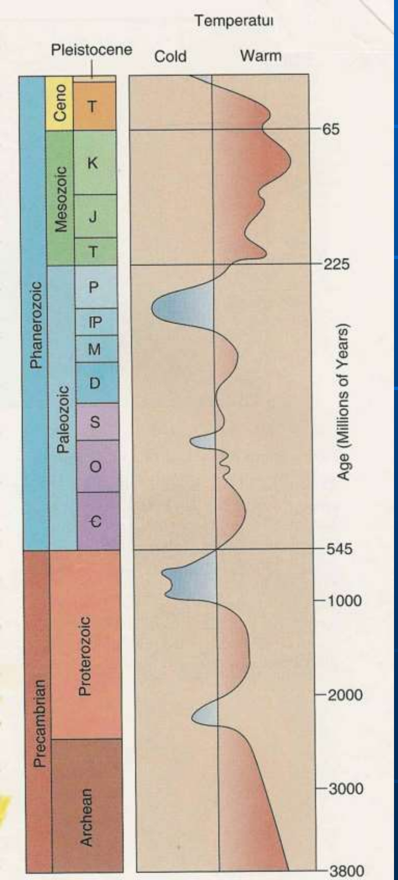
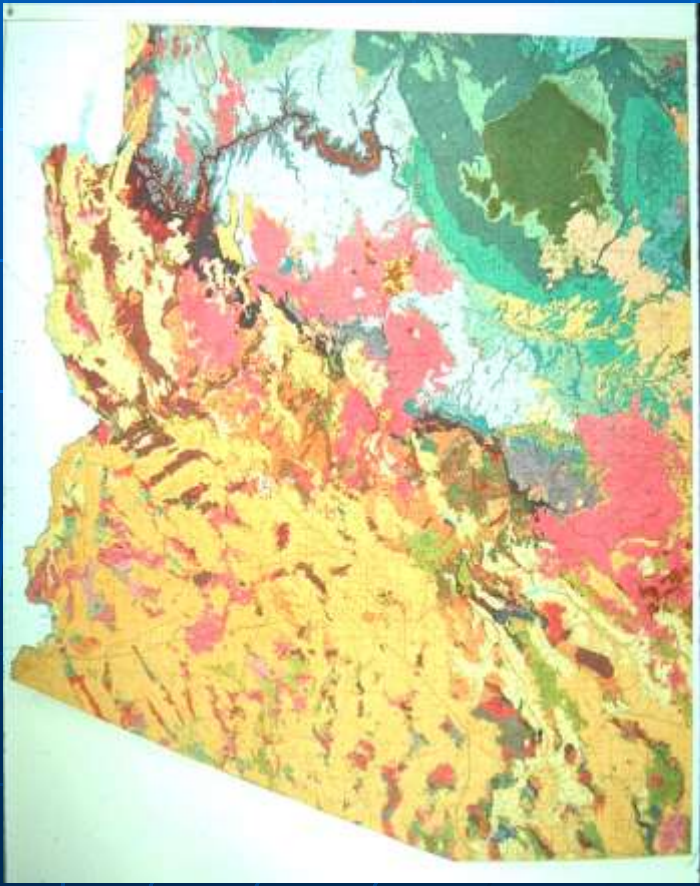
Climate Change in Arizona through Geologic History

Dr. Jan C. Rasmussen

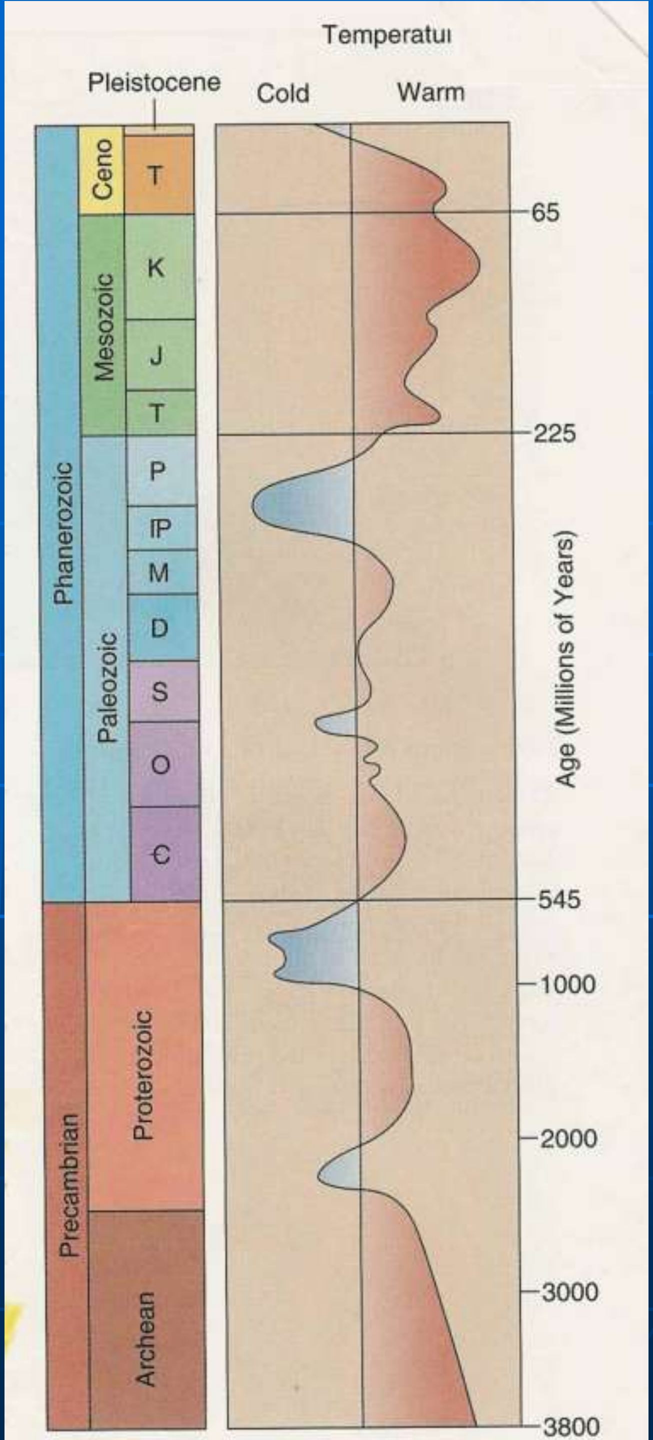
www.janrasmussen.com





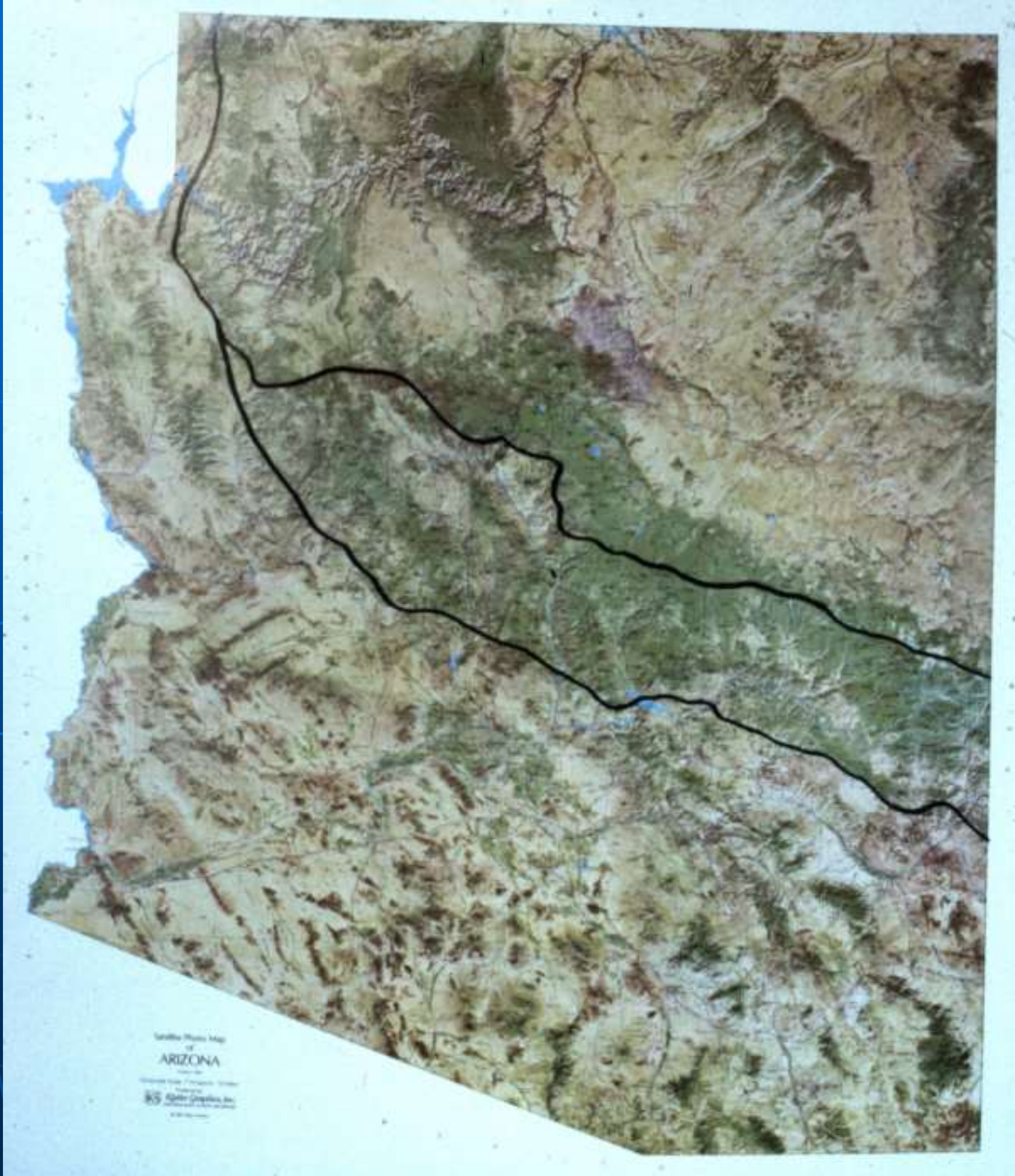
Glaciation through Geologic time

- Depends on plate tectonics through geologic history
- Continental collisions = ice ages
- Big environmental changes through geologic time
- Warm periods vs.
- ice ages ~ every
- 250 million years



Arizona physiography

- Depends on plate tectonics through geologic history
- Big environmental changes through geologic time
- Seas in, seas out
- Warm periods and ice ages



Arizona Physiographic Provinces

Colorado Plateau Province

- canyons
- horizontal sediments
- broad warping

Transition or Central Highlands Province

- lots of faulting
- mostly mountains
- rugged terrain (high relief)

Basin & Range Province

- fault block mountains
- broad alluvial valleys
- sand, clay, salt & gravel - fill up to 10,000 feet thick

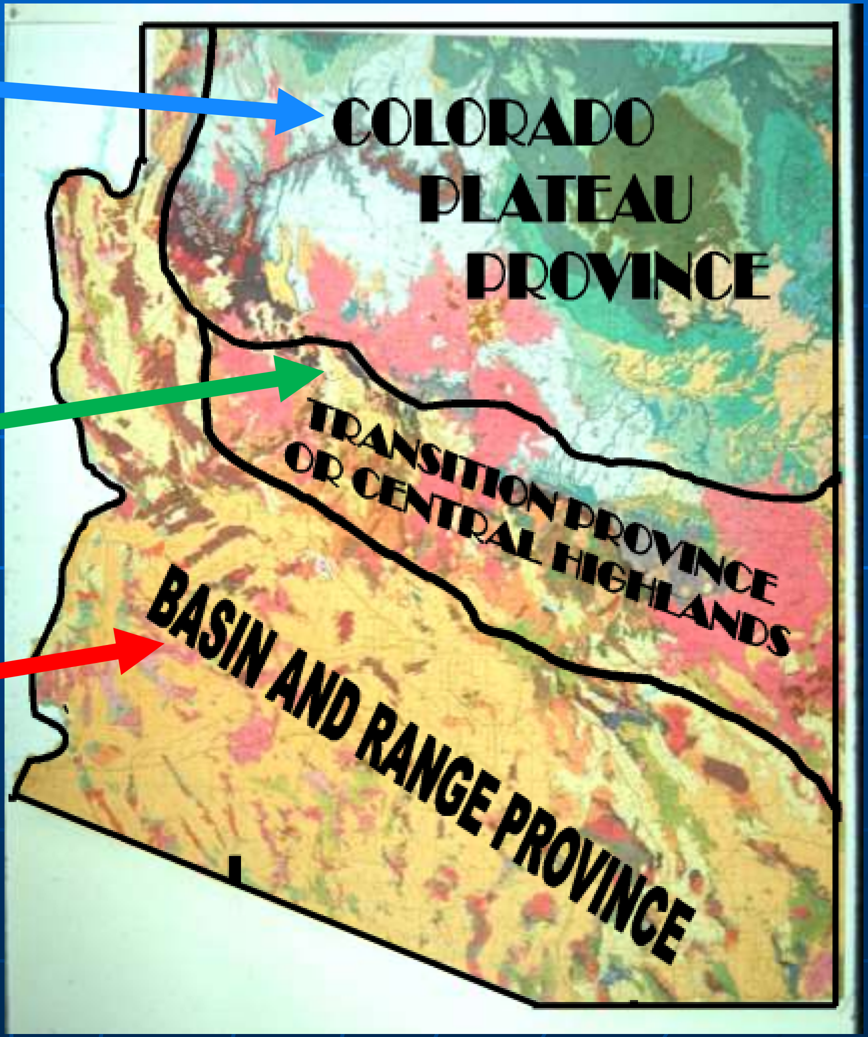
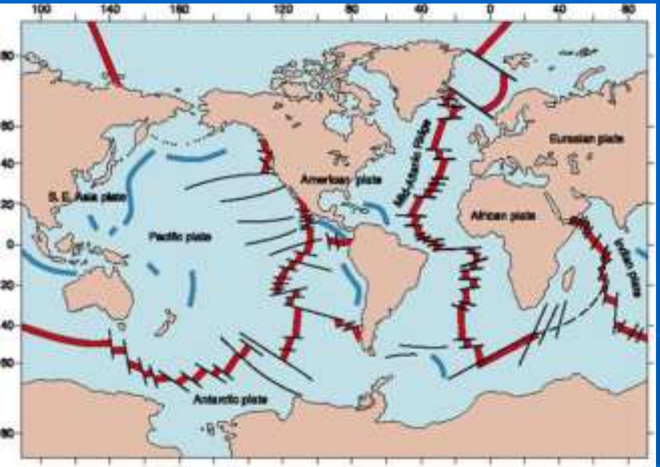
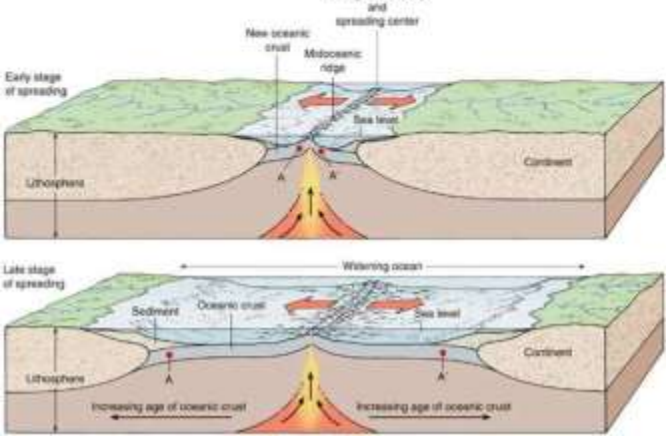
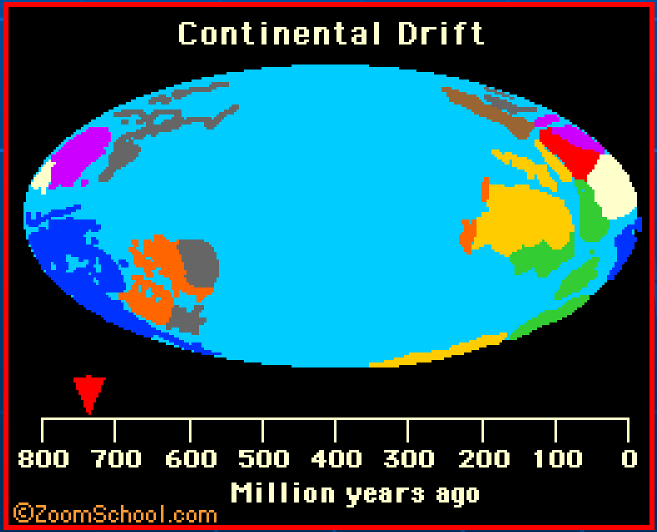


Plate Tectonics

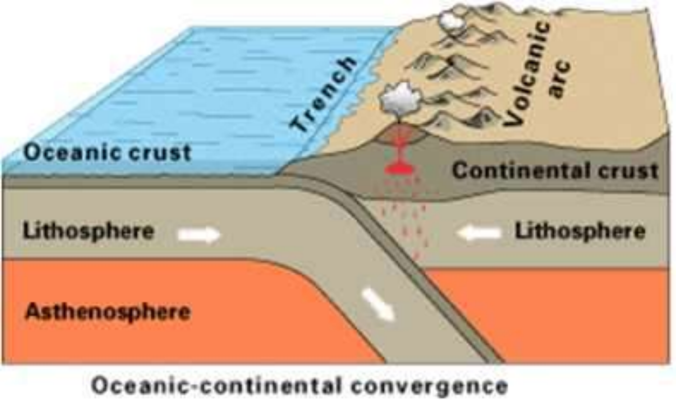


Sea floor spreading and mid-ocean ridge volcanism





Subduction, Volcanoes, Mountains



Continent-continent collision and very tall mountains

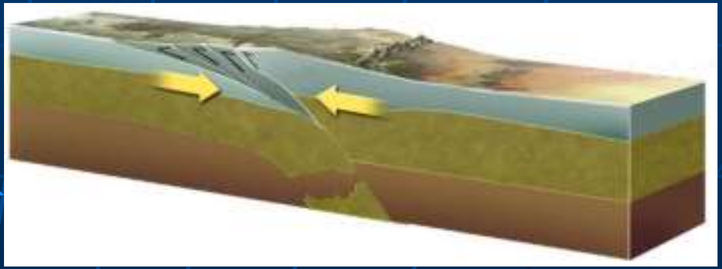
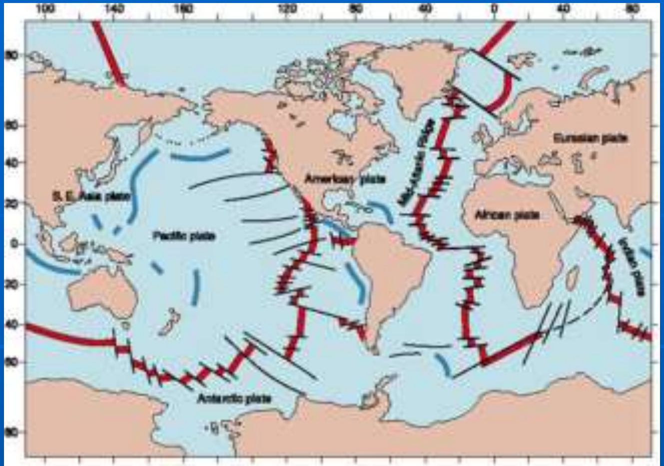
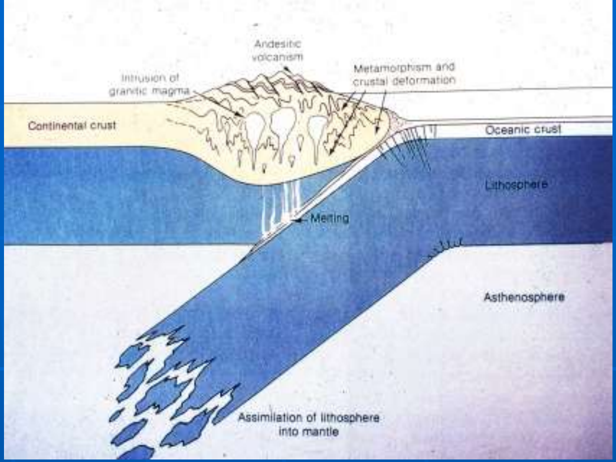


Plate Tectonics

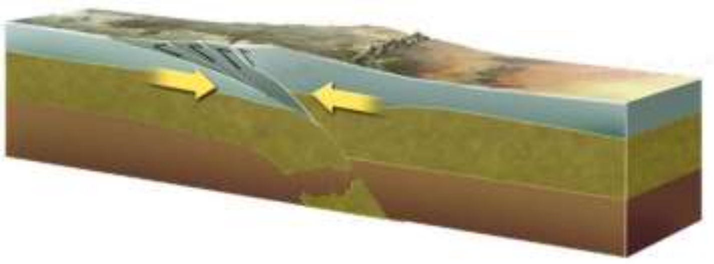


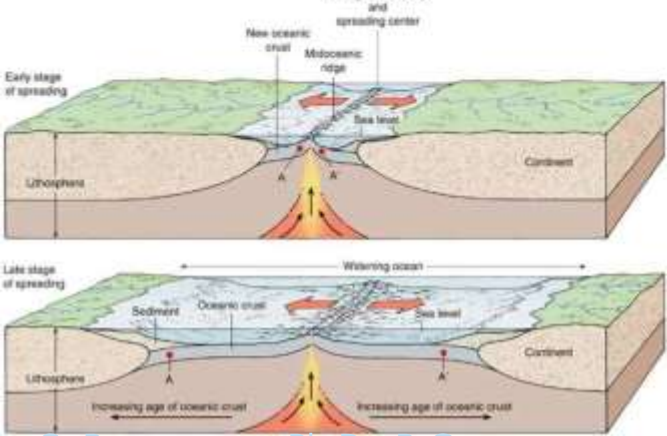
Paleozoic = West-dipping subduction, Volcanoes, Appalachian Mountains



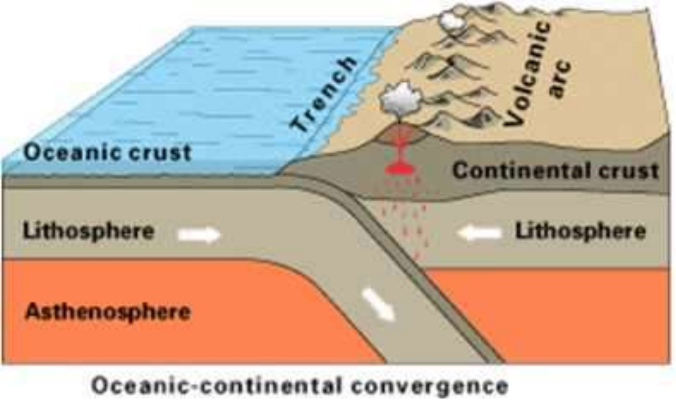
Sea floor spreading and mid-ocean ridge volcanism

Continent-continent collision and very tall mountains





Mesozoic-Cenozoic east-dipping subduction, Volcanoes, Mountains



Temp. & Geologic Time Scale

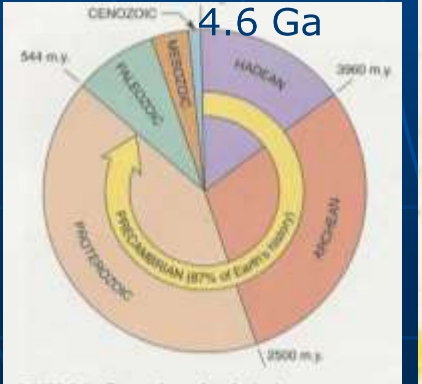
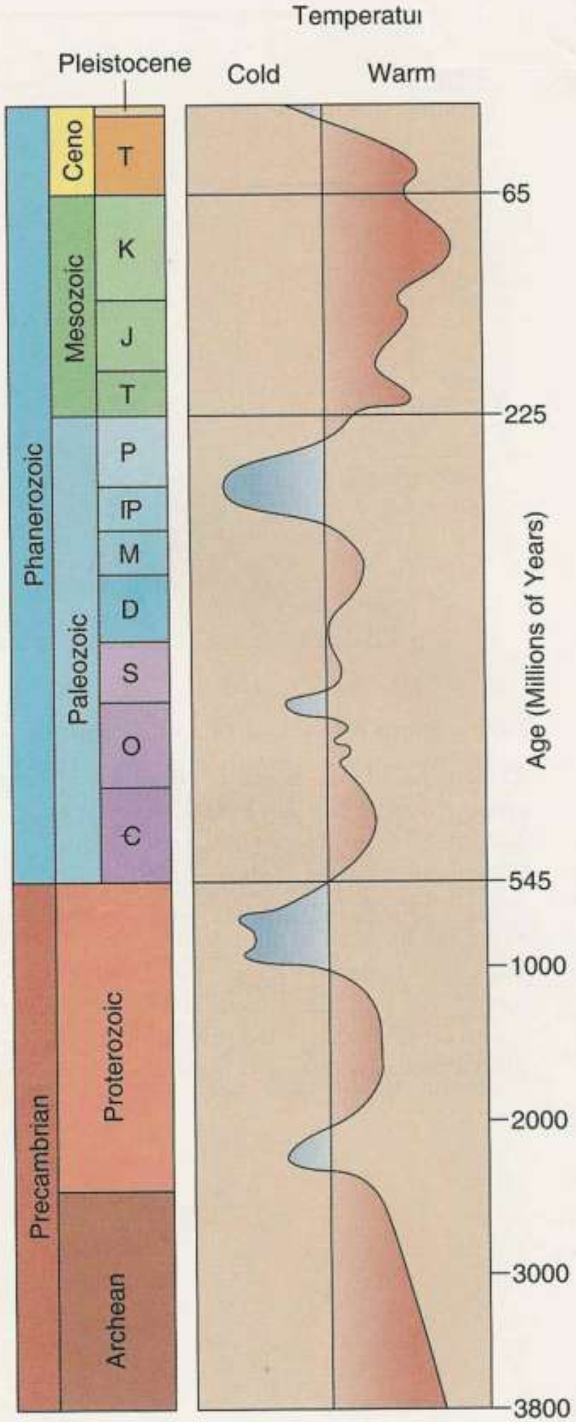
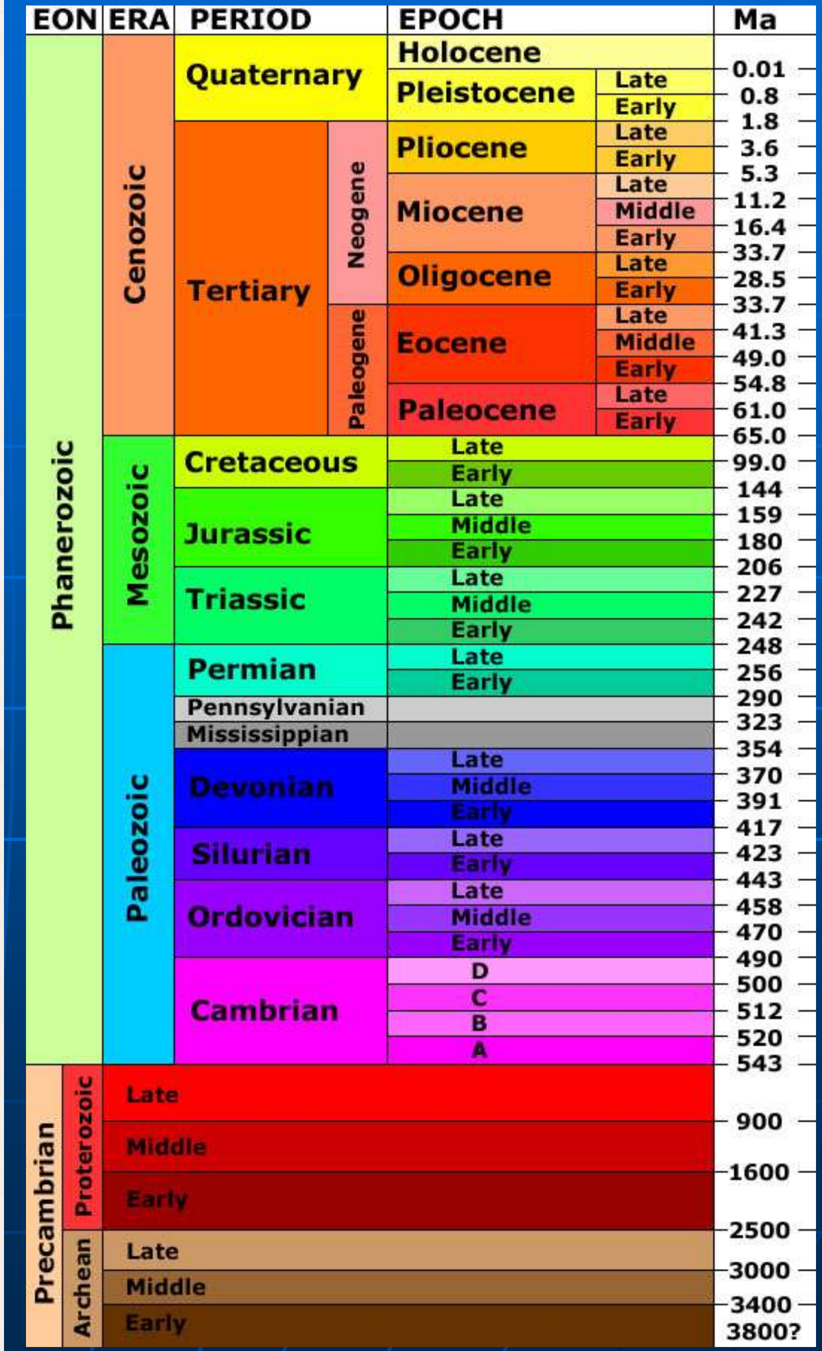


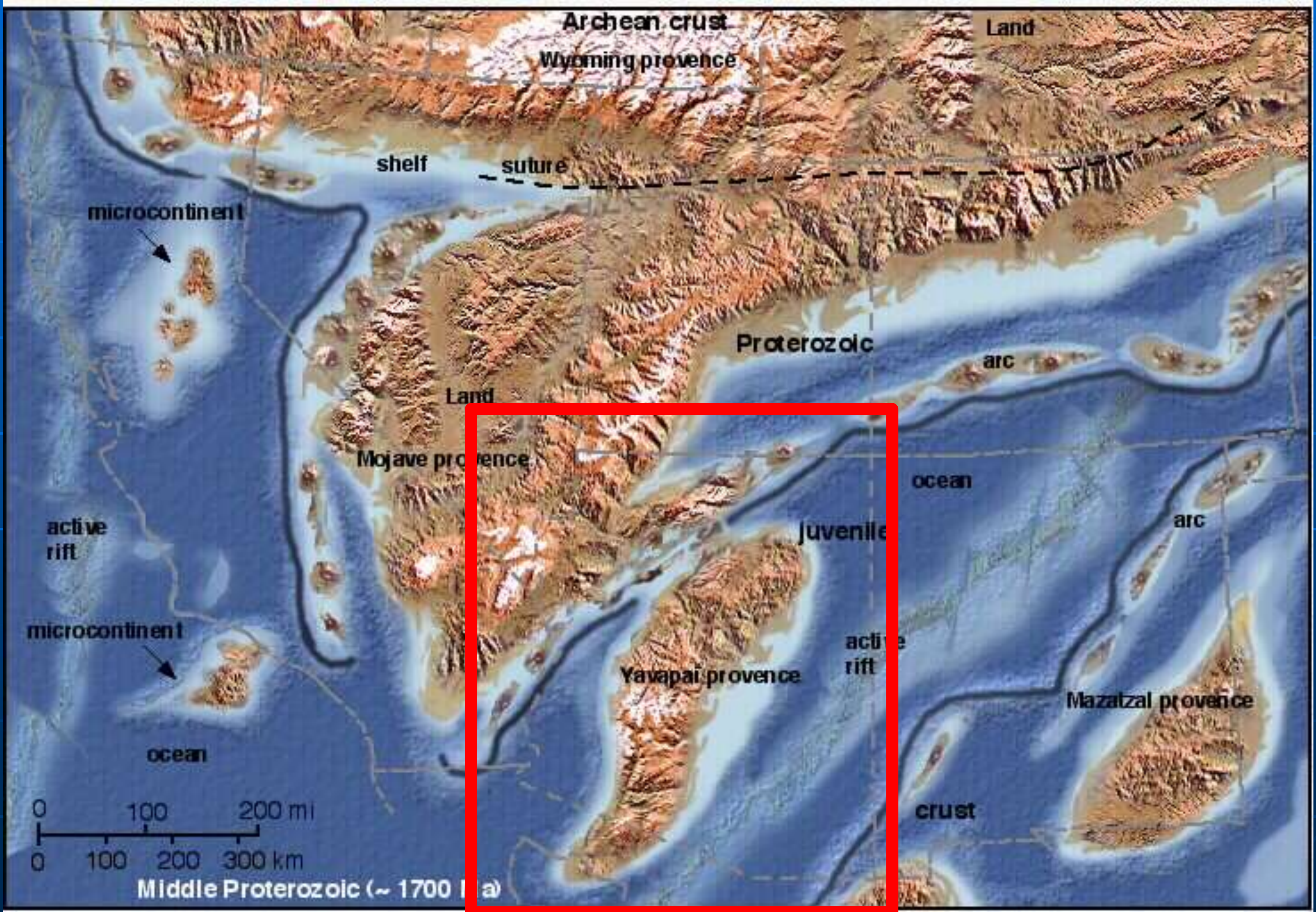
FIGURE 8-1 Proportions of geologic time encompassed by the Precambrian and its Hadean, Archean, and Proterozoic eons.





EON	ERA	PERIOD		EPOCH		Ma
Phanerozoic	Cenozoic	Quaternary		Holocene		0.01
				Pleistocene	Late	0.8
					Early	1.8
		Tertiary	Neogene	Pliocene	Late	3.6
					Early	5.3
				Miocene	Late	11.2
					Middle	16.4
					Early	33.7
				Oligocene	Late	28.5
					Early	33.7
			Paleogene	Eocene	Late	41.3
					Middle	49.0
					Early	54.8
				Paleocene	Late	61.0
					Early	65.0
	Mesozoic	Cretaceous		Late		99.0
				Early		144
		Jurassic		Late		159
				Middle		180
				Early		206
		Triassic		Late		227
				Middle		242
				Early		248
	Paleozoic	Permian		Late		256
				Early		290
		Pennsylvanian				323
		Mississippian				354
		Devonian		Late		370
				Middle		391
				Early		417
		Silurian		Late		423
				Early		443
		Ordovician		Late		458
				Middle		470
				Early		490
		Cambrian		D		500
				C		512
				B		520
				A		543
Precambrian	Proterozoic	Late				900
		Middle				1600
		Early				2500
	Archean	Late				3000
		Middle				3400
		Early				3800?

Meso-proterozoic (1.7 Ga)



PreCambrian Arizona

Inner Gorge - metamorphic rocks

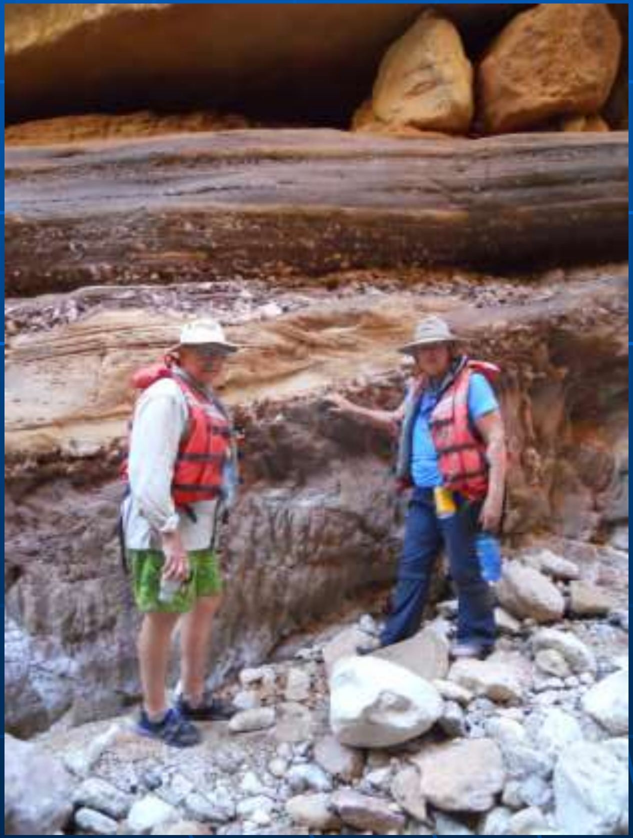
Mountain building episode in younger PreCambrian (older Proterozoic)

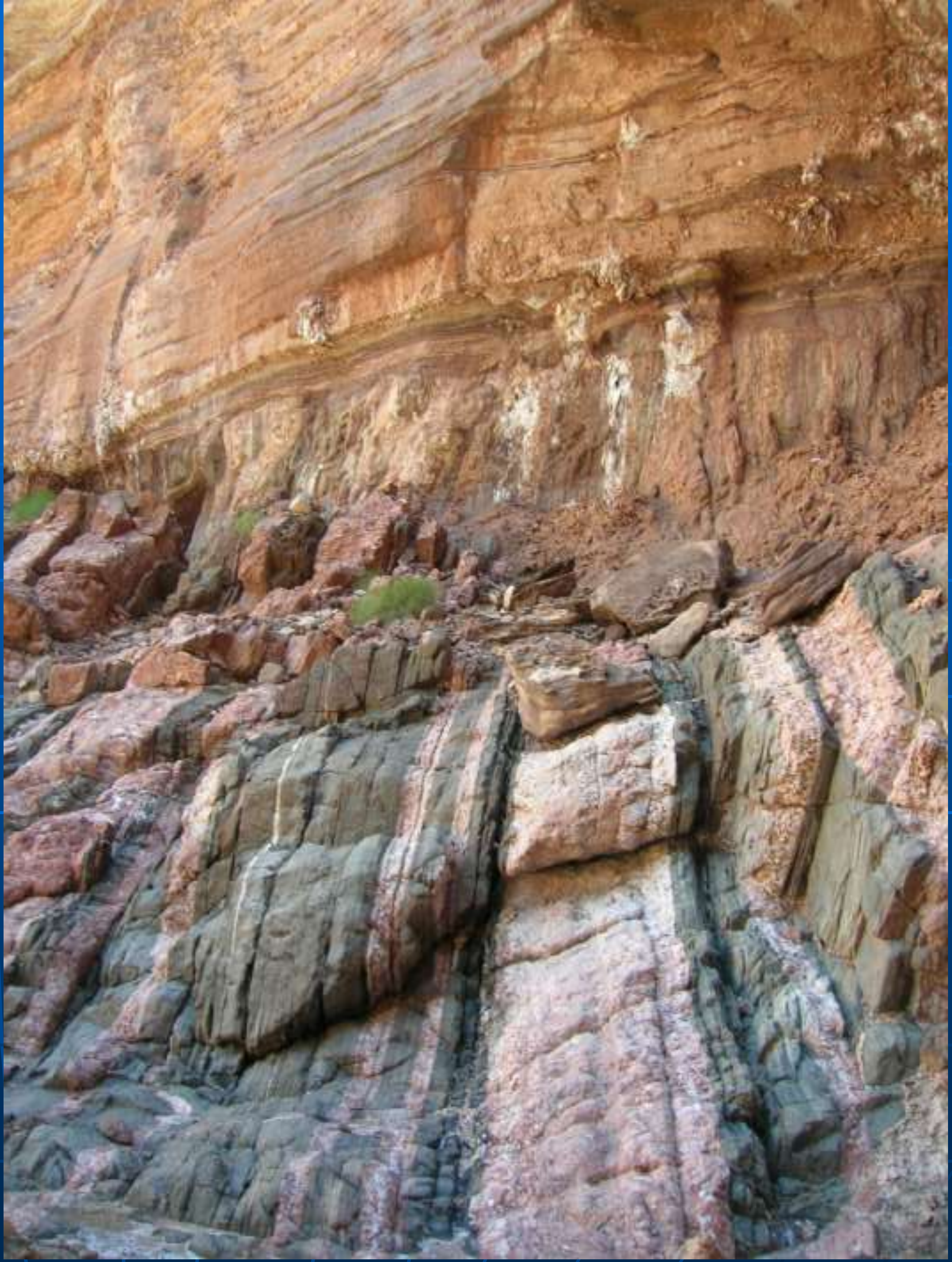
- 1.7 billion years – Mazatzal Orogeny produced Rocky Mt.-style mountains
- Metamorphism, folding, later intrusion of granitic rocks

Inner Gorge Grand Canyon, black Vishnu Schist, intruded by white Zoroaster Granite, Tapeats Sandstone deposited on unconformity

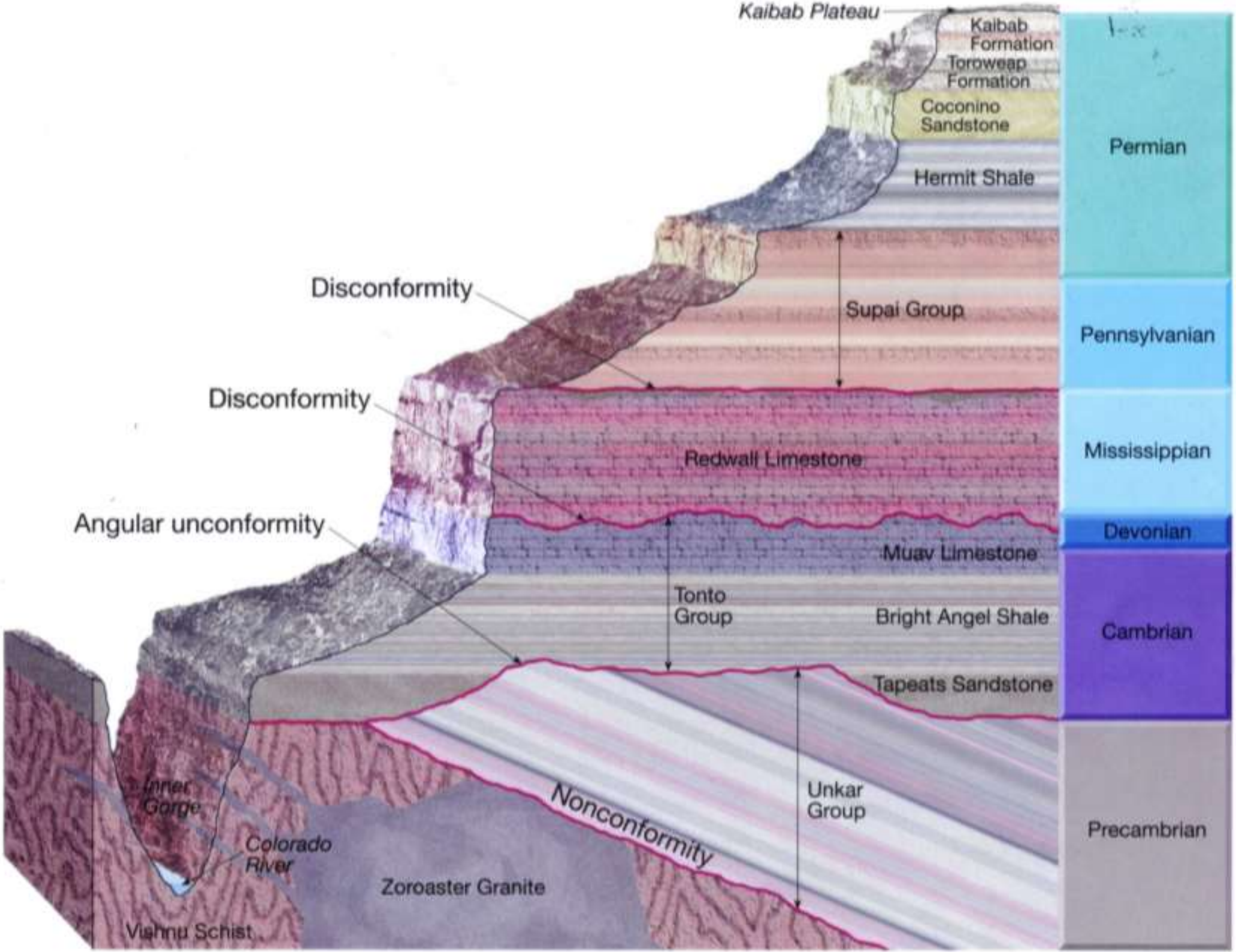
The Great Unconformity

900 million years of erosion
- Schist (1700 Ma) and Granite (1400 M) overlain by sandstone (500 Ma)





Unconformities in the Grand Canyon



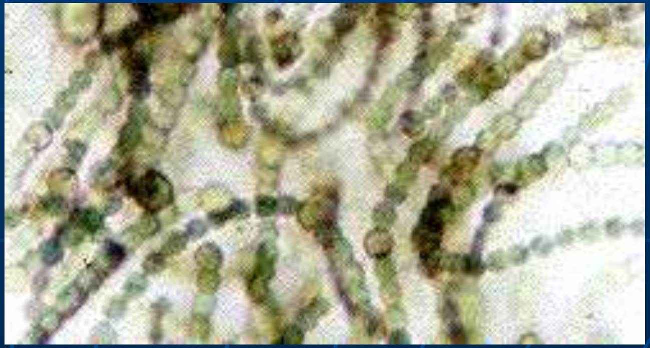
Meso-proterozoic (1.1 Giga-annum [Ga])

Grand Canyon Group

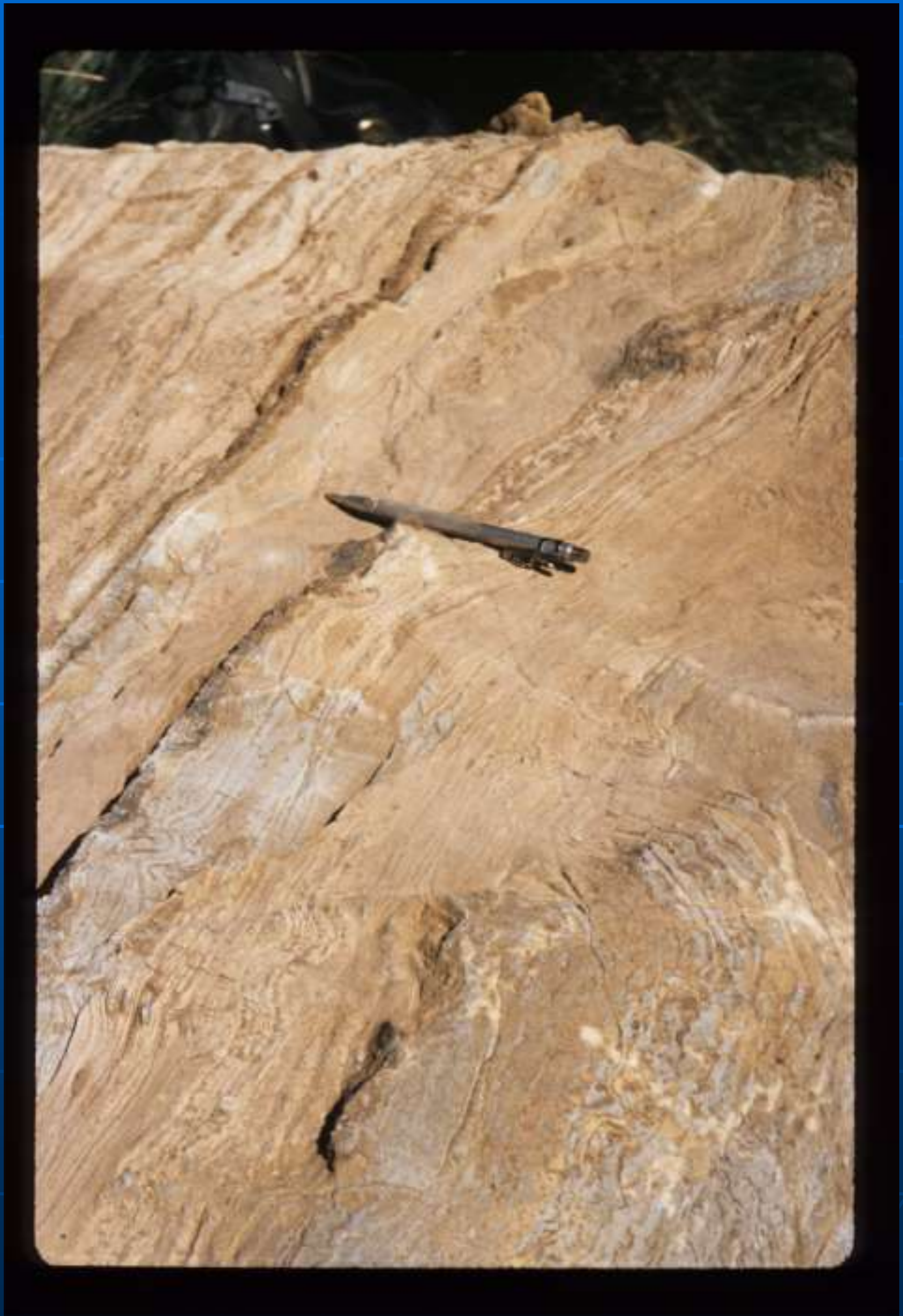
- 1.1 billion years ago - River bed, deltas, lava flows (about 10,000 ft thick). Later faulting created fault block mountains (4,000' offset)
- Eroded away to a nearly flat surface before the deposition of the Tapeats Sandstone 500 million years ago.

Blue-green algae gave O_2

- Photosynthesis by blue green algae (cyanobacteria) since 3.5 billion yrs ago
- When pigments developed in cells, they could absorb and process light.
- The products of this process were energy and oxygen.
- Between 2.4 – 2.2 billion years ago, the greater numbers of cyanobacteria increased production of oxygen.
- By 1.8-1.6 Ga, O_2 rose from 1% to 15%.
- Stromatolites = deposits of calcium carbonate in layers.

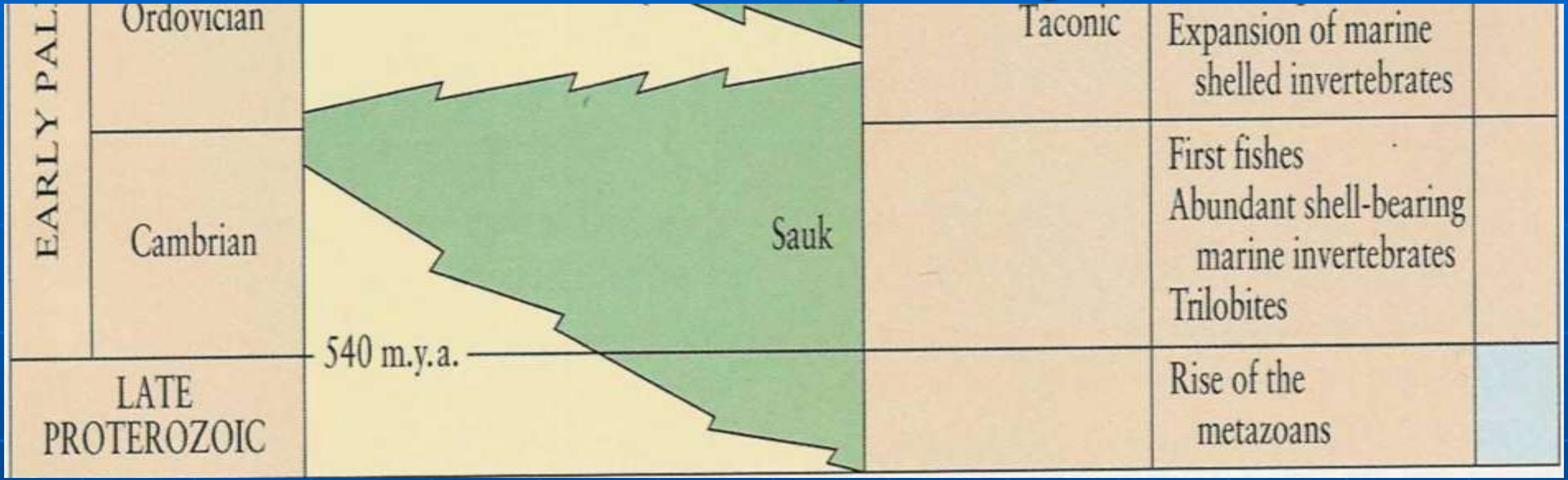


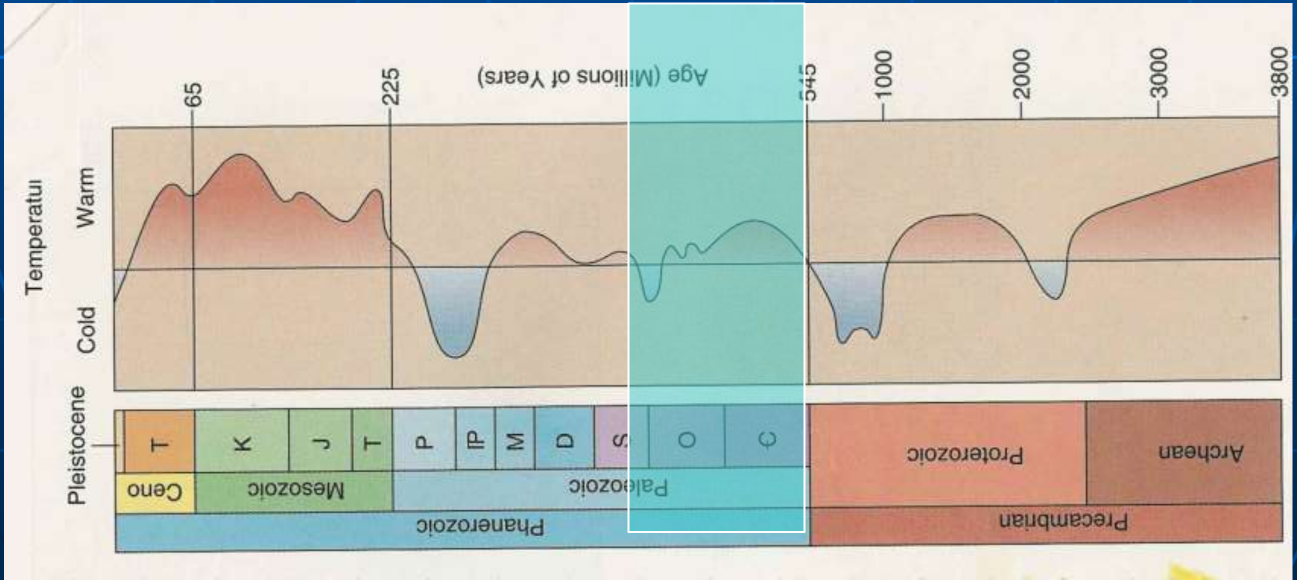
Stromatolites



Cambrian – Early Ordovician

543 - 470 million years ago (Ma)





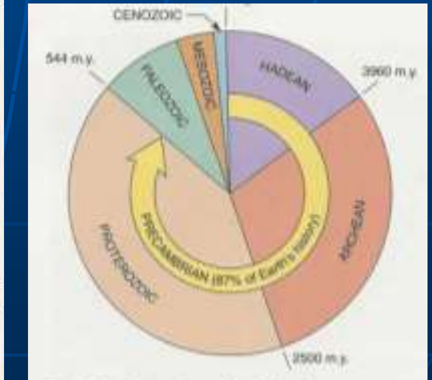
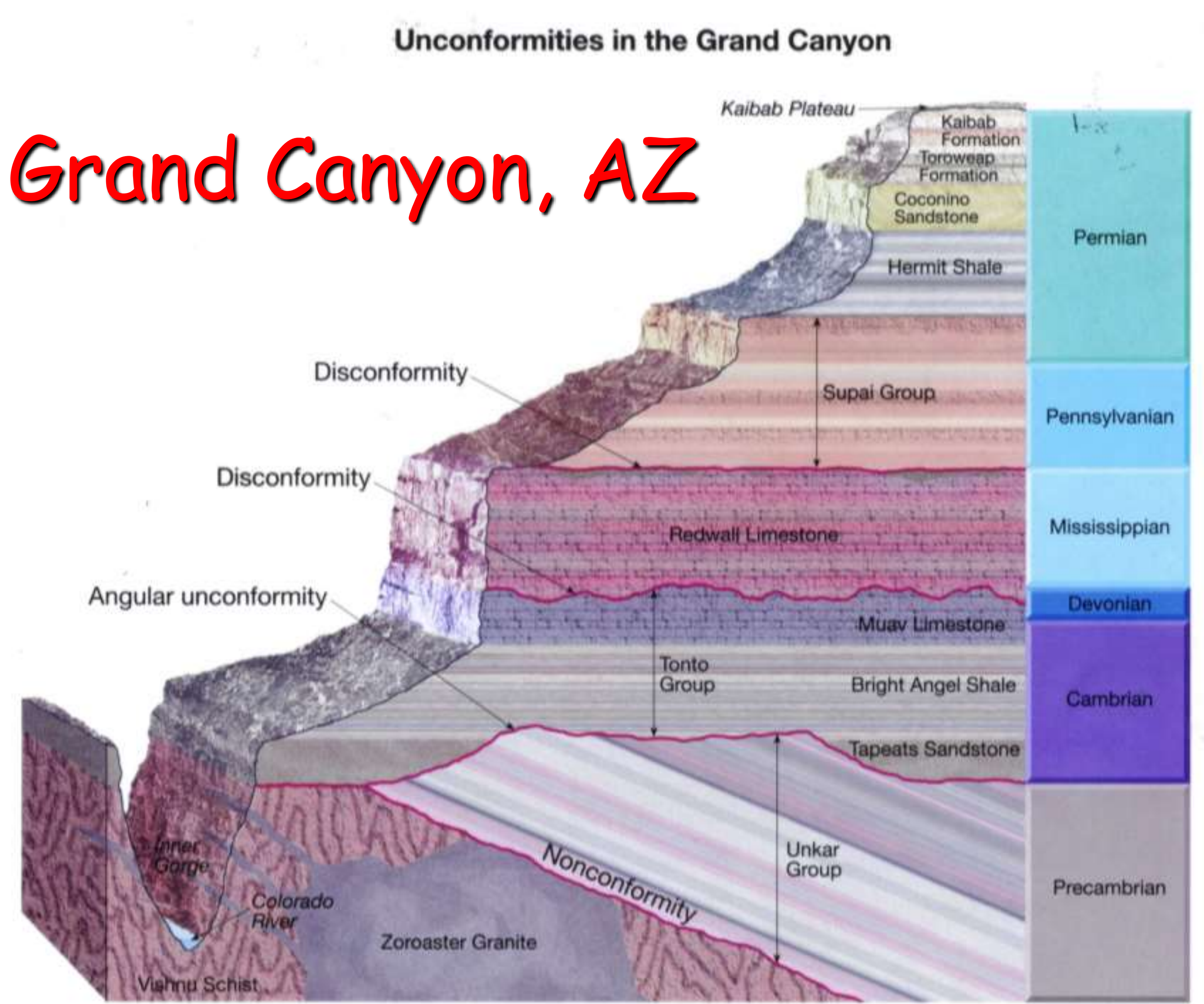


FIGURE 8-1 Proportions of geologic time encompassed by the Precambrian and its Hadean, Archean, and Proterozoic eons.

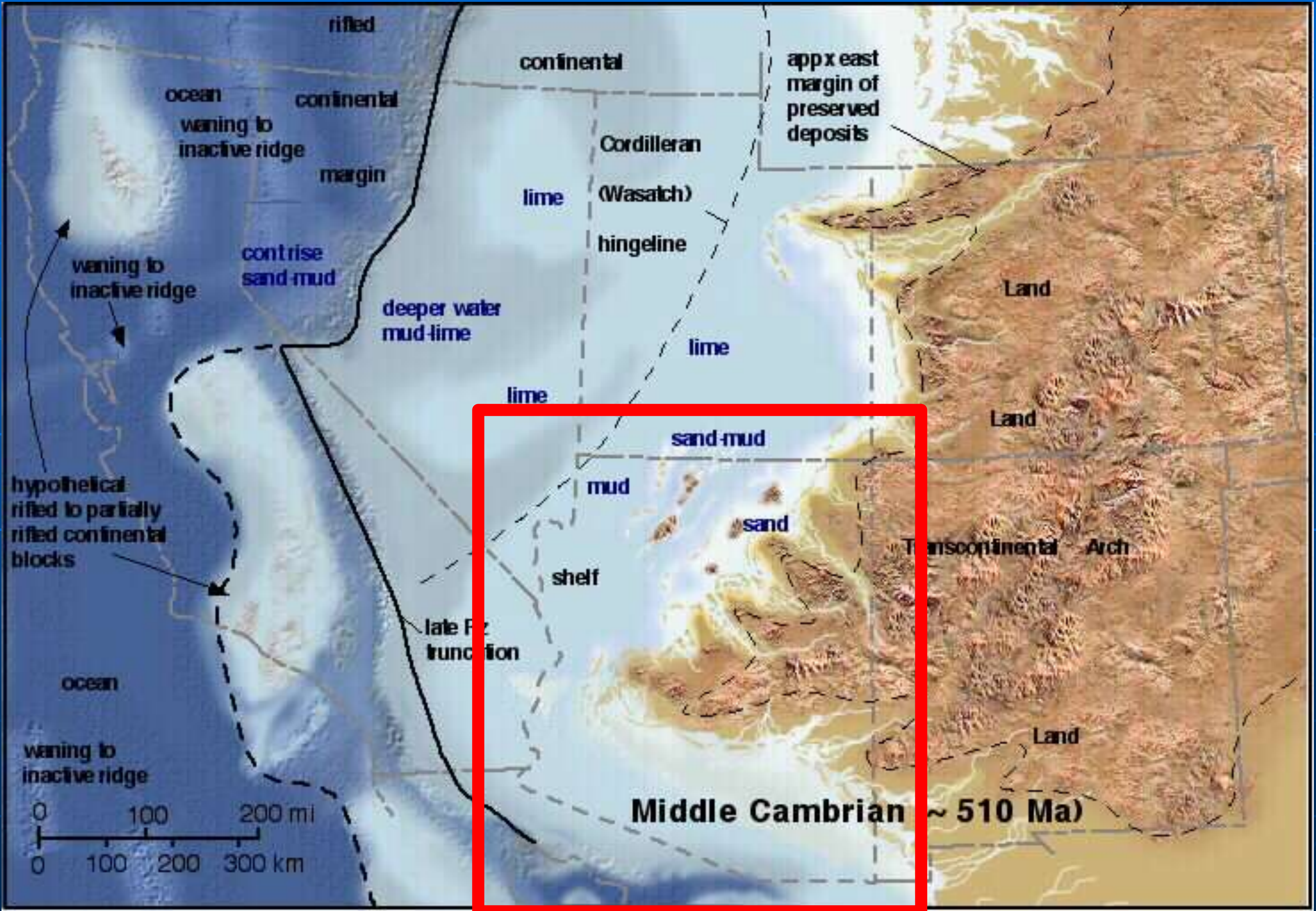
Grand Canyon, AZ



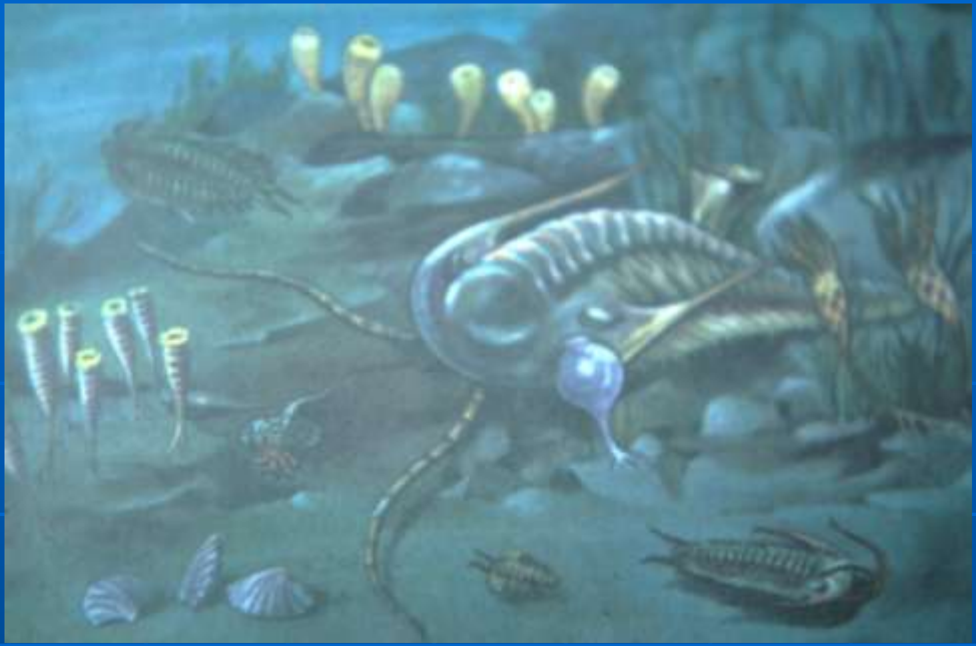
Unconformities in the Grand Canyon

Grand Canyon formations

Cambrian (543-490 Ma)



trilobites



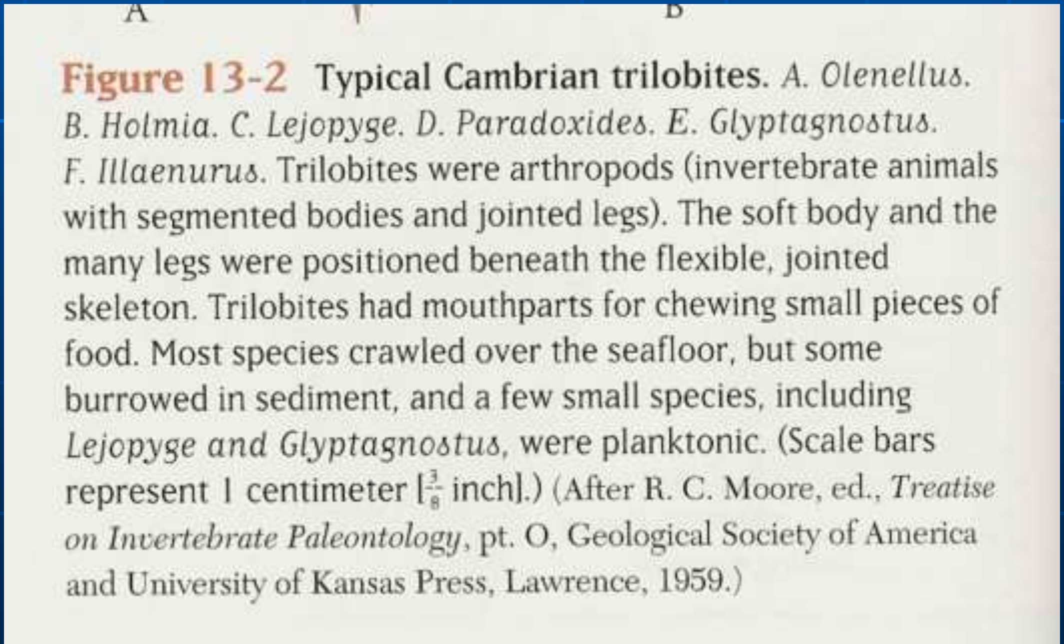
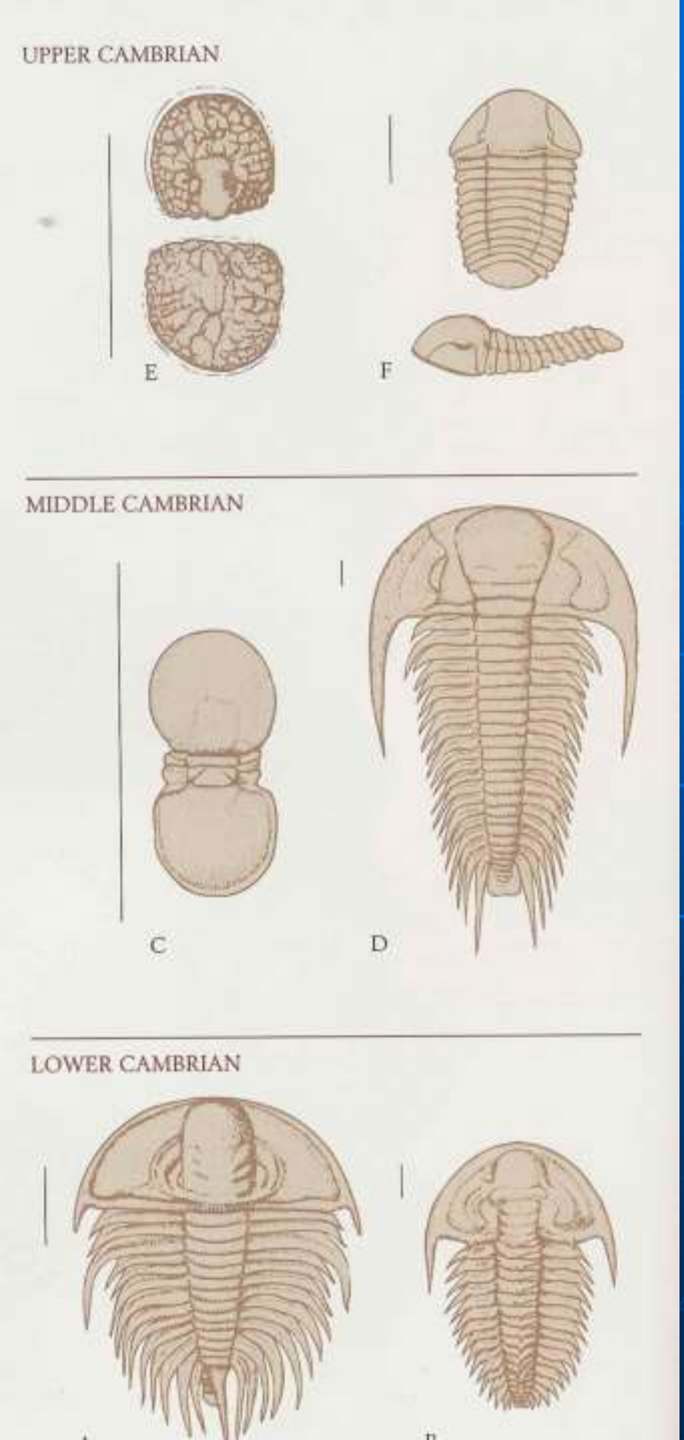
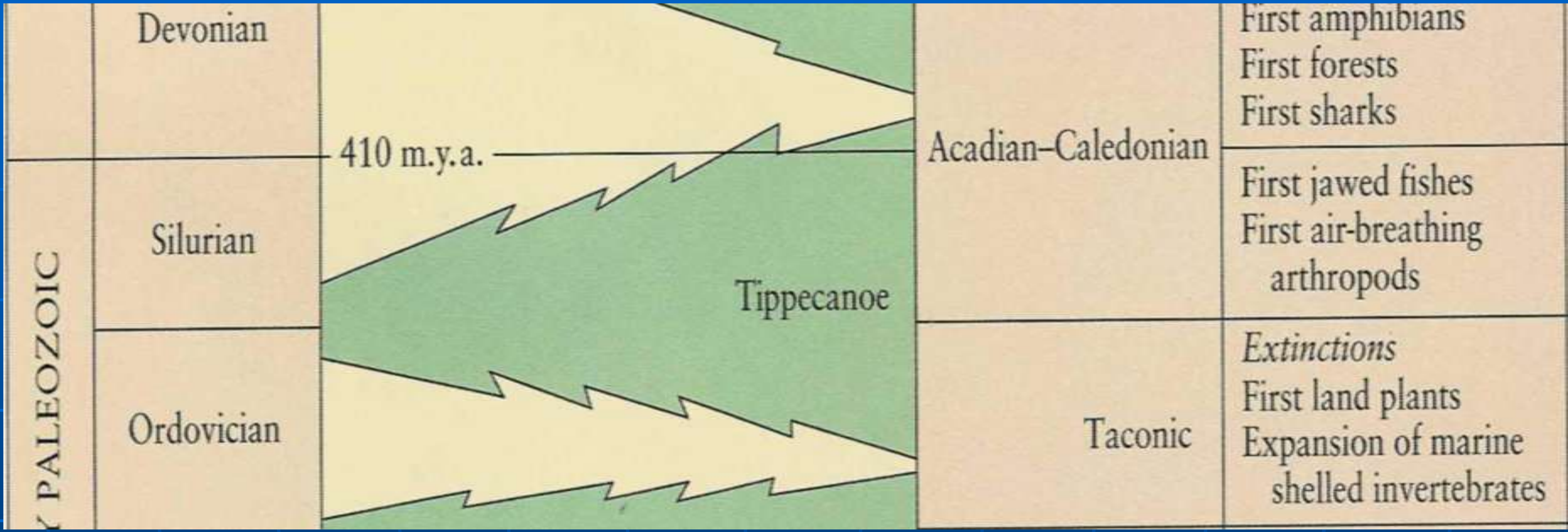
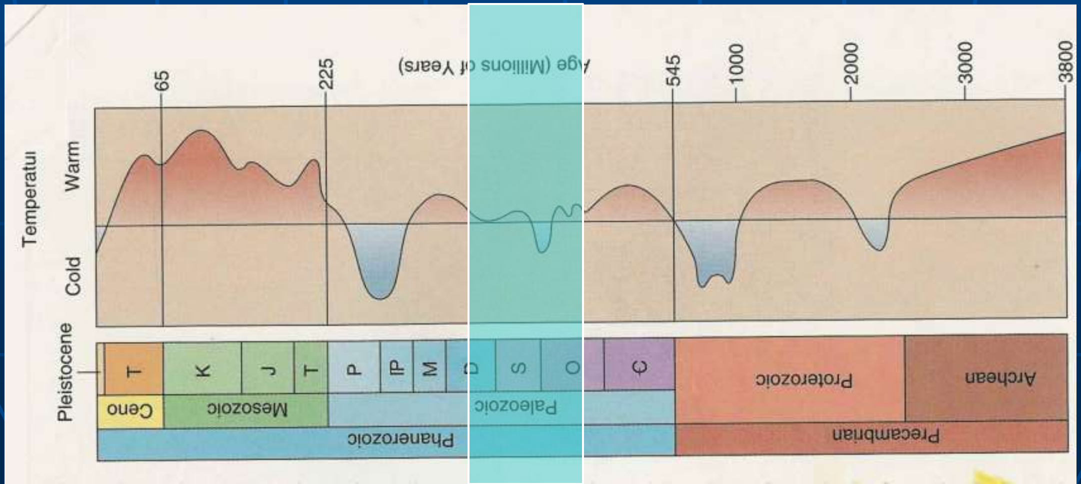


Figure 13-2 **Typical Cambrian trilobites.** A. *Olenellus.* B. *Holmia.* C. *Lejopyge.* D. *Paradoxides.* E. *Glyptagnostus.* F. *Illaenurus.* Trilobites were arthropods (invertebrate animals with segmented bodies and jointed legs). The soft body and the many legs were positioned beneath the flexible, jointed skeleton. Trilobites had mouthparts for chewing small pieces of food. Most species crawled over the seafloor, but some burrowed in sediment, and a few small species, including *Lejopyge and Glyptagnostus,* were planktonic. (Scale bars represent 1 centimeter [$\frac{3}{8}$ inch].) (After R. C. Moore, ed., *Treatise on Invertebrate Paleontology*, pt. O, Geological Society of America and University of Kansas Press, Lawrence, 1959.)



Middle Ordovician – Early Devonian (~470-400 Ma)





Late Ordovician environments (430 Ma)

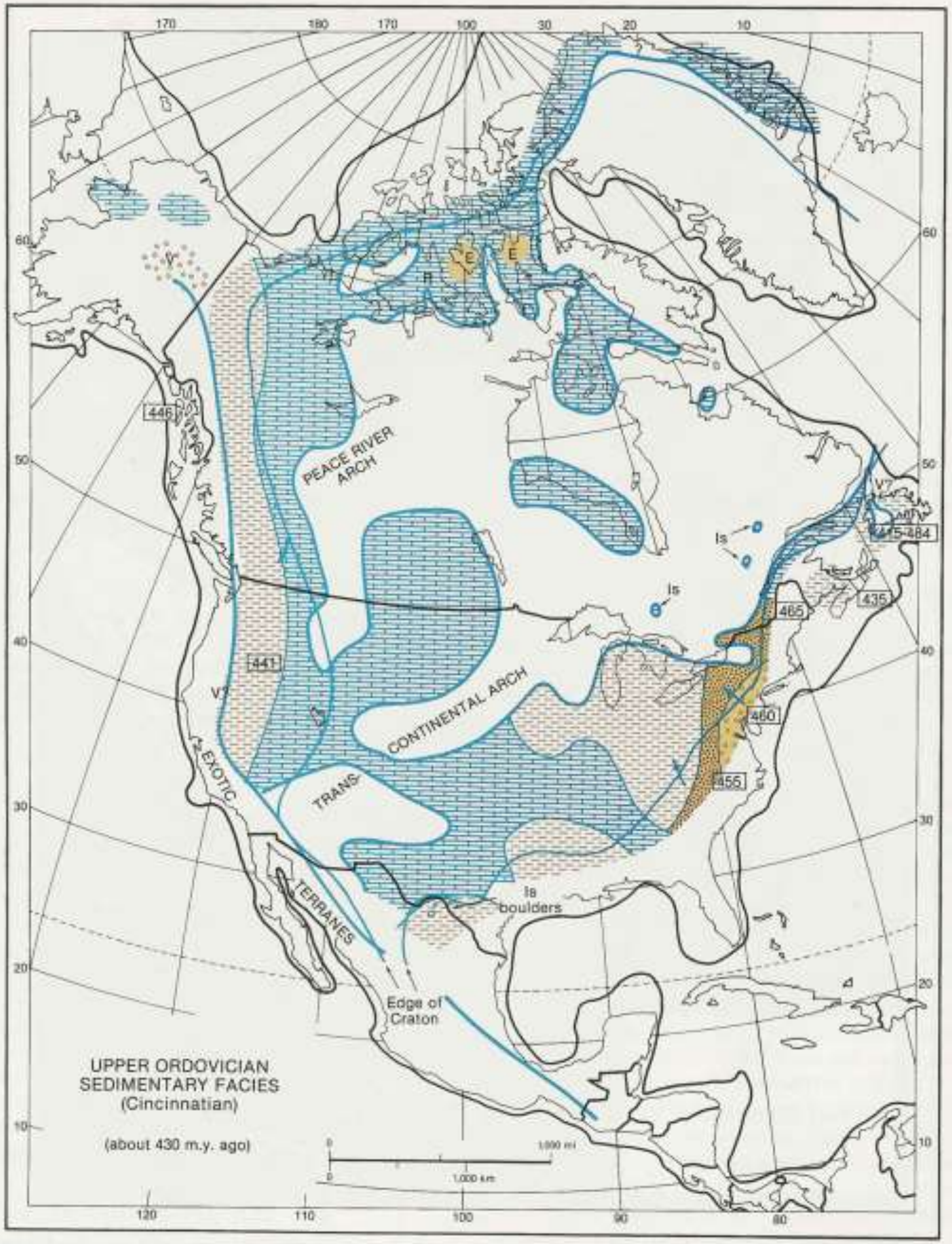
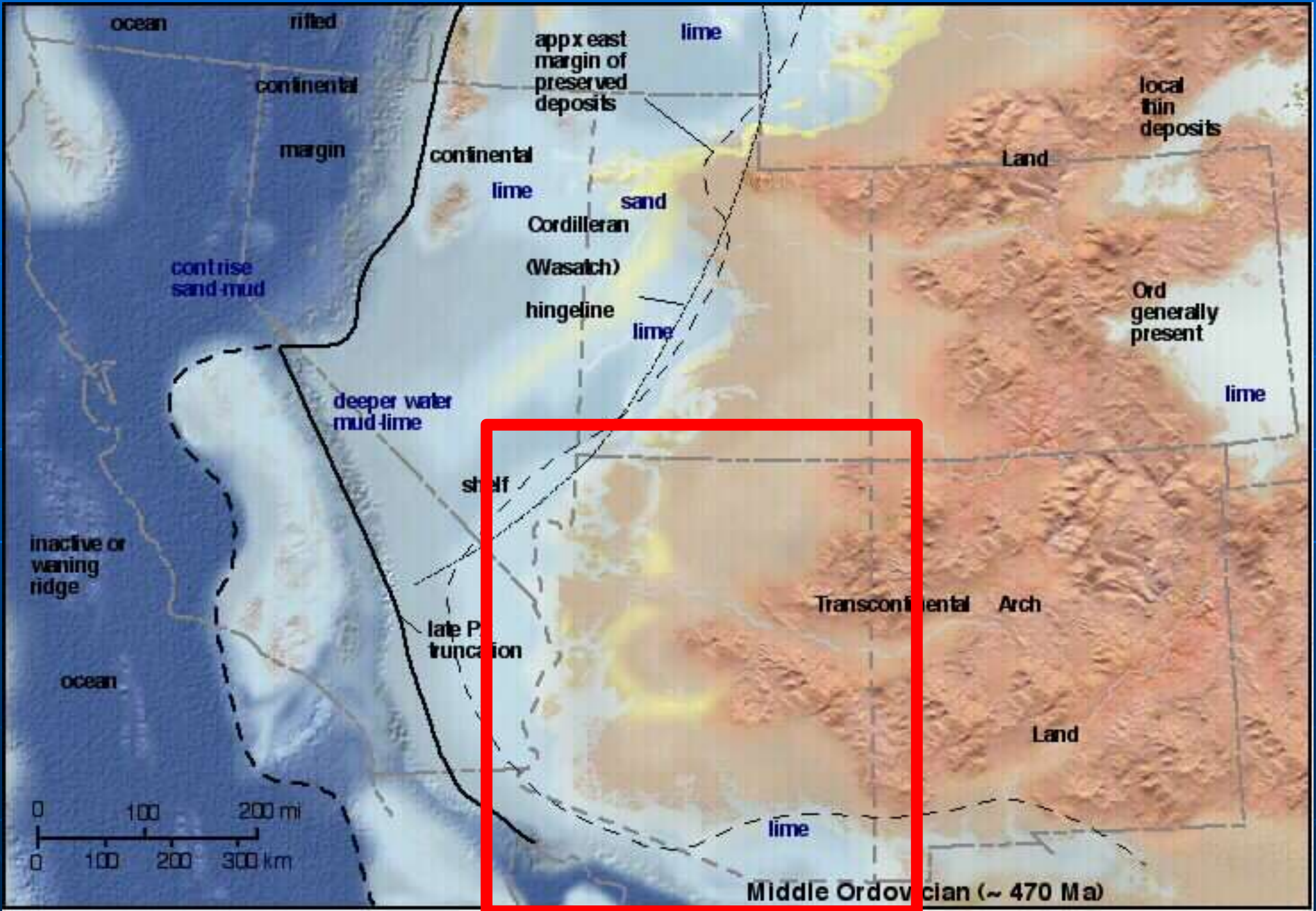


Figure 11.15 Upper Ordovician sediment patterns for North America. Widely scattered patches of sediments on the Canadian Shield prove the great extent of the Late Ordovician sea. Absence of Ordovician strata on several arches proves subsequent warping and erosion of these arches. Note the spread of red beds and marine shales westward from the Appalachian region, forming a clastic wedge. (See Box 10.2 for symbols and sources.)

Ordovician (488-443 Ma)



Ordovician life

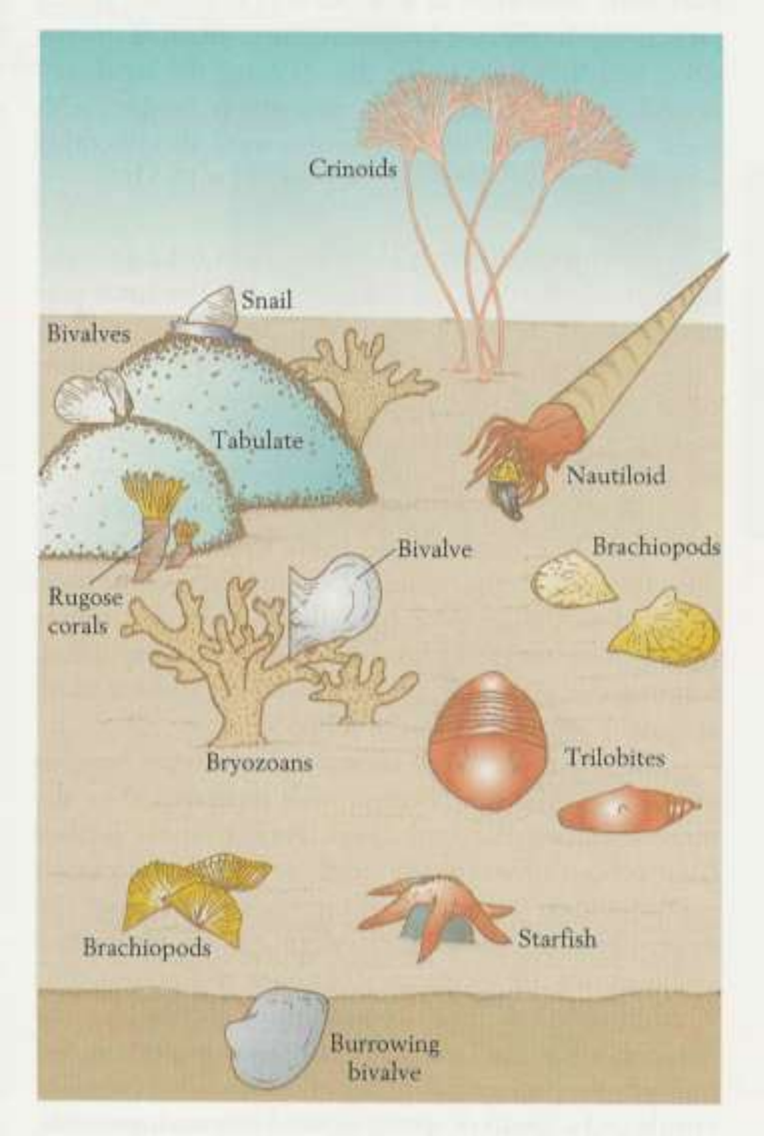
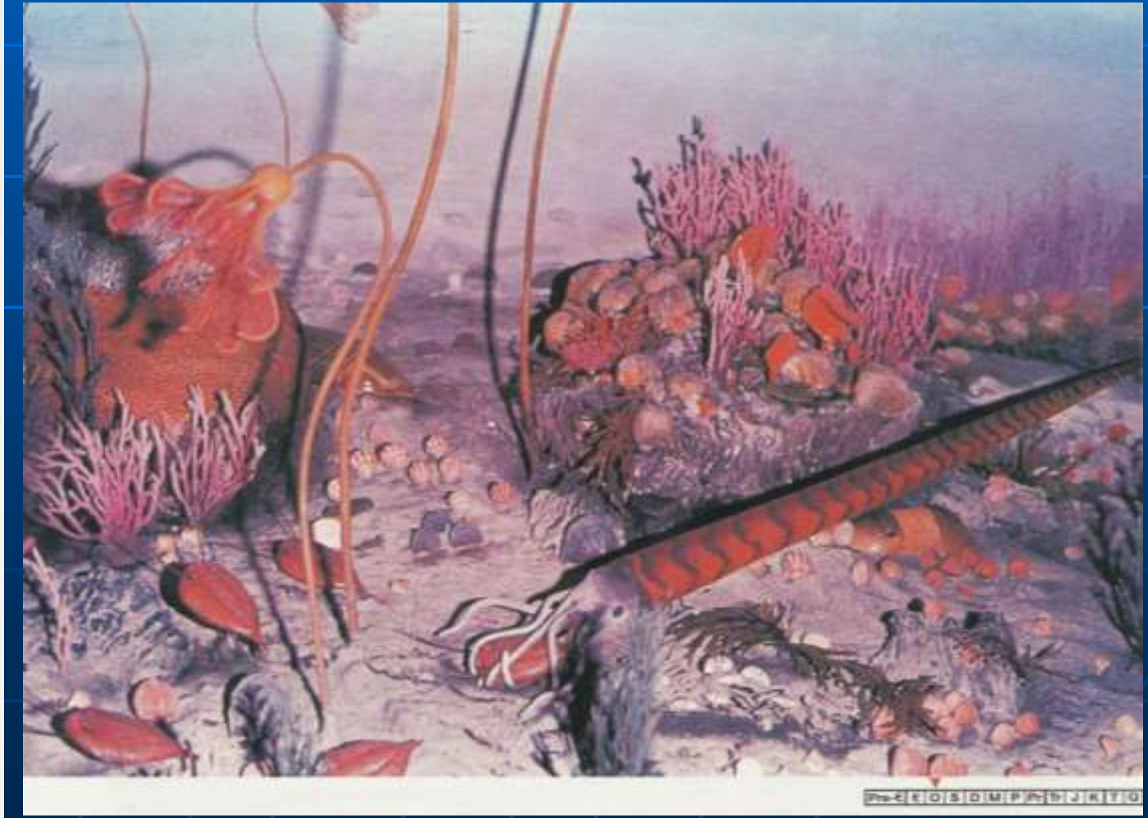
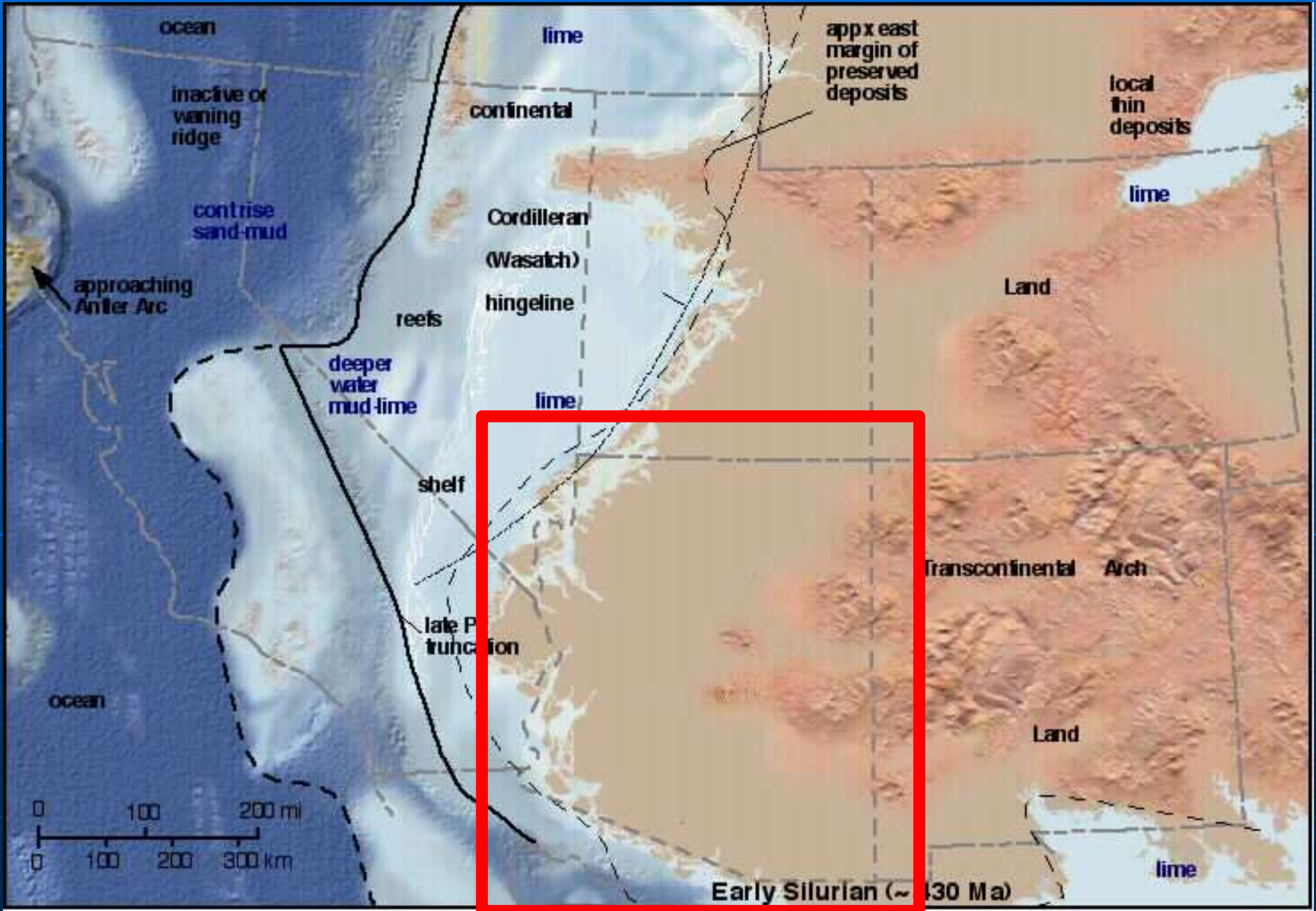


Figure 13-11
Ordovician invertebrate fossils. *A.* A straight-shelled nautiloid about 15 centimeters (6 inches) long. *B.* A spiny trilobite that lived on the sediment surface. *C.* A smooth-shelled burrowing trilobite. *D.* A snail (gastropod). *E.* and *F.* Two kinds of articulate brachiopods. *G.* A bivalve mollusk that lived on the sediment surface. *H.* A branched bryozoan colony. *I.* A tabulate coral colony. *J.* A stromatoporoid colony. *K.* A rugose coral. (Courtesy Smithsonian Institution, photo by Chip Clark.)



Silurian (443-417 Ma)



Silurian - Devonian fossils

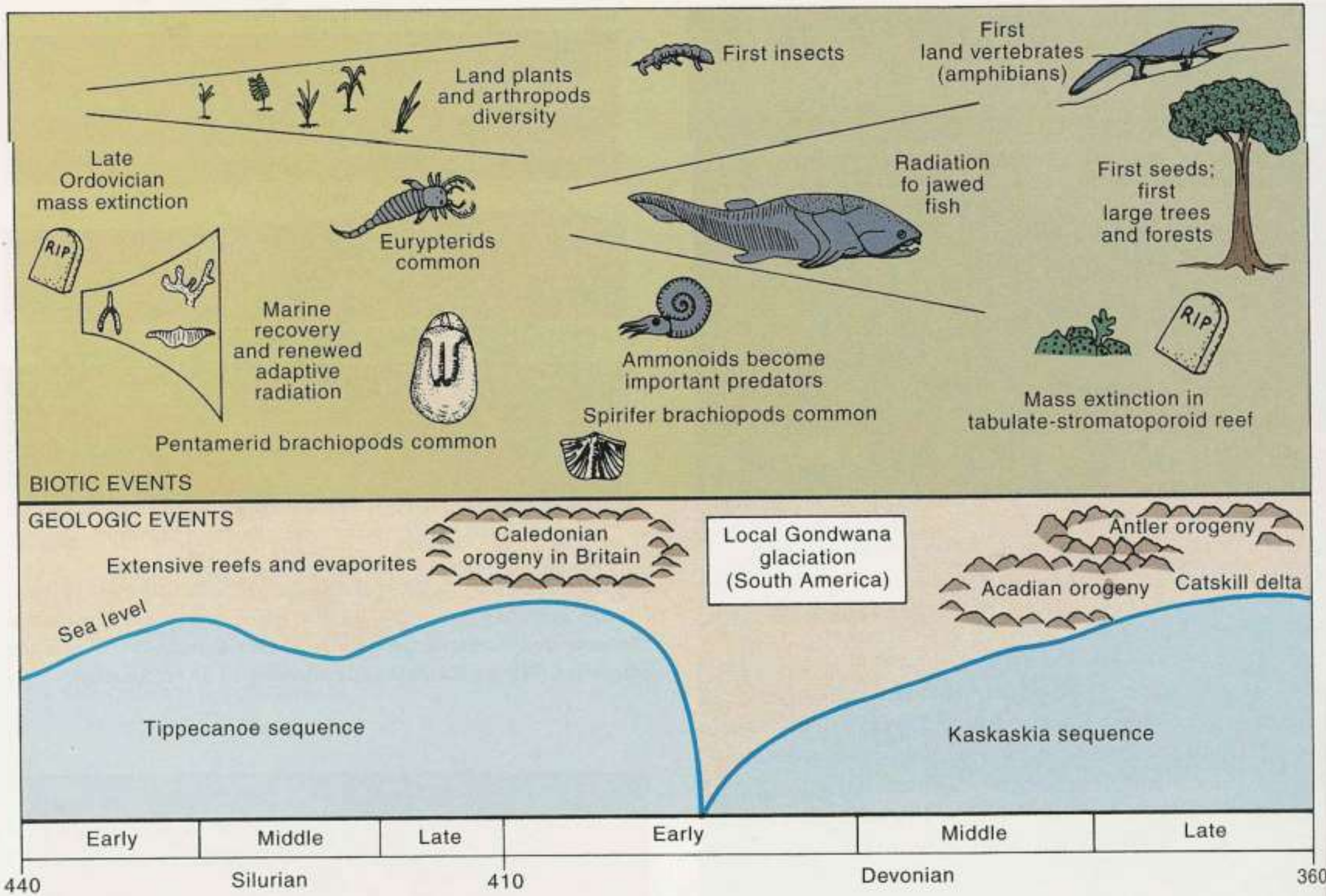
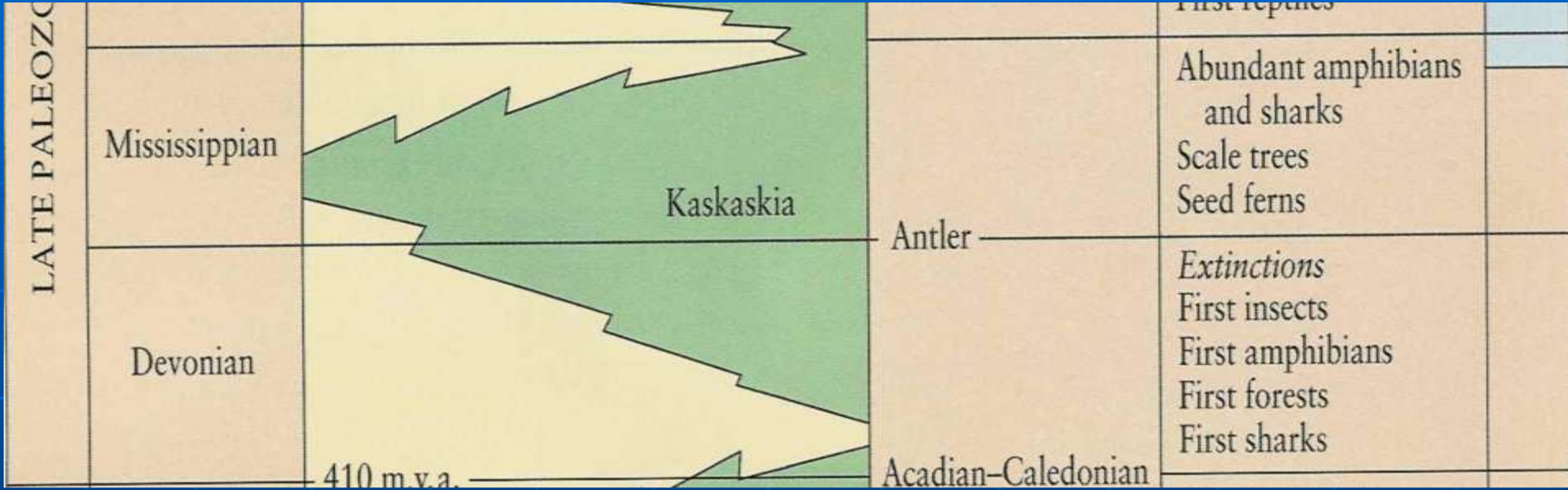
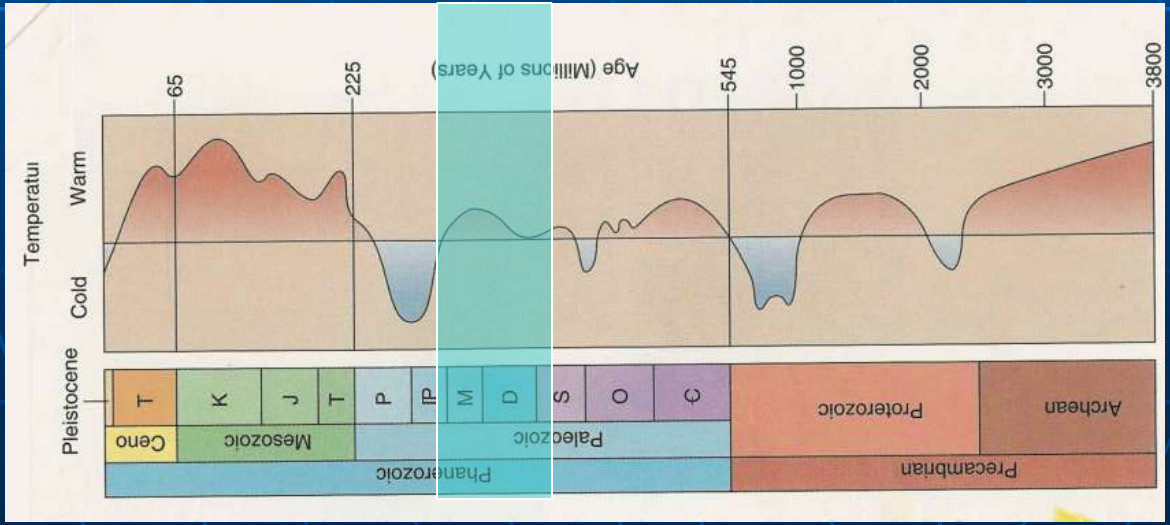


Figure 12.50 Summary time line of events of the Silurian and Devonian.

Devonian – Mississippian

416-359 – 318 Ma





Devonian environments

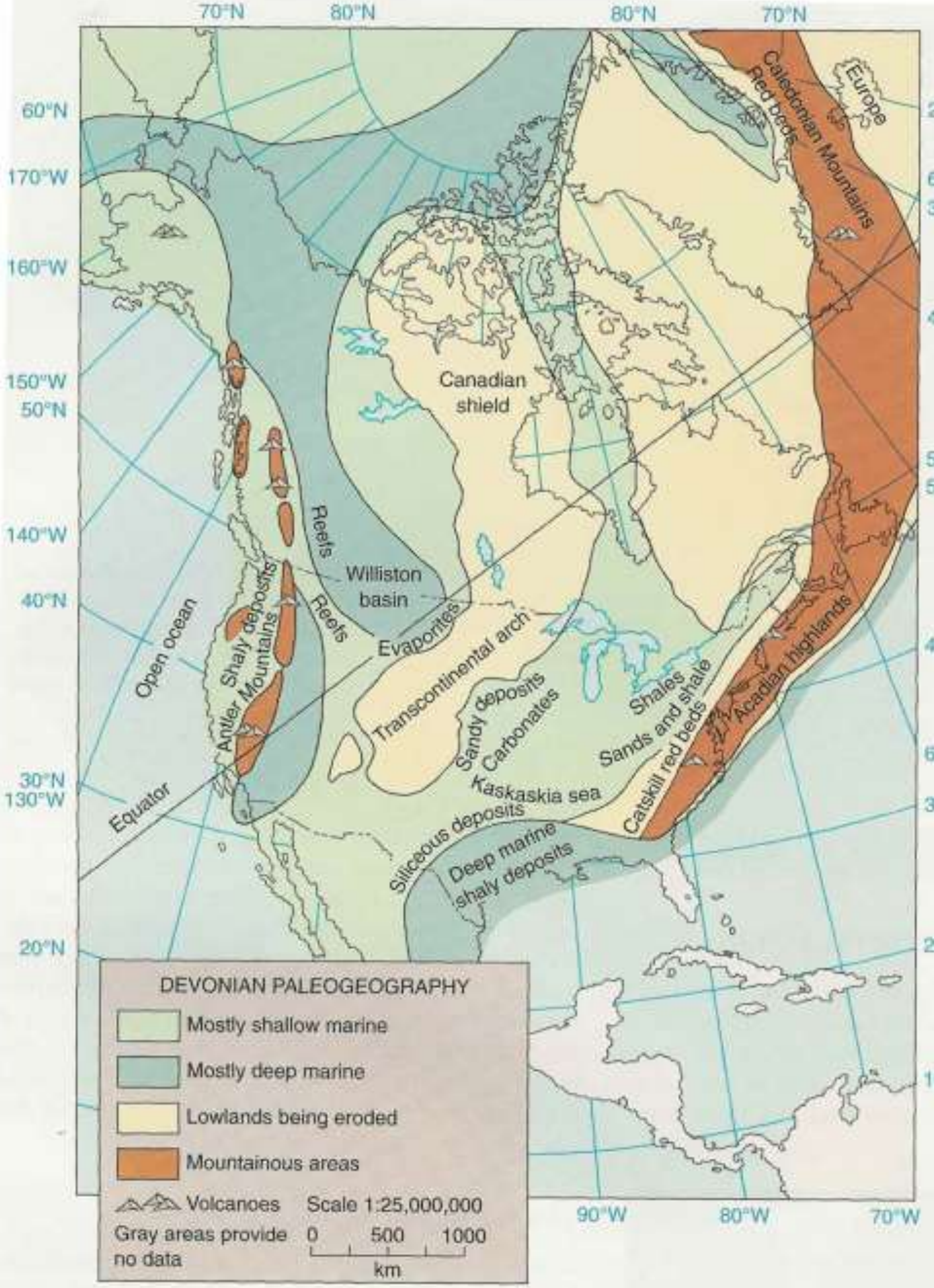


FIGURE 9-4 Paleography of North America during the Devonian Period.

Devonian (416-359 Ma)

Devonian fossils

e solitary horn coral *Zaphrenthis* v

Mucrospirifer

Lithostrotionella.

Platyrachella (

Hexagonaria.

Devonian armored fish

FIGURE 10-62 **The gigantic armored skull and thoracic shield of the formidable late Devonian placoderm fish known as *Dunkleosteus*.** *Dunkleosteus* was over 10 meters (about 30 feet) long. The skull shown here is about 1 meter tall. It is equipped with large bony cutting plates that functioned as teeth. Each eye socket was protected by a ring of four plates, and a special joint at the rear of the skull permitted the head to be raised, thereby making an extra large bite possible. *Dunkleosteus* ruled the seas 350 million years ago. (*Courtesy of the U.S. National Museum of Natural History, Smithsonian Institution; photograph by Chip Clark.*)

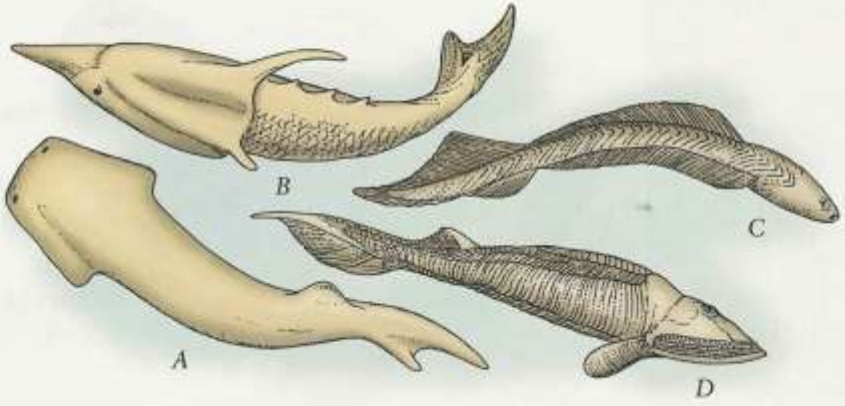


FIGURE 10-60 **Early Paleozoic ostracoderms.** (*A*) *Thelodus*, (*B*) *Pteraspis*, (*C*) *Jamoytius*, and (*D*) *Hemicyclaspis*, drawn to the same scale.

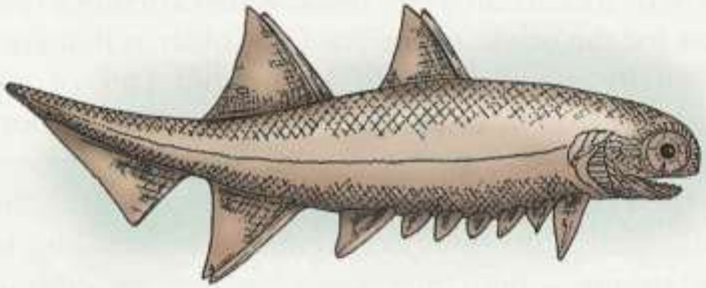


FIGURE 10-61 **The Early Devonian acanthodian fish *Climatius*.** (*After Romer, A. S. 1945.* Vertebrate Paleontology. *Chicago: University of Chicago Press.*)

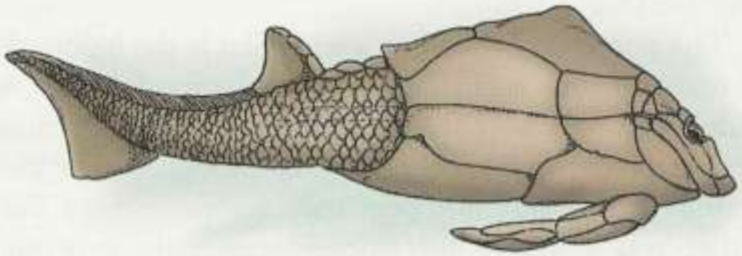


FIGURE 10-63 **The Devonian antiarch fish *Pterichthyodes*.** (*From Romer, A. S. 1945.* Vertebrate Paleontology. *Chicago: University of Chicago Press, p. 54, fig. 38.*)

Devonian plants

Figure 12.11 Artist's conception of the Late Devonian landscape. Tall seed fern and lycopsid trees are conspicuous, but most plants were low-growing psilophytes, lycopsids, sphenopsids, and ferns that clustered close to the water's edge. Against this backdrop, early land arthropods

Mississippian environments

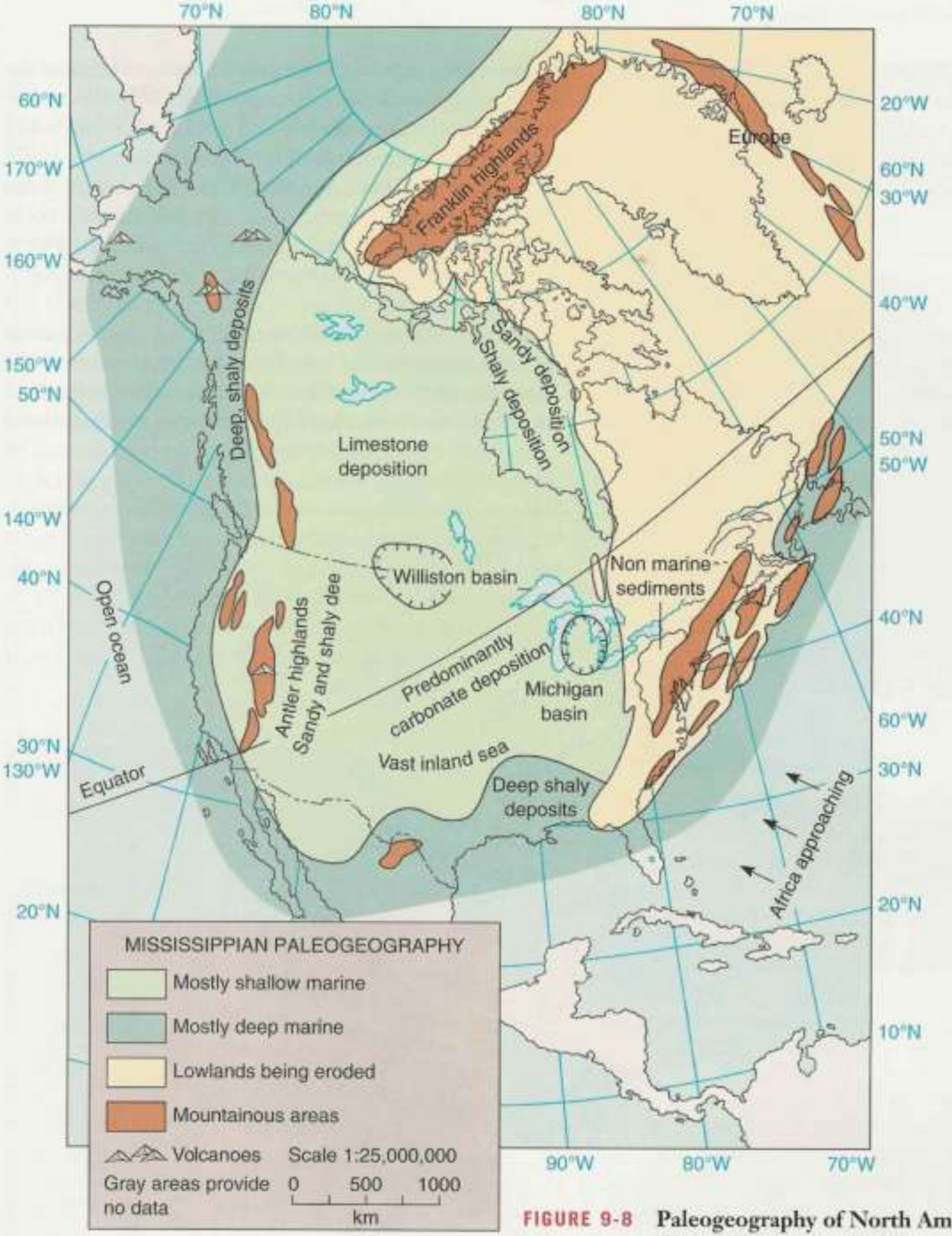
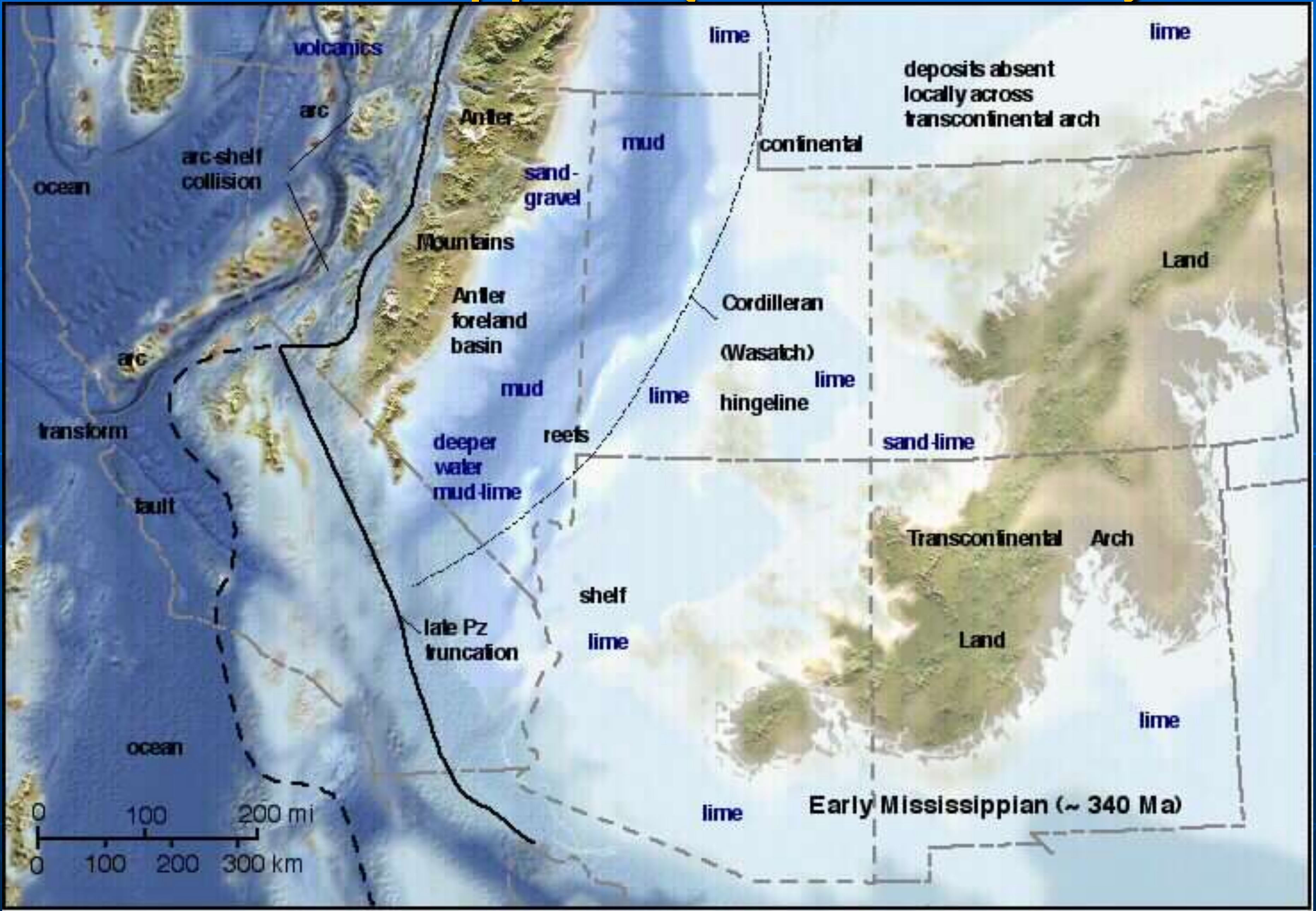


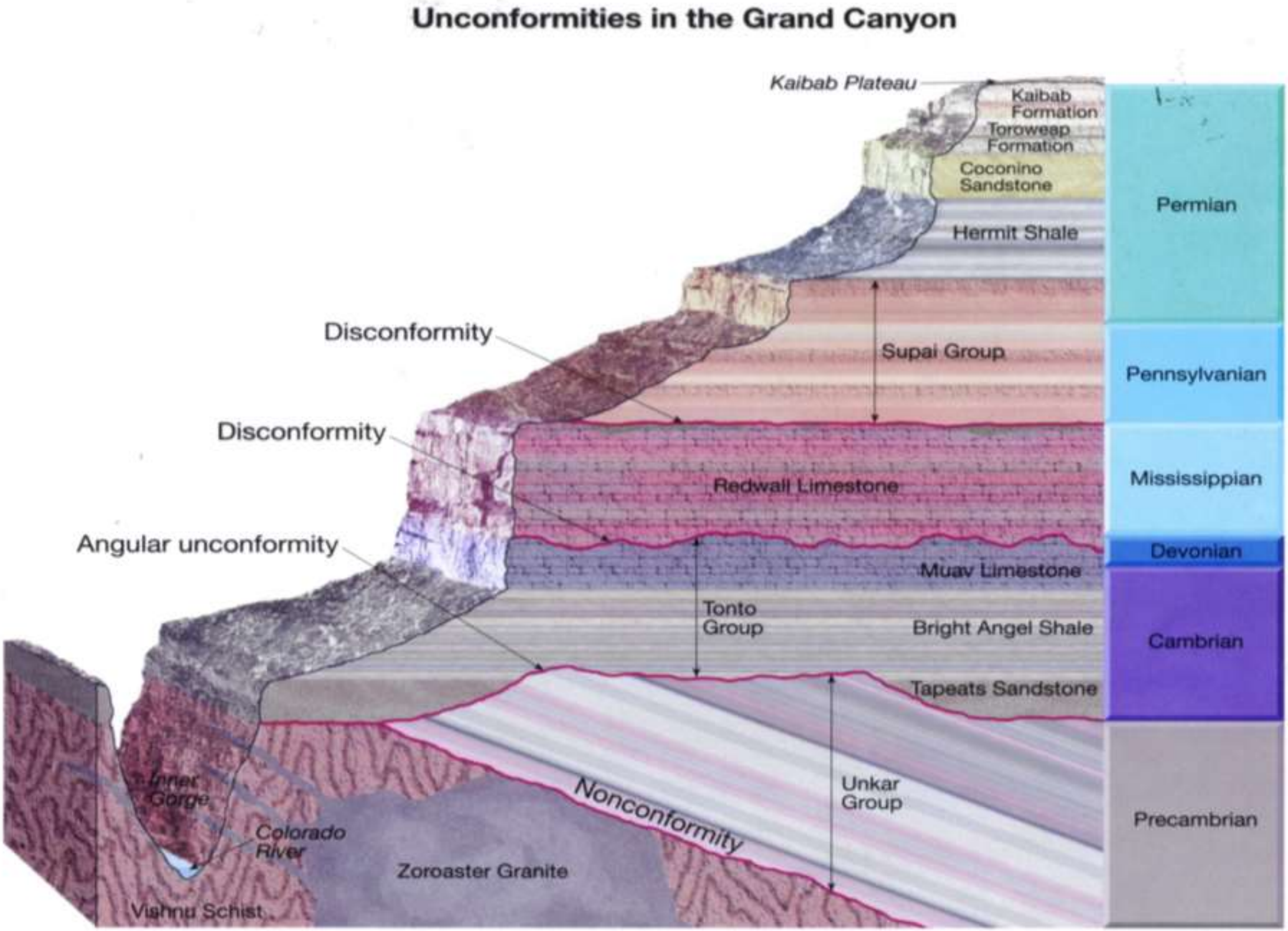
FIGURE 9-8 Paleogeography of North America during the Mississippian Period.

Mississippian (359-318 Ma)



Early Mississippian (~ 340 Ma)

Grand Canyon section

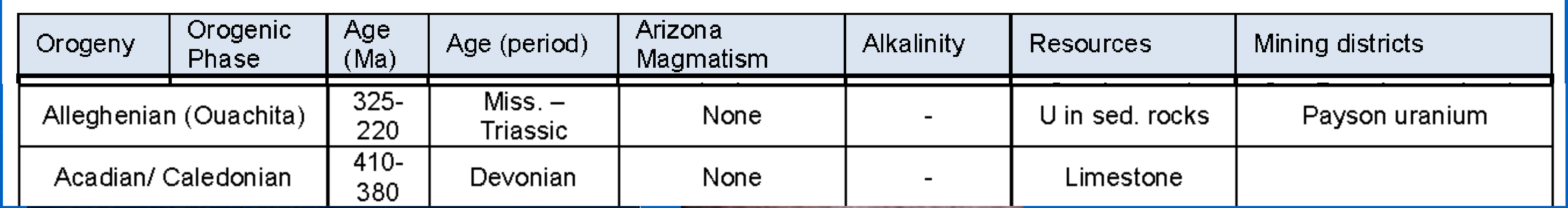


Redwall Limestone

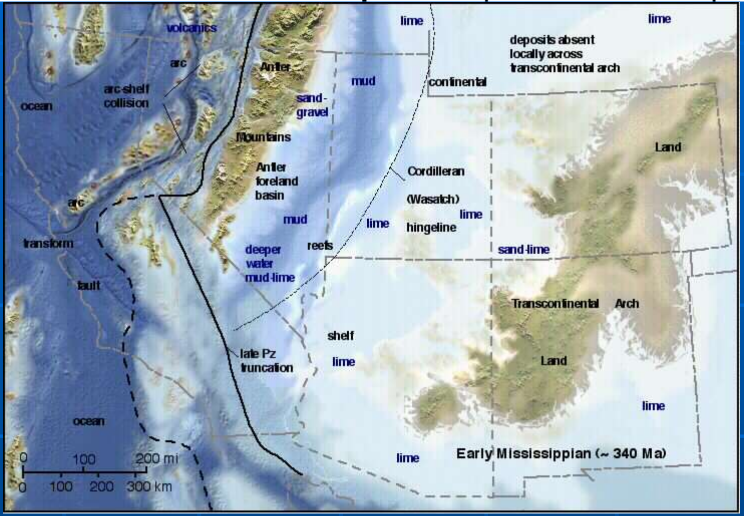
Vesey's paradise in Grand Canyon

Escabrosa Limestone

Lull - Mississippian Limestones



Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	



Redwall Limestone

Escabrosa Limestone

Clarkdale Cement plant

Rillito Cement plant

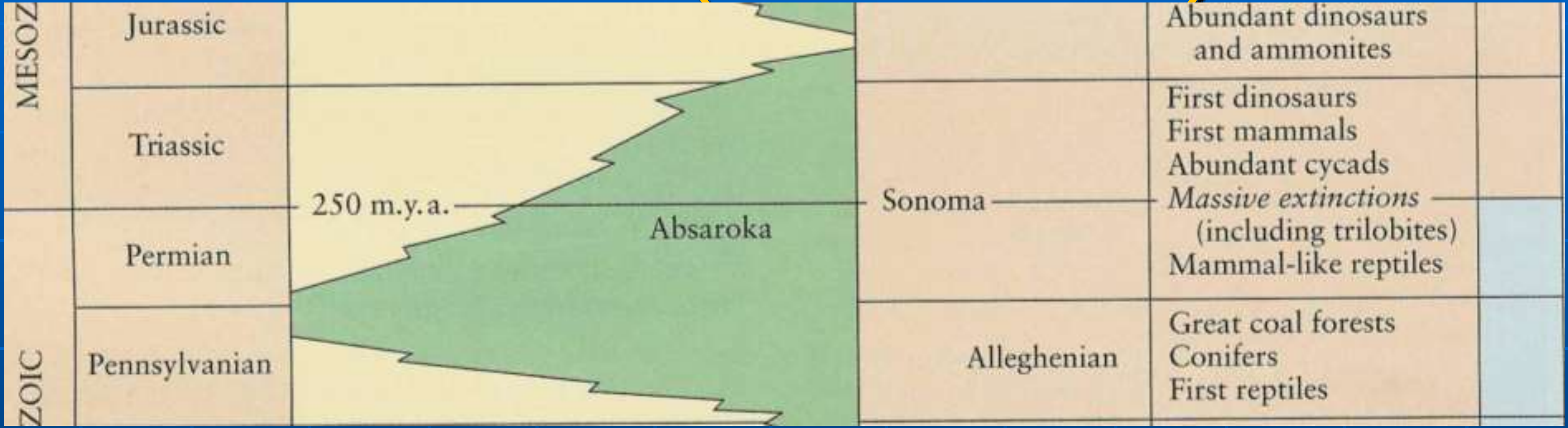
Sahuarita Marble

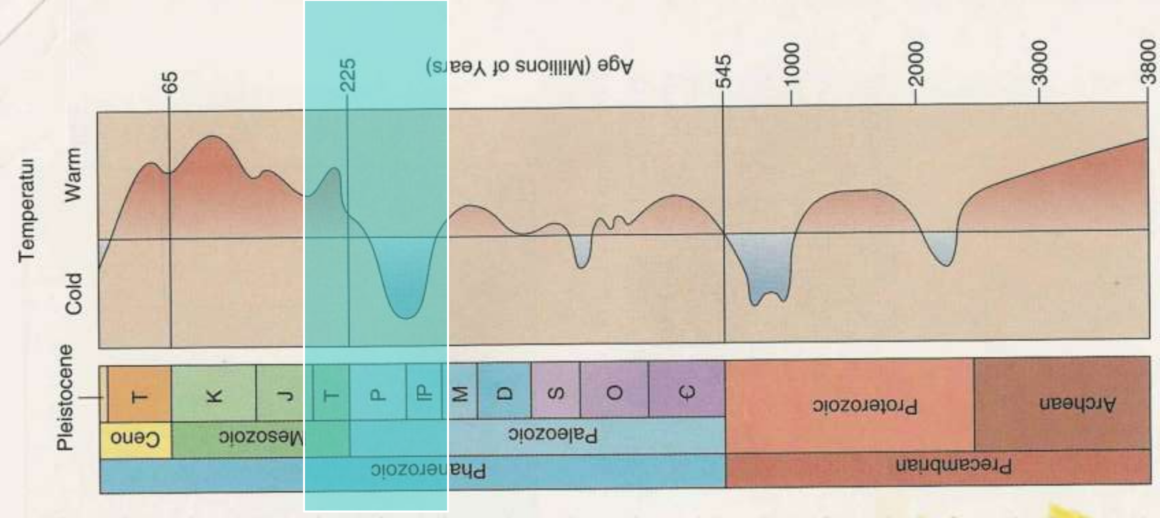
Crinoids

Syringopora - coral

Crinoids
(echinoids related to starfish,
but called sea lilies)

Pennsylvanian (318-299 Ma) – Permian (299-251 Ma) – Triassic (251-200 Ma)





Pennsylvanian environments

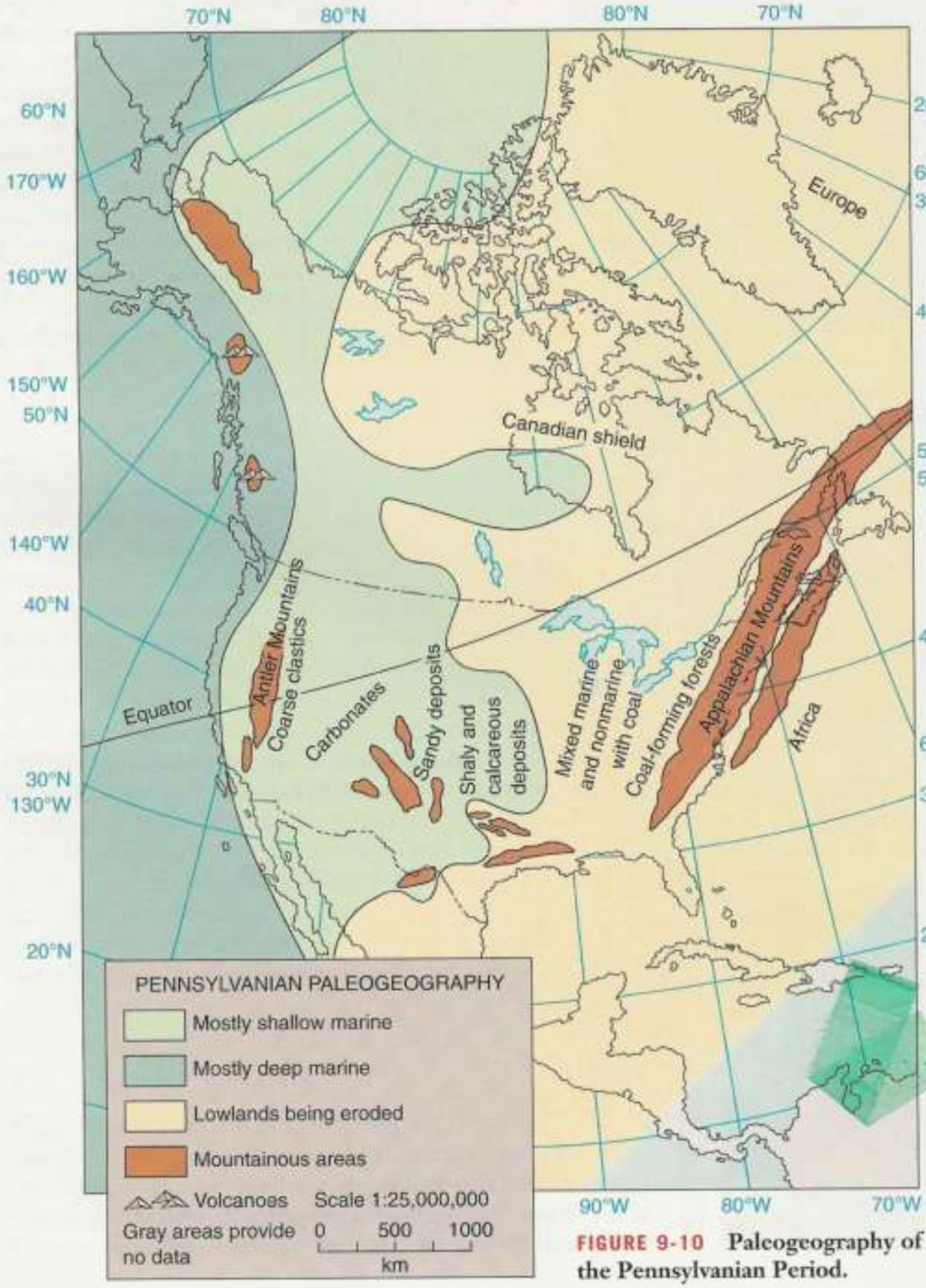
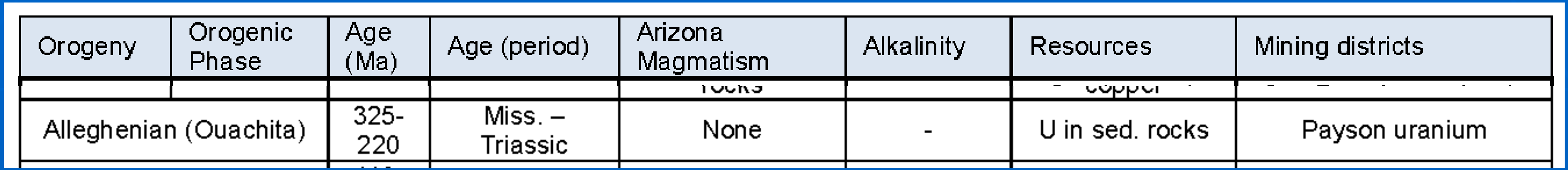
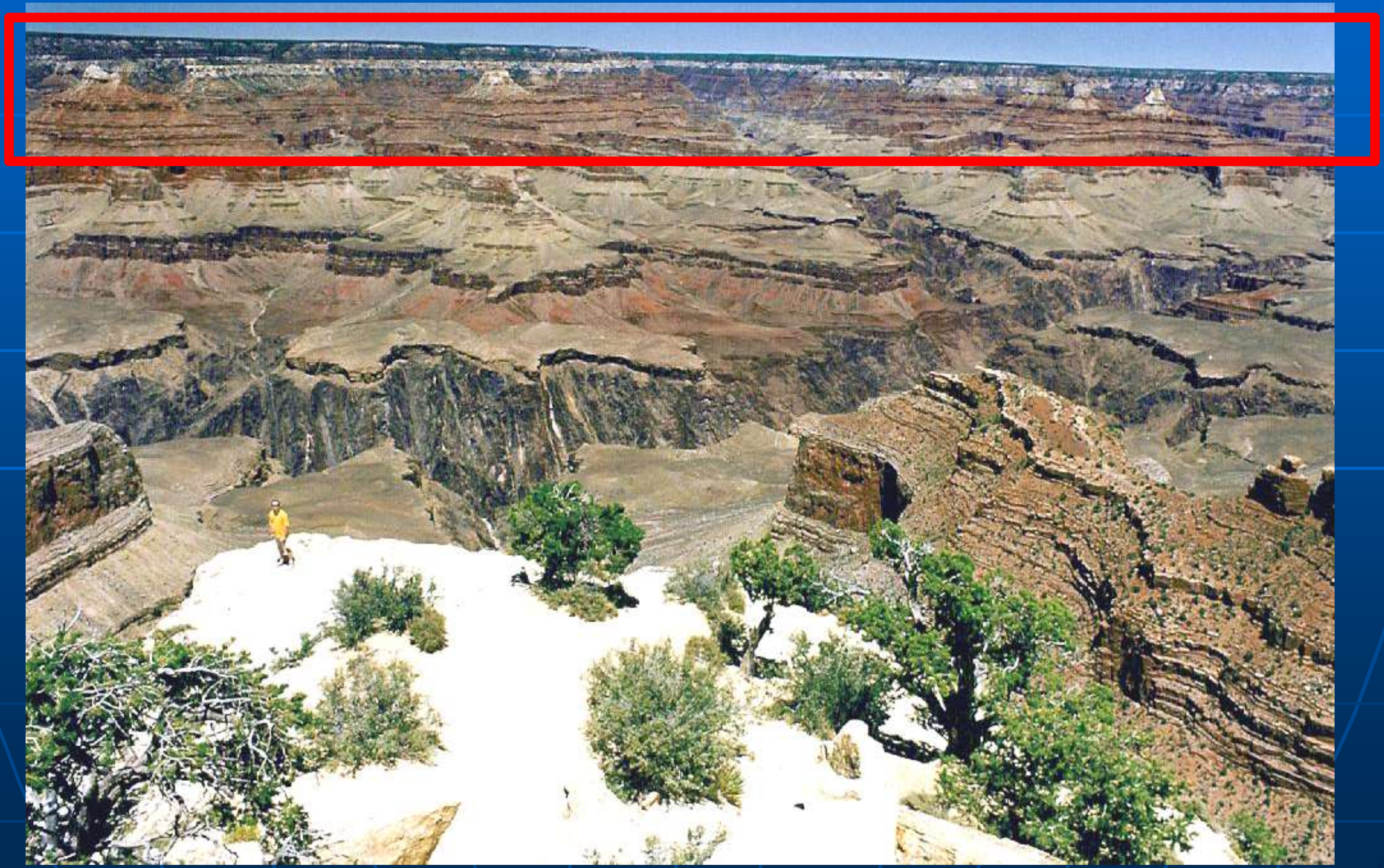


FIGURE 9-10 Paleogeography of North Ame
the Pennsylvanian Period.

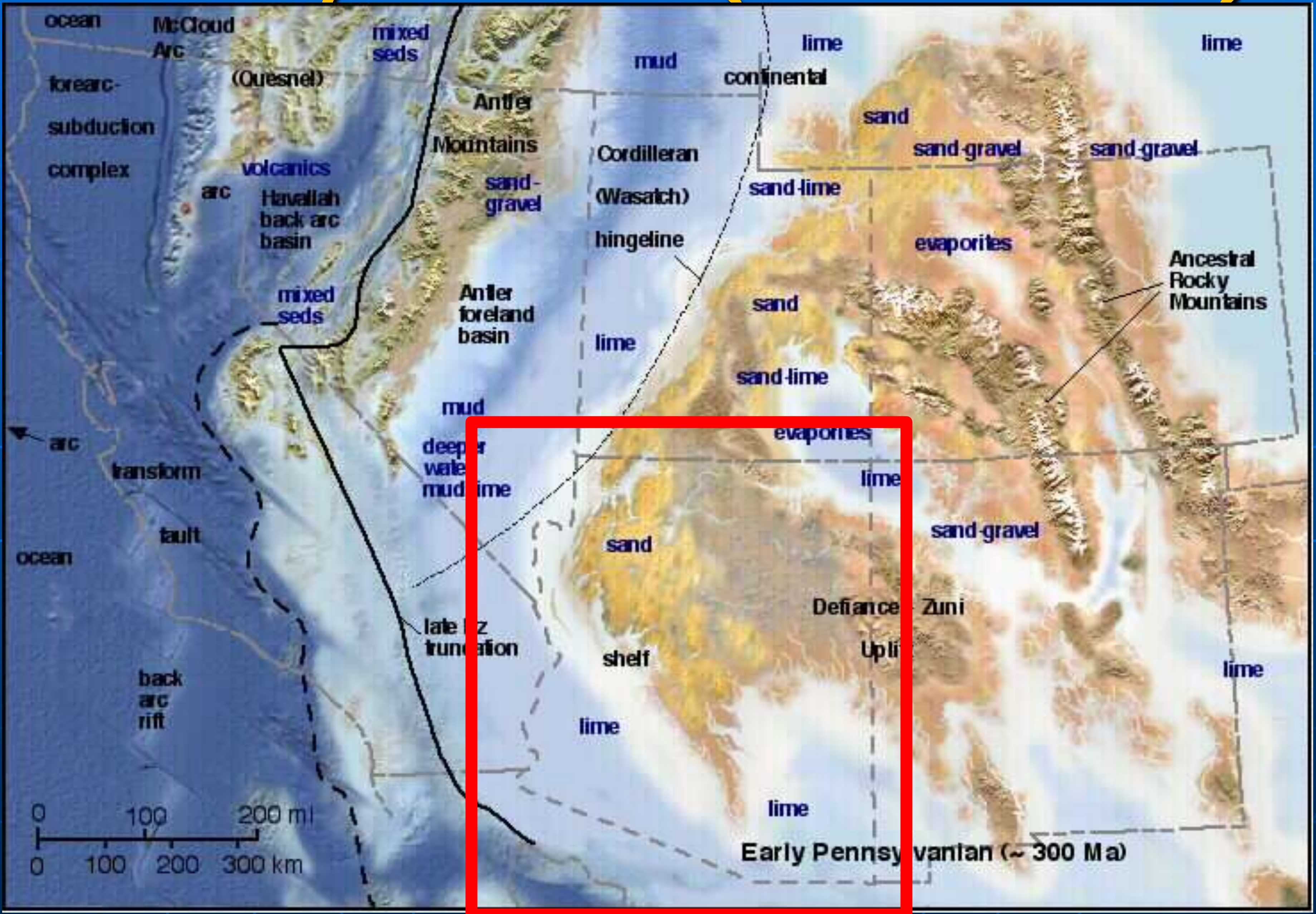
Alleghenian sedimentation in Arizona



Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium



Pennsylvanian (318-299 Ma)



Amphibian fossils

FIGURE 10-77 *Cacops*, a small labyrinthodontic amphibian from the Lower Permian. (*Photograph of a specimen on exhibit at the Field Museum in Chicago.*)

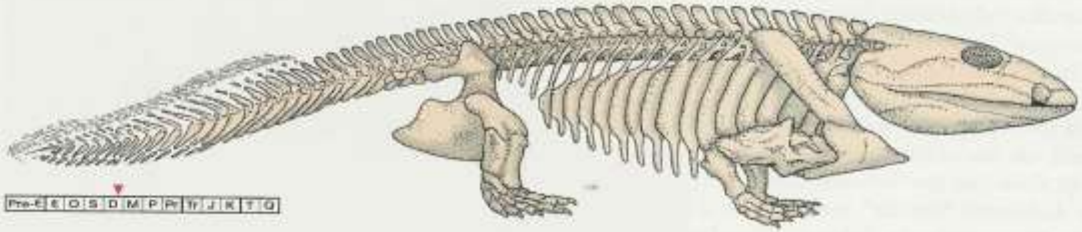


FIGURE 10-76 The skeleton of *Ichthyostega* still retains the fishlike form of its crossopterygian ancestors. (*From Levin, H. L. 1975.* Life Through Time. *Dubuque, Iowa: William C. Brown Co.*)

Pennsylvanian Coal Forest

Pennsylvanian plants

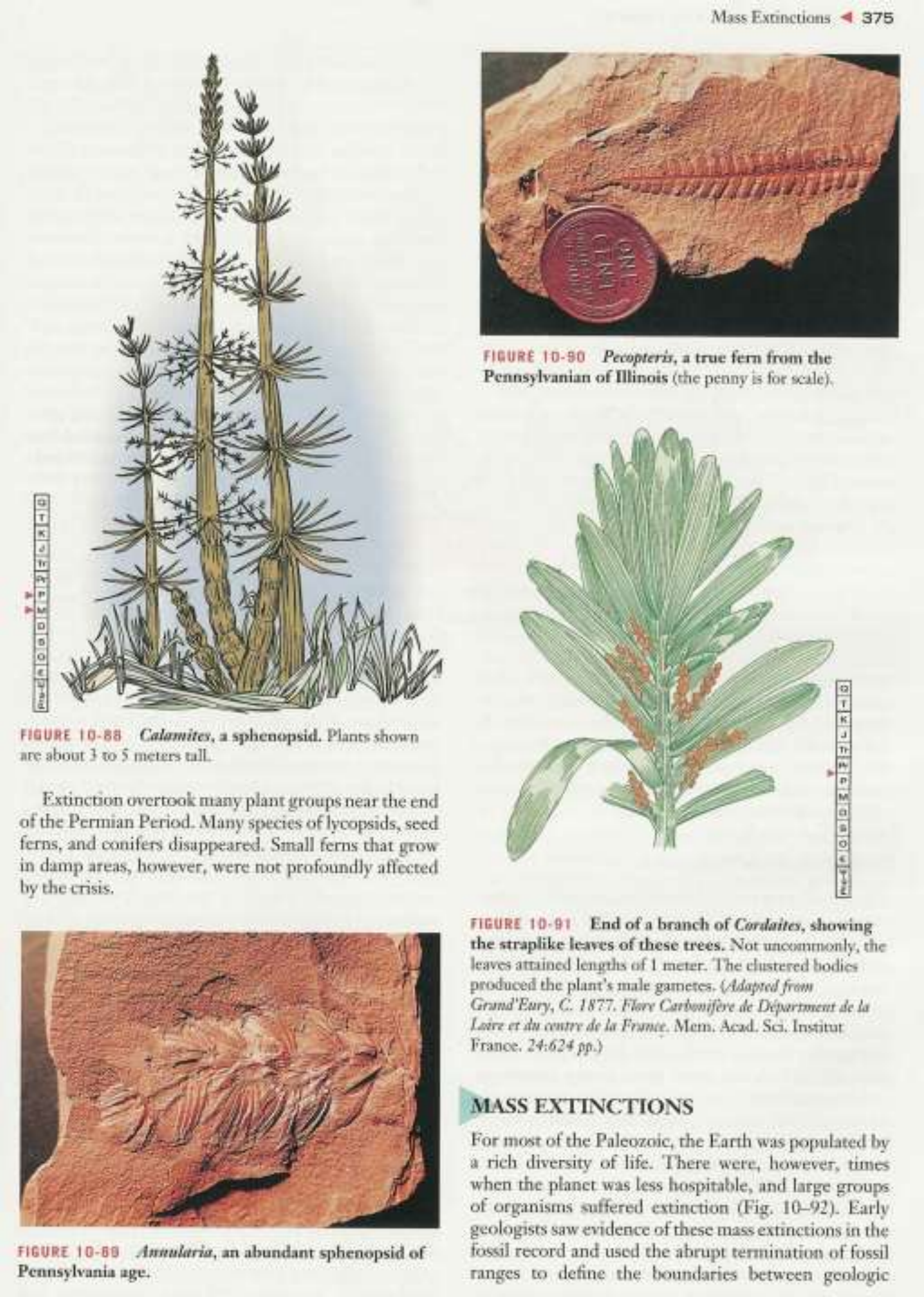


FIGURE 10-88 ***Calamites*, a sphenopsid.** Plants shown are about 3 to 5 meters tall.

FIGURE 10-90 ***Pecopteris*, a true fern from the Pennsylvanian of Illinois** (the penny is for scale).

Extinction overtook many plant groups near the end of the Permian Period. Many species of lycopsids, seed ferns, and conifers disappeared. Small ferns that grow in damp areas, however, were not profoundly affected by the crisis.

FIGURE 10-91 **End of a branch of *Cordaites*, showing the straplike leaves of these trees.** Not uncommonly, the leaves attained lengths of 1 meter. The clustered bodies produced the plant's male gametes. (*Adapted from Grand'Eury, C. 1877. Flore Carbonifère de Départment de la Loire et du centre de la France*. Mem. Acad. Sci. Institut France. *24:624 pp.*)

FIGURE 10-89 ***Annularia*, an abundant sphenopsid of Pennsylvania age.**

MASS EXTINCTIONS

For most of the Paleozoic, the Earth was populated by a rich diversity of life. There were, however, times when the planet was less hospitable, and large groups of organisms suffered extinction (Fig. 10–92). Early geologists saw evidence of these mass extinctions in the fossil record and used the abrupt termination of fossil ranges to define the boundaries between geologic

Cyclic coal beds (Cyclothems)

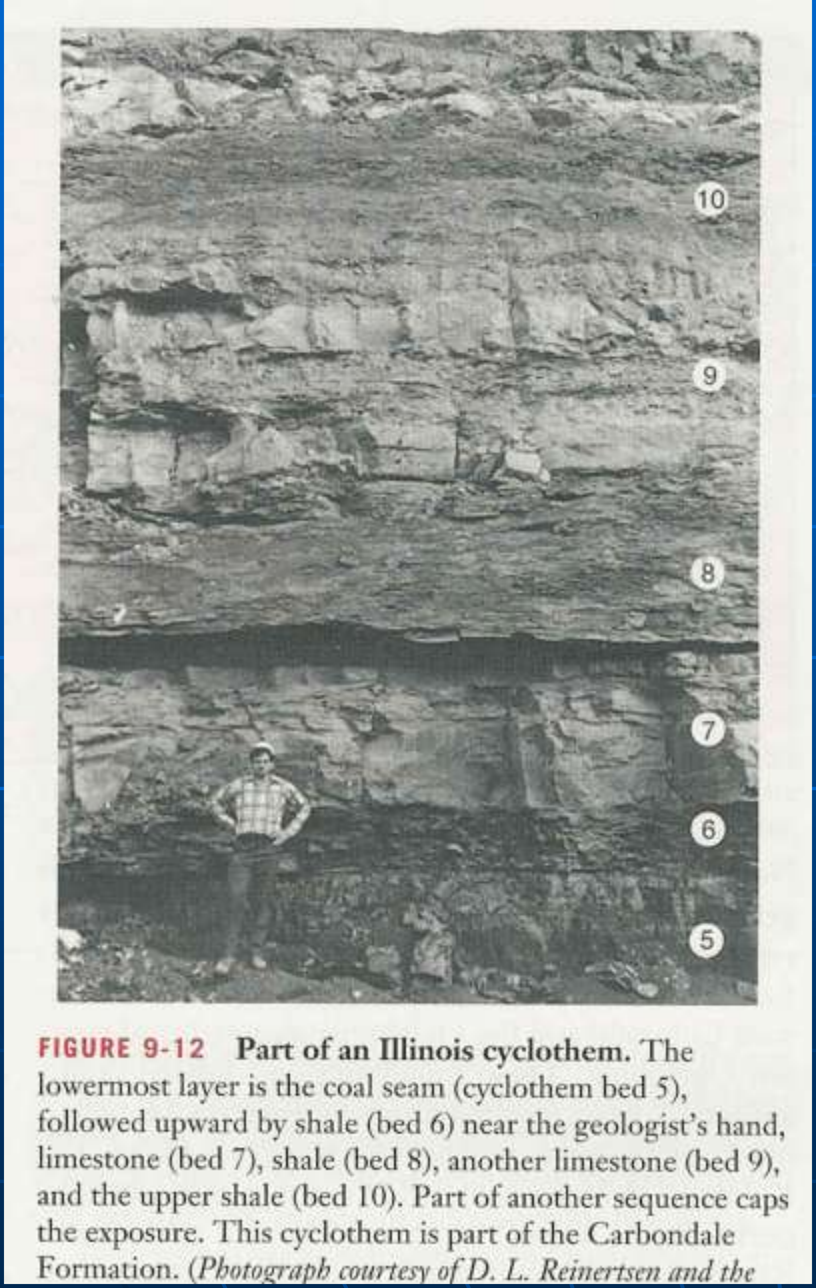


FIGURE 9-12 Part of an Illinois cyclothem. The lowermost layer is the coal seam (cyclothem bed 5), followed upward by shale (bed 6) near the geologist's hand, limestone (bed 7), shale (bed 8), another limestone (bed 9), and the upper shale (bed 10). Part of another sequence caps the exposure. This cyclothem is part of the Carbondale Formation. (*Photograph courtesy of D. L. Reinertsen and the*

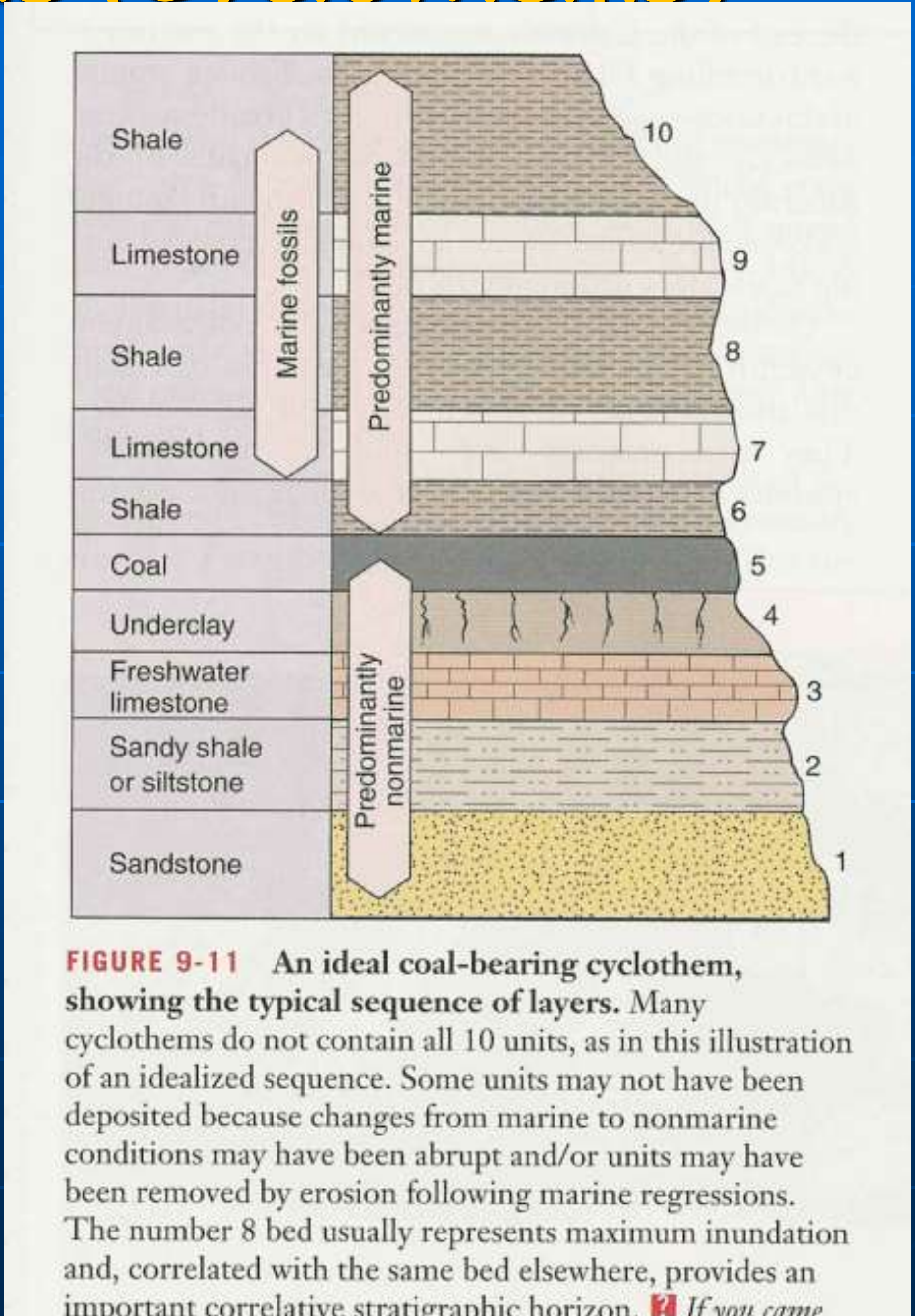
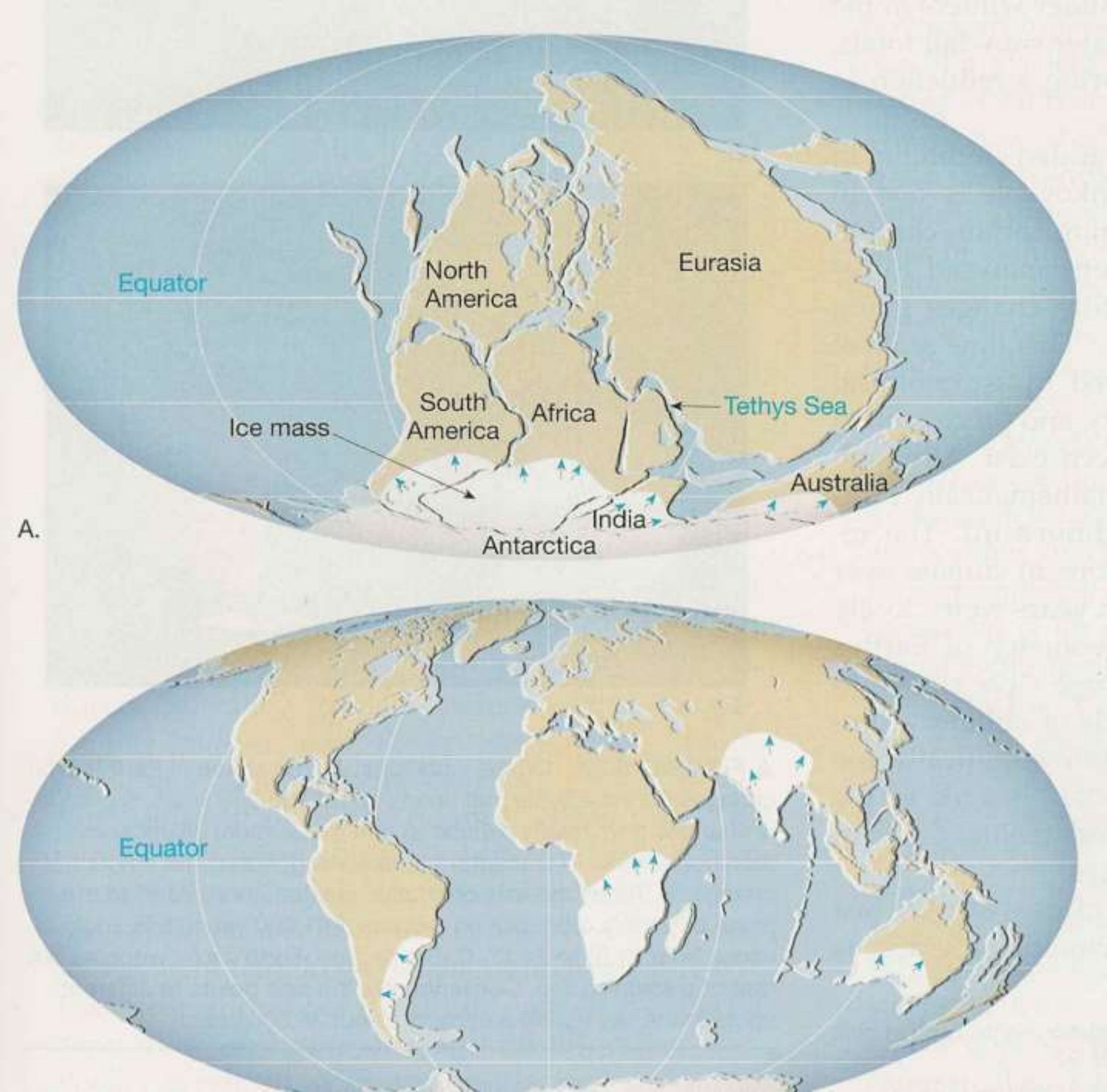


FIGURE 9-11 An ideal coal-bearing cyclothem, showing the typical sequence of layers. Many cyclothems do not contain all 10 units, as in this illustration of an idealized sequence. Some units may not have been deposited because changes from marine to nonmarine conditions may have been abrupt and/or units may have been removed by erosion following marine regressions. The number 8 bed usually represents maximum inundation and, correlated with the same bed elsewhere, provides an important correlative stratigraphic horizon. ? *If you came*

Pennsylvanian-Permian Ice Age



Goosenecks of the San Juan

Pennsylvanian Hermosa Formation

Earp Formation,
Government Draw SE of Tombstone

Late sylvanian (300 Ma)

Permian Supai Group, Sedona

Permian environments

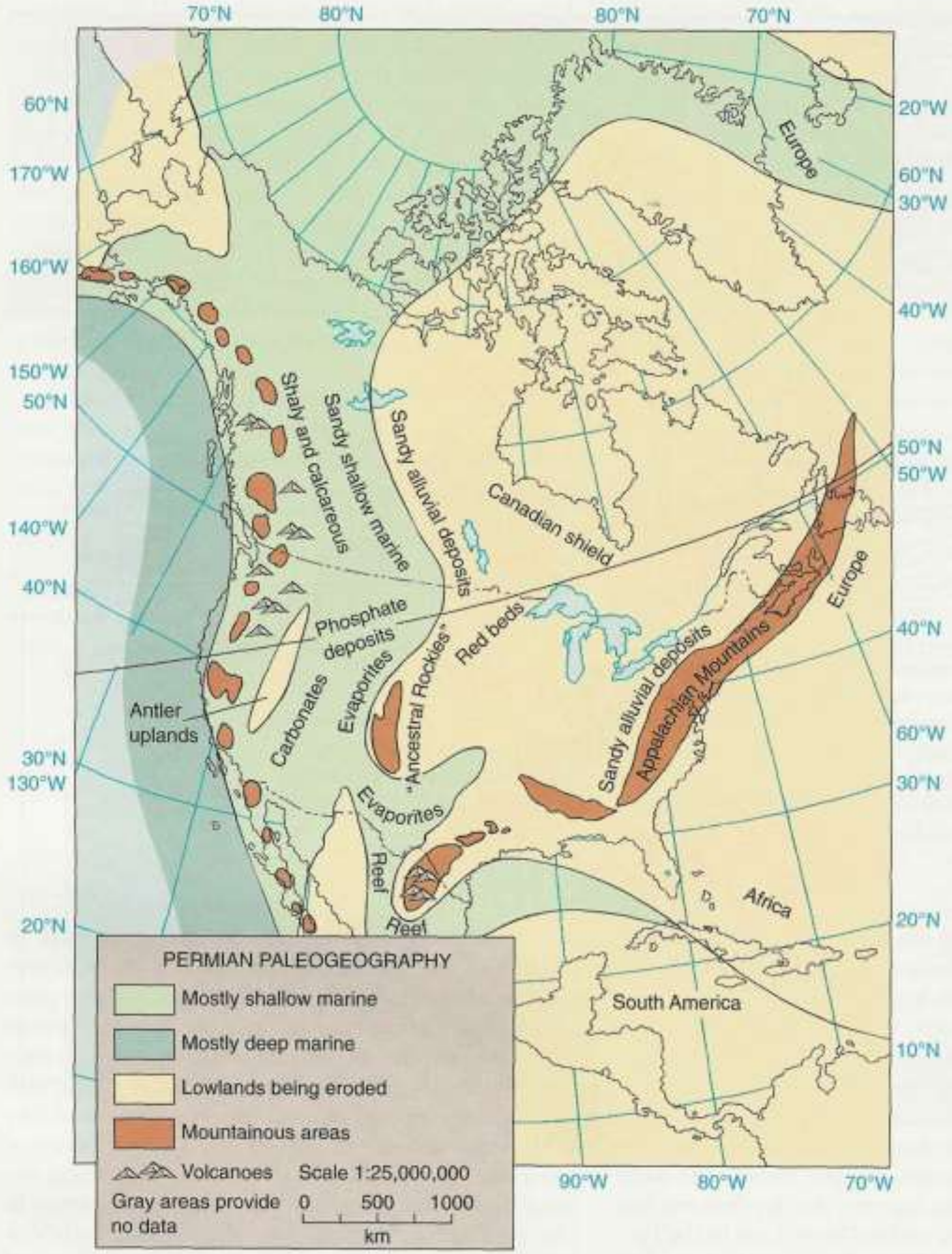
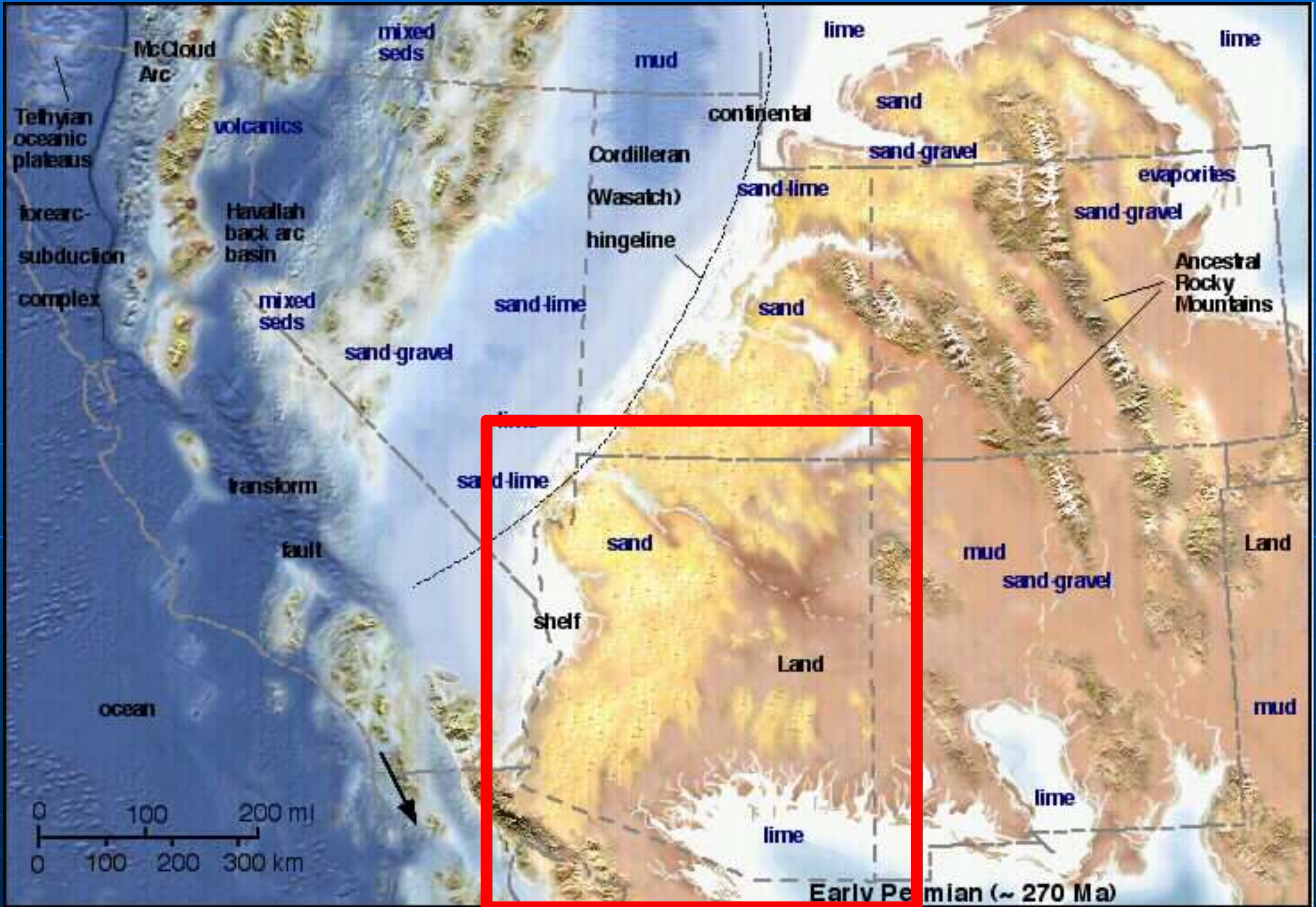


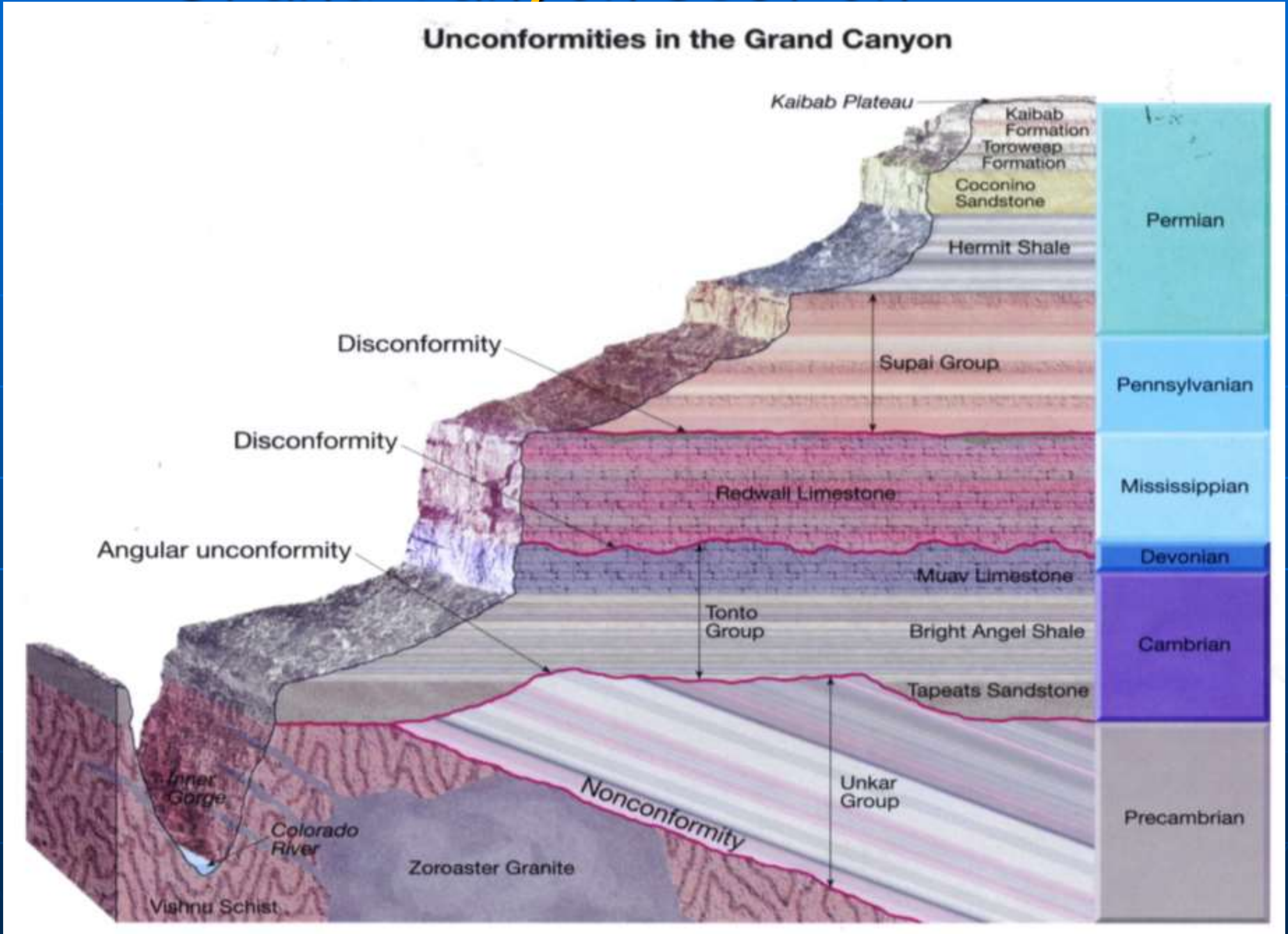
FIGURE 9-18 Generalized paleogeographic map for the Permian Period.

Permian (290-248 Ma)



Early Permian (~ 270 Ma)

Grand Canyon section



Grand Canyon

Mammal-like Reptiles

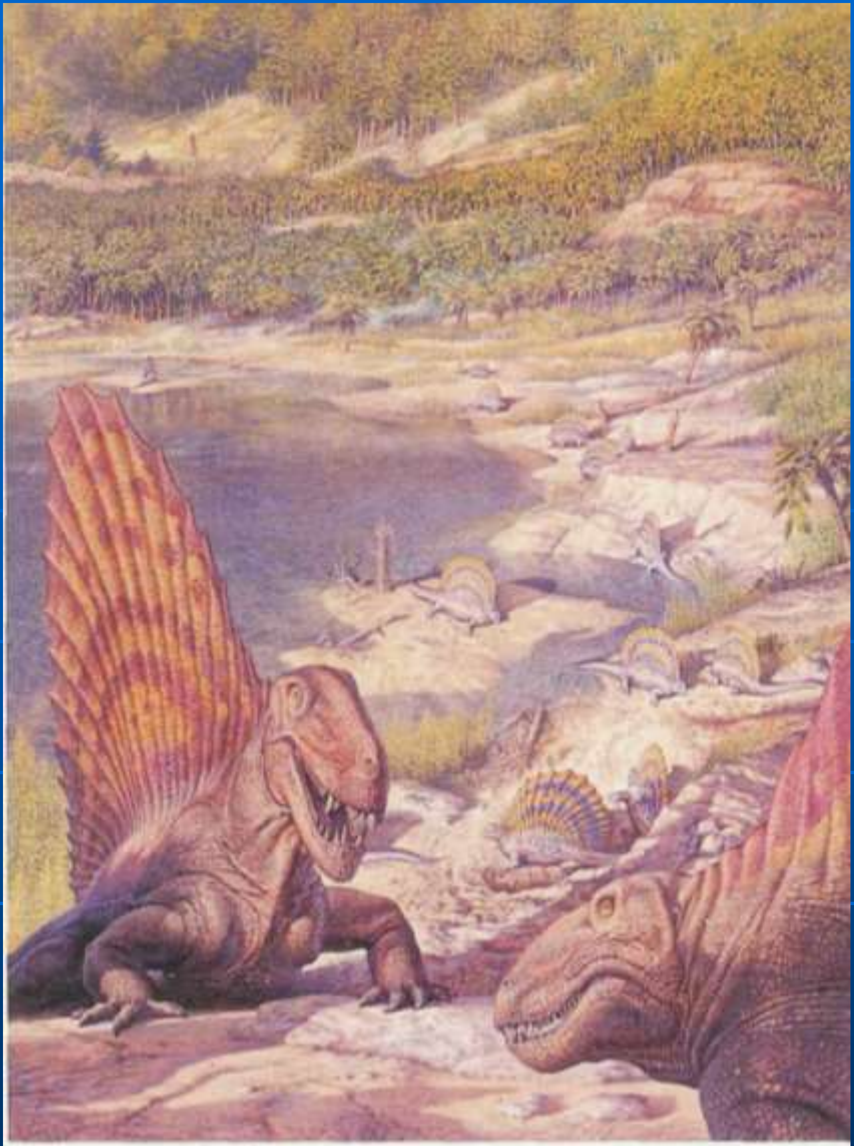


FIGURE 10-78 **Permian reptiles.** The prominent sailback reptile in the left foreground, with a larger skull and daggerlike teeth, is the carnivore *Dimetrodon*. The sailbacks with smaller heads and blunt cheek teeth, in the foreground at right and in the distance, are plant-eaters of the genus *Edaphosaurus*. (Copyright *J. Sibbick*.) ? *Is it likely*

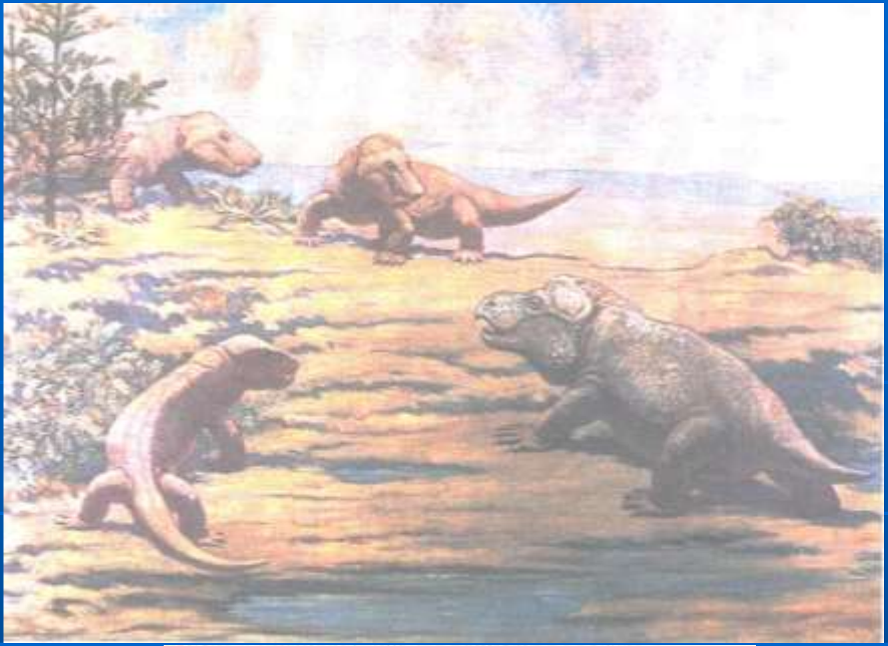
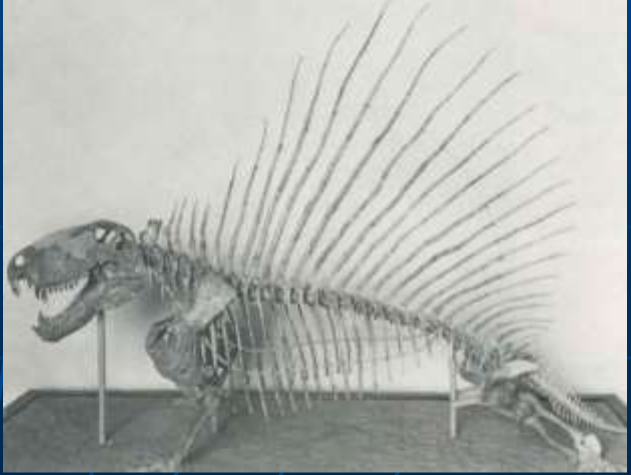
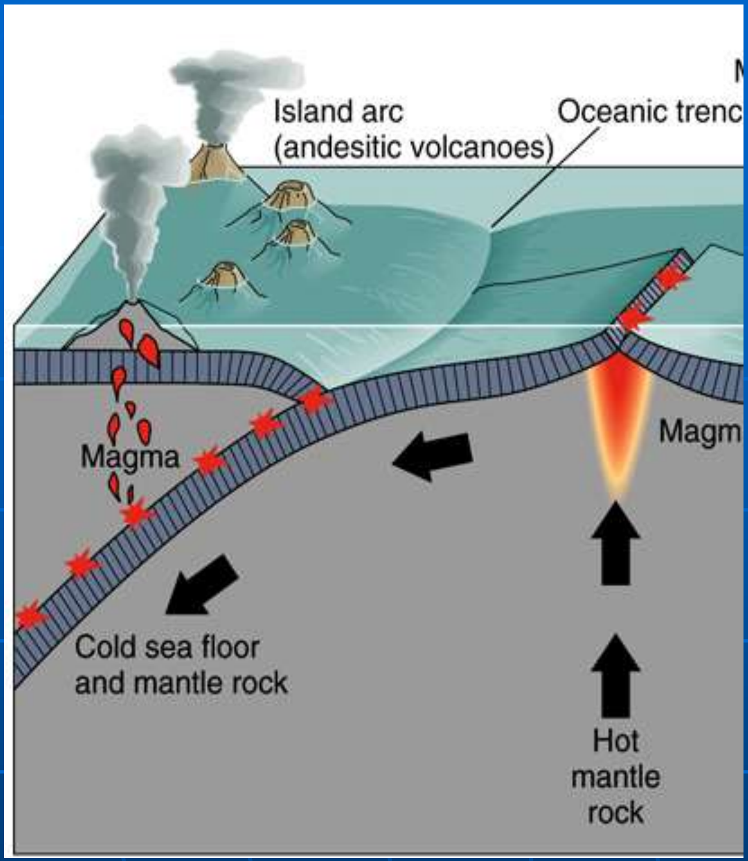


FIGURE 10-80 **Mammal-like reptiles.** The scene depicts three carnivorous forms (*Cynognathus*) about to attack a plant-eating therapsid reptile (*Kannemeyeria*). (*Courtesy of*

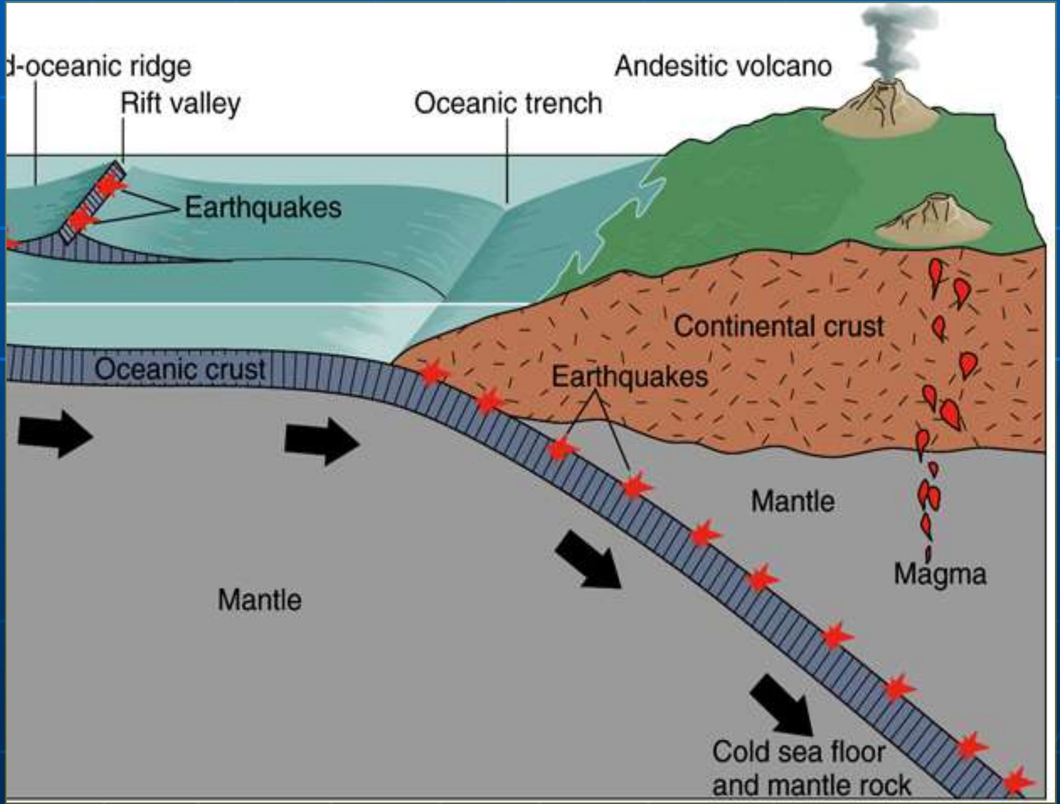


Arizona’s position w.r.t. plate tectonics in Paleozoic vs. Mesozoic



Paleozoic – Arizona was on trailing edge of N. American continent = calm seaways

Mesozoic – Arizona was on leading edge of N. American continent = mountain building, volcanoes, earthquakes, igneous intrusions



Mesozoic – Cenozoic Orogenies

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu
Galiuro	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metaluminous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea
	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley

Triassic plate tectonics

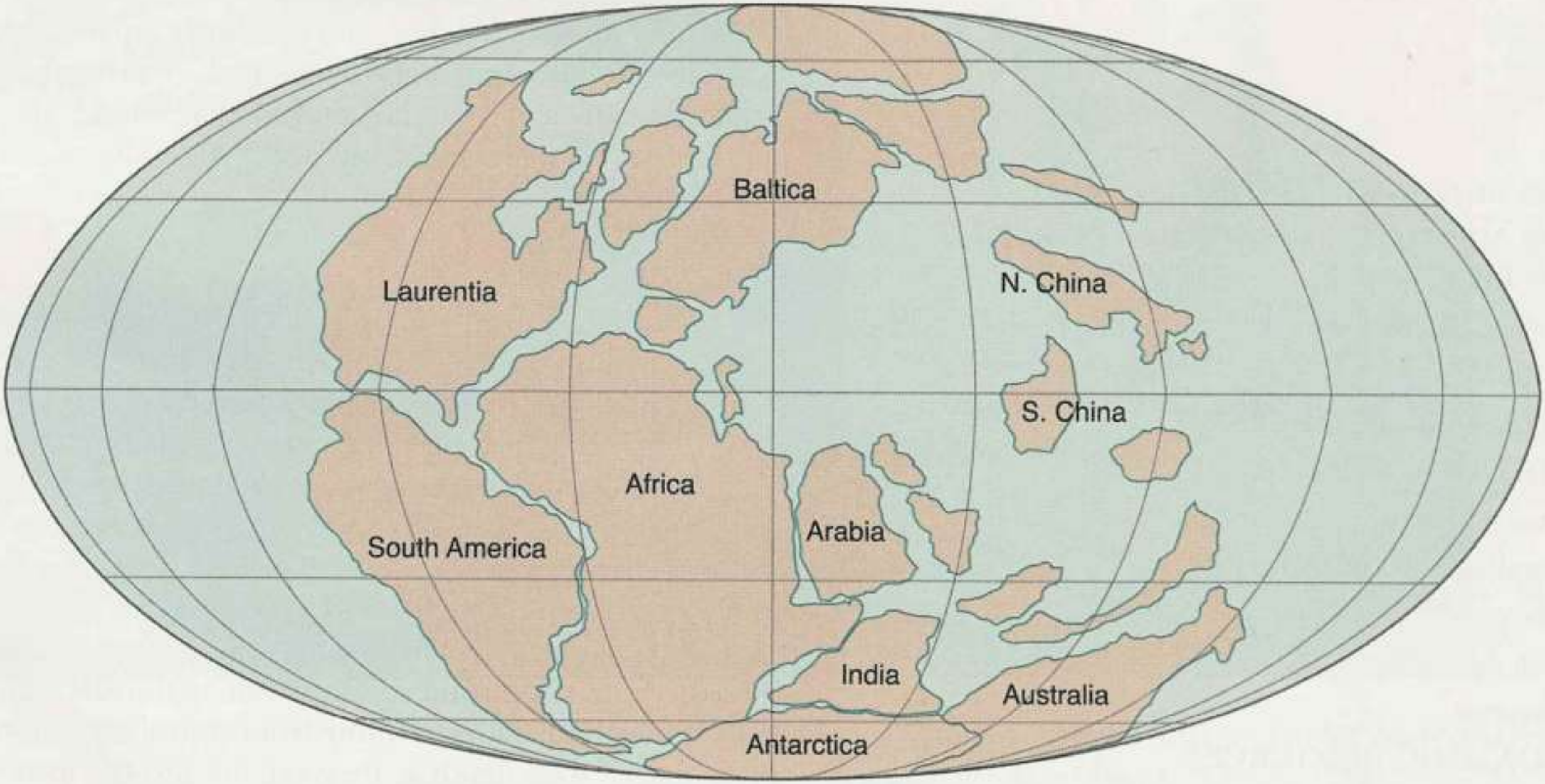
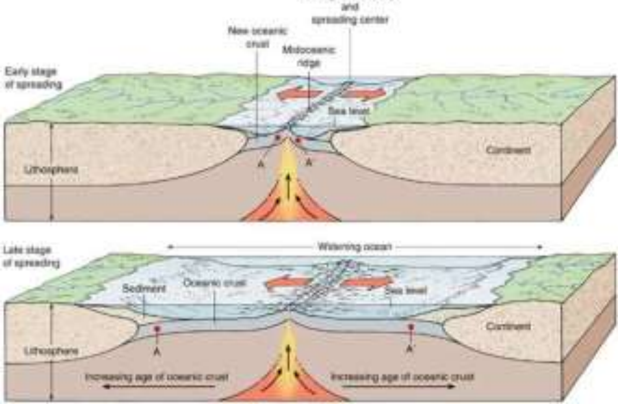
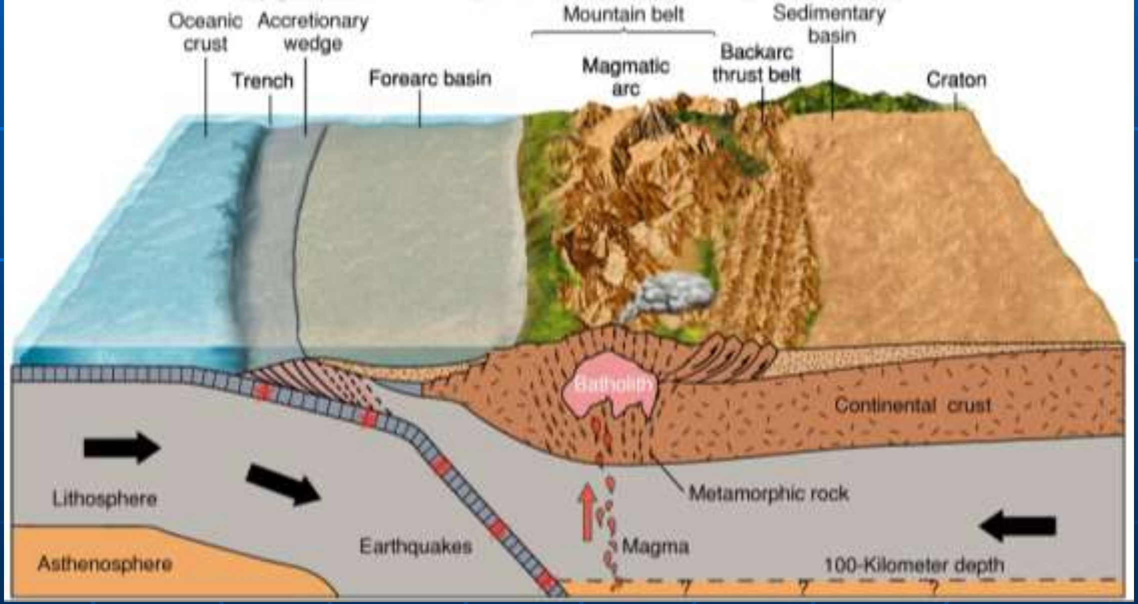


FIGURE 11–1 **Paleogeographic reconstruction of the world about 180 million years ago, when the break-up of Pangea was beginning.** (After Scotese, C. R. and McKerrow, W. S. 1990. Paleogeography and Biogeography, *Geol. Soc. London Mem. 12:1–21.*)

Nevadan Orogeny (230-145 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley





Triassic paleogeography

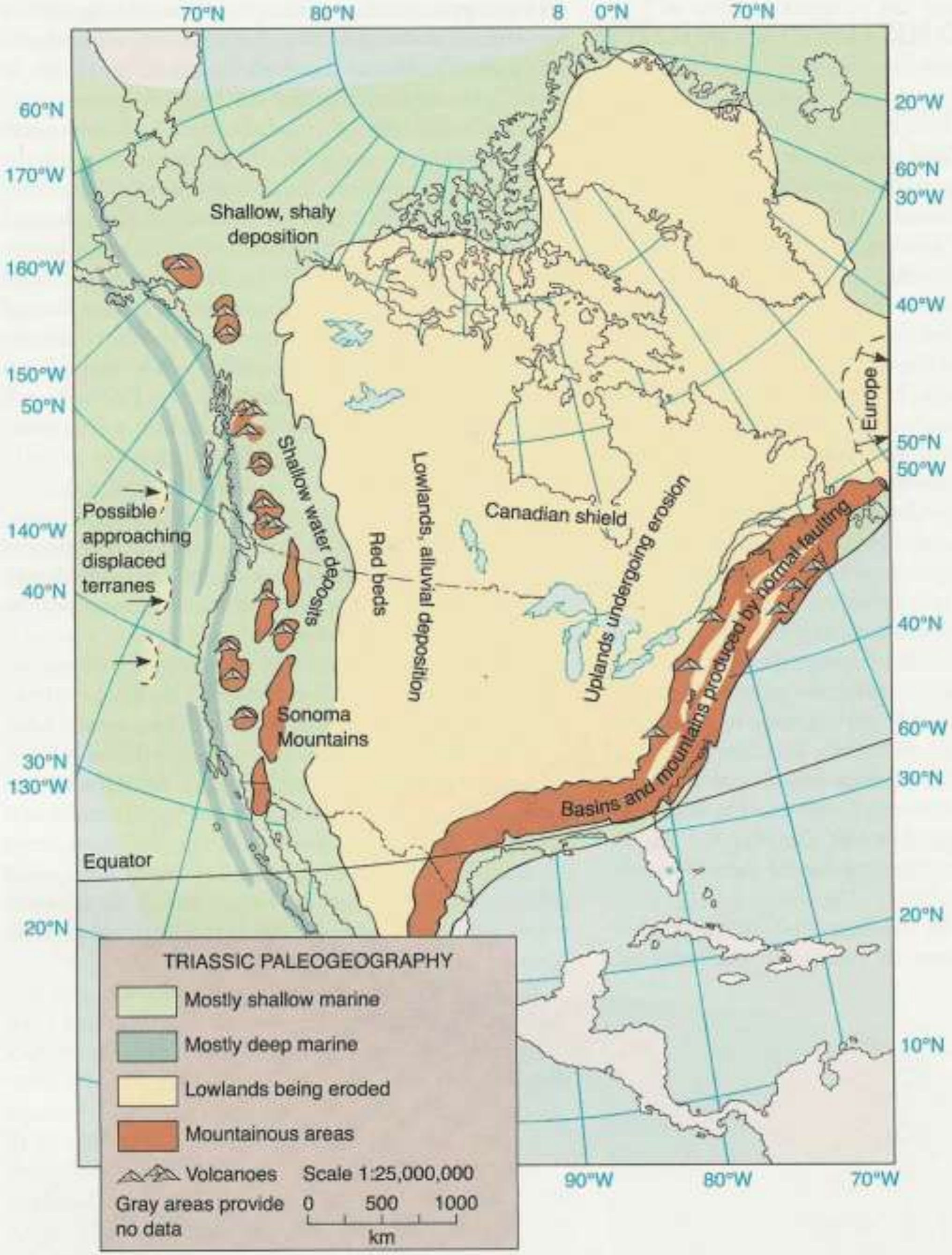
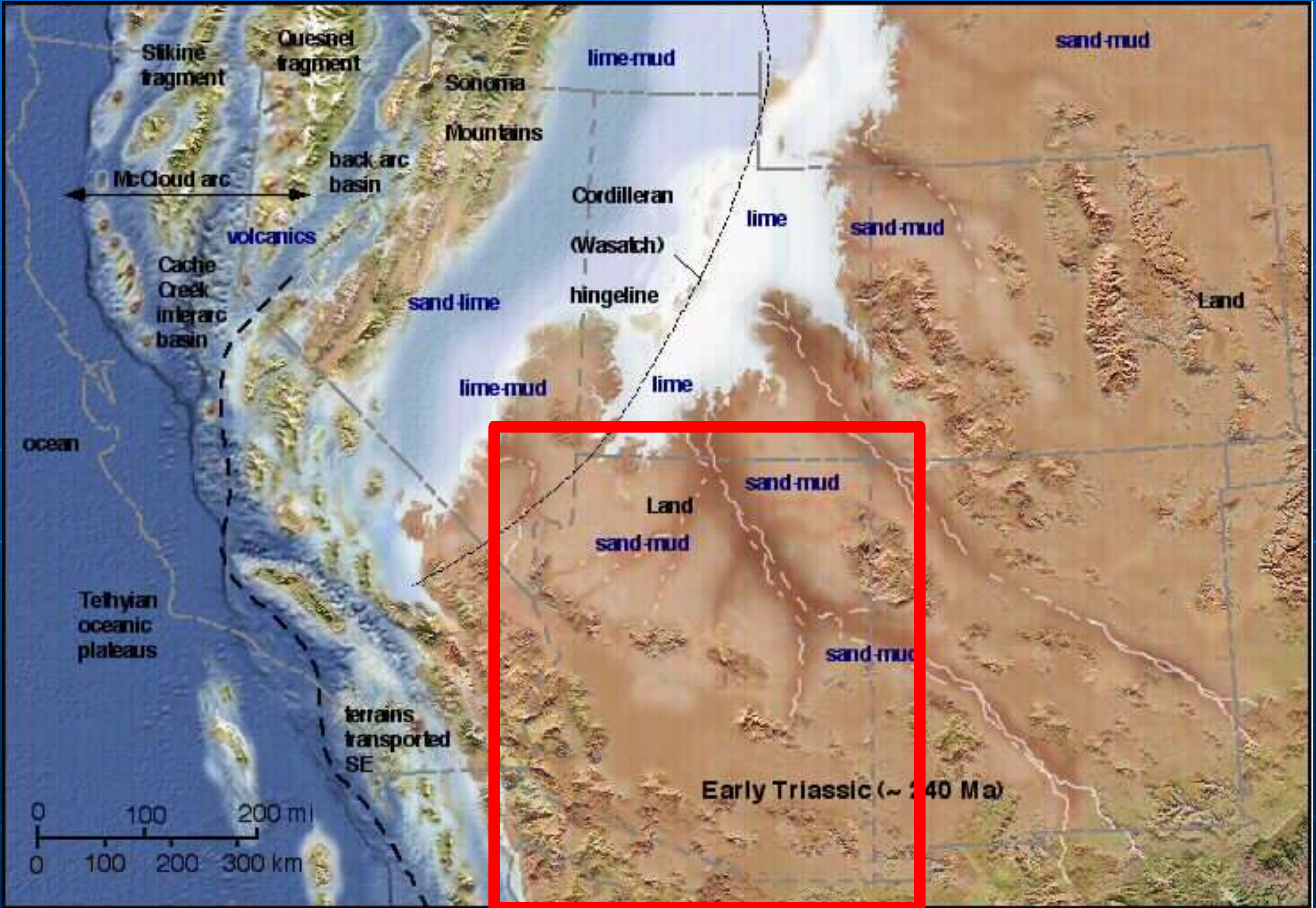


FIGURE 11-3 Generalized paleogeographic map for the Triassic of North America.

What was the cause of the faulting along the eastern margin of the continent?

Triassic (248-206 Ma)



Petrified Forest Fm. - late Triassic

Petrified log, Pet. Forest

Triassic Reptiles

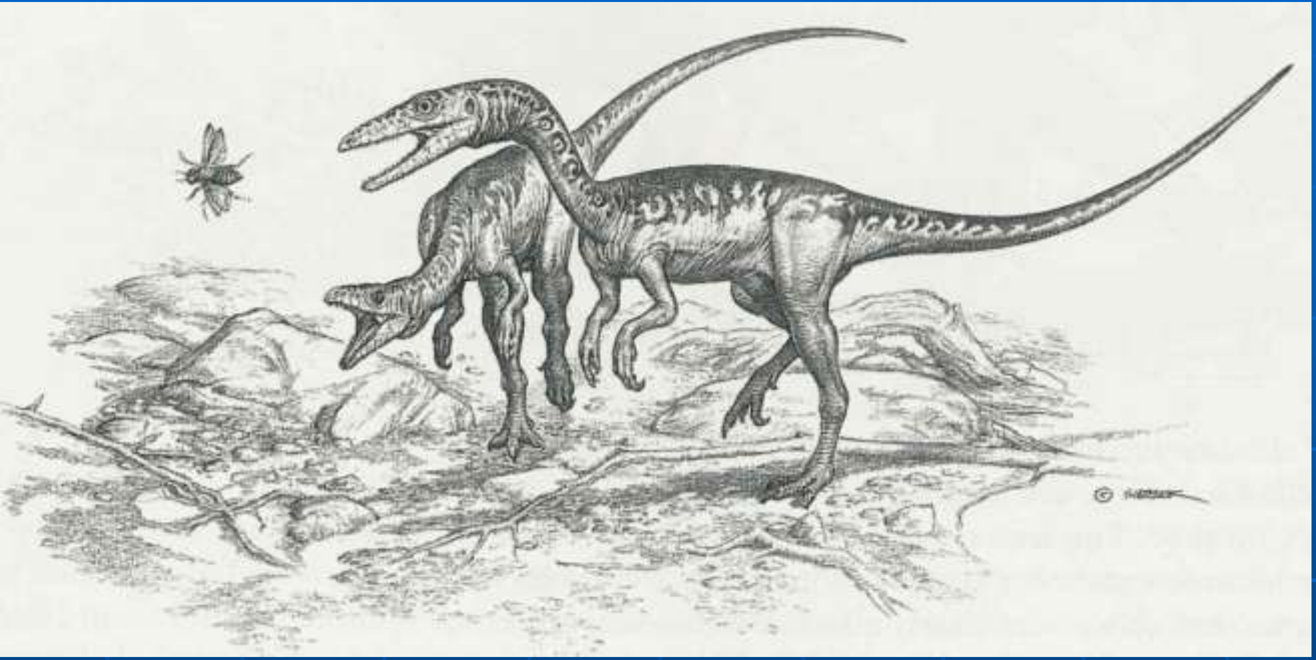


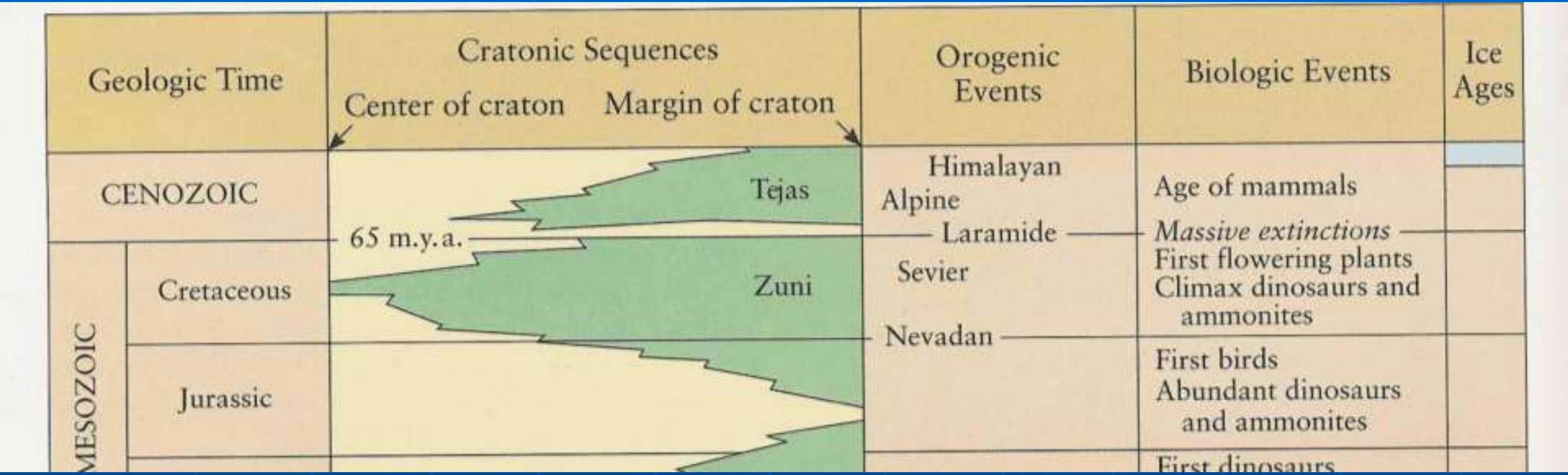
FIGURE 12-21 **The small, agile theopod *Coelophysis* lived about 220 million years ago, during the Late Triassic.** *Coelophysis* was about 3 meters in length. These fast, agile, bipedal predators may have pursued their prey in packs, and there is evidence that they occasionally even ate juveniles of their own species. (*Copyright*

FIGURE 12-17 ***Rutiodon*, a Triassic phytosaur.** Like many other phytosaurs, *Rutiodon* grew to lengths of 10 or more feet. (*Illustration by Carlyn Iverson.*) ? *What living reptile is an example of convergent evolution with Rutiodon?*

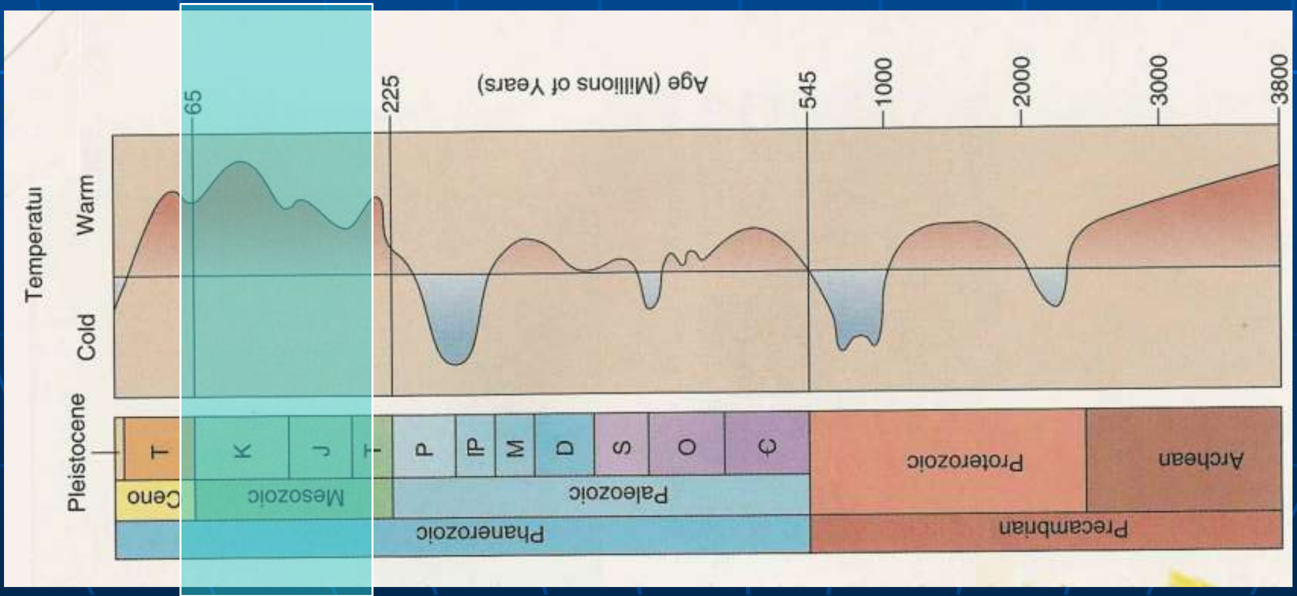
Hesperosuchus from the Triassic of the southwestern United States.

Pet. For. Labyrinthodont teeth

Late Jurassic & Cretaceous
200-65 Ma



Geologic Time		Cratonic Sequences (Center of craton → Margin of craton)	Orogenic Events	Biologic Events	Ice Ages
CENOZOIC		Tejas	Himalayan Alpine	Age of mammals	
		65 m.y.a.	Laramide	*Massive extinctions*	
MESOZOIC	Cretaceous	Zuni	Sevier	First flowering plants Climax dinosaurs and ammonites	
			Nevadan		
	Jurassic			First birds Abundant dinosaurs and ammonites	
				First dinosaurs	



Jurassic paleogeography

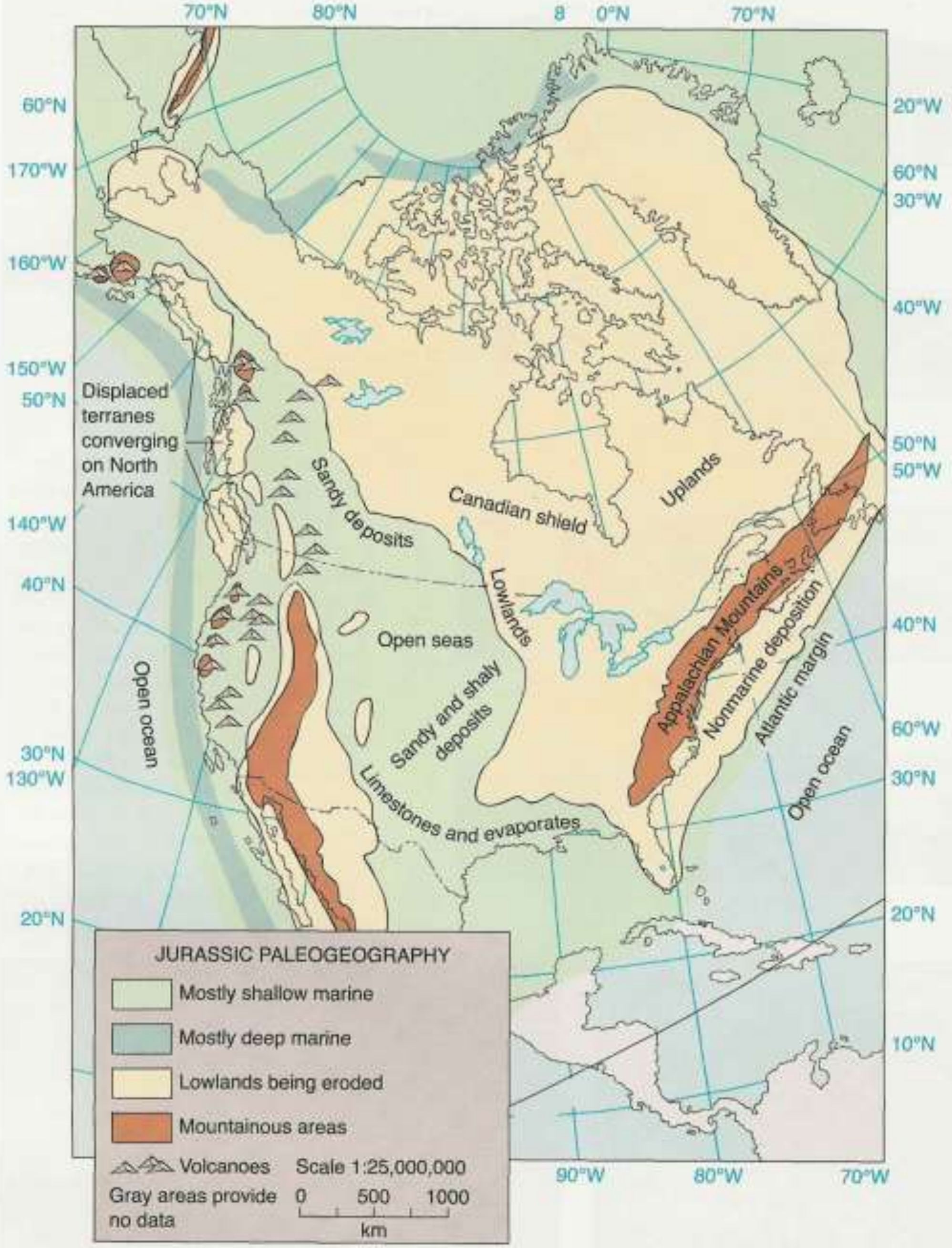
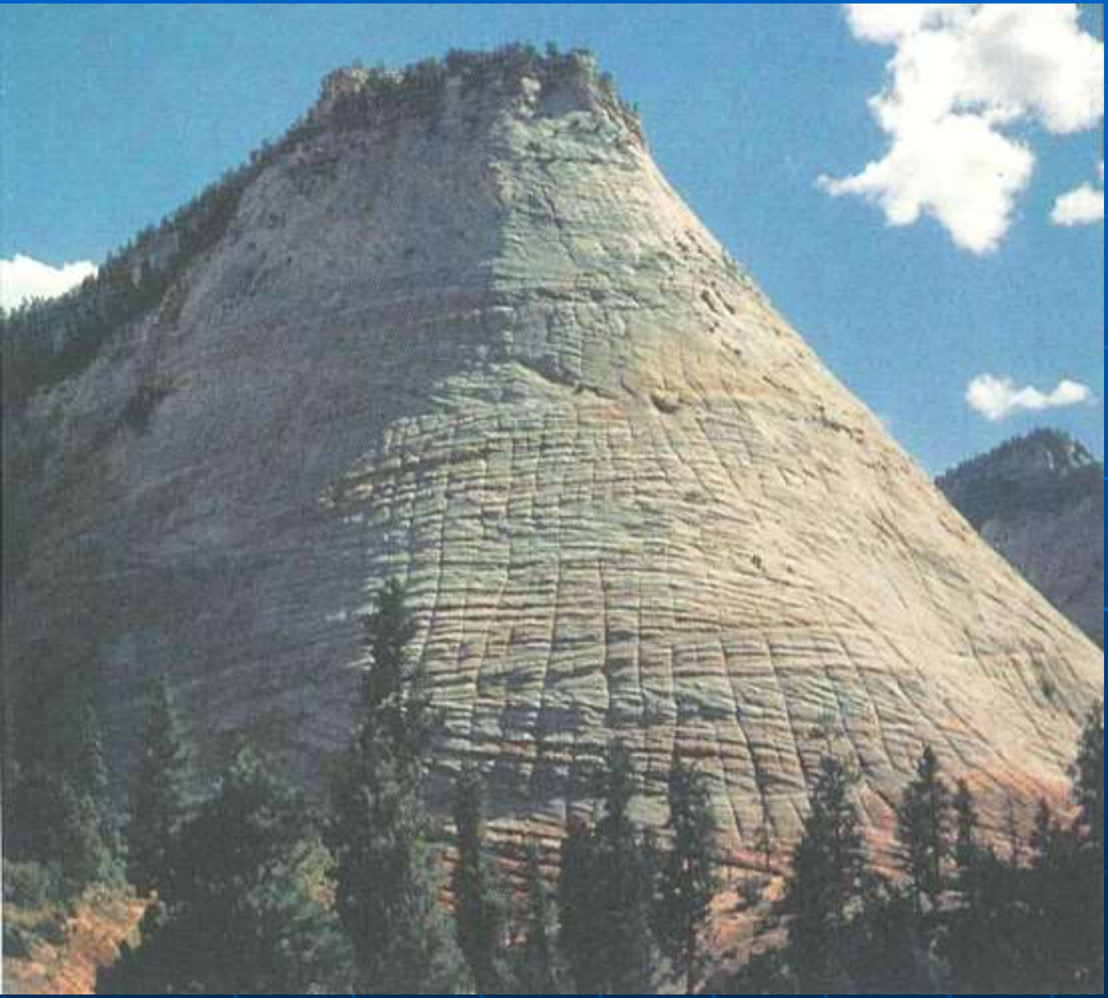


FIGURE 11-7 Generalized paleogeographic map for the Jurassic of North America. *Describe the conditions at the site of your school during the Jurassic Period.*

Middle Jurassic

Navajo Sandstone – Jurassic age



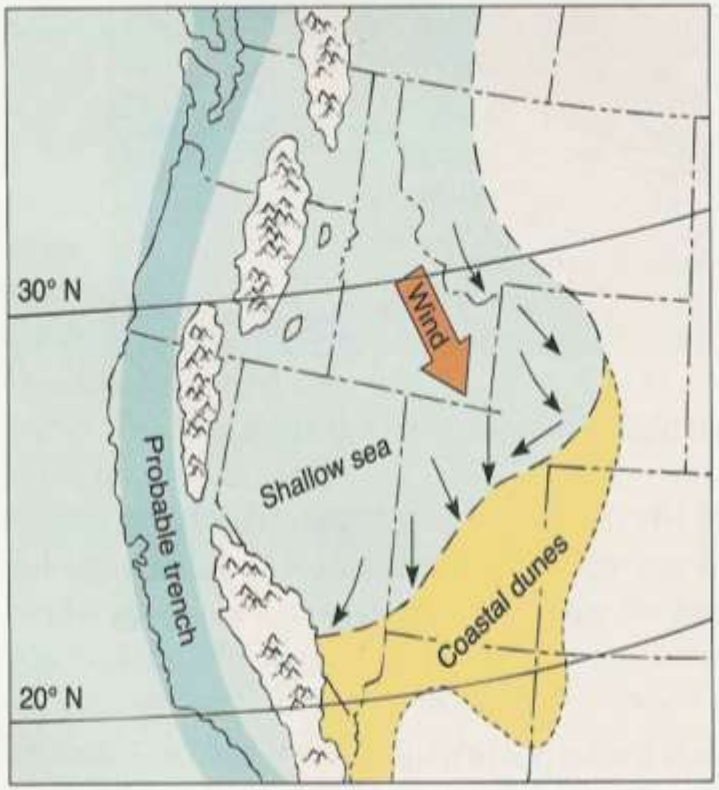


FIGURE 11-26 Paleogeographic map for the early Jurassic of the western United States, showing general extent of sea and land as well as paleolatitudes. (*From Stanley, K. O., Jordan, W. M., and Dott, R. H. 1971.* Bull. Am. Assoc. Petrol. Geol. 55(1):13.)

Rainbow Bridge in Jurassic Ss

Jurassic tracks N.AZ

Jurassic - Stegosaurus

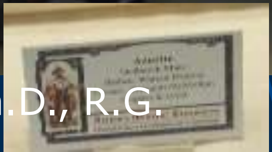
Vermilion Cliffs, Jurassic Ss

Jurassic volcanics Santa Rita Mts.

Jurassic - Bisbee copper-gold mine

Warren district (Bisbee) azurite

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)



Warren district (Bisbee) secondary

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

Sevier Orogeny (145-89 Ma)

Mural Ls. (Bisbee Group) E. of Bisbee

Bisbee Grp., Mural Limestone 100 Ma

Middle Cretaceous (~90 Ma)

Coal swamps N. AZ - (89-85 Ma)

N Arizona – coal in Wepo Fm. at Black Mesa

Photo from Peabody Coal (Freeport-McMoran)

Late Cretaceous – volcanics, Mts.

Early Laramide (85-65 Ma)

Tombstone Hills – Uncle Sam Tuff

Tucson Mts. - Cat Mountain Rhyolite –

Mt. Pinatubo, Philippines 1991

Tombstone – early Laramide (78-65 Ma – silver deposits)

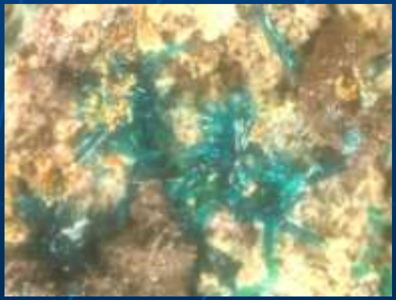
Tombstone silver mines

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero

Emmonsite, Megaw specimen, Sugar White photo

Chlorargyrite – John Betts photo & specimen MinDat.org

Dugganite – Empire mine. Peter Megaw specimen and Sugar White photograph



Megaw specimen, Sugar White photo

Tertiary - 65-0 Ma

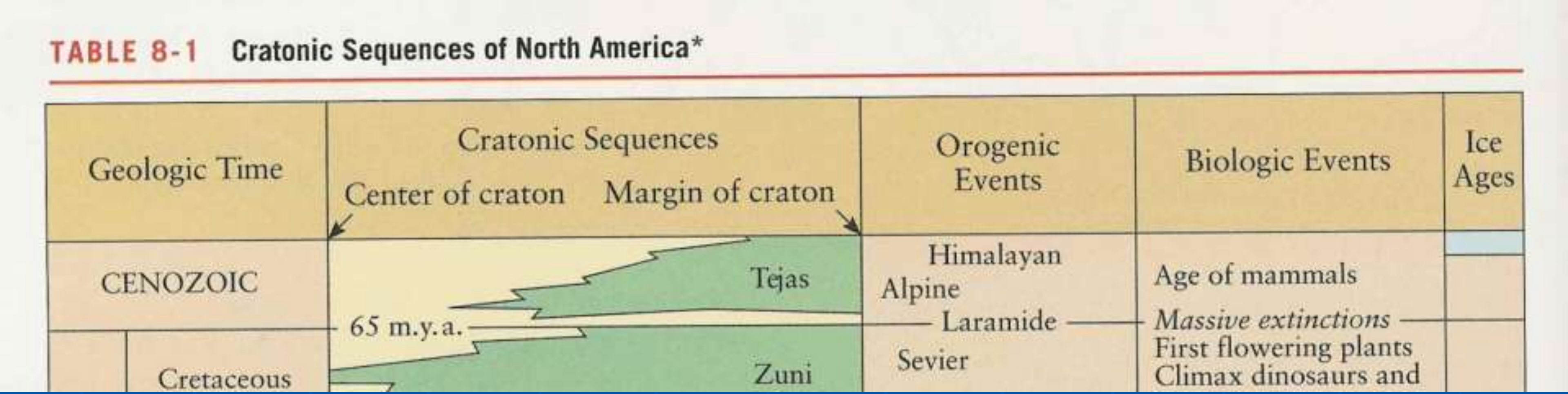
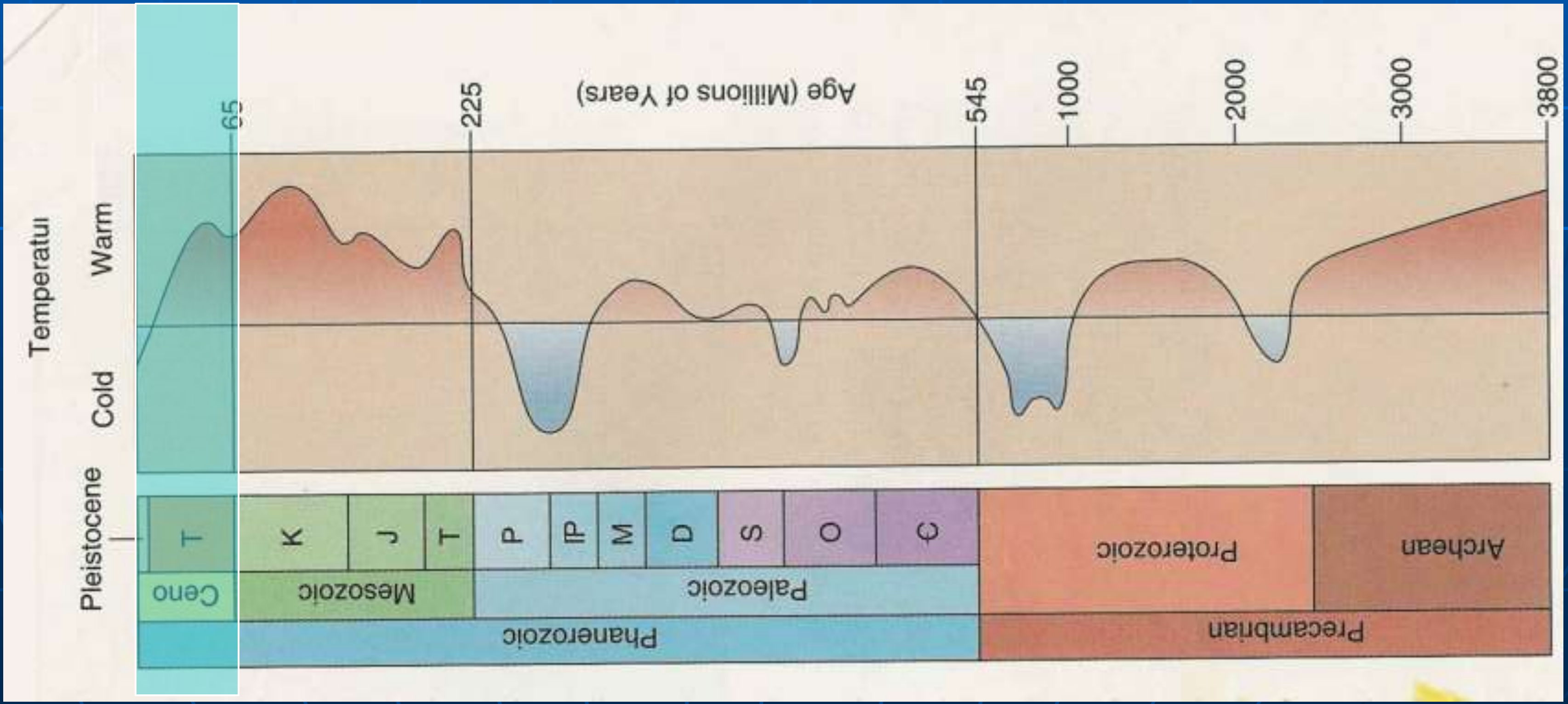


TABLE 8-1 Cratonic Sequences of North America*

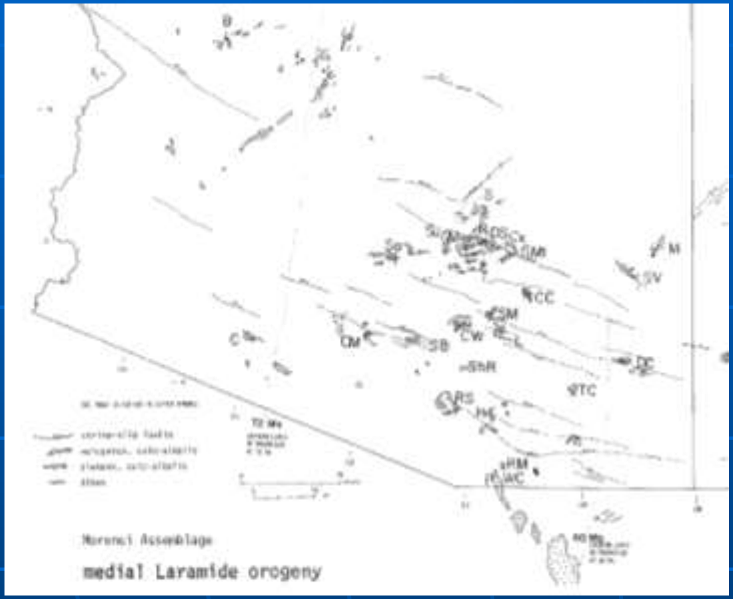
Geologic Time		Cratonic Sequences Center of craton / Margin of craton	Orogenic Events	Biologic Events	Ice Ages
CENOZOIC		Tejas	Himalayan Alpine	Age of mammals	
		65 m.y.a.	Laramide	*Massive extinctions*	
	Cretaceous	Zuni	Sevier	First flowering plants Climax dinosaurs and	



Laramide porphyry copper (65-55 Ma)

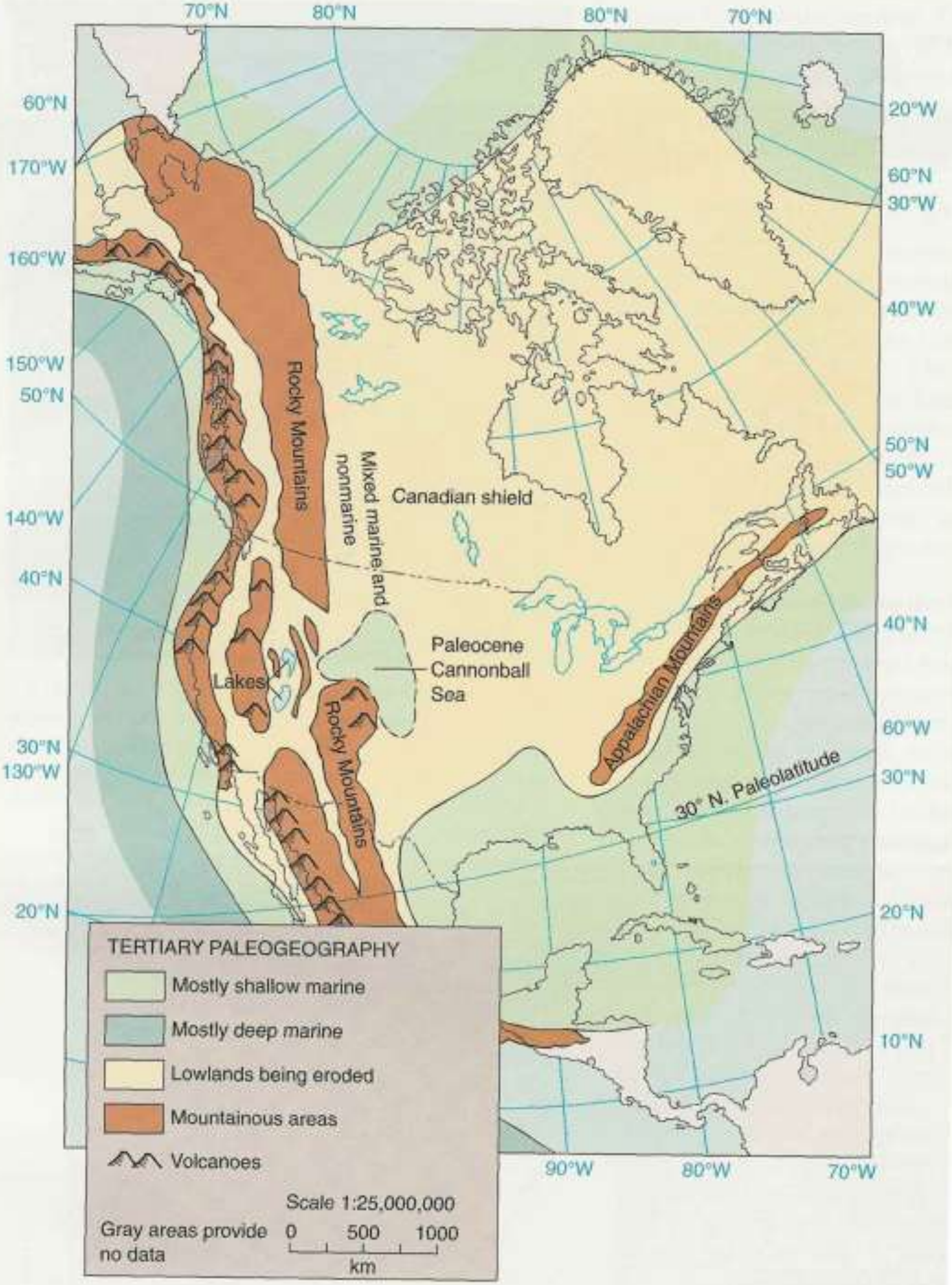
Ray shovel, haul truck
Dave Briggs photos

Middle Laramide - (65-55 Ma)



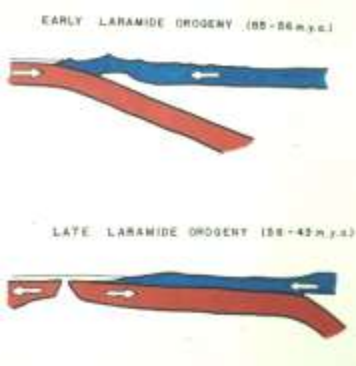
Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
June 2008

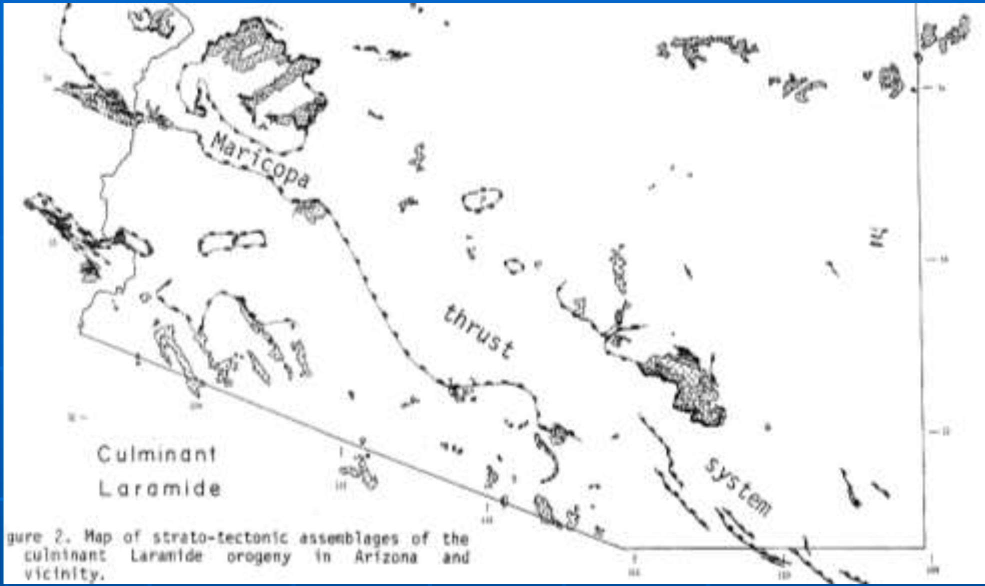
Early Tertiary paleogeography



Tertiary (65-1.8 Ma)

Latest Laramide – (55-43 Ma)





gure 2. Map of strato-tectonic assemblages of the culminant Laramide orogeny in Arizona and vicinity.

Wilderness granite

W. Santa Catalina Mts. From El Conquistador

Texas Canyon granite - ~45 Ma

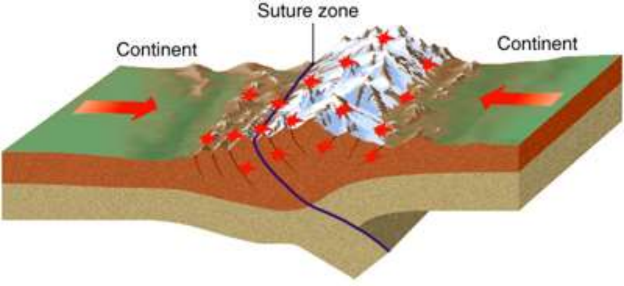
Hot Spots and Hawaii

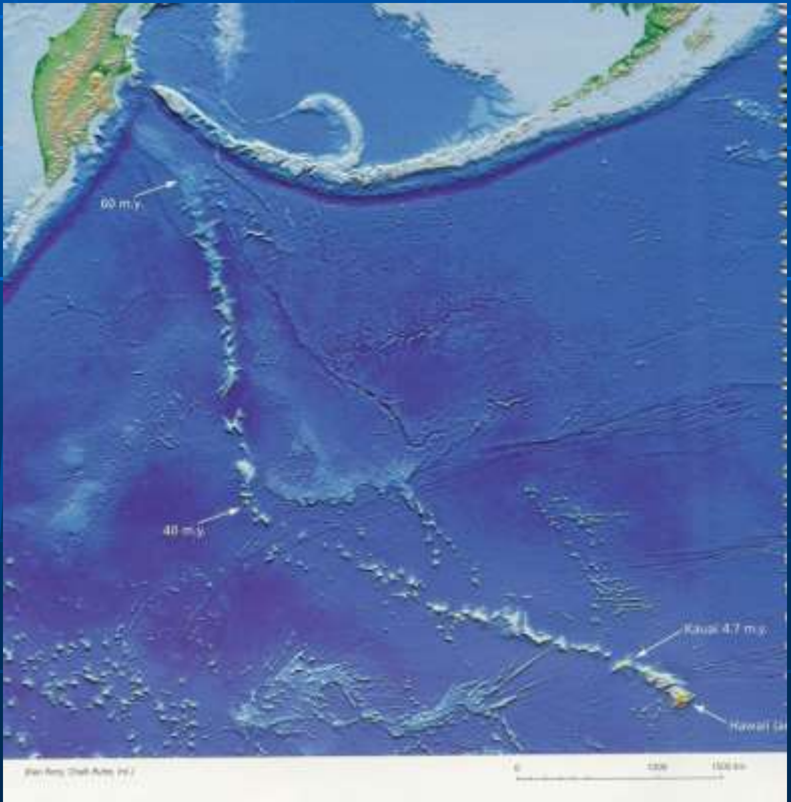
This chain of volcanoes extends NW past Midway Island, and then northward as the Emperor Seamount Chain. The volcanic trail of the Hawaiian hot spot is 6000 km long. A sharp bend in the chain indicates a change in the direction of plate motion about 43 million years ago.

What happened at 43 Ma?

Collision of India into Asia caused plate readjustment.

Change in air mass movement started cooling trend.

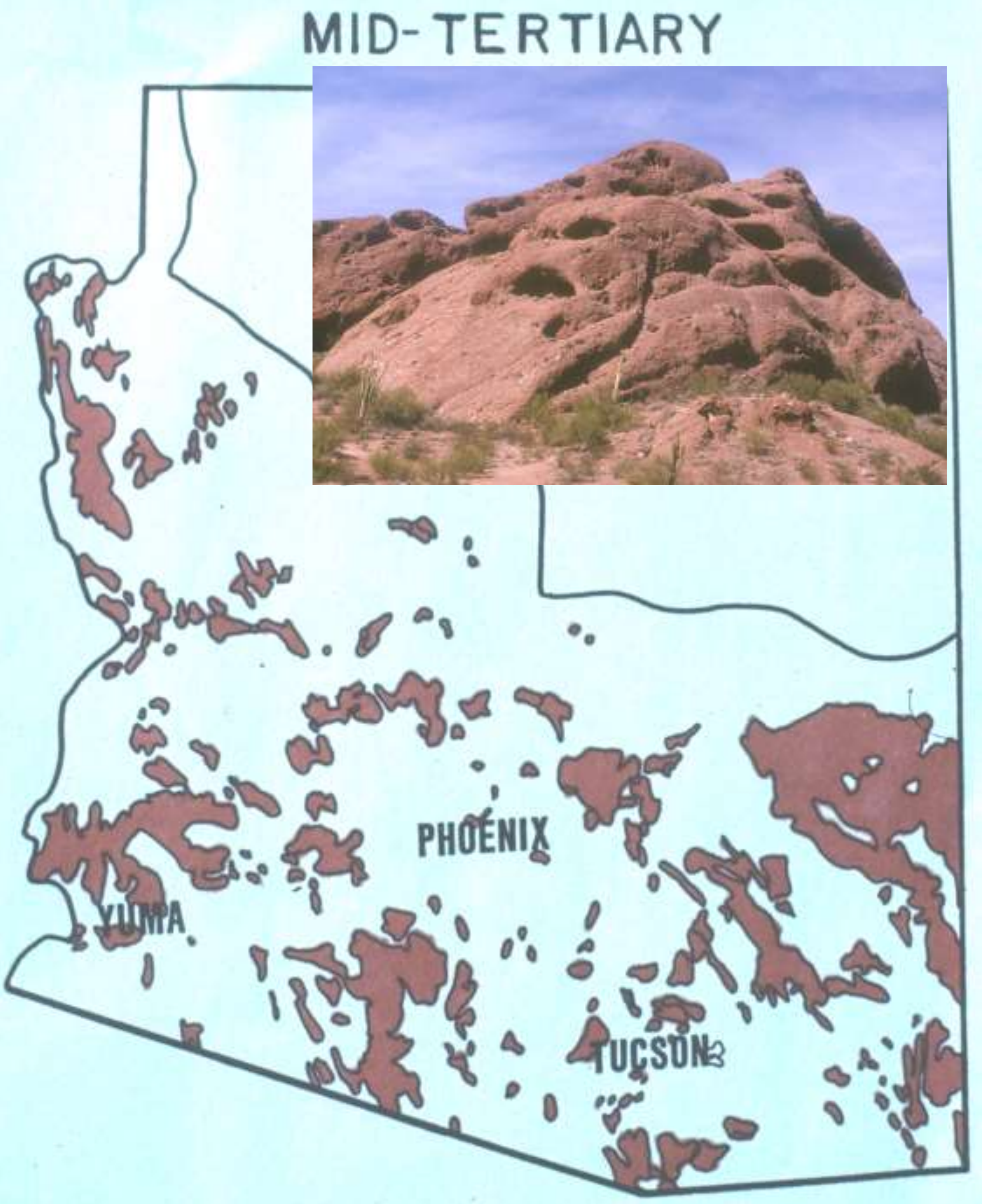




Mid-Tertiary volcanics & deeper plutons

Cochise Stronghold

Superstition Volcanics

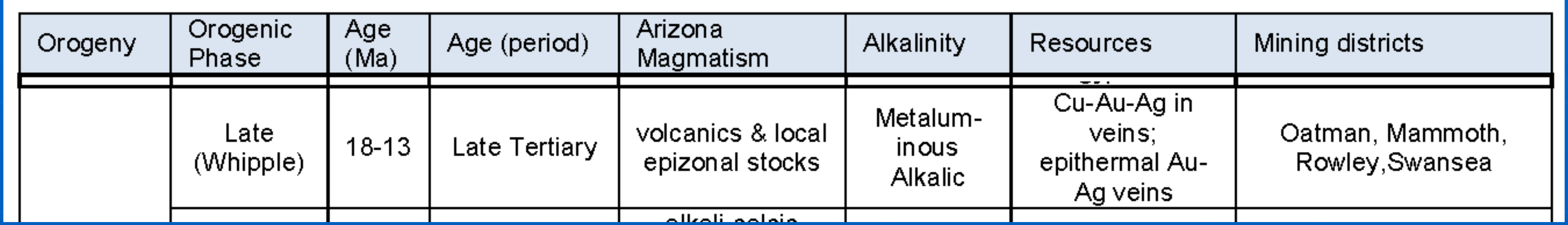


Andesitic stratovolcanoes

— Composite (many eruptions), steep sided

— Commonly violent (e.g., Mount St. Helens)

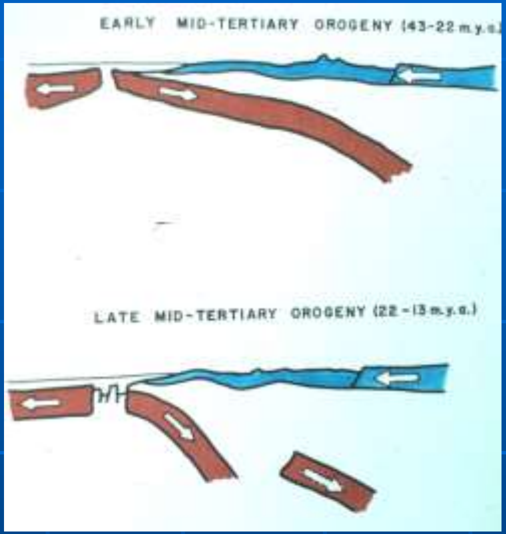
Mammoth-St. Anthony mine (Tiger)

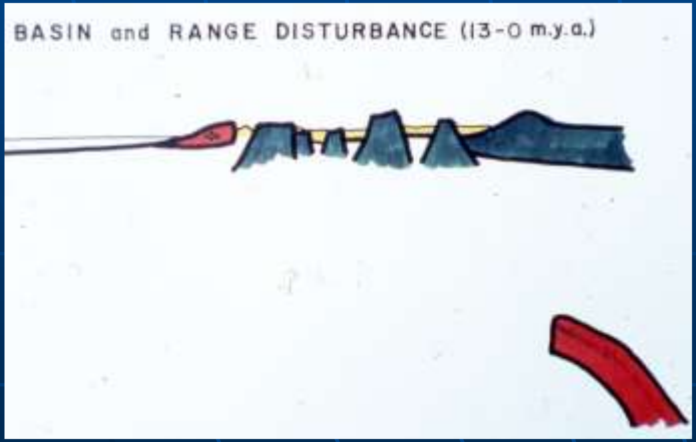


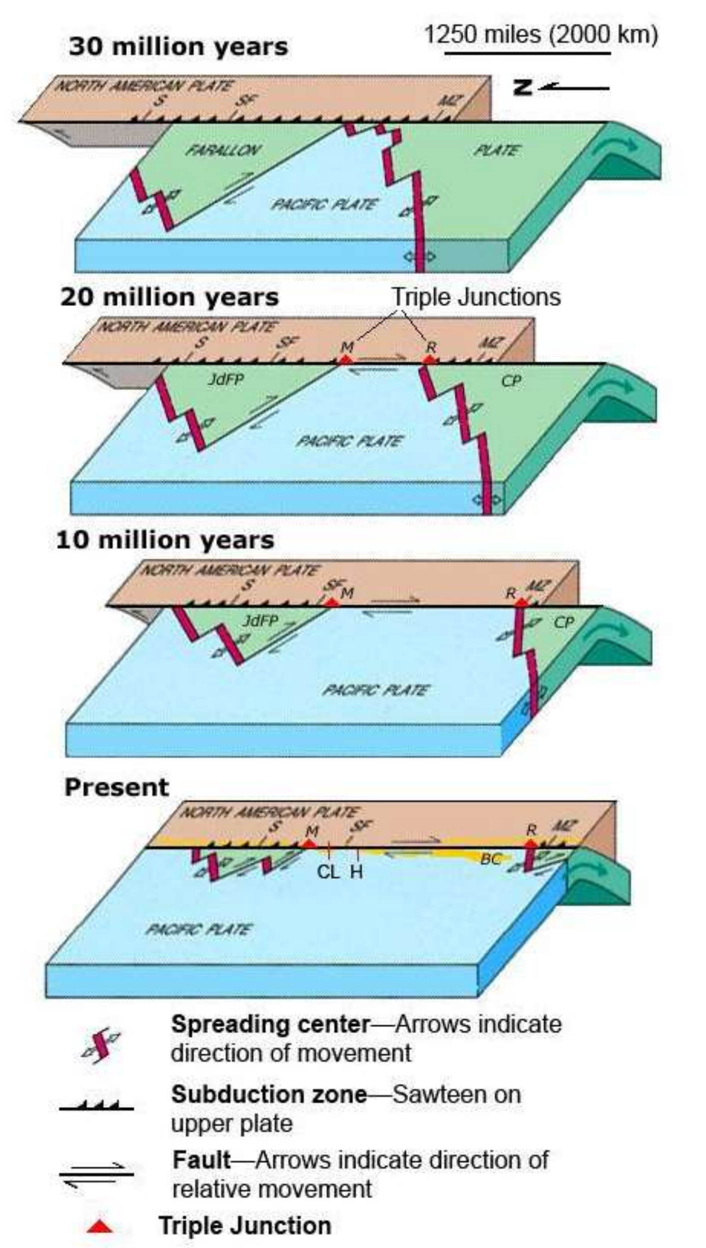
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea

Aerial photos courtesy of BHP Billiton, 2006

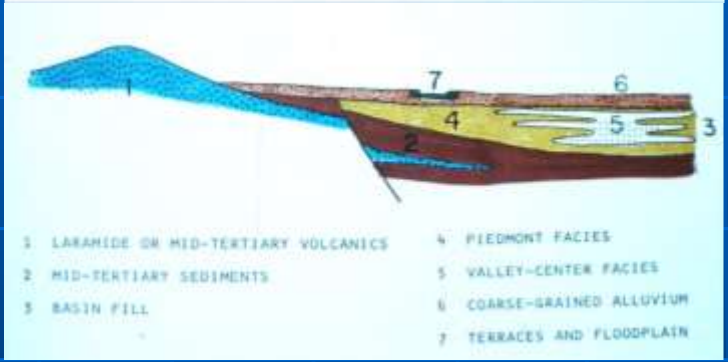
San Andreas fault cuts off eastward-subducting plate







Basin and Range - Valleys filled with sand, gravel, clay, gypsum, & salt



Willcox Playa

Industrial minerals - Late Cenozoic

Sand & gravel

Kalamazoo Clay - 1987

Gypsum rose
St. David

Gravel, sand, clay, gypsum

Late Cenozoic volcanics

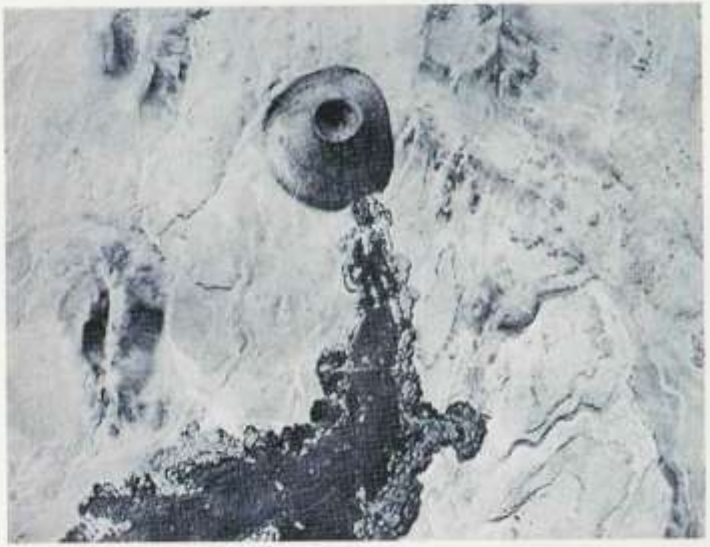
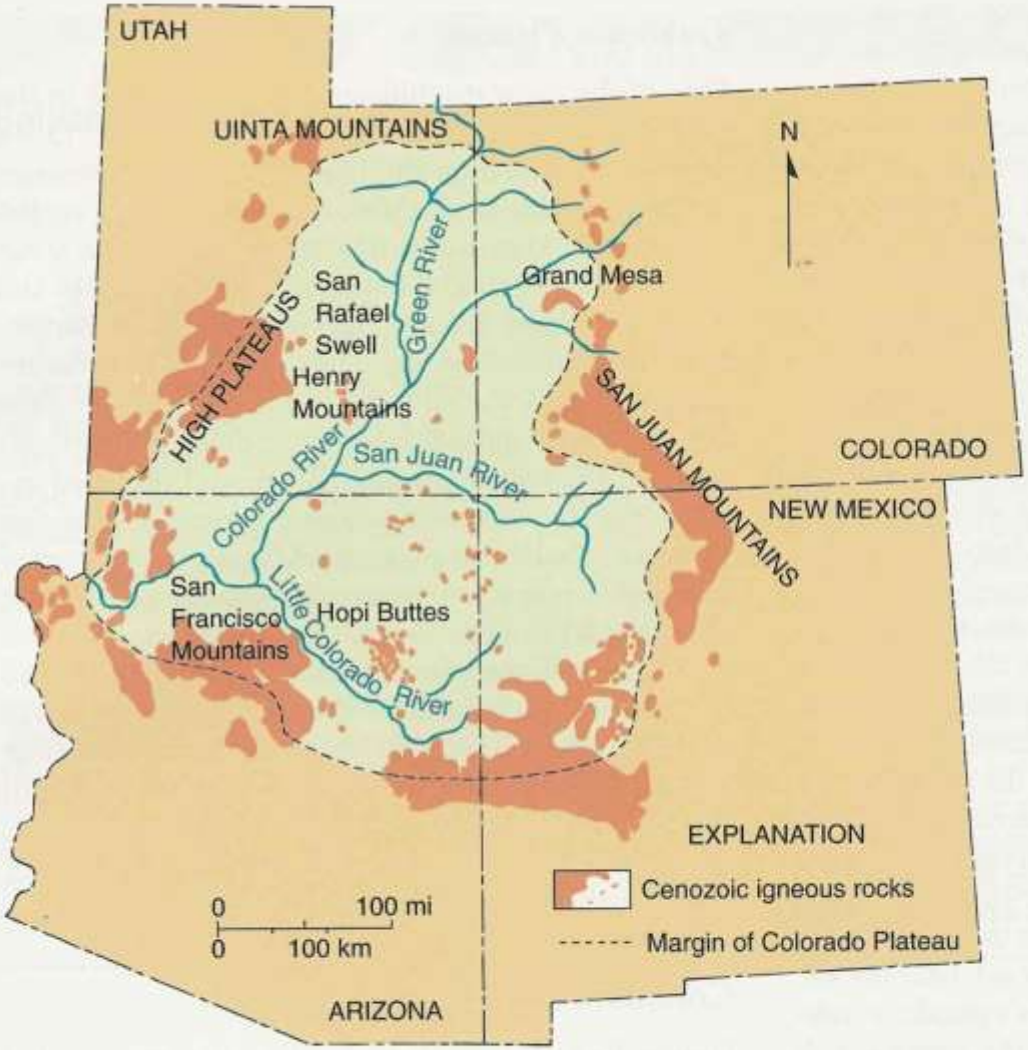


FIGURE 13-20 Vertical aerial photograph of a large cinder cone in the San Francisco volcanic field of northern Arizona. The solidified flow issuing from the cone is 7 kilometers long and more than 30 meters thick.



San Francisco Peaks volcanism 5-0 Ma

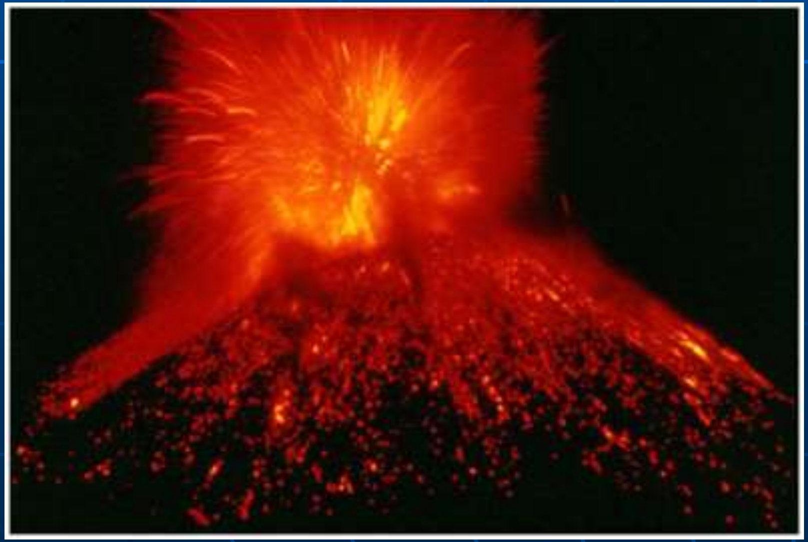
Grand Canyon at Toroweap Valley, West of Visitor Center; Lava flow at Vulcan's Throne into canyon

Lava flow into the Grand Canyon

Basalt lava flow created Lava Falls in the Grand Canyon

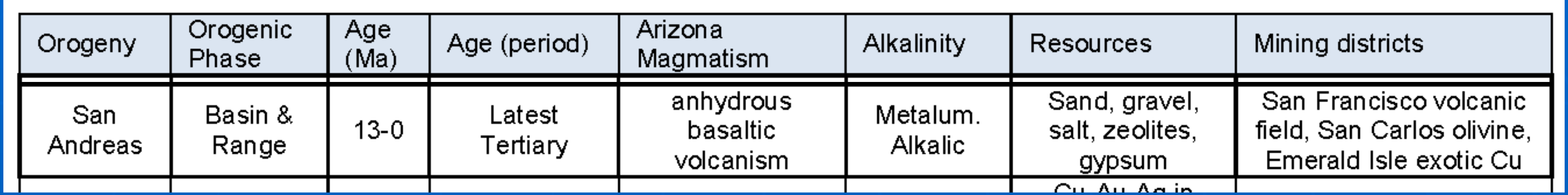
Hawaiian type Volcanic Eruptions

- Lava flows, ash and cinder eruptions



Sunset Crater
1066 AD eruption

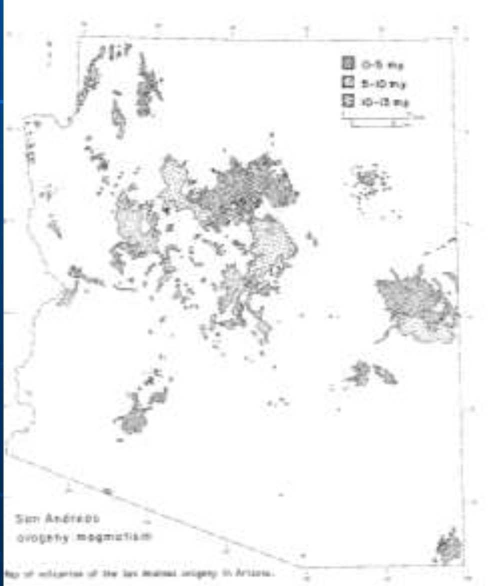
San Andreas – Basin & Range (13-0 Ma)



Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu
						Cu Au Ag in	


Olivine in basalt, San Carlos


cinders




San Francisco Peaks, Flagstaff

LaBrea tarpits, Los Angeles – Pleistocene 1 Ma

Pleistocene glaciation

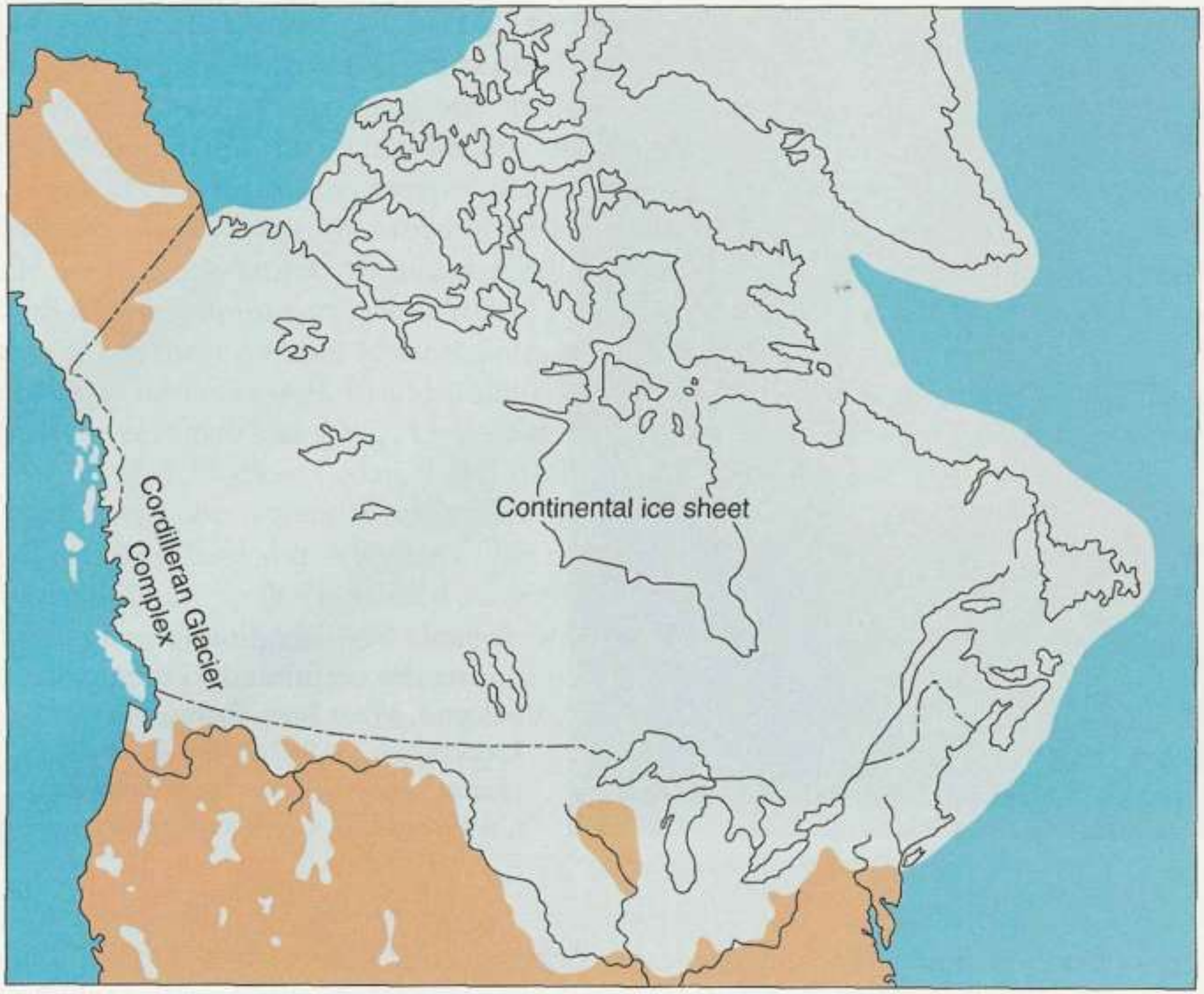
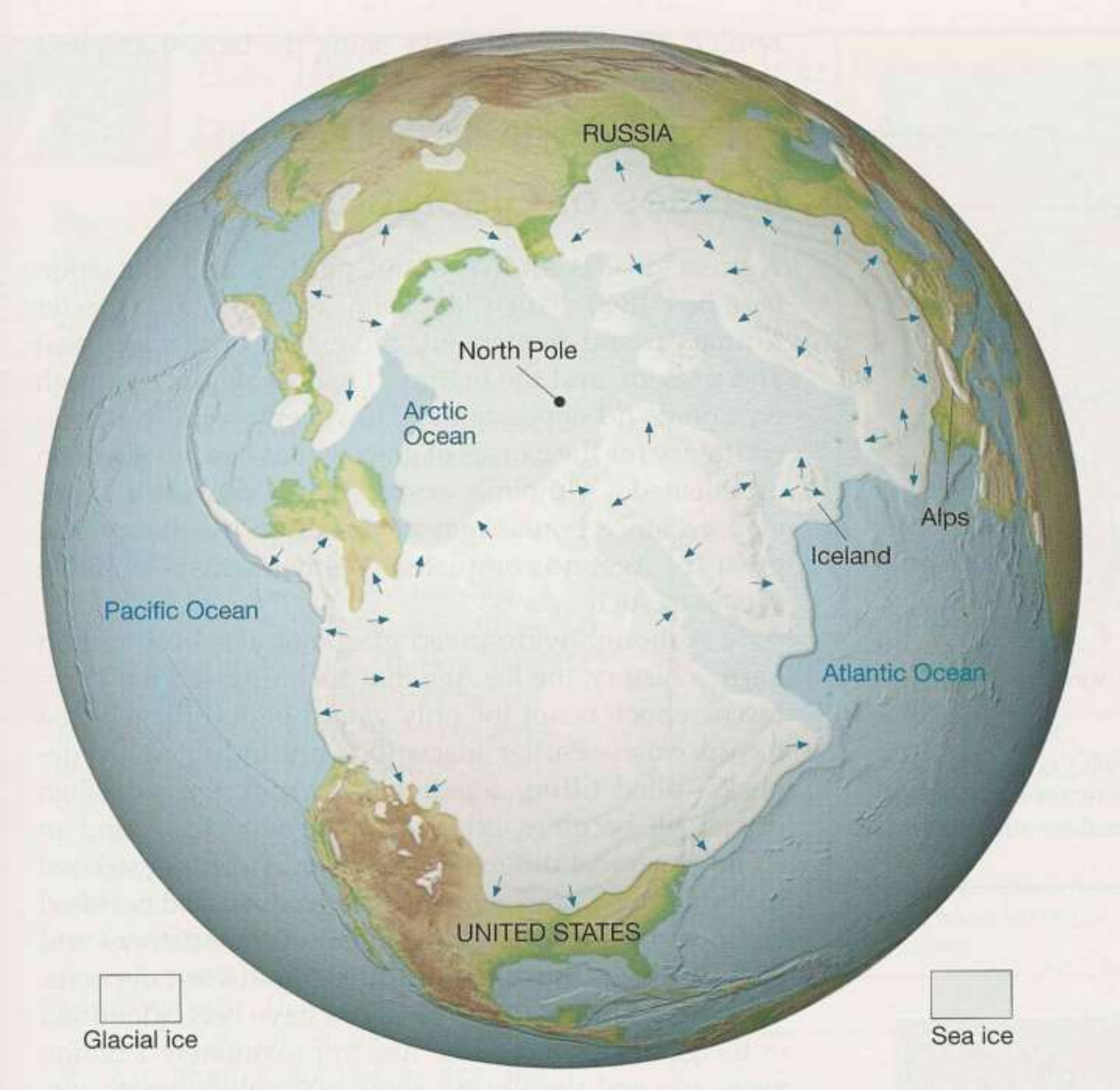


FIGURE 13-36 Areal coverage of continental glaciers in North America during the latest glacial advance, about 18,000 years ago. (*Courtesy of Thompson, G.R. and Turkl, J. 1997*, Modern Physical Geology, *Philadelphia: Saunders College Publishing.*)

Pleistocene maximum glaciation – 18,000 years ago



Carbon dioxide, last 100,000,000 years

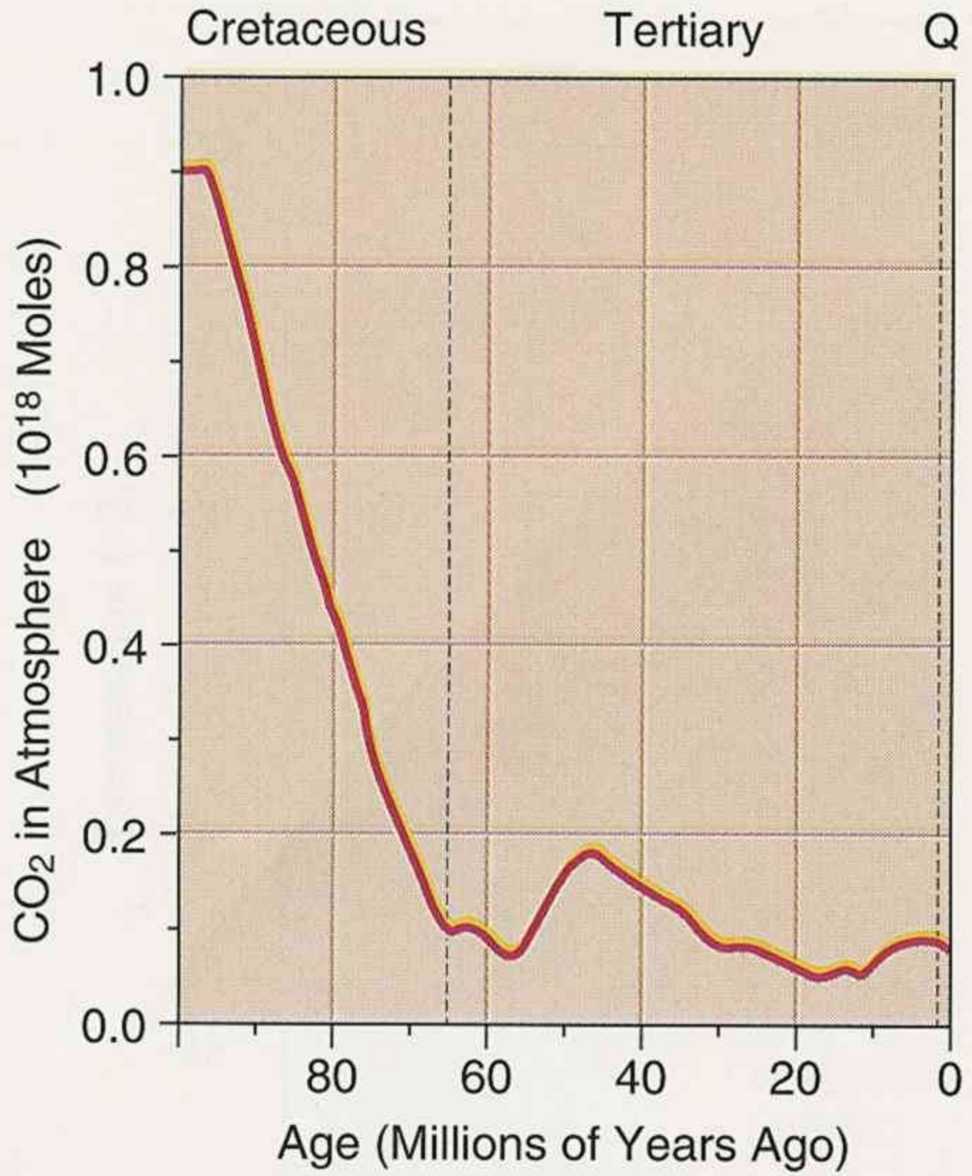
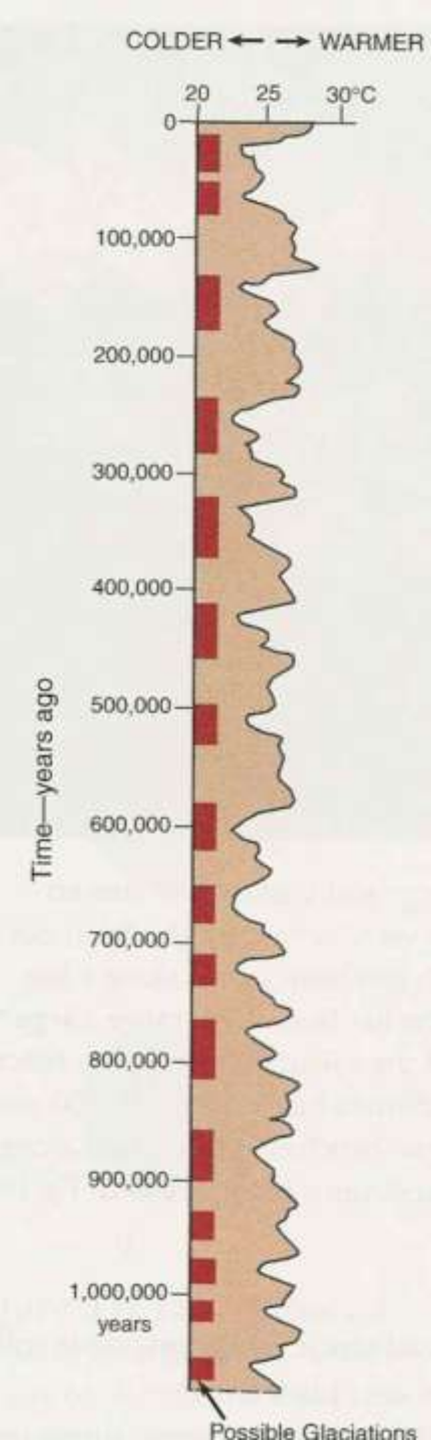


Figure 14.40 **The abundance of carbon dioxide in Earth's atmosphere** has declined dramatically during the last 100 million years. Loss of this important greenhouse gas may have allowed Earth to cool enough for glaciers to accumulate.

1,000,000 years of temperature change



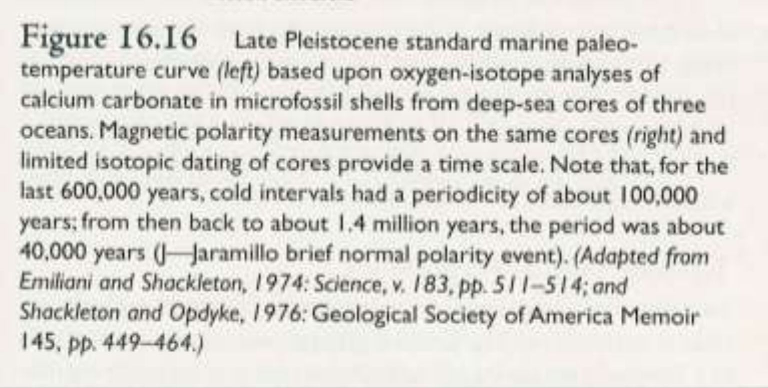


Figure 16.16 Late Pleistocene standard marine paleotemperature curve *(left)* based upon oxygen-isotope analyses of calcium carbonate in microfossil shells from deep-sea cores of three oceans. Magnetic polarity measurements on the same cores *(right)* and limited isotopic dating of cores provide a time scale. Note that, for the last 600,000 years, cold intervals had a periodicity of about 100,000 years; from then back to about 1.4 million years, the period was about 40,000 years (J—Jaramillo brief normal polarity event). *(Adapted from Emiliani and Shackleton, 1974: Science, v. 183, pp. 511–514; and Shackleton and Opdyke, 1976:* Geological Society of America Memoir 145, pp. 449–464.)

Glacial and Interglacial stages, last 2 million years

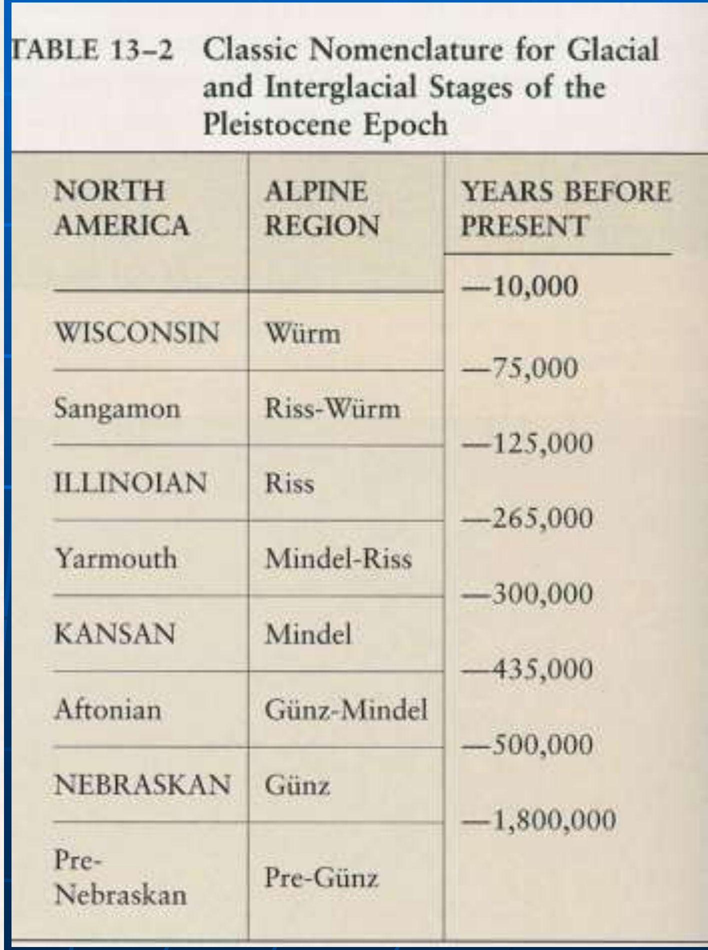
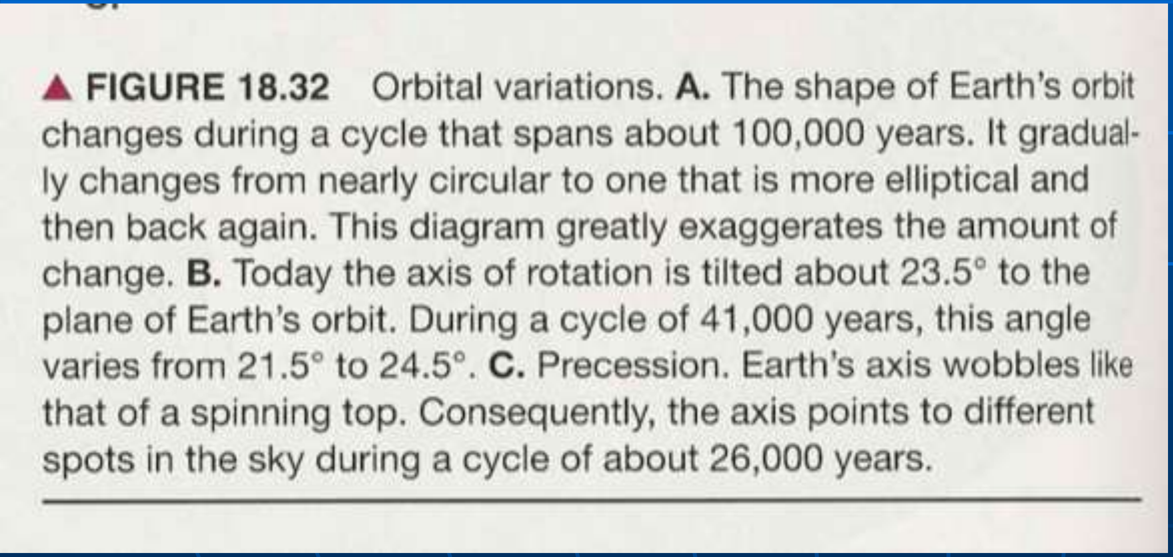


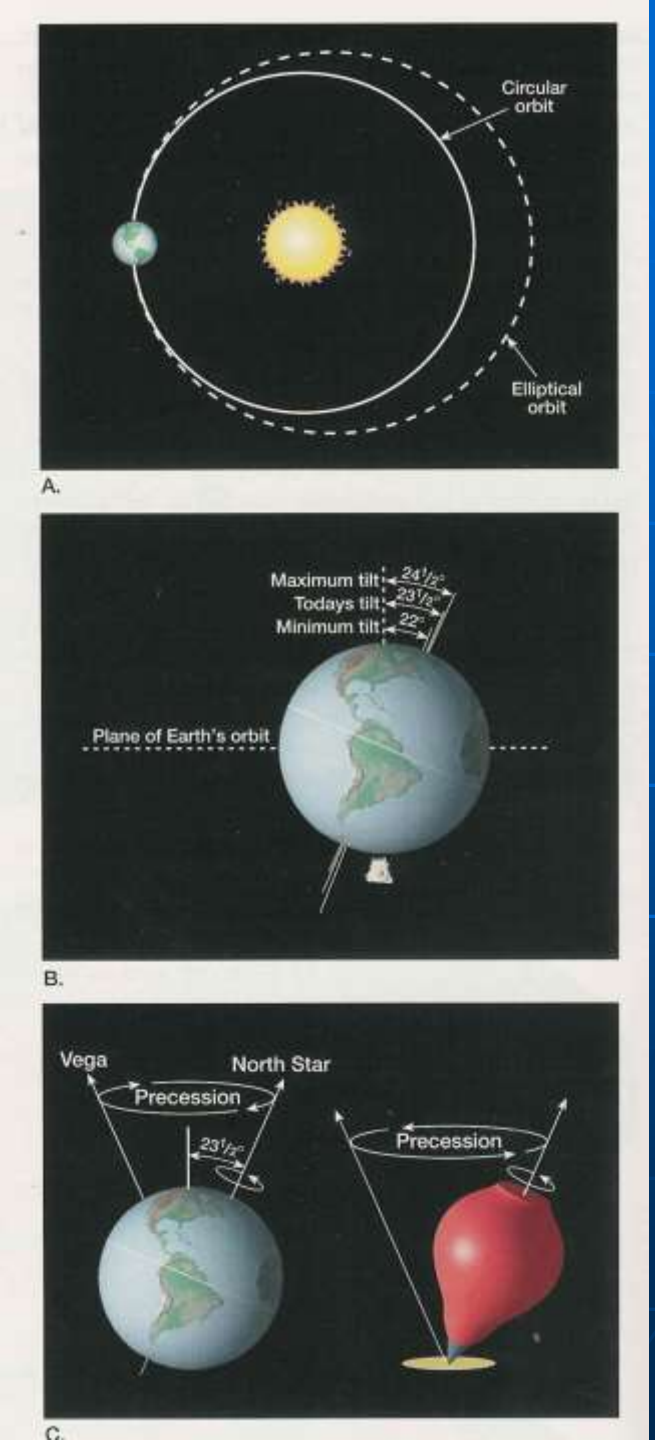
TABLE 13–2 Classic Nomenclature for Glacial and Interglacial Stages of the Pleistocene Epoch

NORTH AMERICA	ALPINE REGION	YEARS BEFORE PRESENT
WISCONSIN	Würm	—10,000
Sangamon	Riss-Würm	—75,000
ILLINOIAN	Riss	—125,000
Yarmouth	Mindel-Riss	—265,000
KANSAN	Mindel	—300,000
Aftonian	Günz-Mindel	—435,000
NEBRASKAN	Günz	—500,000
Pre-Nebraskan	Pre-Günz	—1,800,000

Milankovitch causes of glaciation



▲ FIGURE 18.32 Orbital variations. **A.** The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to one that is more elliptical and then back again. This diagram greatly exaggerates the amount of change. **B.** Today the axis of rotation is tilted about 23.5° to the plane of Earth's orbit. During a cycle of 41,000 years, this angle varies from 21.5° to 24.5°. **C.** Precession. Earth's axis wobbles like that of a spinning top. Consequently, the axis points to different spots in the sky during a cycle of about 26,000 years.



Milankovitch curves – last 800,000 years

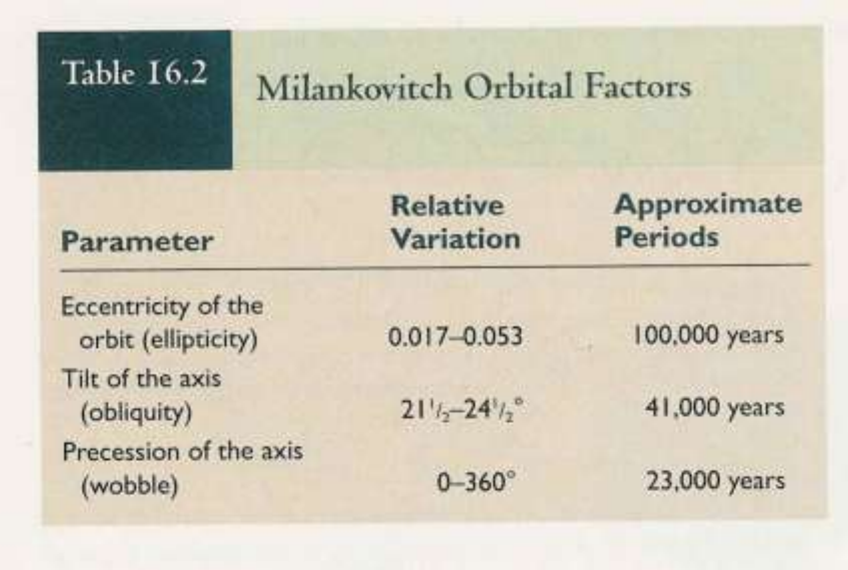


Table 16.2 Milankovitch Orbital Factors

Parameter	Relative Variation	Approximate Periods
Eccentricity of the orbit (ellipticity)	0.017–0.053	100,000 years
Tilt of the axis (obliquity)	21½–24½°	41,000 years
Precession of the axis (wobble)	0–360°	23,000 years

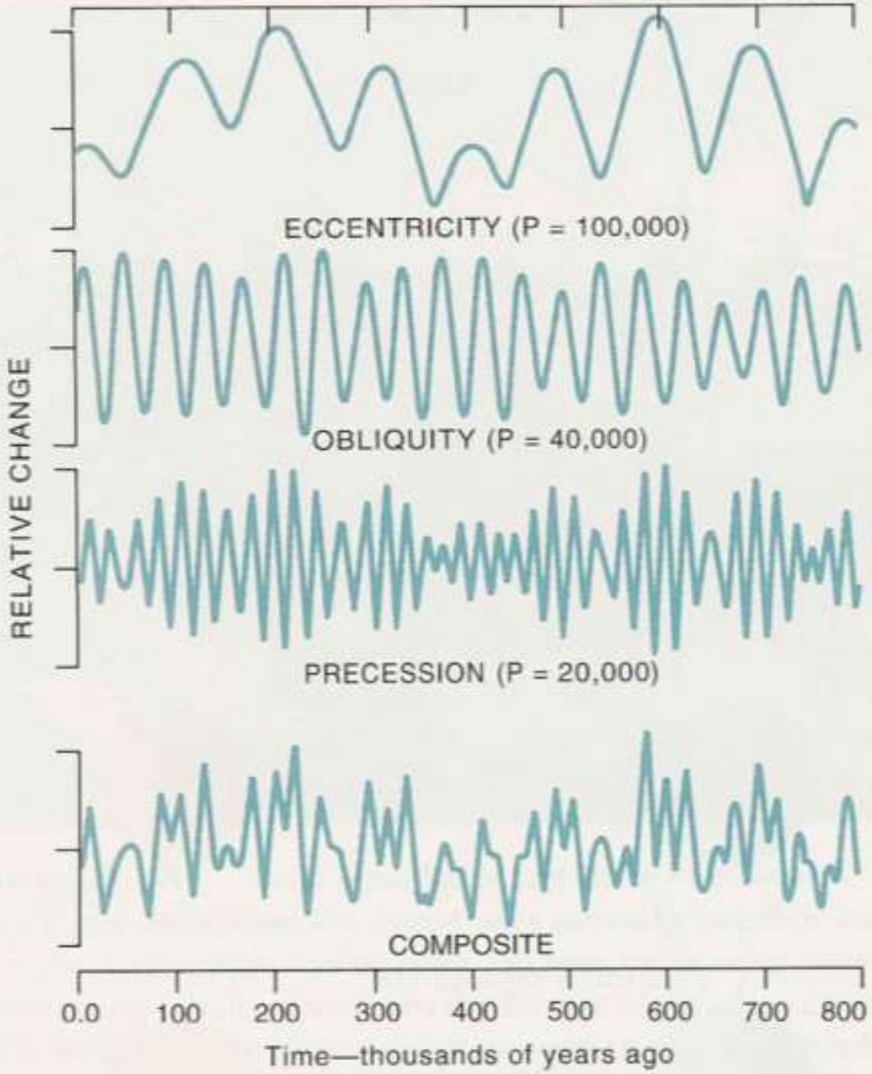
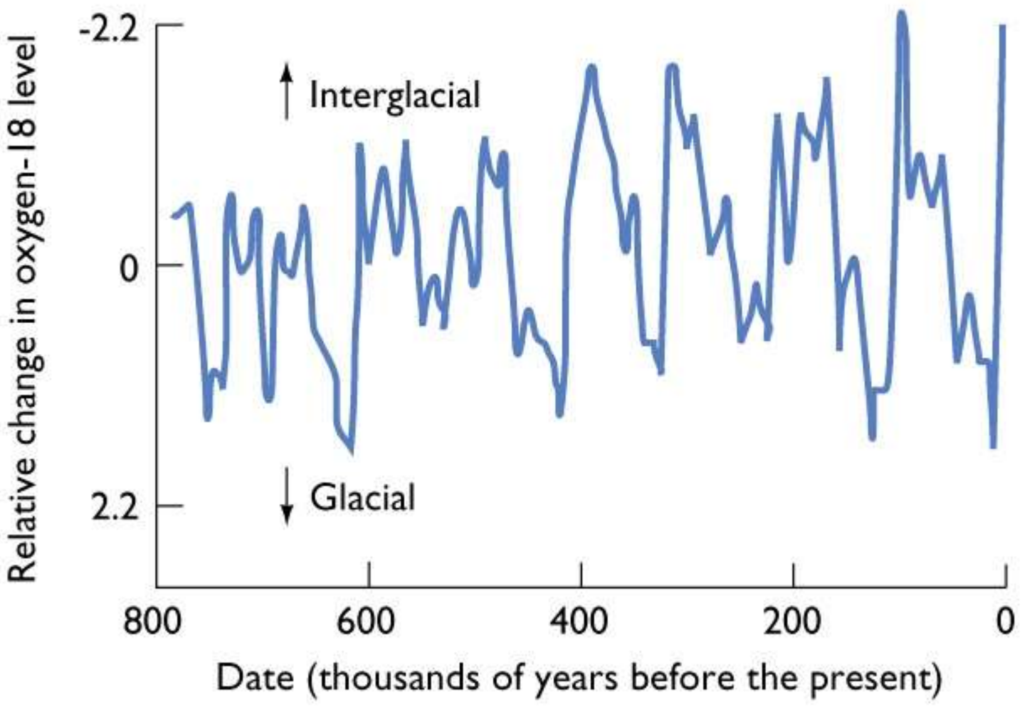
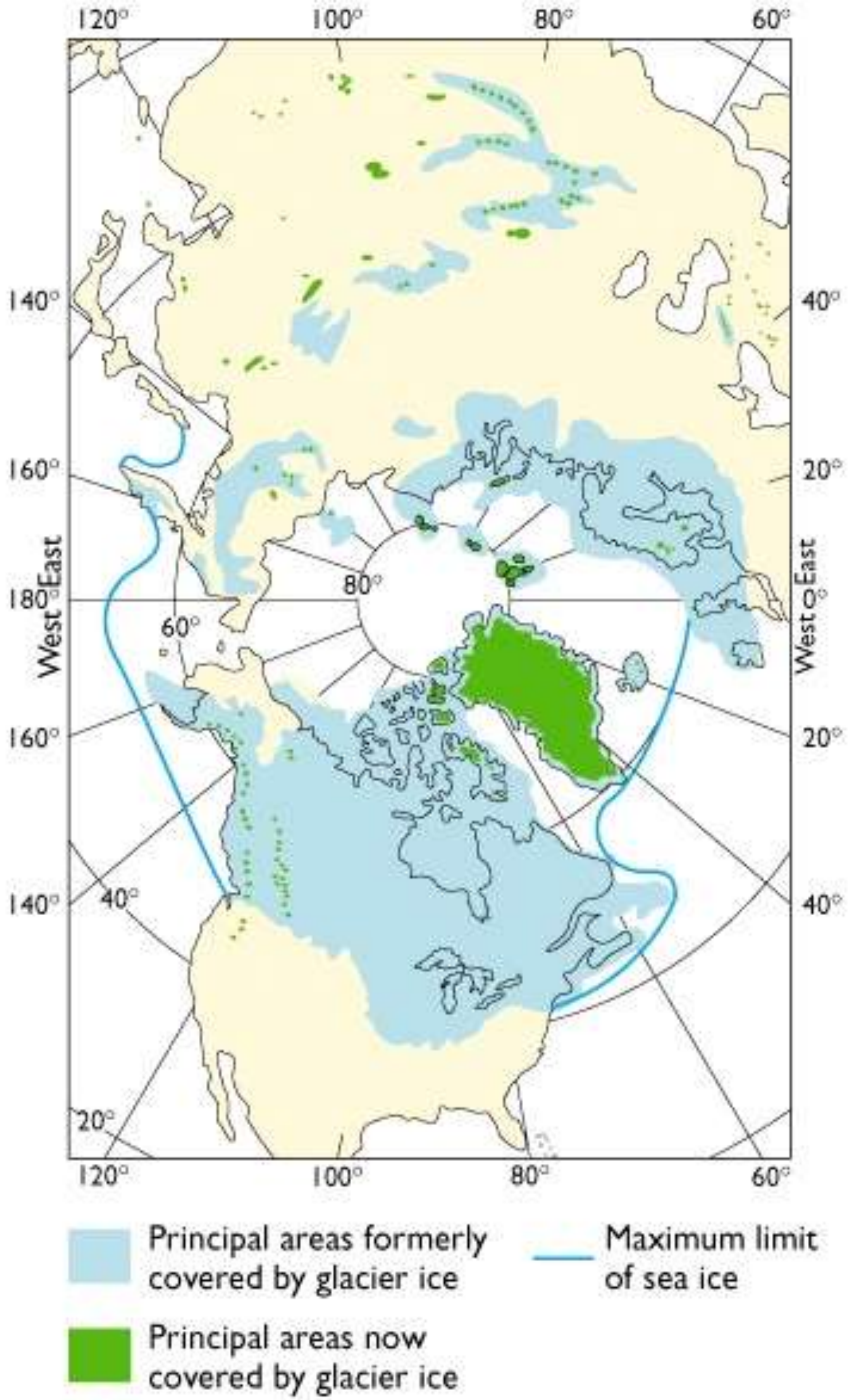


Figure 16.20 Variations in the Milankovitch orbital factors, eccentricity of the earth's orbit, obliquity of the axis, and precession o the equinoxes. The different approximate periods (P) for each of these factors are indicated (see Table 16.2), and a composite curve shows the result of adding all three curves together. *(Adapted from Berger, 1976: Celestial Mechanics, v. 15, pp. 53–74.)*

Pleistocene glaciation (Ice Ages) – 800,000 years to present





500,000 years - Pleistocene temperatures

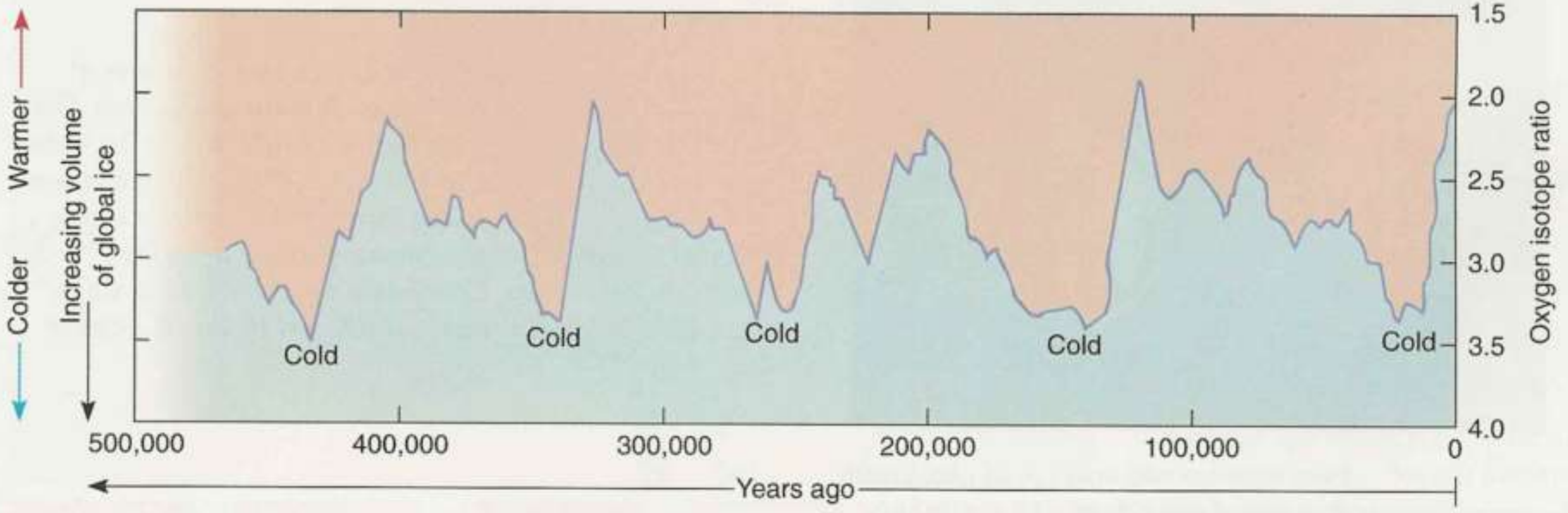
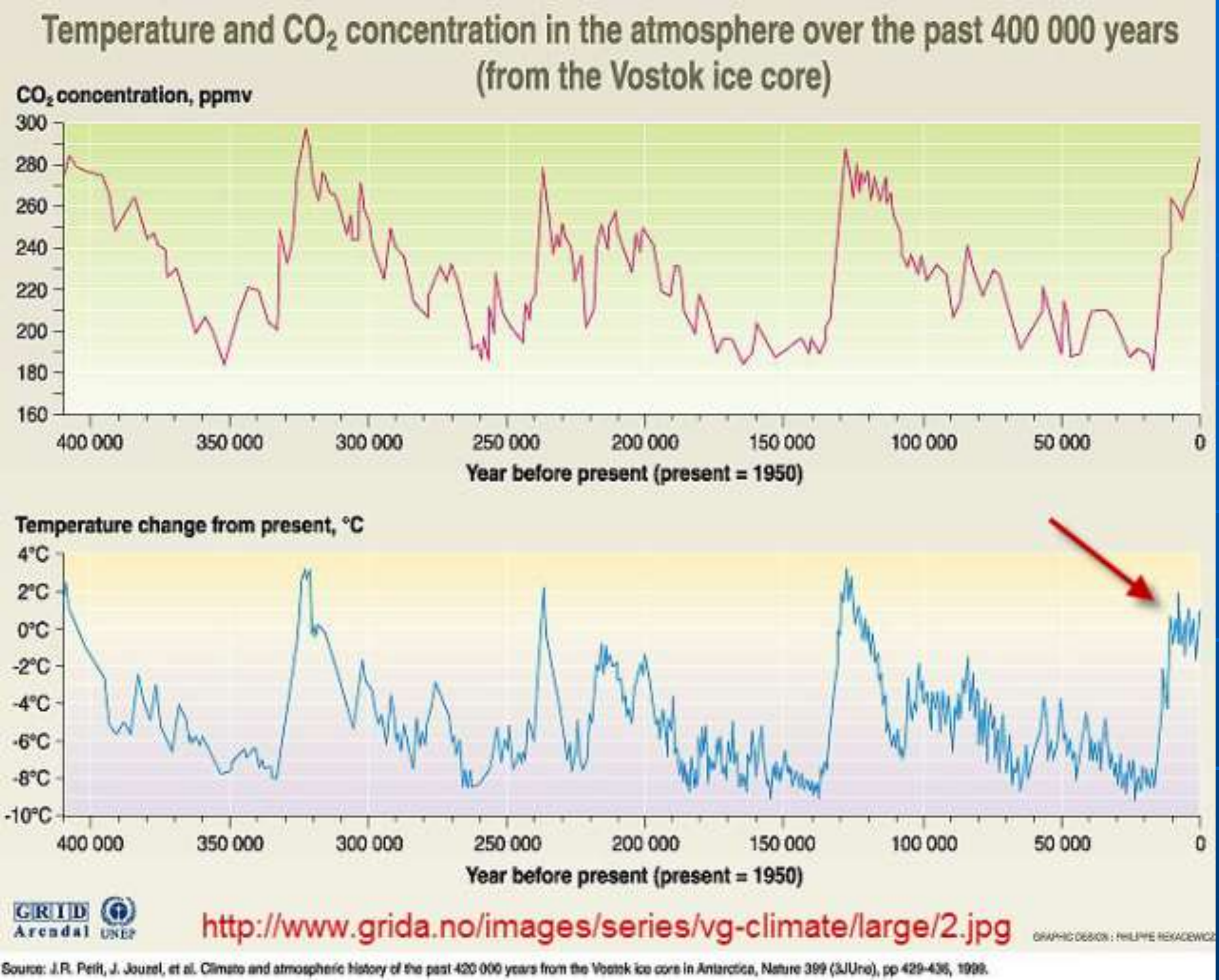


FIGURE 13-43 **Curve reflecting variations in the global volume of ice (and, indirectly, paleotemperatures) during the past 500,000 years.** Data are from radiometric dating and isotope measurements of cores from the Indian Ocean. (*Data from Hays, J. D., and Shackleton,* N. J. 1976. Science *194:1121–1132.*)

Last 400,000 years - Vostok Ice cores



Temperature and CO_2 concentration in the atmosphere over the past 400 000 years (from the Vostok ice core)

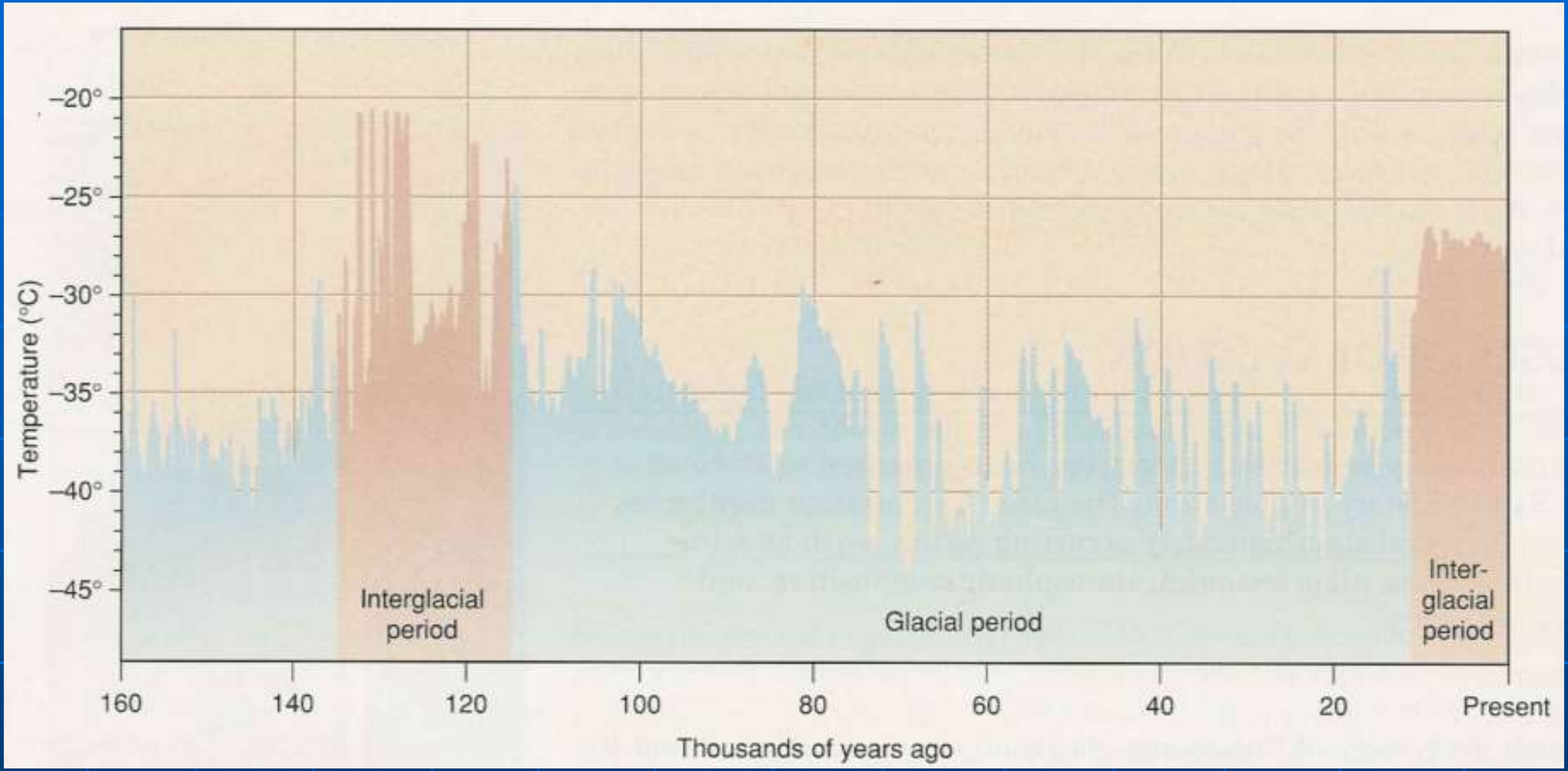
http://www.grida.no/images/series/vg-climate/large/2.jpg

Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

The top graph shows CO2 concentration in the atmosphere; the bottom one shows average temperature departure from the 1950 value. Two observations are readily apparent:

1. For the last 400,000 years at least, "normal" = "COLD!"
2. The warm periods are but brief interludes between ice ages. Wild temperature fluctuations were common before any possible impact of human civilizations. The anomaly is the stability of the moderate temperatures during the Holocene, the last 12,000 years (indicated by my red arrow), when warm weather fostered the development of human agriculture, cultures and civilization.

Climate Change, last 160,000 years



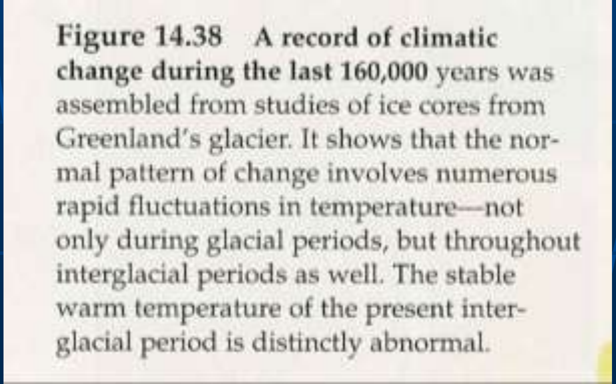
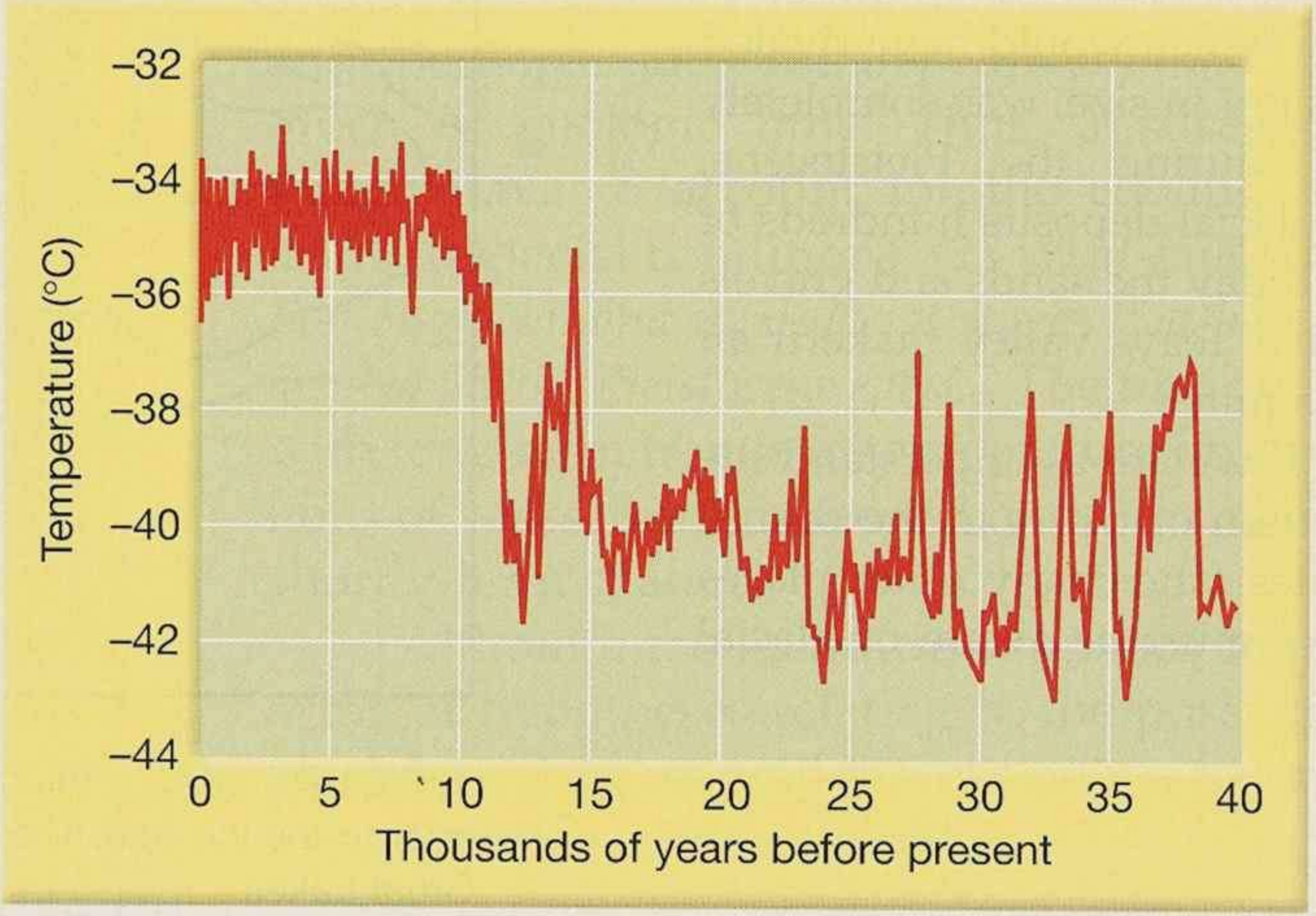


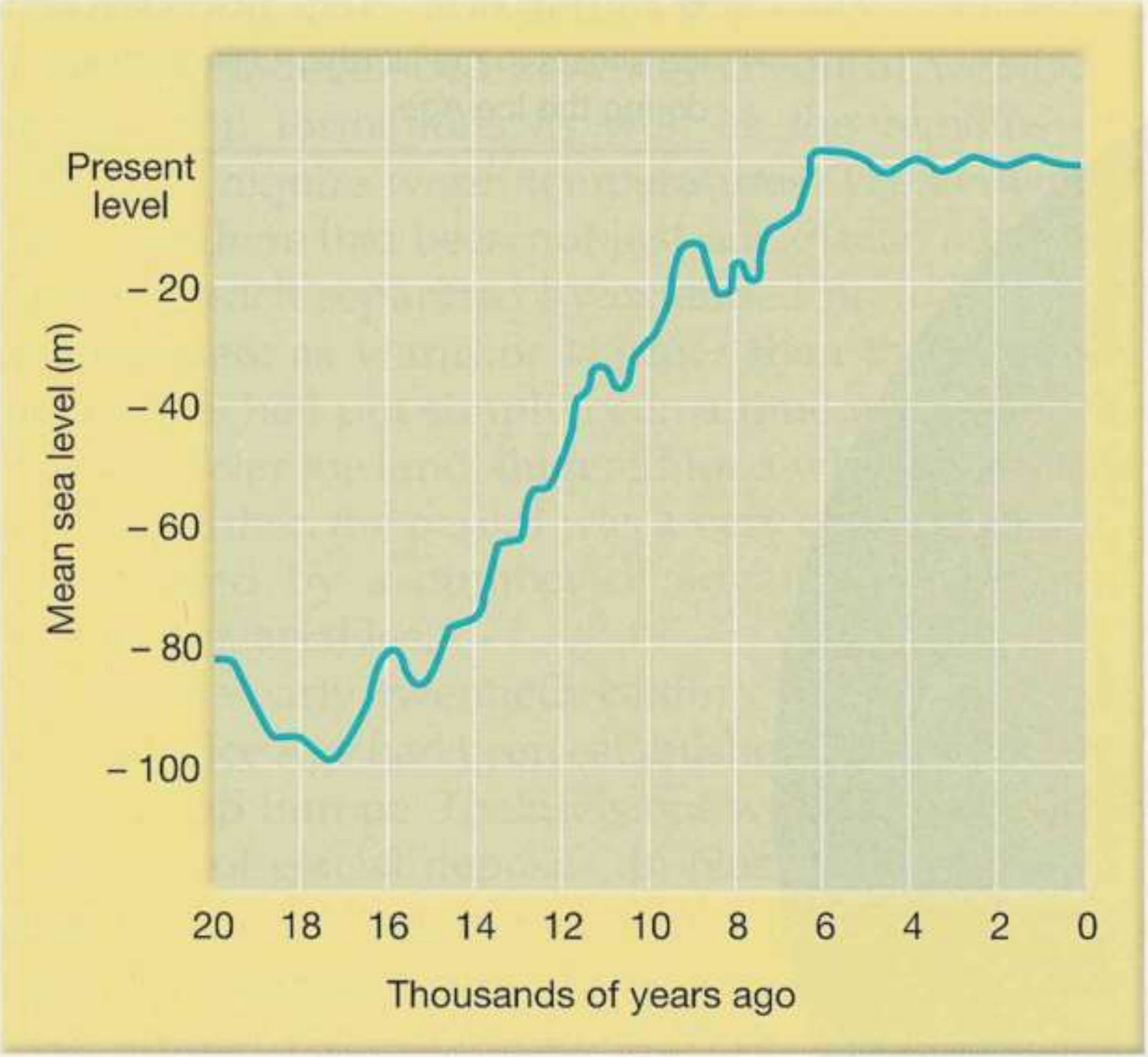
Figure 14.38 A record of climatic change during the last 160,000 years was assembled from studies of ice cores from Greenland's glacier. It shows that the normal pattern of change involves numerous rapid fluctuations in temperature—not only during glacial periods, but throughout interglacial periods as well. The stable warm temperature of the present interglacial period is distinctly abnormal.

40,000 years temperature change



▲ **FIGURE 18.E** This graph showing temperature variations over the past 40,000 years is derived from oxygen isotope analysis of ice cores recovered from the Greenland ice sheet. *(After U.S. Geological Survey)*

Sea Level curve – 20,000 yrs



▲ **FIGURE 18.29** Changing sea level during the past 20,000 years. The lowest level shown on the graph represents the time about 18,000 years ago when the most recent ice advance was at a maximum.

Last 10,000 yrs temperature

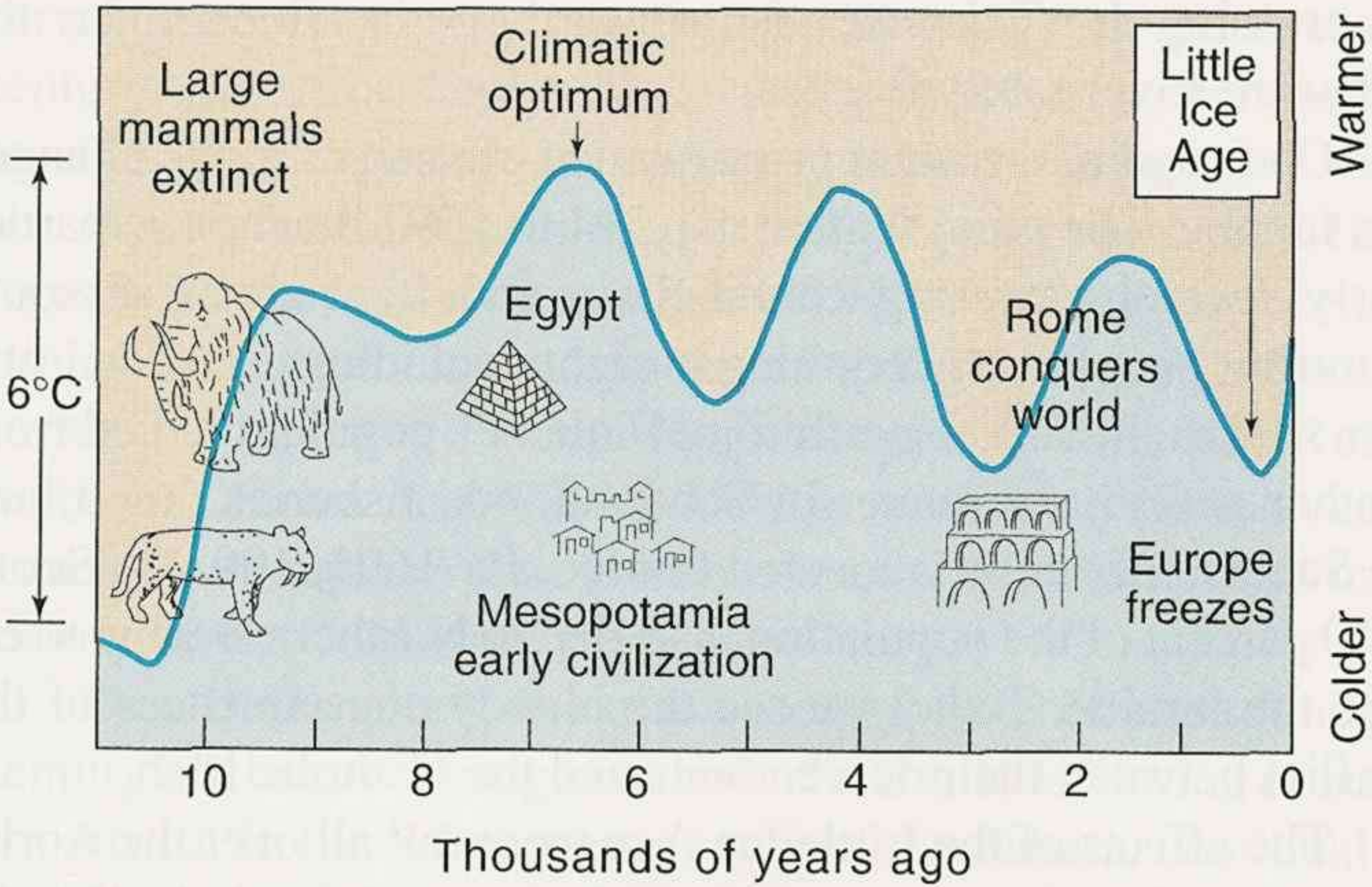
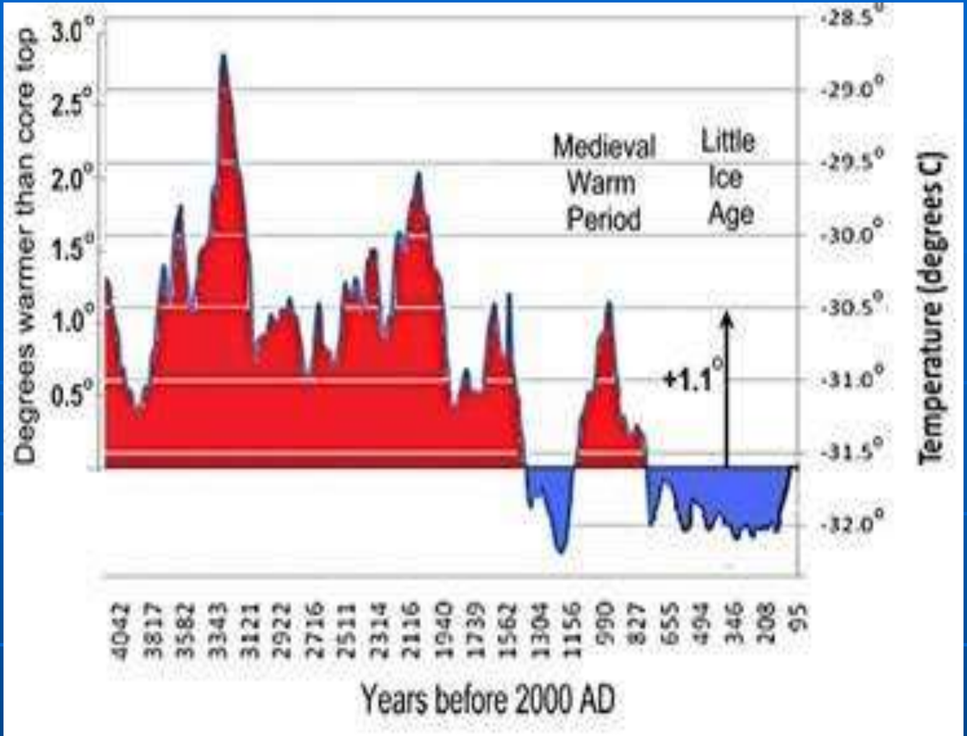


Figure 16.35 The effects of climatic cycles on the past 10,000 years of human history.

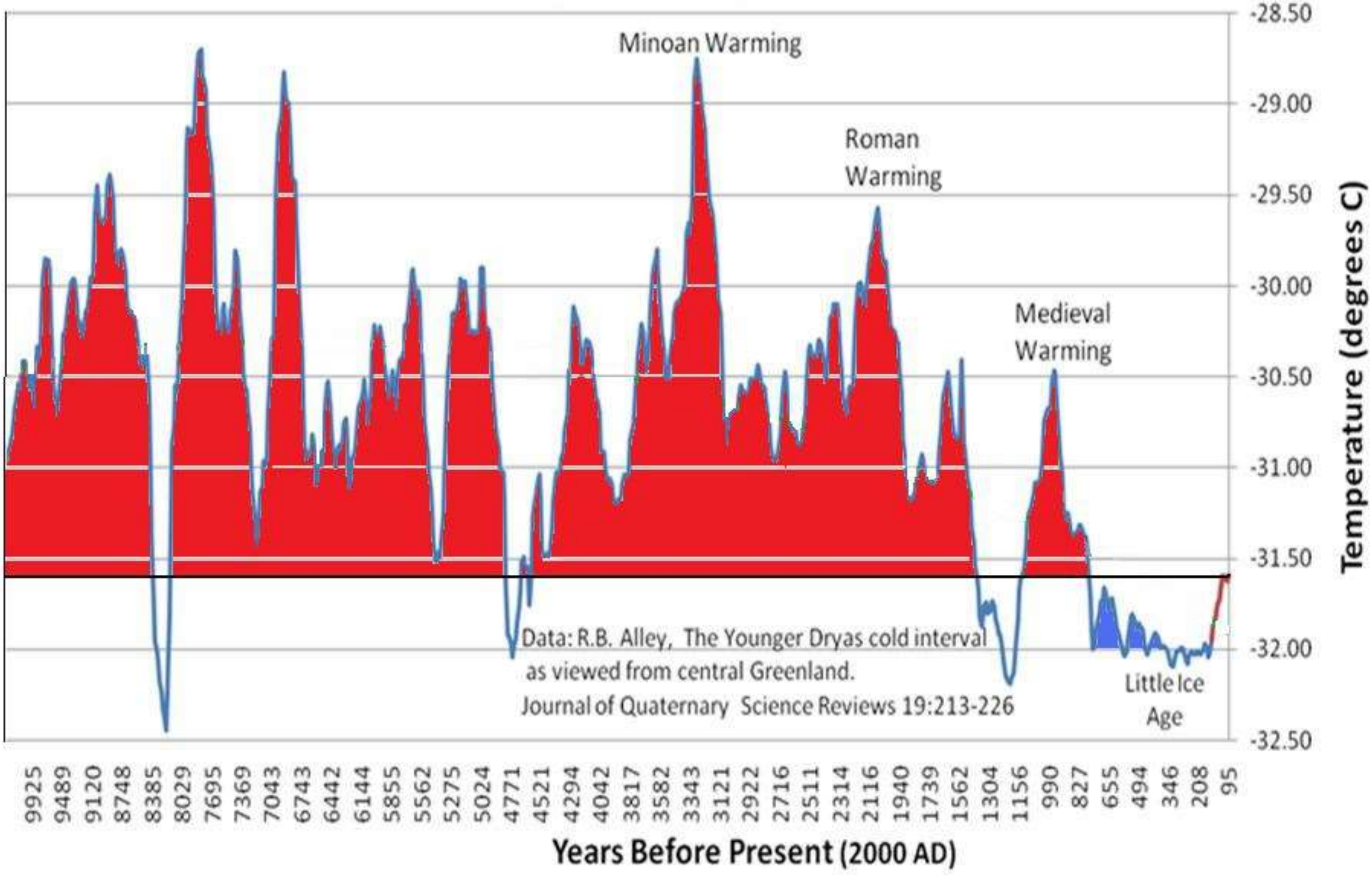
Last 10,000 years

Greenland ice core temperature



The 1880-1915 cool period was followed by the 1915-1945 warm period, the 1945-1977 cool period, and the 1978-1998 warm period (Figure 4). The rate of warming from 1913 to 2013 is about 0.7°C per century (which is about the same as the warming rate over the past 400 years as we have been thawing out of the Little Ice, long before atmospheric CO2 began to rise significantly).

Greenland GISP2 Ice Core - Temperature Last 10,000 Years



Data: R.B. Alley, The Younger Dryas cold interval as viewed from central Greenland. Journal of Quaternary Science Reviews 19:213-226

Temperature change, last 5,500 years

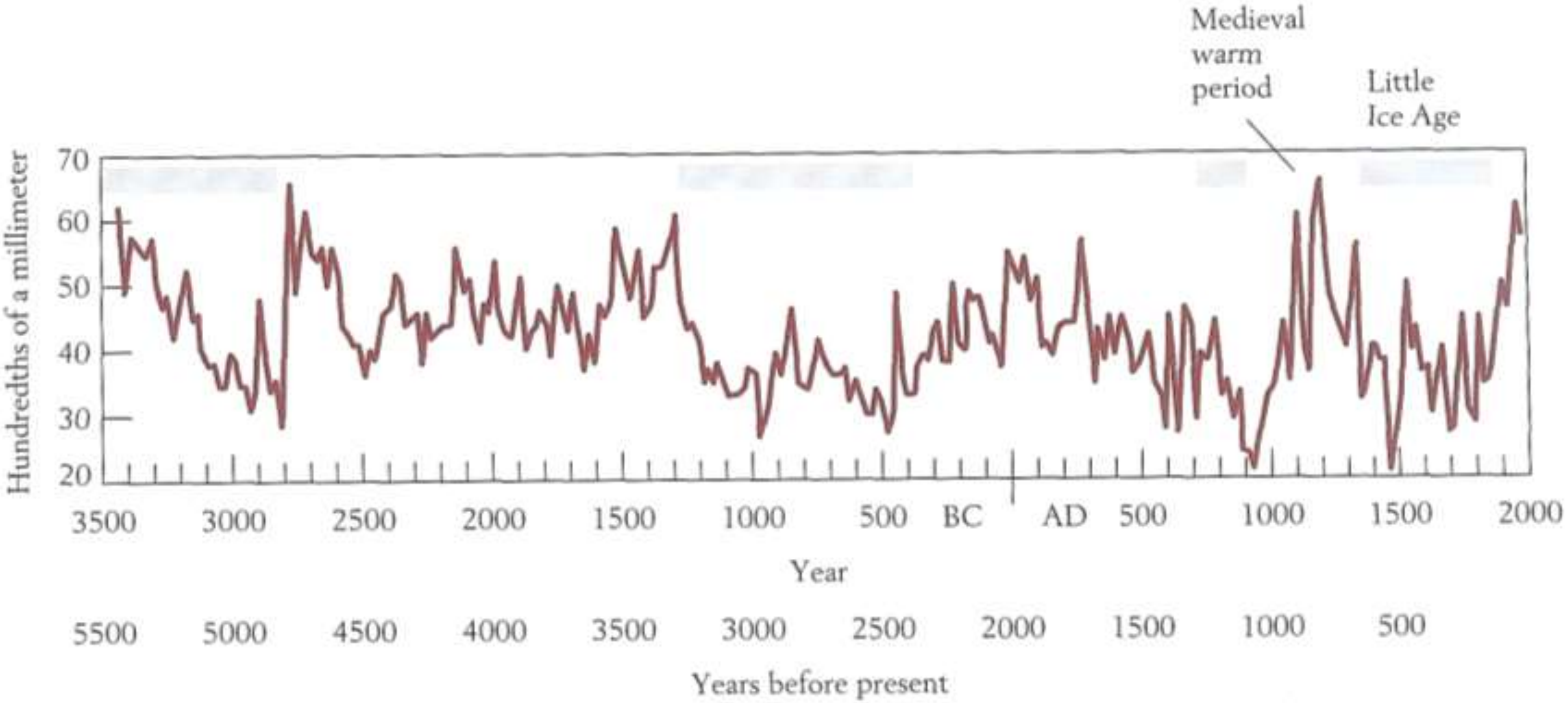
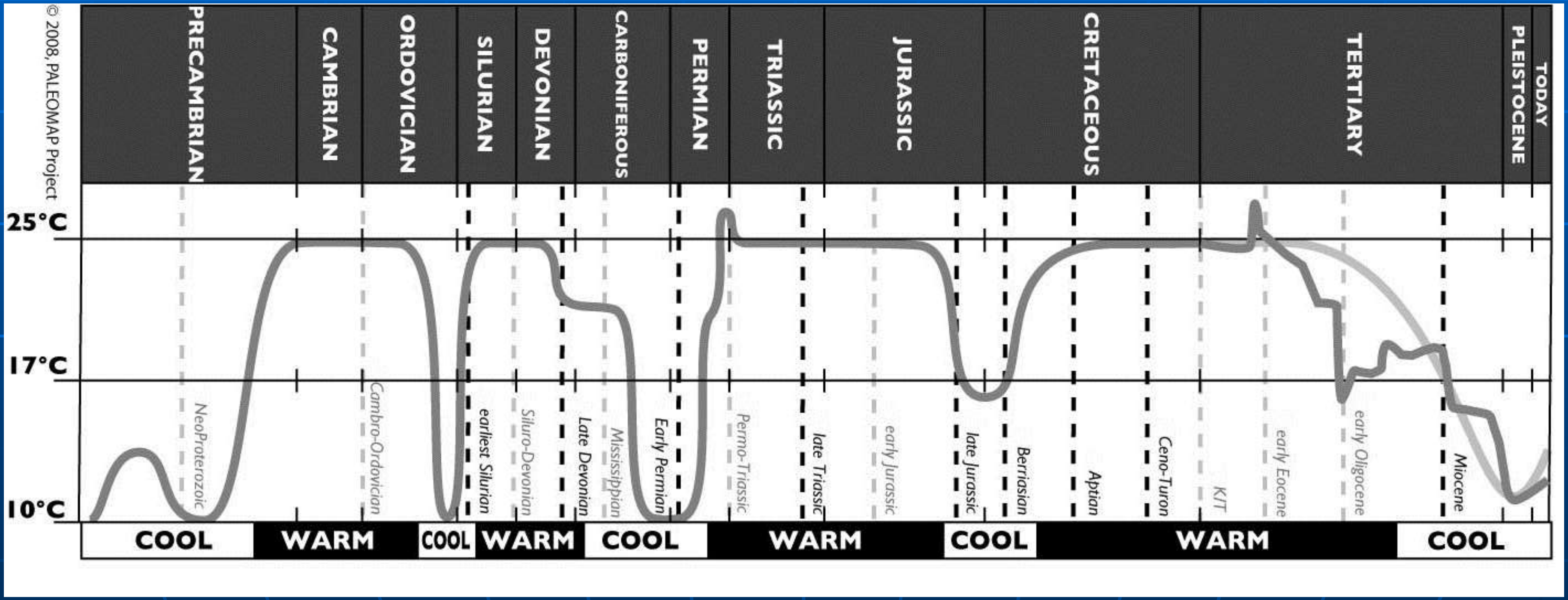
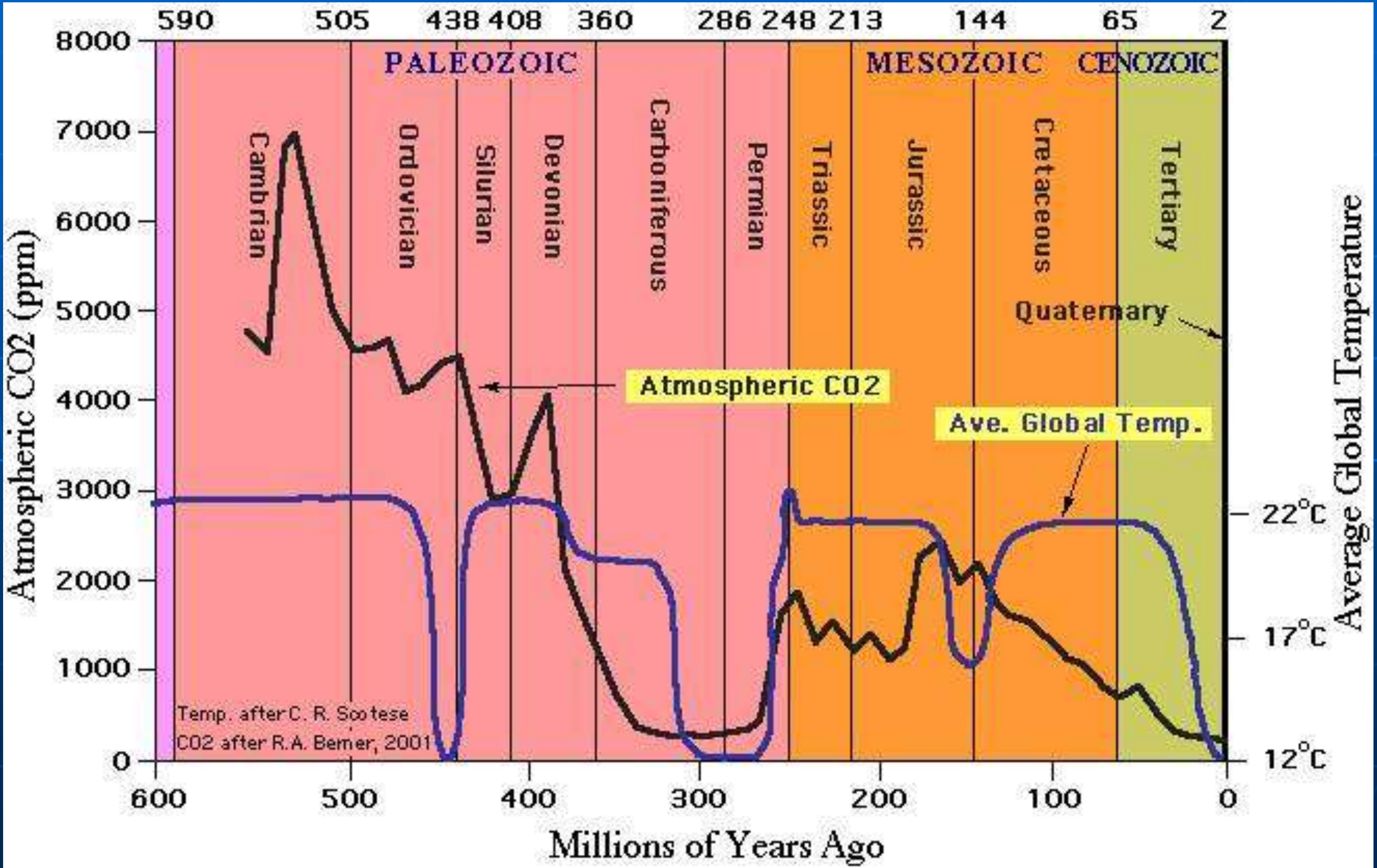


Figure 20-10 **Cold intervals of the past 5500 years recorded by widths of annual growth rings in bristlecone pines near the upper tree line of the White Mountains of California.** (Data from V. C. La Marche, in H. H. Lamb, *Climate History and the Modern World*, Routledge, London, 1995.)

Temperatures from 1,200,000,000 to present



CO$_2$ and Temperatures from 600,000,000 to present



Temp. after C. R. Scotese
CO2 after R.A. Berner, 2001

Glaciation through Geologic time

- Depends on plate tectonics through geologic history
- Continental collisions = ice ages
- Big environmental changes through geologic time
- Warm periods vs.
- ice ages ~ every
- 250 million years