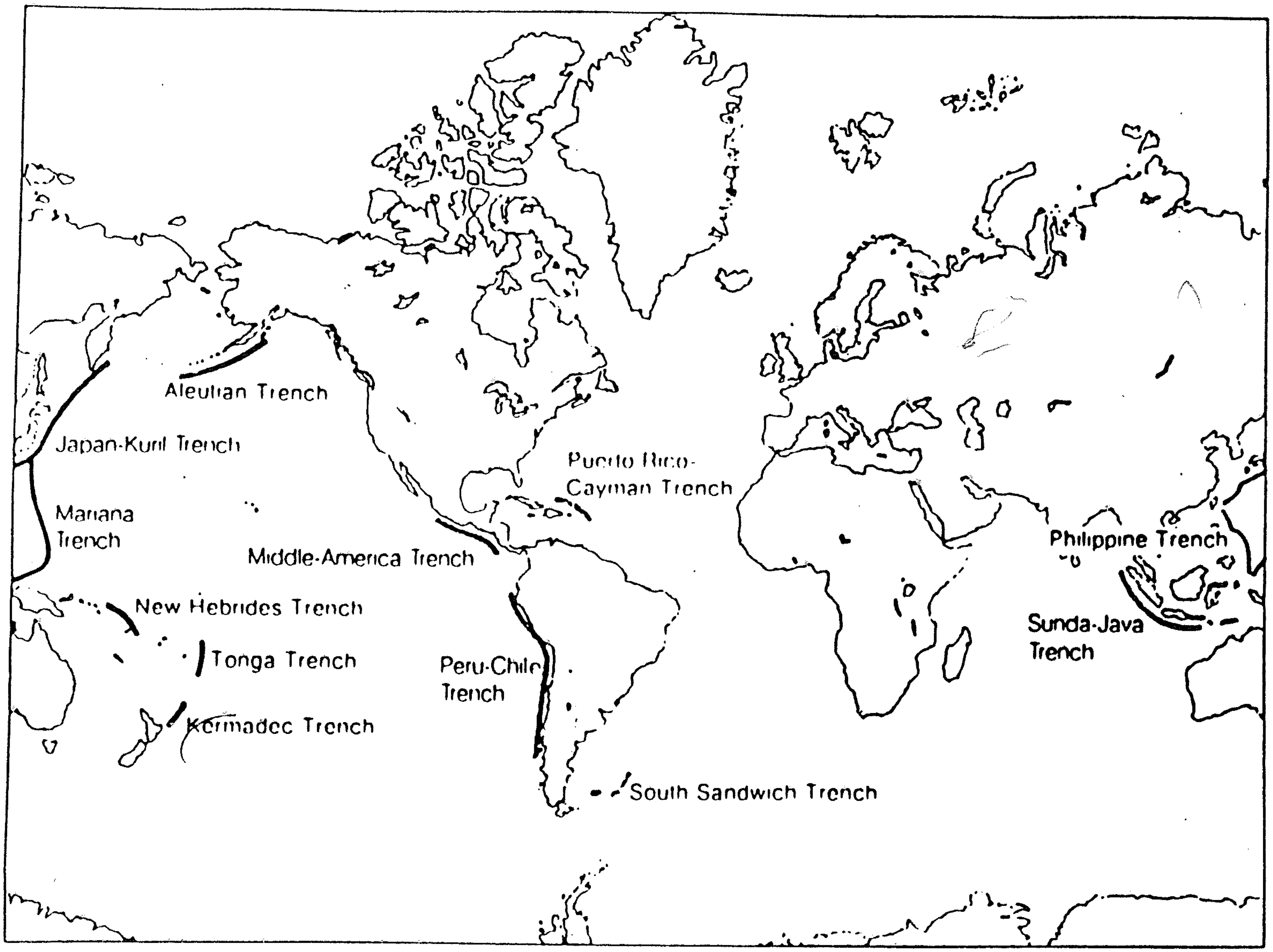


Figure 2.10 Major ocean trenches of the world.

Table 2–2 • THE LAYERS OF THE EARTH

	LAYER	COMPOSITION	DEPTH	PROPERTIES
Crust	Oceanic crust Continental crust	Basalt Granite	5–10 km 20–70 km	Cool, hard, and strong Cool, hard, and strong
Lithosphere	Lithosphere includes the crust and the uppermost portion of the mantle	Varies; the crust and the mantle have different compositions	75–125 km	Cool, hard, and strong
Mantle	Uppermost portion of the mantle included as part of the lithosphere Asthenosphere Remainder of upper mantle Lower mantle	Entire mantle is ultramafic rock. Its mineralogy varies with depth	Extends to 350 km Extends from 350 to 660 km Extends from 660 to 2900 km	Hot, weak, and plastic, 1% or 2% melted Hot, under great pressure, and mechanically strong High pressure forms minerals different from those of the upper mantle
Core	Outer core Inner core	Iron and nickel Iron and nickel	Extends from 2900 to 5150 km Extends from 5150 km to the center of the Earth	Liquid Solid

Table 2–1 • CHARACTERISTICS AND EXAMPLES OF PLATE BOUNDARIES

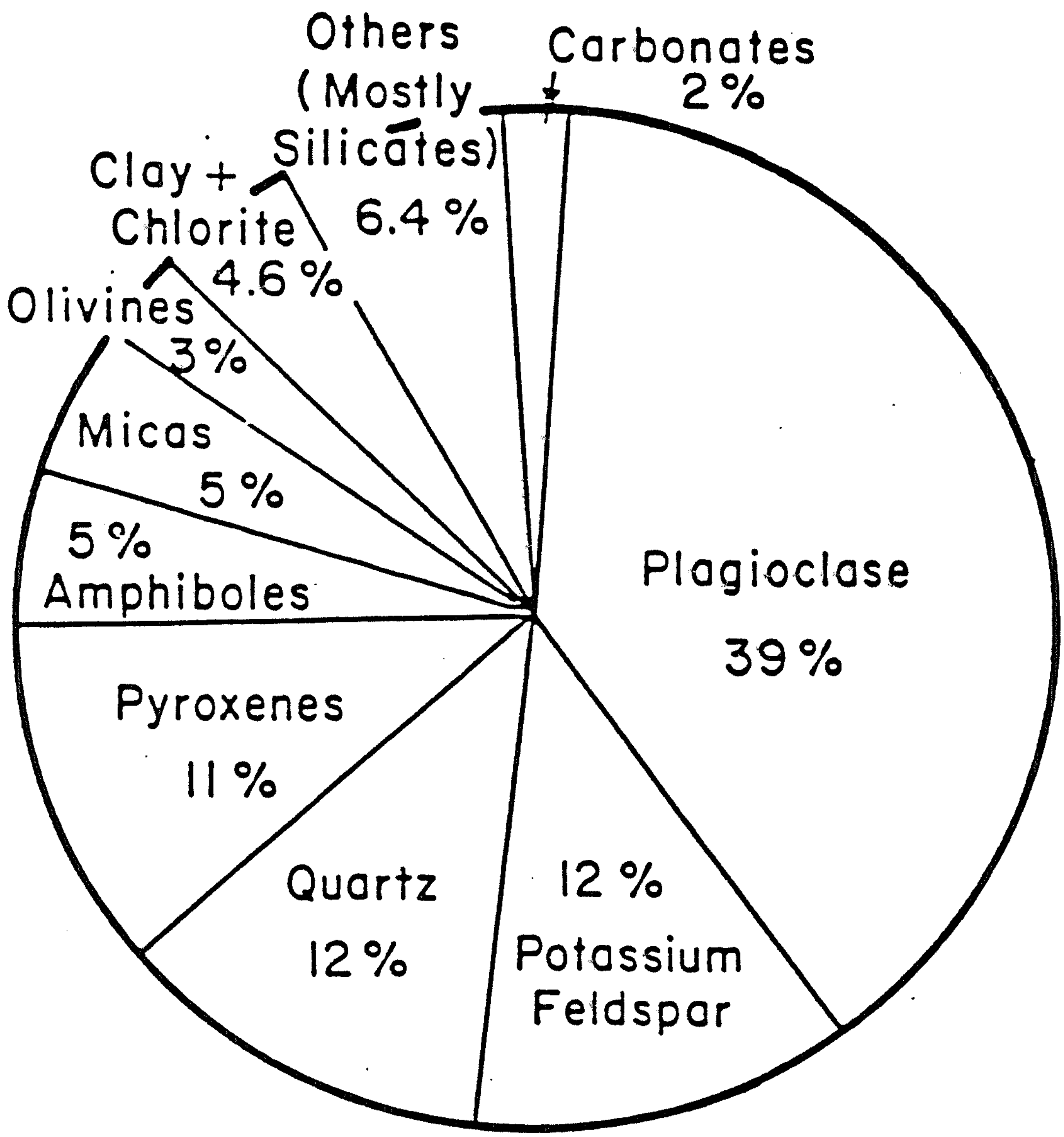
TYPE OF BOUNDARY	TYPES OF PLATES INVOLVED	TOPOGRAPHY	GEOLOGIC EVENTS	MODERN EXAMPLES
Divergent	Ocean-ocean	Mid-oceanic ridge	Sea-floor spreading, shallow earthquakes, rising magma, volcanoes	Mid-Atlantic ridge
	Continent-continent	Rift valley	Continents torn apart, earthquakes, rising magma, volcanoes	East African rift
Convergent	Ocean-ocean	Island arcs and ocean trenches	Subduction, deep earthquakes, rising magma, volcanoes, deformation of rocks	Western Aleutians
	Ocean-continent	Mountains and ocean trenches	Subduction, deep earthquakes, rising magma, volcanoes, deformation of rocks	Andes
	Continent-continent	Mountains	Deep earthquakes, deformation of rocks	Himalayas
Transform	Ocean-ocean	Major offset of mid-oceanic ridge axis	Earthquakes	Offset of East Pacific rise in South Pacific
	Continent-continent	Small deformed mountain ranges, deformations along fault	Earthquakes, deformation of rocks	San Andreas fault

KINDS OF PLATE MARGINS AND CHARACTERISTIC FEATURES

Crust on each plate	feature	kinds of margin divergent	convergent	transform Faults
Oceanic-Oceanic	Topography	Oceanic ridge with central rift valley	Seafloor trench	Ridges and valleys created by oceanic crust
	Earthquake	All foci less 100km deep	Foci from 0 to 700km	Foci as deep as 100km
	Volcanism	Basaltic lavas	Andesitic volcanoes in an arc of islands parallel to trench	Volcanism rare, basaltic along "leaky" faults
	Examples	Mid-Atlantic Ridge	Tonga-Kermadec Trench: Aleutian Trench	Kane Fracture
Oceanic-Continental	Topography	-	Seafloor trench	-
	Earthquake	-	Foci from 0 to 700km deep	-
	Volcanism	-	Andesitic volcanoes in mountain range parallel to trench	-
	Examples	(no examples)	Western Coast of South America	(no examples)
Continental-Continental	Topography	Rift valley	Young mountain range	Fault zone that displaces surface features
	Earthquake	All foci less than 100km deep	Foci as deep as 300km over a broad region	Foci as deep as 100km throughout a broad region
	Volcanism	Basaltic and rhyolitic volcanoes	No volcanism: intense metamorphism and intrusion granitic plutons	No volcanism
	Examples	African Rift Valley	Himalaya, Alps	San Andreas Fault

ABUNDANCE OF ELEMENTS IN THE EARTH'S CRUST

Element	Symbol	Atom Number	Per Cent by Weight	Per Cent by Volume
Oxygen	0	8	46.6	93.77
Silicon	Si	14	27.72	.86
Aluminum	Al	13	8.13	.47
Iron	Fe	26	5.00	.43
Calcium	Ca	20	3.63	1.03
Sodium	Na	11	2.83	1.32
Potassium	K	19	2.59	1.83
Magnesium	Mg	12	2.09	.29
Titanium	Ti	22	0.62	
Hydrogen	H	1	0.14	
Phosphorus	P	15	0.13	
Carbon	C	6	0.094	
Manganese	Mn	25	0.09	
Sulfur	S	16	0.08	
Barium	Ba	56	0.05	
Chlorine	Cl	17	0.045	
Chromium	Cr	24	0.035	
Fluorine	F	9	0.029	
Zirconium	Zr	40	0.025	
Nickel	Ni	28	0.019	
			99.947	
Others			0.053	



Pie diagram showing volume percent of minerals in the crust of the earth (data from Ronov and Yaroshevsky, 1969)

- Minerals
  - Silicates (95%)
    - Ferromagnesians (dark-colored)
    - Non-Ferromagnesians (light-colored, most abundant)
  - Non-Silicates (5%)
    - Carbonates $(CO_3)^{2-}$ (calcite, dolomite)
    - Sulfates $(SO_4)^{2-}$ (gypsum, barite)
    - Sulfides (S) (pyrite, galena, sphalerite, chalcocite)
    - Oxides $(O_2)^{2-}$ (magnetite, hematite, corundum)
    - Hydroxides $(OH)^{-}$ (gibbsite, brucite)
    - Halides (metals + halogens) (halite, flourite)
    - Phosphates (PO_4) (apatite)
    - Native Elements (gold, silver)

- Silicates
  - Ferromagnesians
    - Olivine $(Mg, Fe)_2SiO_4$
    - Augite
    - Biotite (black mica)
    - Chlorite
    - Hornblende
    - Garnet
  - Non Ferromagnesians
    - Quartz (SiO_2)
    - Muscovite (White Mica)
    - Feldspar: (most abundant)
      - i. *orthoclase* (K-feldspar)
      - ii. *plagioclase*:
        - Albite(sodic)
        - Anorthite(Calcic)

Table 3-3
Major silicate structures.

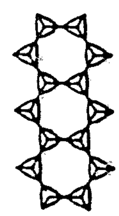
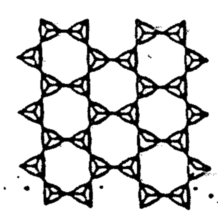
Geometry of linkage of SiO_4 tetrahedra	*Si/O ratio*		*Example mineral*	*Formula*
Isolated tetrahedra: linked by bonds sharing oxygens only through cation	1:4		Olivine	$(Mg,Fe)_2SiO_4$
Single chains: each tetrahedron linked to two others by shared oxygens. Chains bonded by cations	1:3		Pyroxene	$(Mg,Fe)SiO_3$
Double chains: 2 chains joined by shared oxygens as well as cations	4:11		Amphibole	$(Ca_2Mg_5)Si_8O_{22}(OH)_2$
Sheets: each tetrahedron linked to 3 others by shared oxygens. Sheets bonded by cations or alumina sheets	2:5		Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Frameworks: each tetrahedron shares all its oxygens with other SiO_4 tetrahedra (in quartz) or AlO_4 tetrahedra	3:8		Feldspar (Albite)	$NaAlSi_3O_8$
	1:2		Quartz	SiO_2

Table 2-3 Common Rock-Forming Silicates

Silicate	Formula	Silicon:Oxygen Ratio* (silicate structure)	Properties
Quartz	SiO_2	1:2 (framework)	Hardness of 7; breaks by fracture; six-sided prismatic crystals; specific gravity 2.65
Alkali feldspars	$KAlSi_3O_8$	1:2 (framework)	Hardness of 6.0–6.5; strong cleavage in two directions at right angles; pink or white in color; specific gravity 2.5–2.6
Plagioclase feldspars	$(Ca,Na)AlSi_3O_8$	1:2 (framework)	Hardness of 6.0–6.5; strong cleavage in two directions at right angles; white to bluish-gray in color; specific gravity 2.6–2.7
Muscovite mica	$K_2Al_4(Si_6Al_2O_{20})(OH,F)_2$	1:2.5 (sheet)	Hardness of 2–3; perfect cleavage in one direction; colorless and transparent to light green-gray; specific gravity 2.8–3.0
Biotite mica	$K_2(Mg,Fe)_6Si_3O_{10}(OH)_2$	1:2.5 (sheet)	Hardness of 2.5–3.0; perfect cleavage in one direction; black to dark brown in color; specific gravity 2.7–3.2
Amphiboles	$(Na,Ca)_2(Mg,Al,Fe)_5(Si,Al)_8O_{22}(OH)_2$	1:2.75 (double chain)	Hardness of 5–6; cleaves in two directions at 56° and 124°; black to dark green in color; specific gravity 3.0–3.3
Pyroxenes	$(Mg,Fe,Ca,Na)(Mg,Fe,Al)Si_2O_6$	1:3 (single chain)	Hardness of 5–6; cleaves in two directions at about 90°; black to dark green in color; specific gravity 3.1–3.5
Olivine	$(Mg,Fe)_2SiO_4$	1:4 (independent tetrahedra)	Hardness of 6.5–7.0; green in color; breaks by fracture; specific gravity 3.2–3.6

*luminum ion y substitute for some silicon ions in certain minerals. These count licon ions for purposes of the silicon:oxygen ratio.

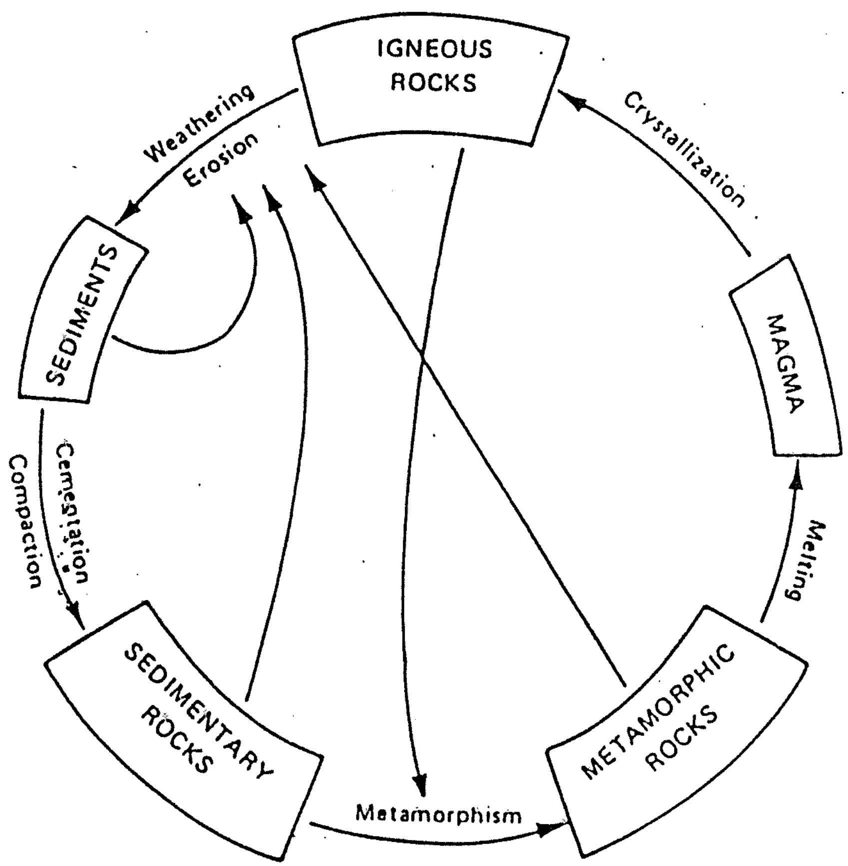
Table 2-4 **Common Nonsilicate Minerals**

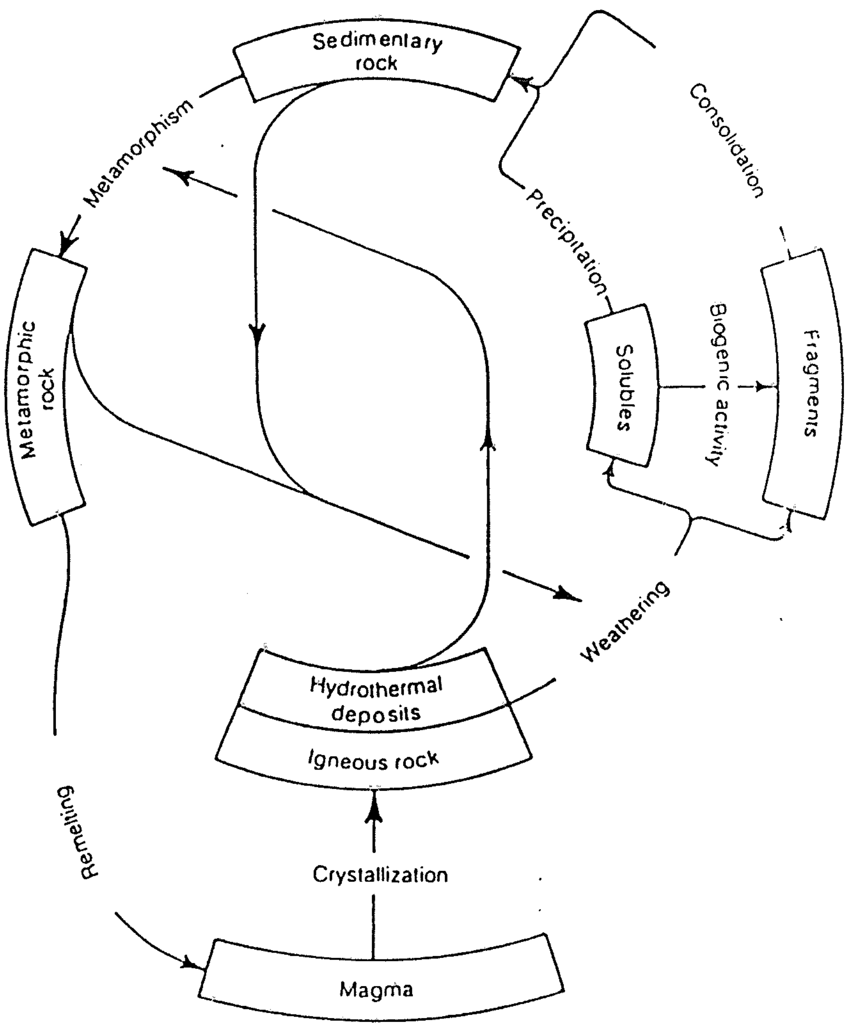
Mineral Type	Composition	Examples	Uses
Carbonates	Metallic ion(s) plus carbonate ion complex (CO_3^{2-})	Calcite ($CaCO_3$)	Cement
		Dolomite ($CaMg(CO_3)_2$)	Cement
Oxides	Metallic ion(s) plus oxygen ion (O^{2-})	Hematite (Fe_2O_3)	Iron ore
		Magnetite (Fe_3O_4)	Iron ore
		Corundum (Al_2O_3)	Gems, abrasives
		Cassiterite (SnO_2)	Tin ore
		Rutile (TiO_2)	Titanium ore
		Ilmenite ($FeTiO_3$)	Titanium ore
		Uraninite (UO_2)	Uranium ore
Sulfides	Metallic ion(s) plus sulfur (S^{2-})	Galena (PbS)	Lead ore
		Pyrite (FeS_2)	Sulfur ore
		Cinnabar (HgS)	Mercury ore
		Sphalerite (ZnS)	Zinc ore
		Molybdenite (MoS_2)	Molybdenum ore
		Chalcopyrite ($CuFeS_2$)	Copper ore
Sulfates	Metallic ion(s) plus sulfate ion (SO_4^{2-})	Gypsum ($CaSO_4 \cdot 2H_2O$)	Plaster
		Anhydrite ($CaSO_4$)	Plaster
		Barite ($BaSO_4$)	Drilling mud
Native elements	Minerals consisting of a single element	Gold (Au)	Jewelry, coins, electronics
		Silver (Ag)	Jewelry, coins, photography
		Platinum (Pt)	Jewelry, catalyst for gasoline production
		Diamond (C)	Jewelry, drill bits, cutting tools

Table 3–5 · IMPORTANT MINERAL GROUPS

GROUP	MEMBER	FORMULA	ECONOMIC USE
Oxides	Hematite	Fe_2O_3	Ore of iron
	Magnetite	Fe_3O_4	Ore of iron
	Corundum	Al_2O_3	Gemstone, abrasive
	Ice	H_2O	Solid form of water
	Chromite	$FeCr_2O_4$	Ore of chromium
Sulfides	Galena	PbS	Ore of lead
	Sphalerite	ZnS	Ore of zinc
	Pyrite	FeS_2	Fool's gold
	Chalcopyrite	$CuFeS_2$	Ore of copper
	Bornite	Cu_5FeS_4	Ore of copper
	Cinnabar	HgS	Ore of mercury
Sulfates	Gypsum	$CaSO_4 \cdot 2H_2O$	Plaster
	Anhydrite	$CaSO_4$	Plaster
	Barite	$BaSO_4$	Drilling mud
Native elements	Gold	Au	Electronics, jewelry
	Copper	Cu	Electronics
	Diamond	C	Gemstone, abrasive
	Sulfur	S	Sulfa drugs, chemicals
	Graphite	C	Pencil lead, dry lubricant
	Silver	Ag	Jewelry, photography
	Platinum	Pt	Catalyst
Halides	Halite	$NaCl$	Common salt
	Fluorite	CaF_2	Used in steel making
	Sylvite	KCl	Fertilizer
Carbonates	Calcite	$CaCO_3$	Portland cement
	Dolomite	$CaMg(CO_3)_2$	Portland cement
	Aragonite	$CaCO_3$	Portland cement
Hydroxides	Limonite	$FeO(OH) \cdot nH_2O$	Ore of iron, pigments
	Bauxite	$Al(OH)_3 \cdot nH_2O$	Ore of aluminum
Phosphates	Apatite	$Ca_5(F,Cl,OH)(PO_4)_3$	Fertilizer
	Turquoise	$CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$	Gemstone
Silicates	(See Figures 3–18 and 3–19 for silicate minerals.)		

The ROCK CYCLE





Volcanic Features, and Plate Tectonic Settings

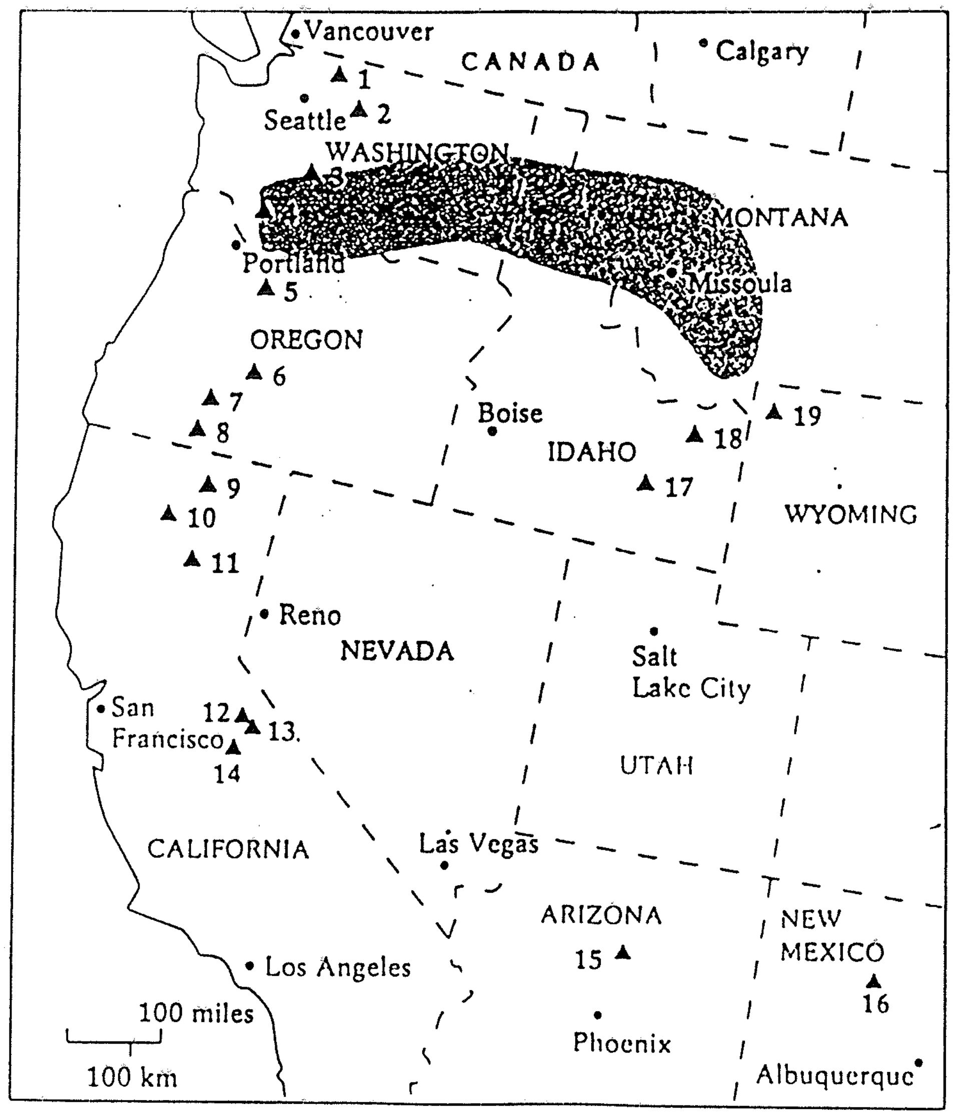
Lava Type	Eruptive Style	Typical Volcanic Landforms	Common Volcanic Products and Effects	Common Plate Tectonic Setting	North American Example(s)
Basaltic (mafic composition)	Quiet, effusive	Lava plateaus, shield volcanoes, occasional cinder cones	Aa lava, pahoehoe lava, vesicular basalts, pillow lavas, columnar basalts	Divergent plate boundaries (such as the mid-Atlantic ridge), oceanic intraplate hot spots (such as underlies Hawaii), intraplate rifts (such as the East African rift)	Columbia River lava plateau (Washington and Oregon), Belknap Crater (eastern Oregon), Craters of the Moon (Idaho)
Andesitic (intermediate composition)	Fairly explosive, pyroclastic	Composite cones, cinder cones	Relatively viscous lava, lahars, welded tuffs (from pyroclastic flows)	Subduction zones	Cascades (British Columbia, Washington, Oregon, northern California), Aleutians (Alaska)
Rhyolitic (felsic composition)	Very explosive, pyroclastic	Volcanic domes, calderas	Extremely viscous lava, ash-flow deposits, welded tuffs (from pyroclastic flows)	Subduction zones, especially at continental margins, intracontinental rifts, intracontinental hot spots	Yellowstone plateau (Wyoming, Montana), Jemez Mountains (Rio Grande rift, New Mexico), Long Valley Caldera (eastern Sierra Nevada, California)

Table 3-1 Common Igneous Compositions

Composition Type	Percentage of Silica	Other Major Elements	Relative Viscosity of Magma	Temperature at Which First Crystals Solidify	Igneous Rocks Produced
Ultramafic	<40%	Mg, Fe, Al, Ca	Very low	>1200°C (2200°F)	Peridotite (plutonic) Komatiite (volcanic)
Mafic	40–50%	Al, Ca, Fe, Mg	Low	~1000–1200°C (1830–2200°F)	Gabbro (plutonic) Basalt (volcanic)
Intermediate	60%	Al, Ca, Na, Fe, Mg	Medium	~800–1000°C (1475–1830°F)	Diorite (plutonic) Andesite (volcanic)
Felsic	>70%	Al, K, Na	High	~600–800°C (1100–1475°F)	Granite (plutonic) Rhyolite (volcanic)

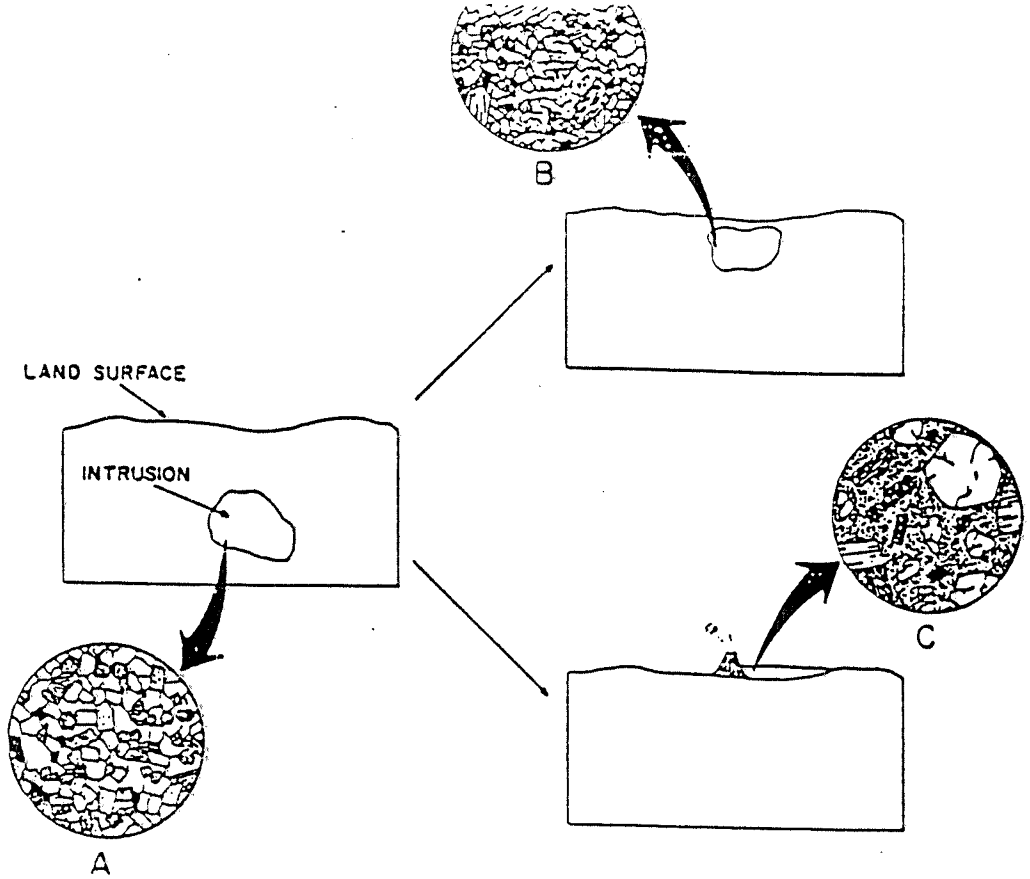
Major Volcano (Eruption date)

1 Mt. Baker (1880)
2 Glacier Peak (1750?)
3 Mt. Rainier (1854)
4 Mt. St. Helens (1980)
5 Mt. Hood (1865–1866)
6 Three Sisters/Newberry Caldera (1853?)
7 Crater Lake (Mt. Mazama) (about 6845 years ago)
8 Mt. McLoughlin
9 Medicine Lake Volcano (1910)
10 Mt. Shasta (1855)
11 Lassen Peak (1914–1917)
12 Mono Craters (about 200,000 years ago)
13 Long Valley Caldera (about 700,000 years ago)
14 Inyo Craters
15 Sunset Crater
16 Valles Caldera
17 Craters of the Moon
18 Island Park Caldera
19 Yellowstone National Park

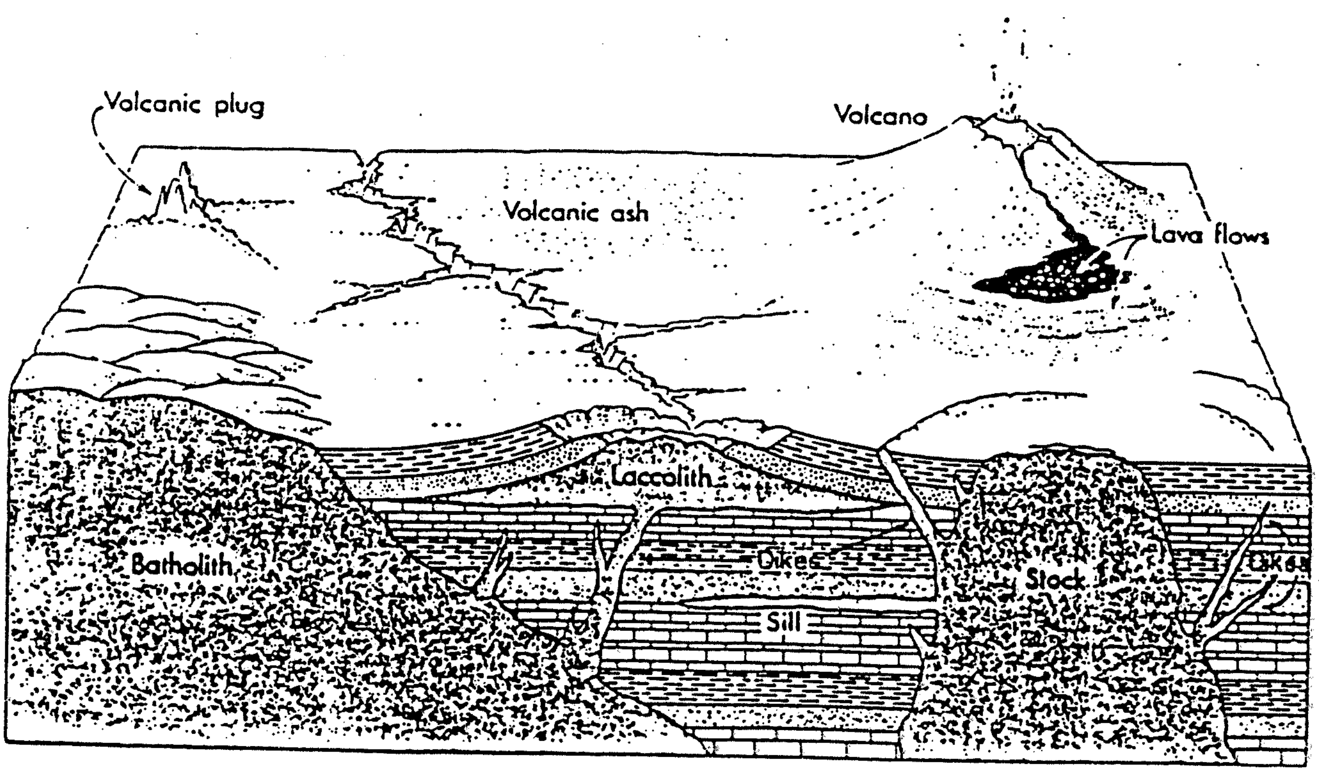


Extent of ash fall from Mount St. Helens' 1980 eruption

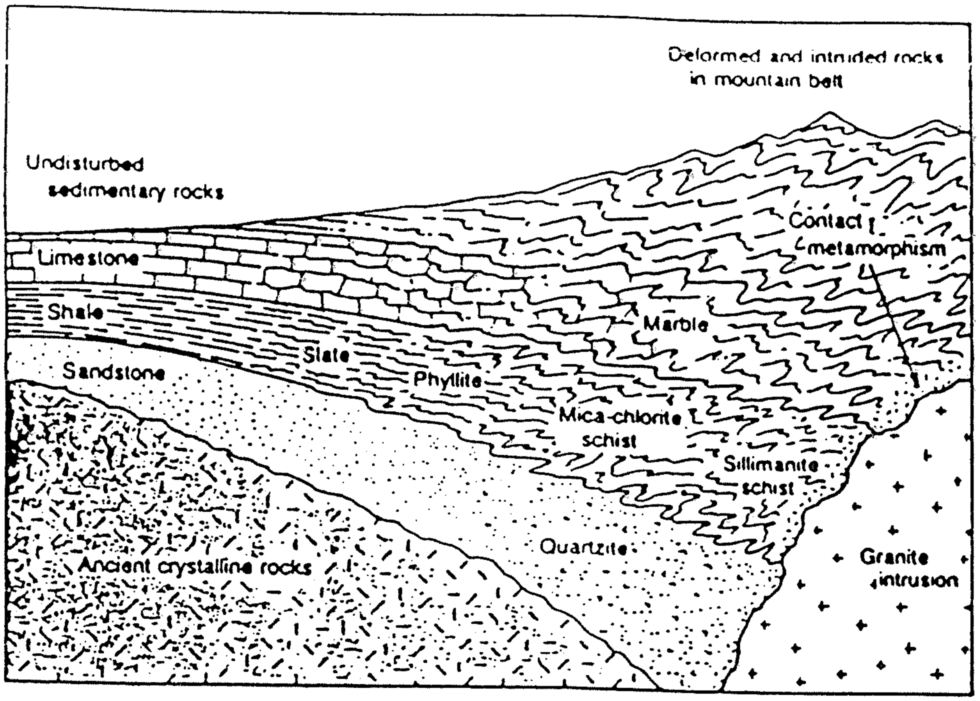
Extent of ash fall from Mount Mazama (~6845 years ago)



Generalized cross-sections illustrating the development of igneous rock textures. Insets are enlargements of microscopic textural views; diameter of each field is approximately 2 cm. (A) Magma intrudes the earth's crust and completely crystallizes. Resultant igneous rocks have an equigranular texture (B) If magma moves upward during crystallization it will have a complex cooling history. If magma completely crystallizes within the crust, resultant igneous rocks will contain phenocrysts of early-formed crystals in a phaneritic matrix (C) If magma is extruded, an aphanitic groundmass will develop. Resultant igneous rocks will have large phenocrysts of early-formed crystals in an aphanitic groundmass



Block diagram showing various modes of occurrence of igneous rocks.



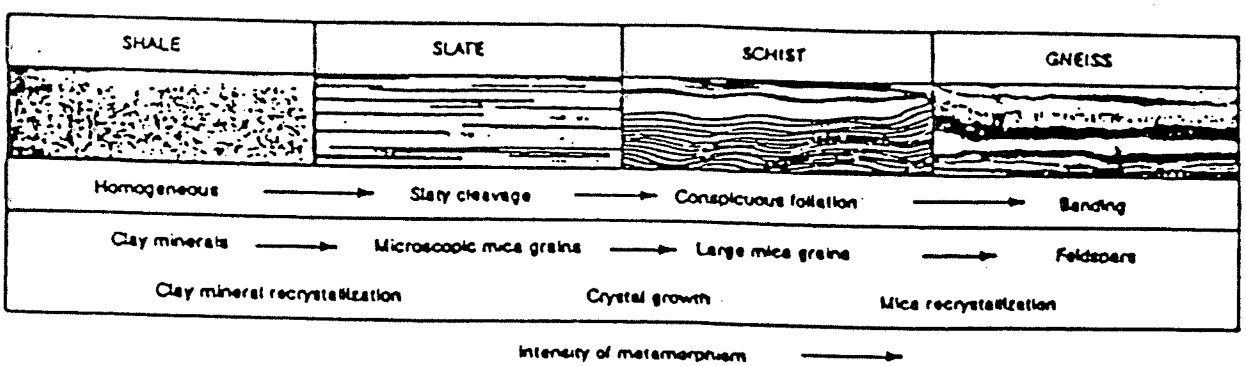


Figure 7.6 The metamorphism of shale can involve a series of steps, depending on the intensity of temperature and pressure. Shale can change to slate, schist, or even gneiss.

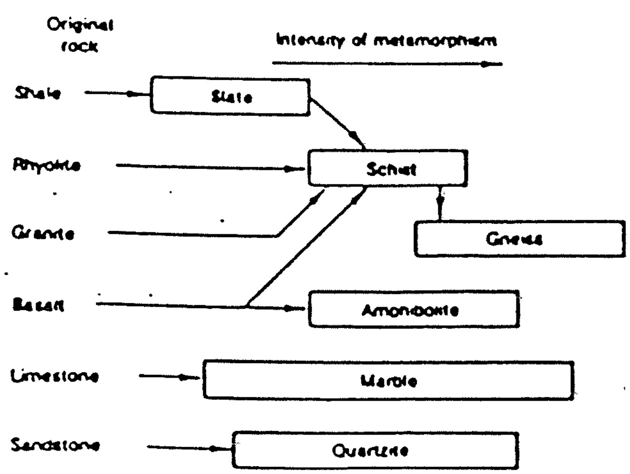
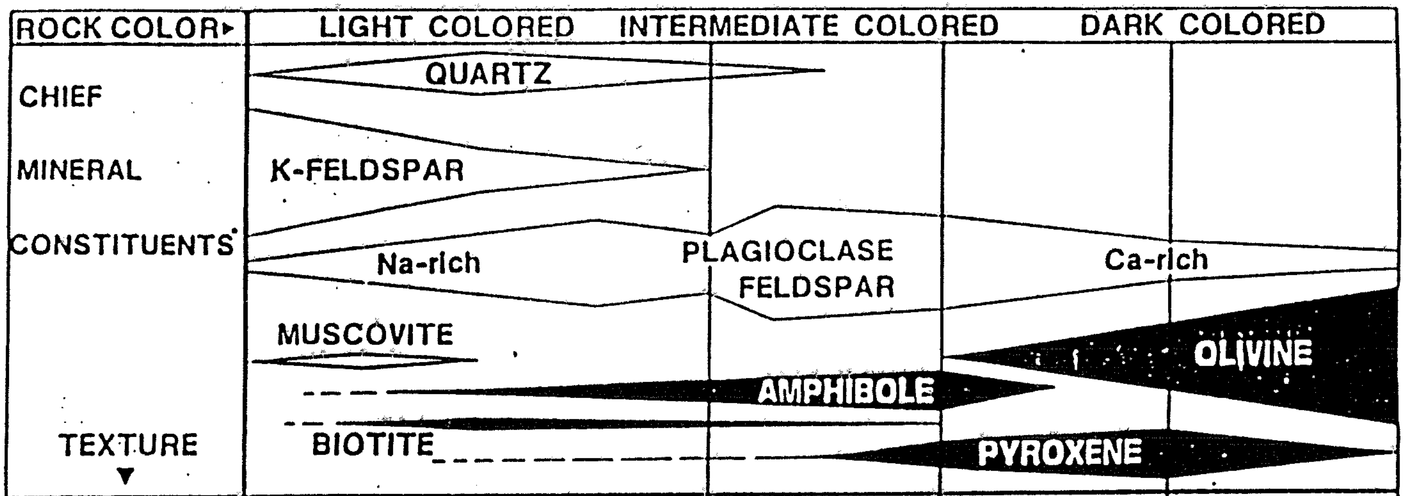


Figure 7.7 The origin of common metamorphic rocks is complex. In some cases, such as metaconglomerate, quartzite, and marble, the nature of the original rocks is easily determined. In other cases, such as schist and gneiss, it is difficult and sometimes impossible to determine the type of source rock. This diagram is a simplified flow chart showing the origin of some of the common metamorphic rocks.

Classification and Identification Chart for Hand Specimens of Common Igneous Rocks.



TEXTURE ▼	LIGHT COLORED	INTERMEDIATE COLORED	DARK COLORED	
Phaneritic	GRANITE	DIORITE	GABBRO	PERIDOTITE
Aphanitic	RHYOLITE	ANDESITE	BASALT	
Glassy	OBSIDIAN PUMICE			

Chemical Weathering Products of Common Rock-Forming Silicate Minerals

	Mineral	Composition	Important Decomposition Products	
			Minerals	Other
	Quartz	SiO_2	Quartz Grains	Some silica in solution
Feldspars	Orthoclase	$K(AlSi_3O_8)$	Clay	Some silica in solution Potassium carbonate (soluble)
Feldspars	Albite (Sodium Plagioclase) Anorthite (Calcium Plagioclase)	$Na(AlSi_3O_8)$ $Ca(Al_2Si_2O_8)$	Clay	Some silica in solution Sodium and calcium carbonates (soluble)
Ferromagnesians	Biotite Augite Hornblende	Fe, Mg, Ca Silicates of Al	Clay Limonite Hematite	Some silica in solution Carbonates of calcium and magnesium (soluble)
Ferromagnesians	Olivine	$(Fe,Mg)_2SiO_4$	Limonite Hematite	Some silicates in solution Carbonates of iron and magnesium (soluble)

GEOLOGIC TIME SCALE

Time Units of the Geologic Time Scale					Development of Plants and Animals
Eon	Era	Period	Epoch		
Phanerozoic	Cenozoic	Quarternary	Holocene	0.01	Humans develop
			Pleistocene	1.6	
		Tertiary	Pliocene	5.3	"Age of Mammals"
			Miocene	23.7	
			Oligocene	36.6	
			Eocene	57.8	
			Paleocene	66.4	Extinction of dinosaurs and many other species
	Mesozoic	Cretaceous	"Age of Reptiles"	144	First flowering plants
		Jurassic		208	First birds
		Triassic		245	Dinosaurs dominant
	Paleozoic	Permian	"Age of Amphibians"	286	Extinction of trilobites and many other marine animals
		Carboniferous: Pennsylvanian		320	First reptiles
		Carboniferous: Mississippian		360	Large coal swamps Amphibians abundant
		Devonian	"Age of Fishes"	408	First insect fossils Fishes dominant
		Silurian		438	First land plants
		Ordovician	"Age of Invertebrates"	505	First fishes Trilobites dominant
		Cambrian		570	First organisms with shells
Proterozoic	Collectively called Precambrian, comprises about 87% of the geologic time scale			2500	First multicelled organisms
Archean				3800	First one-celled organisms
Hadean				4600	Age of oldest rocks Origin of the earth

Table 18.2
Major divisions of geologic time.

Cenozoic Era (Age of Recent Life)	Quaternary period	The several geologic eras were originally named Primary, Secondary, Tertiary, and Quaternary. The first two names are no longer used; Tertiary and Quaternary have been retained but used as period designations.
	Tertiary period	
Mesozoic Era (Age of Middle Life)	Cretaceous period	Derived from Latin word for chalk (*creta*) and first applied to extensive deposits that form white cliffs along the English Channel.
	Jurassic period	Named for the Jura Mountains, located between France and Switzerland, where rocks of this age were first studied.
	Triassic period	Taken from word "trias" in recognition of the threefold character of these rocks in Europe.
Paleozoic Era (Age of Ancient Life)	Permian period	Named after the province of Perm in Russia, where these rocks were first studied.
	Pennsylvanian period	Named for the state of Pennsylvania, where these rocks have yielded much coal.
	Mississippian period	Named for the Mississippi River valley, where these rocks are well exposed.
	Devonian period	Named after Devonshire County, England, where these rocks were first studied.
	Silurian period	Named after Celtic tribes, the Silures and the Ordovices, that lived in Wales during the Roman Conquest.
	Ordovician period	
	Cambrian period	Taken from the Roman name for Wales (Cambria), where rocks containing the earliest evidence of complex forms of life were first studied.
Precambrian		The time between the birth of the planet and the appearance of complex forms of life. More than 85 percent of the earth's estimated 4.6 billion years falls into this span.

Source: U.S. Geological Survey.