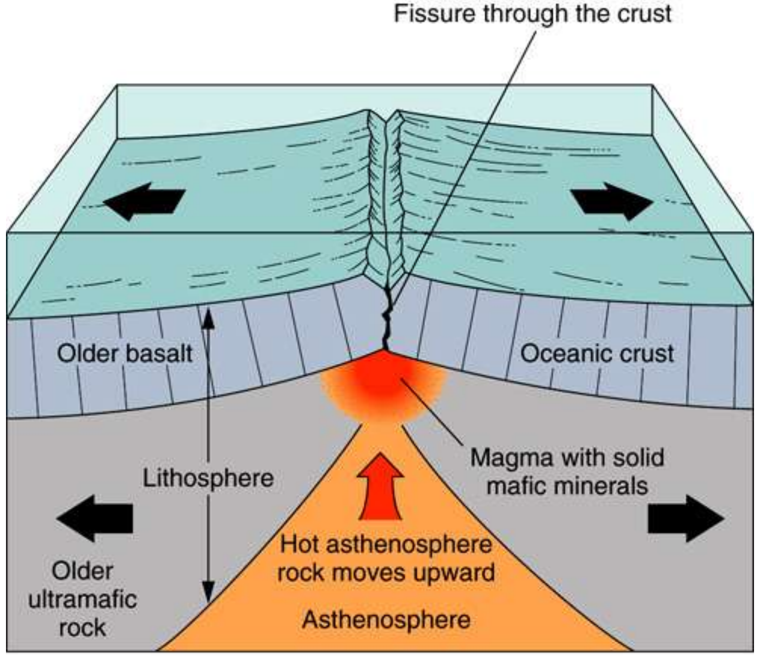
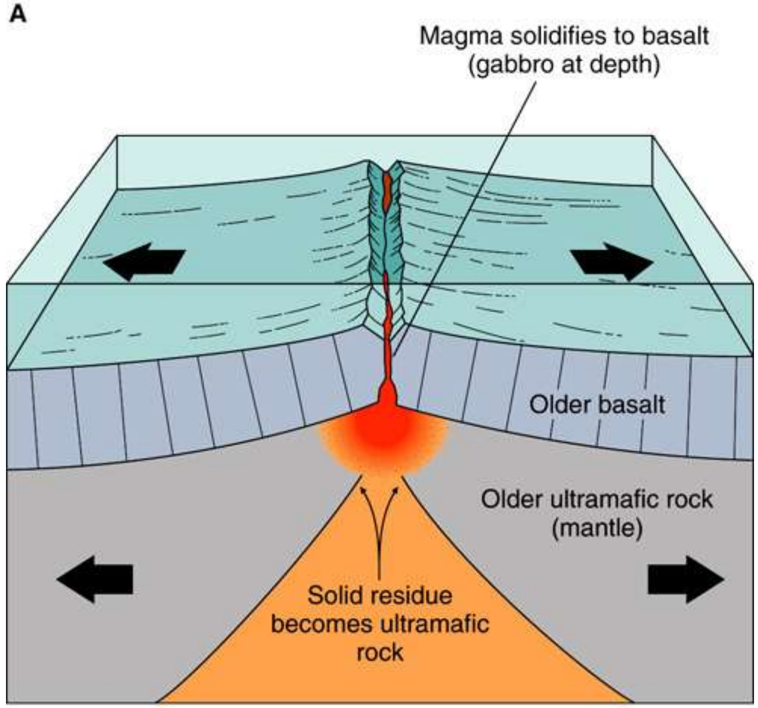


Fig. 03.22


Fissure through the crust
Older basalt
Oceanic crust
Lithosphere
Magma with solid mafic minerals
Hot asthenosphere rock moves upward
Older ultramafic rock
Asthenosphere

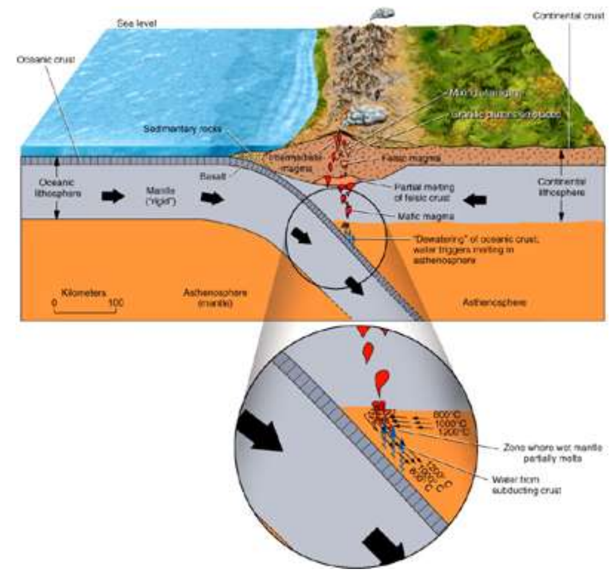
A


Magma solidifies to basalt (gabbro at depth)
Older basalt
Older ultramafic rock (mantle)
Solid residue becomes ultramafic rock

B

Igneous Activity and Plate Tectonics

- Felsic igneous rocks are commonly formed adjacent to *convergent boundaries*
  - Hot rising magma causes partial melting of the granitic continental crust
- *Intraplate volcanism*
  - Rising mantle plumes can produce localized hotspots and volcanoes when they produce magmas that rise through oceanic or continental crust
  - Hawaii is an example



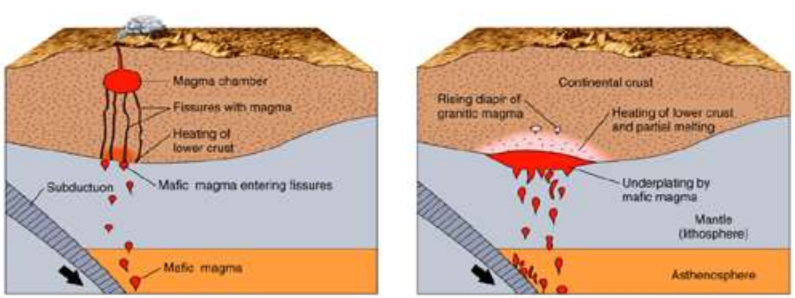


Fig. 03.15

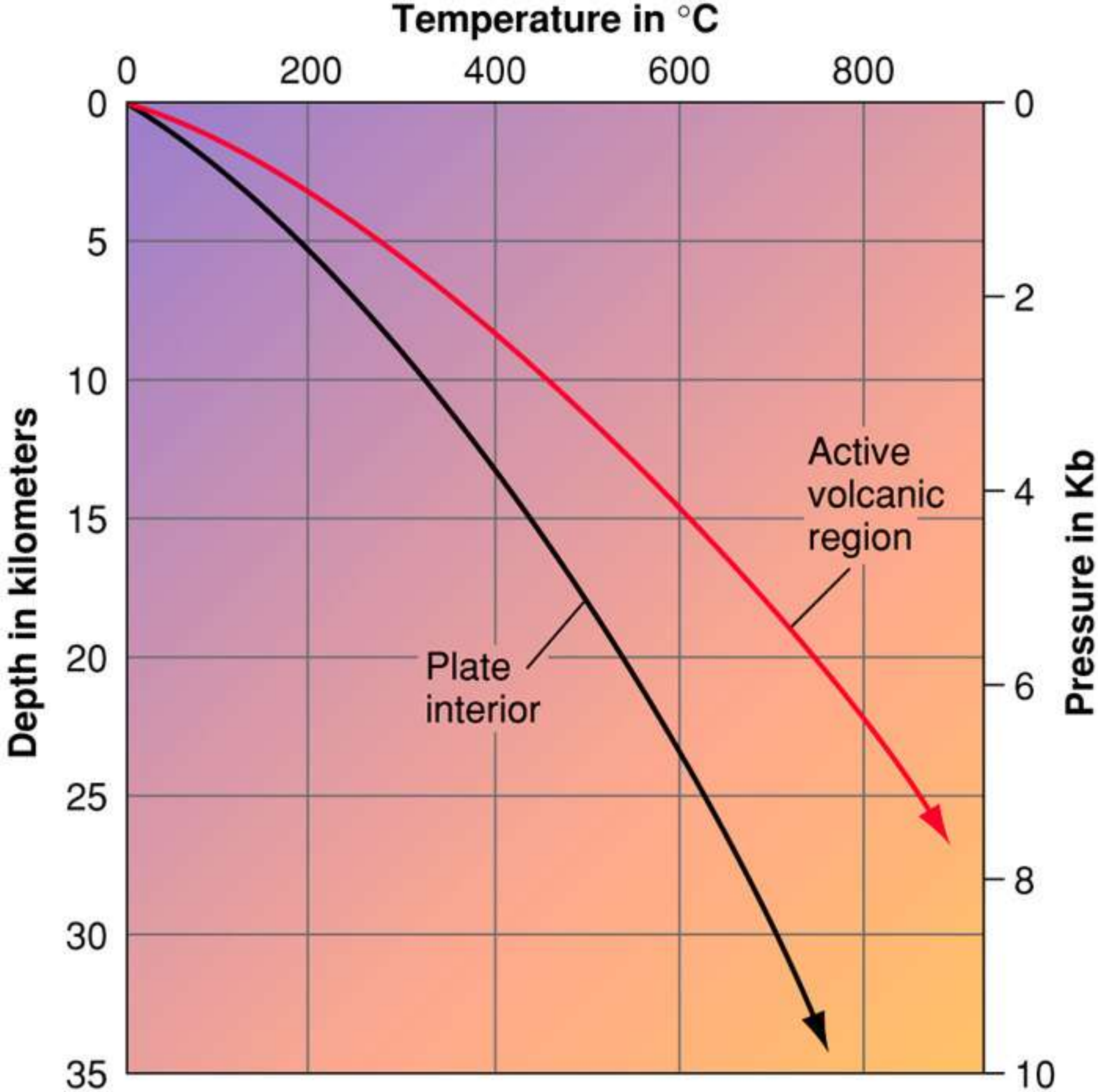
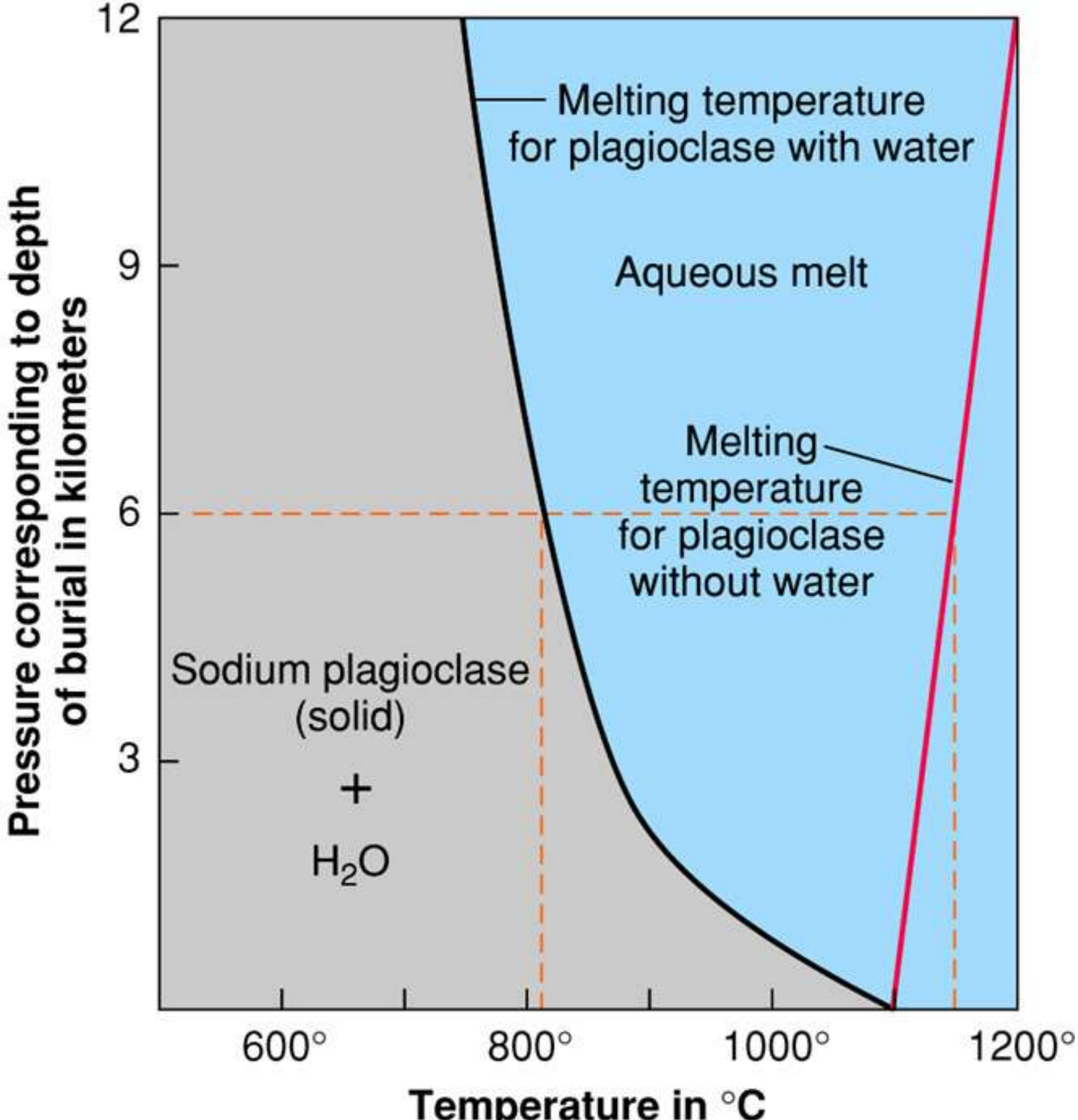

Temperature in °C
0
200
400
600
800
Depth in kilometers
0
5
10
15
20
25
30
35
Pressure in Kb
0
2
4
6
8
10
Active volcanic region
Plate interior

Fig. 03.16



12
9
6
3
Pressure corresponding to depth of burial in kilometers
Melting temperature for plagioclase with water
Aqueous melt
Melting temperature for plagioclase without water
Sodium plagioclase (solid) + H_2O
600°
800°
1000°
1200°
Temperature in °C

Fig. 03.17

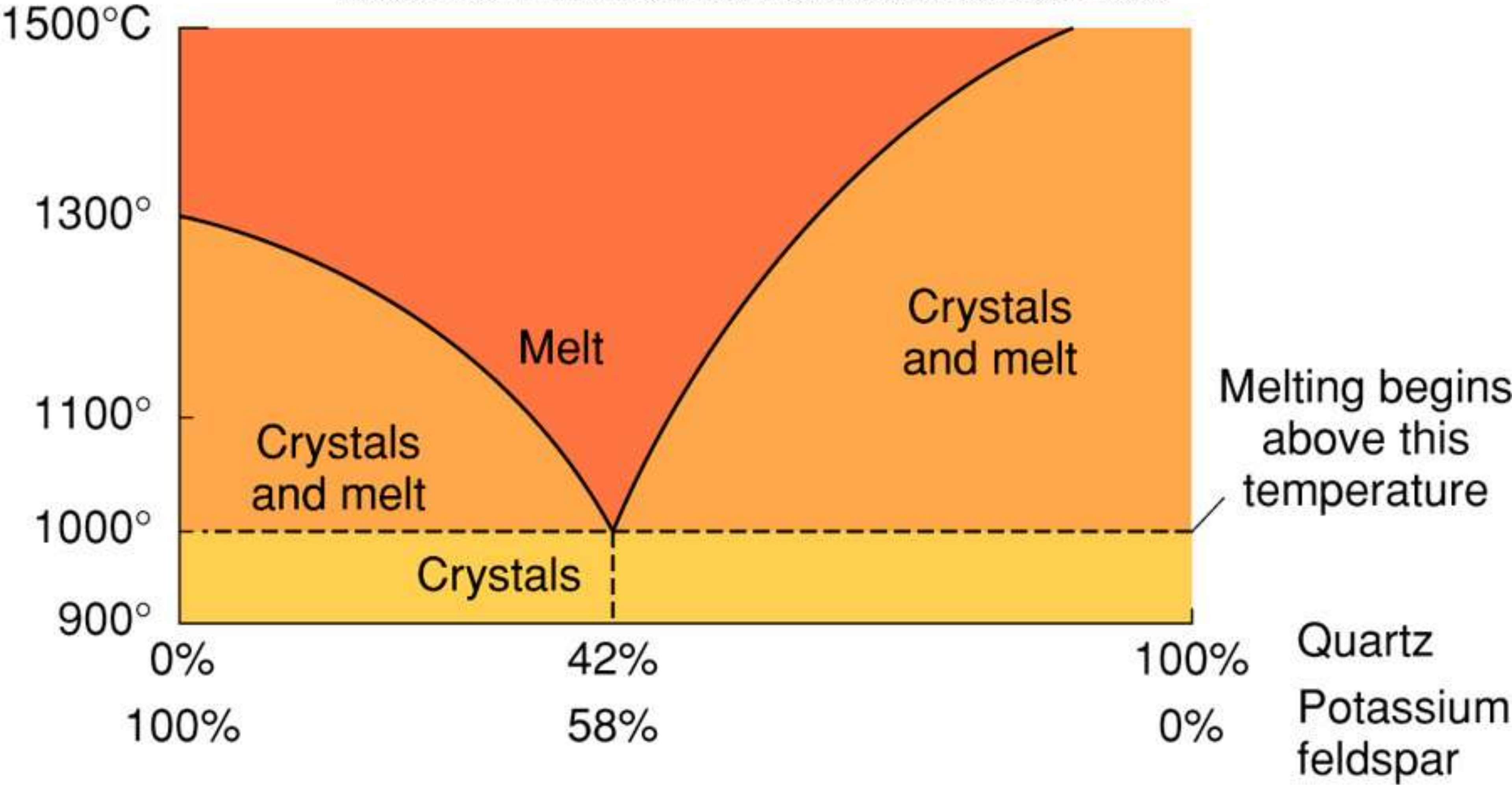

1500°C
1300°
1100°
1000°
900°
Melt
Crystals and melt
Crystals and melt
Crystals
Melting begins above this temperature
0%
42%
100%
Quartz
100%
58%
0%
Potassium feldspar

Fig. 03.18

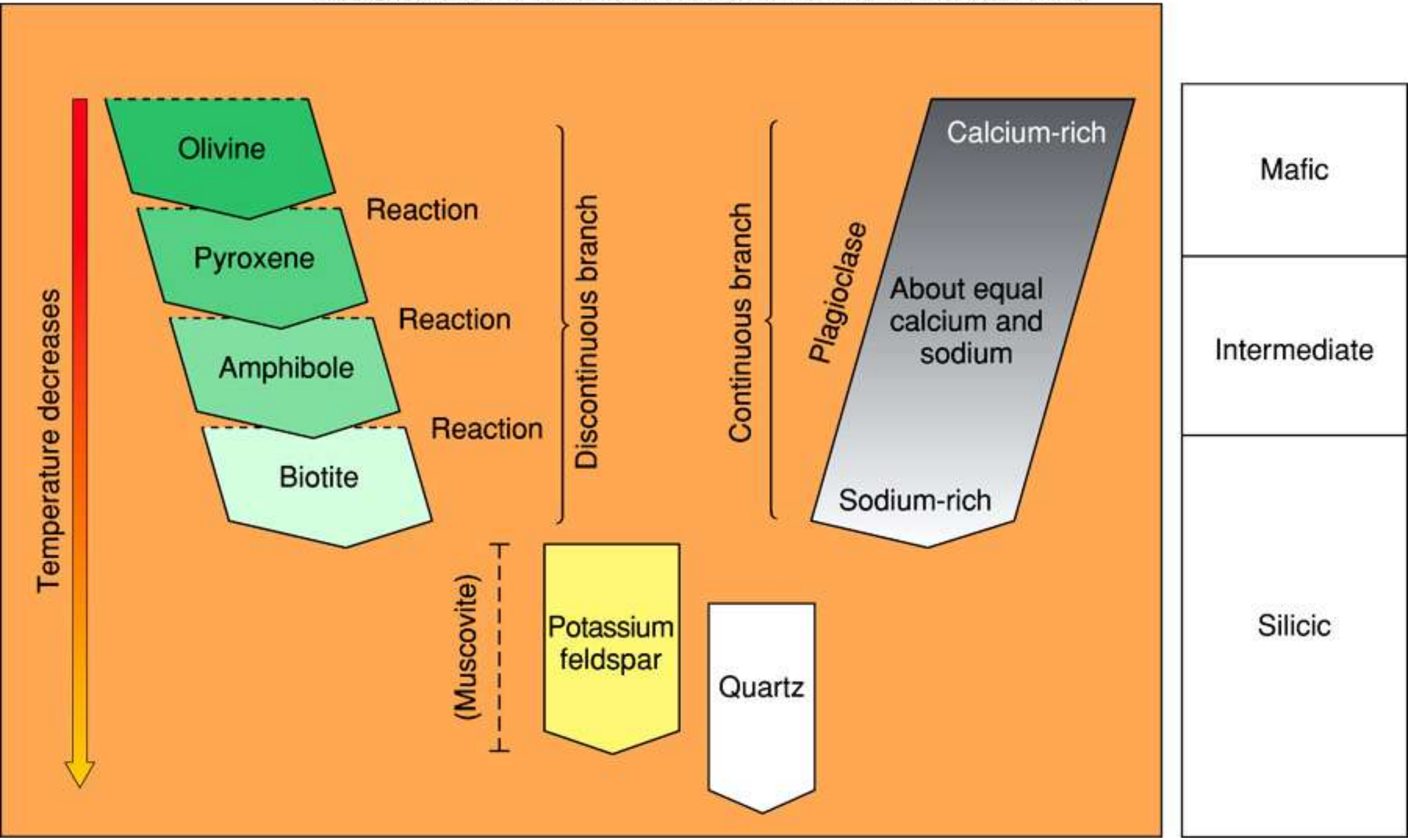

Temperature decreases
Olivine
Reaction
Pyroxene
Reaction
Amphibole
Reaction
Biotite
Discontinuous branch
Continuous branch
Plagioclase
Calcium-rich
About equal calcium and sodium
Sodium-rich
(Muscovite)
Potassium feldspar
Quartz
Mafic
Intermediate
Silicic

Fig. 03.20

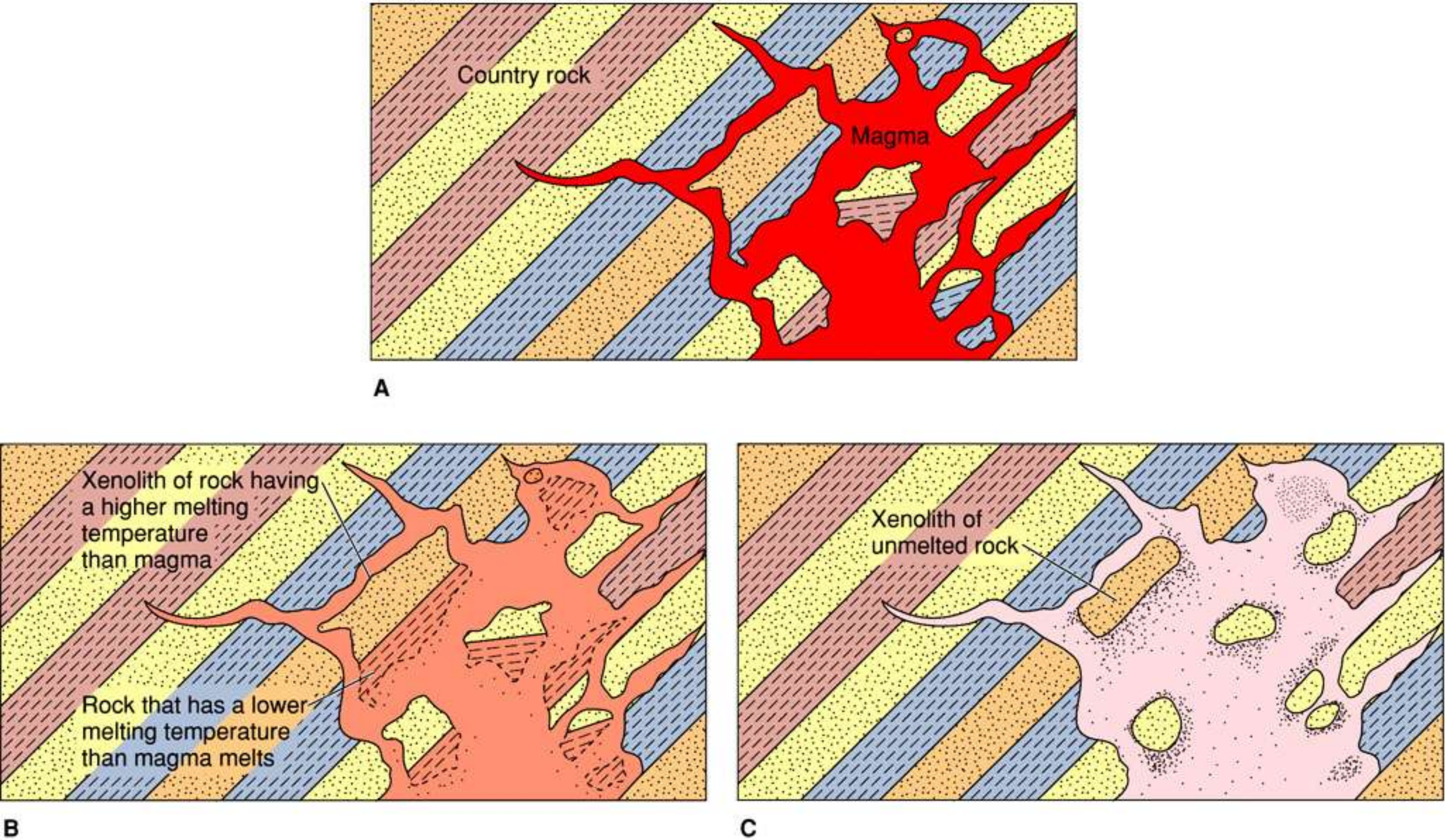

Country rock
Magma
A
Xenolith of rock having a higher melting temperature than magma
Rock that has a lower melting temperature than magma melts
B
Xenolith of unmelted rock
C

Fig. 03.23

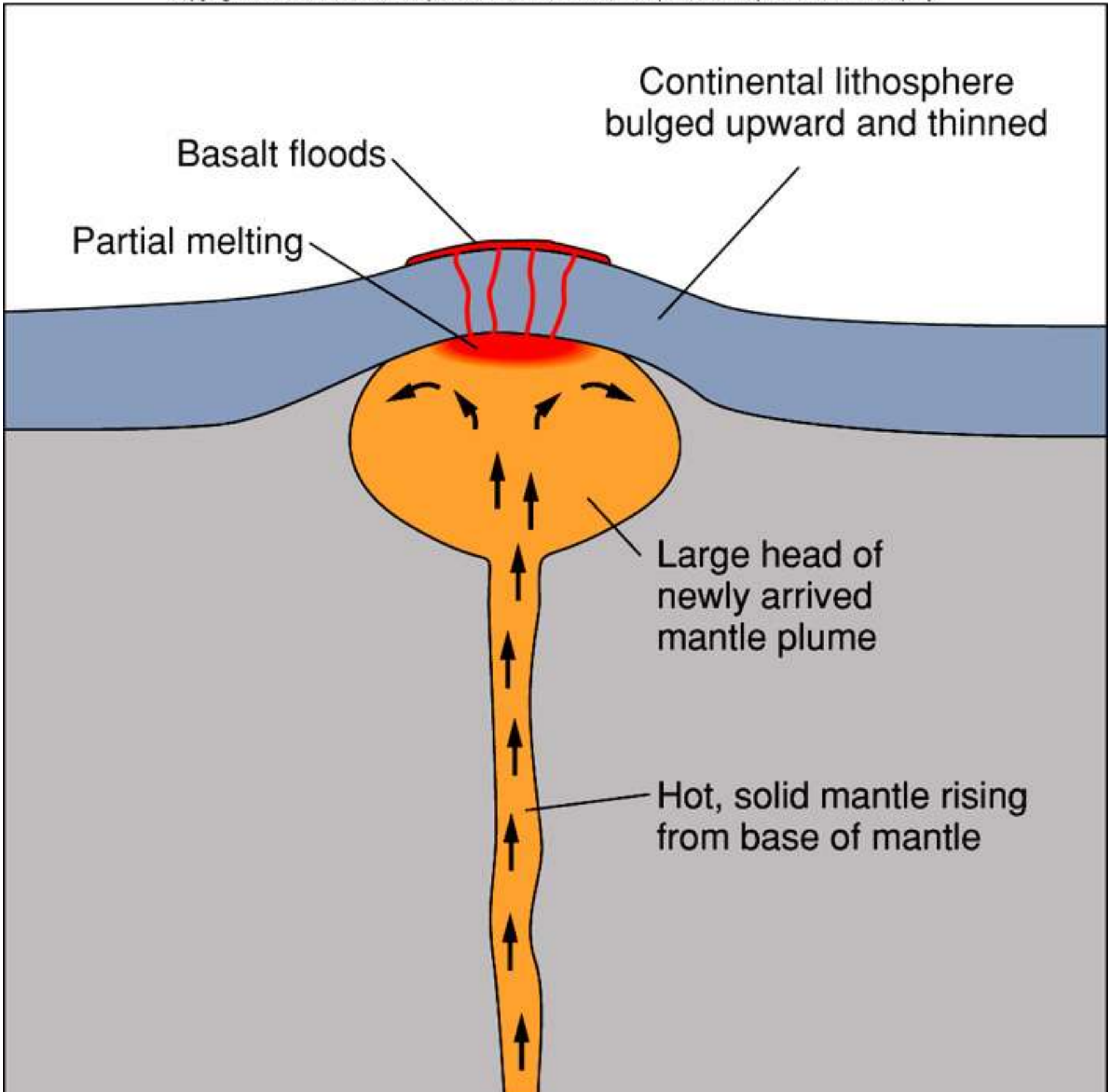
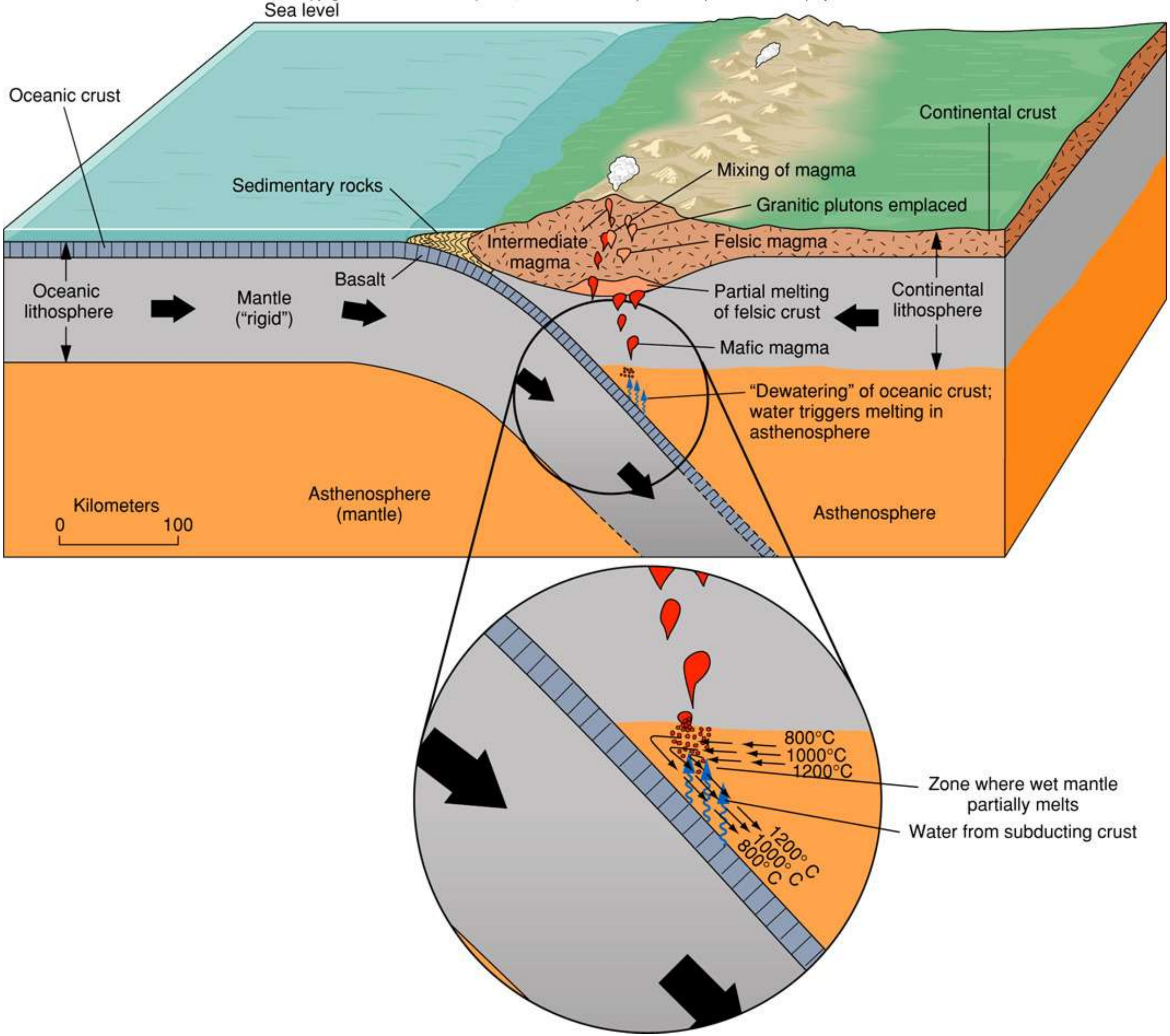

Continental lithosphere bulged upward and thinned
Basalt floods
Partial melting
Large head of newly arrived mantle plume
Hot, solid mantle rising from base of mantle

Fig. 03.24



Sea level
Oceanic crust
Sedimentary rocks
Continental crust
Mixing of magma
Granitic plutons emplaced
Intermediate magma
Felsic magma
Basalt
Oceanic lithosphere
Mantle ("rigid")
Partial melting of felsic crust
Continental lithosphere
Mafic magma
"Dewatering" of oceanic crust; water triggers melting in asthenosphere
Kilometers
0
100
Asthenosphere (mantle)
Asthenosphere
800°C
1000°C
1200°C
Zone where wet mantle partially melts
Water from subducting crust
1200° C
1000° C
800° C

Fig. 03.25

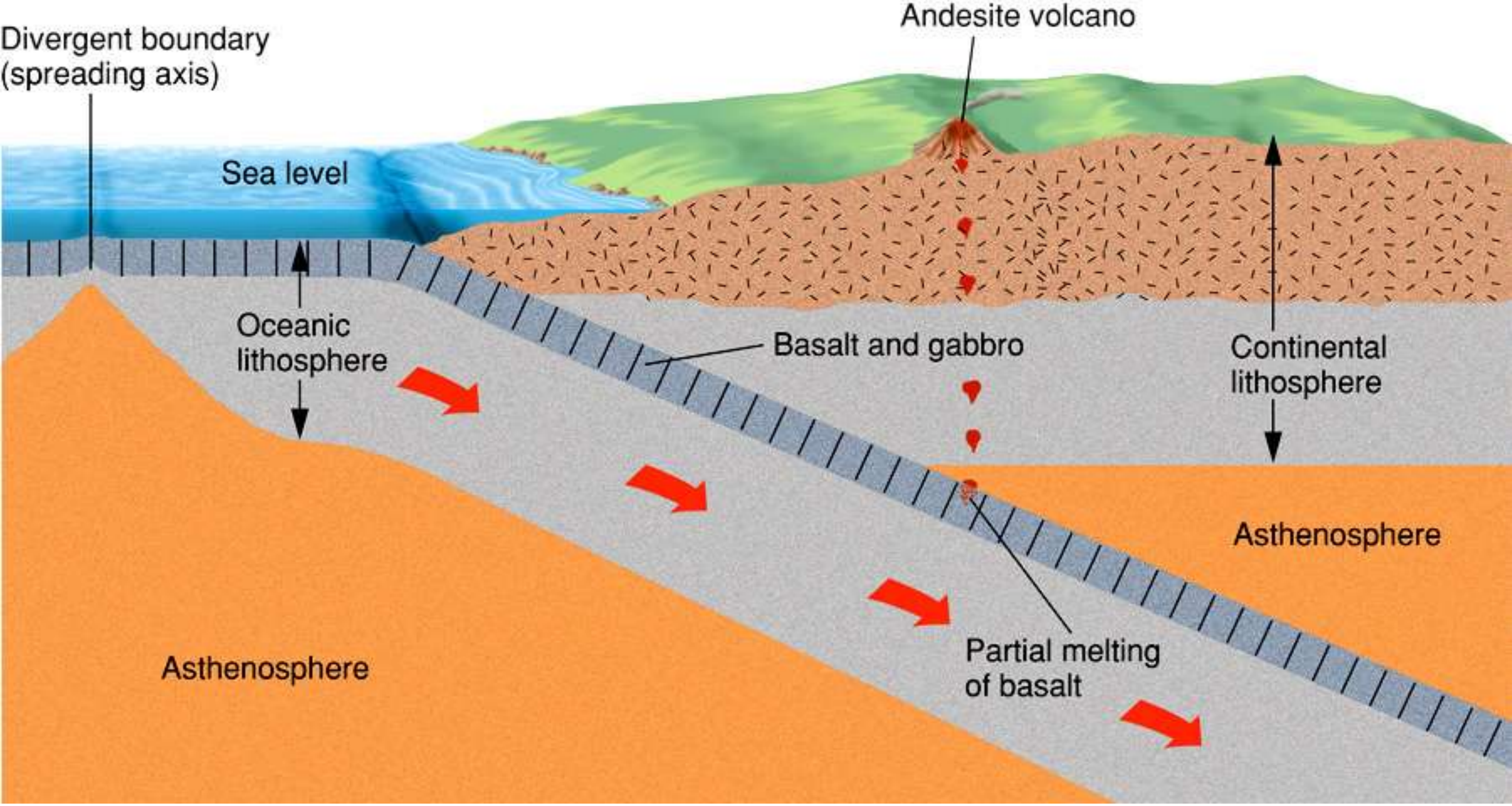

Andesite volcano
Divergent boundary
(spreading axis)
Sea level
Oceanic
lithosphere
Basalt and gabbro
Continental
lithosphere
Asthenosphere
Partial melting
of basalt
Asthenosphere

Table 03.02

Table 3.2 Relationships between Rock Types and Their Usual Plate Tectonic Setting

Rock	Original Magma	Final Magma	Processes	Plate Tectonic Setting
basalt & gabbro	mafic	mafic	partial melting of mantle (asthenosphere)	1. divergent boundary—oceanic crust created 2. Intraplate • plateau basalt • volcanic island chains (e.g., Hawaii)
andesite & diorite	mafic (usually)	intermediate	partial melting of mantle (asthenosphere) followed by: • differentiation or • assimilation or • magma mixing	convergent boundary
granite & rhyolite	silicic	silicic	partial melting of lower crust	1. convergent boundary 2. intraplate • over mantle plume

Chromite - settling