Geologic History of Arizona

By

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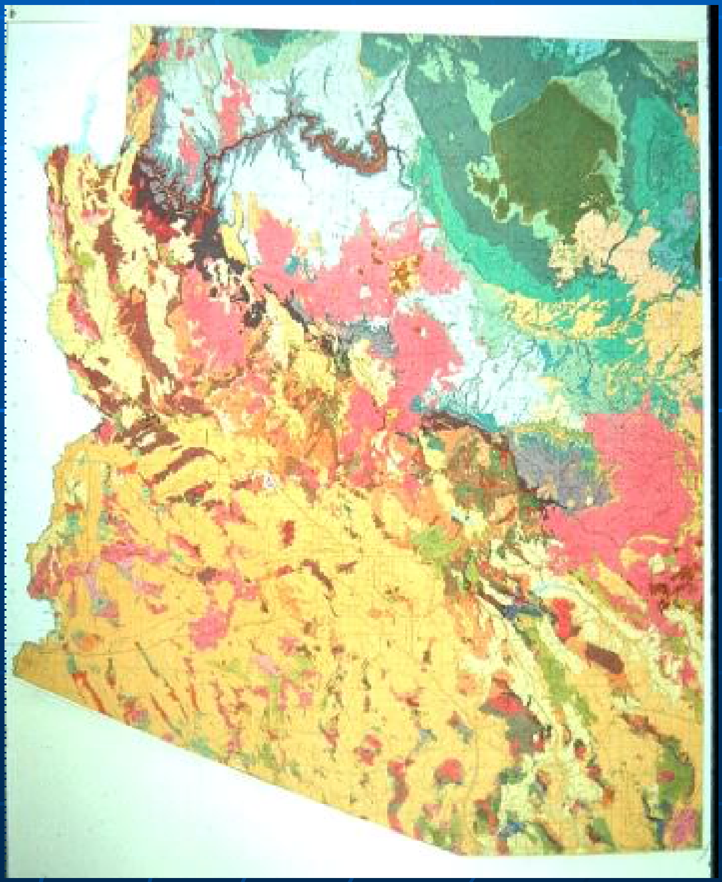
Arizona Mining and Mineral Museum

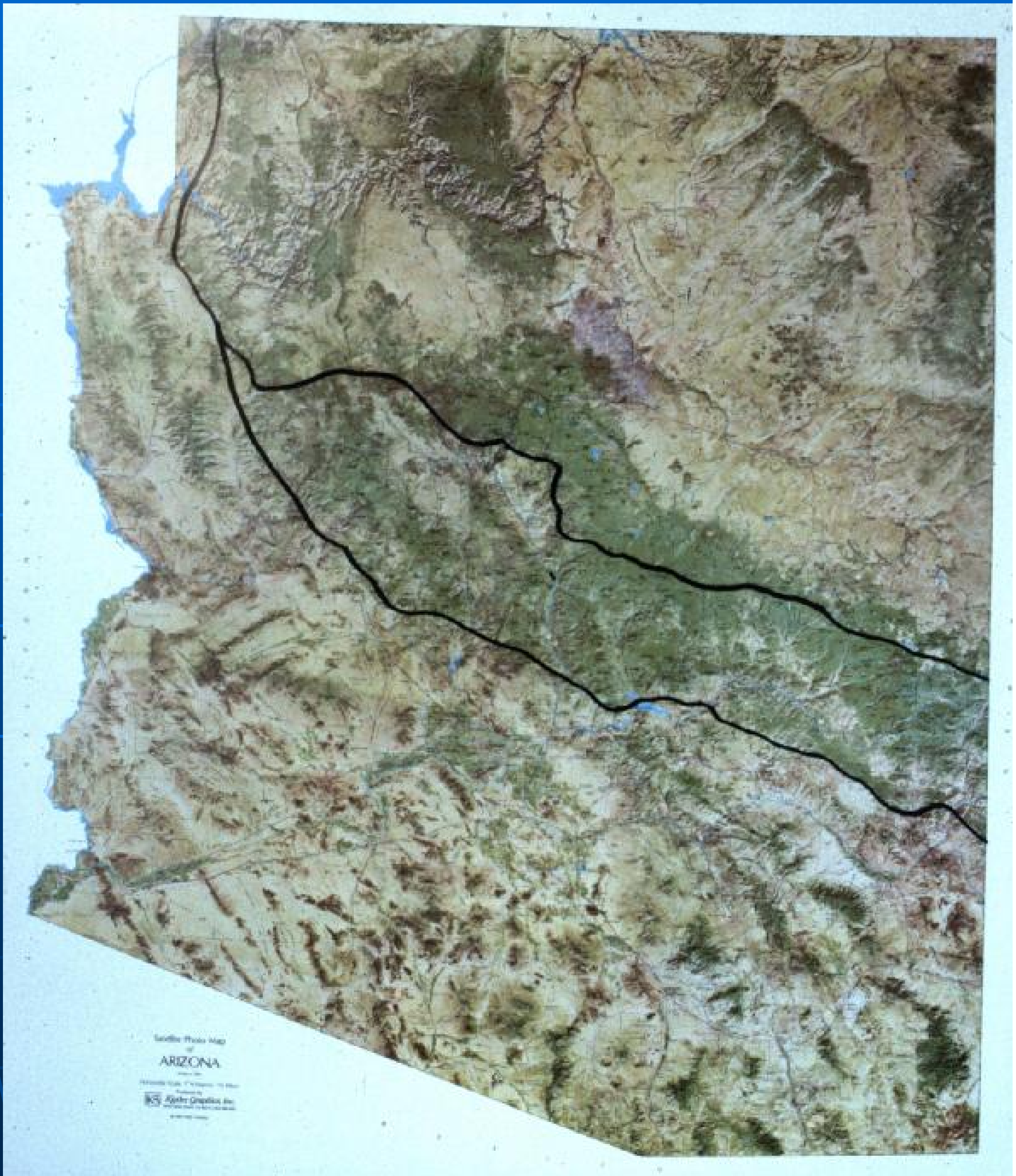


Arizona provinces

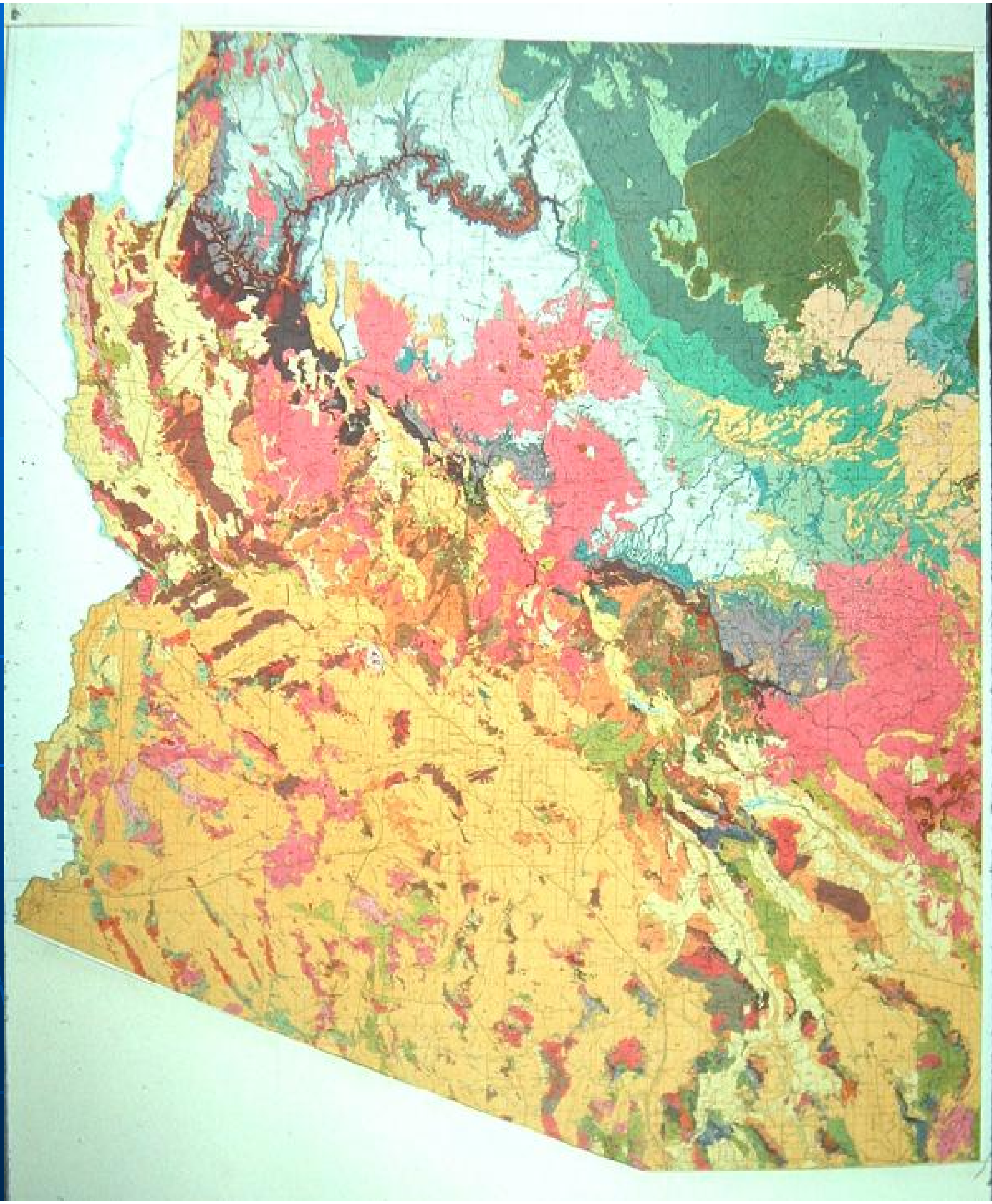
Colorado Plateau

Transition Zone

Basin and Range



AZ geologic map



Arizona Provinces

Colorado Plateau Province

- canyons
- horizontal-ish sediments
- broad warping

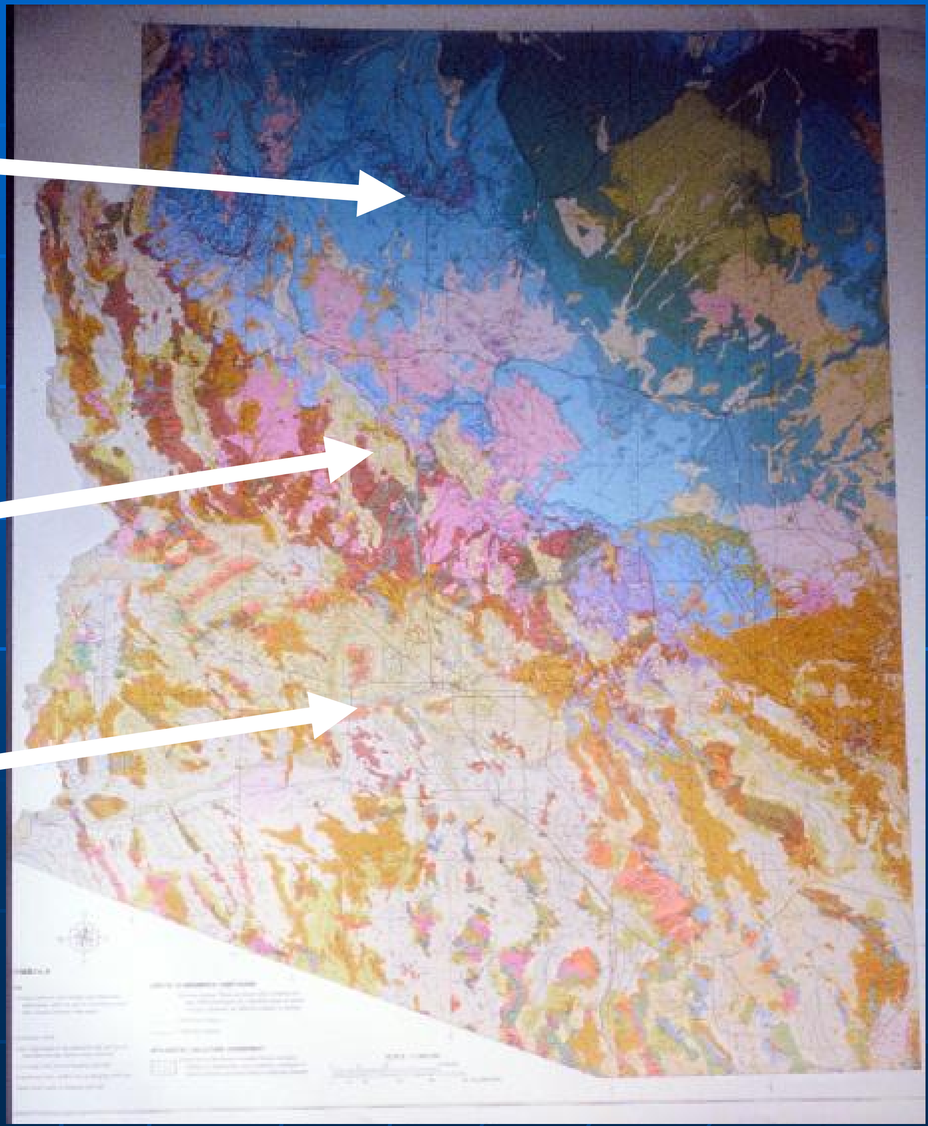
Transition or Central Highlands Province

- lots of faulting
- rugged terrain (lots of relief)

Basin & Range Province

- block fault mountains
- broad alluvial valleys – fill

  up to 10,000? feet thick



Geologic time scale

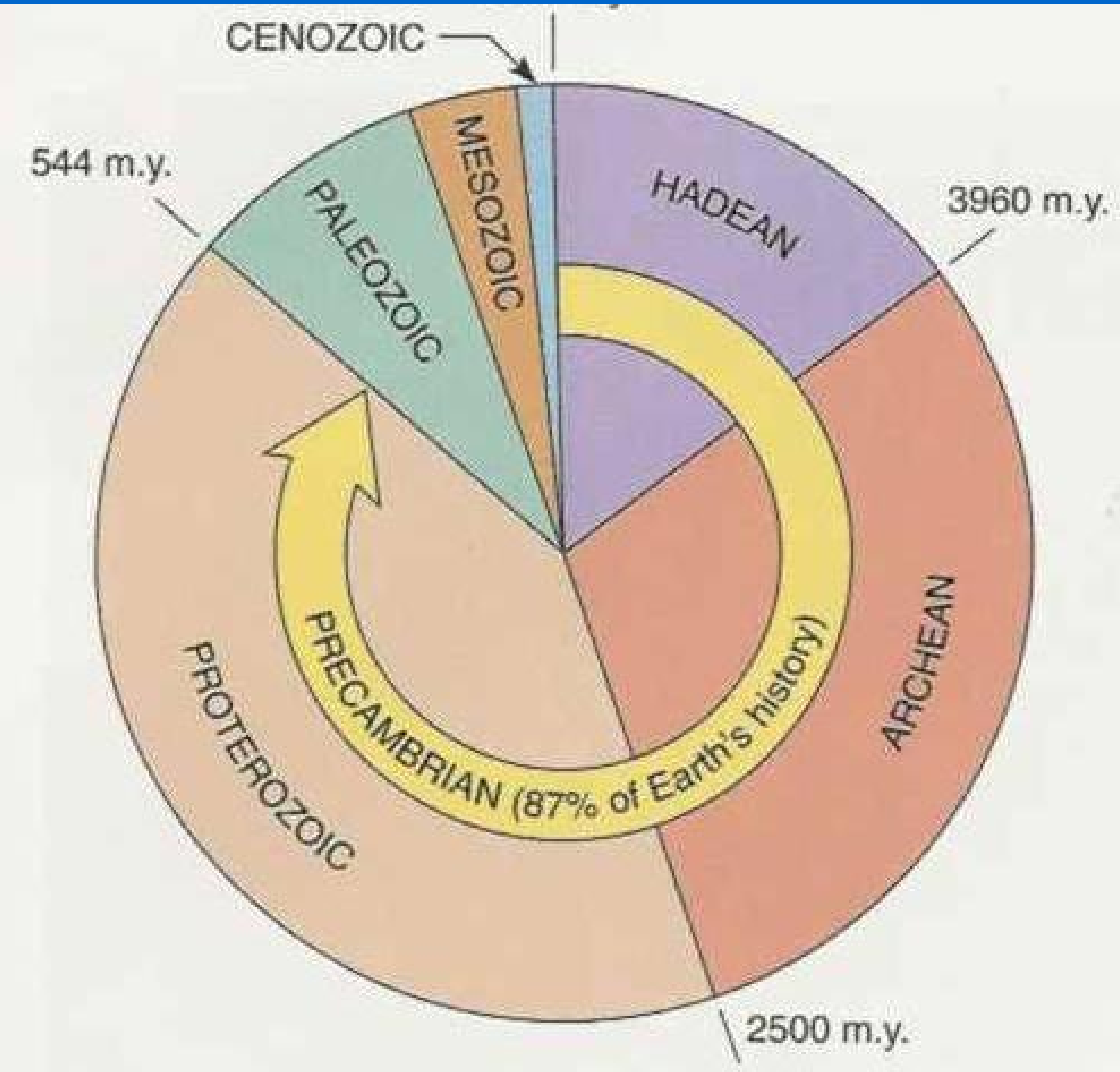
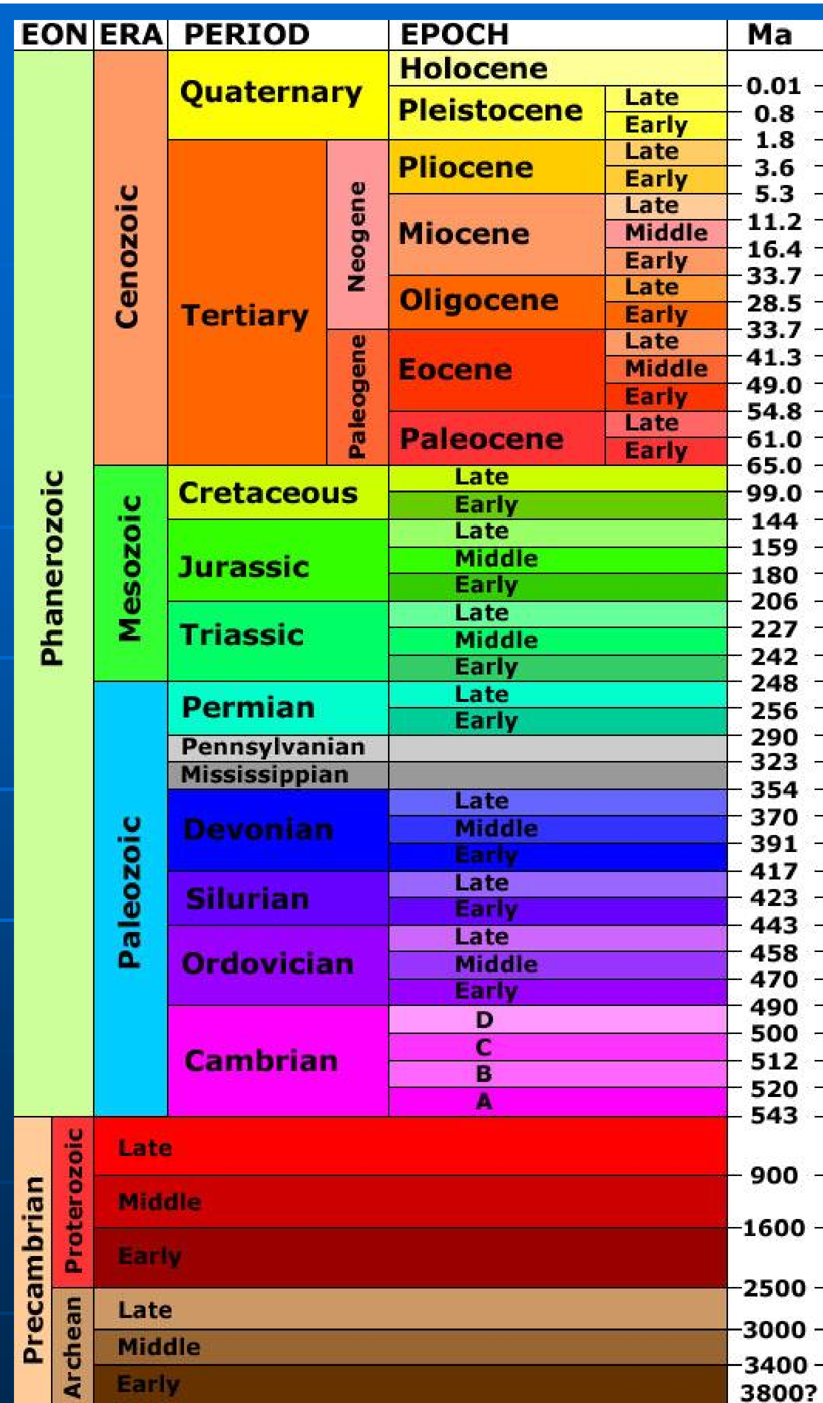
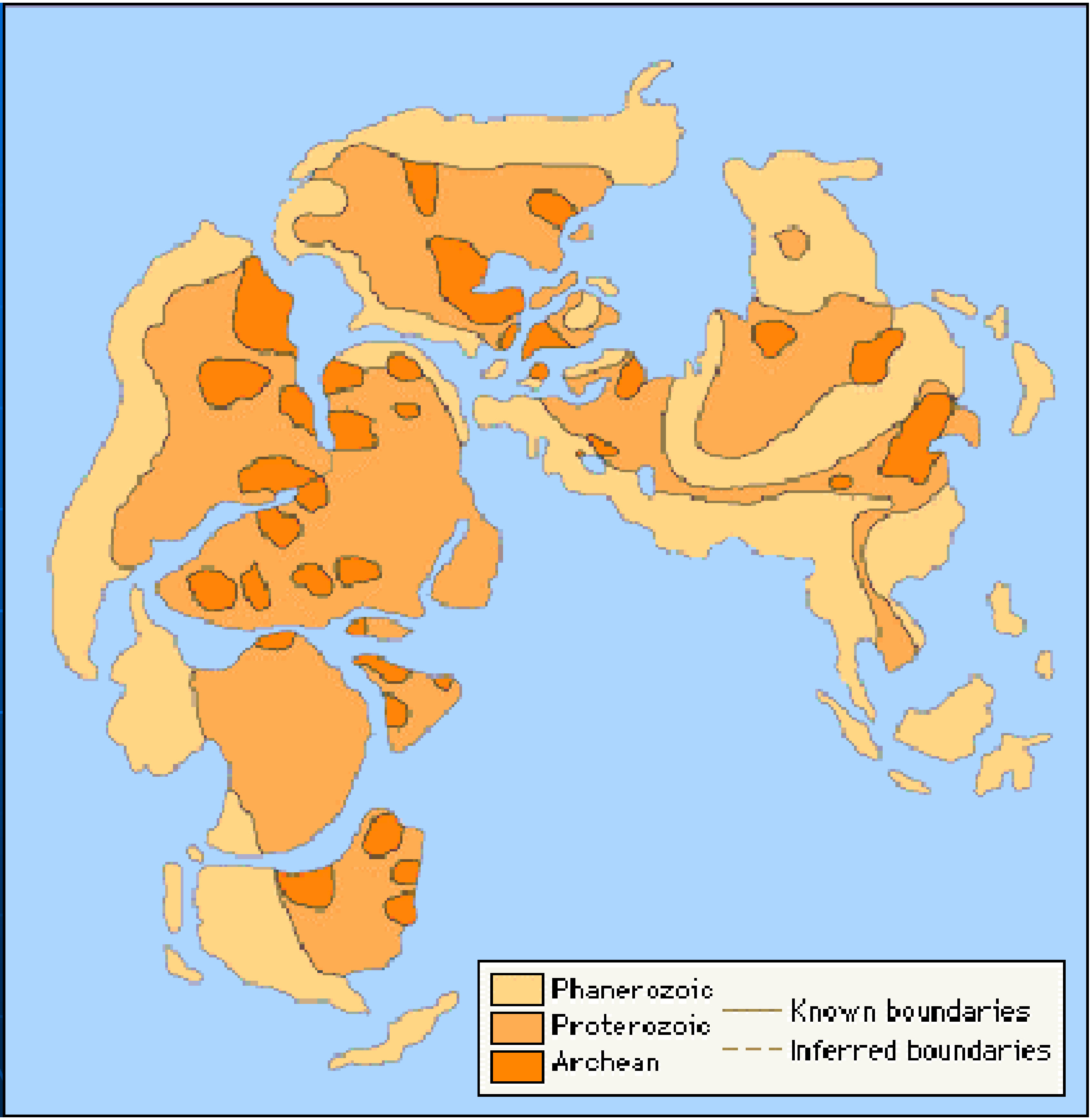


FIGURE 6-1 Proportions of geologic time encompassed by the Precambrian and its Hadean, Archean, and Proterozoic eons.

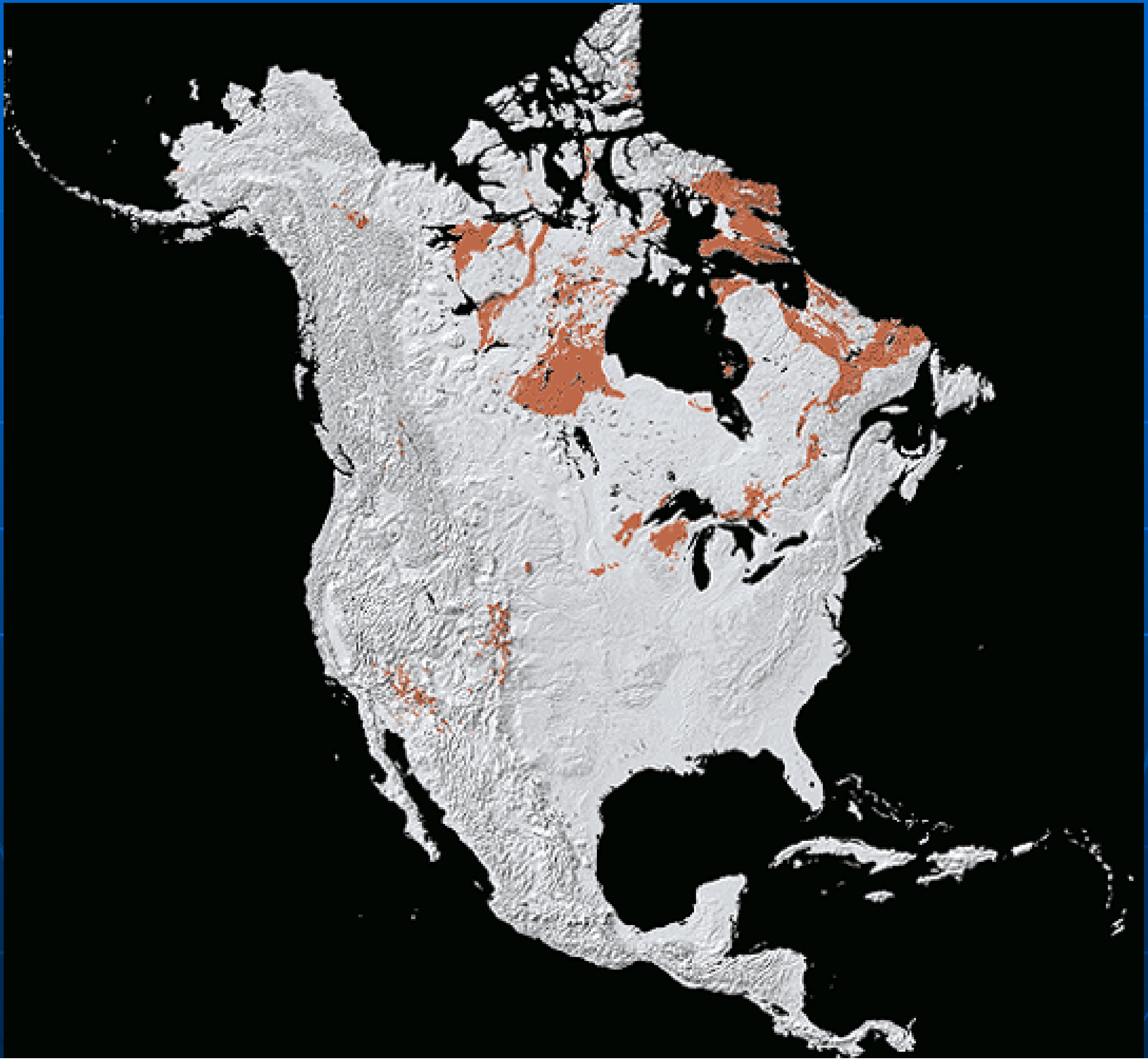
Geologic Time Scale



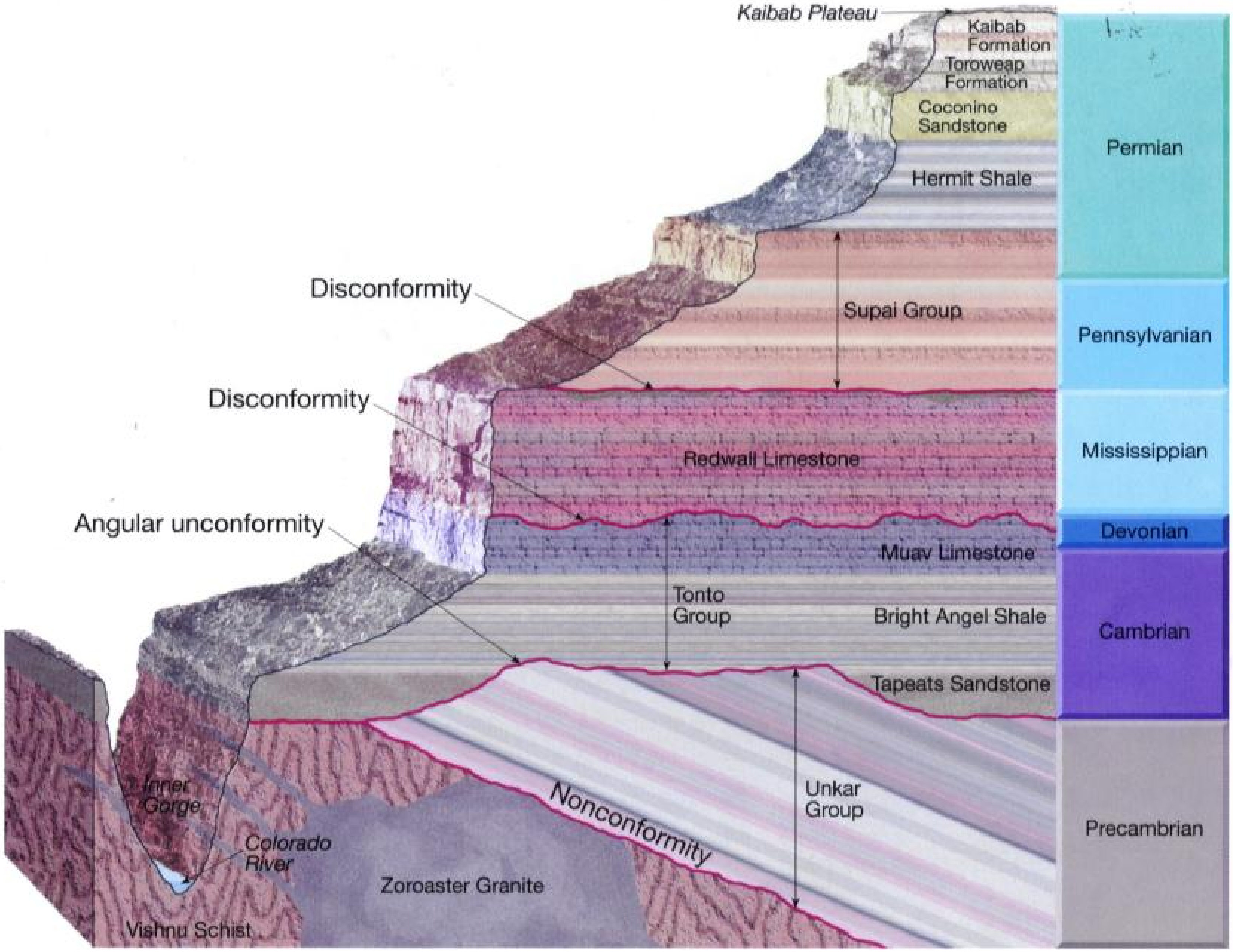
Archean cratons



Early Proterozoic (2.4-1.6 Ga)



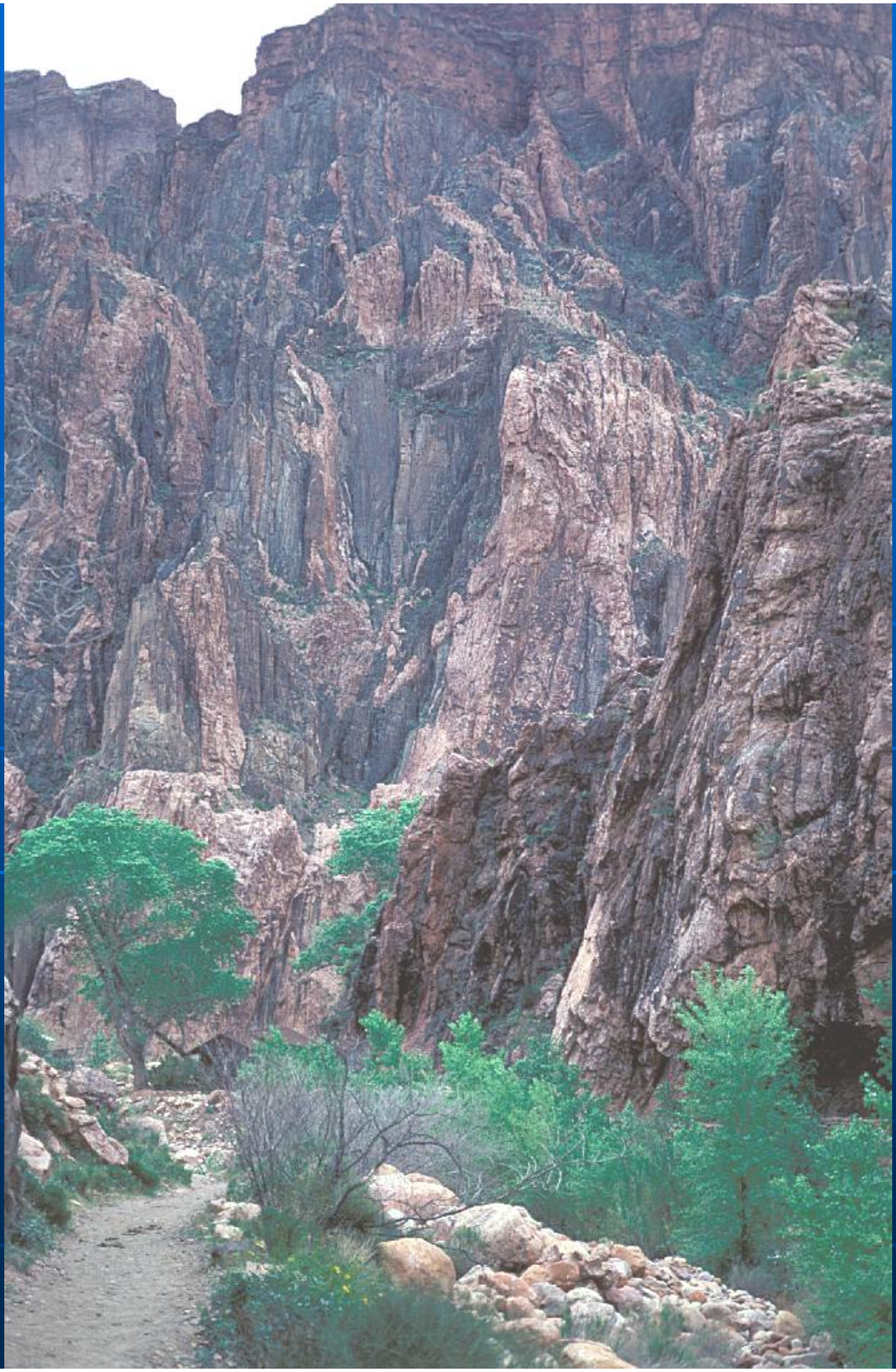
Unconformities in the Grand Canyon



Inner Gorge Grand Canyon: Tapeats on Vishnu Schist, Zoroaster Granite

Vishnu Schist - Grand Canyon

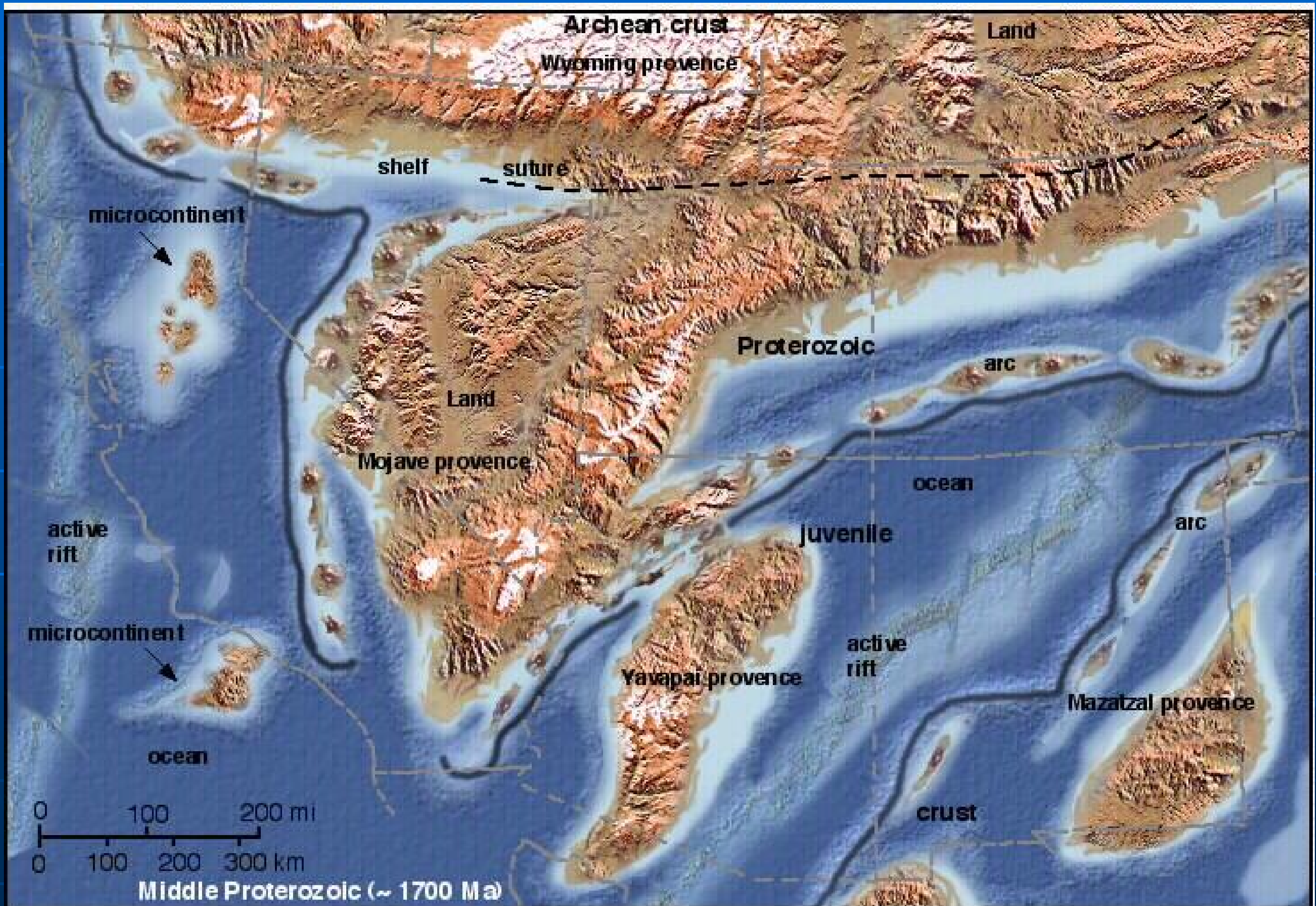
Vishnu Schist



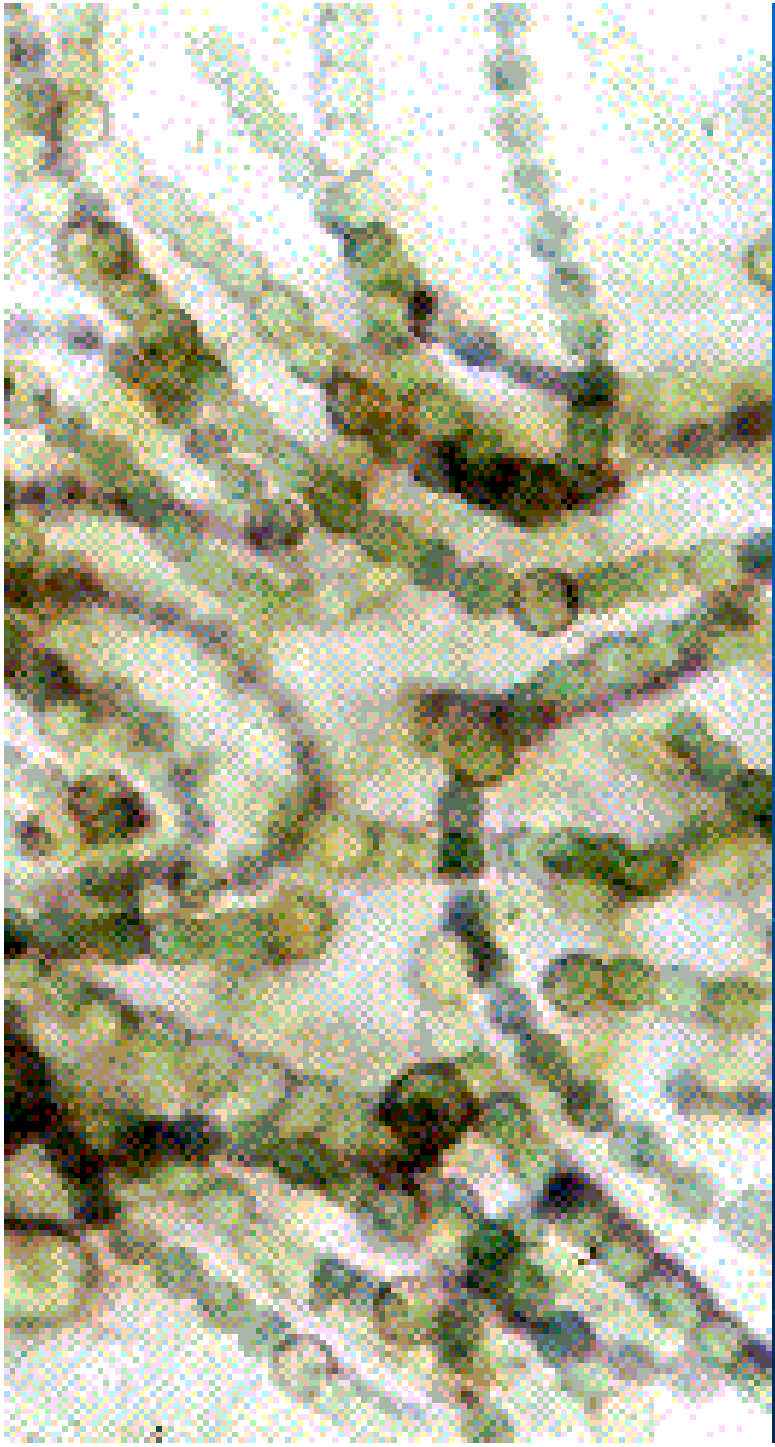
Proterozoic Banded Iron Formation

Iron mines – Banded Iron Formations (BIF)

Meso-protero-zoic (1.7 Ga)



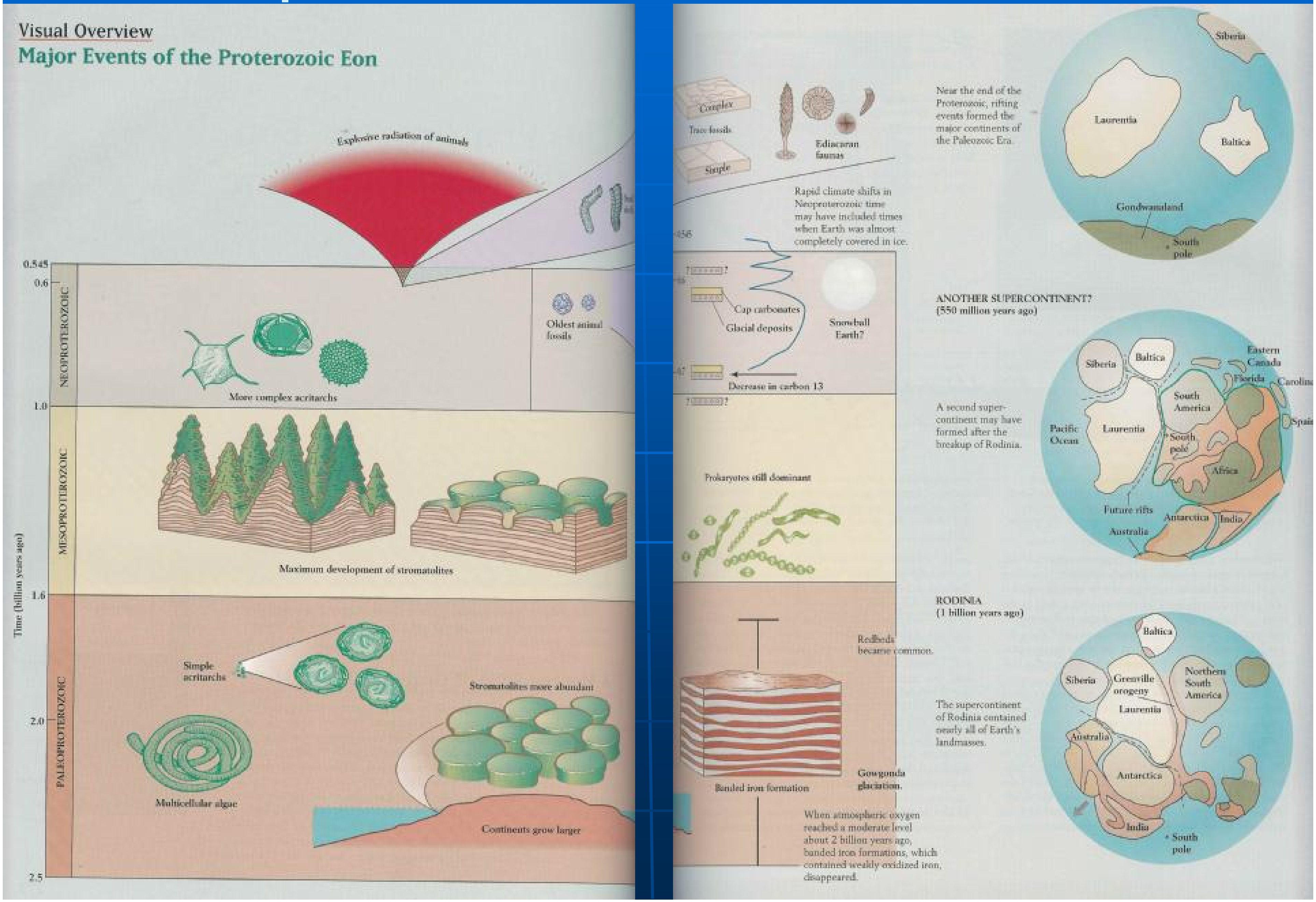
From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html



BIG Changes 1.8-1.6 bya

- The reduced iron begins to be used up, therefore the oxygen produced by cyanobacteria is released into the atmosphere.
- The amount of oxygen in the atmosphere JUMPS from about 1% of it's current levels to about 15%!!!
- At that time most organisms were anaerobic, making oxygen a poisonous gas. By nature oxygen is a violent element, attacking the chemical bonds of organic molecules.
- Many microbial species became extinct.
- Only organisms that could adapt to the environment survived, thus leading to the evolution of more modern life

Mesoproterozoic



Meso-proterozoic (1.1 Ga)

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

PreCambrian Arizona

Inner Gorge pC metamorphic rocks of Grand Canyon

Younger pC sediments (about 10,000 ' thick) of Grand Canyon

Two mountain building episodes divide the PreCambrian of Arizona.

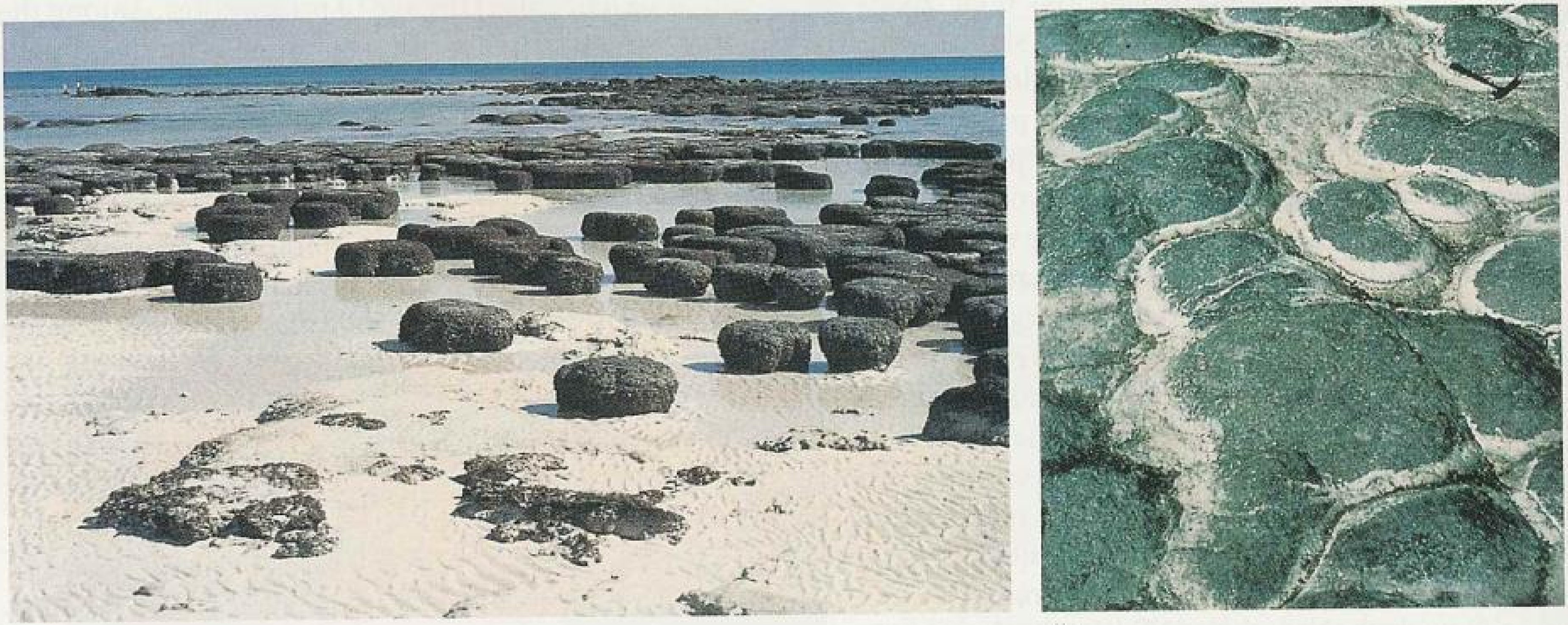
- The older – 1.7 billion years – Mazatzal Orogeny produced Rocky Mt.-style mountains, that eroded away to a nearly flat surface (GREAT UNCONFORMITY)
- **The younger – 1 billion years – basin & range-style mountains (4000' offset) also eroded away to a nearly flat surface before the deposition of the Tapeats Sandstone 540 (or so) million years ago.**

Blue-green algae gave O2

- Photosynthesis had taken place for about 1 billion years in an organism called cyanobacteria (since 3.5 bya).
- Photosynthesis probably evolved when pigments developed in cells, allowing them to absorb and later process light. The products of this process were, among other things, energy and oxygen.
- Between 2.4 – 2.2 billion years ago, the increased numbers of cyanobacteria increased the production of oxygen.
- The stromatolites deposited layers of calcium carbonate in layers.

Stromatolites

Stromatolites



(A) (B)

FIGURE 6-44 **Present-day and ancient stromatolites.** (*A*) Present-day columnar stromatolites growing in the intertidal zone of Shark Bay, Australia. Metabolic activities of colonial marine cyanobacteria result in the formation of these structures. Fine particles of calcium carbonate settle between the tiny filaments of the matlike colonies and are bound with a mesh of organic matter. Successive additional layers result in the laminations that are the most distinctive characteristic of stromatolites. (*B*) Fossil stromatolites from Precambrian rocks exposed in southern Africa. (*A, courtesy of J. Ross; B, courtesy of J. W. Schopf, UCLA.*)

Grand Canyon stratigraphy

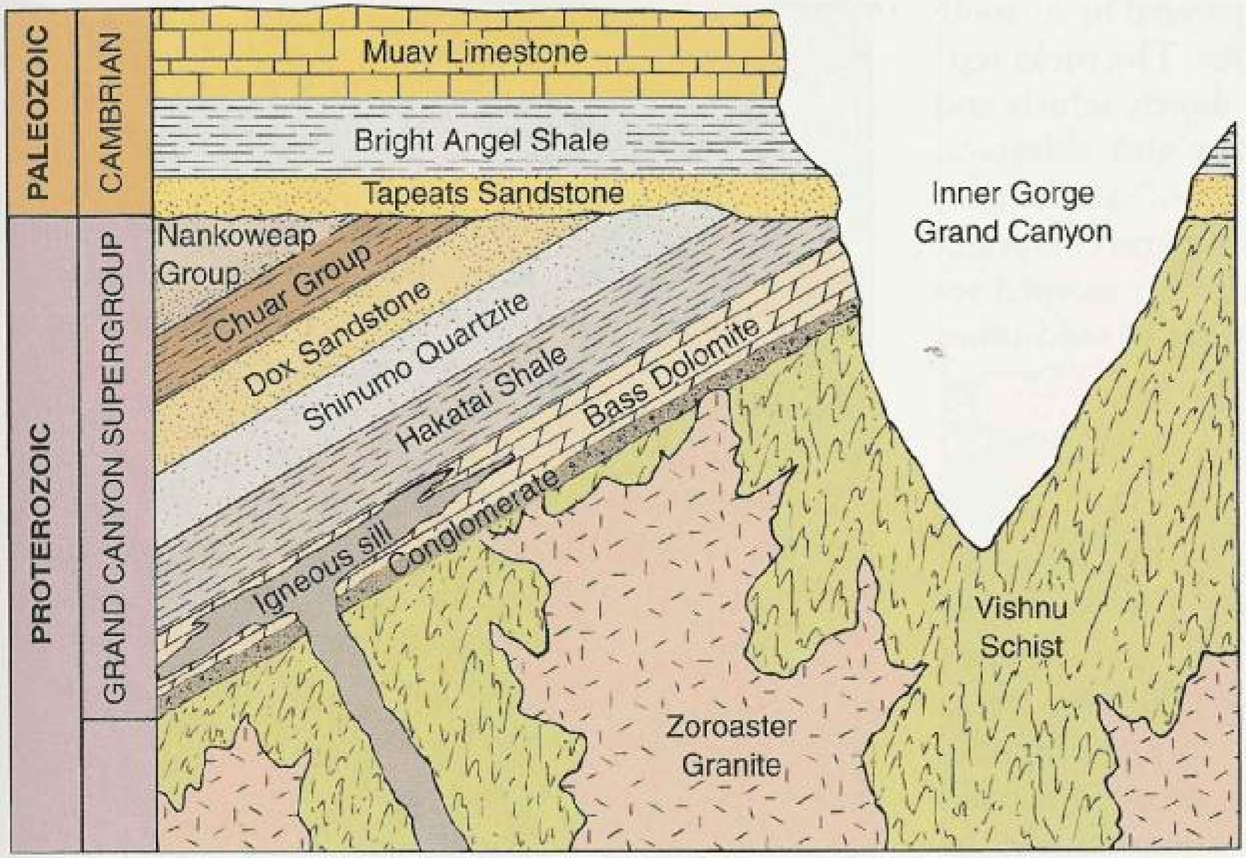
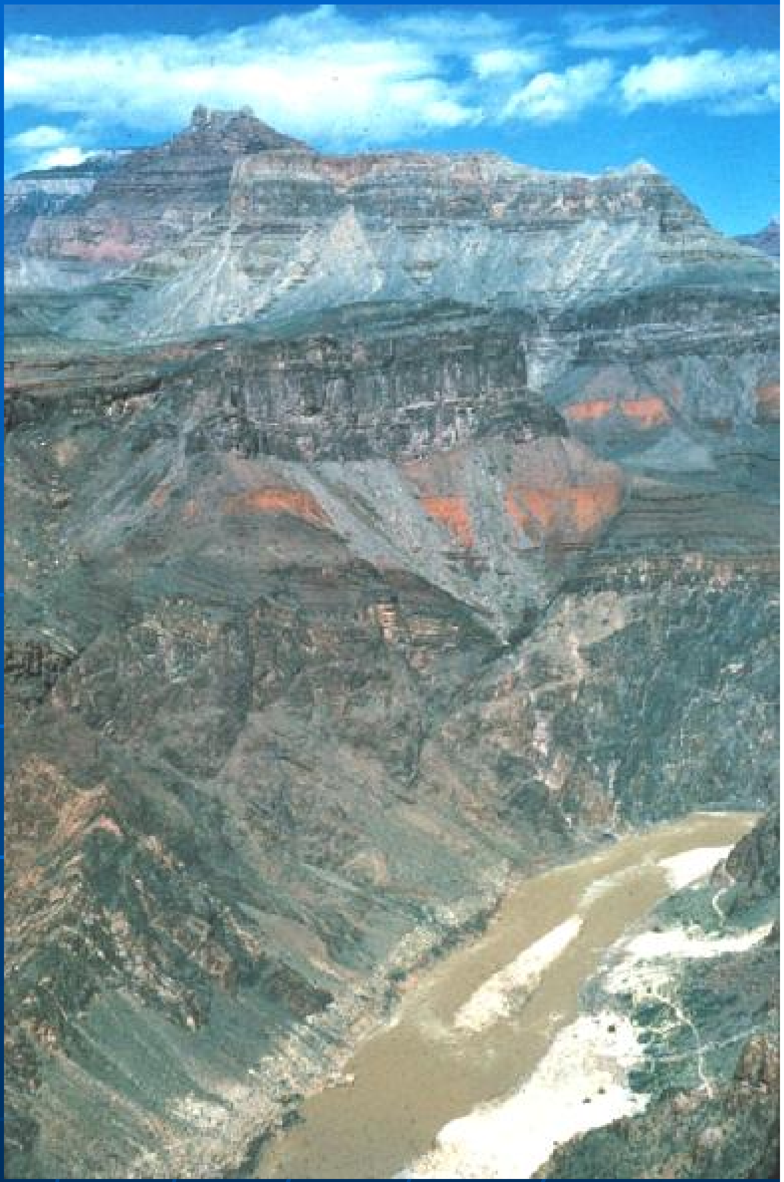
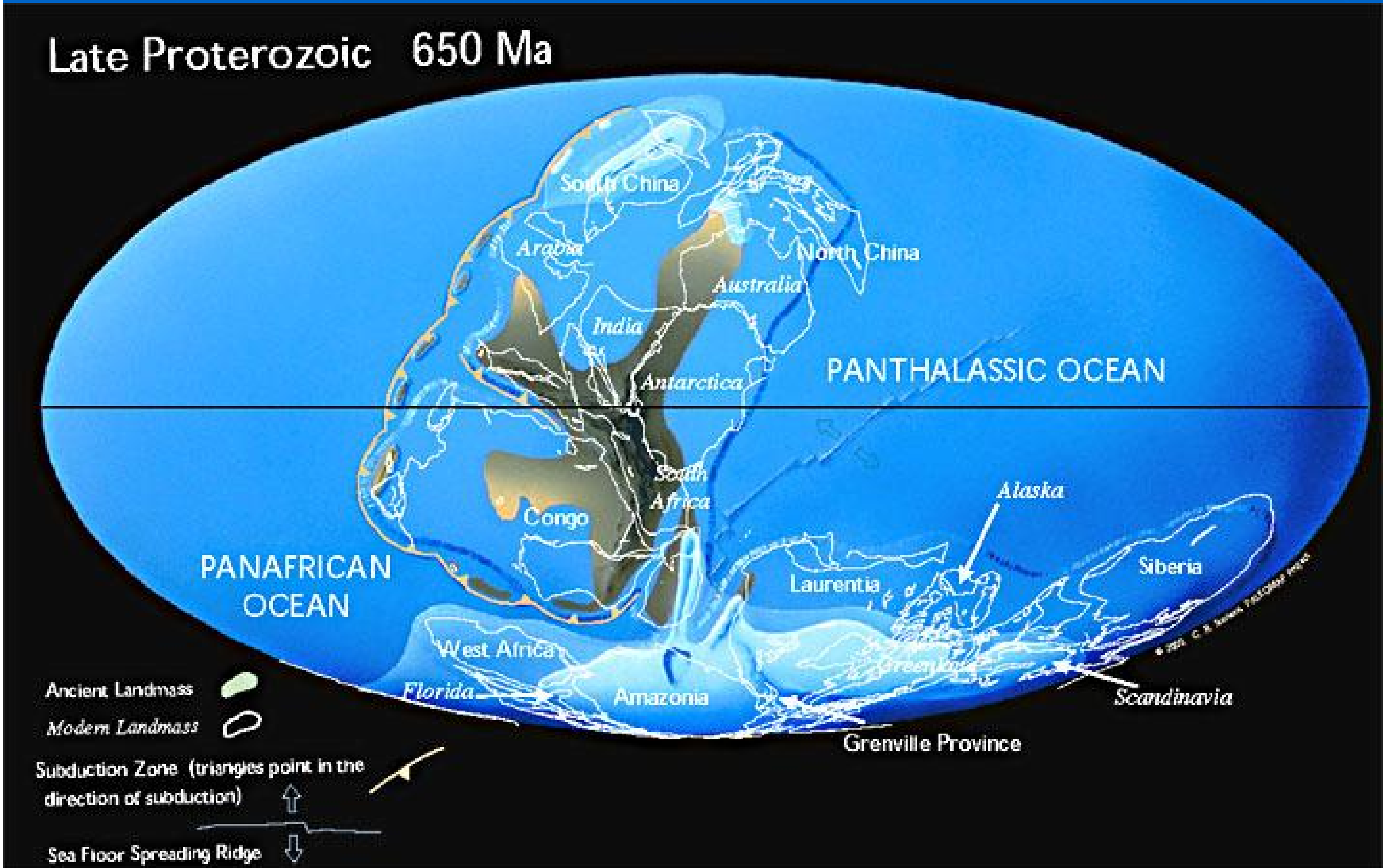


FIGURE 7-14 **Vishnu Schist, Grand Canyon Supergroup, and other rocks in the Grand Canyon of the Colorado River.** ? *Indicate by arrows and labels two kinds of unconformities in this cross-section. Is the conglomerate at the base of the Grand Canyon Group an expected lithology for the initial strata above an erosional unconformity?*

Grand Canyon Group

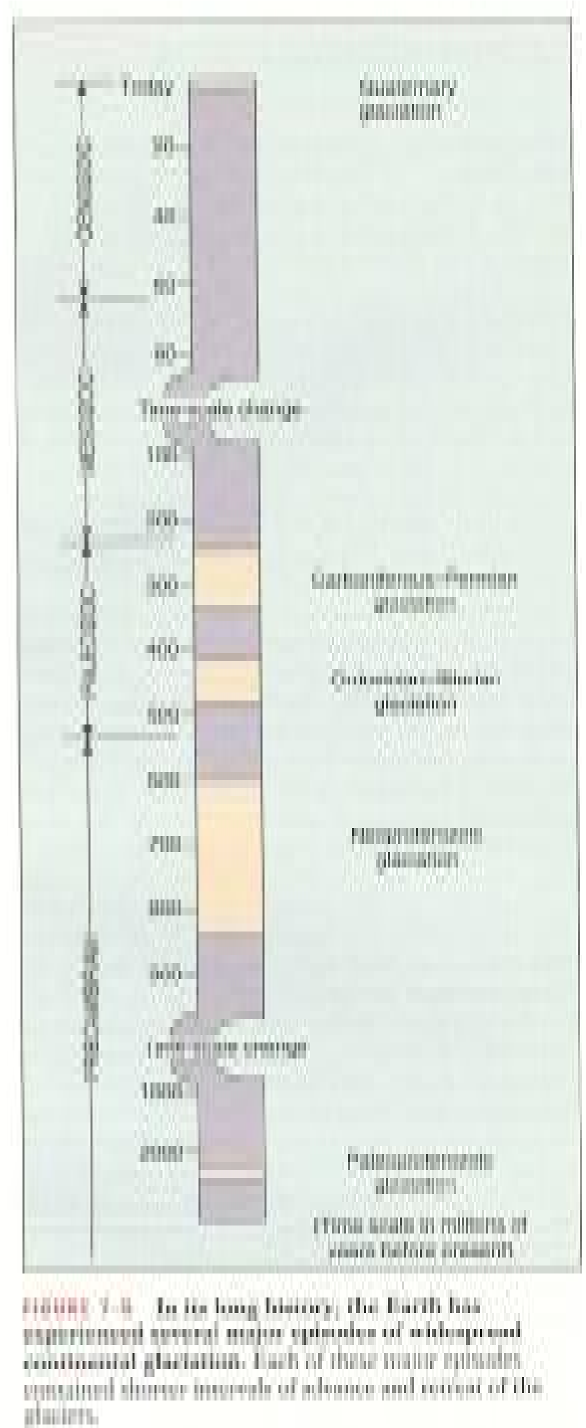


Rodinia



Late Proterozoic 650 Ma
South China
Arabia
North China
Australia
India
Antarctica
PANTHALASSIC OCEAN
South Africa
Congo
Alaska
PANAFRICAN OCEAN
Laurentia
Siberia
West Africa
Greenland
Florida
Amazonia
Scandinavia
Grenville Province
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge

Glaciation times



The Mazatzal Quartzite

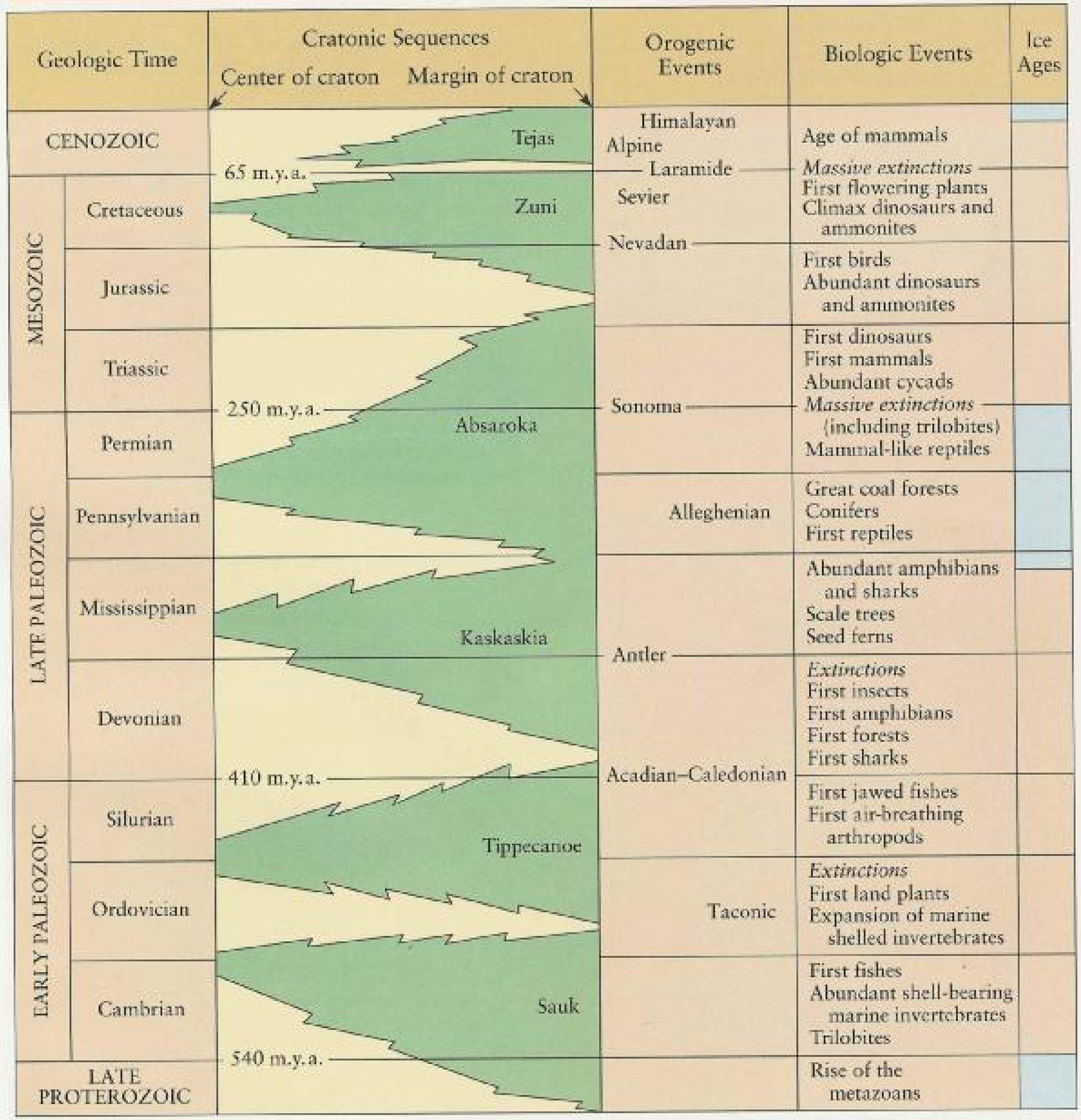
Cratonic sequences

Unconformity bounded

Continental assembly

Erosion & uplift

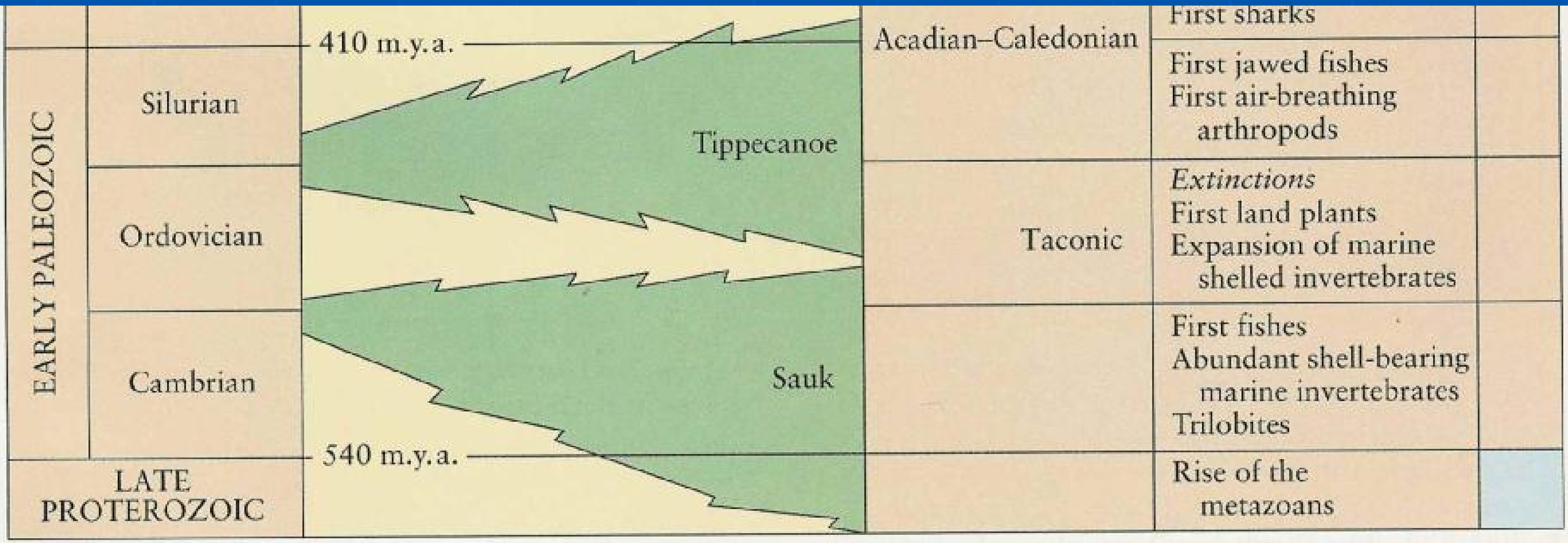
TABLE 8-1 Cratonic Sequences of North America*



*The green areas represent sequences of strata. They are separated by major unconformities, indicated in yellow. Note that the rock record is most complete near cratonic margins, just as the time spans represented by unconformities are greatest near the center of the craton. Major biologic, orogenic, and glacial events are added for reference. (Cratonic sequence model after Sloss, L. L. 1965. *Bull Geol. Soc. Amer.* 74:93–114.)

Sauk sequence

Cambrian – Early Ordovician



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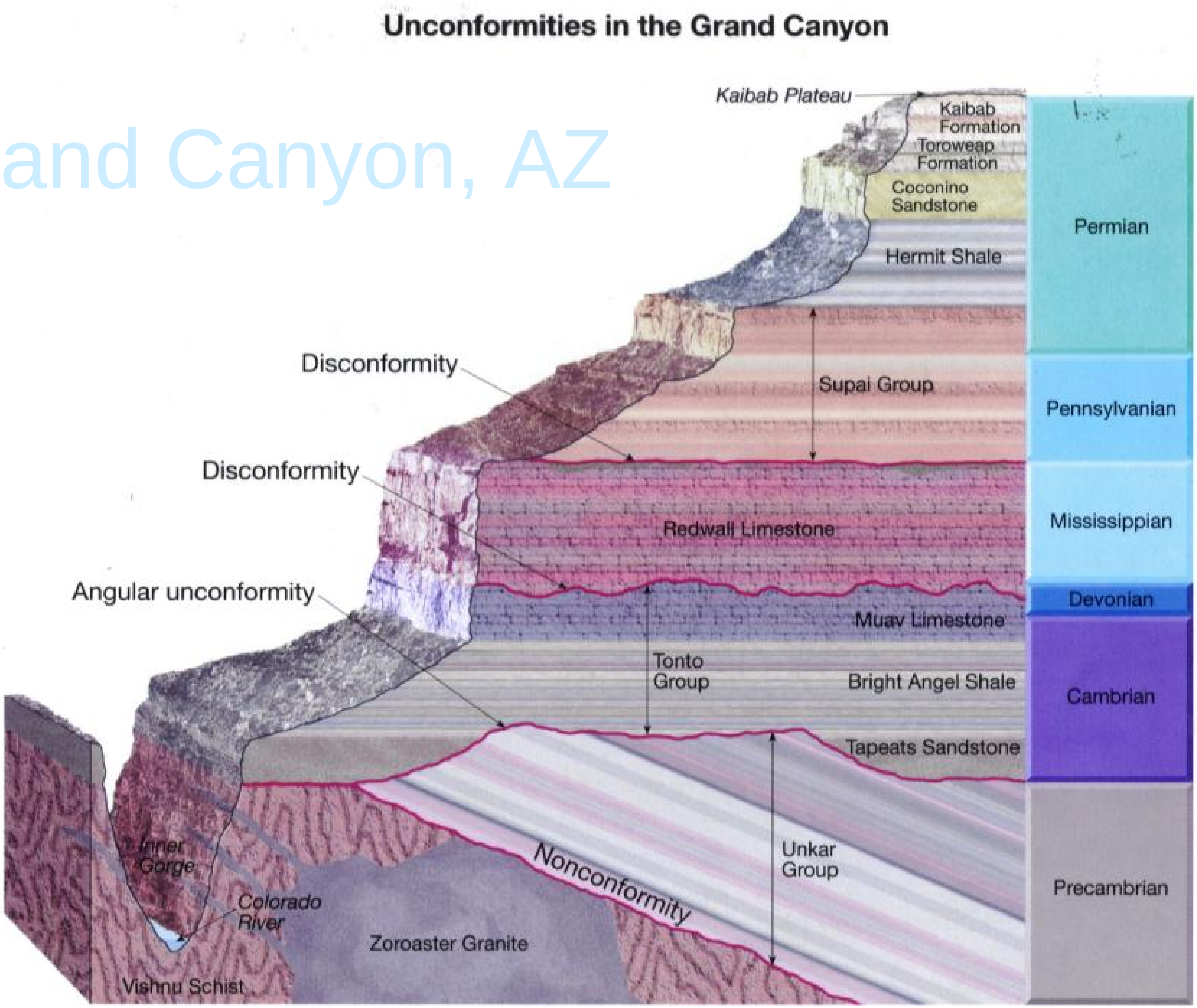
Great Unconformity in Inner Gorge, Grand Canyon: Tapeats SS on Vishnu Schist

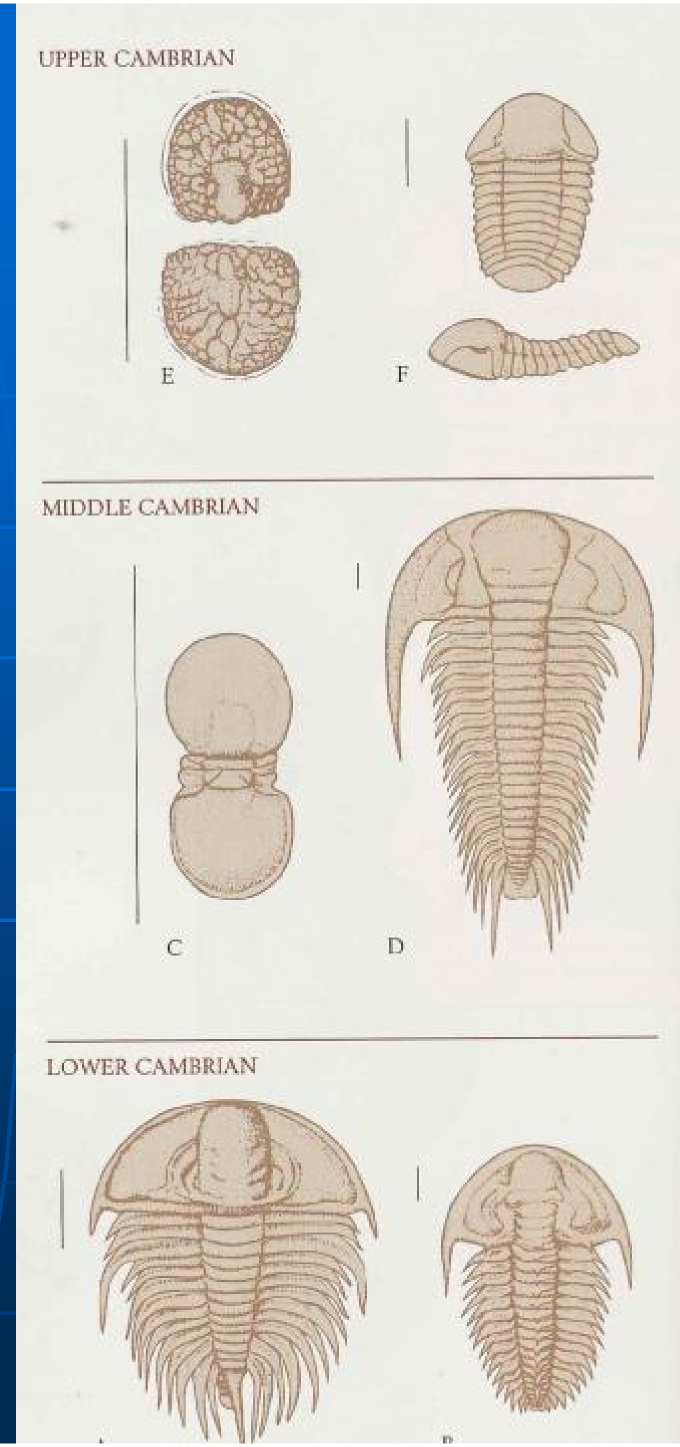
Grand Canyon section

Grand Canyon, AZ

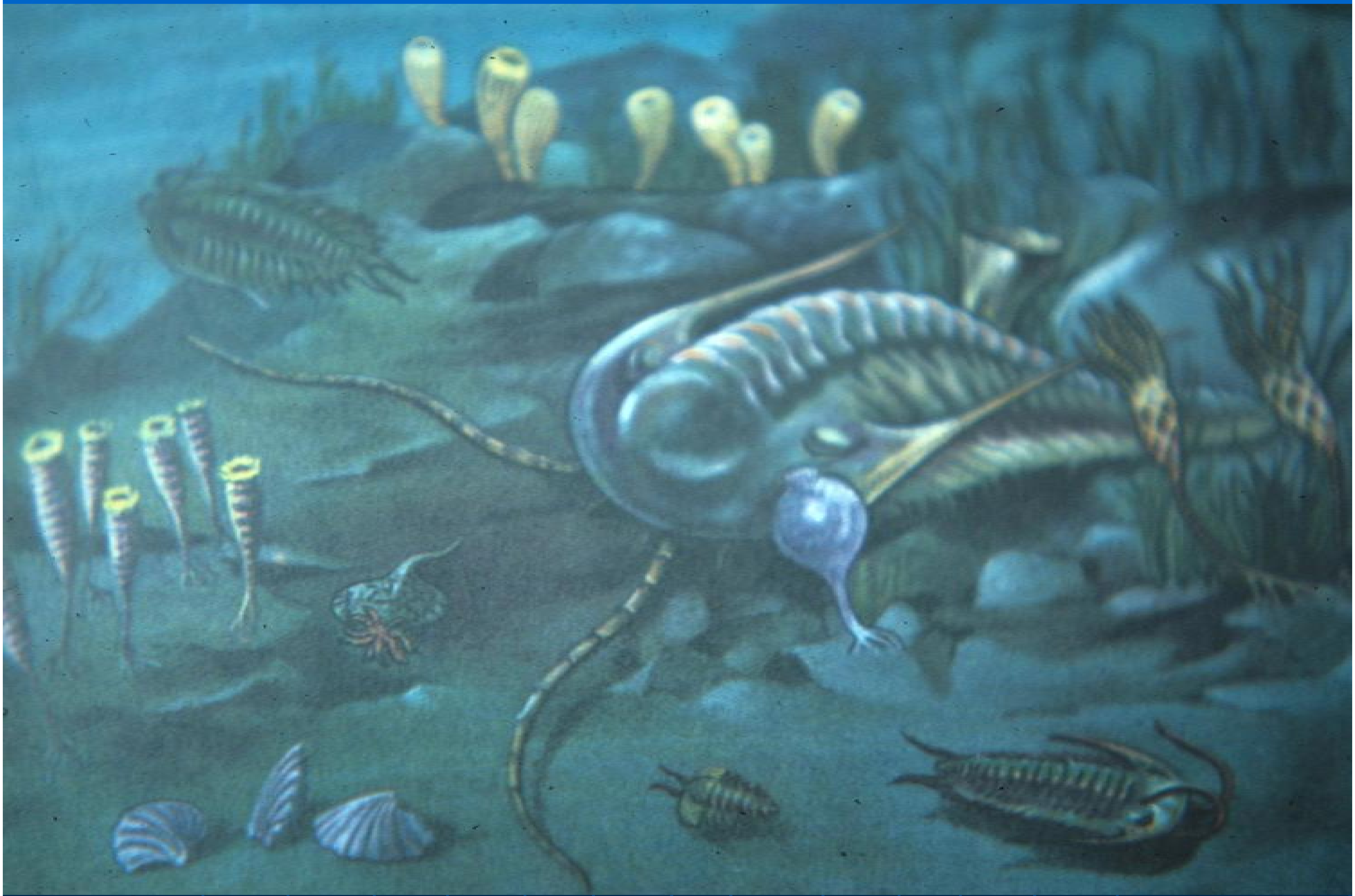


trilobites

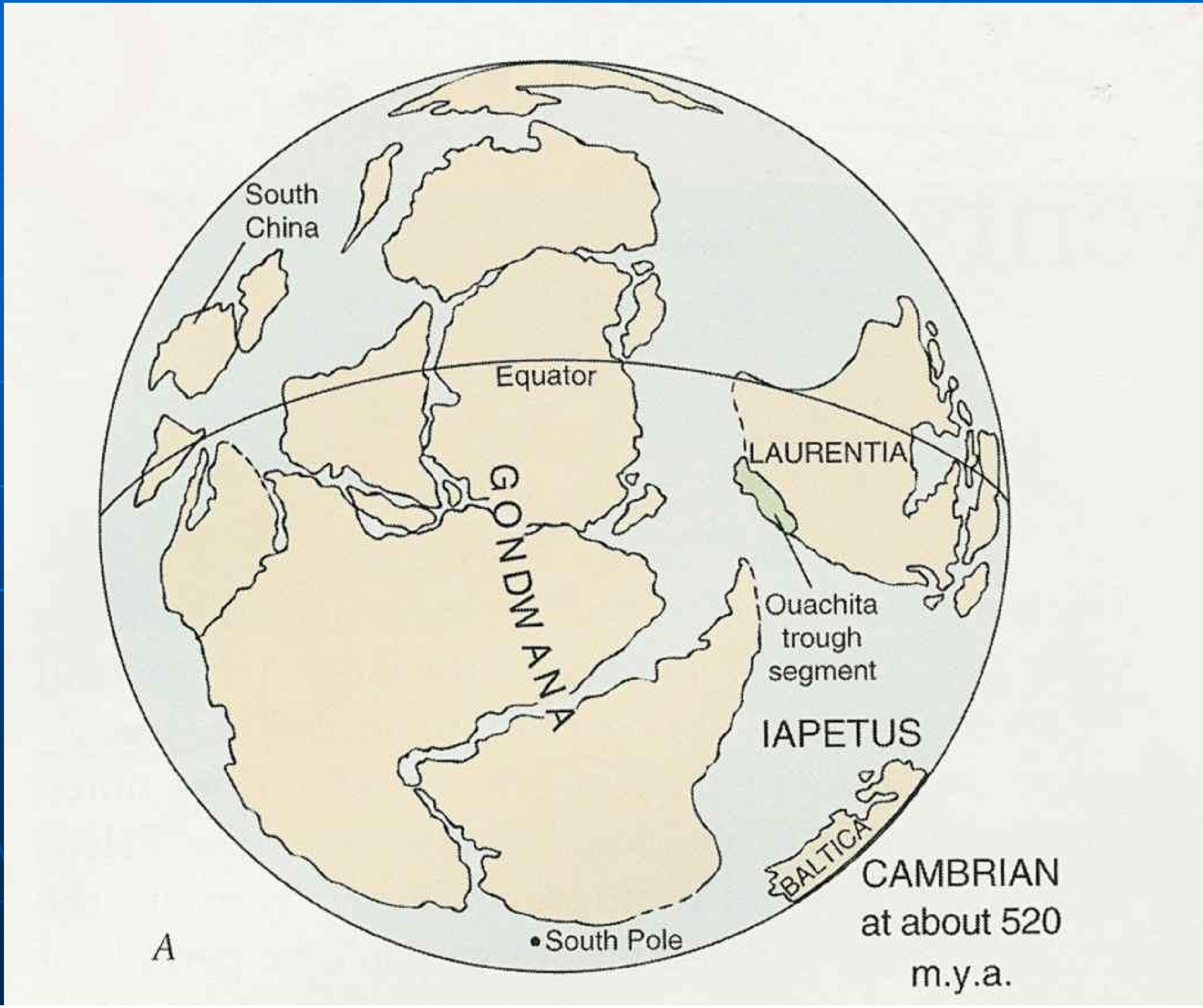
Figure 13-2 Typical Cambrian trilobites. *A. Olenellus. B. Holmia. C. Lejopyge. D. Paradoxides. E. Glyptagnostus. F. Illaenurus.* Trilobites were arthropods (invertebrate animals with segmented bodies and jointed legs). The soft body and the many legs were positioned beneath the flexible, jointed skeleton. 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.)



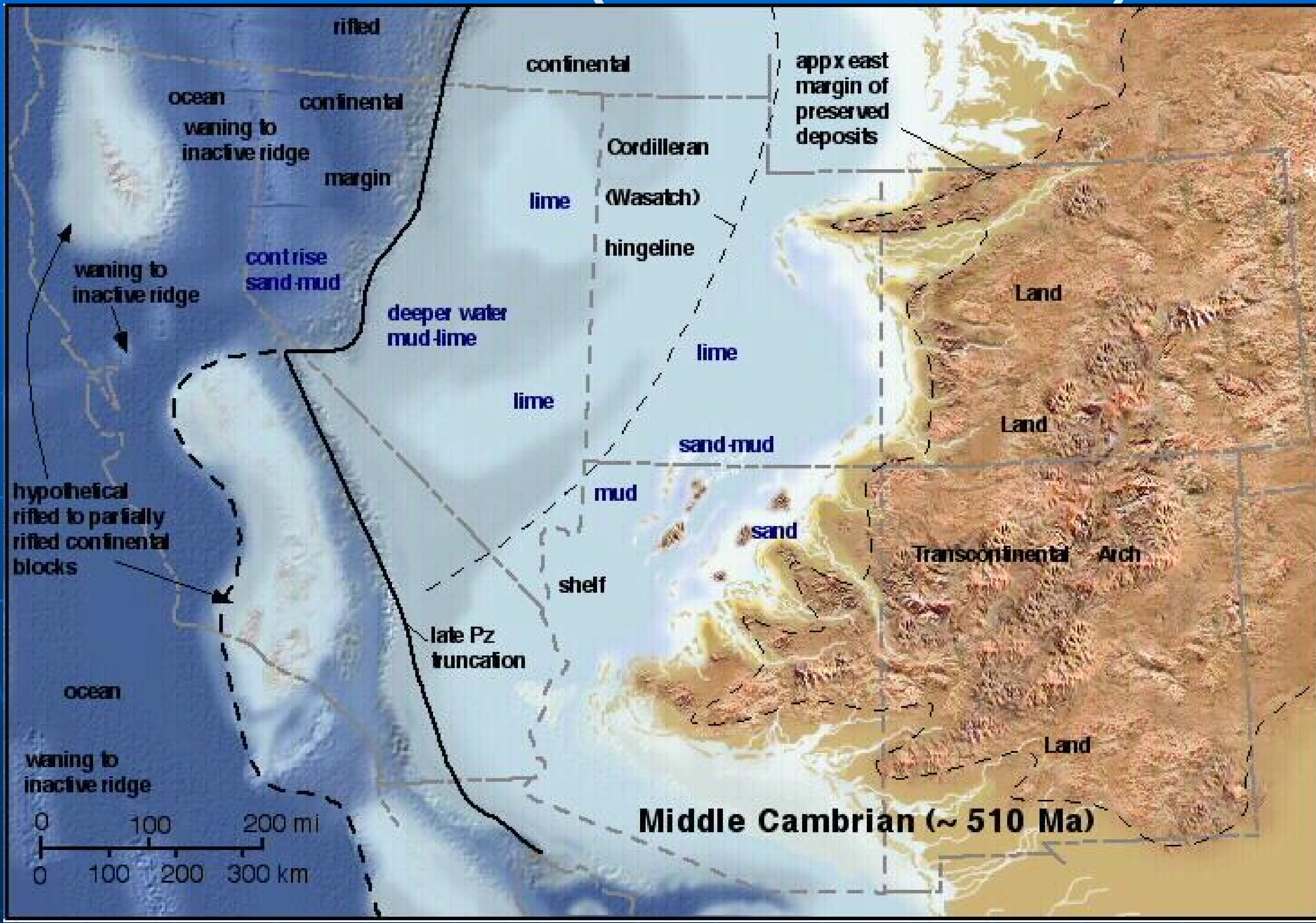
Cambrian fauna



Cambrian plate tectonics



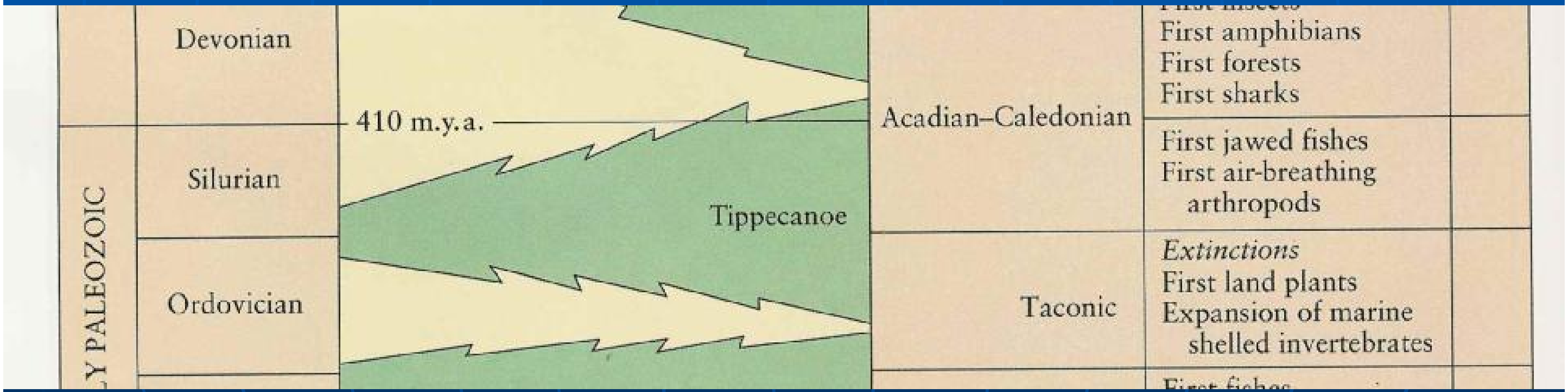
Cambrian (543-490 Ma)



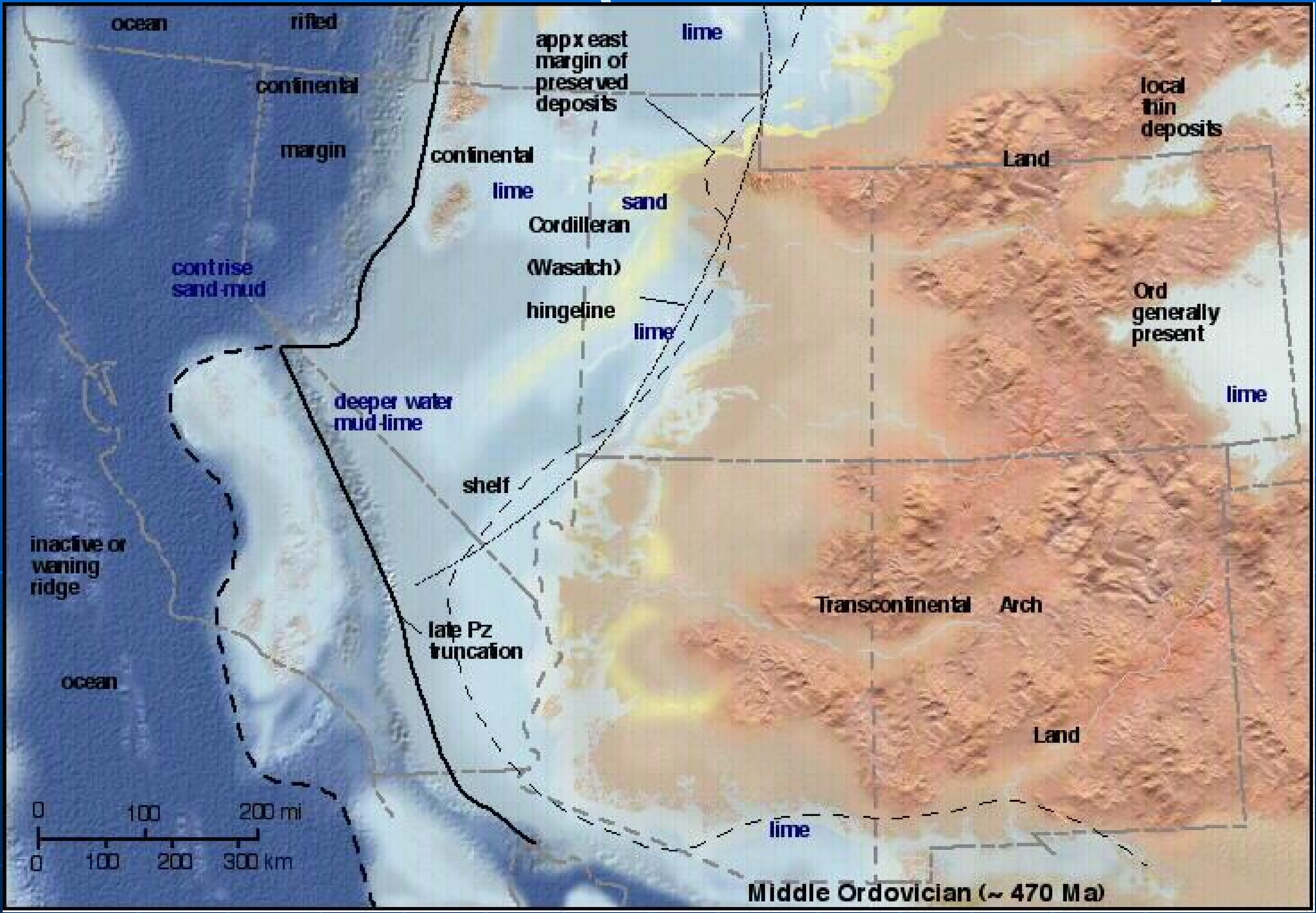
From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Tippecanoe sequence

Middle Ordovician – Early Devonian



Ordovician (490-443 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Oolites – current winnowed

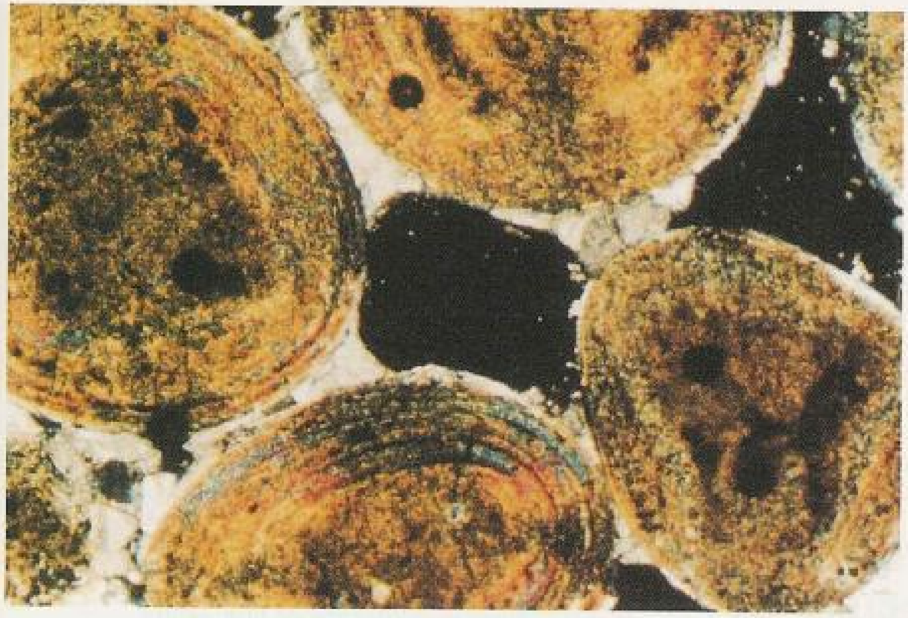
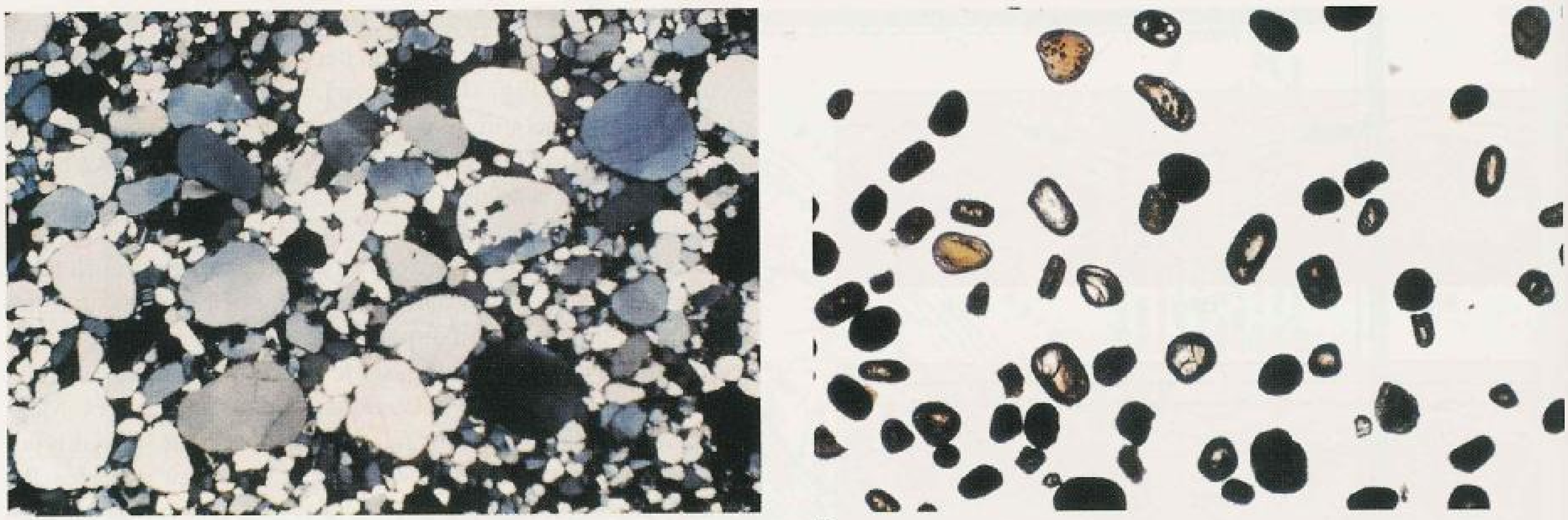


Figure 10.19 Microscopic photograph of modern oolite grains (average 1 to 2 mm in diameter) from Bahama Bank submarine dunes like those of Fig. 10.17. Each sphere consists of concentric laminations of carbonate precipitated around a nucleus grain. Cementation by carbonate has begun where the spheres touch. *(Photo by P. M. Harris; Courtesy of SEPM.)*

Figure 10.17 Air view of large submarine sand dunes formed by tide- and storm-driven currents on the Little Bahama Banks. Dune crests are only 1 to 2 meters below the water surface. The dunes consist of oolite. *(Photo By: M. O. Hayes, Courtesy of SEPM.)*

Clean sandstone



A. B.

Figure 10.13 Microscopic photographs of typical Upper Cambrian sandstones, southern Wisconsin. *A:* Quartz grains averaging 0.25 millimeter diameter. Rounding is so exceptional for larger grains as to suggest an abrasive history equivalent in distance to rolling by water around the earth thirty or forty times. *B:* Concentrated fraction of well-rounded mineral grains of relatively high specific gravity (2.8 to 3.5) from a Cambrian sandstone like that in *A*. Minerals present average 0.15 millimeter and consist of very durable zircon, tourmaline, and garnet. Such minerals constitute less than 1 percent by weight of typical Cambrian sandstone. *(A: R. H. Dott, Jr.; B: Courtesy of John A. Andrew.)*

Ord paleogeo

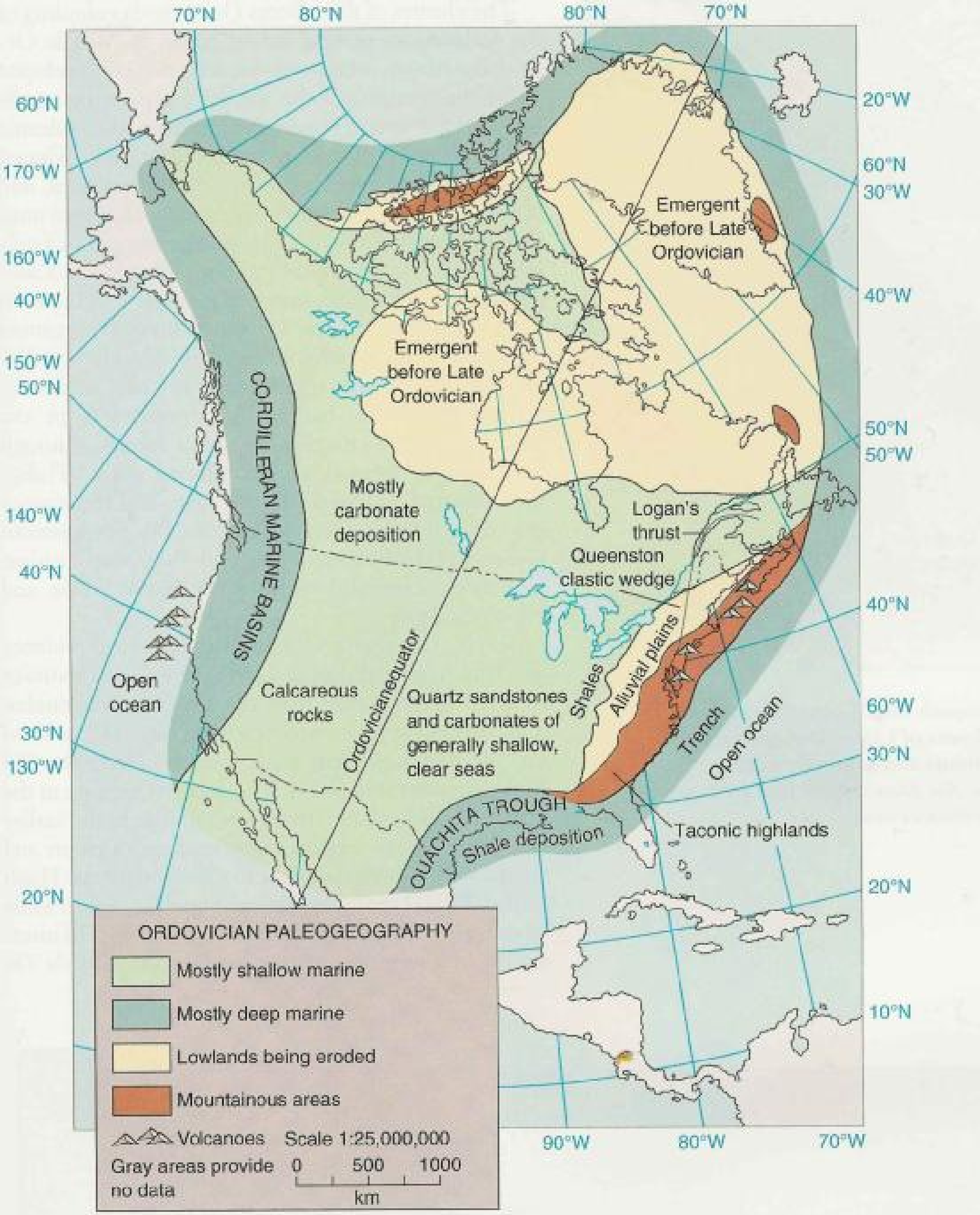


FIGURE 8-27 Paleogeographic map of Ordovician North America.

Ordovician Plate Tectonics

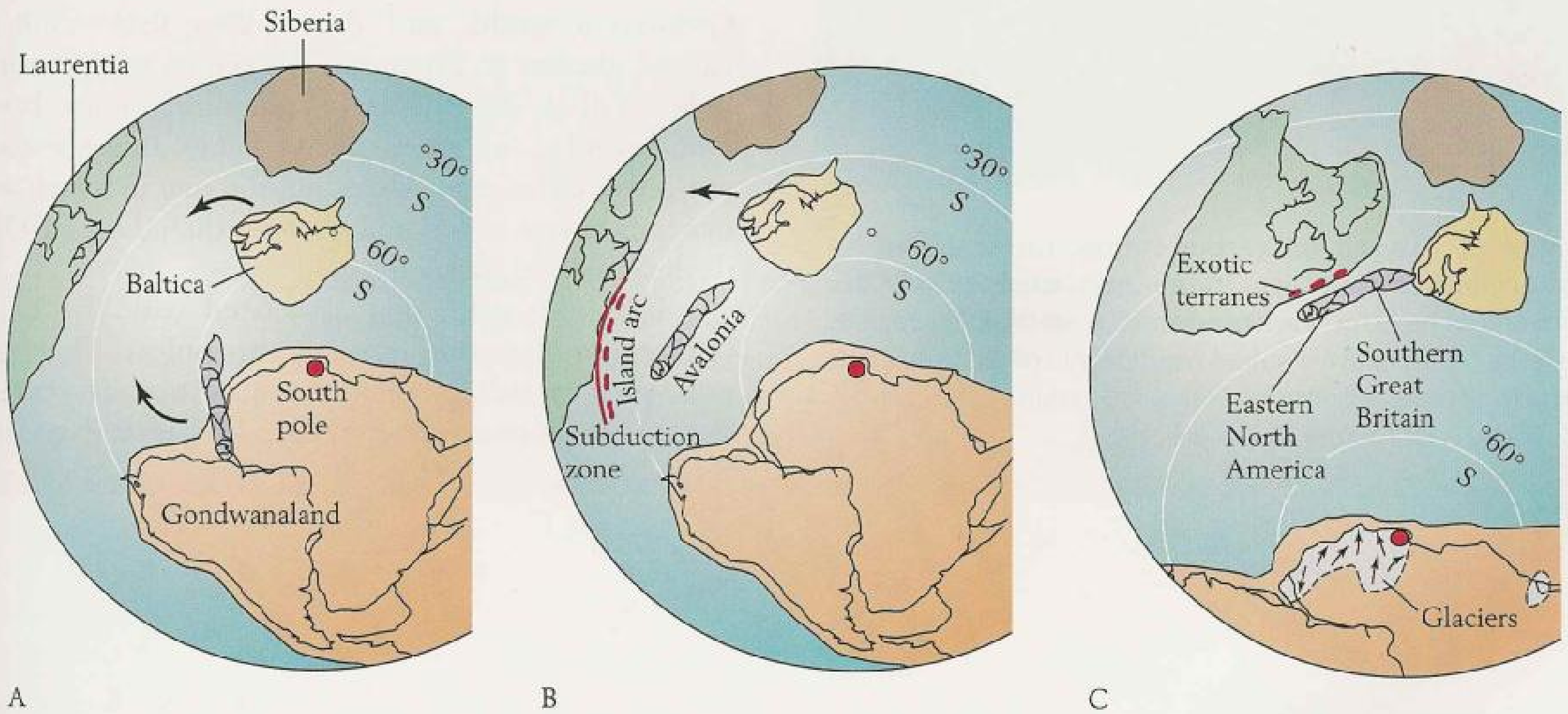
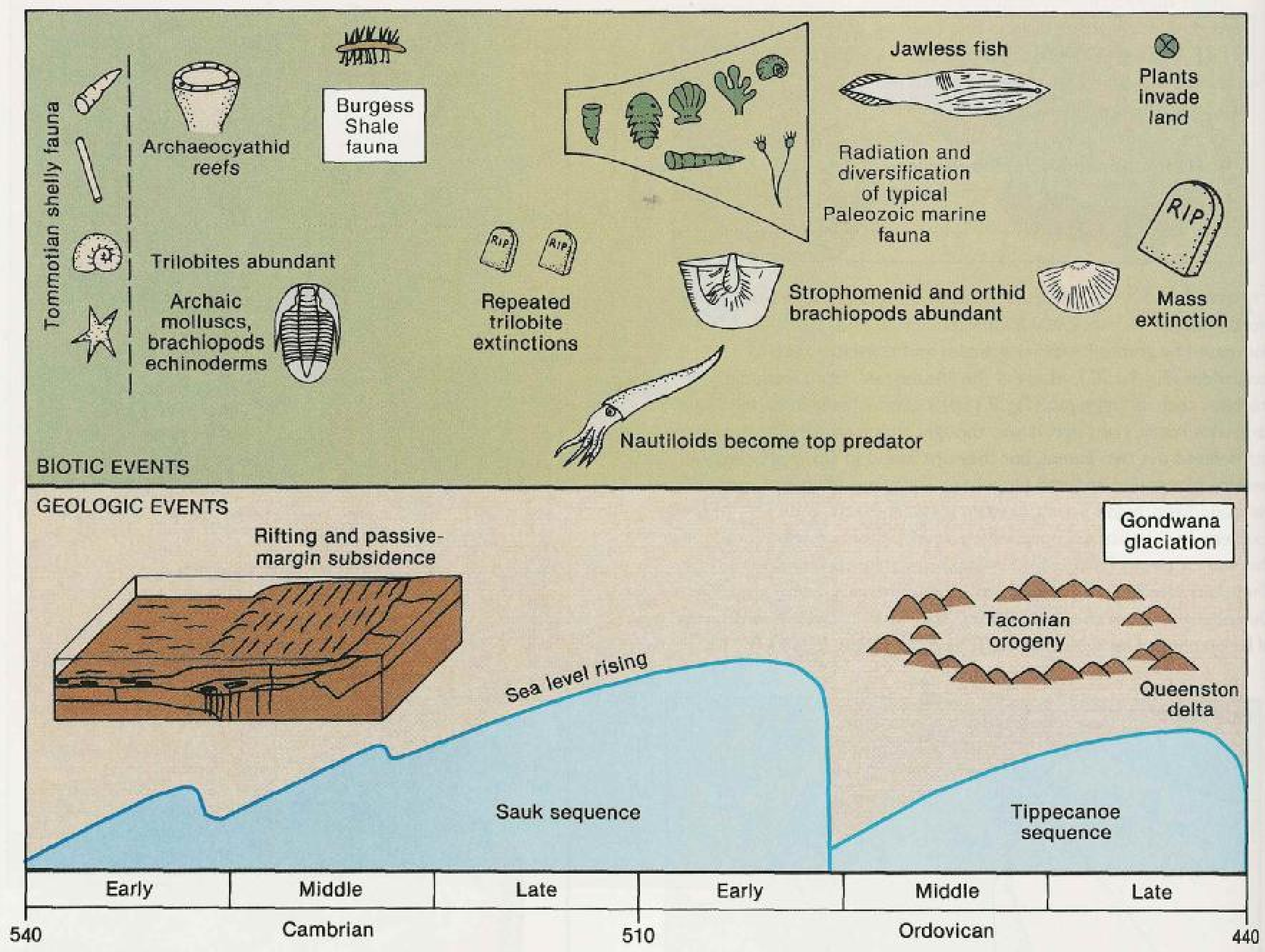


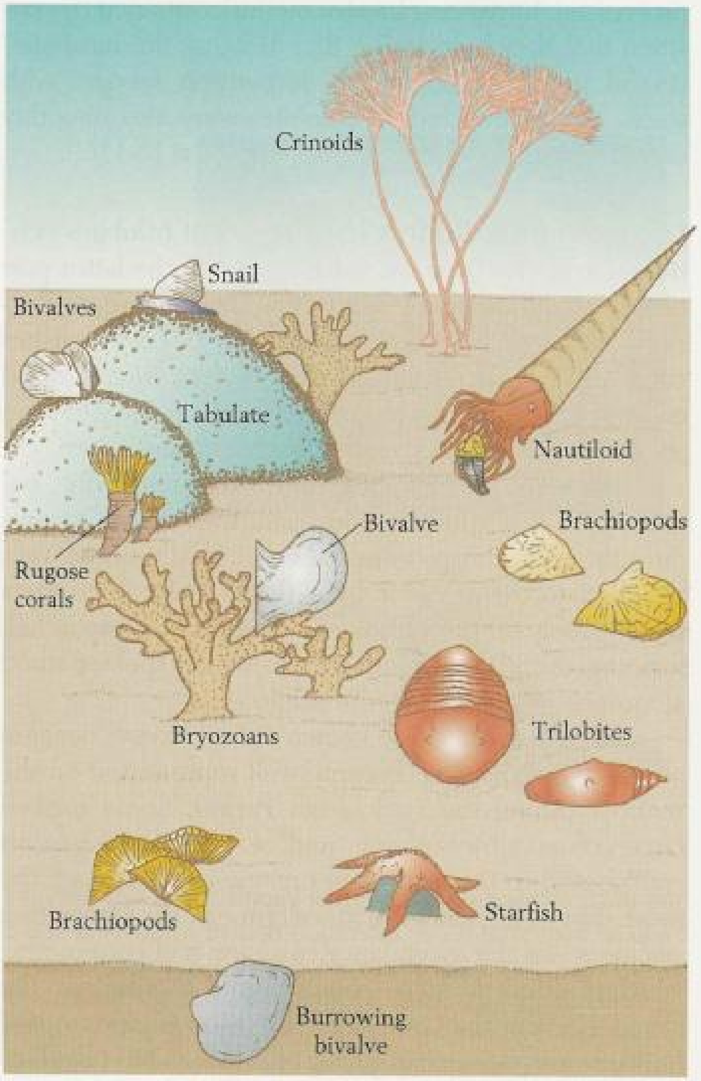
Figure 13-20 Movement of landmasses during Ordovician time. Avalonia was a fragment of Gondwanaland that moved toward Laurentia. Volcanic islands to its north collided with Laurentia, forming exotic terranes now located in Maine and eastern Canada. Near the end of the Ordovician, glaciers expanded over Gondwanaland near the south pole. (After B. A. van der Pluijm and R. Van der Voo, *Geol. Assn. Can. Spec. Paper* 41:127–136, 1995.)

Early Paleozoic faunas



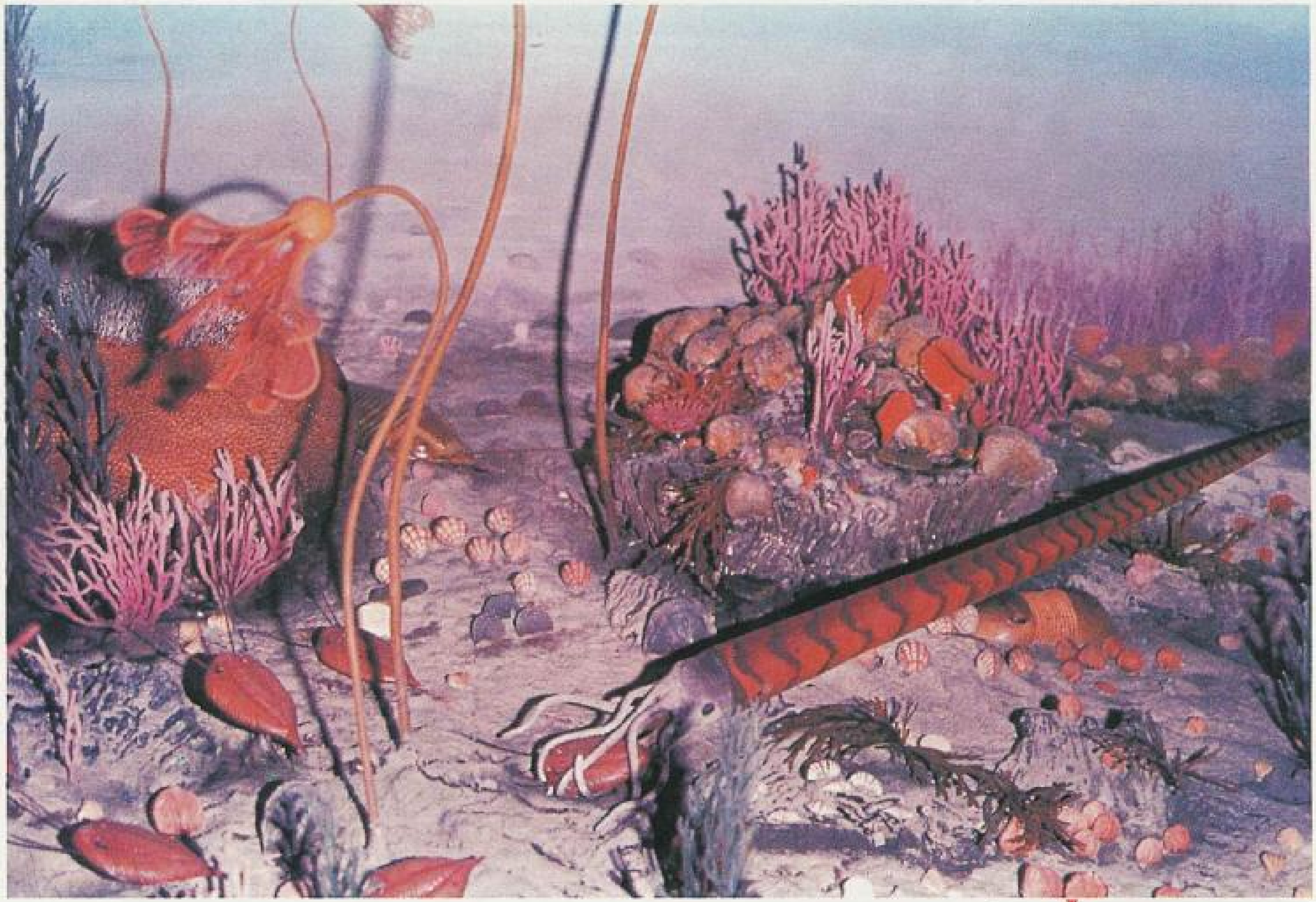
Ord life

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.)



◀ **Figure 13-12** **Life of a Late Ordovician seafloor in the area of Cincinnati, Ohio.** Fossils of many of the groups of animals represented here can be seen in Figure 13-11. Note that at this early stage of Phanerozoic evolution, relatively few animals lived within the sediment. At the left a snail crawls over a large tabulate coral colony, and two bivalve mollusks are attached to another tabulate colony by strong threads. Another bivalve is similarly attached to a branch of a bryozoan colony. Two solitary rugose corals, lodged alongside the tabulate colonies, have their tentacles outstretched for food. Stalked crinoids are waving about at the top of the picture, feeding on suspended matter with their arms. To their right, a large nautiloid prepares to eat a trilobite that it has trapped in its tentacles; below the nautiloid's eye is a spoutlike siphon that the animal uses to expel water for jet propulsion. Two kinds of suspension-feeding brachiopods live on the seafloor. In the right foreground are trilobites of a type that left trace fossils, indicating a burrowing mode of life. In the central foreground a starfish prepares to devour a bivalve by prying apart the shell halves with its sucker-covered arms; then, by extruding its stomach, the starfish can digest the bivalve within its opened shell.

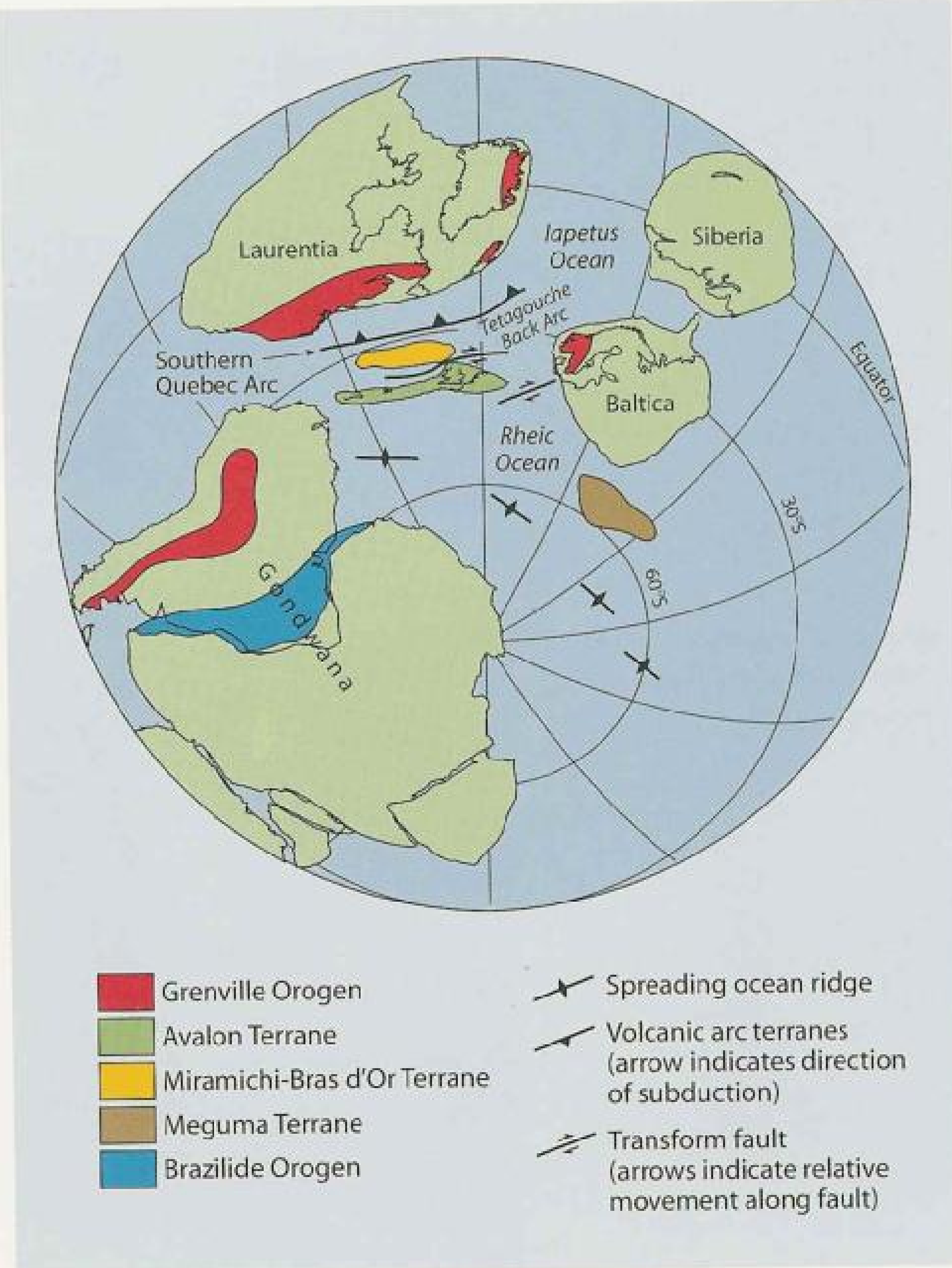
Ord life



Pre-€ | € | O | S | D | M | P | Pr | Tr | J | K | T | Q

FIGURE 8-14 Restoration of some of the common invertebrates that populated the floors of shallow epeiric seas during the Ordovician. The large semispherical object on the left is the skeleton of a colonial coral. In front of the coral and elsewhere in view are "branching twig" colonial bryozoans, and in the left foreground are trilobites, one of which is being eaten by the cephalopod with a conical shell. The long-stemmed creatures with branching arms are crinoids. Many different species of the bivalved organisms known as brachiopods can be seen. (*Diorama in the National Museum of Natural History, Smithsonian Institution.*)

Late Ord paleogeo



Global paleogeography of the late Ordovician, 455 million years ago.

Late Ord facies

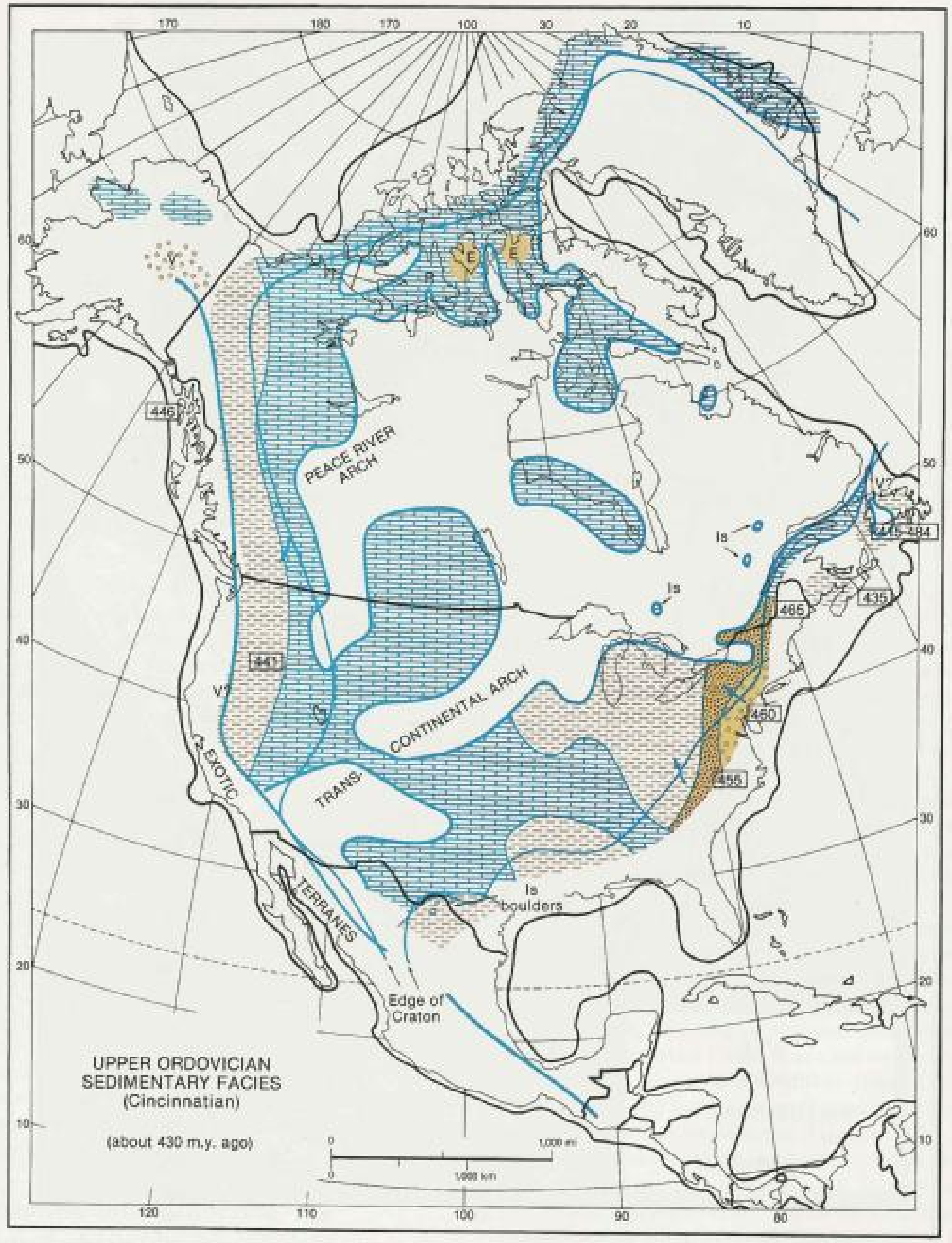


Figure 11.15 Upper Ordovician sediment patterns for North America. Widely scattered patches of sediments on the Canadian Shield prove the great extent of the Late Ordovician sea. Absence of Ordovician strata on several arches proves subsequent warping and erosion of these arches. Note the spread of red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

Late Ord fauna

Figure 11.2 Diorama of the Late Ordovician sea floor, based on fossils from the Cincinnati Arch region. The largest predator was the squidlike, straight-shelled nautiloid in the foreground. A large, well-armored trilobite swims in the lower left, and abundant brachiopods and horn corals cover the sea floor. Delicate crinoids *(right background)* and branching bryozoans *(left background)* occupy the higher levels of the sea floor. *(Image # K10276(4) American Museum of Natural History.)*

Ordovician fossils

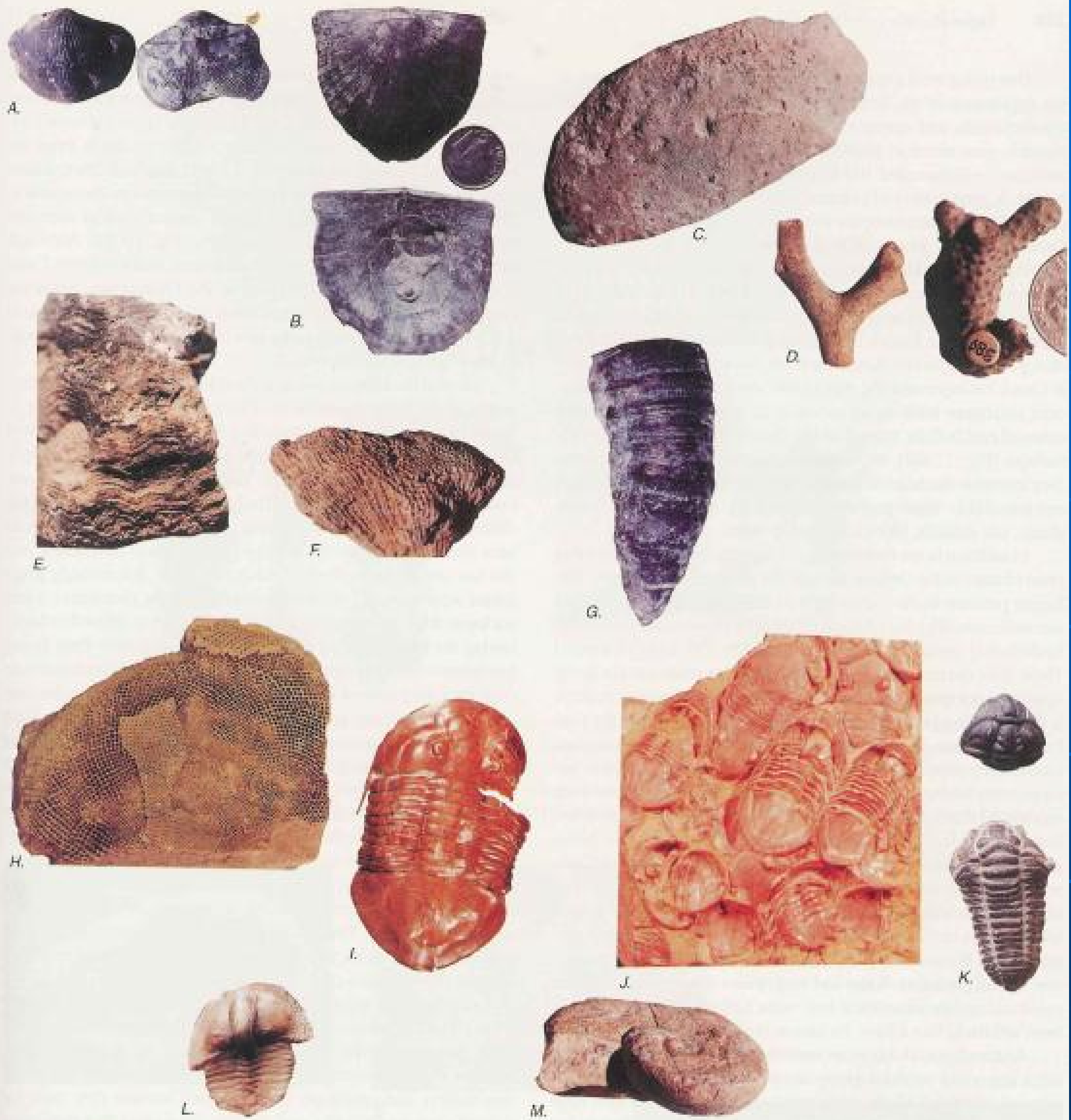
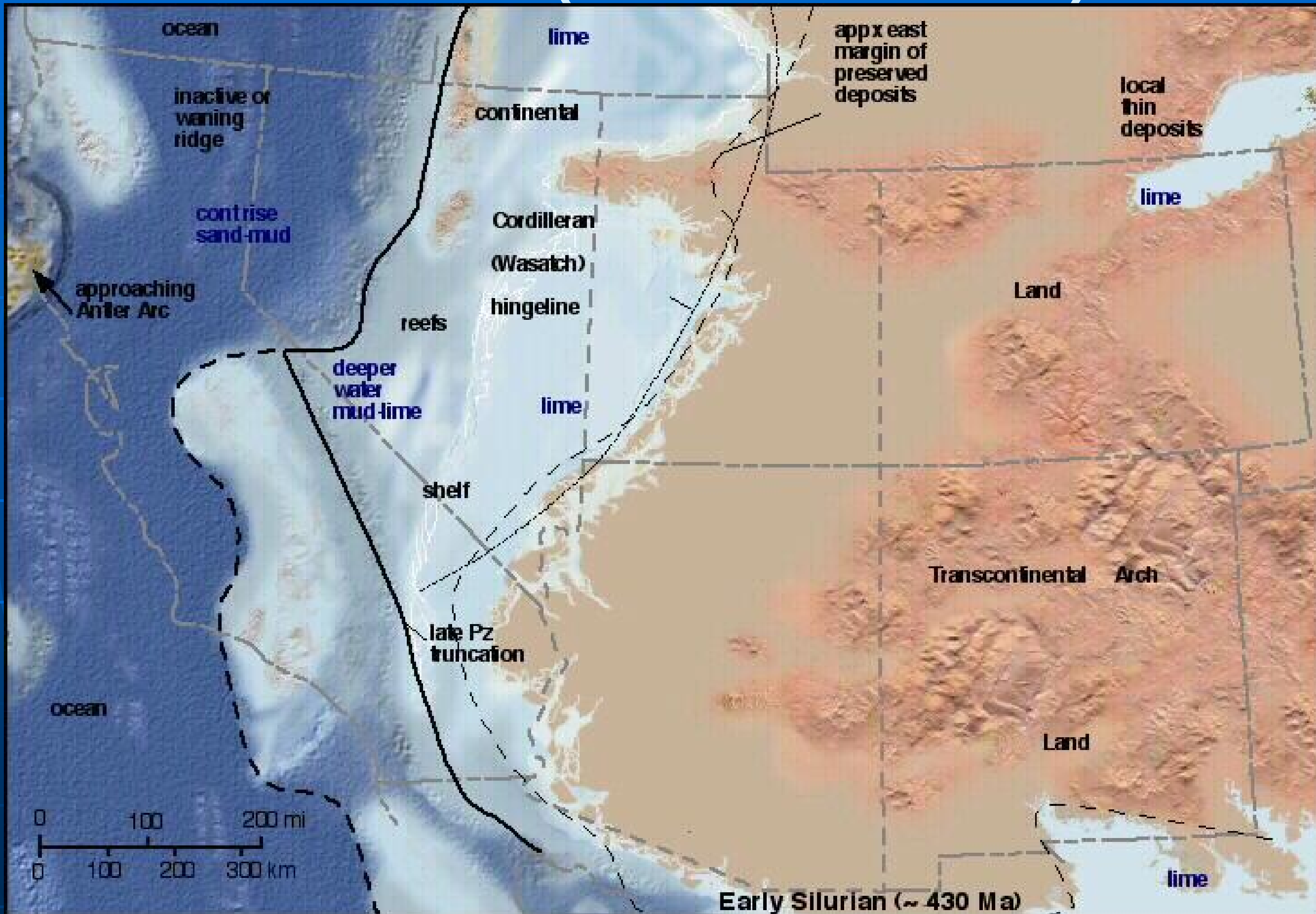


Figure 11.6 Representative Ordovician fossils. *A:* The primitive articulate brachiopod *Hebertella*, a common orthid. *B:* The "D"-shaped strophomenid brachiopod *Rafinesquina*. Both orthids and strophomenids were abundant on the Ordovician sea floor (see Fig. 11.3). *C:* The massive, lumpy bryozoan *Prasopora*. *D:* The delicate, branching bryozoan *Hallopora*. Ordovician reefs were built by members of several different phyla, including *E:* layered stromatoporoid sponges; *F:* the "honeycomb" tabulate coral *Favosites*; *G:* the solitary rugosid ("horn coral") *Streptelasma*; *H:* the "sunflower corals," or receptaculitids, now thought to be skeletons of dasycladacean algae. In response to predators, Ordovician trilobites became more specialized for burrowing, or protected by more spines and armor than their Cambrian predecessors. They included *I:* the foot-long "snowplow" trilobite, *Isotelus* (this specimen shows a healed bite mark on its right cheek); *J:* a mass-death assemblage of a similar trilobite, *Homotelus*; *K: Flexicalymene*, a trilobite that could roll up like a sowbug; *L:* the "lace-collar" trilobite *Cryptolithus*, with the delicate, lacy brim on the front of the head, long cheek spines, short body and "Jimmy Durante nose." *M:* The peculiar Ordovician gastropod *Maclurites*. This early experiment in snail evolution apparently carried the shell with the point directed down and forward, the opposite of most modern marine gastropods. Some macluritids were very large, reaching almost a foot in diameter. *(Photos I and J copyright 1992 Loren E. Babcock; all other photos by D. R. Prothero.)*

Silurian (443-417 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Silurian paleogeo

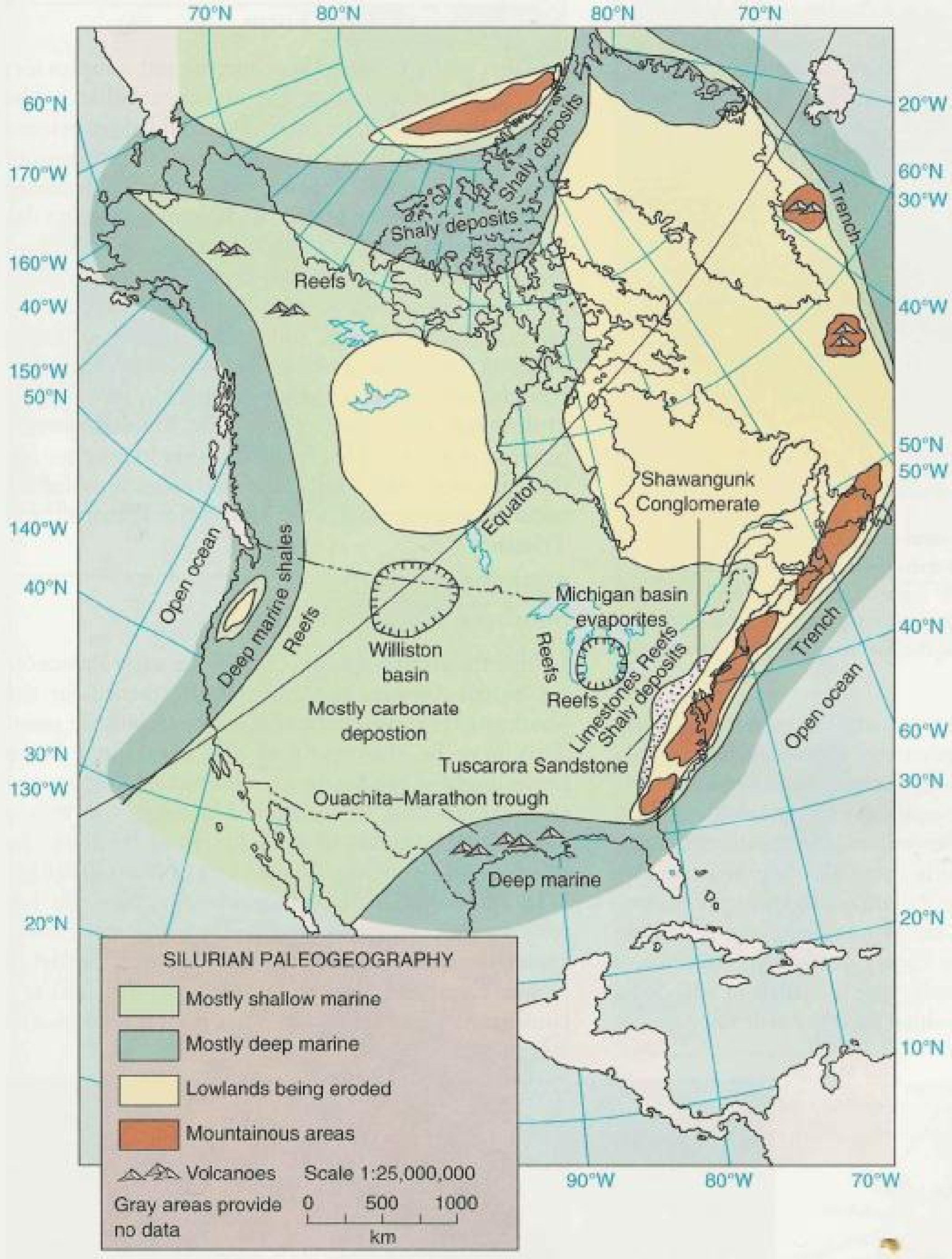


FIGURE 8-30 Paleogeographic map of Silurian North America.

Silurian - Devonian fossils

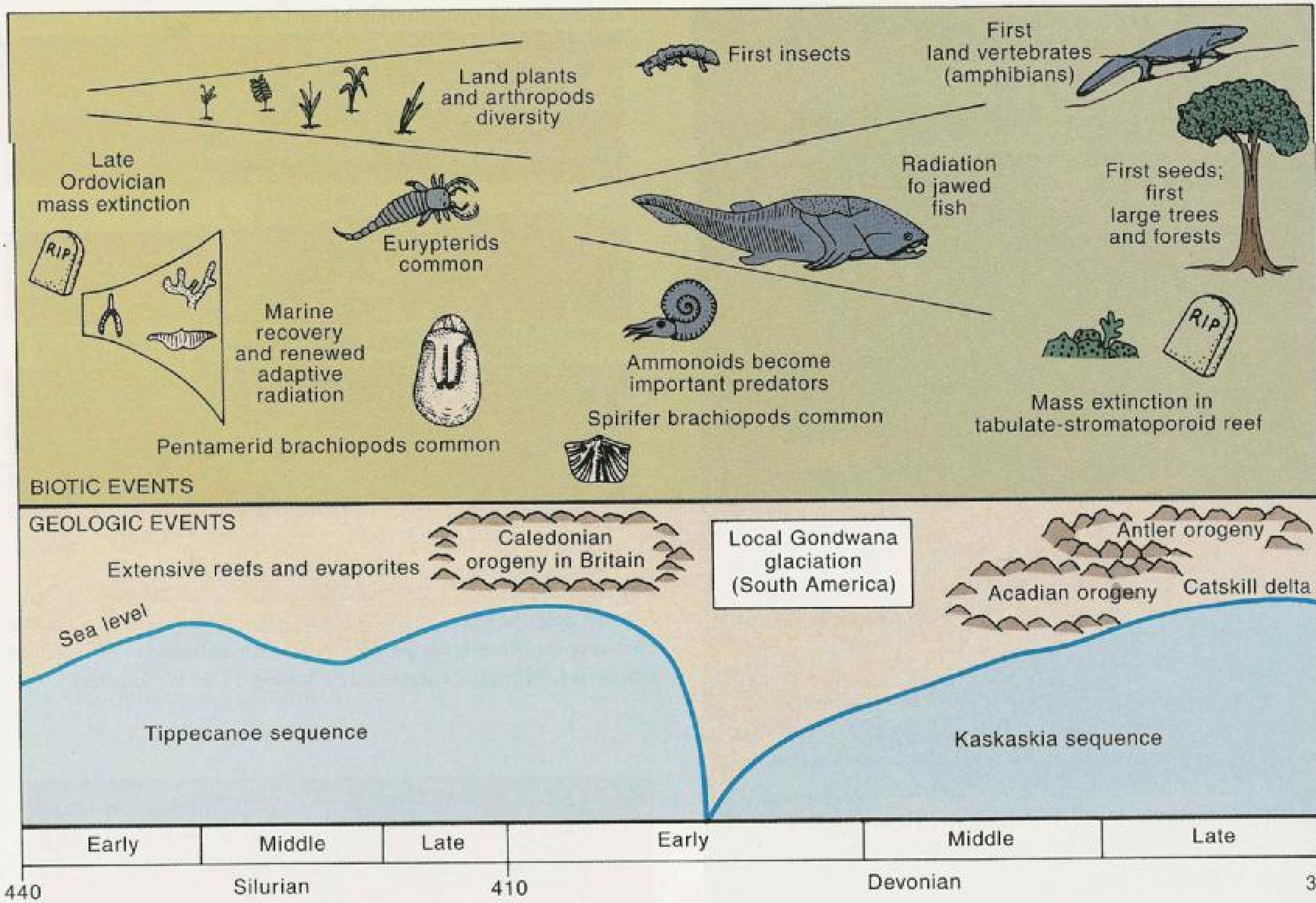
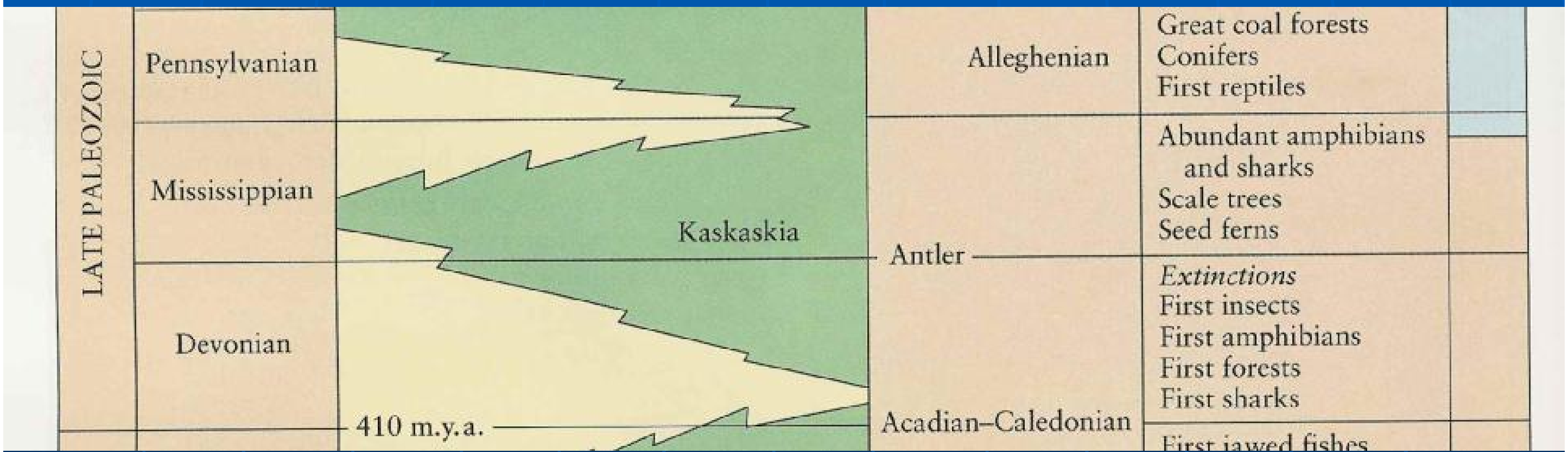


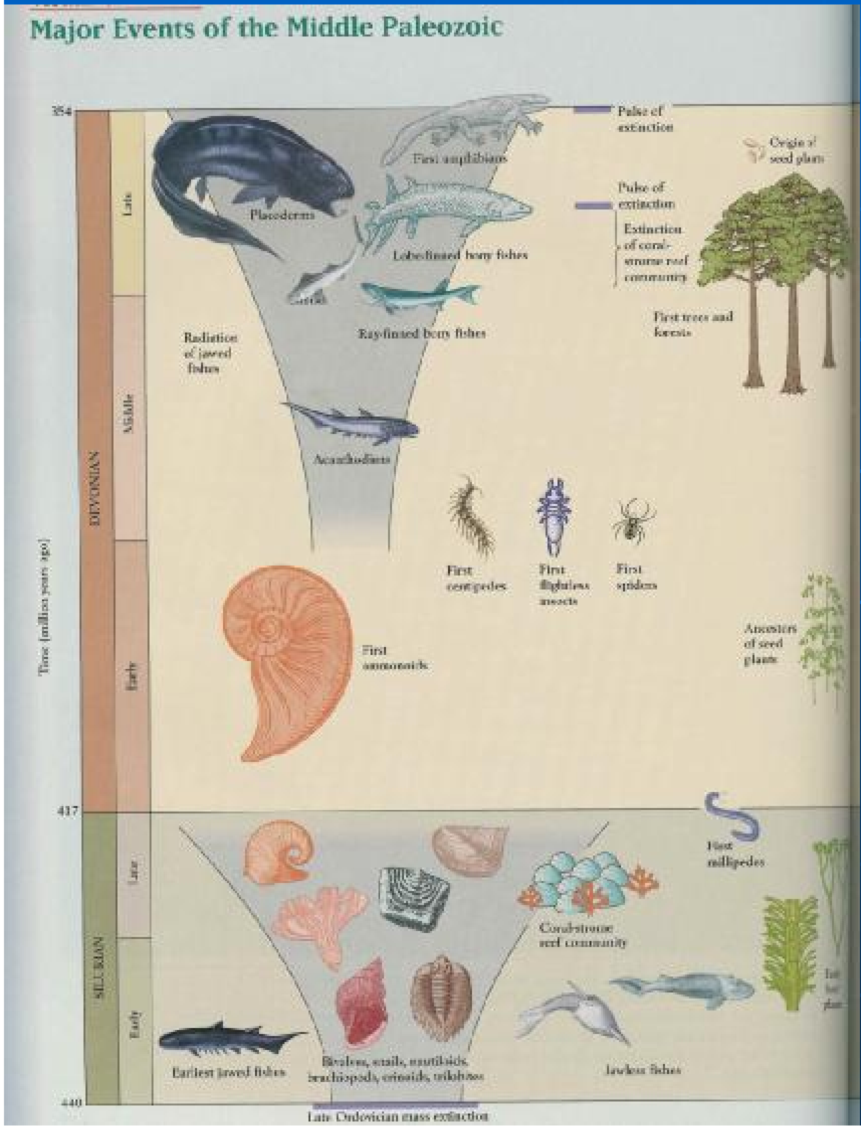
Figure 12.50 Summary time line of events of the Silurian and Devonian.

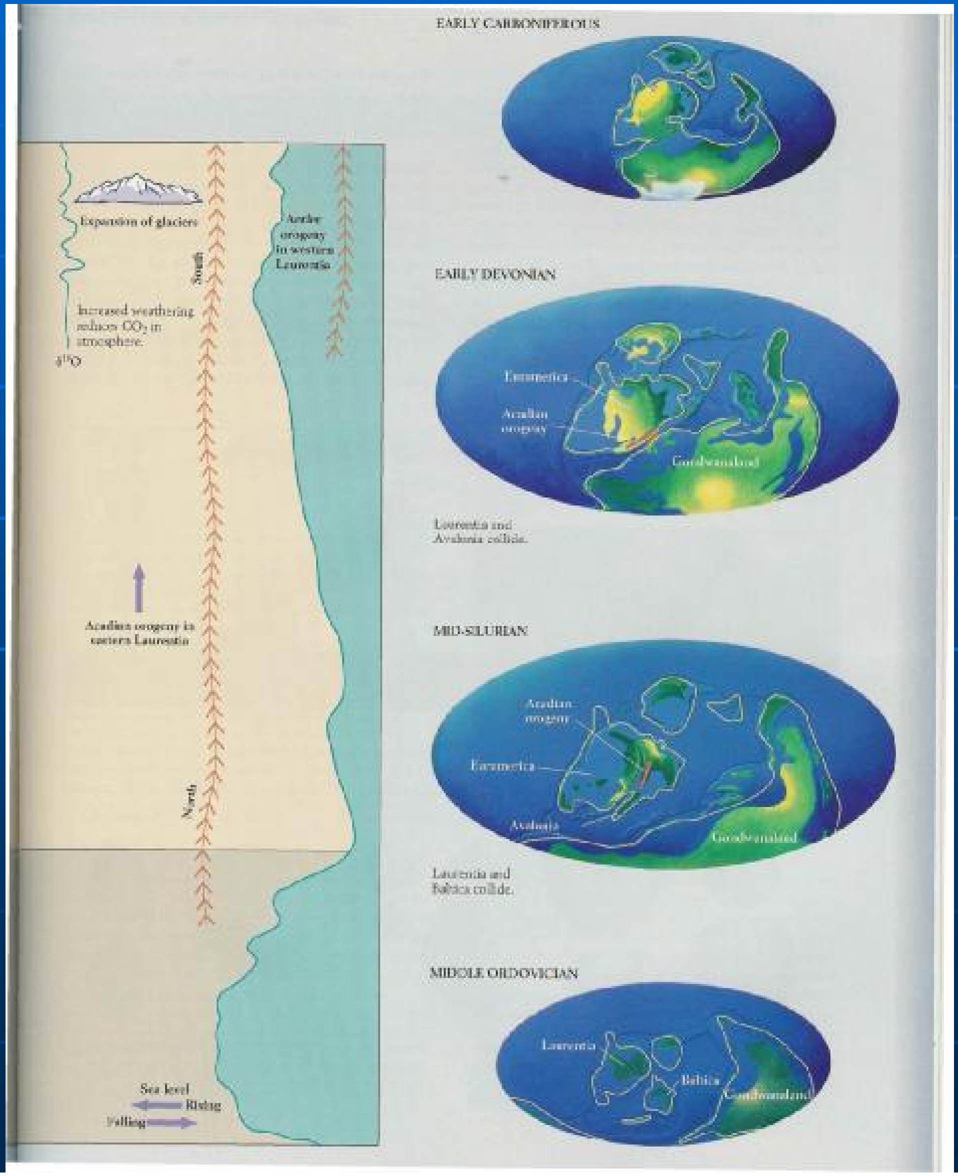
Kaskaskia sequence

Devonian - Mississippian



Mid Paleozoic events





Devonian paleogeo-graphy

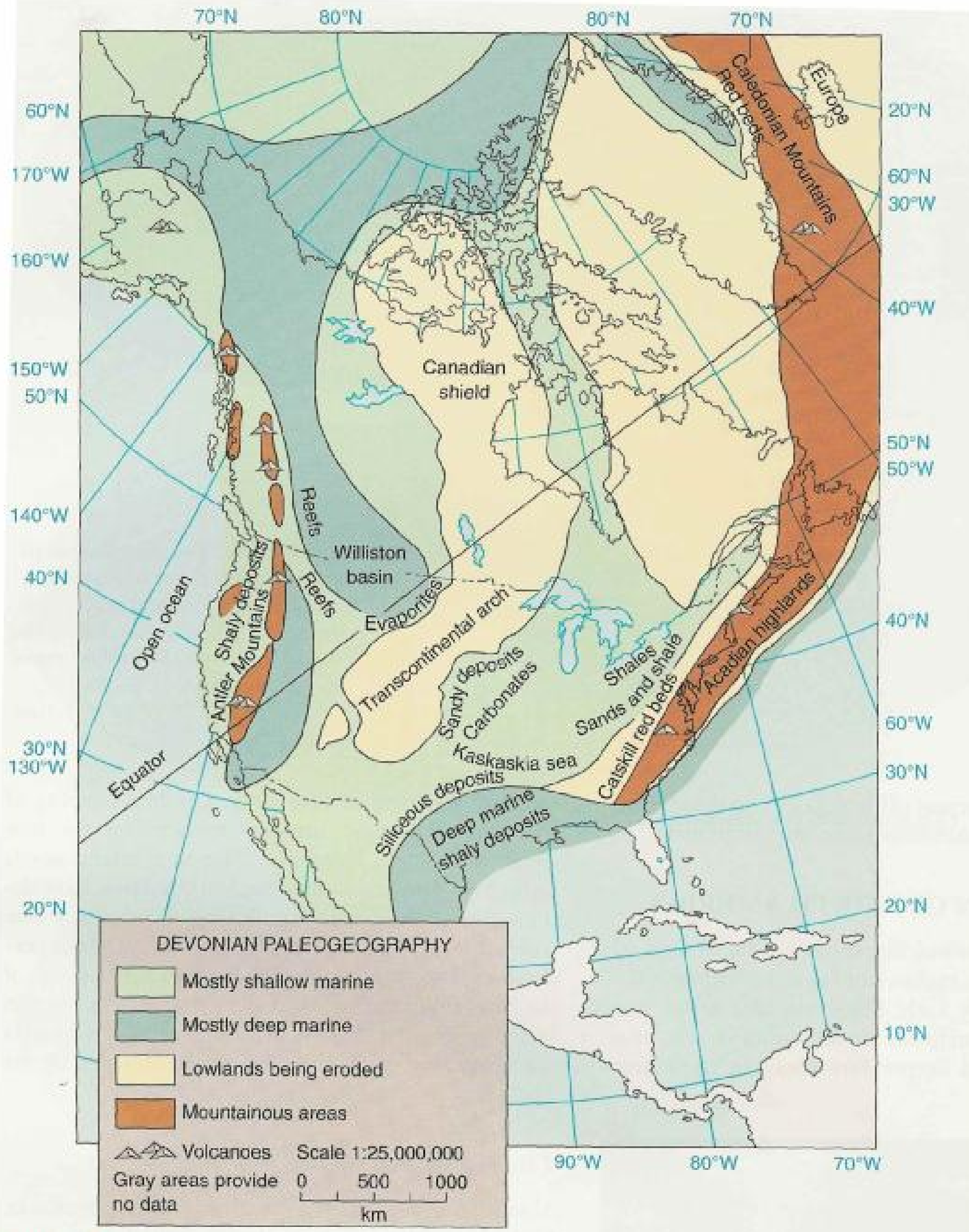


FIGURE 9-4 Paleography of North America during the Devonian Period.

Devonian corals

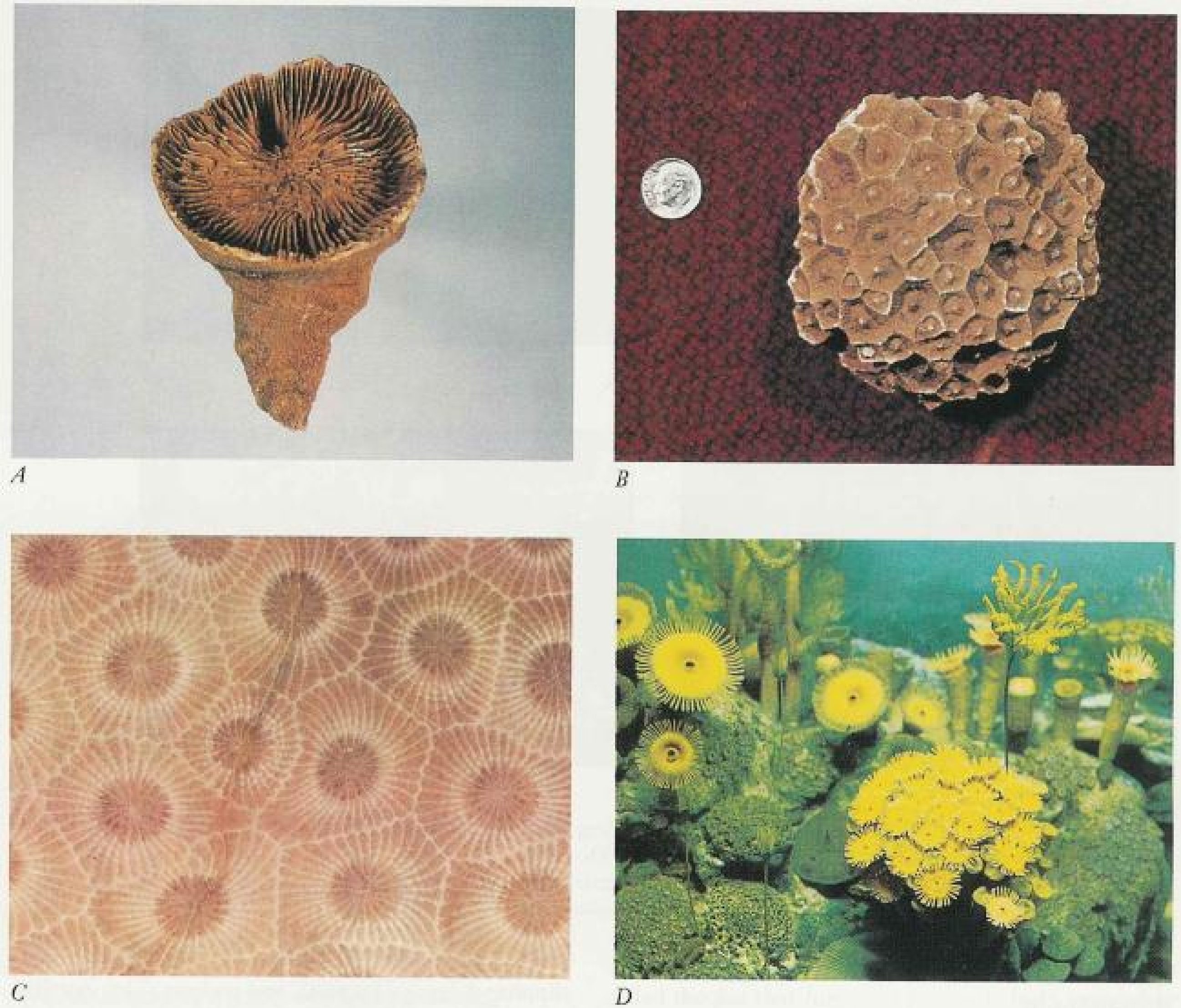


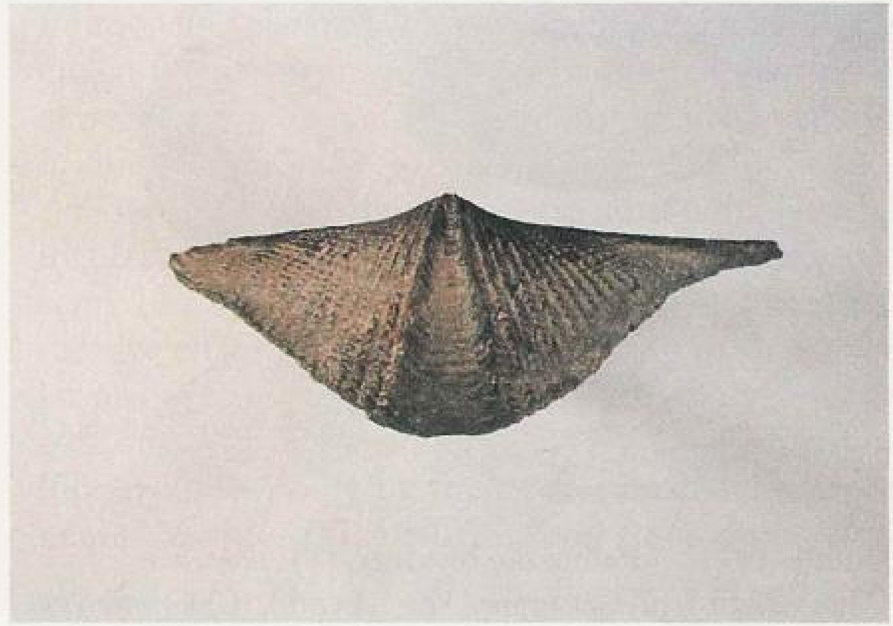
FIGURE 10-24 Devonian rugose corals. (*A*) The solitary horn coral *Zaphrenthis* with clearly visible radiating septa in the hornlike theca. (*B*) The compound (colonial) rugose coral *Lithostrotionella*. (*C*) A polished slab of the compound coral *Hexagonaria*. Water-worn fragments of this coral are found along the shore of Lake Michigan at Petoskey, Michigan, and this accounts for its being called Petoskey stone. Although not a rock, Petoskey stone is the designated state rock of Michigan. (*D*) Reconstruction of compound and solitary rugose corals on the floor of a Devonian epeiric sea. (*Diorama photograph courtesy of the U. S. National Museum of Natural History, Smithsonian Institution.*) ? *What was the purpose or function of the septa in rugose corals?*

Devonian brachiopods

B

C

FIGURE 10-29 Devonian spiriferid brachiopods. (*A*) *Mucrospirifer* (*B*) *Platyrachella* (*C*) spiriferid brachiopod with shell broken to reveal the internal spiral supports for the lophophore (natural size).



A

B

Devonian fish

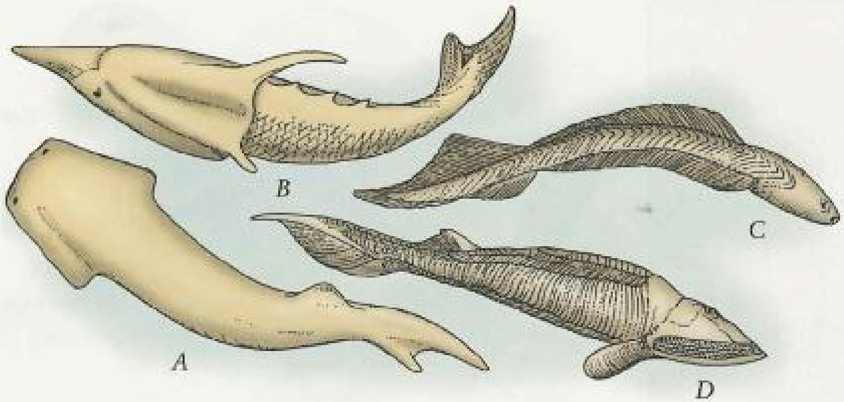


FIGURE 10-60 **Early Paleozoic ostracoderms.** (*A*) *Thelodus*, (*B*) *Pteraspis*, (*C*) *Jamoytius*, and (*D*) *Hemicyclaspis*, drawn to the same scale.

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.*)

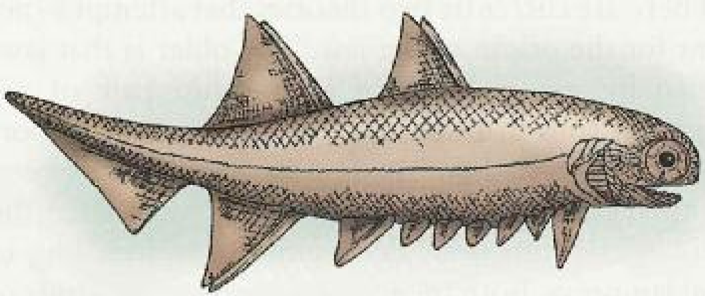


FIGURE 10-61 **The Early Devonian acanthodian fish *Climatius*.** (*After Romer, A. S. 1945.* Vertebrate Paleontology. *Chicago: University of Chicago Press.*)

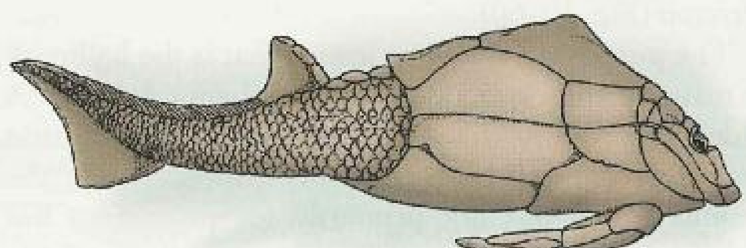


FIGURE 10-63 **The Devonian antiarch fish *Pterichthyodes*.** (*From Romer, A. S. 1945.* Vertebrate Paleontology. *Chicago: University of Chicago Press, p. 54, fig. 38.*)

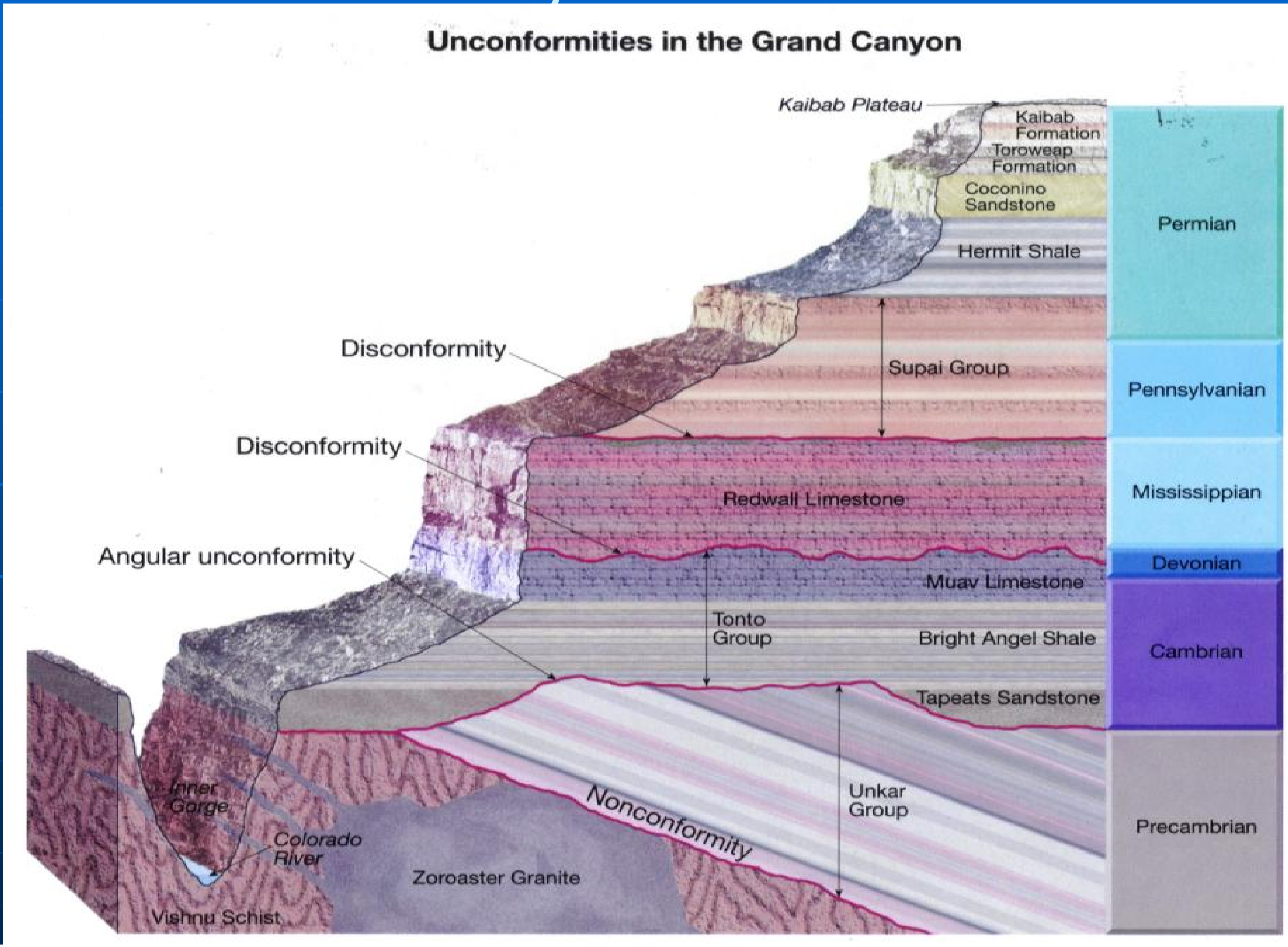
Devonian plants

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 flourished, and eventually the first amphibians crawled out of the water. *(Painting by Zdenek Burian.)*

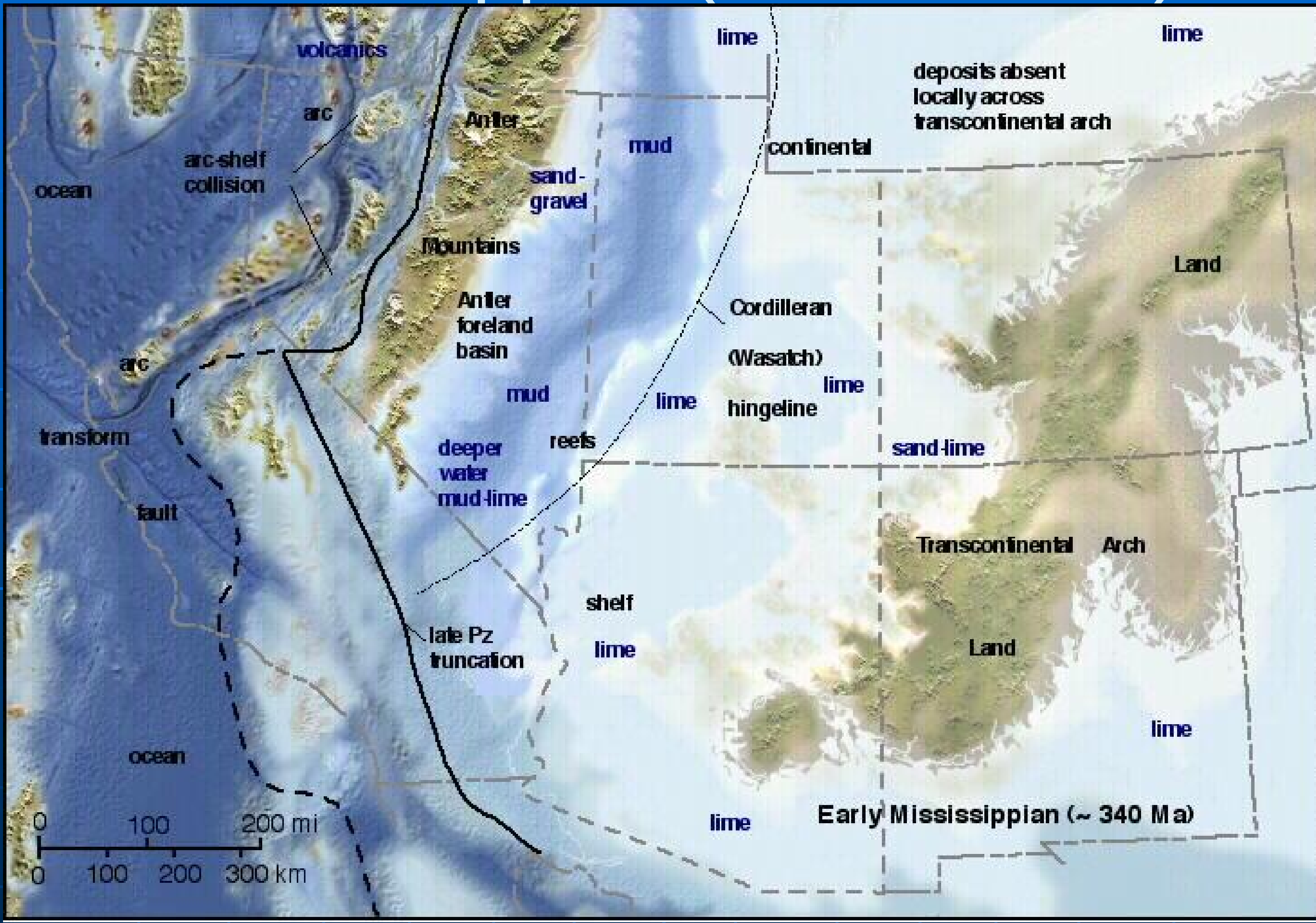
Devonian (417-354 Ma)

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Grand Canyon section

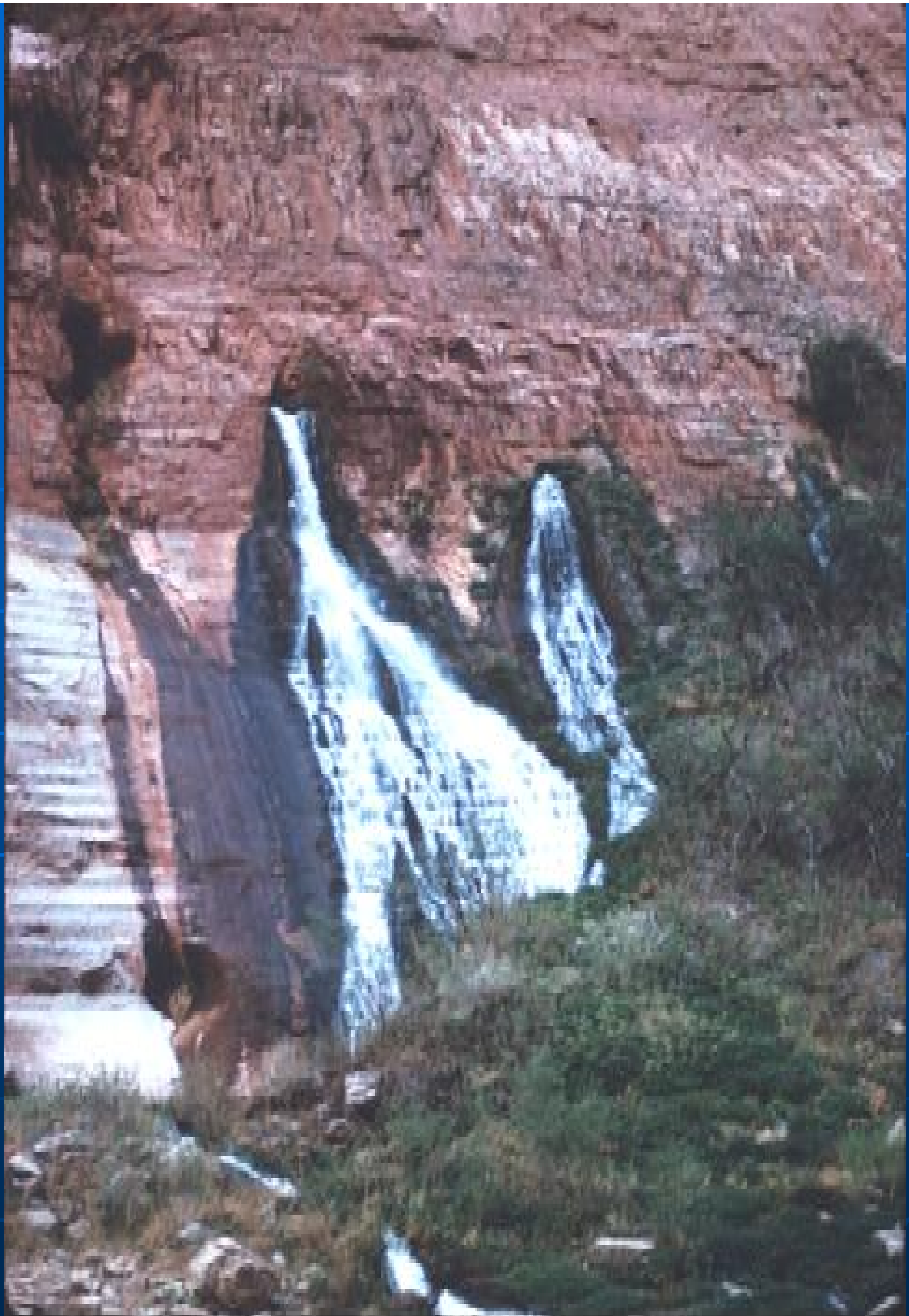


Mississippian (354-323 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Redwall Limestone



Escabrosa Limestone

Crinoidal Limestone

A

B

Pro-€ | € | O | S | D | M | P | Pr | Tr | J | K | T | Q

FIGURE 9-6 **Crinoidal limestone.** (*A*) Specimen of limestone (Burlington Formation) in which crinoid fragments (mostly stem plates) stand out in relief because of weathering. (*B*) Reconstruction of crinoids growing on the floor of the Kaskaskia (Mississippian) sea. (*B, courtesy of the National Museum of Natural History, Smithsonian Institution.*)

Syringopora

Mississippian paleogeo- graphy

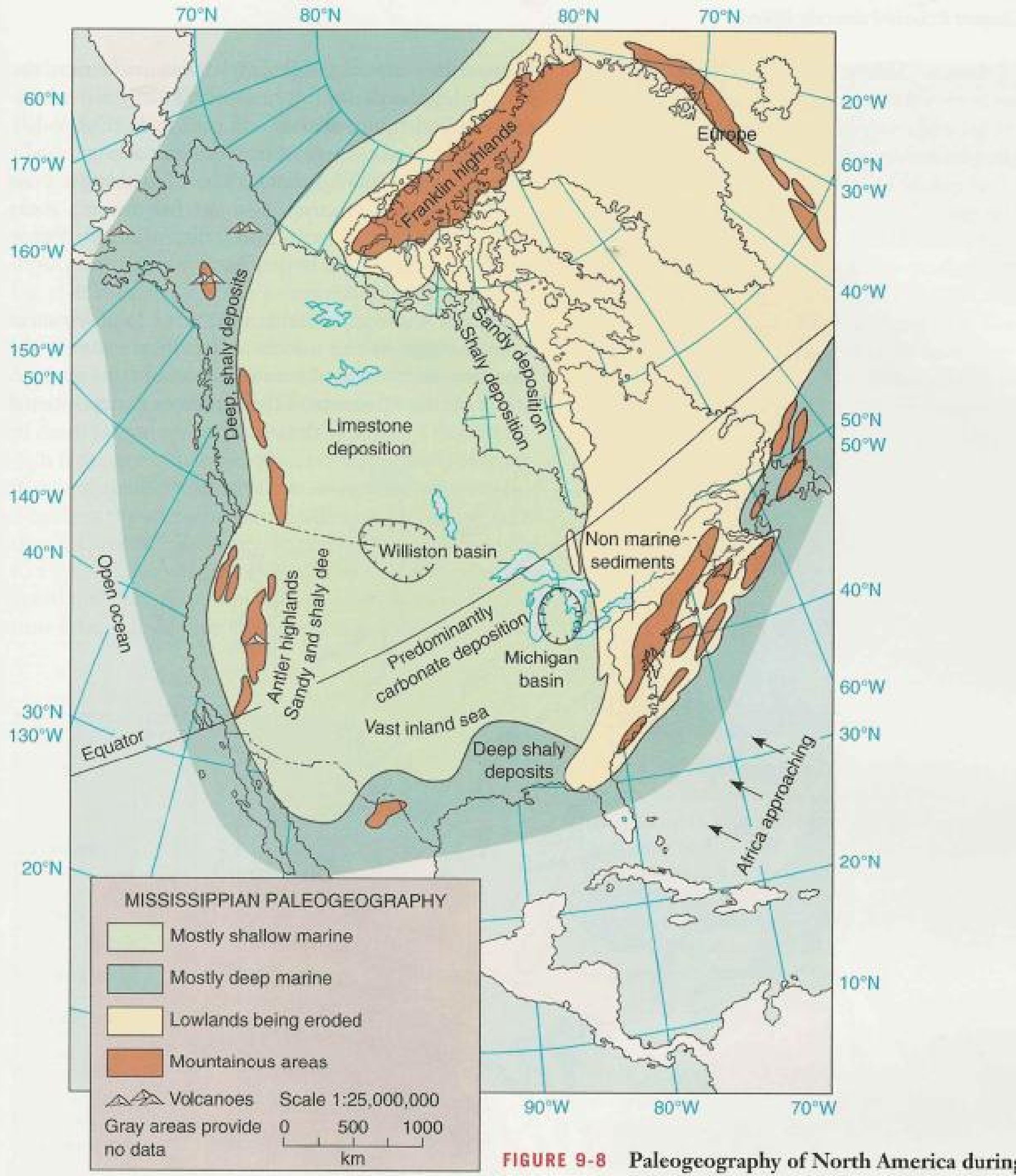
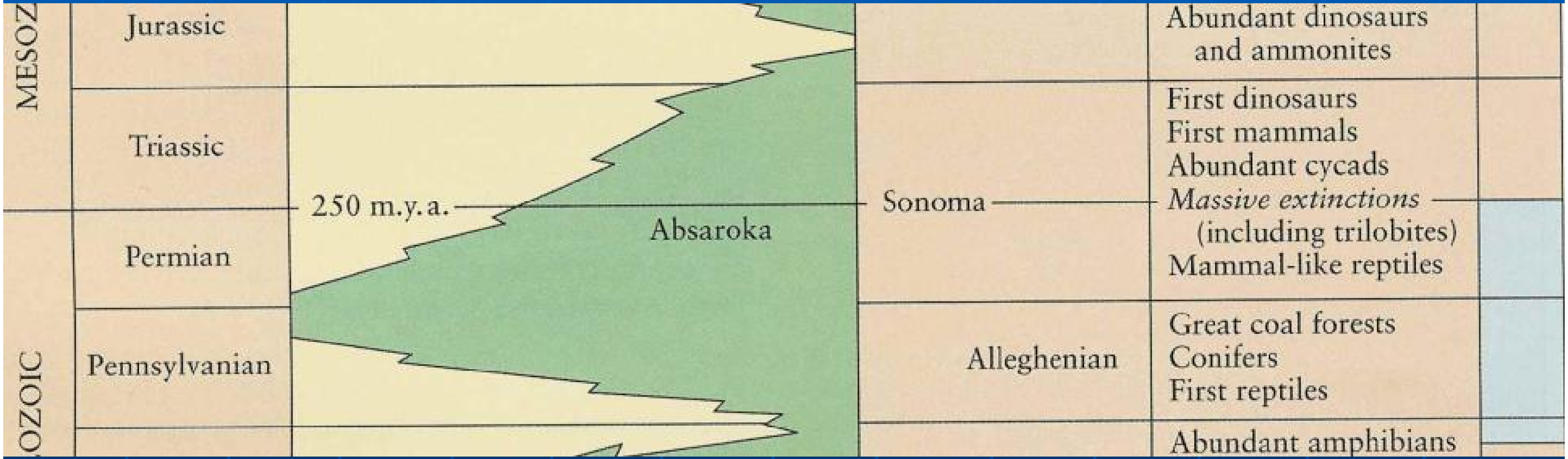


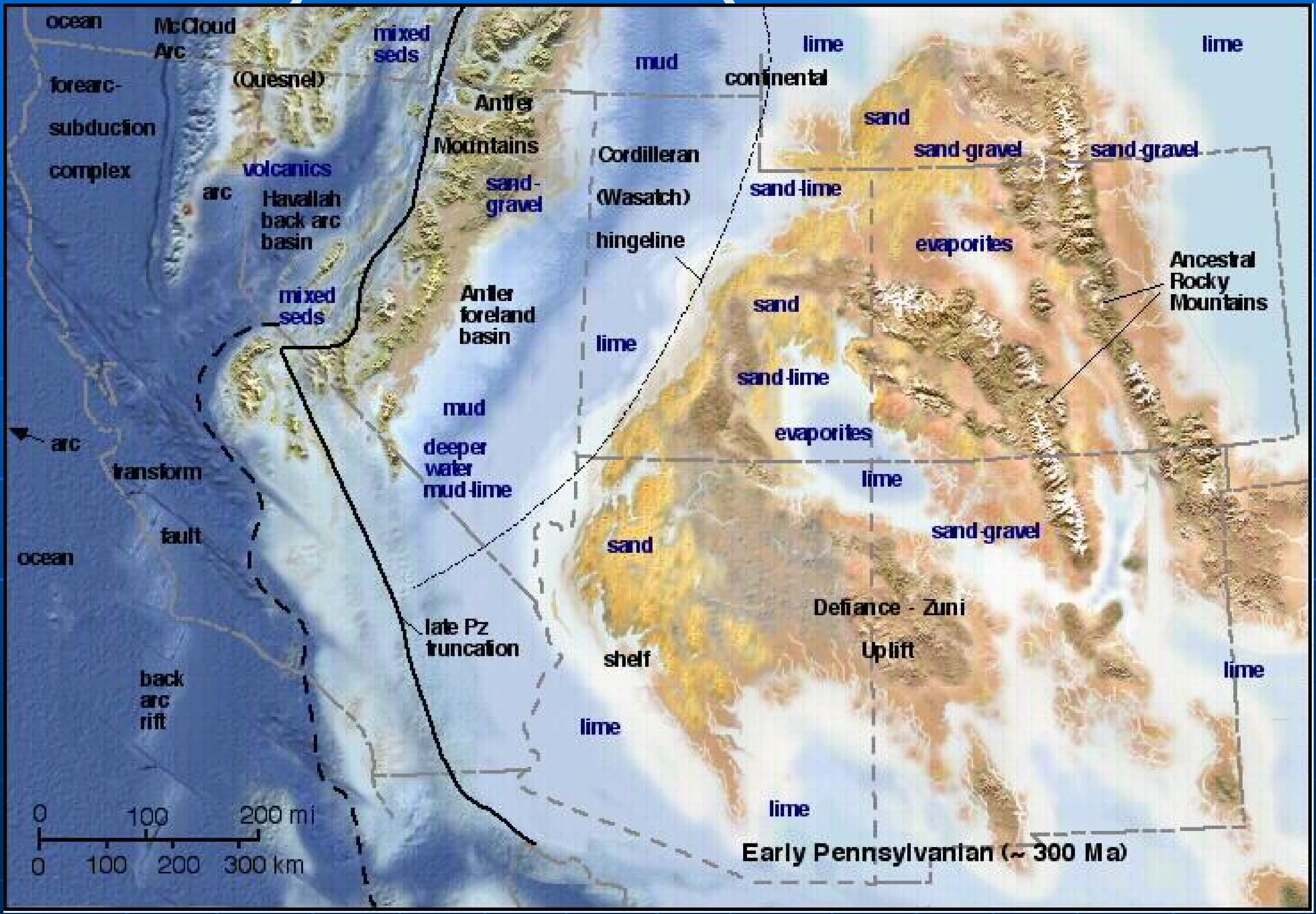
FIGURE 9-8 Paleogeography of North America during the Mississippian Period.

Absaroka sequence

Pennsylvanian – Permian – Triassic



Pennsylvanian (323-290 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Pennsylvanian paleogeography

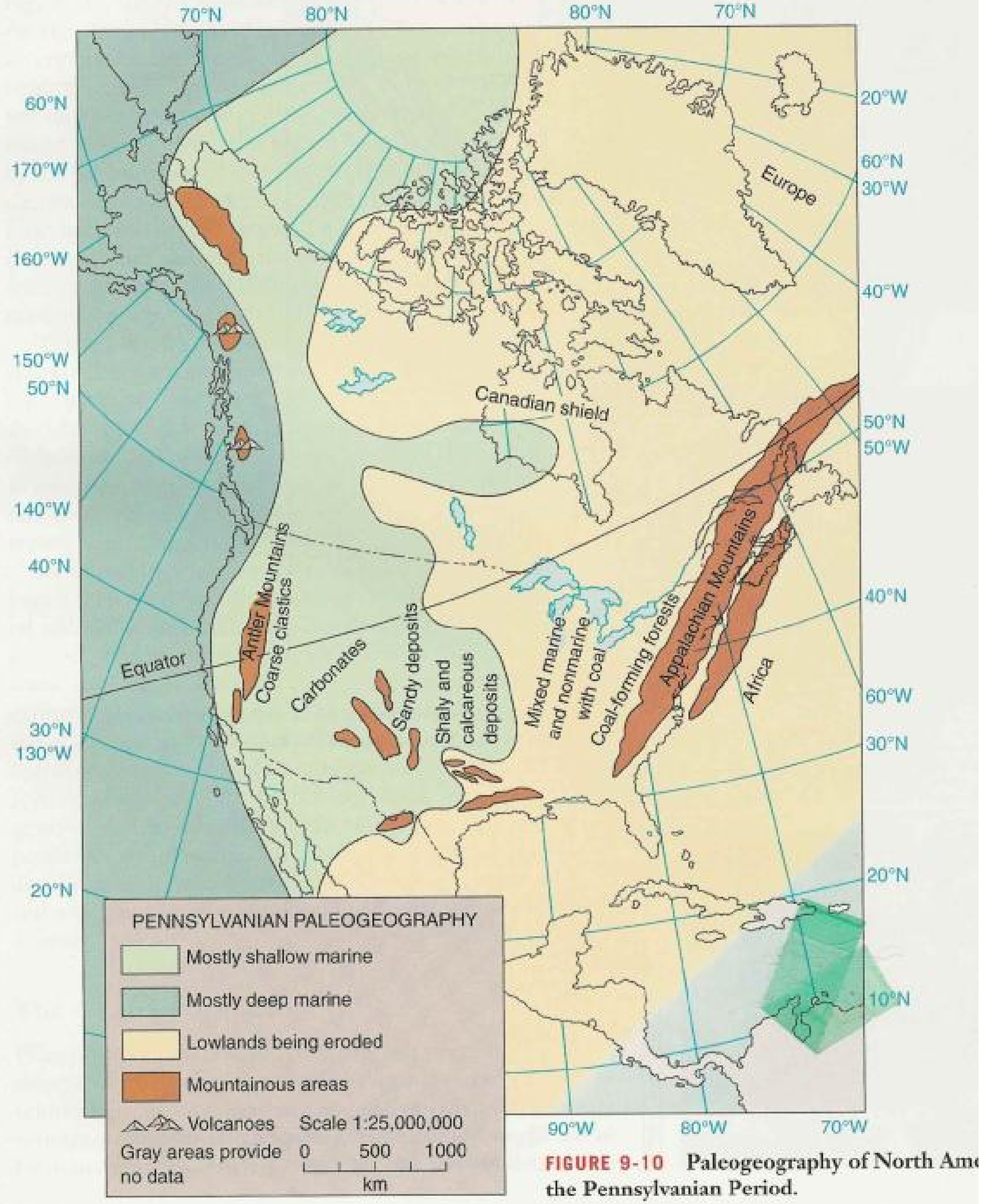


FIGURE 9-10 Paleogeography of North Am[...] the Pennsylvanian Period.

Pennsylvanian paleogeography, Western U.S.

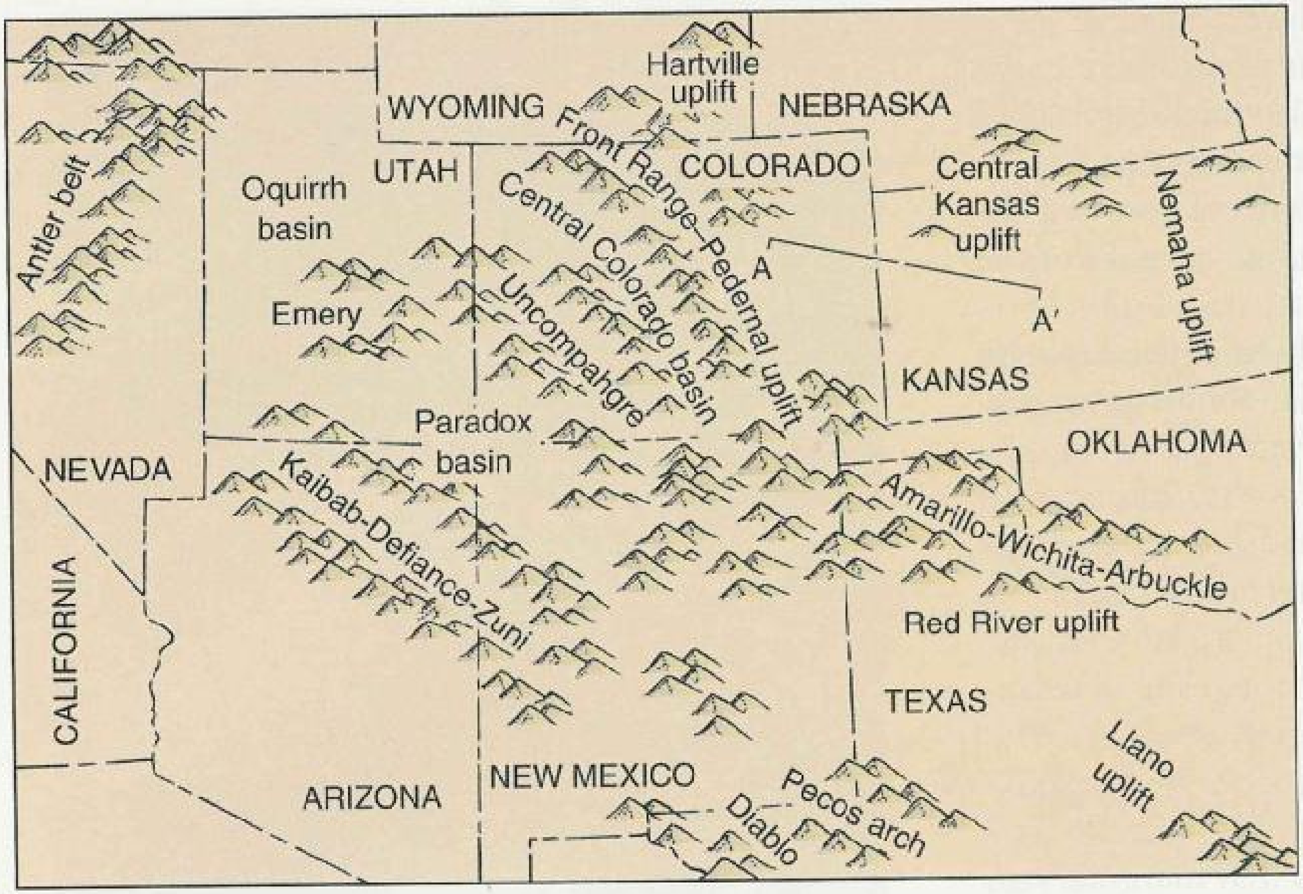


FIGURE 9-13 Location of the principal highland areas of the southwestern part of the craton during Pennsylvanian time.

Amphibian fossils

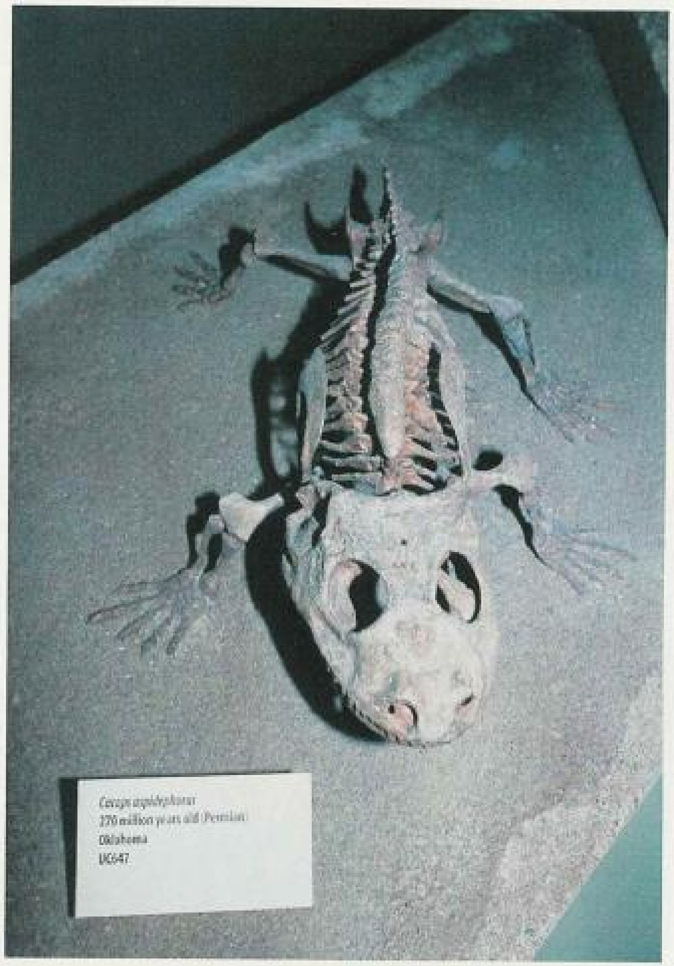


FIGURE 10-77 ***Cacops*, a small labyrinthodontic amphibian from the Lower Permian.** *(Photograph of a specimen on exhibit at the Field Museum in Chicago.)*

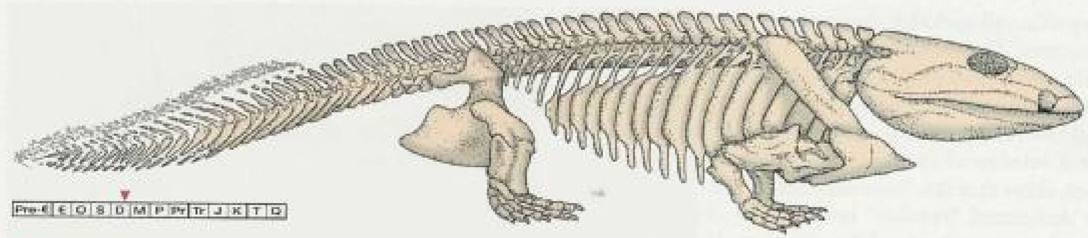


FIGURE 10-76 **The skeleton of *Ichthyostega* still retains the fishlike form of its crossopterygian ancestors.** (*From Levin, H. L. 1975.* Life Through Time. *Dubuque, Iowa: William C. Brown Co.*)

Appalachian paleo-geography Permian

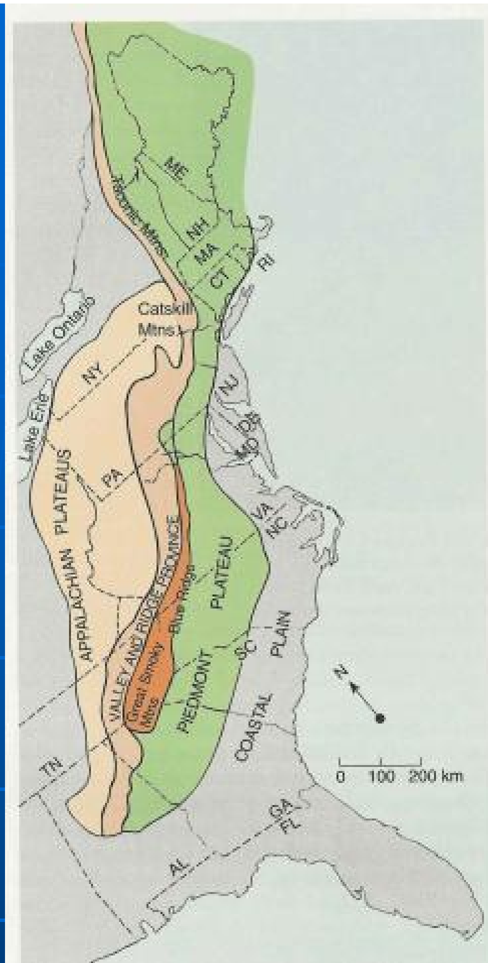


FIGURE 9-28 Physiographic provinces of the eastern United States.

The effects of the Allegheny orogeny were profound and included Permian compression of early continental shelf and rise sediments as well as strata deposited along the bordering tract of the craton. The great folds now visible in the Ridge and Valley Province were developed during this orogeny. Less visible at the surface but

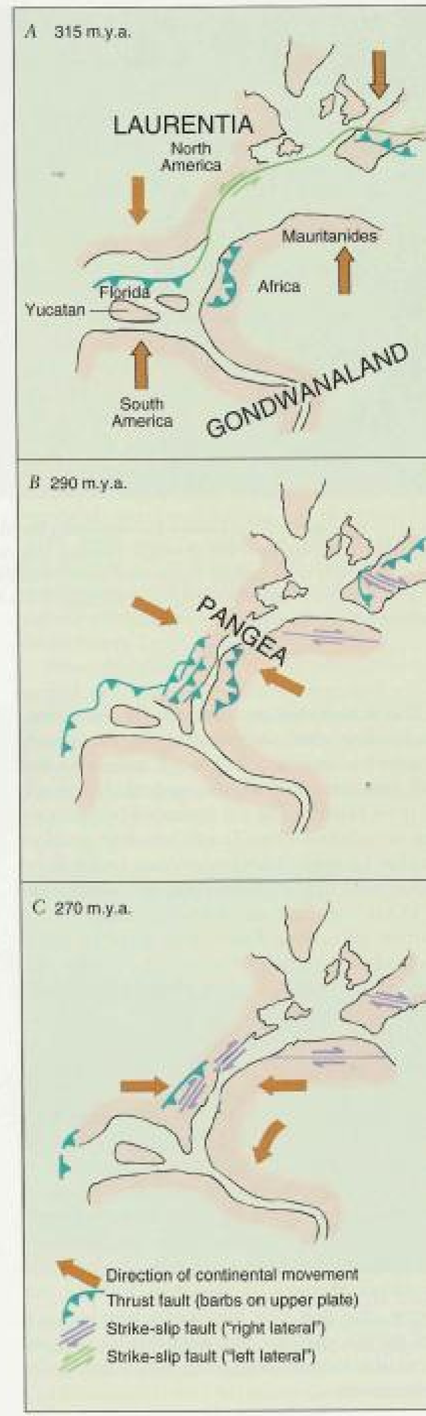


FIGURE 9-29 Plate tectonic model for late Paleozoic continental collisions, proposed by P. E. Sacks and D. T. Secor, Jr. (*A*) Early Pennsylvanian, (*B*) Late Pennsylvanian, (*C*) Permian. (*Adapted from Sacks, P. E., and Secor, D. T., Jr. 1990. Science 250:1702–1705.*)

Calamites

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

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

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

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.*)

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

Cyclothem rocks

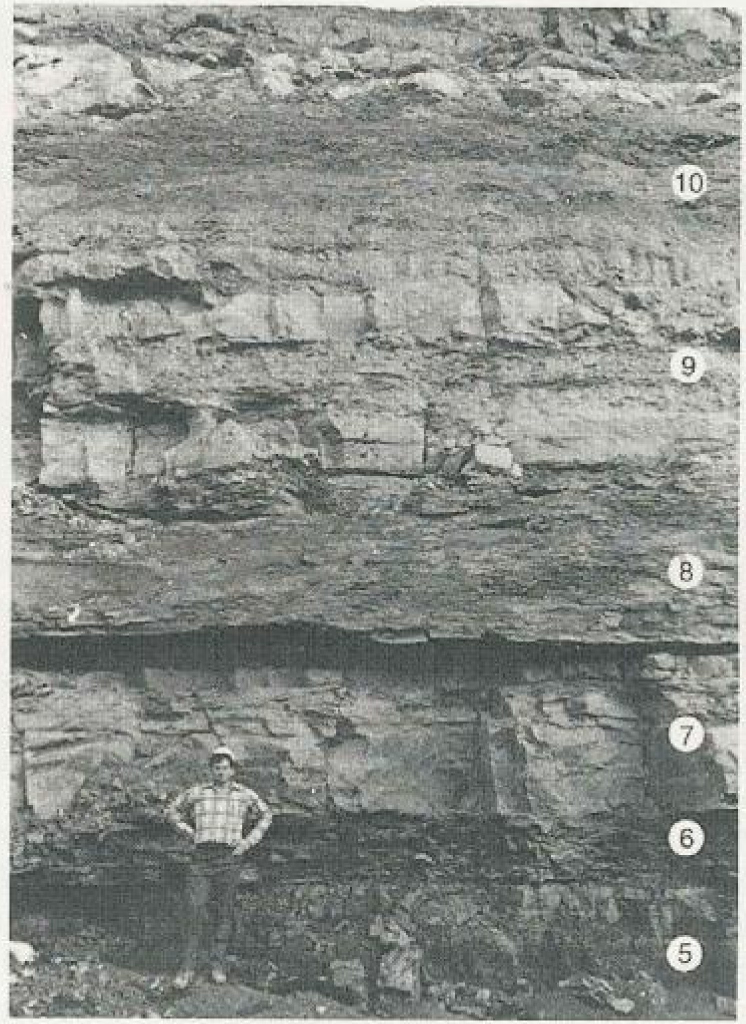


FIGURE 9-12 Part of an Illinois cyclothem. The lowermost layer is the coal seam (cyclothem bed 5), followed upward by shale (bed 6) near the geologist's hand, limestone (bed 7), shale (bed 8), another limestone (bed 9), and the upper shale (bed 10). Part of another sequence caps the exposure. This cyclothem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

Typical cyclothem

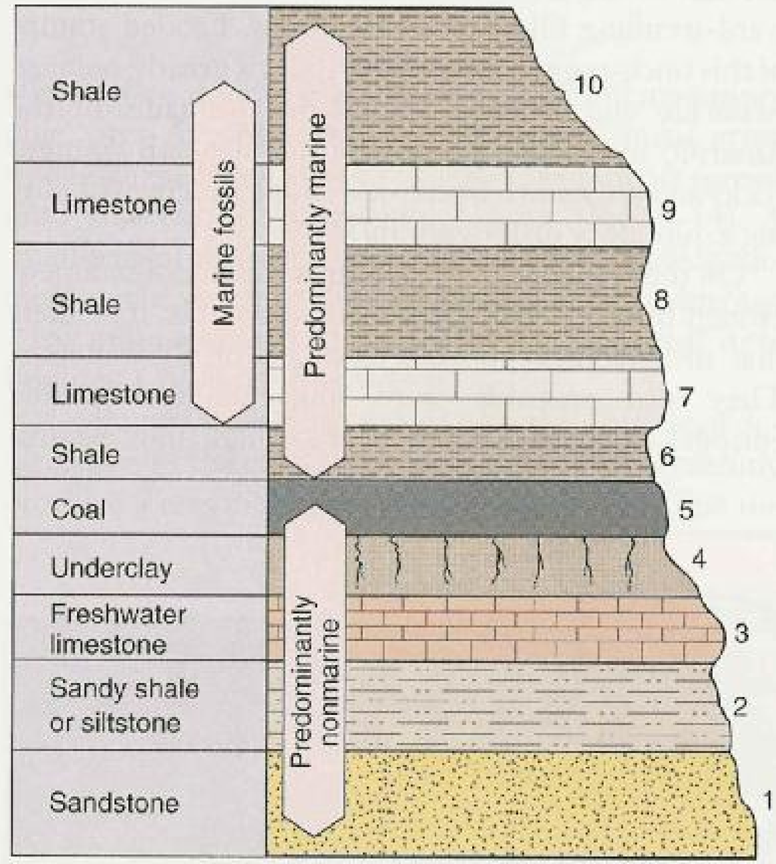


FIGURE 9-11 An ideal coal-bearing cyclothem, showing the typical sequence of layers. Many cyclothems do not contain all 10 units, as in this illustration of an idealized sequence. Some units may not have been deposited because changes from marine to nonmarine conditions may have been abrupt and/or units 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 across a limestone that was part of a cyclothem, how might you ascertain that it was a marine rather than a freshwater limestone?*

Penn. Coal forest

Paradox Basin

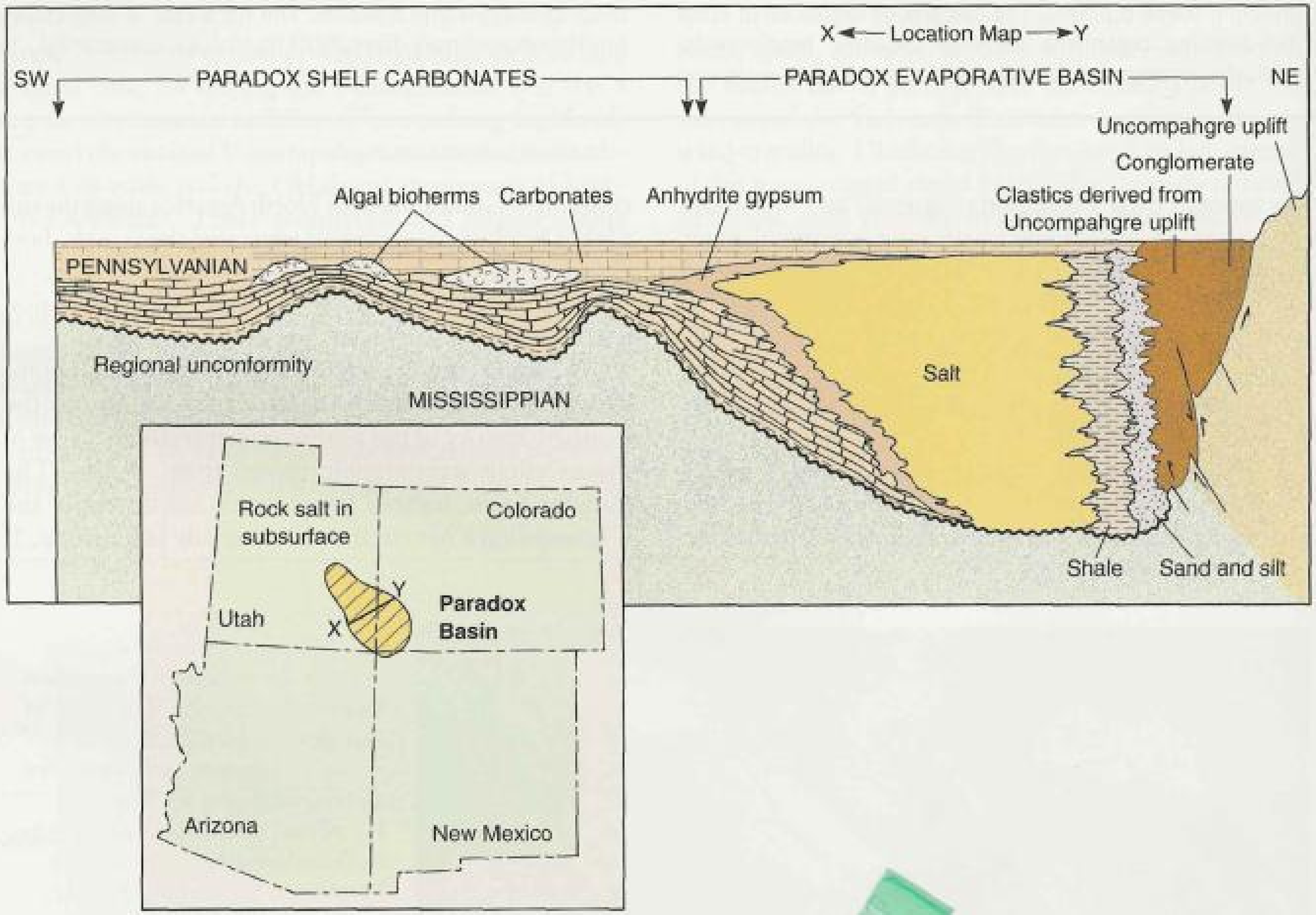
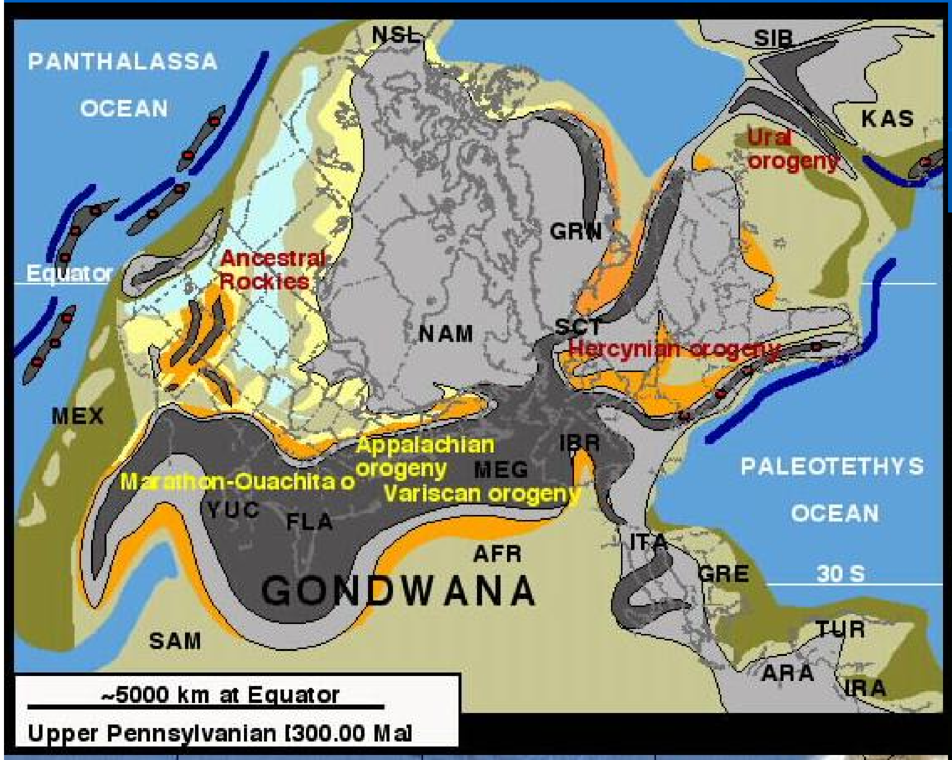


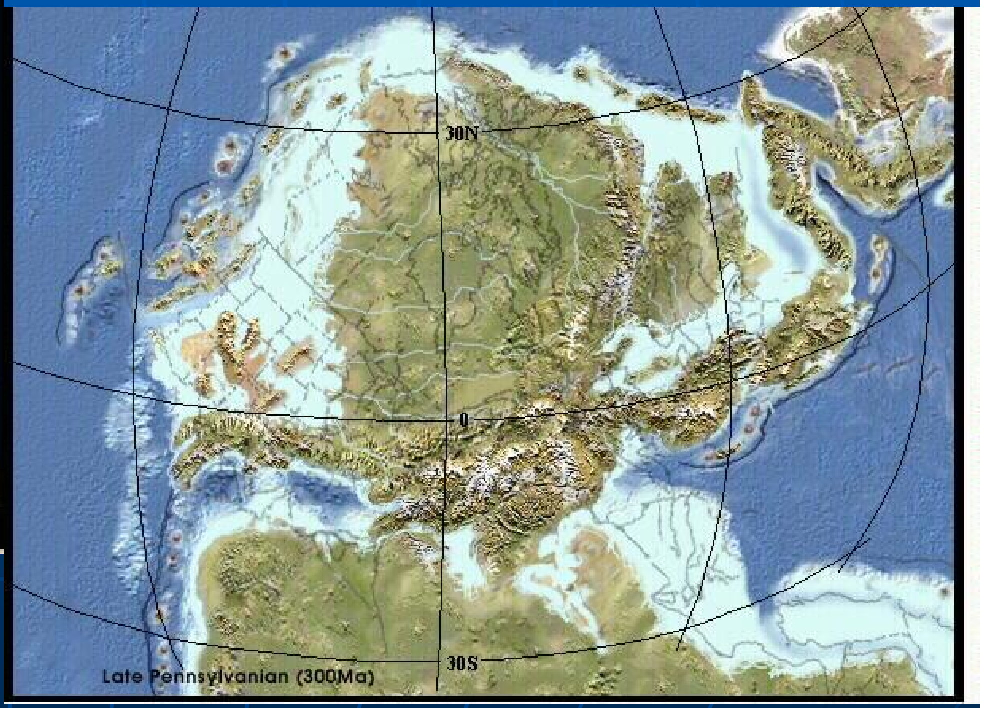
FIGURE 9-16 Generalized cross-section through the Paradox basin, an evaporative basin of Pennsylvanian age in southeastern Utah and southwestern Colorado. Erosion of uplands resulting from the Uncompahgre Uplift produced the coarse, arkosic clastics at the northeastern side of the cross-section. These clastics merge with evaporites of the Paradox basin and then carbonates of the Paradox shelf. Reeflike masses of calcareous algae called algal bioherms occur within the carbonate section. Because of their porosity, petroleum and natural gas have accumulated in many of the bioherms. (*Simplified from Baars, D. L. et. al. 1988. Basins of the Rocky Mountain region. Sedimentary Cover–North American Craton: U.S. DNAG (Decade of North American Geology) D-2:198–220.*)

Goosenecks of the San Juan

Government Draw

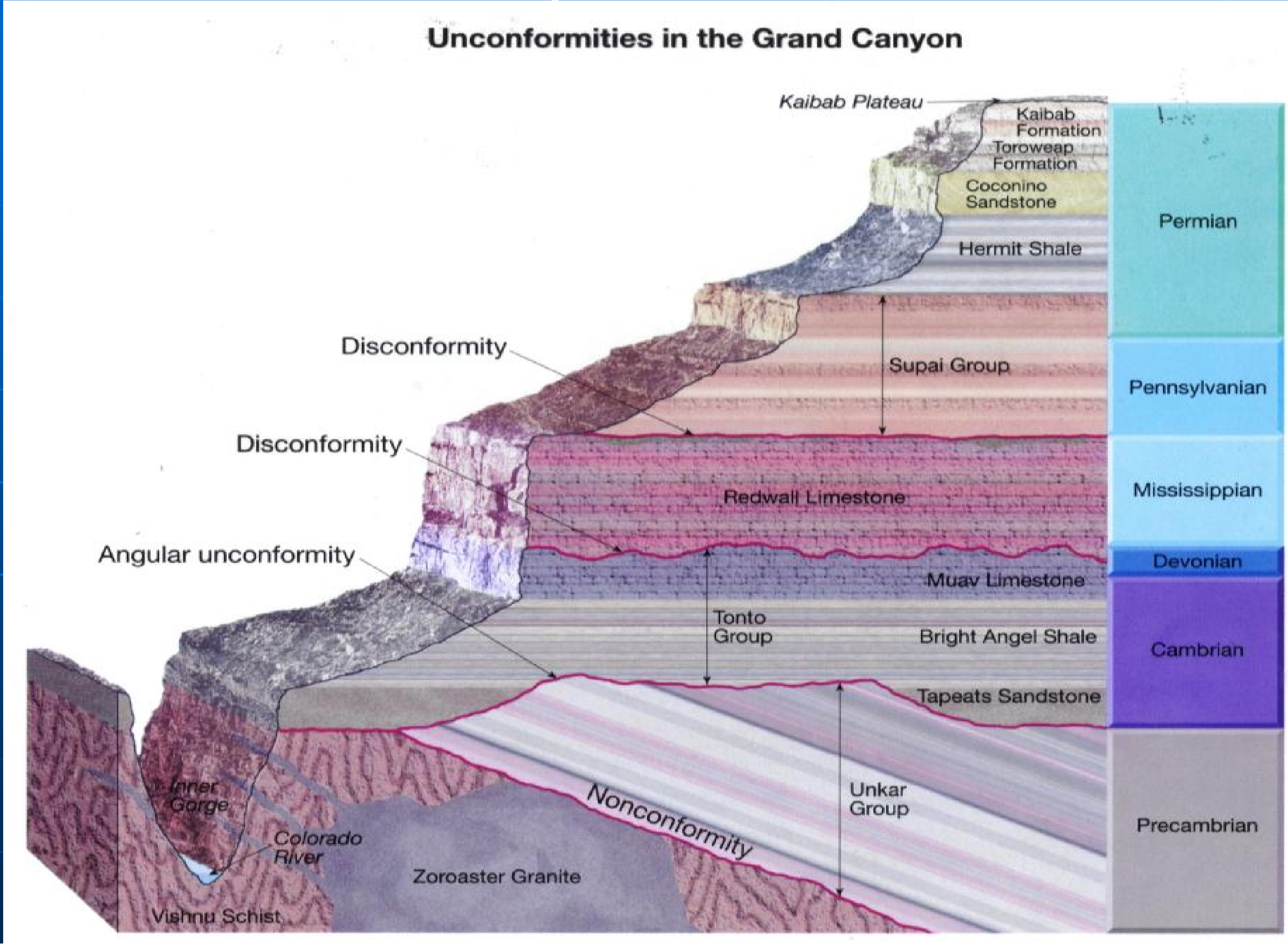
Late Penn. 300 Ma paleogeography





Sedona

Grand Canyon section



Grand Canyon

Productid brachiopod

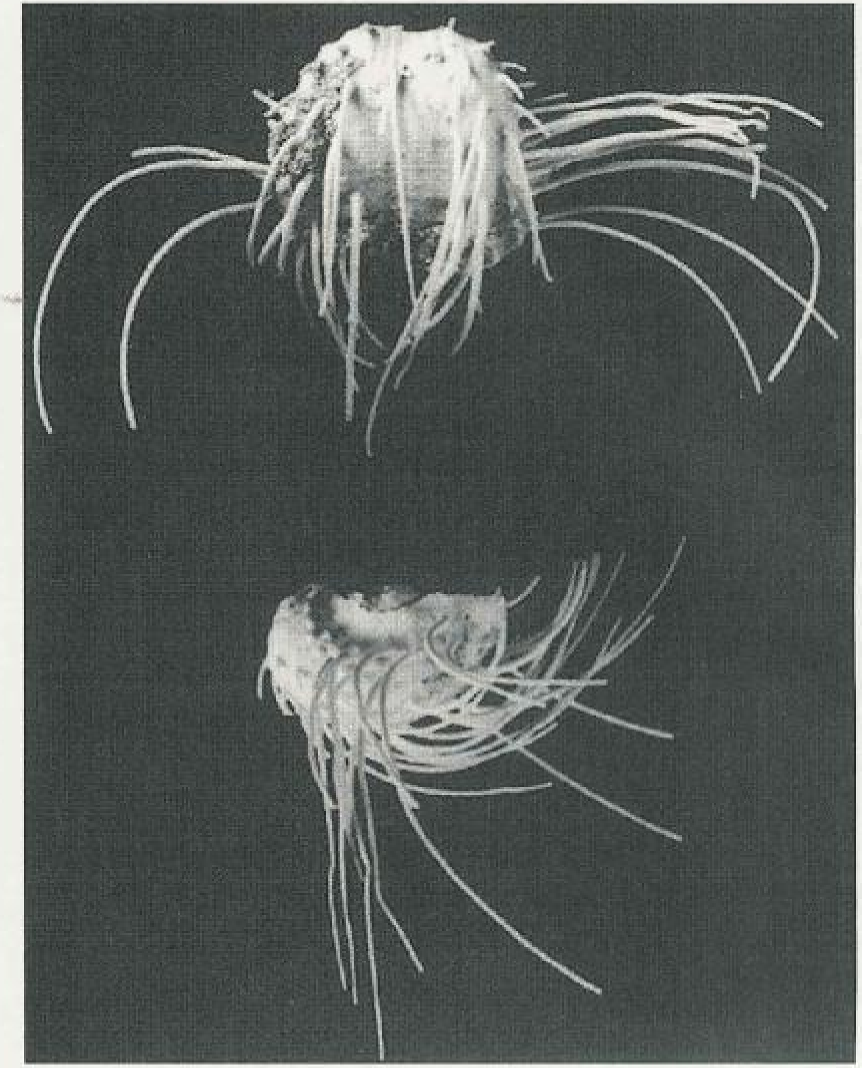
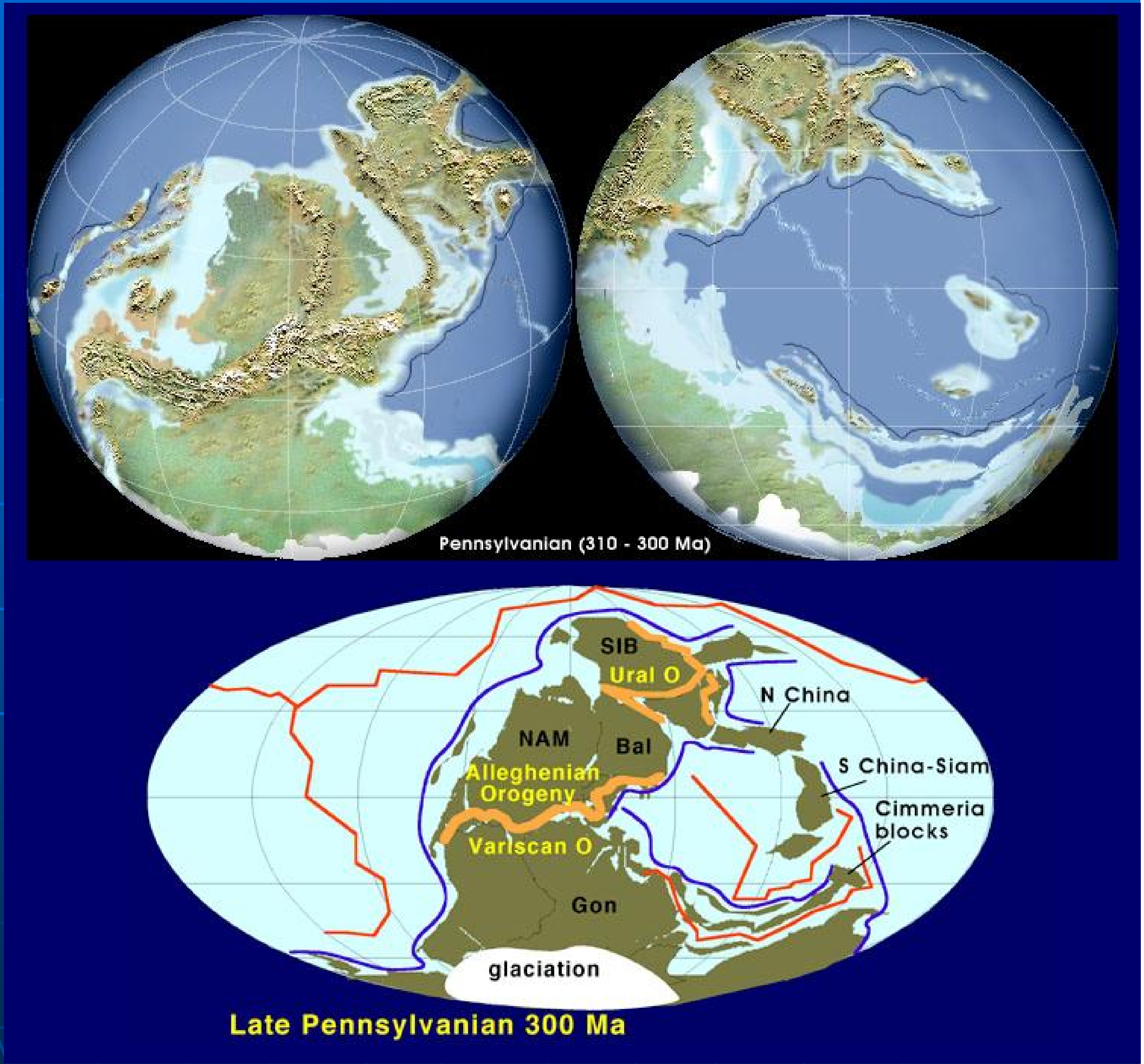
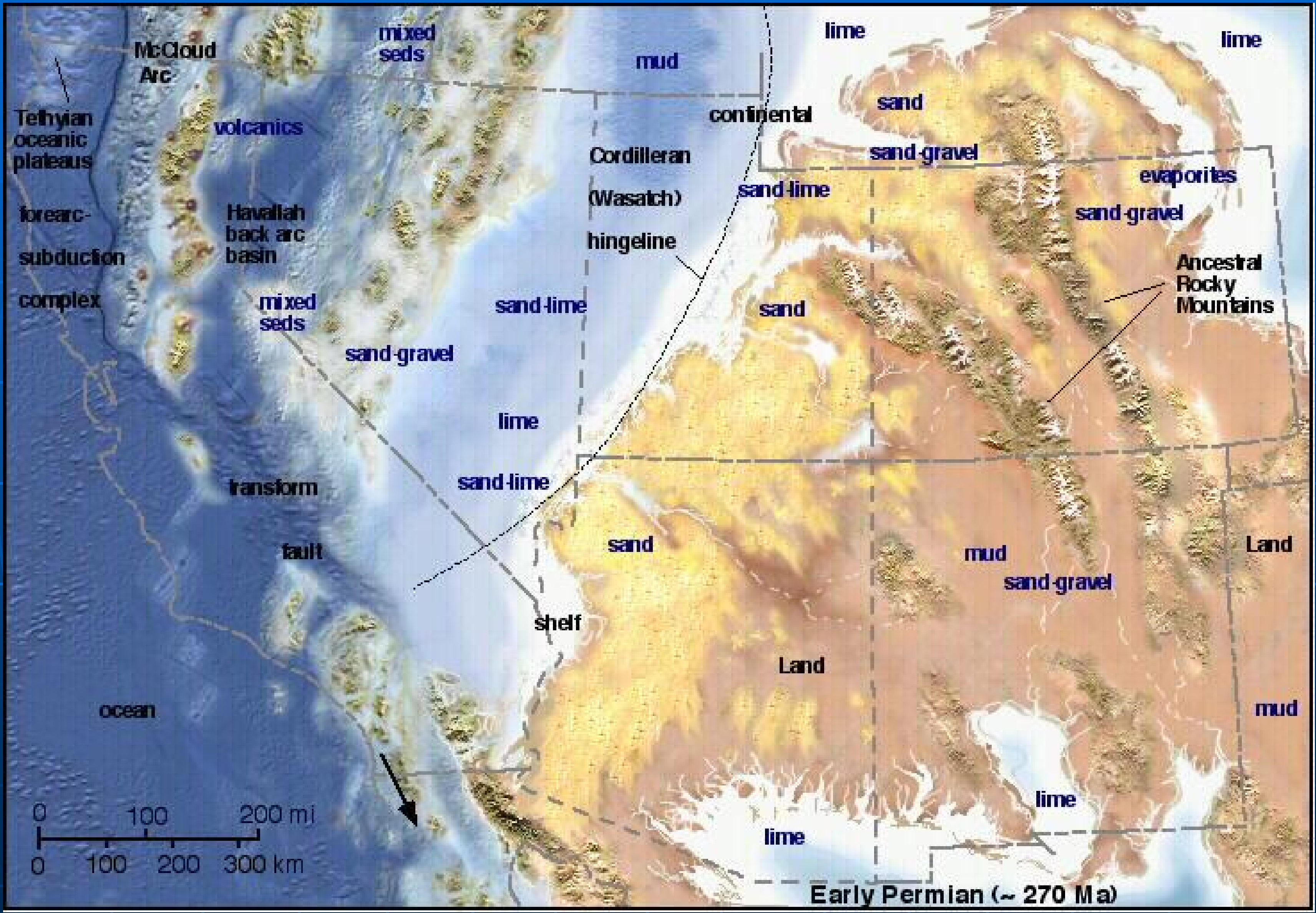


FIGURE 10-30 Ventral (upper photograph) and side (lower photograph) views of the Permian spinose productid brachiopod *Marginifera ornata* from the Salt Range of West Pakistan. Valves (not including spines) are about 2 centimeters wide. (*Courtesy of R. E. Grant, U.S. Geological Survey.*) ? *What was the probable purpose or function of the spines?*

Pennsylvanian paleogeography globes



Permian (290-248 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Dimetrodon

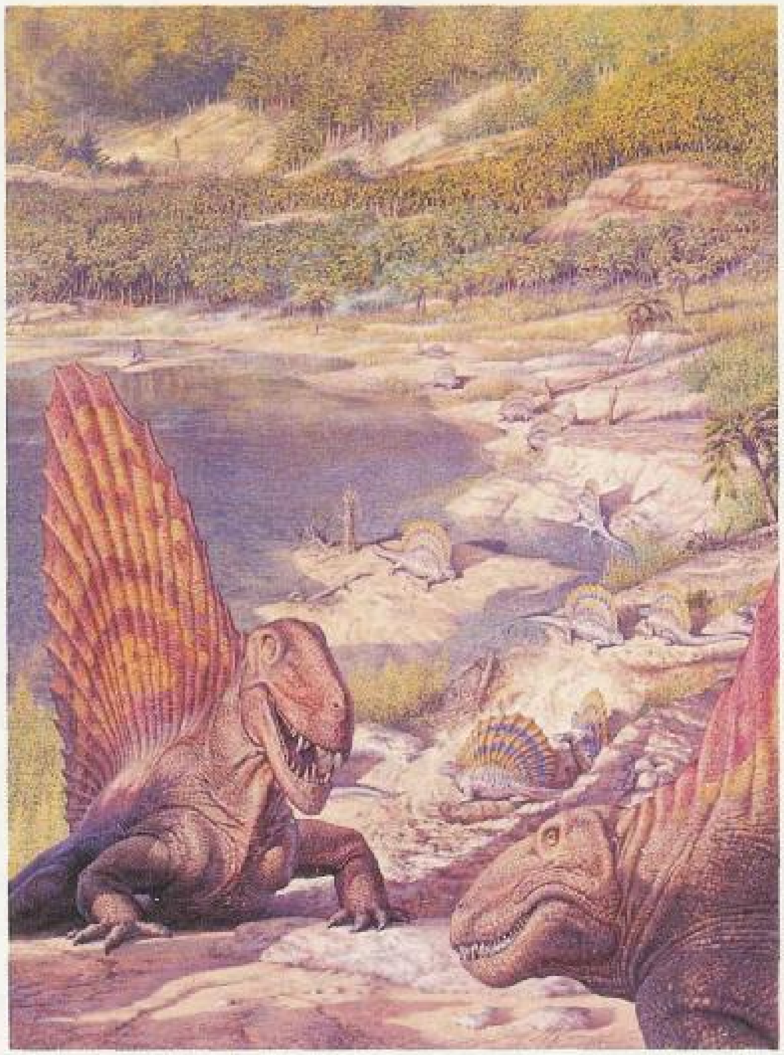


FIGURE 10-78 **Permian reptiles.** The prominent sailback reptile in the left foreground, with a larger skull and daggerlike teeth, is the carnivore *Dimetrodon*. The sailbacks with smaller heads and blunt cheek teeth, in the foreground at right and in the distance, are plant-eaters of the genus *Edaphosaurus*.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

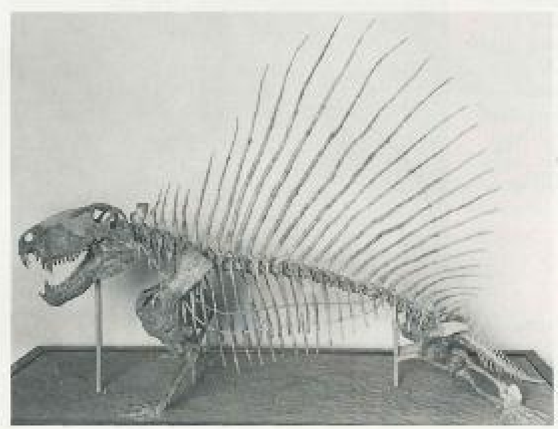


FIGURE 10-79 **Mounted skeleton of the Permian "sail-reptile"** ***Dimetrodon gigas.*** *(Courtesy of the U. S. National Museum of Natural History, Smithsonian Institution.)*

Mammal-like reptile

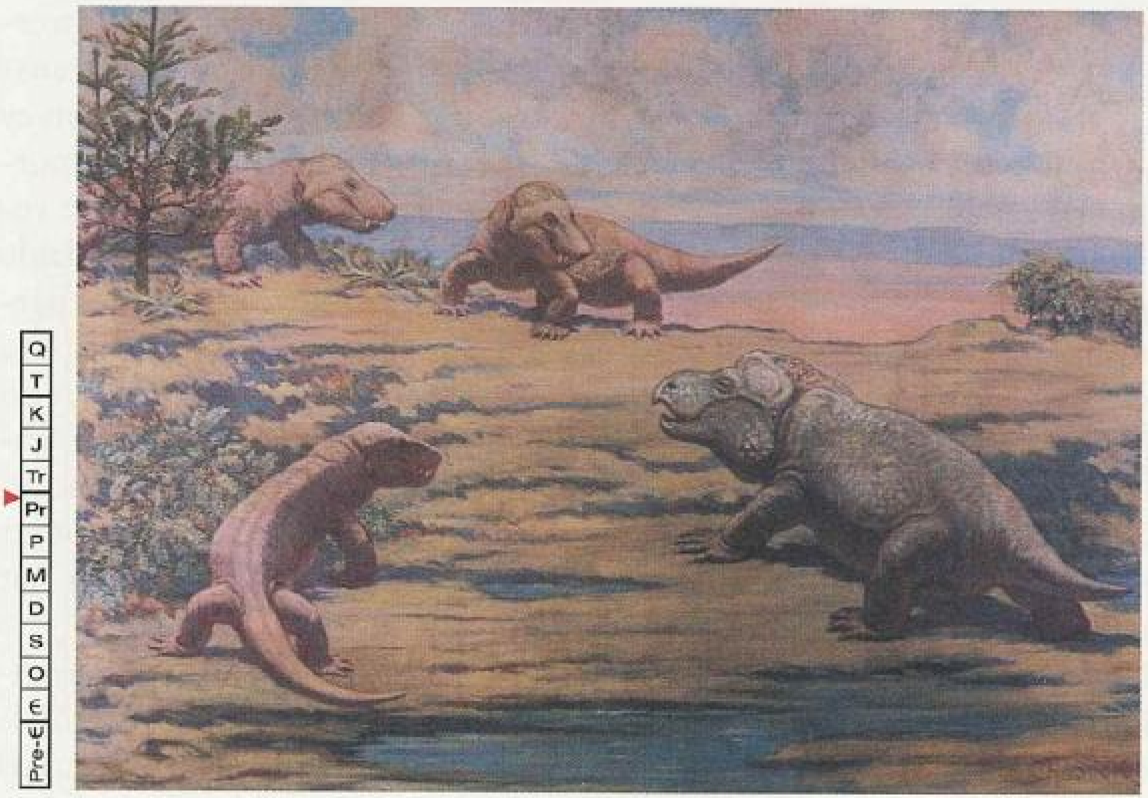
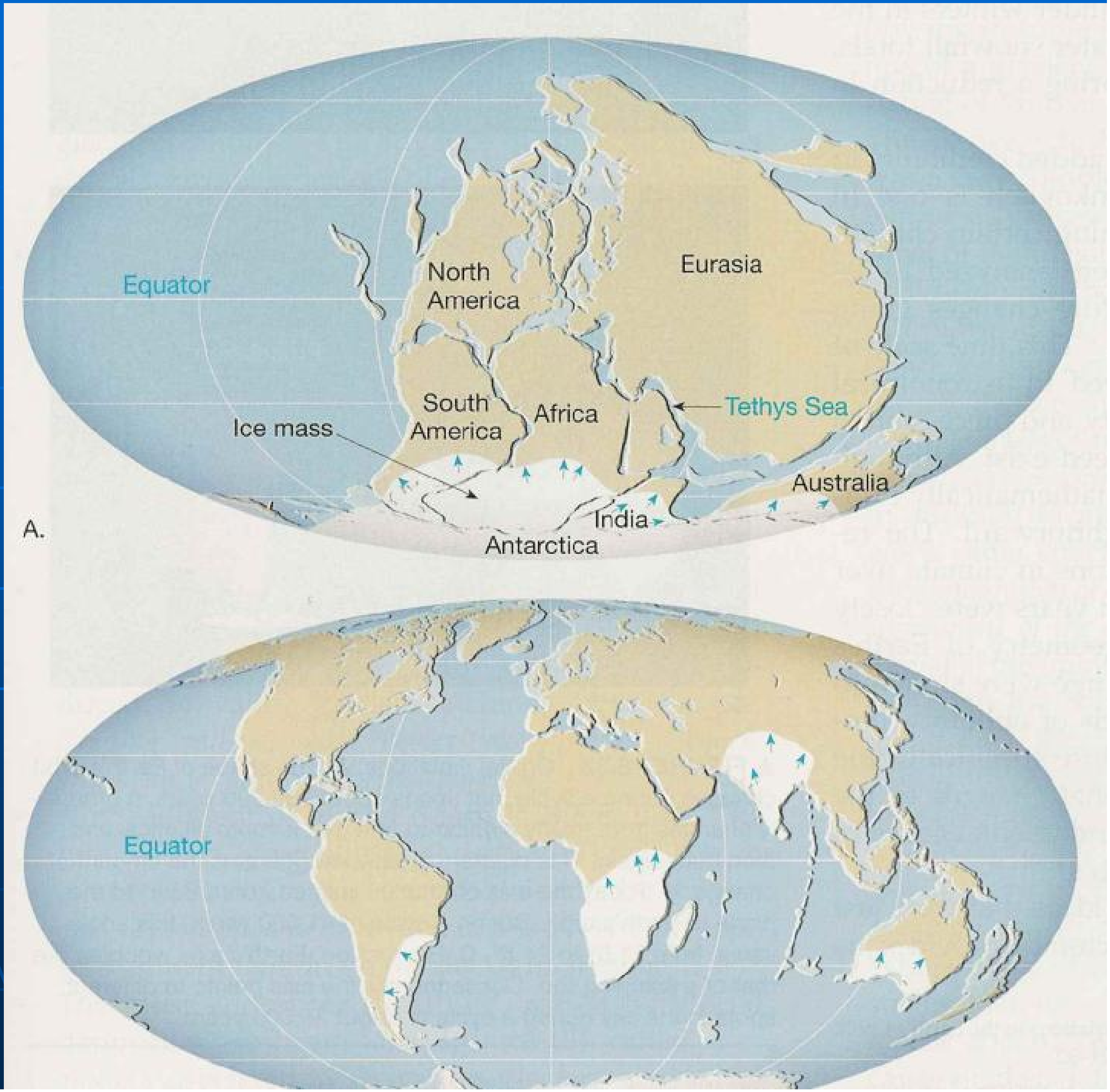


FIGURE 10-80 Mammal-like reptiles. The scene depicts three carnivorous forms (*Cynognathus*) about to attack a plant-eating therapsid reptile (*Kannemeyeria*). (*Courtesy of The Field Museum of Natural History, Chicago; painting by C. R. Knight.*)

Permian Ice Age



Permian paleogeography

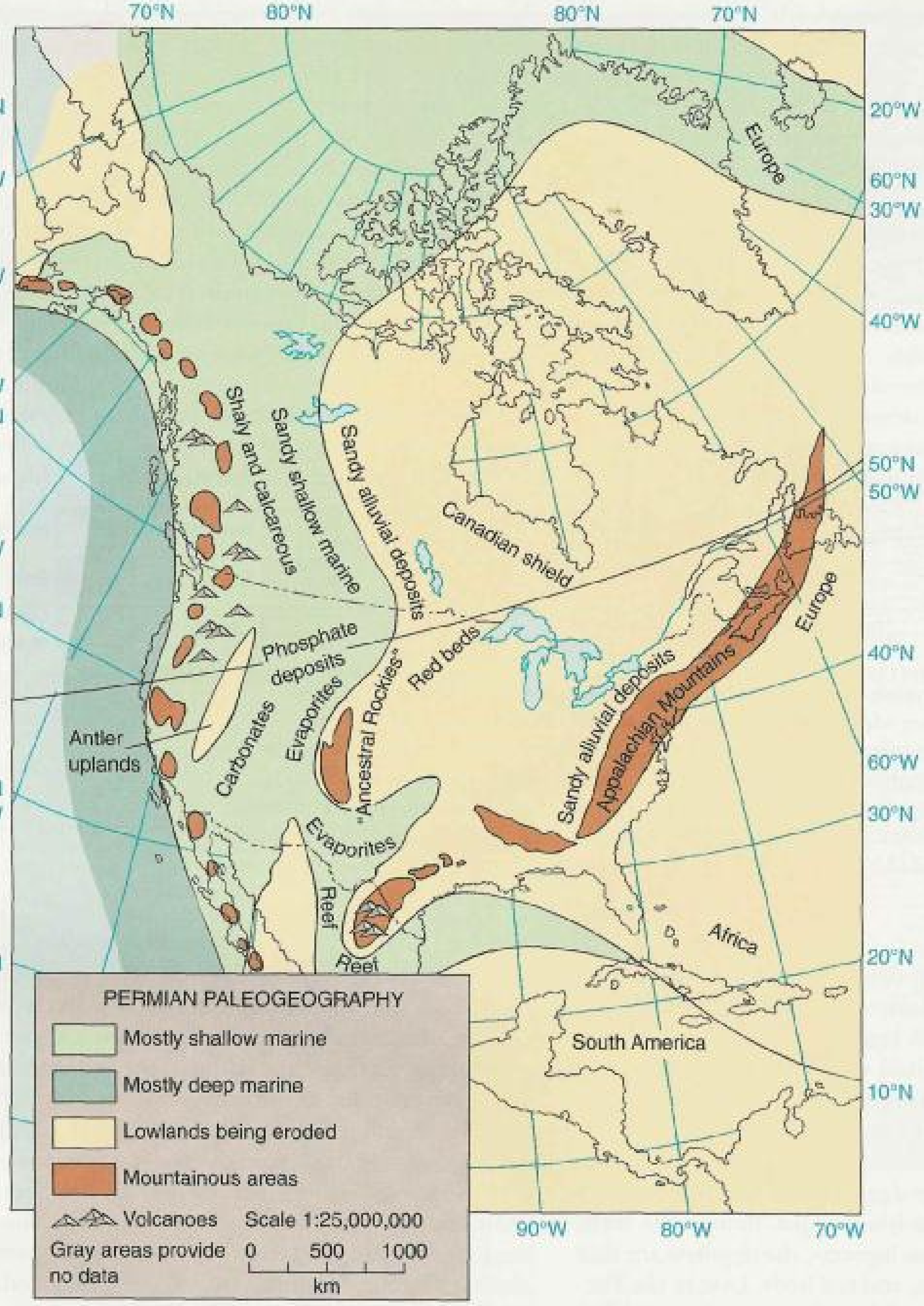
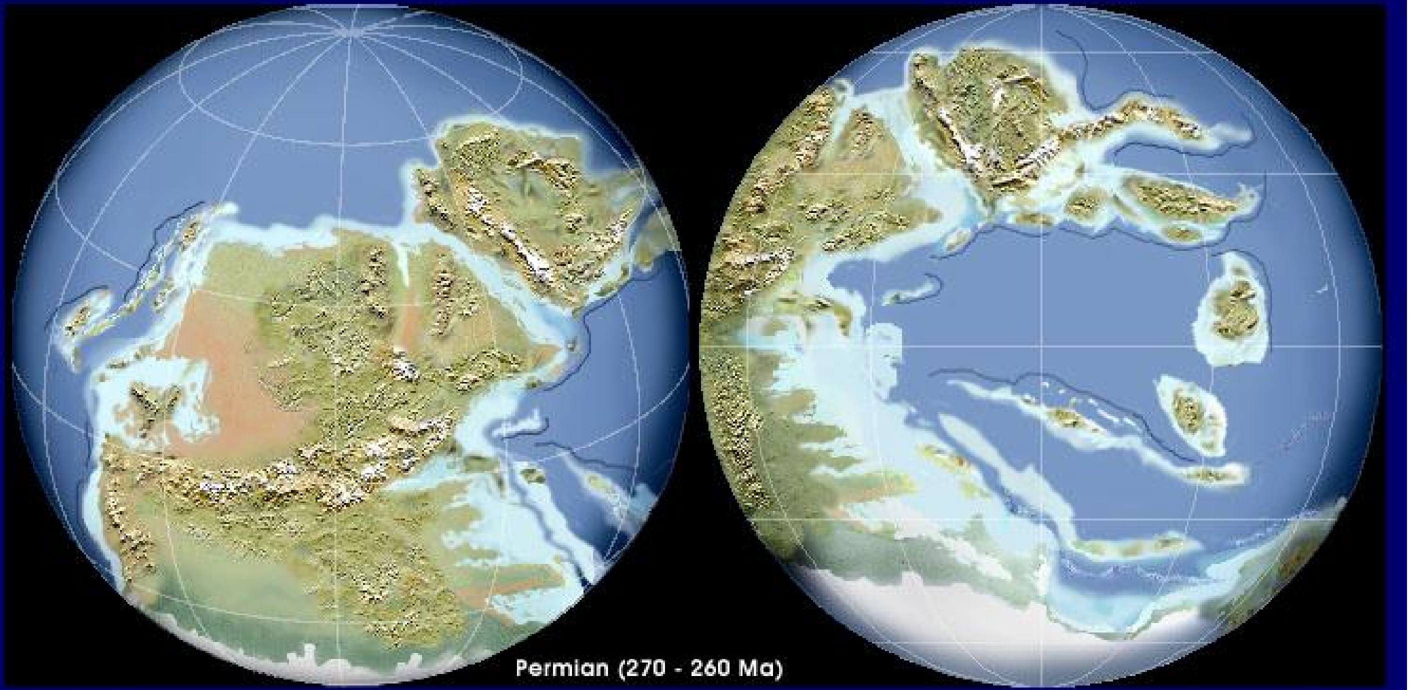
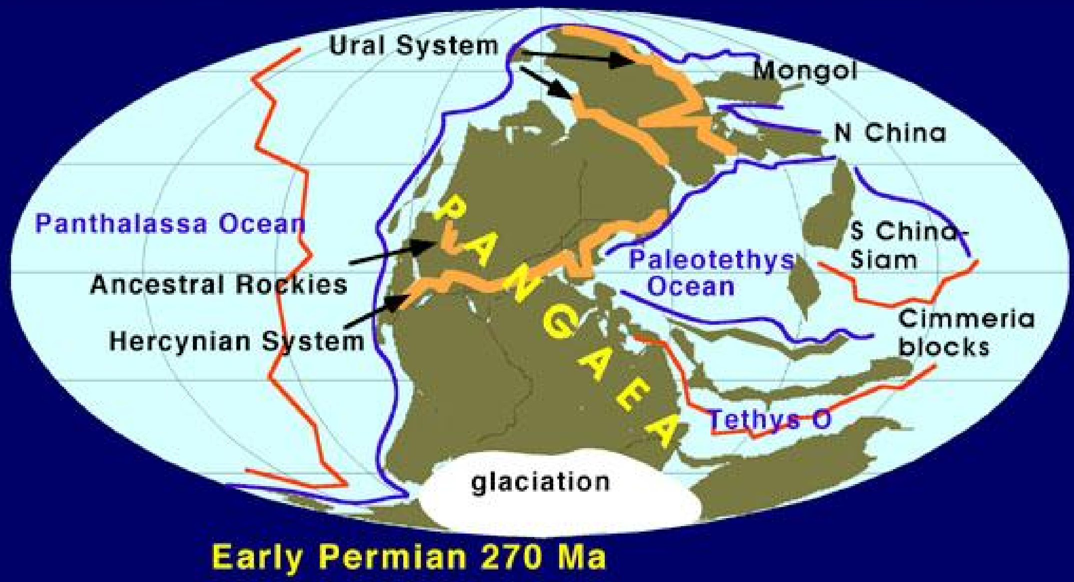


FIGURE 9-18 Generalized paleogeographic map for the Permian Period.

Permian paleogeography globes





extinctions

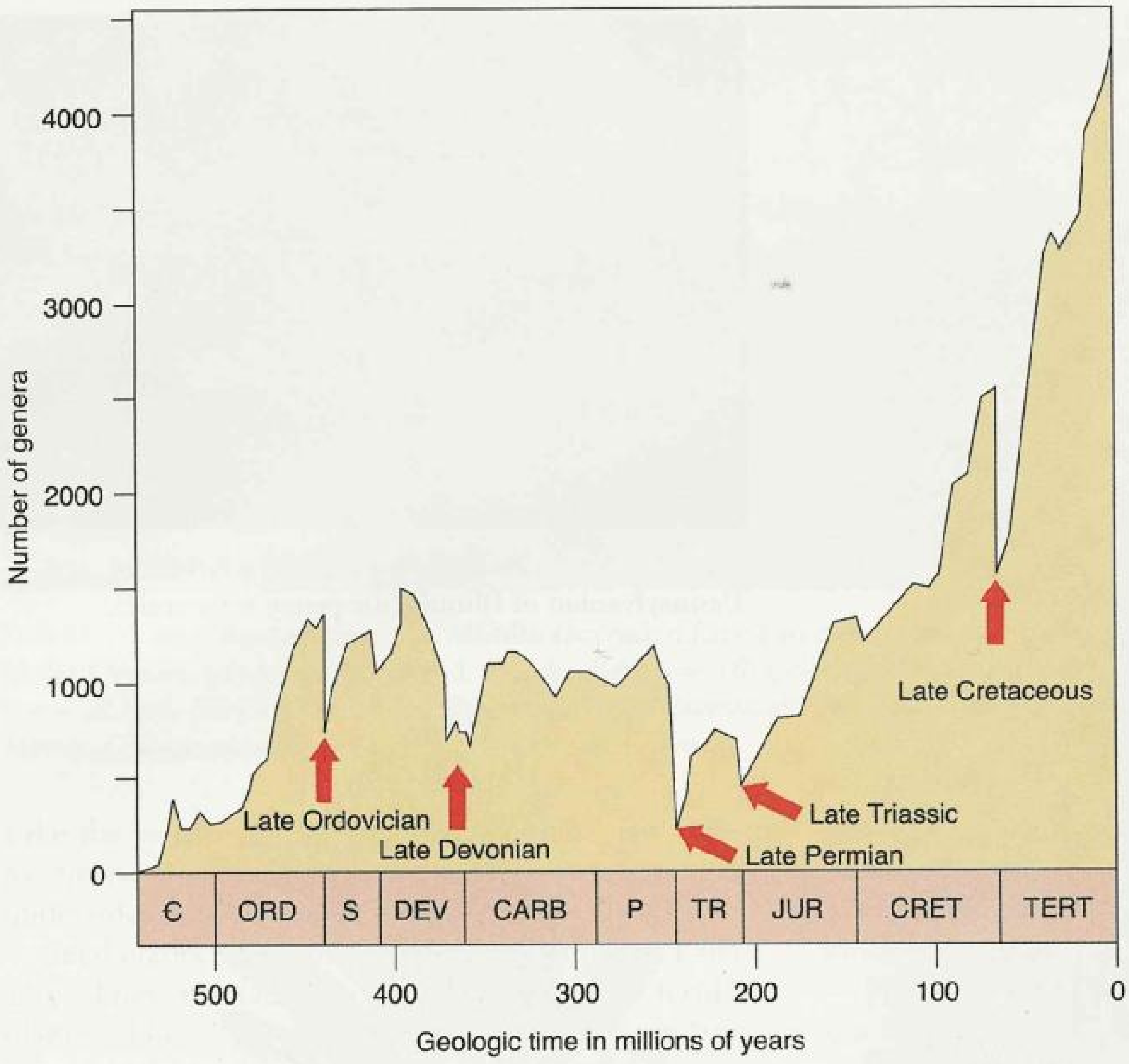
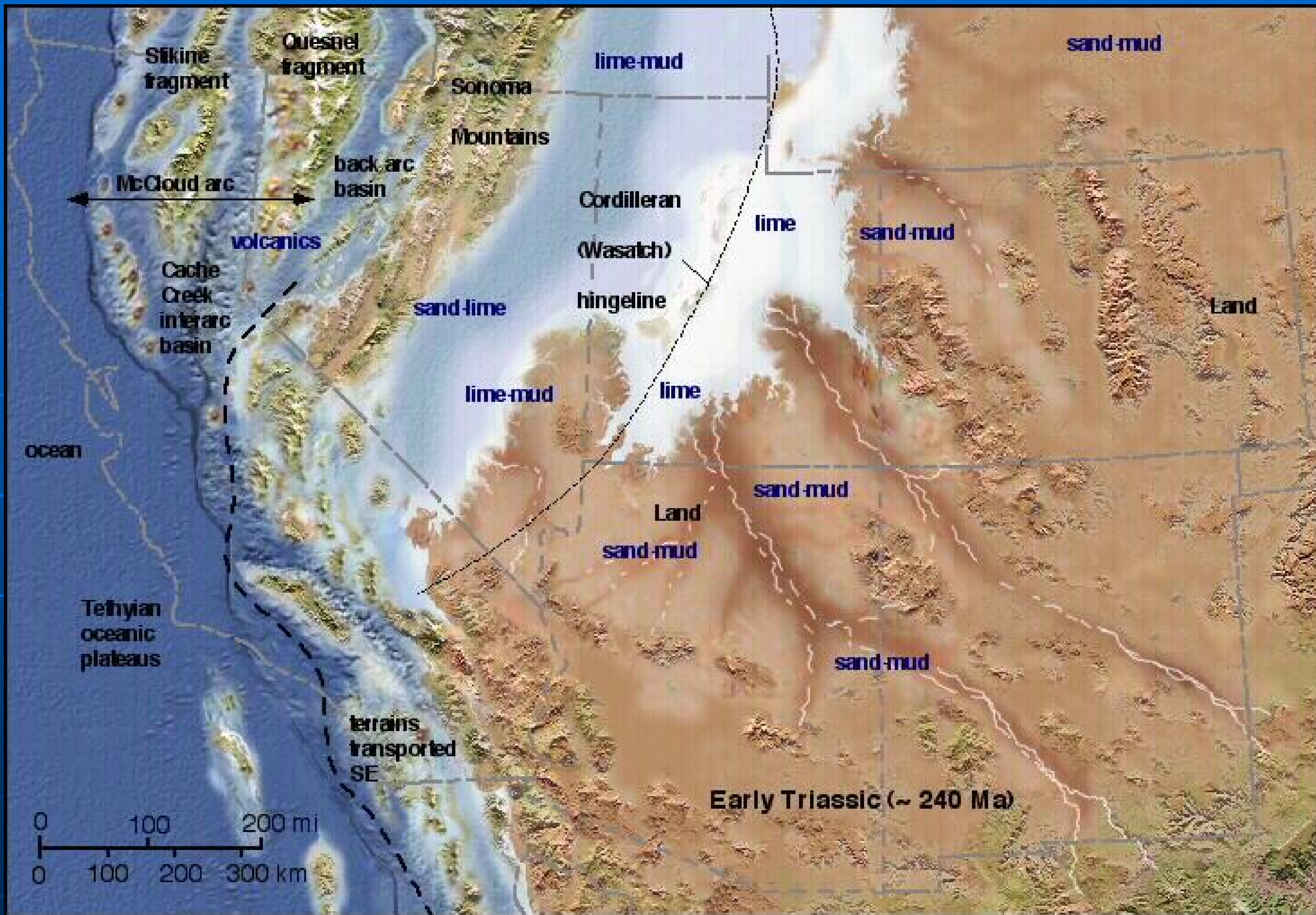


FIGURE 10-92 Diversity of marine animals, compiled from a database recording first and last occurrences of more than 34,000 genera. The graph depicts five major episodes of mass extinction (global extinctions over a short span of geologic time). (*Adapted from Sepkoski, J. J., Jr. 1994.* Geotimes *39(3):15–17.*)

Triassic (248-206 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Triassic plate tectonics

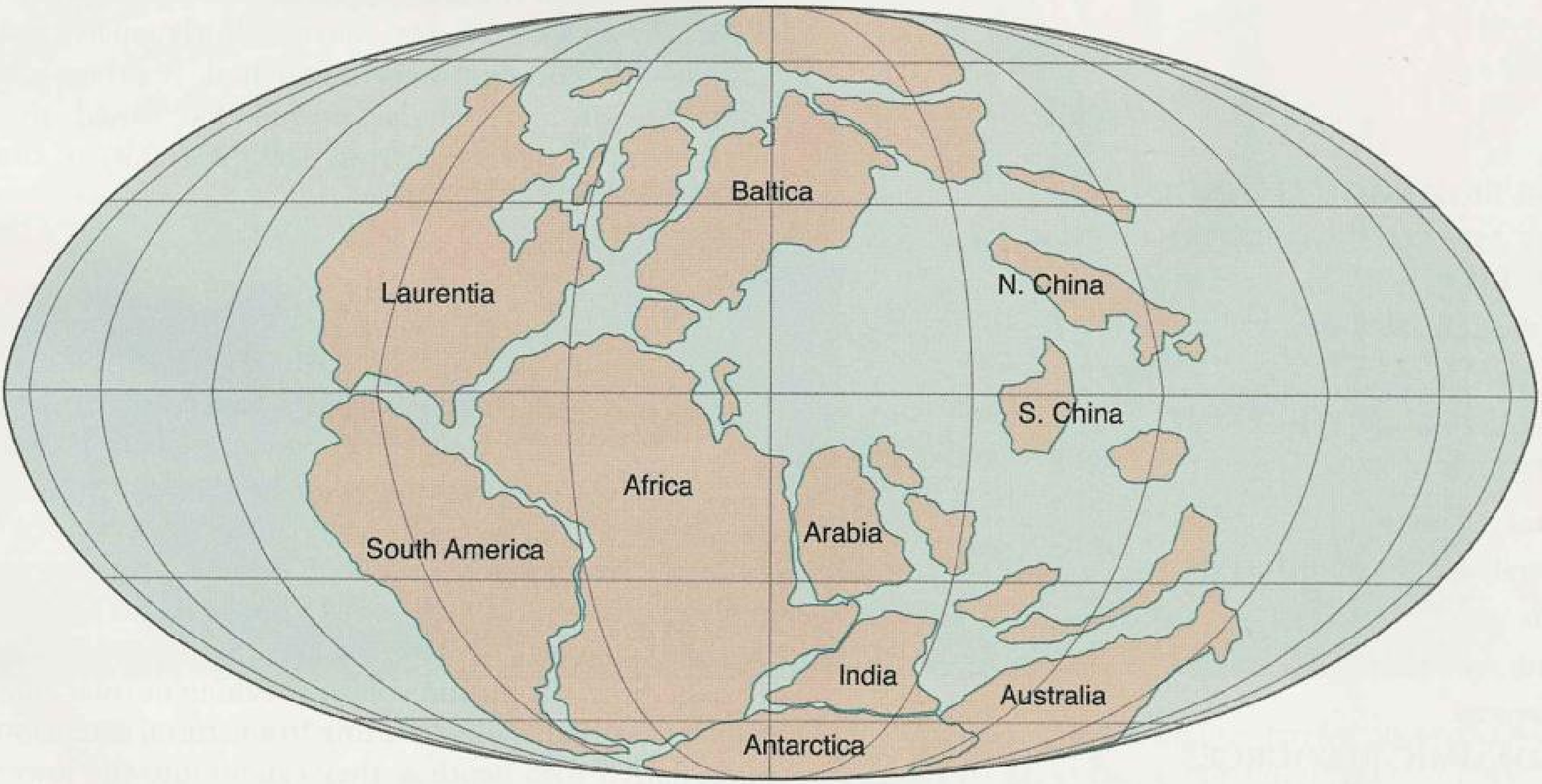


FIGURE 11–1 Paleogeographic reconstruction of the world about 180 million years ago, when the break-up of Pangea was beginning. (After Scotese, C. R. and McKerrow, W. S. 1990. Paleogeography and Biogeography, *Geol. Soc. London Mem. 12:1–21.*)

Triassic basins, E. U.S.

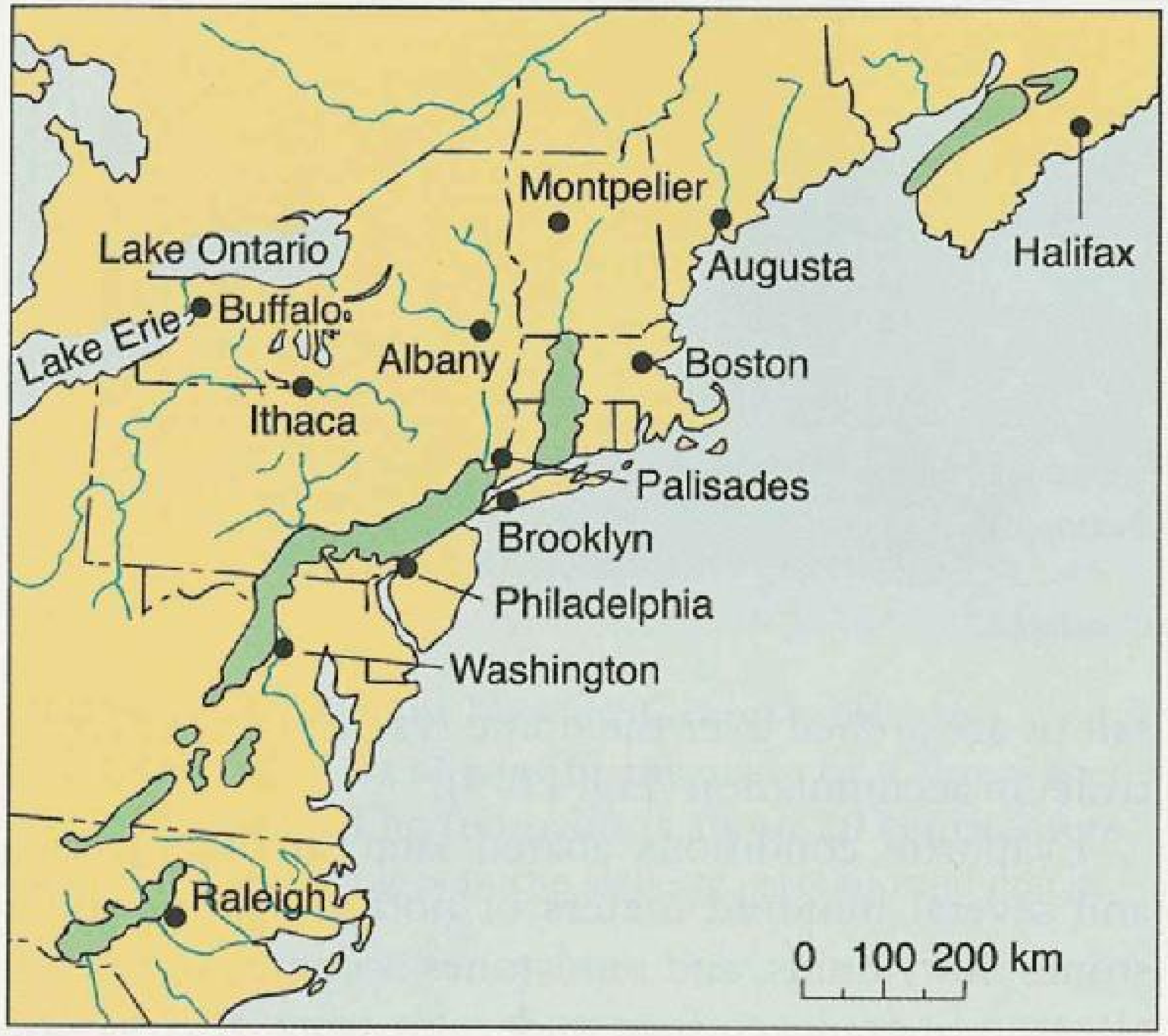


FIGURE 11–2 Outcrop areas of Triassic rocks in eastern North America. Green areas show troughlike deposits of Late Triassic age.

Petrified Forest

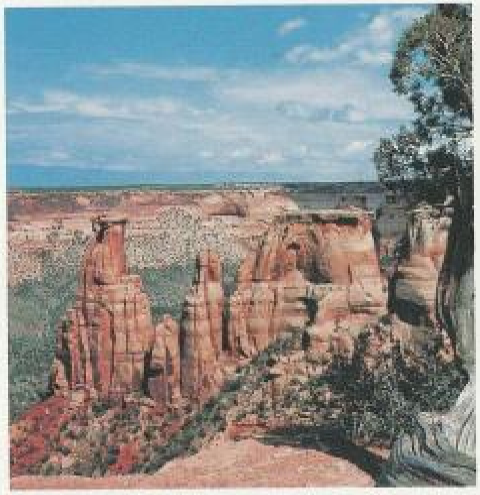


FIGURE 11-17 **The erosional features of the foreground are sculpted from the Lower Jurassic Wingate Sandstone, beneath which lies the red Chinle Formation. The cliffs in the far background are also Wingate Sandstone.** Colorado National Monument near Grand Junction, Colorado. (*Courtesy of R. J. Weimer, Colorado School of Mines.*)

sandy deposits transported by winds. (However, such so-called festoon cross-bedding is not always caused by winds, for submarine dunes may have similar form.)

The Painted Desert of Arizona is developed mostly in Chinle rocks (Fig. 11–18). The formation is known throughout the world for the petrified logs of conifers it contains. Each year, thousands of tourists examine these logs, now turned to colorful agate, in Petrified Forest National Park (Fig. 11–19). Apparently, during times of Triassic floods, the trees were left on sandbars or trapped in log jams and covered by sediment. Percolating solutions of underground water subsequently replaced the wood with silica.

JURASSIC TO EARLY TERTIARY TECTONICS Most of the orogenic activity in the Cordillera during the Mesozoic was a result of the continuing eastward subduction of oceanic lithosphere beneath the continental crust of the North American plate. That subduction varied in rate, in inclination, and, to a small degree, in direction. It resulted in eastward-shifting phases of deformation, which initially affected the far western part of the Cordillera and then proceeded eastward to reach the margin of the craton.

The deformational and magmatic activity associated with the western tract is termed the **Nevadan orogeny**. During the Triassic, and increasingly during the Jurassic and Cretaceous, graywackes, mudstones,

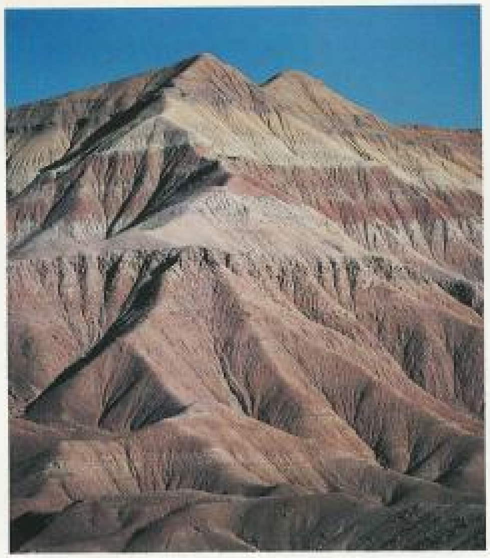


FIGURE 11-18 **Typical exposure of the Triassic Chinle Formation, Painted Desert, Arizona.** Some of the red bands represent ancient soils (paleosols). (*Photograph by J. Cowlin.*)

FIGURE 11-19 **Petrified logs, Petrified Forest National Park, Arizona.** The petrified logs and wood fragments are *Araucarioxylon*. They have been weathered from the Chinle Formation of Triassic age. (*Courtesy of L. F. Hintze.*)

Coelophysis

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*

Triassic reptiles

FIGURE 12-16 ***Hesperosuchus*** **from the Triassic of the southwestern United States.** Adult *Hesperosuchus* was about 4 feet long. (*Illustration by Carlyn Iverson.*)

the trend toward similar form in unrelated organisms is called **convergence**. Phytosaurs and crocodiles are good examples of evolutionary convergence. Indeed, the most visible distinction between the two groups is the position of the nostrils, which are at the end of the snout in crocodiles but were just in front of the eyes in phytosaurs. Phytosaurs were among the largest land animals of the Triassic. Some attained lengths of 11 meters (about 35 feet).

The Dinosaurs

Of all the vertebrates that have ever lived on this planet, few are more fascinating than the dinosaurs (Fig. 12–18). Dinosaurs are the most awesome and familiar of prehistoric beasts. As mentioned above, these headliners of the Mesozoic Era include two groups: the **Saurischia** (lizard-hipped) and the **Ornithischia** (bird-hipped). As suggested by these names, the

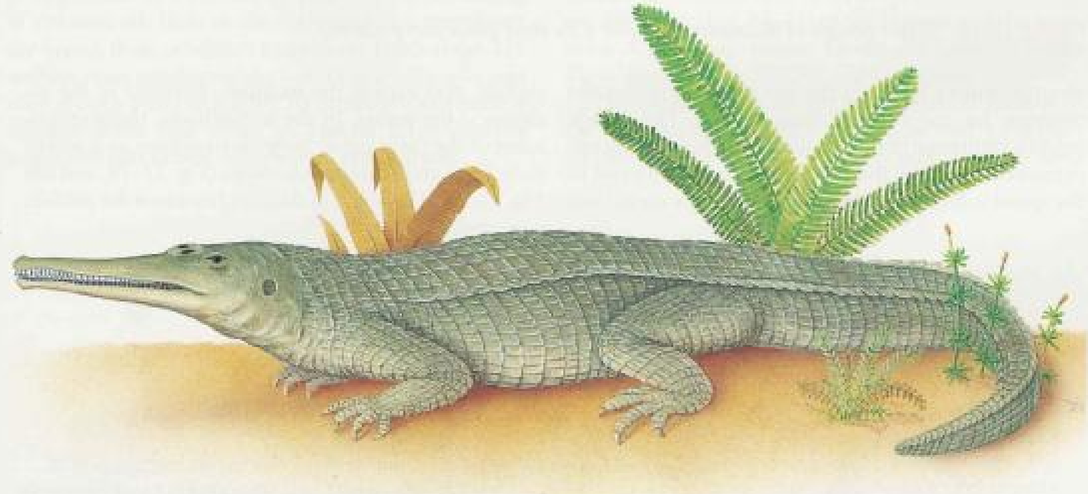


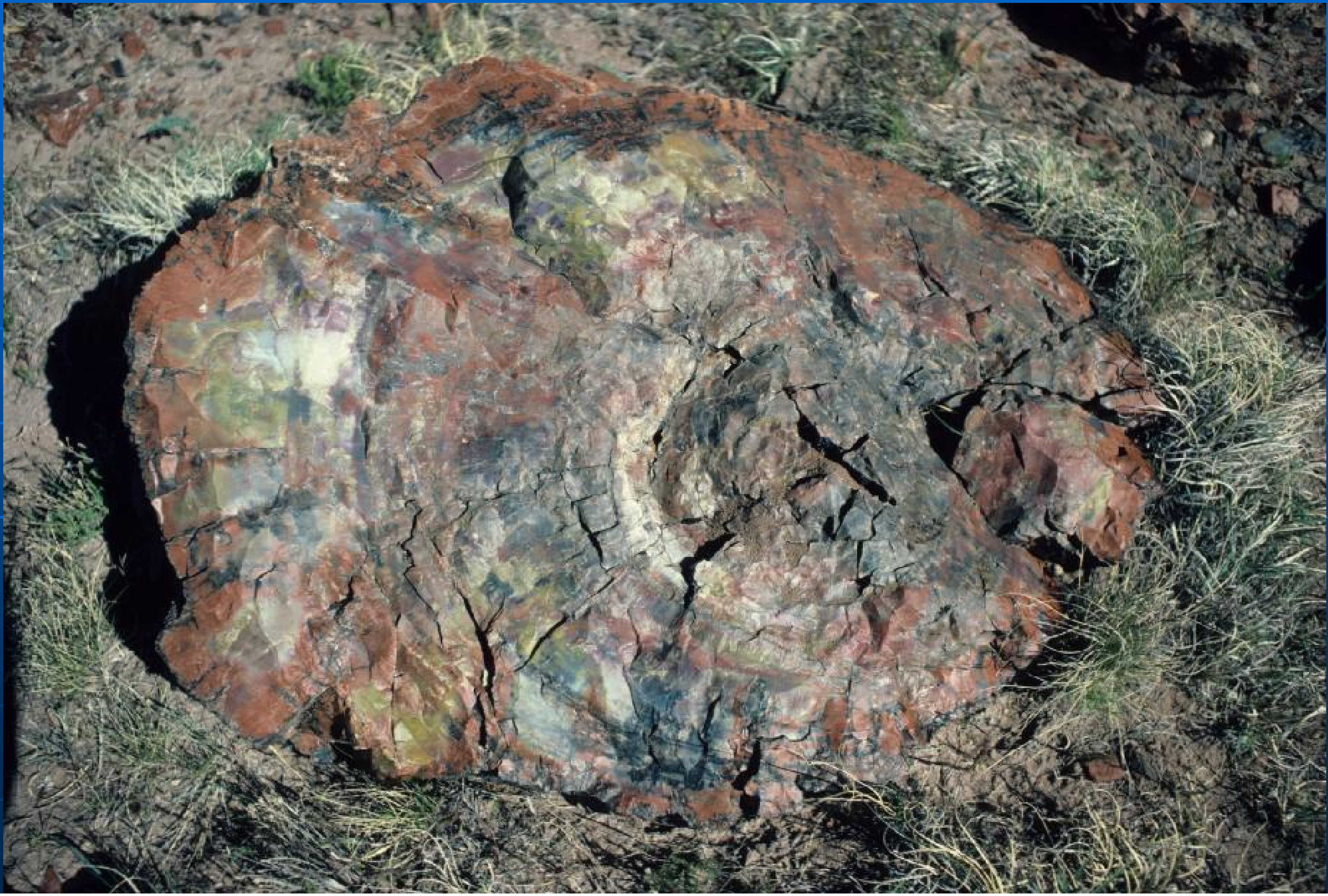
FIGURE 12-17 ***Rutiodon*, a Triassic phytosaur.** Like many other phytosaurs, *Rutiodon* grew to lengths of 10 or more feet. (*Illustration by Carlyn Iverson.*) ? *What living reptile is an example of convergent evolution with Rutiodon?*

Pet. For. Labyrinthodont teeth

phytosaur

Petrified Forest Fm.

Petrified Forest



Pet. For.
cycads

Recreation Redbeds – Tuc Mts

Triassic paleogeography

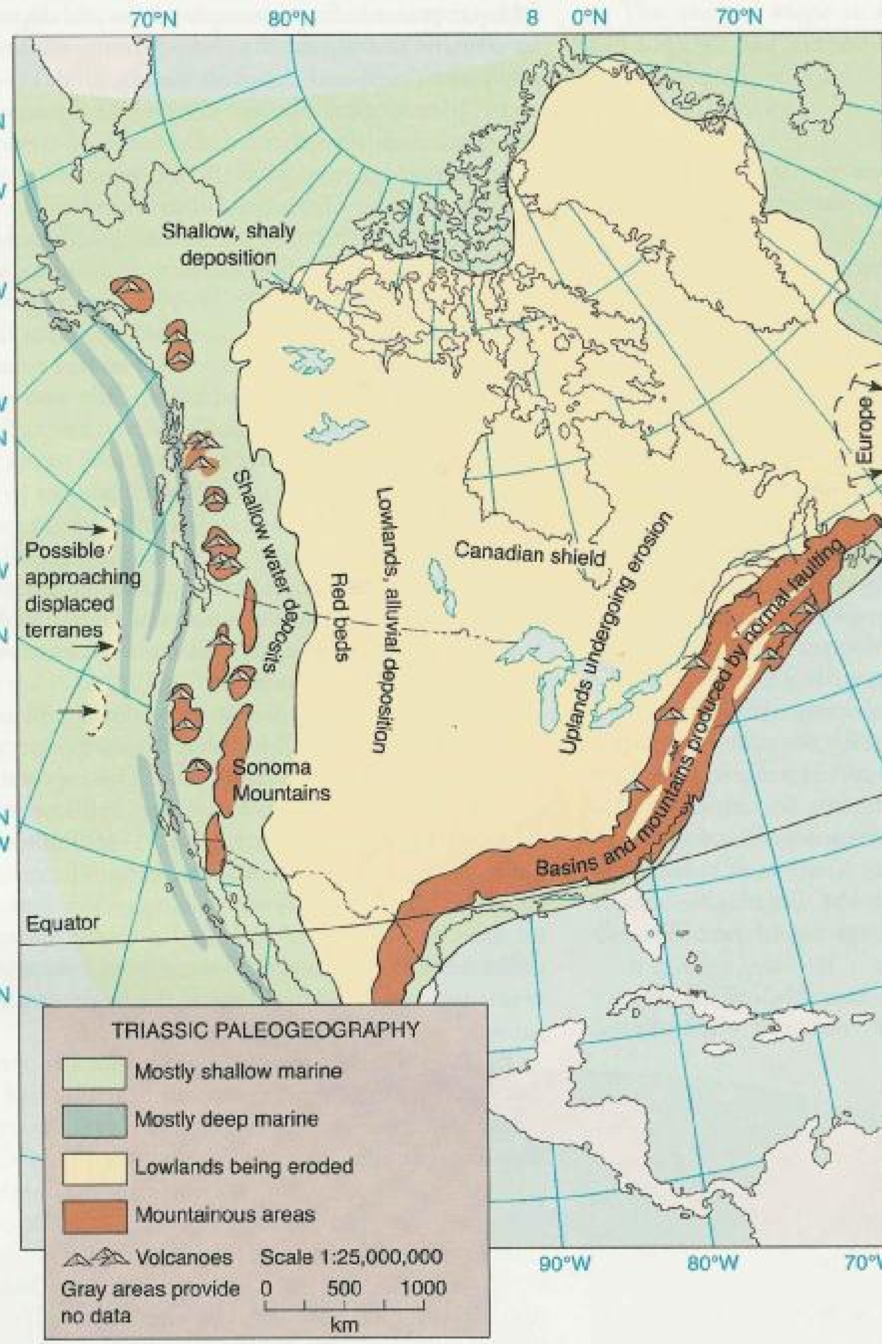


FIGURE 11–3 Generalized paleogeographic map for the Triassic of North America.
What was the cause of the faulting along the eastern margin of the continent?

Late Triassic

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Zuni sequence

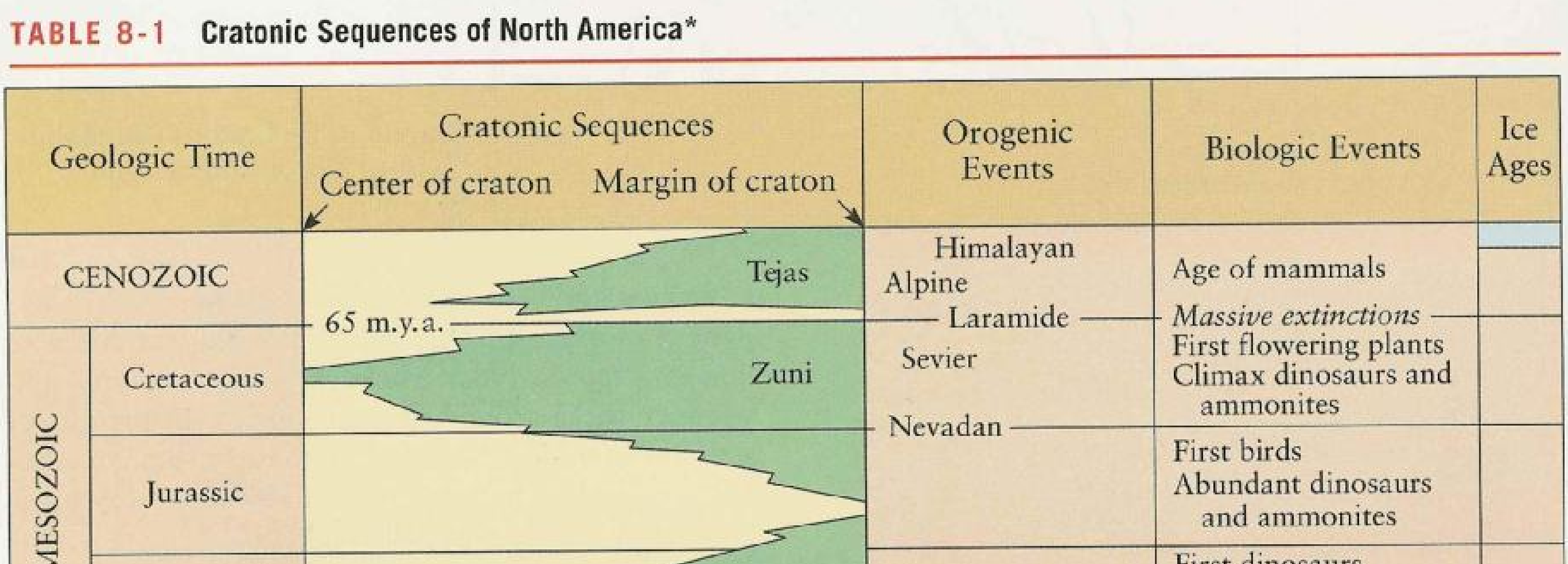
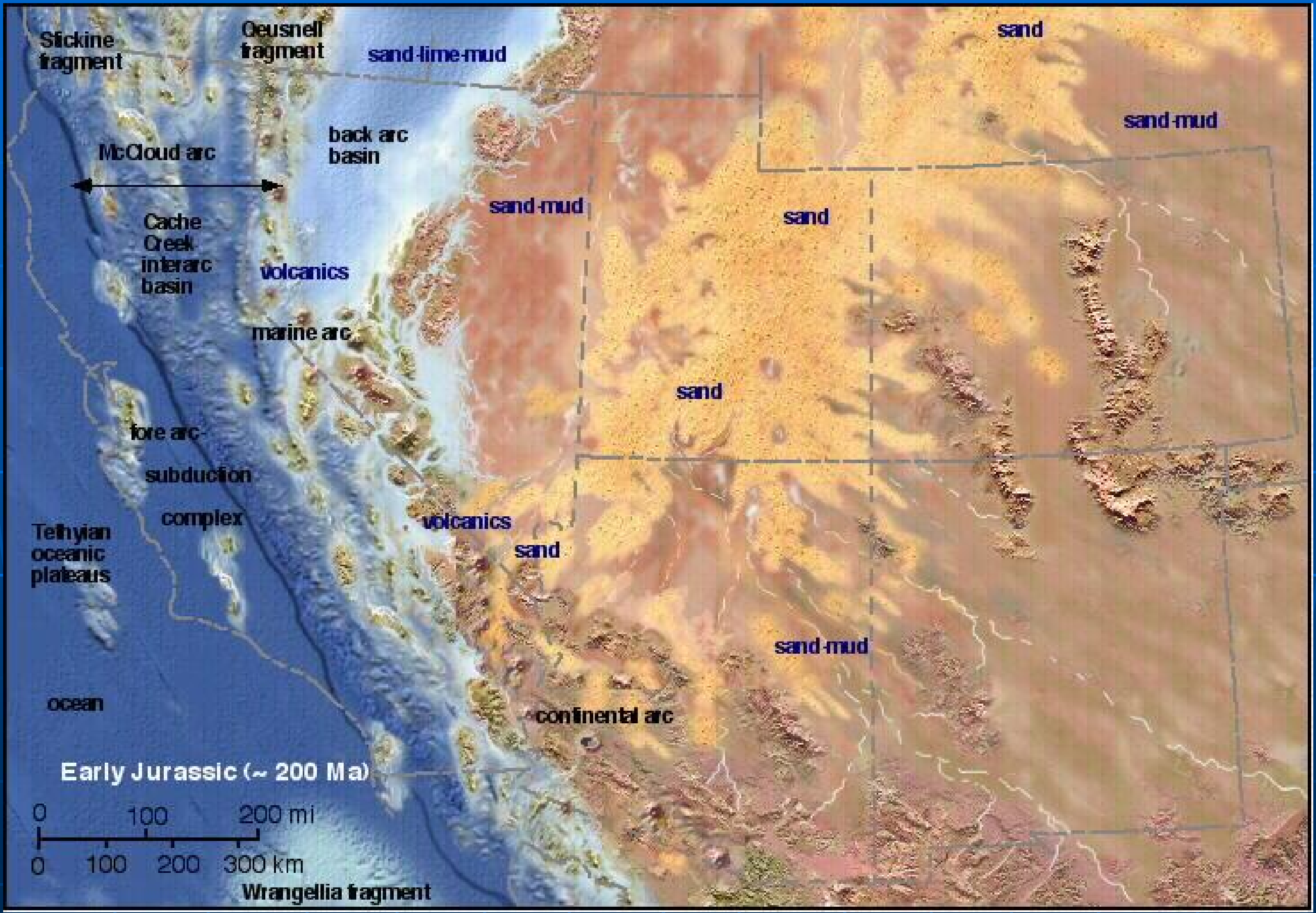


TABLE 8-1 Cratonic Sequences of North America*

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*	
MESOZOIC	Cretaceous	Zuni	Sevier	First flowering plants Climax dinosaurs and ammonites	
			Nevadan		
	Jurassic			First birds Abundant dinosaurs and ammonites	
				First dinosaurs	

Jurassic (206-144 Ma)



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Jurassic paleogeography

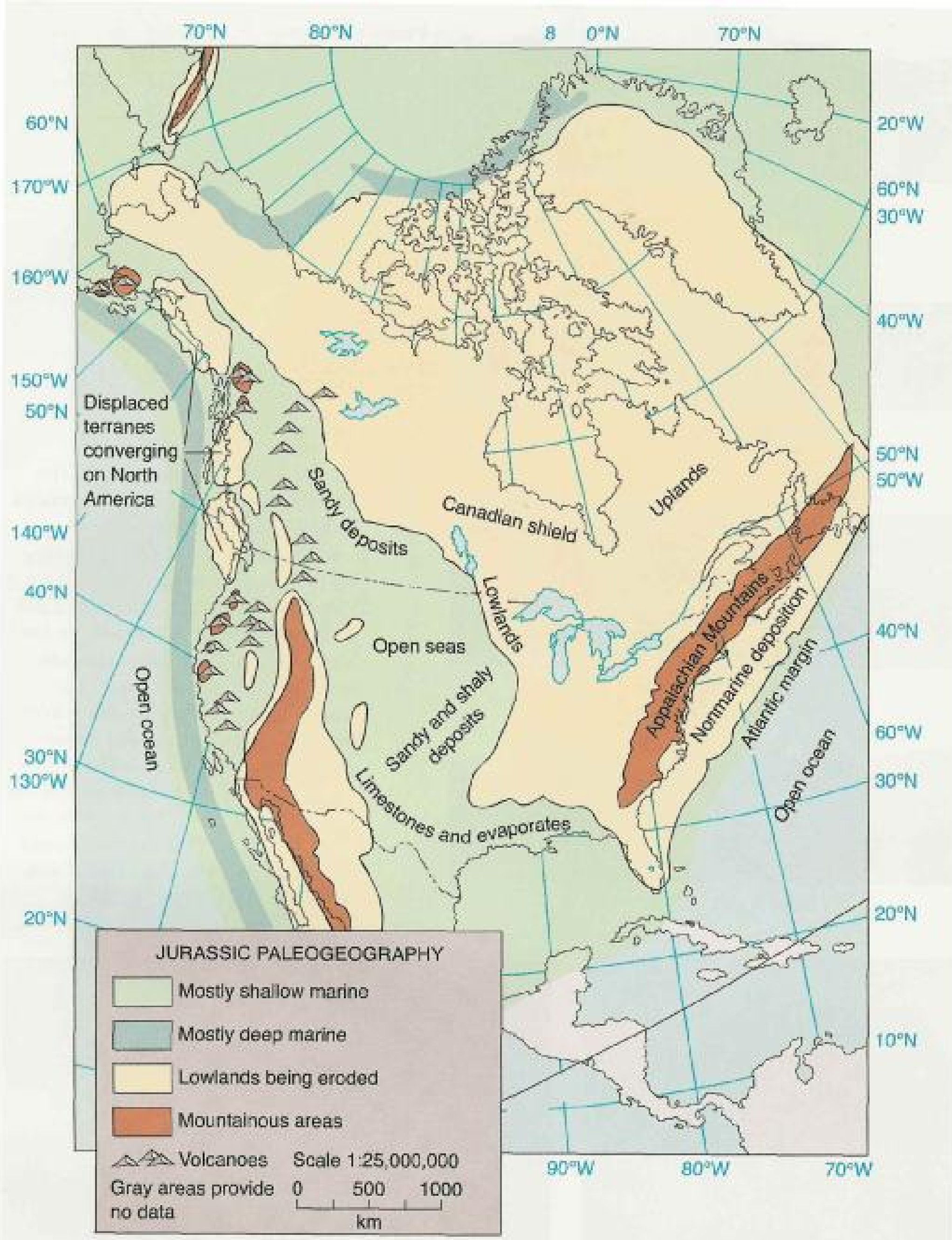


FIGURE 11–7 Generalized paleogeographic map for the Jurassic of North America.
Describe the conditions at the site of your school during the Jurassic Period.

Jurassic salt

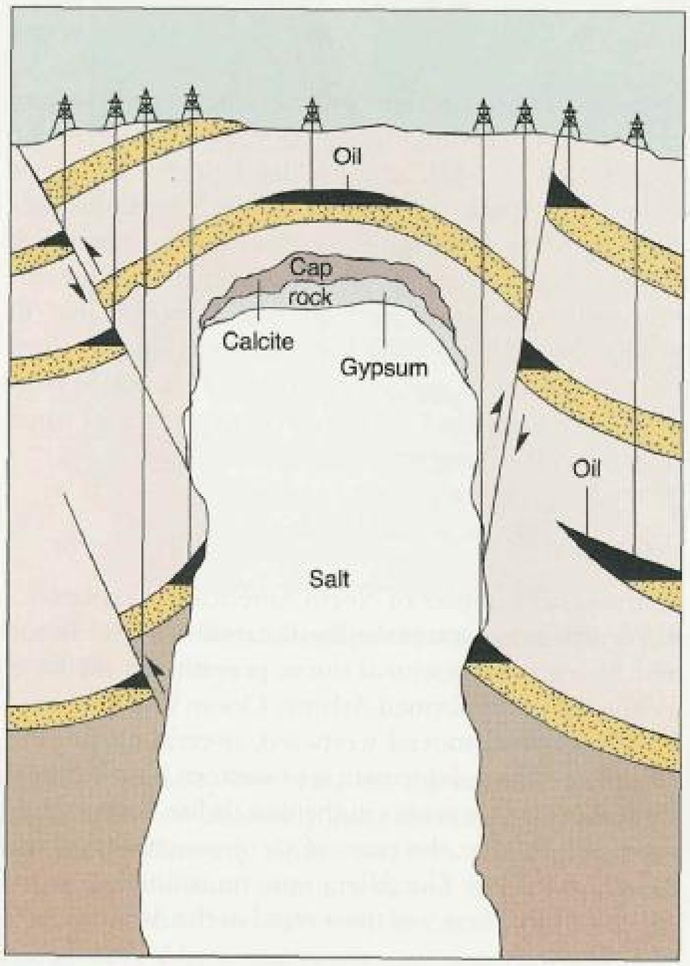


FIGURE 11-9 Salt dome, illustrating possibilities for oil entrapment in domelike structures (top center) by faults and by pinchout of oil-bearing strata.

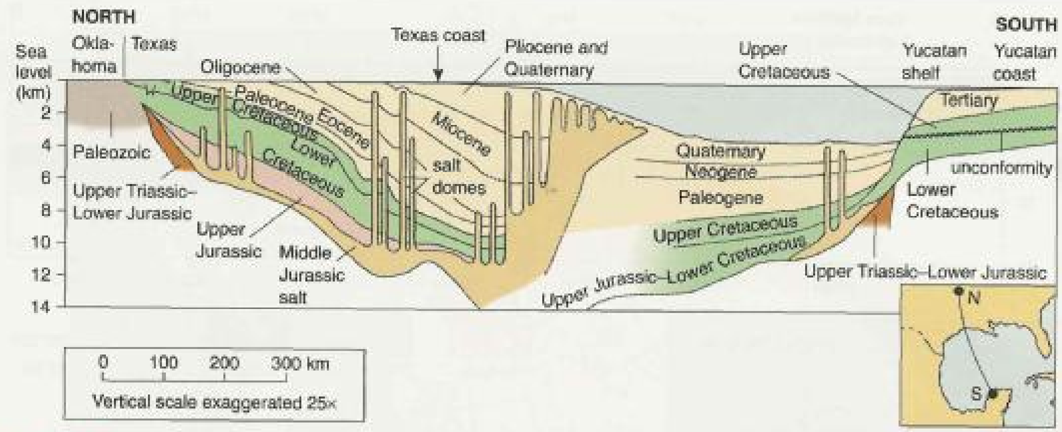
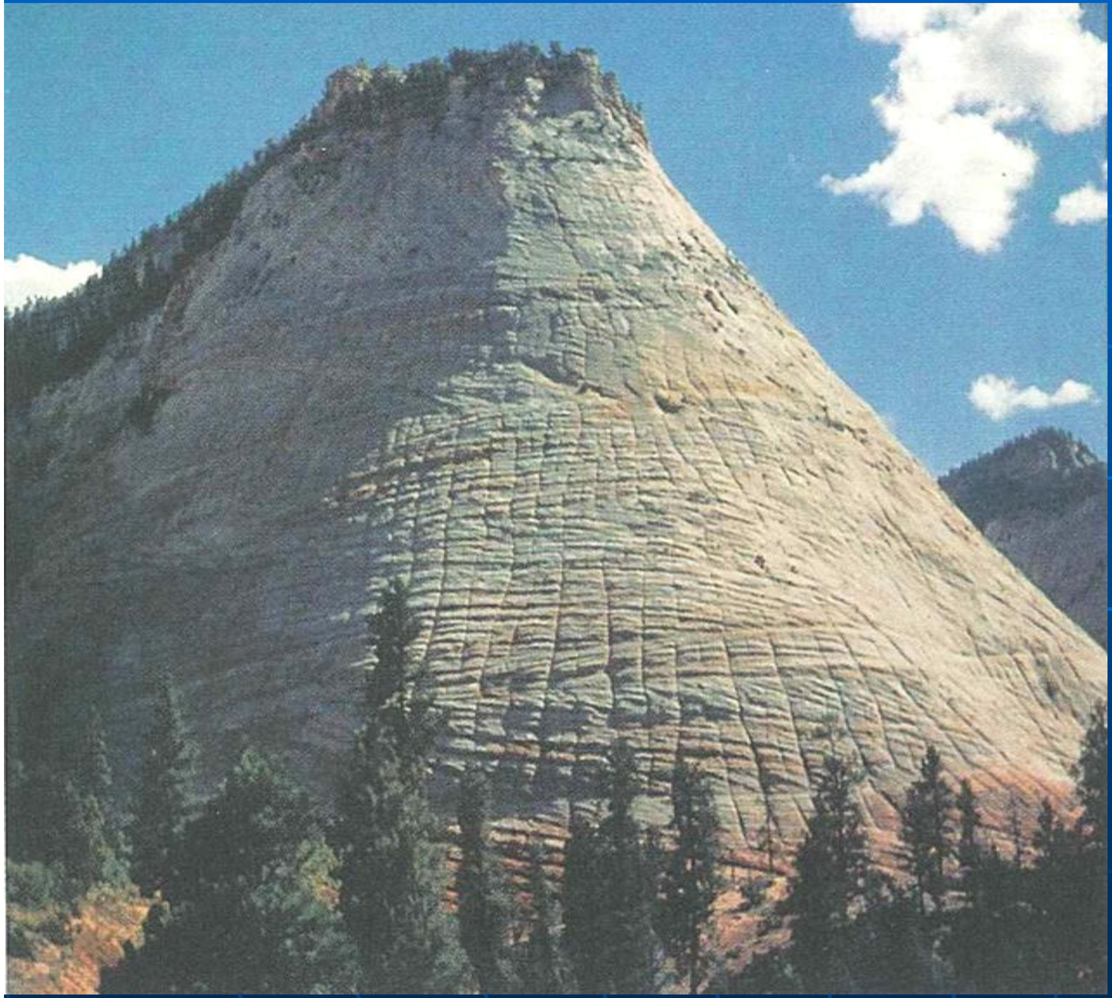


FIGURE 11-8 North–South cross-section of the Gulf of Mexico basin. *(Adapted from Salvadore, A. 1991. Geology of North America, pp. 1–12. Boulder, CO: Geological Society of America.)*

Navajo Sandstone



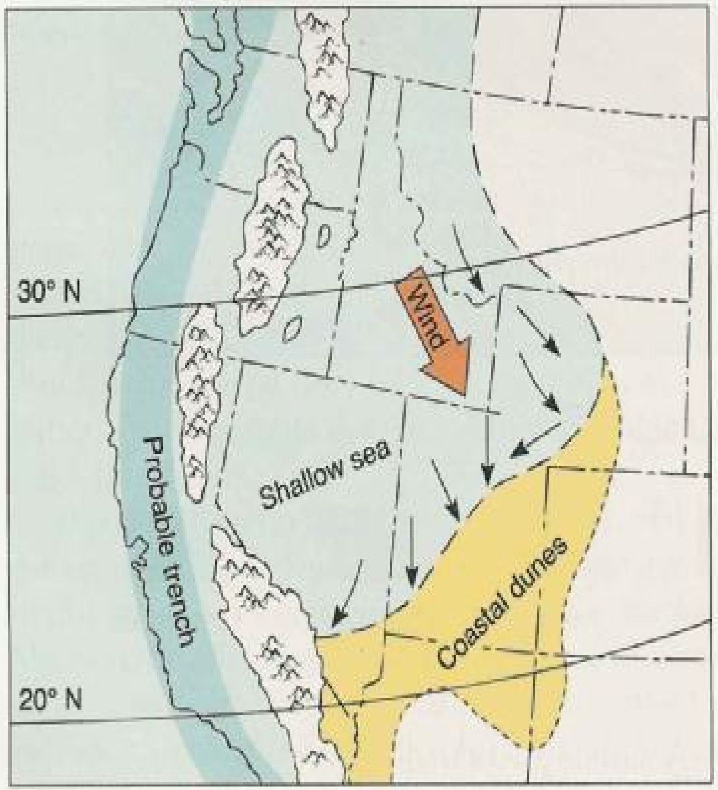
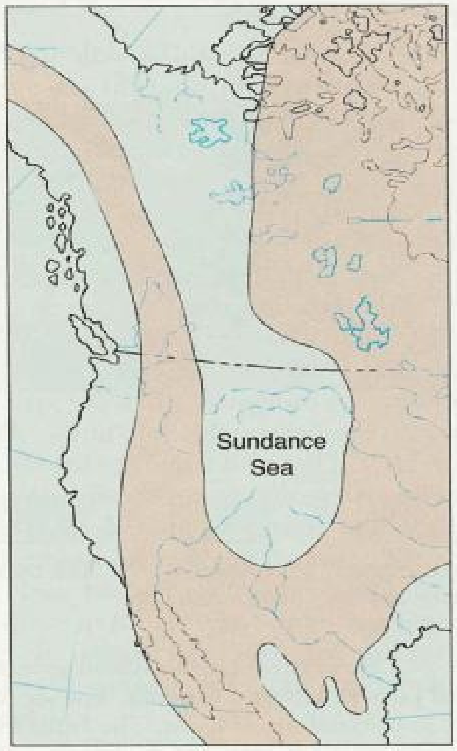


FIGURE 11-26 Paleogeographic map for the early Jurassic of the western United States, showing general extent of sea and land as well as paleolatitudes. (*From Stanley, K. O., Jordan, W. M., and Dott, R. H. 1971.* Bull. Am. Assoc. Petrol. Geol. 55(1):13.)

Jurassic volcanics Santa Rita Mts.

Middle Jurassic seaway



GURE 11-27 Region in the western North America undated by the Middle Jurassic Sundance Sea. (Land eas are shown in tan, marine areas in blue.)

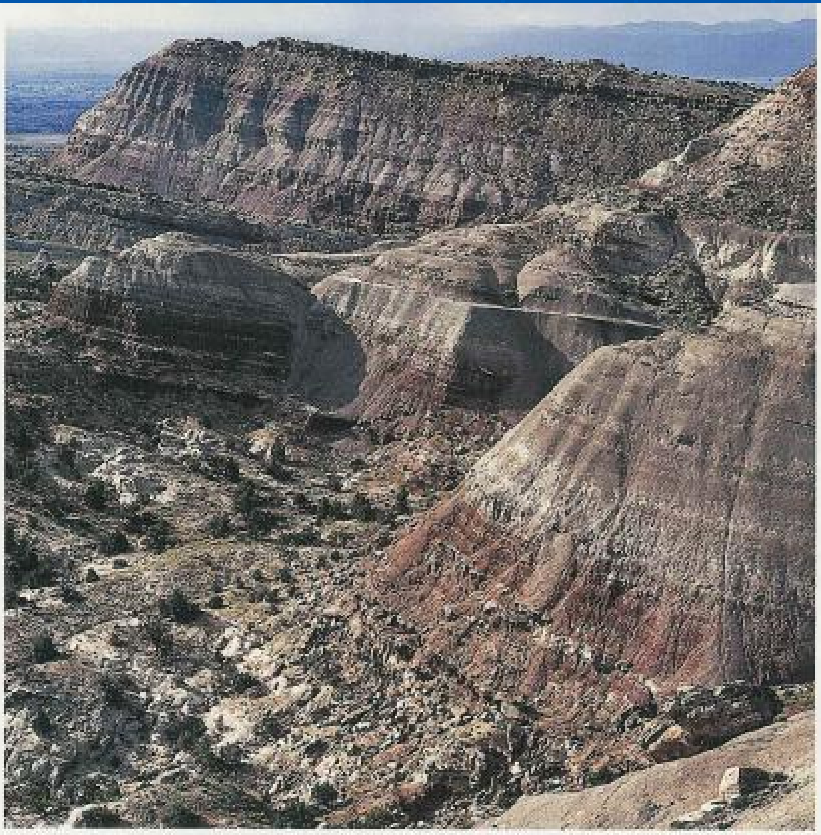


FIGURE 11-28 The Jurassic Morrison Formation near Grand Junction, Colorado. (*Copyright Francois Gohier/Photo Researchers, Inc.*)

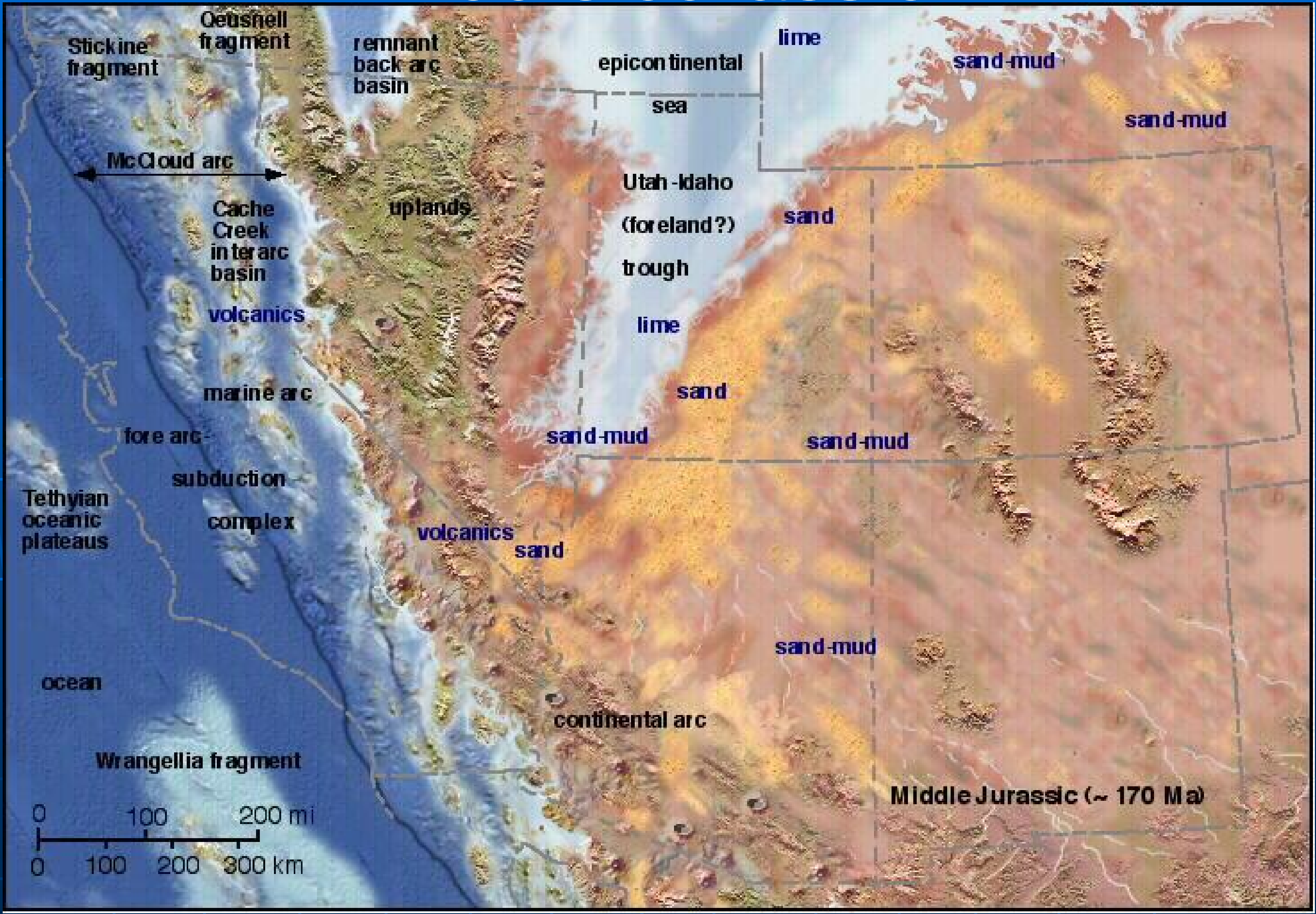
Jurassic tracks N.AZ

Vermilion Cliffs, N Az

Jurassic Stegosaurus

Rainbow Bridge

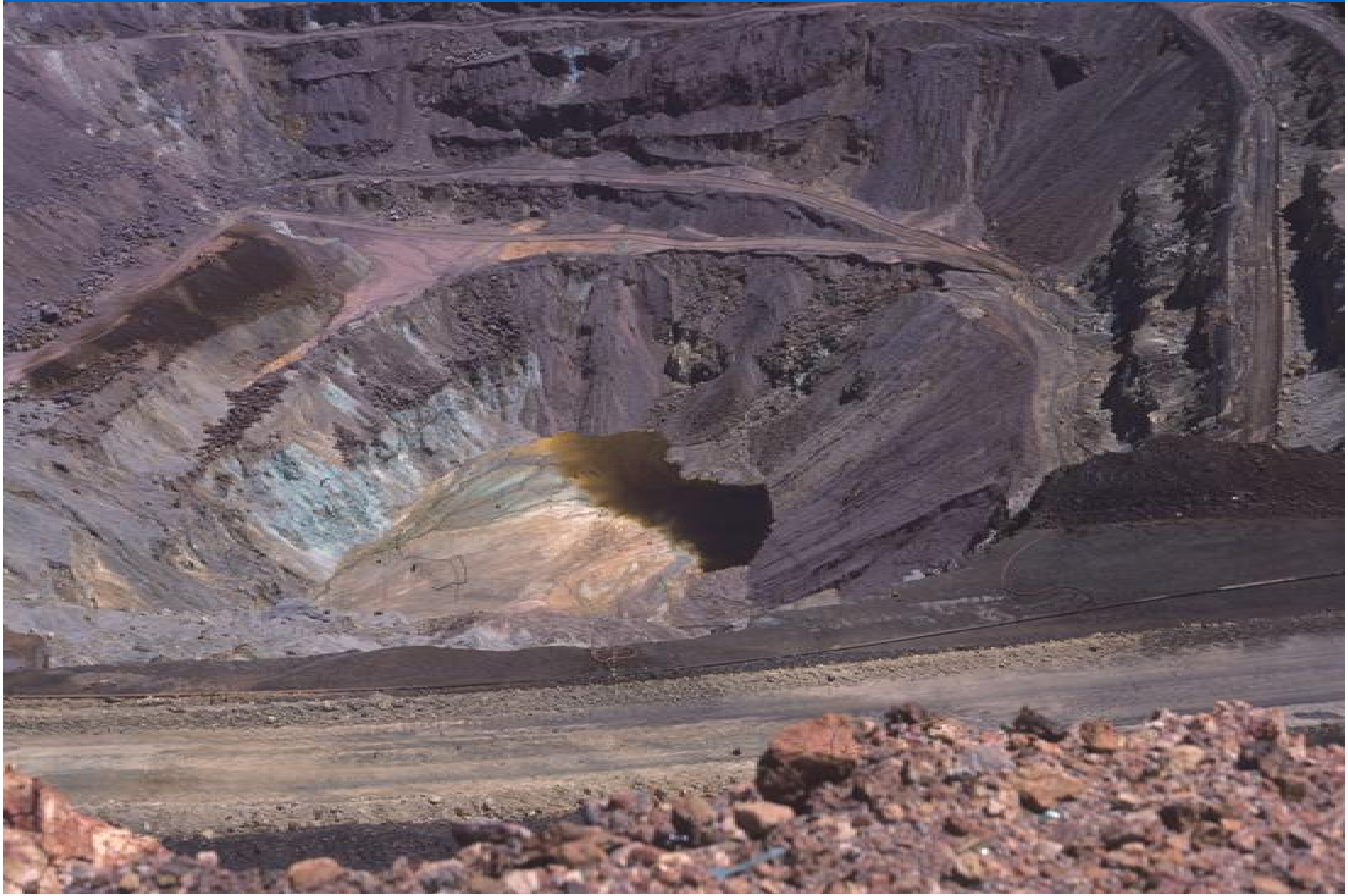
Middle Jurassic



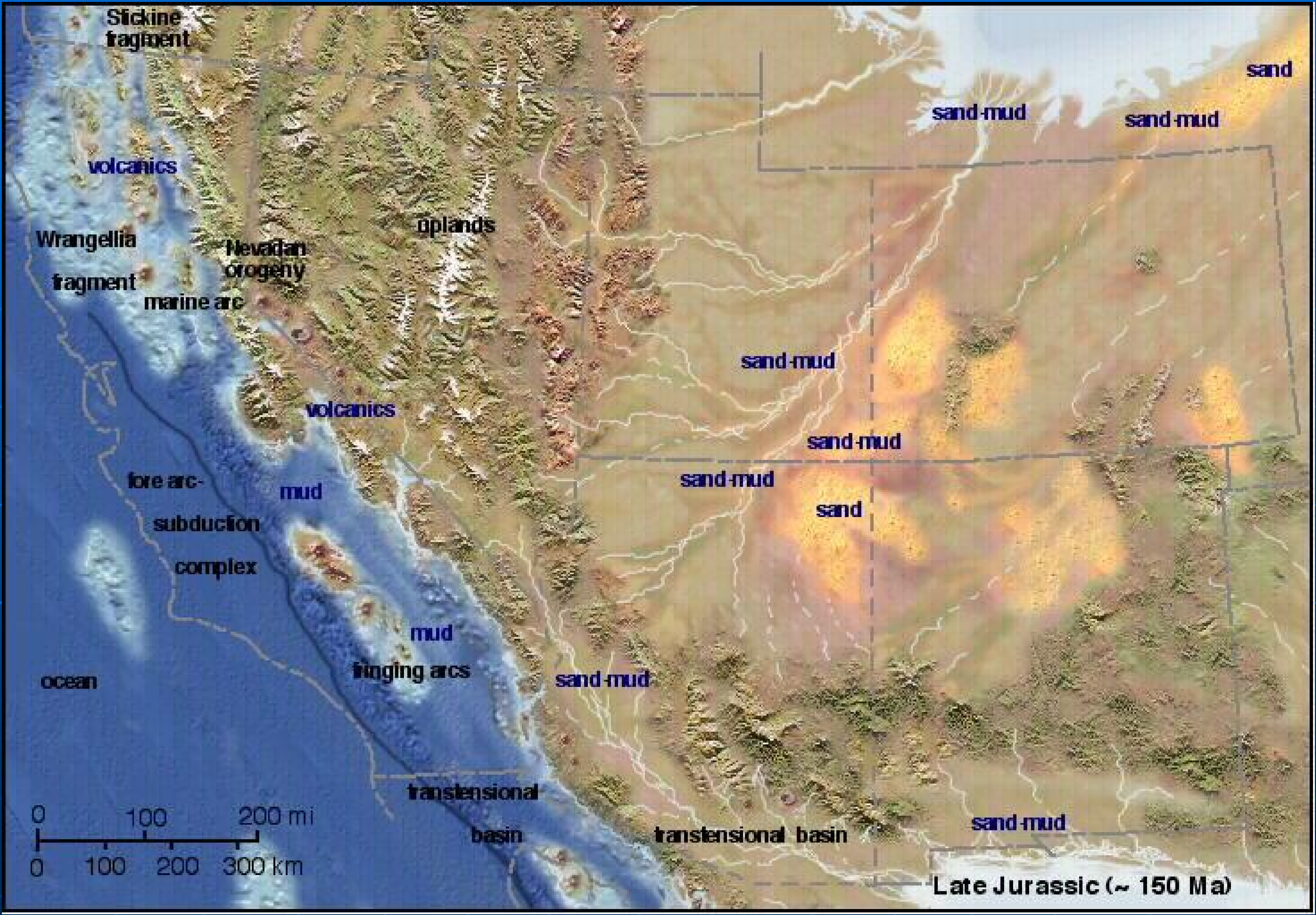
From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Brown Mtn. ASDM

Lavender pit Bisbee



Late Jurassic



From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Early Cretaceous

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Middle Cretaceous (~90 Ma)

From Ron Blakey NAU website: <u>http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html</u>

Bisbee Gp. Mural Ls

Sevier/ Laramide thrust faults

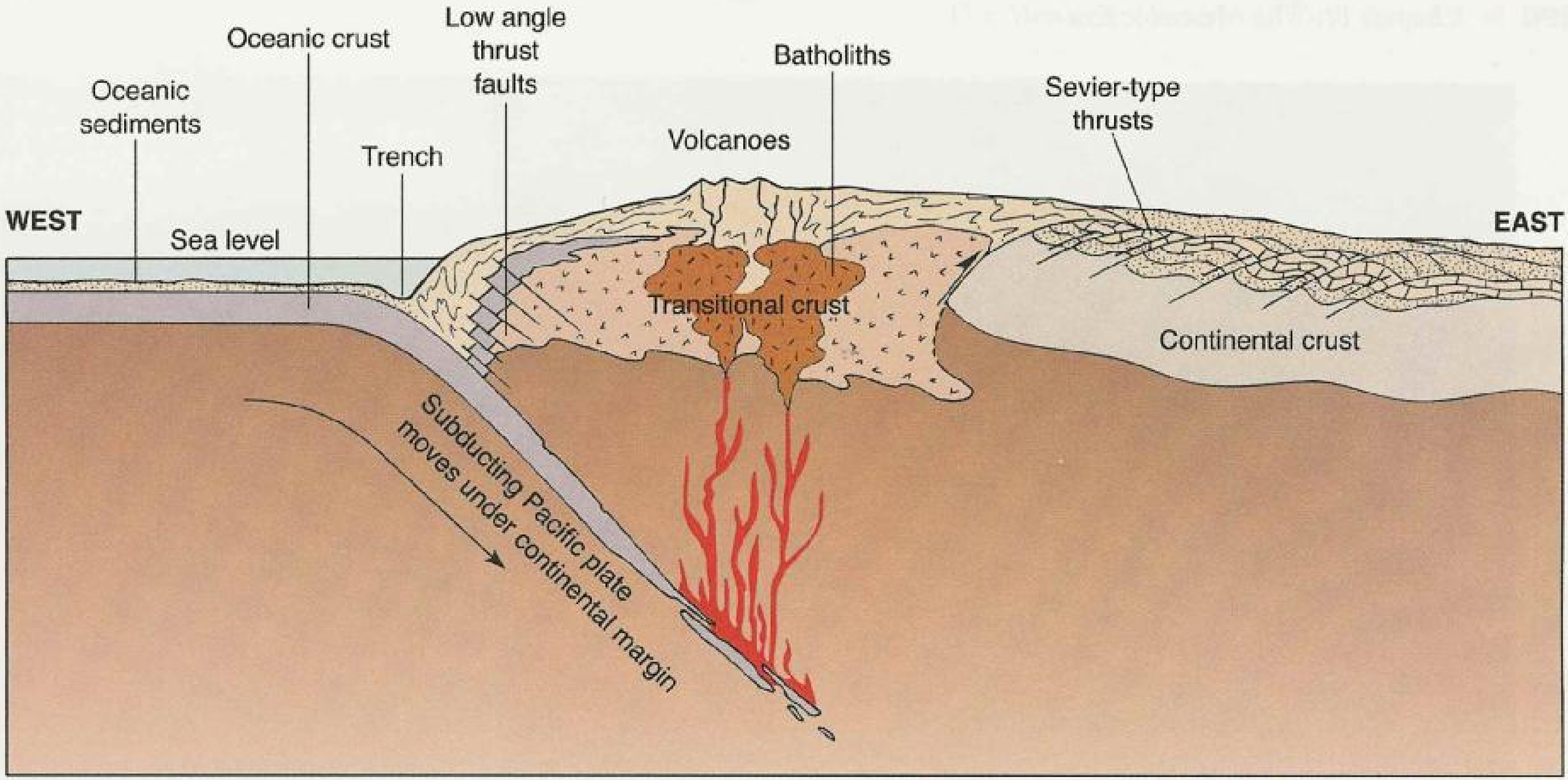


FIGURE 11-23 An advanced stage in the evolution of the North American Cordillera, with structures developing as a consequence of underthrusting of the continent by the Pacific oceanic plate. Note the multiple, imbricated, low-angle thrusts on the east side of the section. (*The diagram is simplified from Dewey, J. F., and Bird, J. M. 1970.* J. Geophys. Res. 75(14):2638.) ? *Where along the cross-section would one find an ophiolite suite of rocks?*

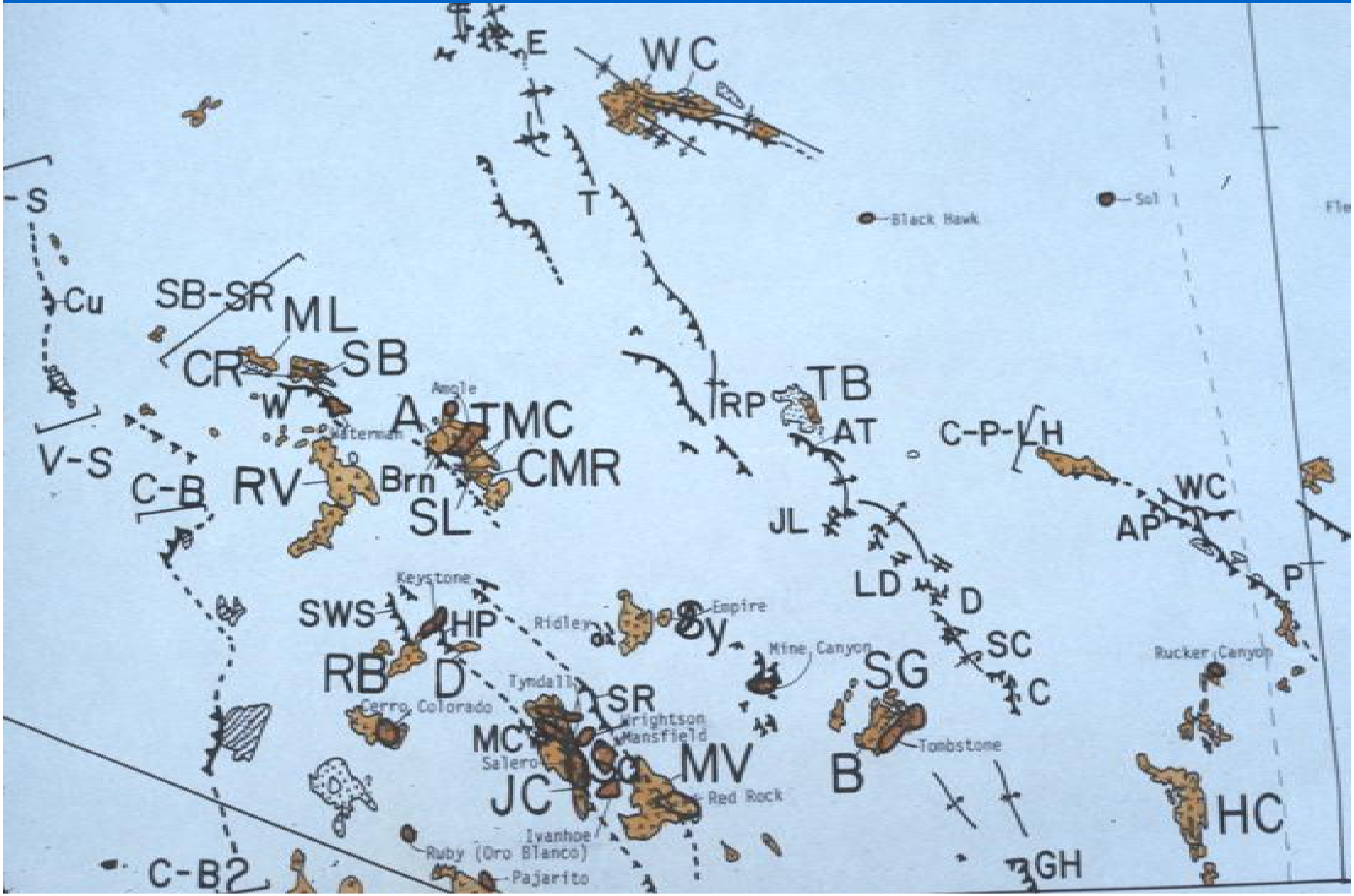
Late Cretaceous

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Tombstone Ag mine

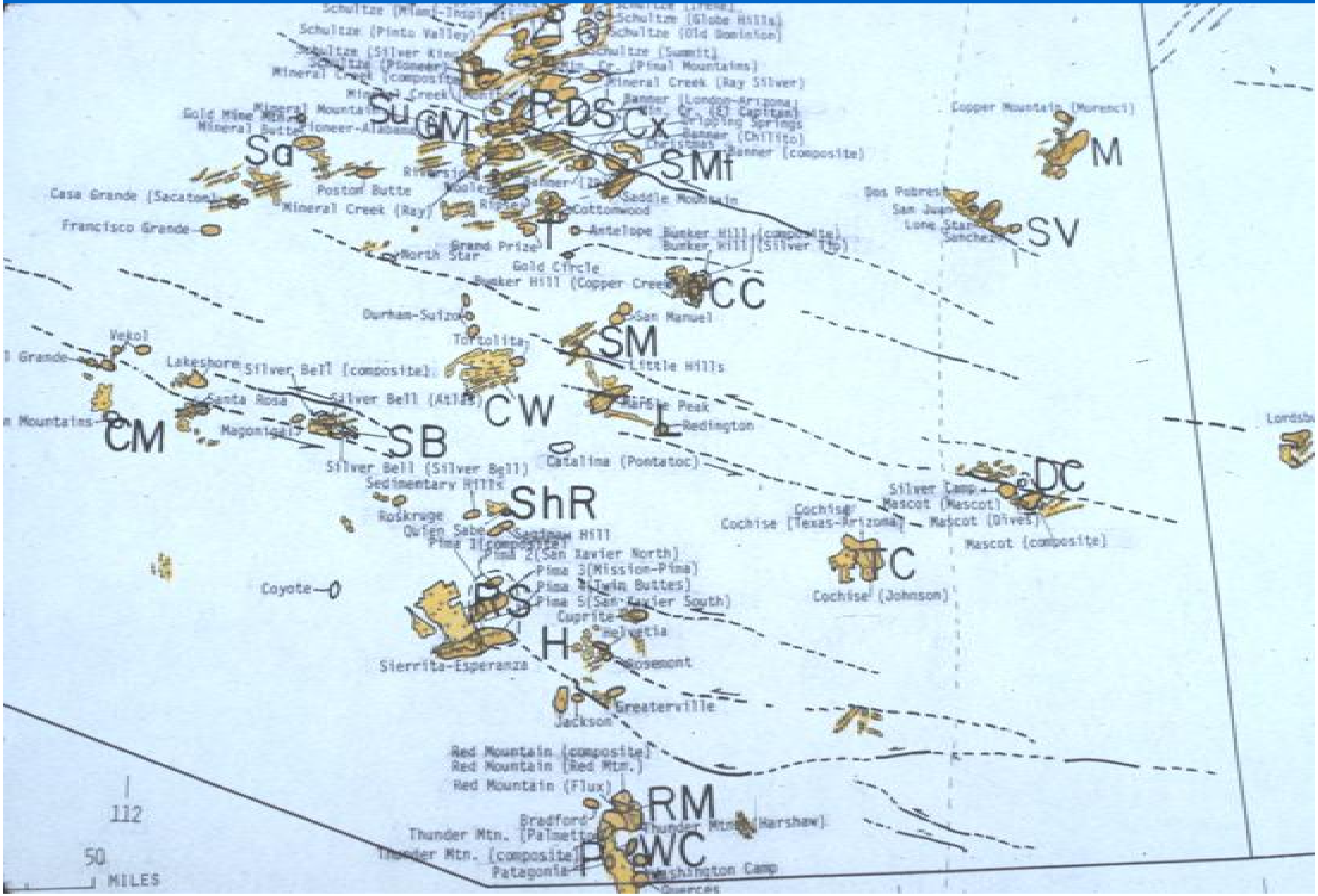
Gates Pass – 74 Ma rhyolite

Tombstone assemblage



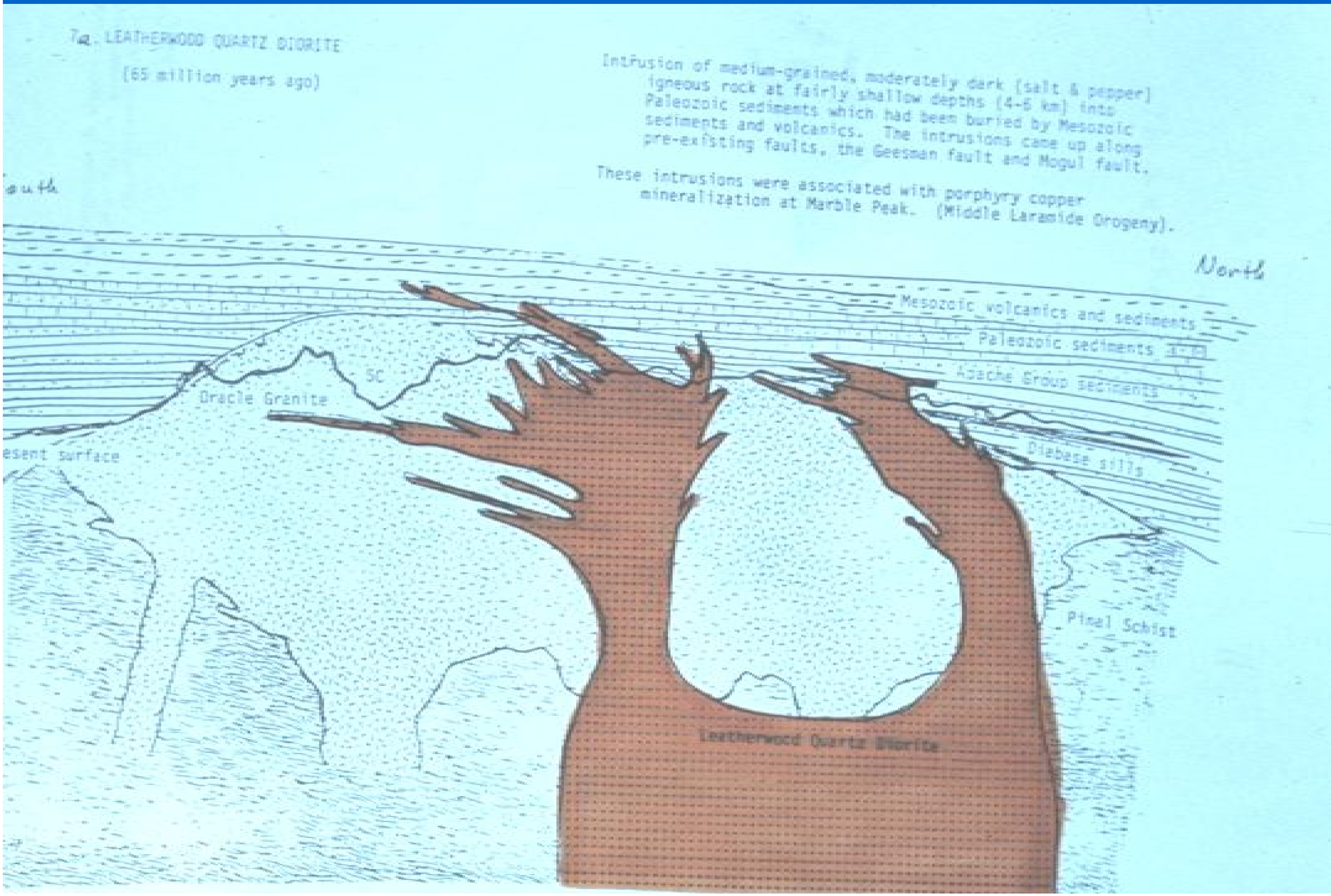
Cat Mtn. rhyolite

Morenci assemblage



Morenci assemblage

Leatherwood QMP



Cretaceous paleogeography

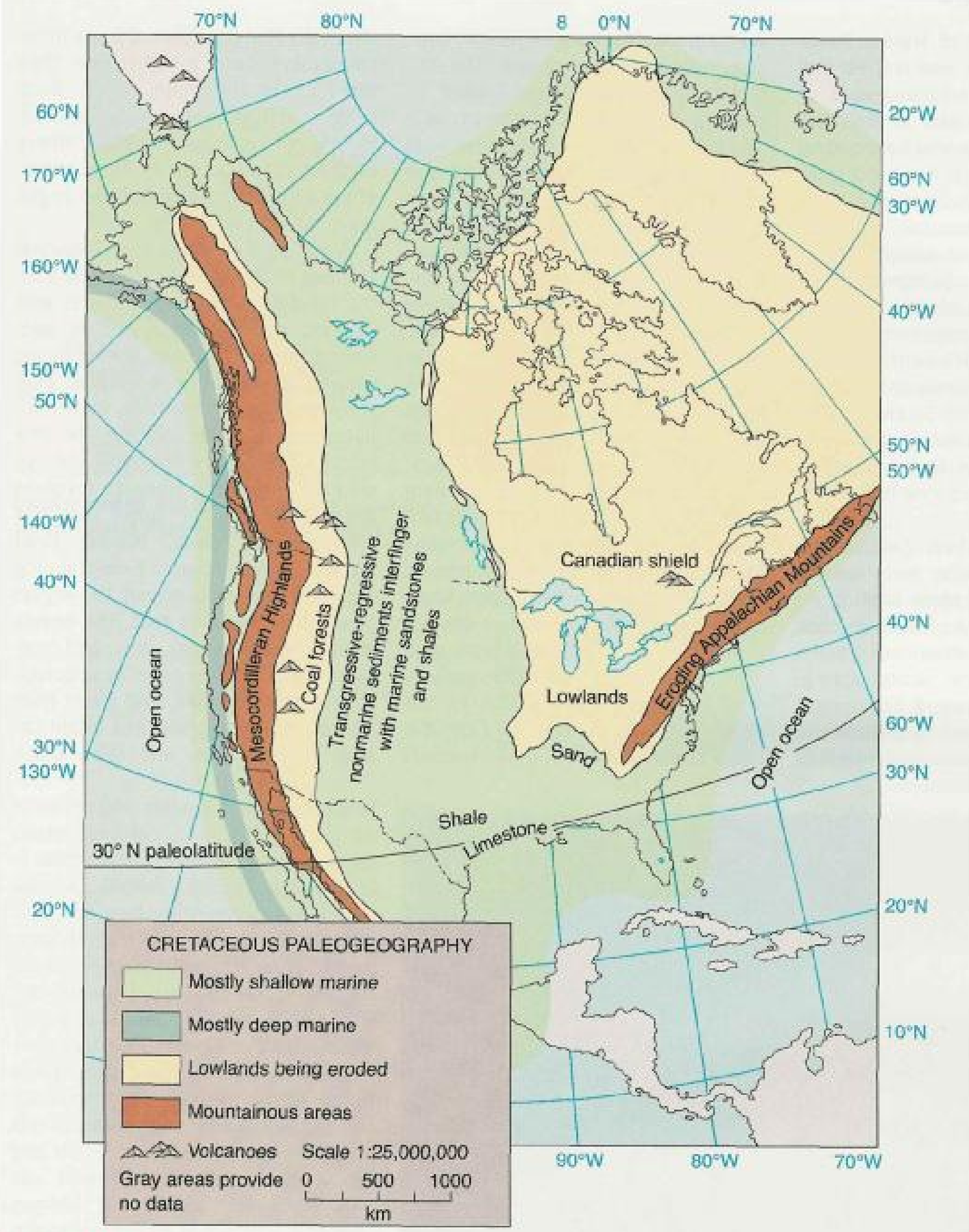
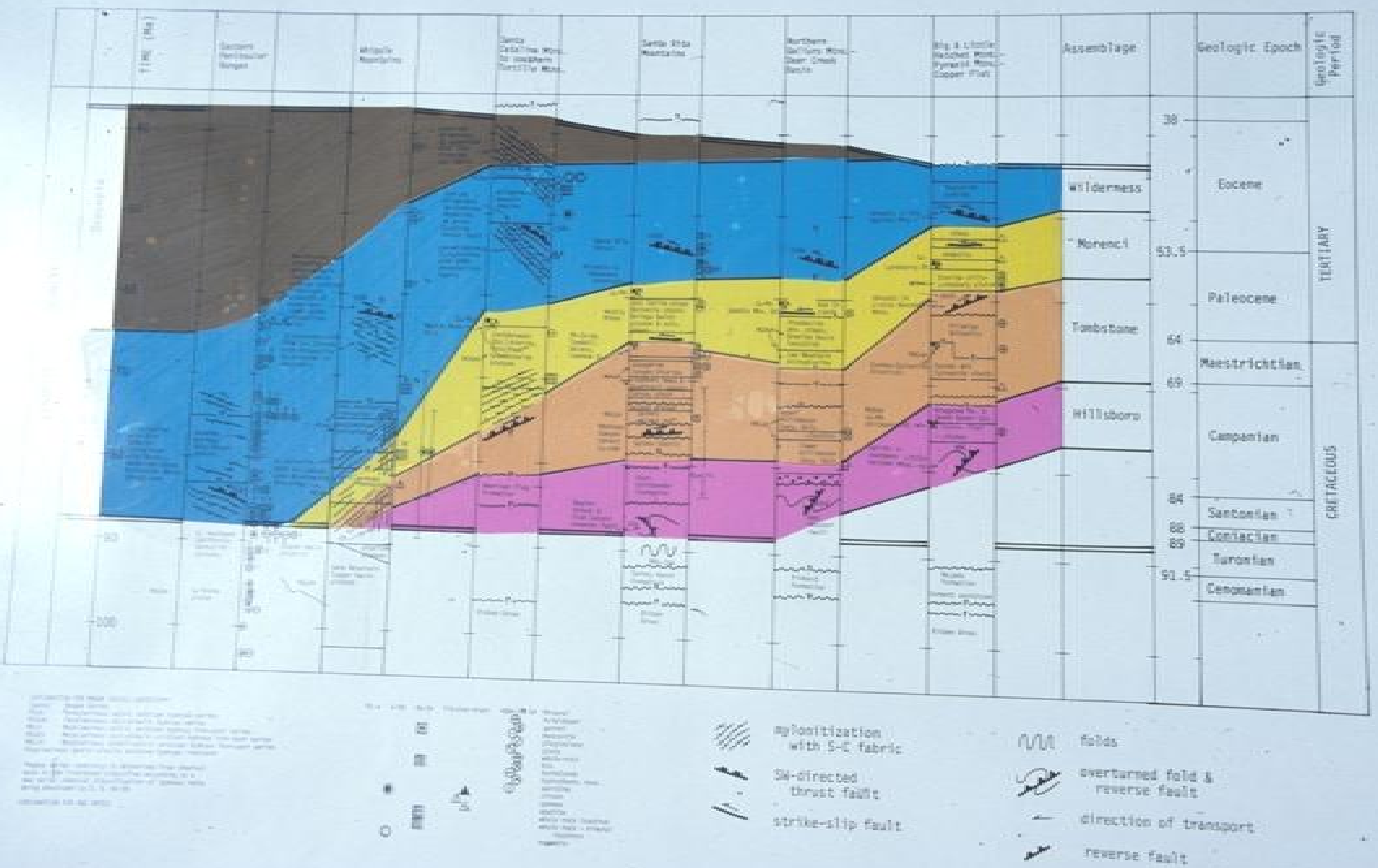


FIGURE 11-12 Generalized paleogeographic map for the Cretaceous of North America.

Laramide orogeny



Tejas sequence

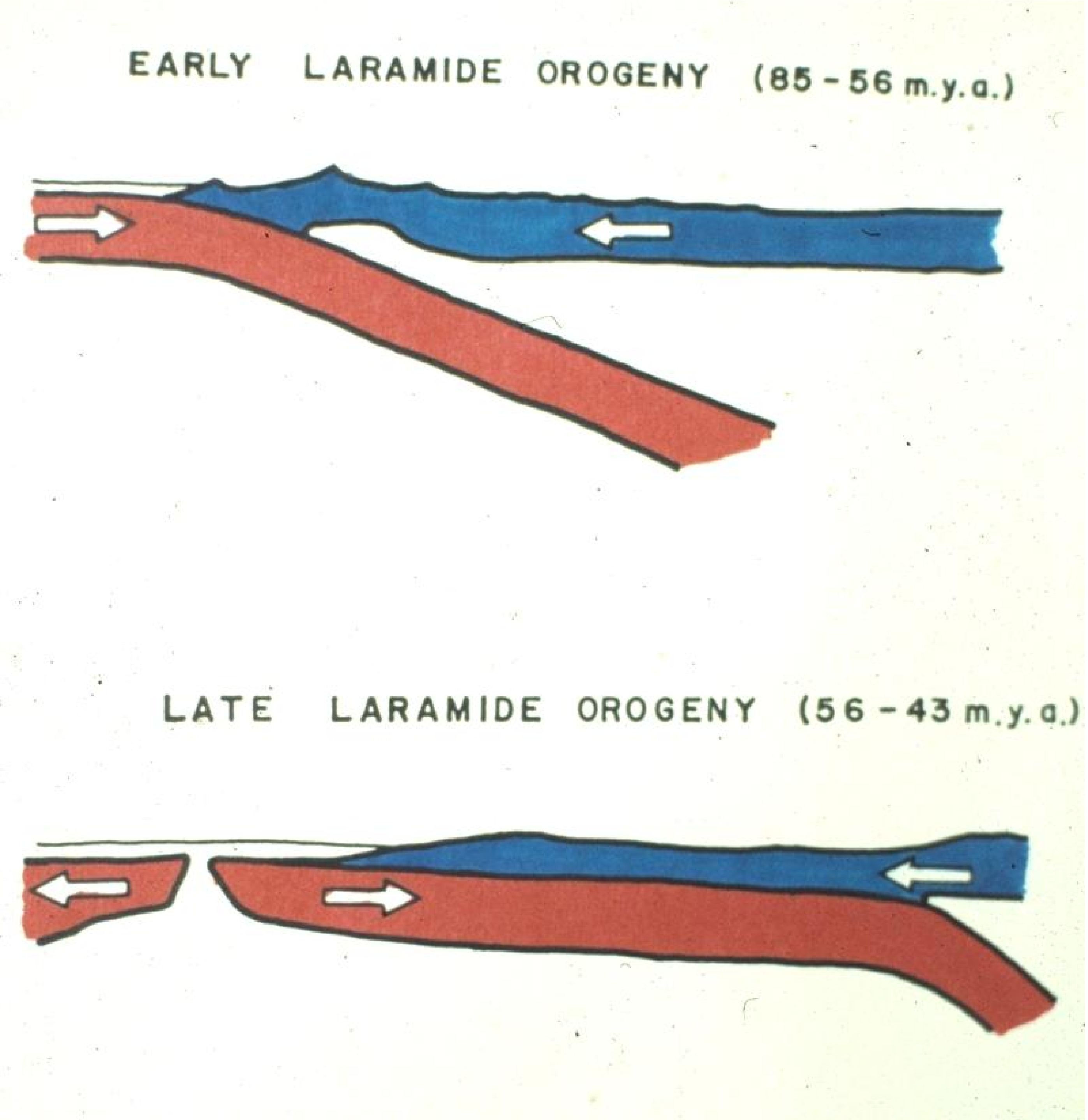
TABLE 8-1 Cratonic Sequences of North America*

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	

Tertiary (65-1.8 Ma)

From Ron Blakey NAU website: http://jan.ucc.nau.edu/~rcb7/paleogeogwus.html

Laramide slab flattening



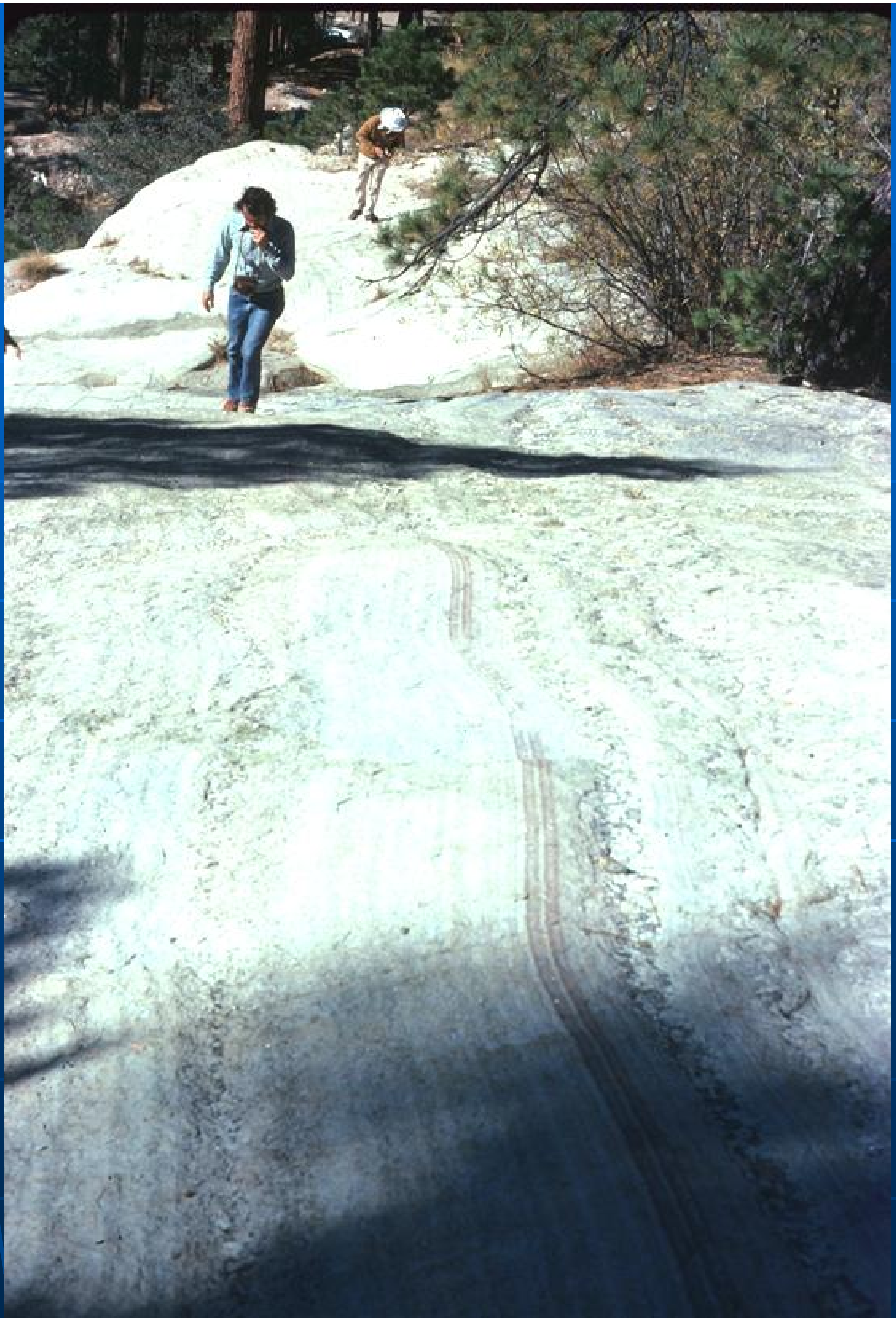
Texas Canyon

Wilderness – 43 Ma

Catalina Mts. forerange

Santa Catalina Mts. SW dips

Catalina - Garnet



Eocene erosion surface

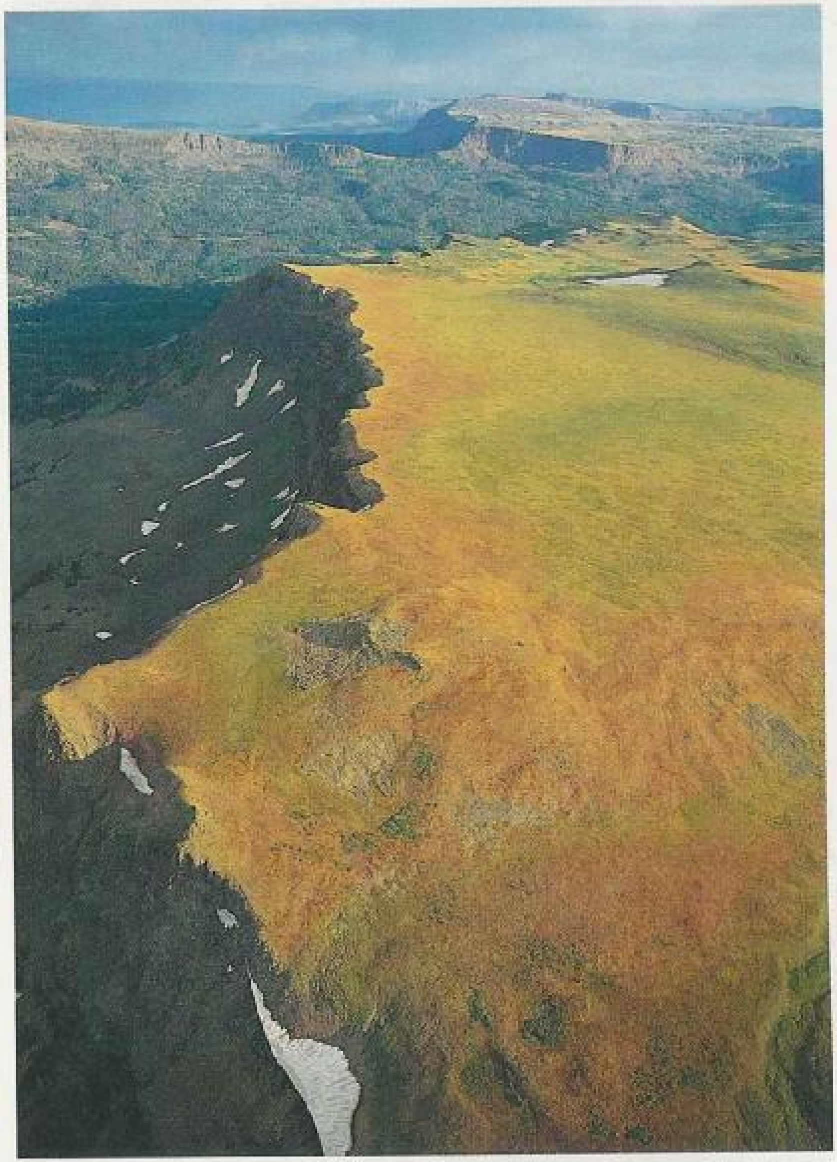


Figure 18-25 The subsummit surface formed by the flat-topped Rocky Mountains. This surface, seen here near Derby Peak, Colorado, formed near the end of the Eocene Epoch and has since been uplifted and dissected by erosion. (Michael Collier.)

Mogollon Rim gravels

Early Tertiary paleogeography

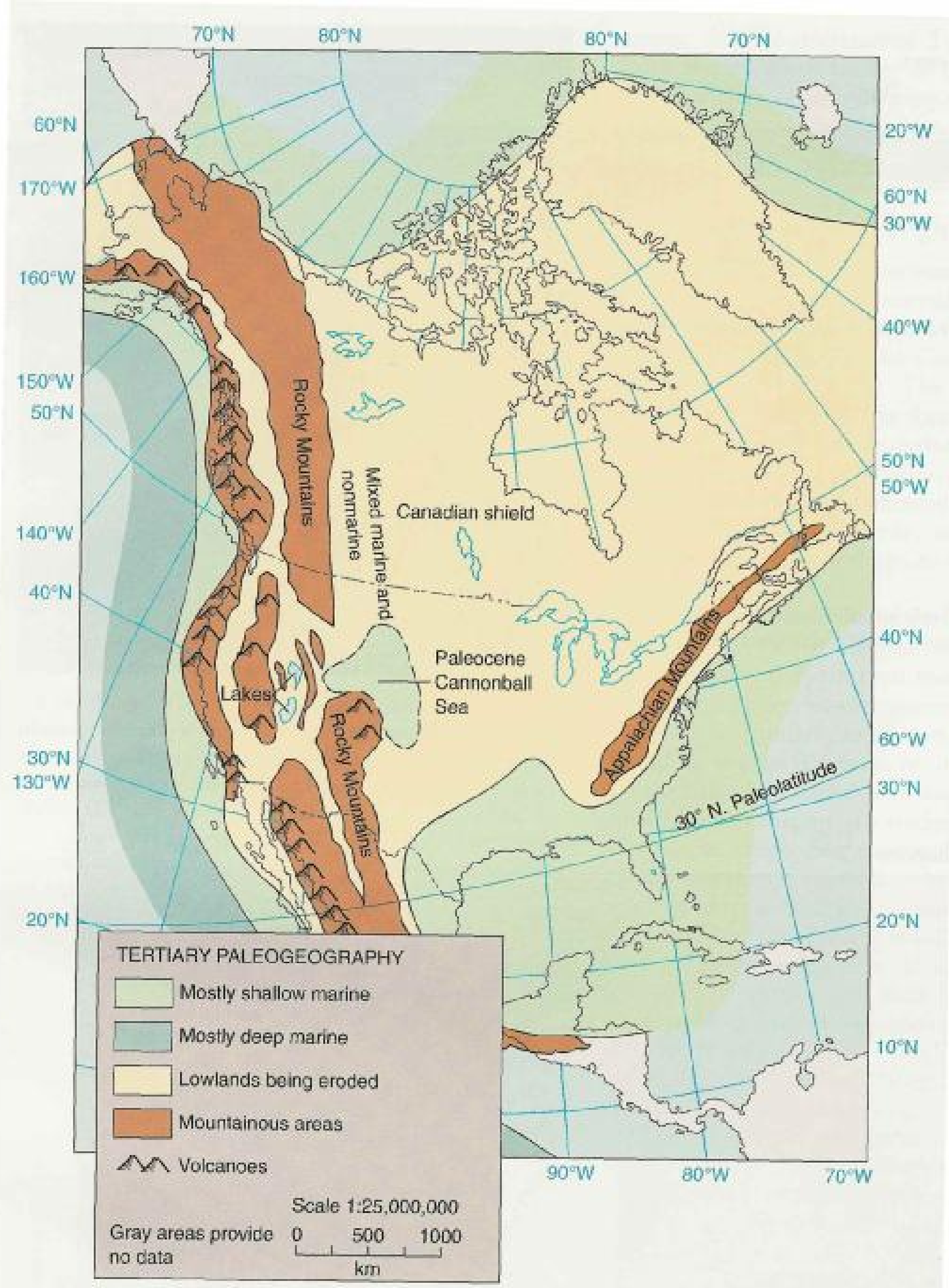


FIGURE 13-6 Paleogeographic map of North America during the early Tertiary.

Cenozoic basins

FIGURE 13-7 Cedar Breaks National Monument in Utah. Here the Eocene Cedar Breaks Formation has been eroded into steep ravines, pinnacles, and razor-sharp divides. Early explorers in the region used the term "breaks" to describe the change in topography where an elevated level area "breaks down" by eroding to a lower elevation. (*Copyright Charles Ott/Photo Researchers, Inc.*)

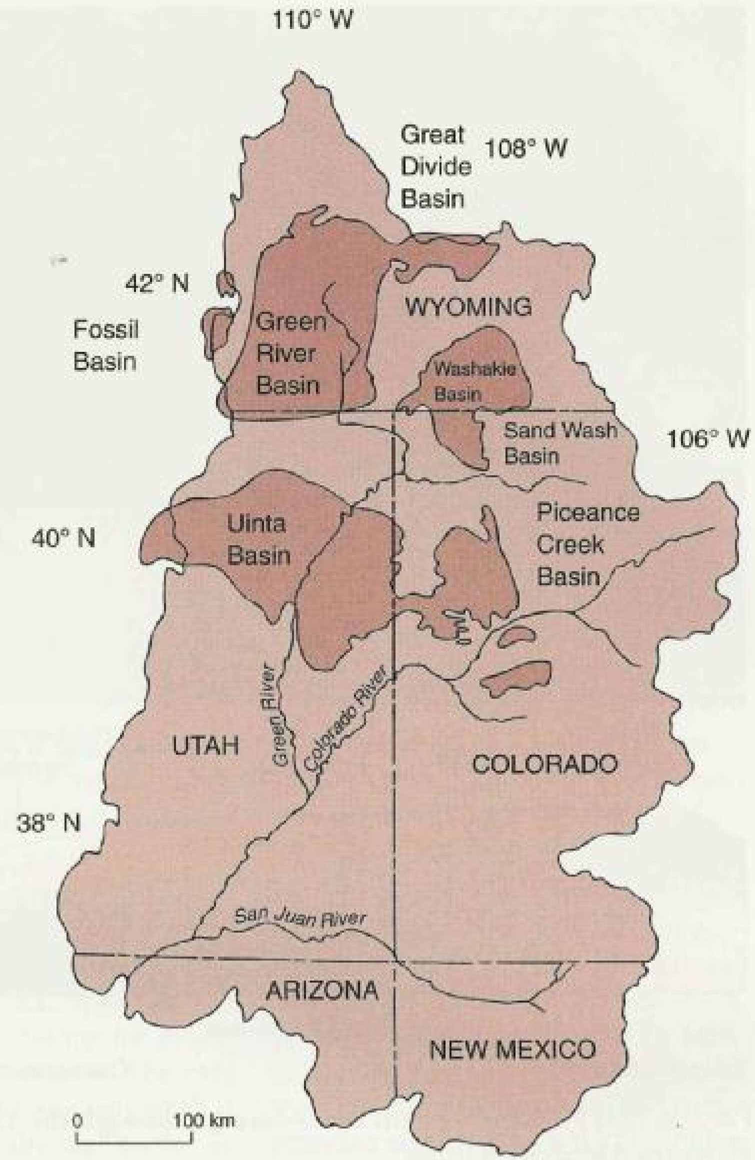
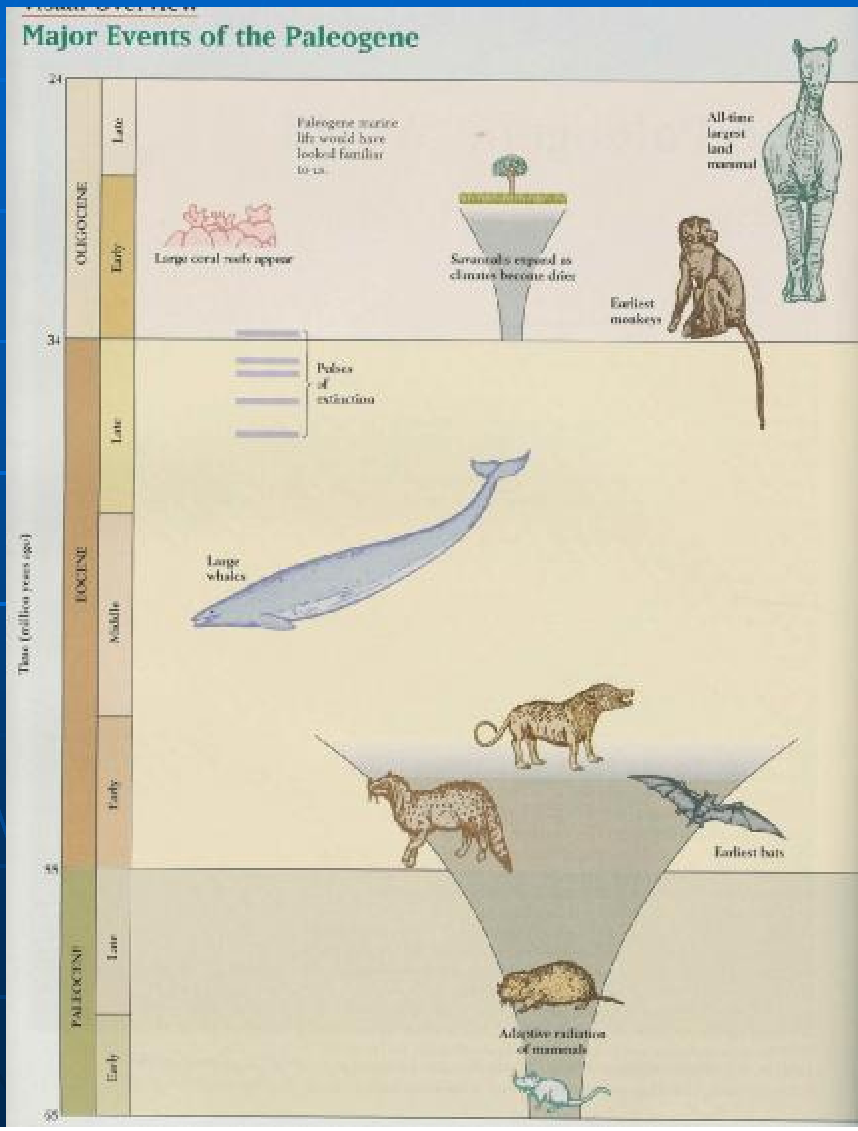
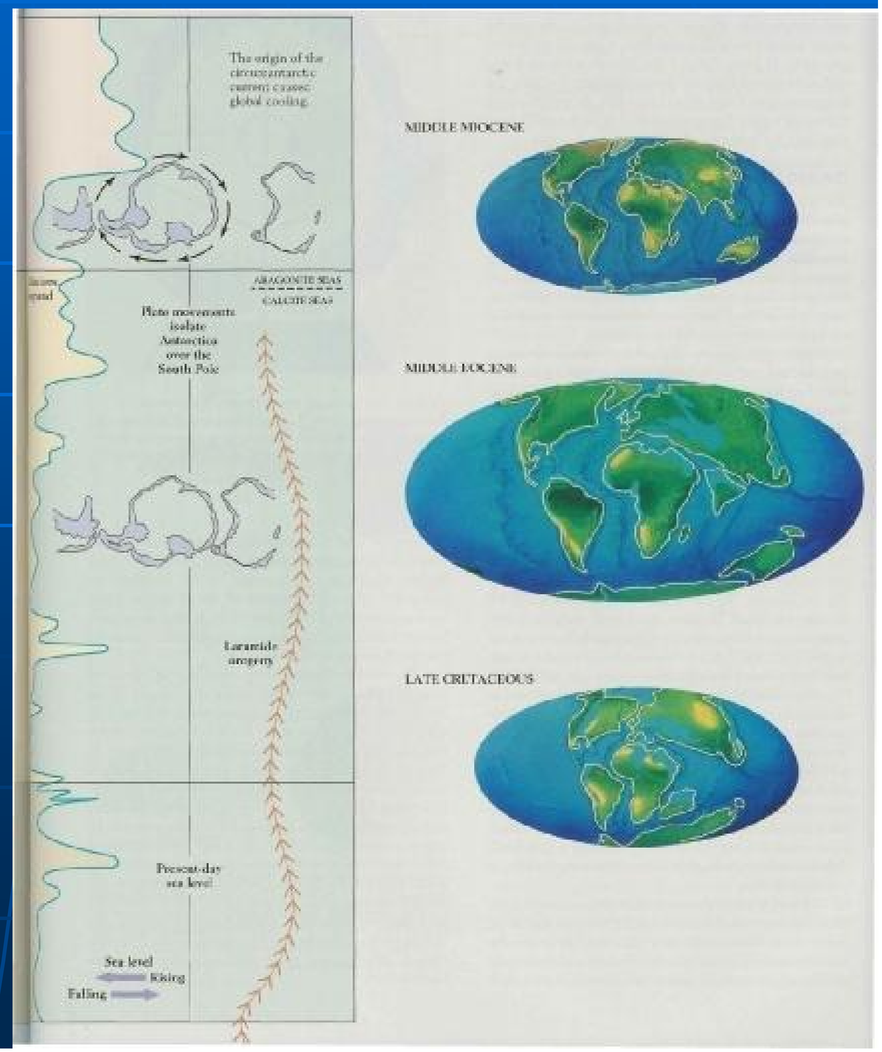


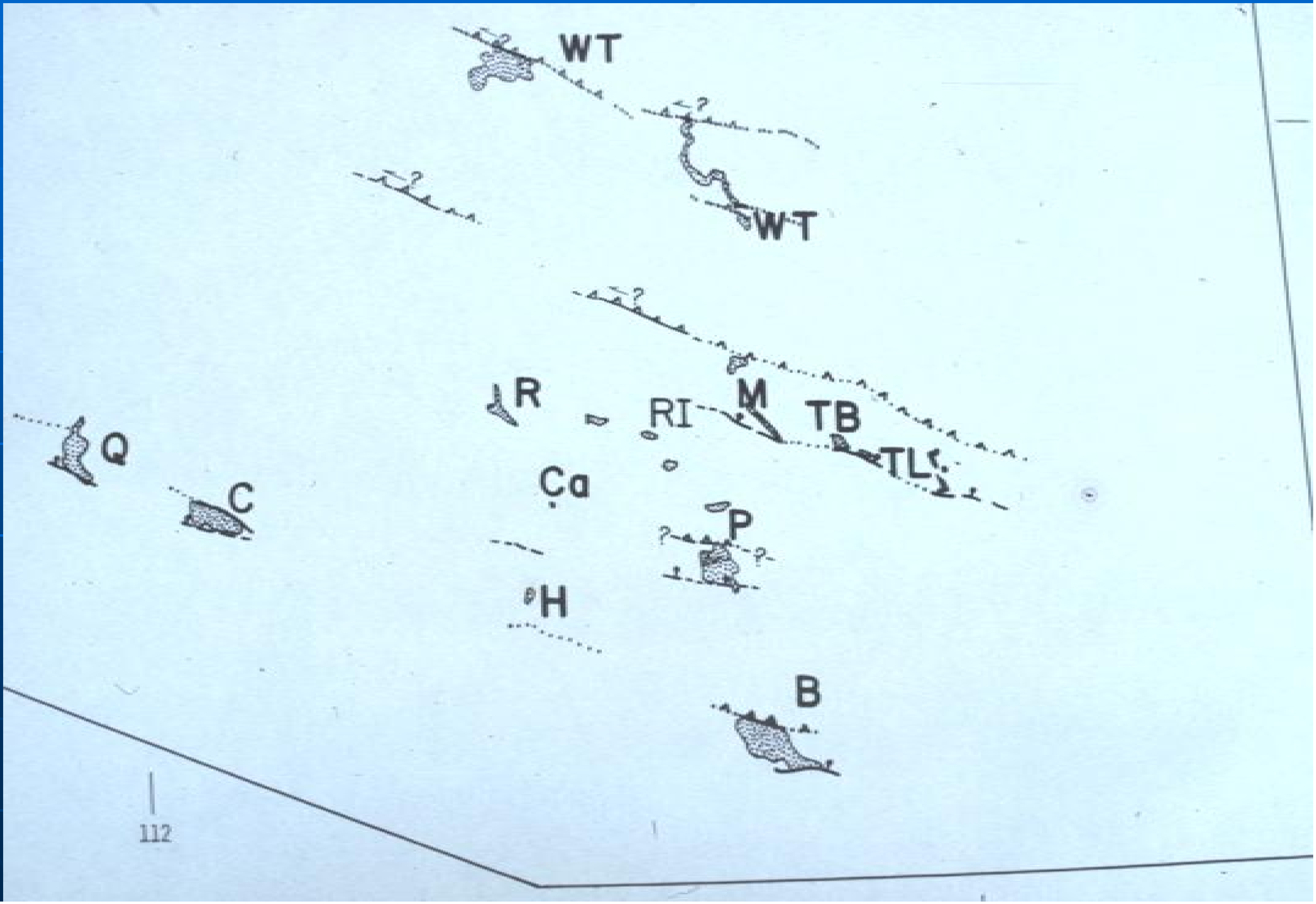
FIGURE 13-8 Cenozoic basins of Colorado, Utah, and Wyoming containing important oil shale deposits. Map boundary is the Upper Colorado River drainage basin. (*Simplified from Rickert, D. A., Ulman, W. J., and Hampton, E. R. [eds.] 1979.* Synthetic Fuels Development, *U.S. Geologic Survey publication.*)

Paleogene events





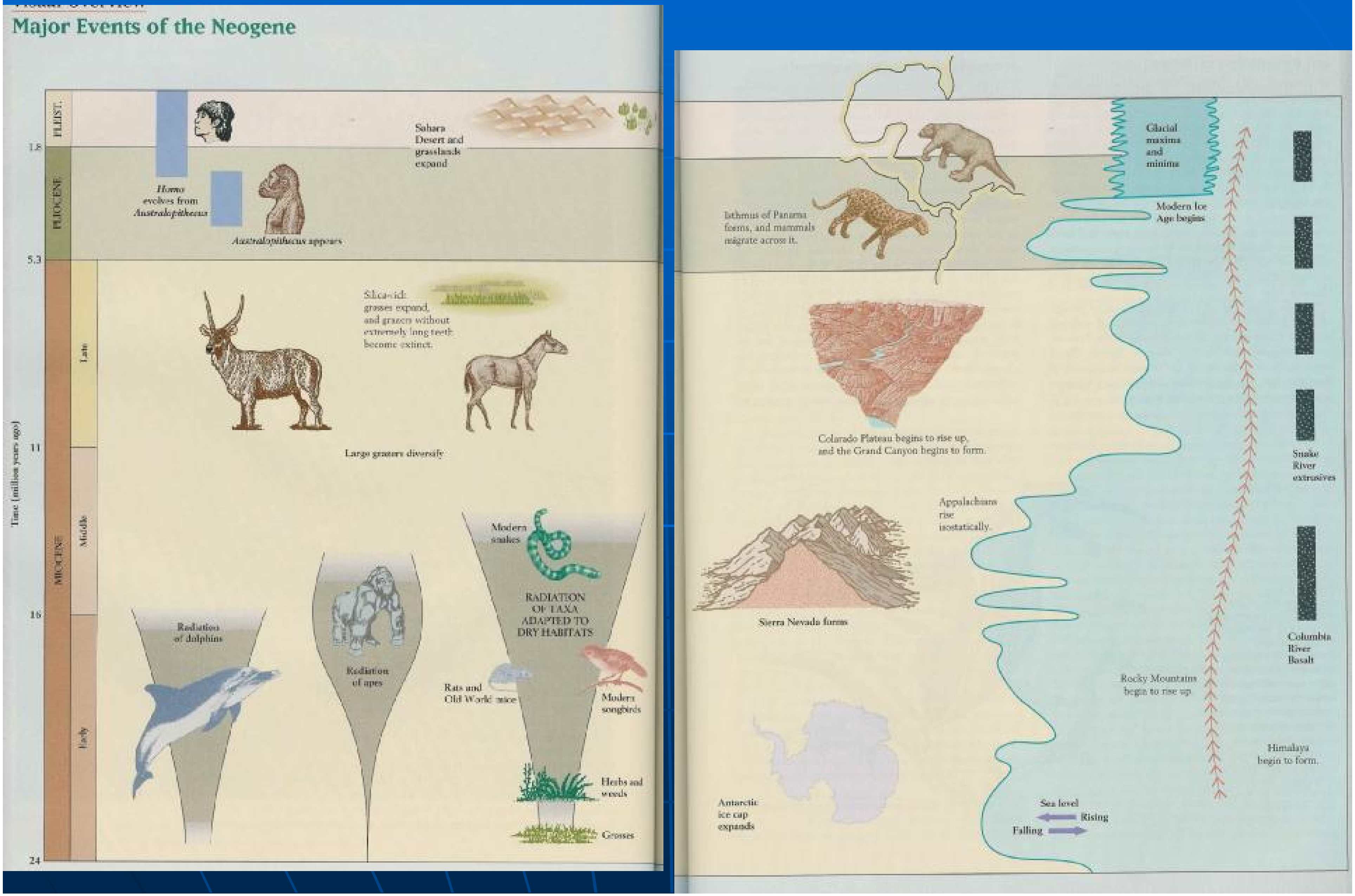
Early Tertiary basins AZ



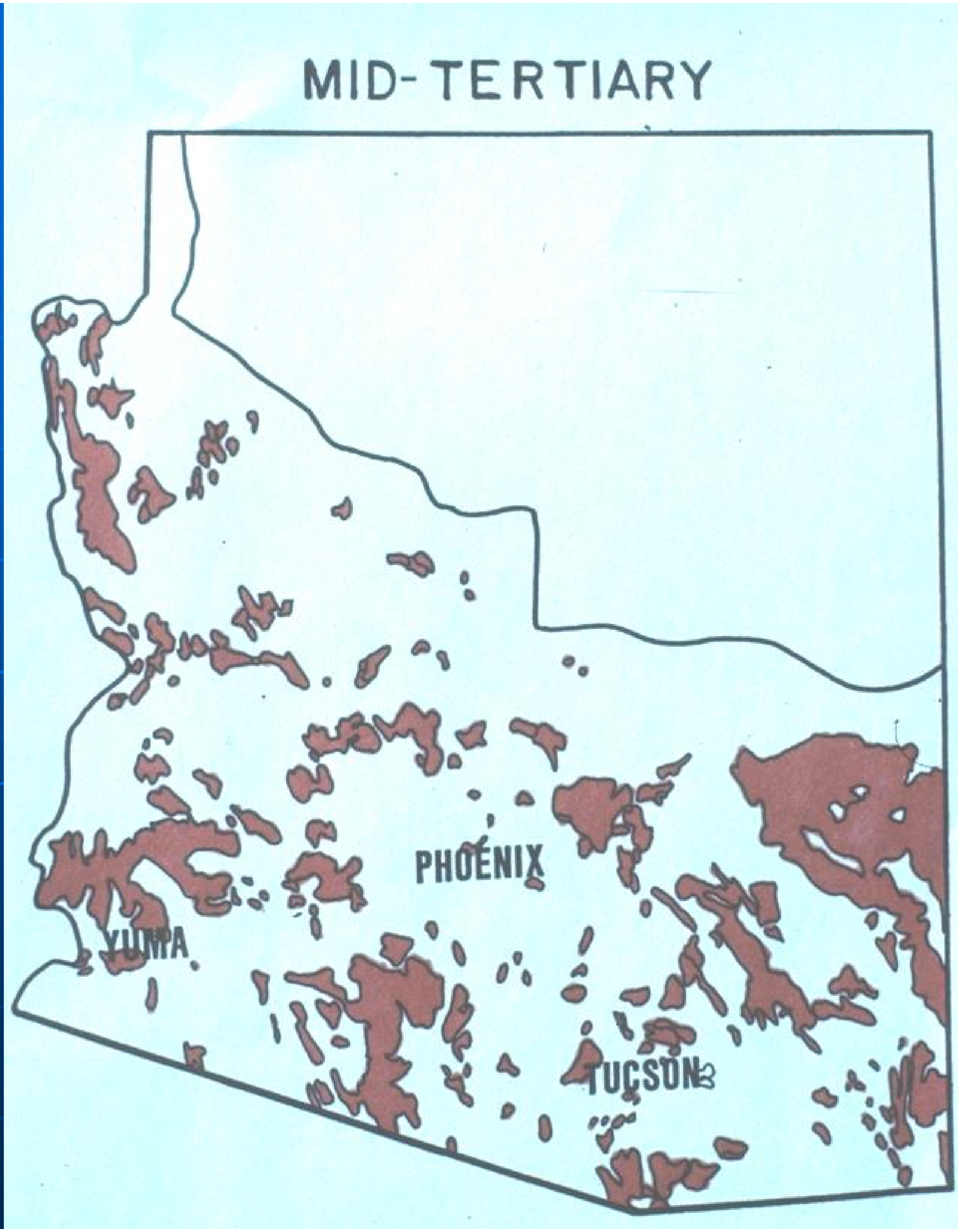
Pantano clay pit

Basin fill overlying Pantano

Neogene events

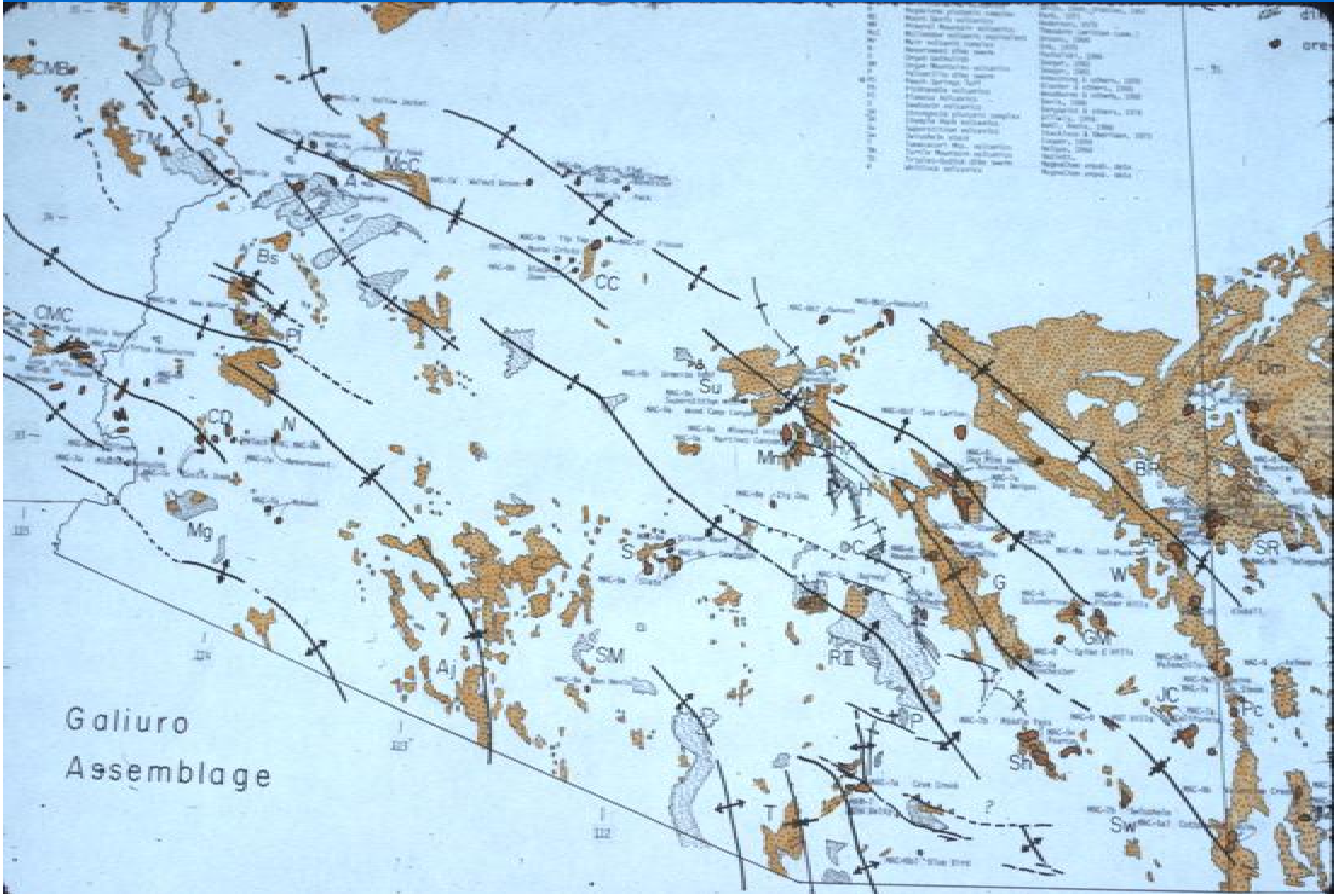


Mid-Tertiary volcanics

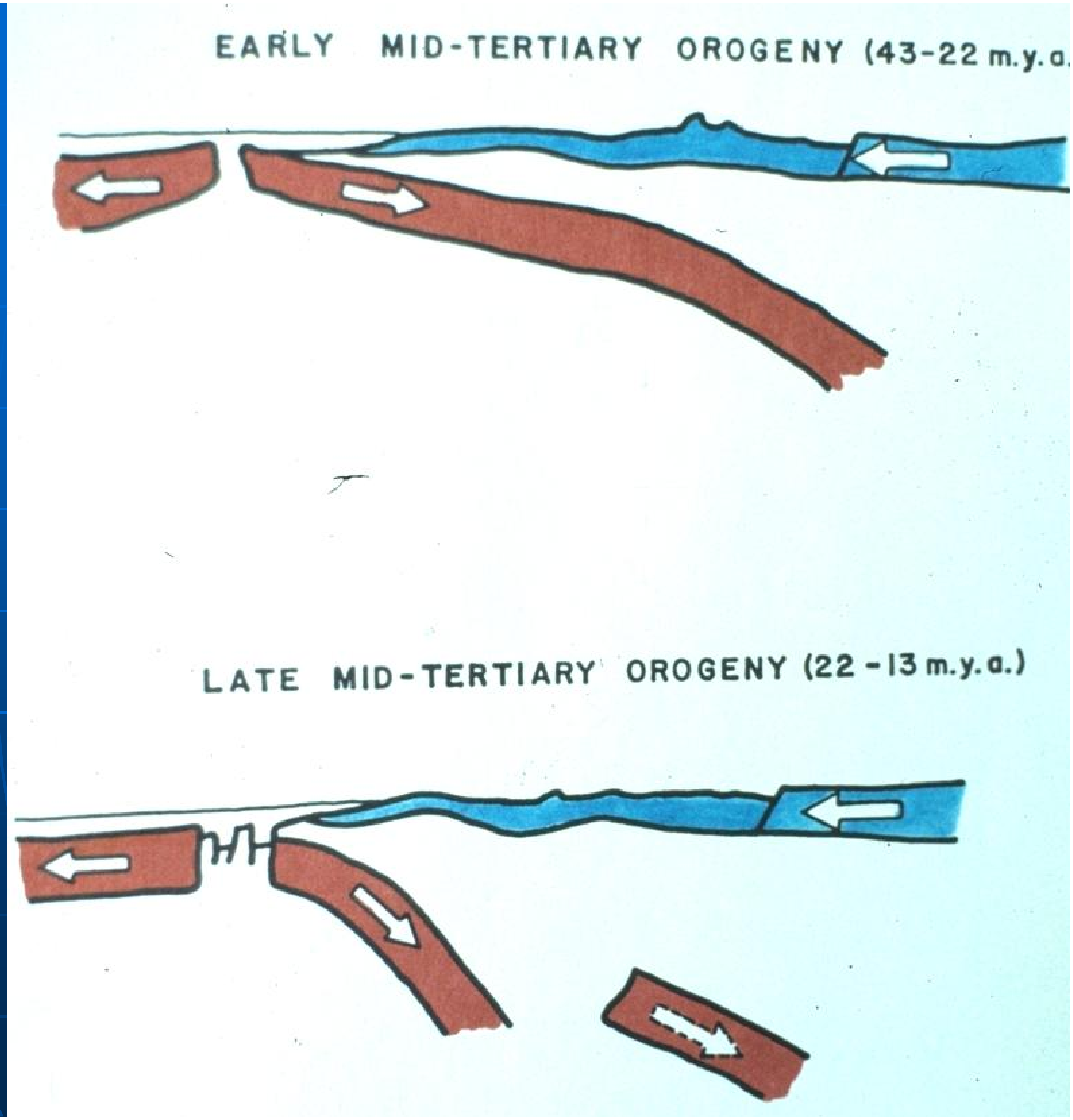


Safford Peak

Mid-Tertiary volcanics (Galiuro)



Mid-Tertiary steepening slab



Cochise Stronghold - Dragoons

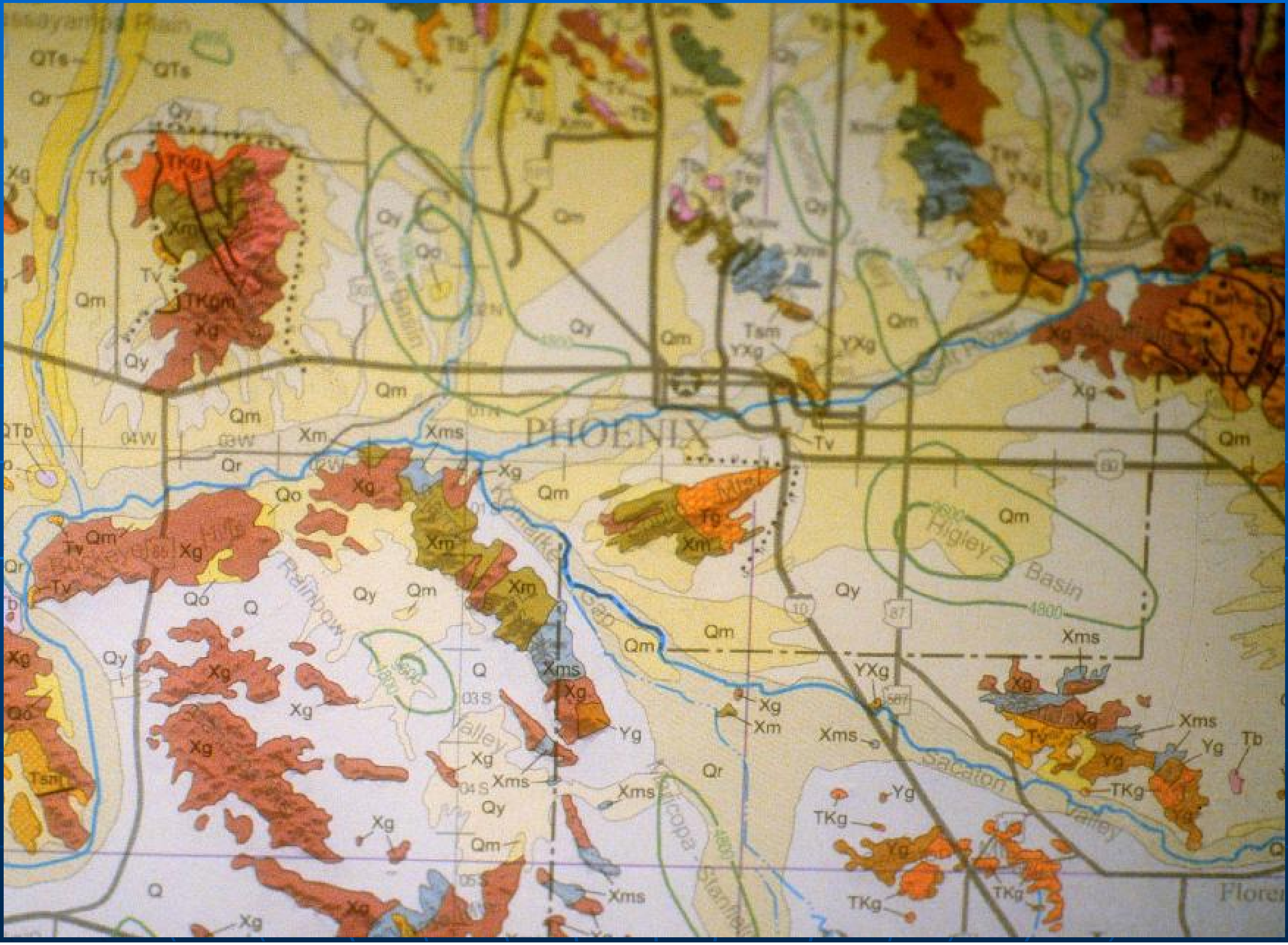
Lincoln Ranch Thrust PC over T

Chiricahua Monument

Organ Pipe monument

Picacho Peak

PHOENIX



SUPERSTITIONS

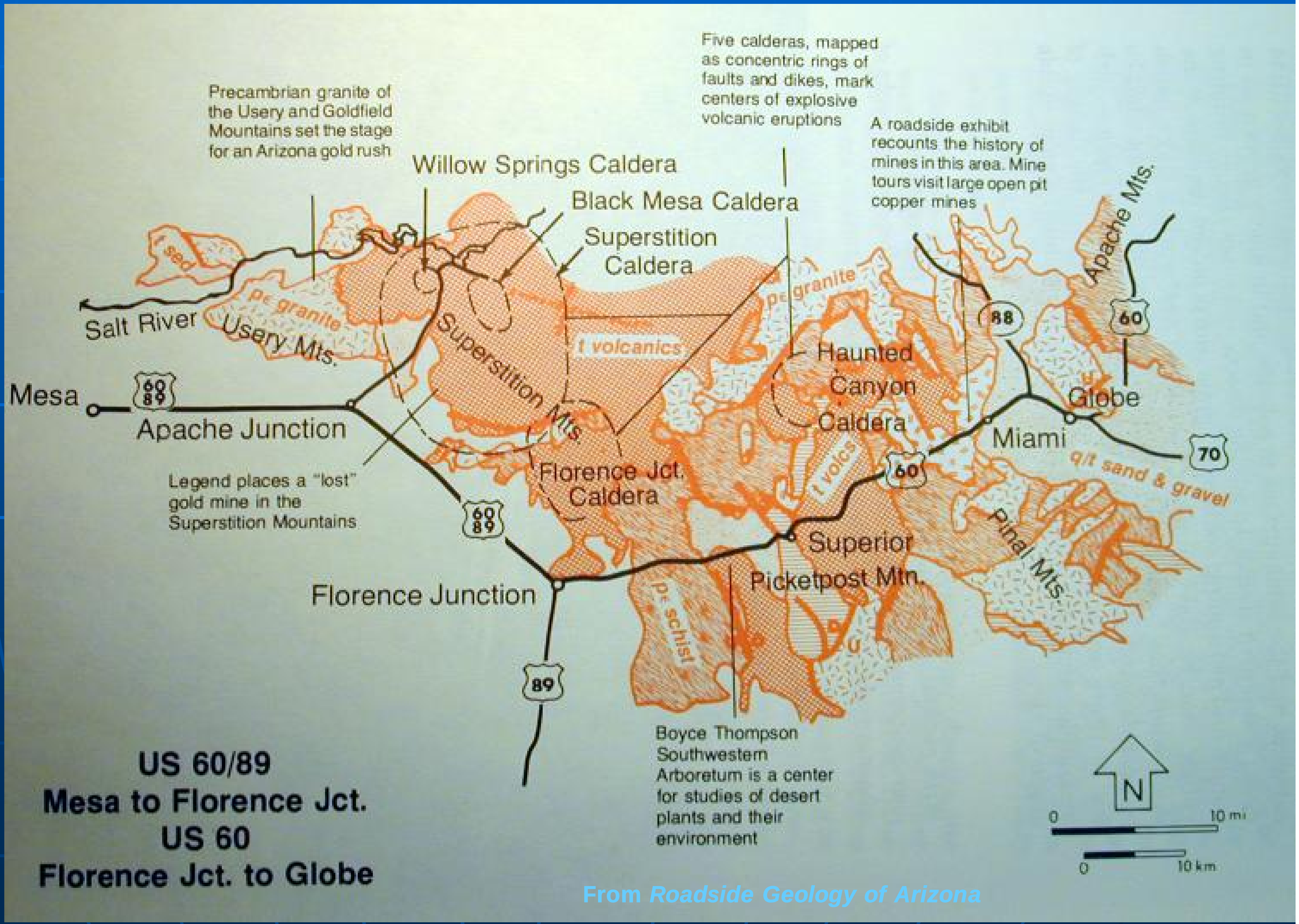
Superstition Volcanic Field

3-5 separate calderas

VERY silicic, explosive volcanoes

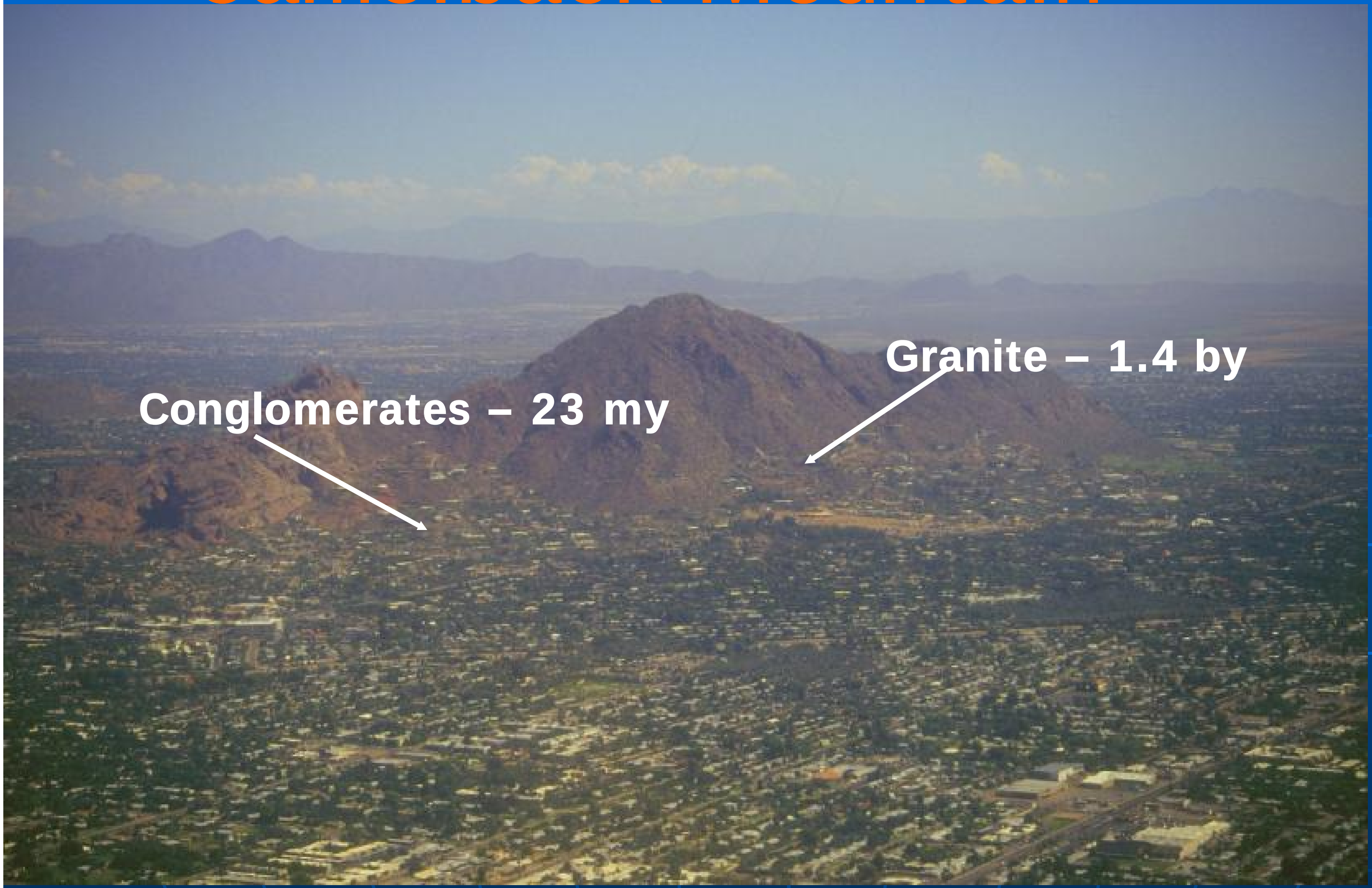
25-15 Ma

up to 10,000 ft. of ash deposited



From *Roadside Geology of Arizona*

Camelback Mountain



As the Colorado Plateau to the north uplifted, southward flowing streams and landslides deposited sands and gravels atop what is now the camel's hump. The mountain formed during the Basin & Range event, between 5 & 14 Ma.

Papago Buttes

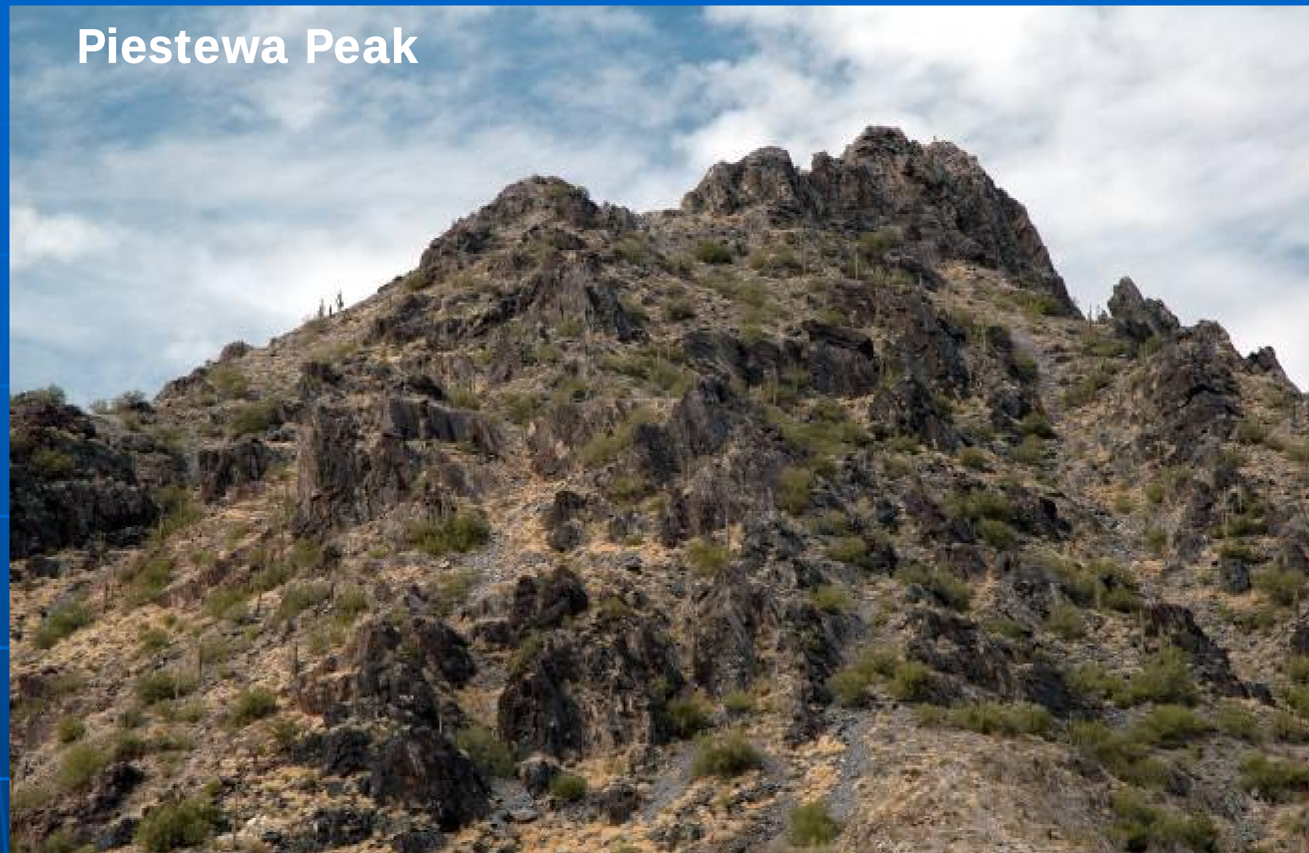
Van Buren.

TAFONI are holes produced by weathering, predominately in arid climates.

Phoenix Mountains

- Rocks are Precambrian igneous & metamorphic AND Tertiary sedimentary rocks
- Tilting occurred during metamorphic core complex deformation

  (tilted rocks at Camelback Mt also)
- Uplift of Phoenix Mountains during Basin & Range Disturbance



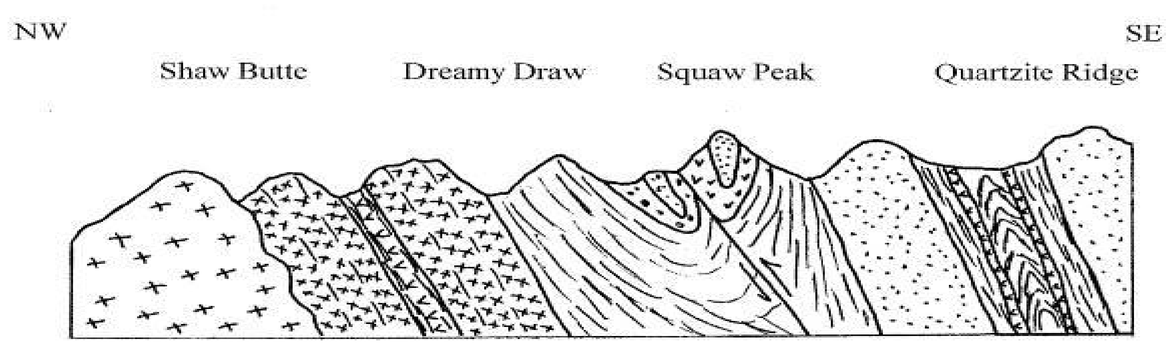
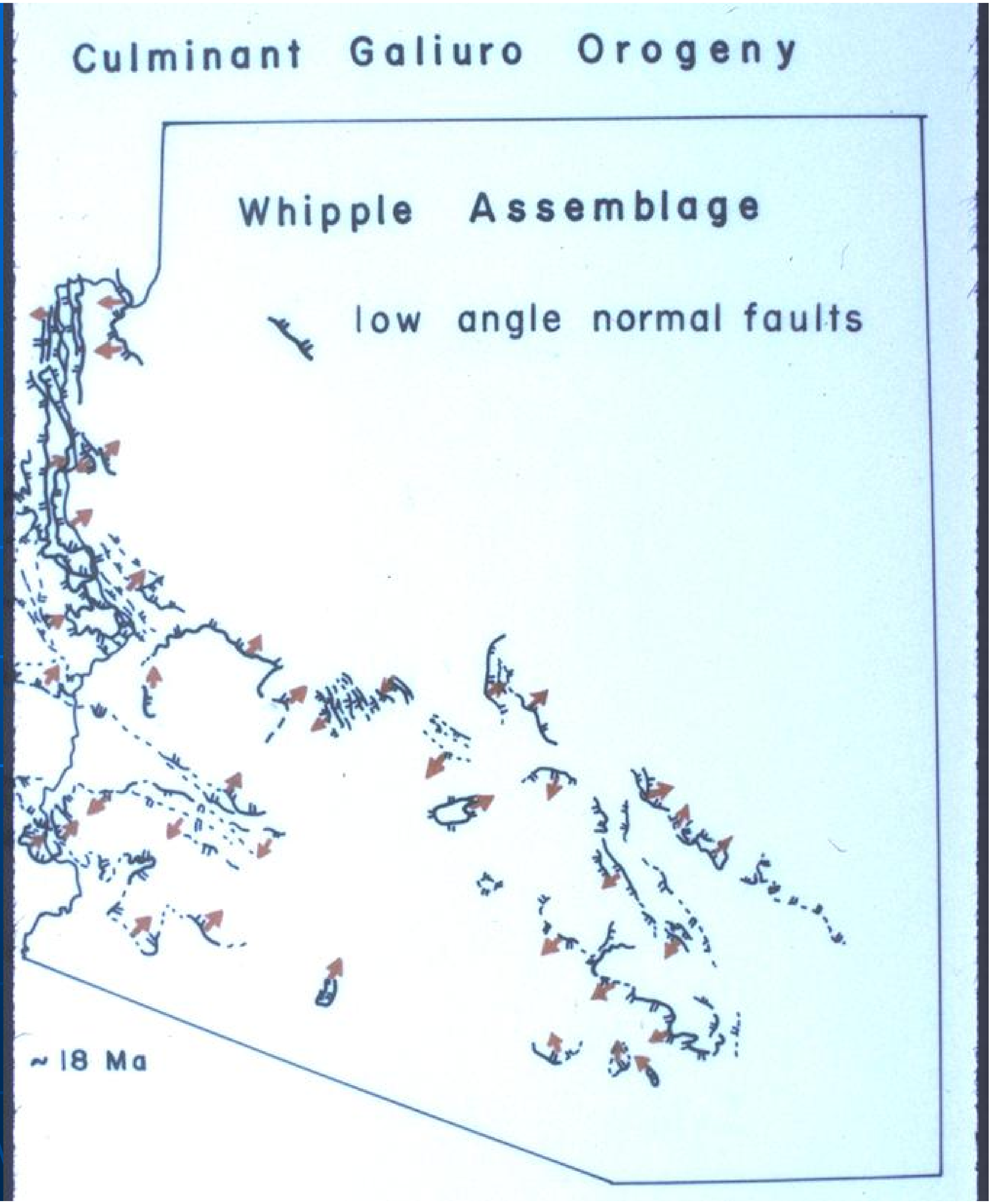


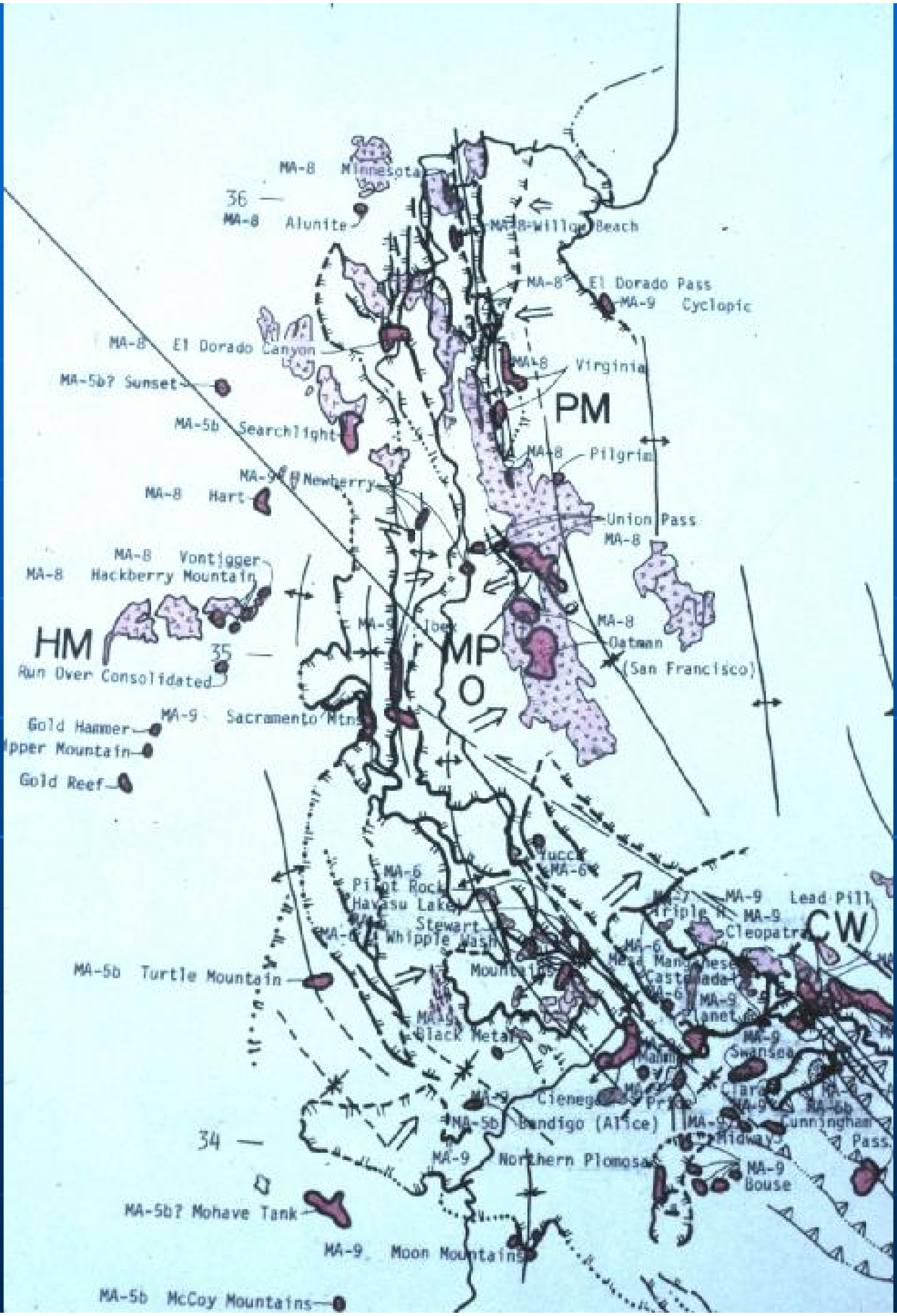
Figure 2. Schematic cross section across the Phoenix Mountains (from Johnson, 2000).

From Geologic Field Guide to the Phoenix Mountains, Central Arizona by Julia Johnson & Stephen Reynolds; Guidebook for AGS Spring Field Trip 4/20/2002

Whipple structures



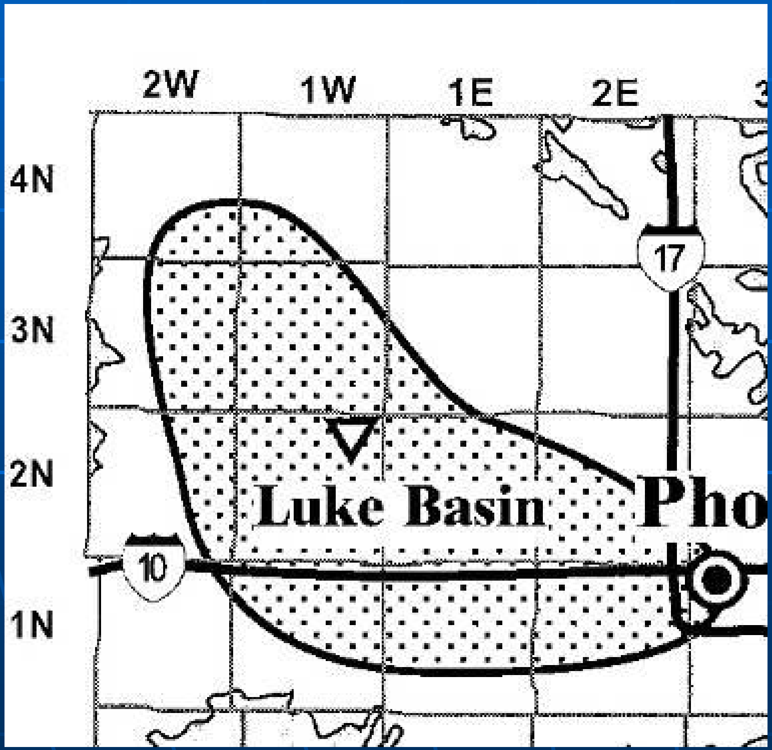
Whipple assemblage



Tumamoc Hill – from South

Basin and Range Assemblage

Luke Salt Body



Evaporites of Miocene basin

- wells have drilled through a maximum of 4258' of halite, but have not penetrated the base of the deposit
- salt deposit is 8 miles long, 5 miles wide, over 1 mile thick (15 mi^3)
- salt may be 10,000 feet thick (as the Luke Basin is 11,200 feet deep)
- may have moved upward 600' (not a dome, but some flow)

Late Cenozoic volcanics

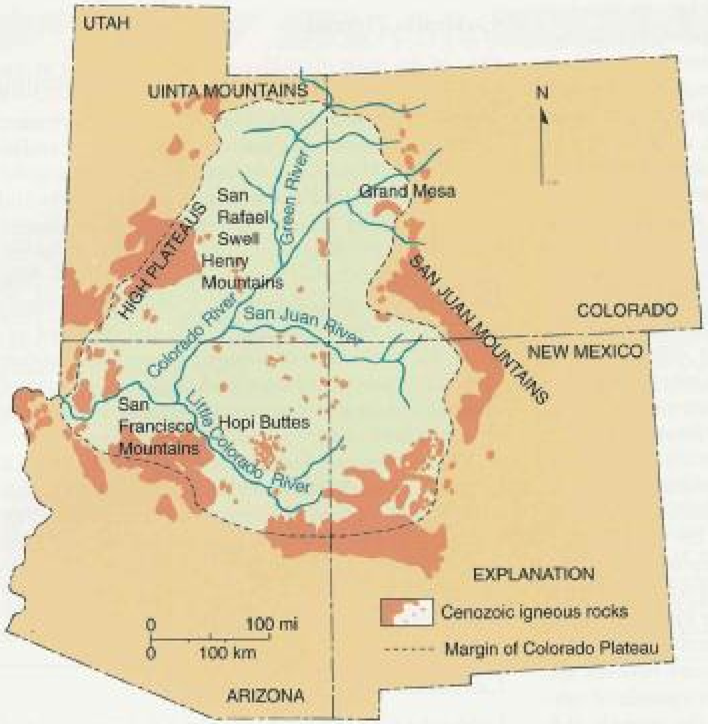


FIGURE 13-19 Location of volcanic and other centers of igneous activity of Cenozoic age in the Colorado Plateau and its periphery. (*From Hunt, C. B. 1956* Cenozoic Geology of the Colorado Plateau, *U.S. Geological Survey Professional Paper 279.*)

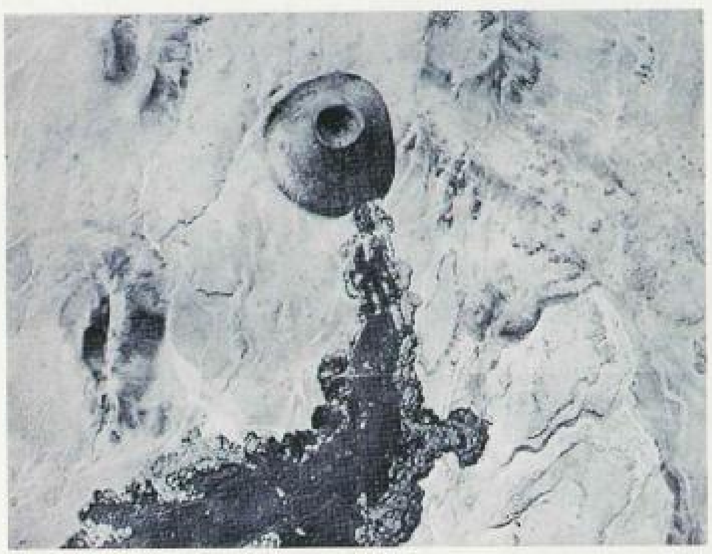
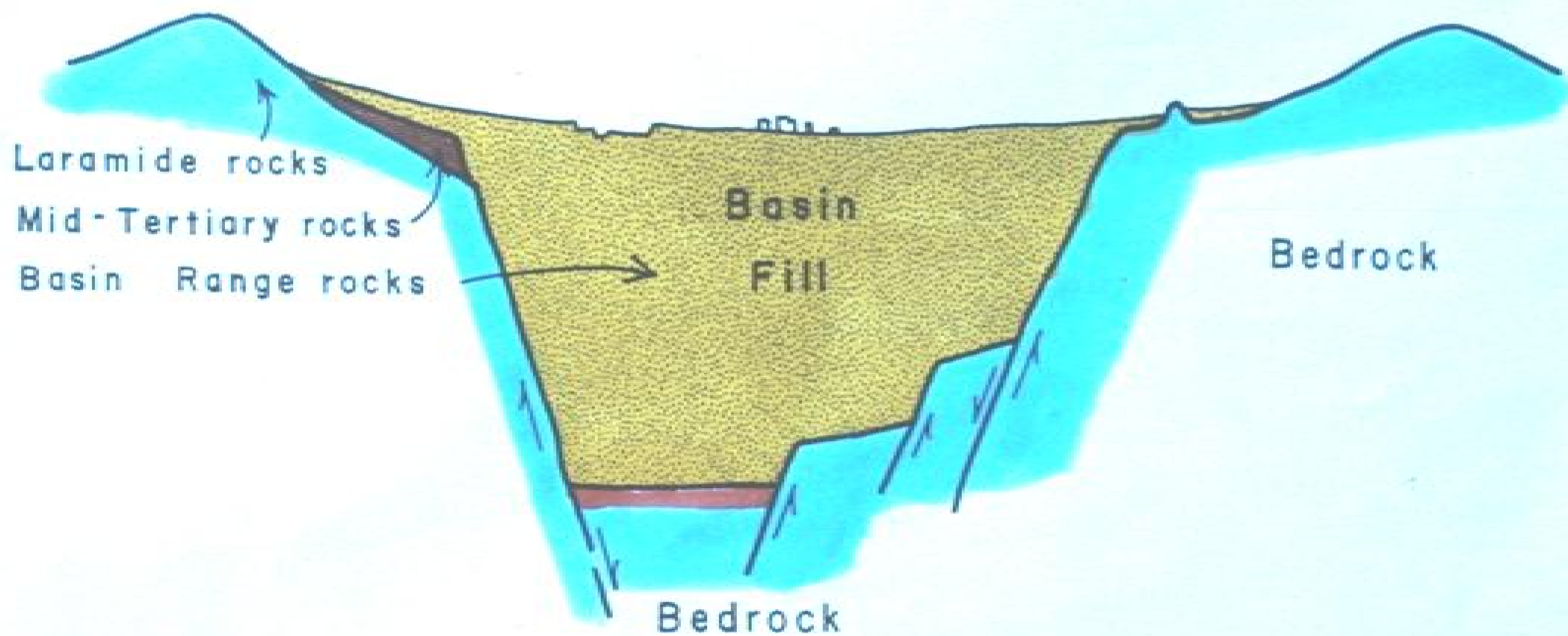


FIGURE 13-20 Vertical aerial photograph of a large cinder cone in the San Francisco volcanic field of northern Arizona. The solidified flow issuing from the cone is 7 kilometers long and more than 30 meters thick. (*Courtesy of U.S. Geological Survey.*) ? *Did the lava flow from the volcano before or after the extrusion of the pyroclastics that built the cinder cone?*

Down-dropped basin

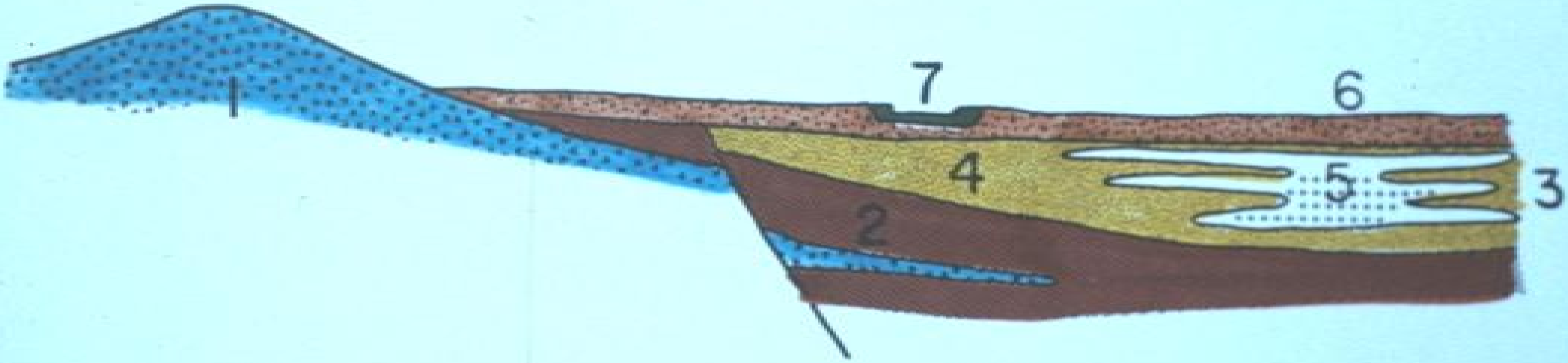


San Pedro Valley B&R

Sonoita – basin fill

Basin fill

Basin cross-section detail



1 LARAMIDE OR MID-TERTIARY VOLCANICS

2 MID-TERTIARY SEDIMENTS

3 BASIN FILL

4 PIEDMONT FACIES

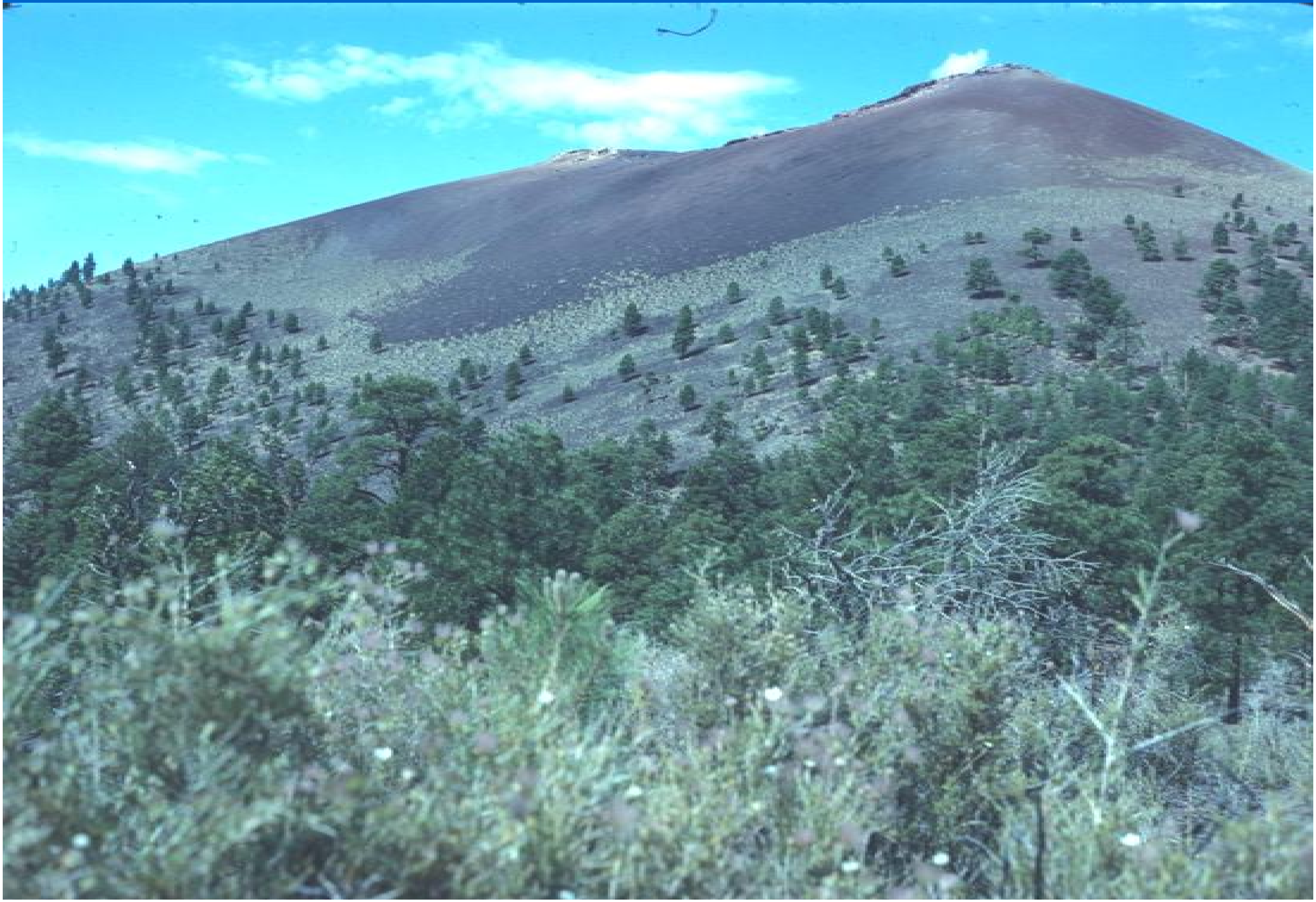
5 VALLEY-CENTER FACIES

6 COARSE-GRAINED ALLUVIUM

7 TERRACES AND FLOODPLAIN

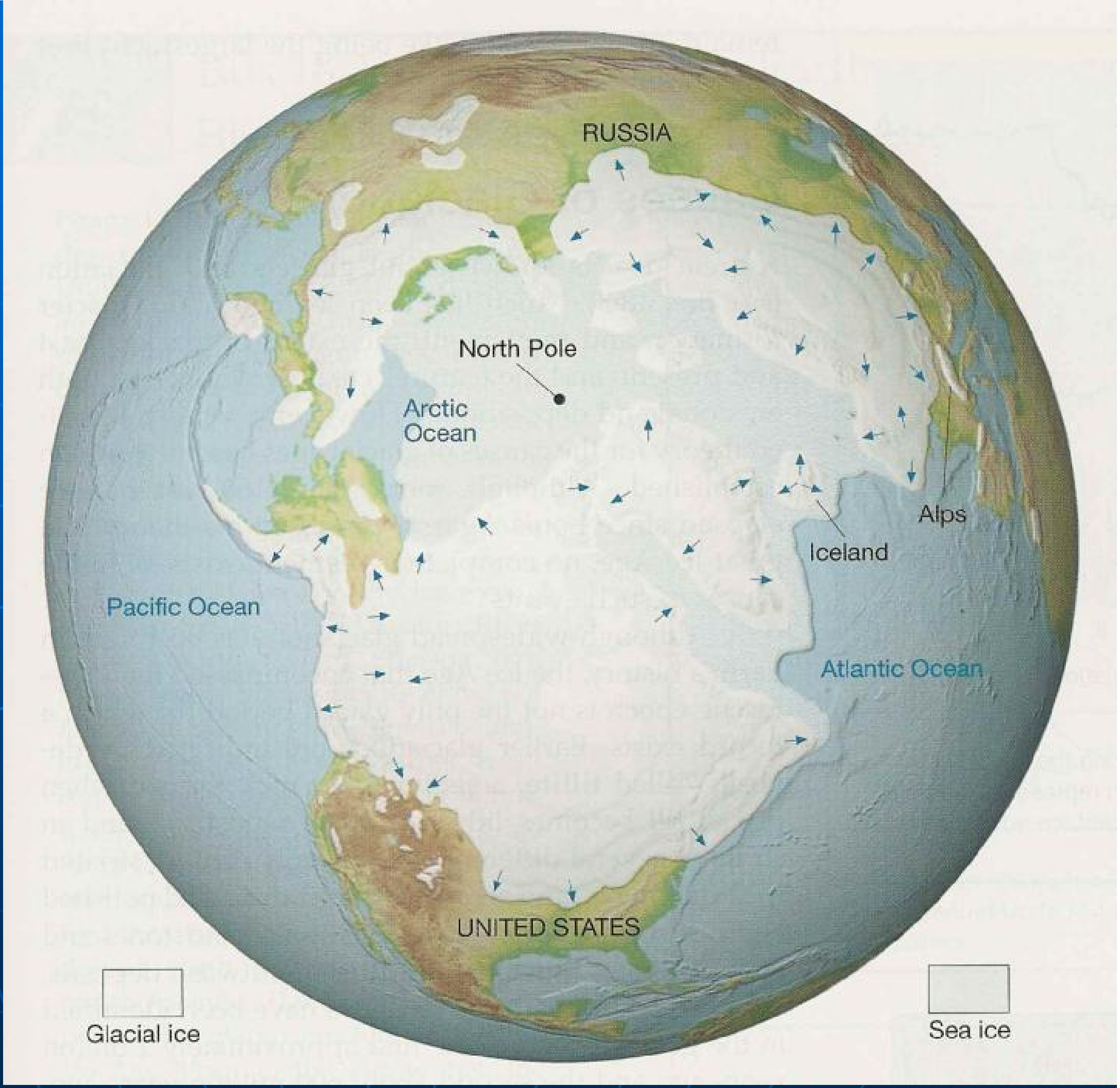
San Francisco Peaks

Sunset Crater



Grand Canyon at Toroweap Valley, West of Visitor Ctr. Note lava flow at Vulcan's Throne

Pleistocene maximum glaciation



Pleistocene glaciation

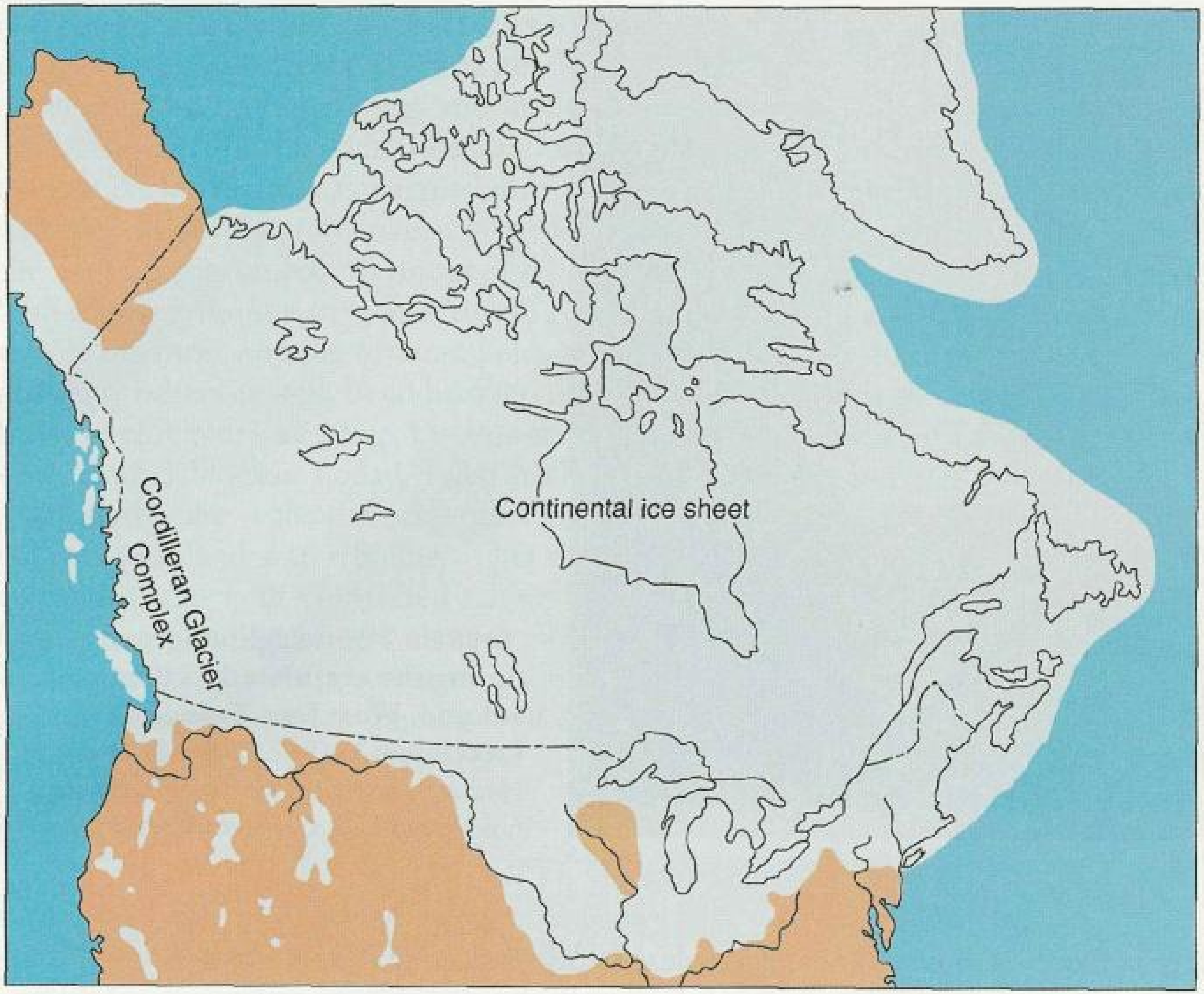


FIGURE 13-36 Areal coverage of continental glaciers in North America during the latest glacial advance, about 18,000 years ago. (*Courtesy of Thompson, G.R. and Turkl, J. 1997*, Modern Physical Geology, *Philadelphia: Saunders College Publishing*.)

Pleistocene temperatures

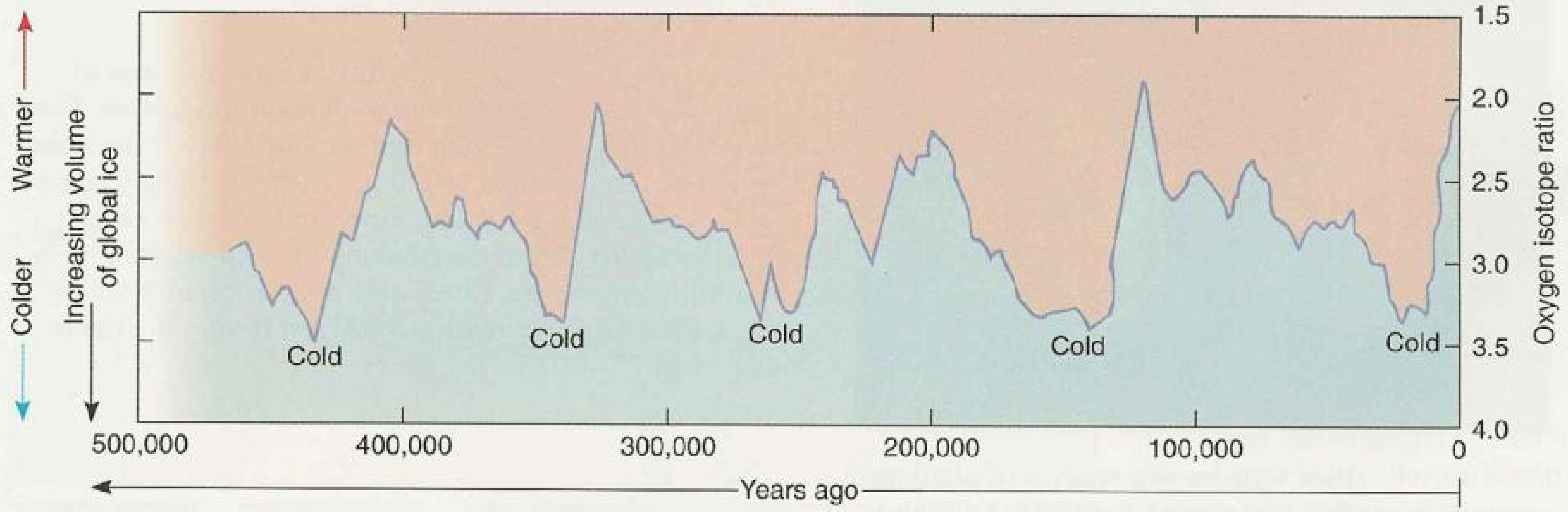
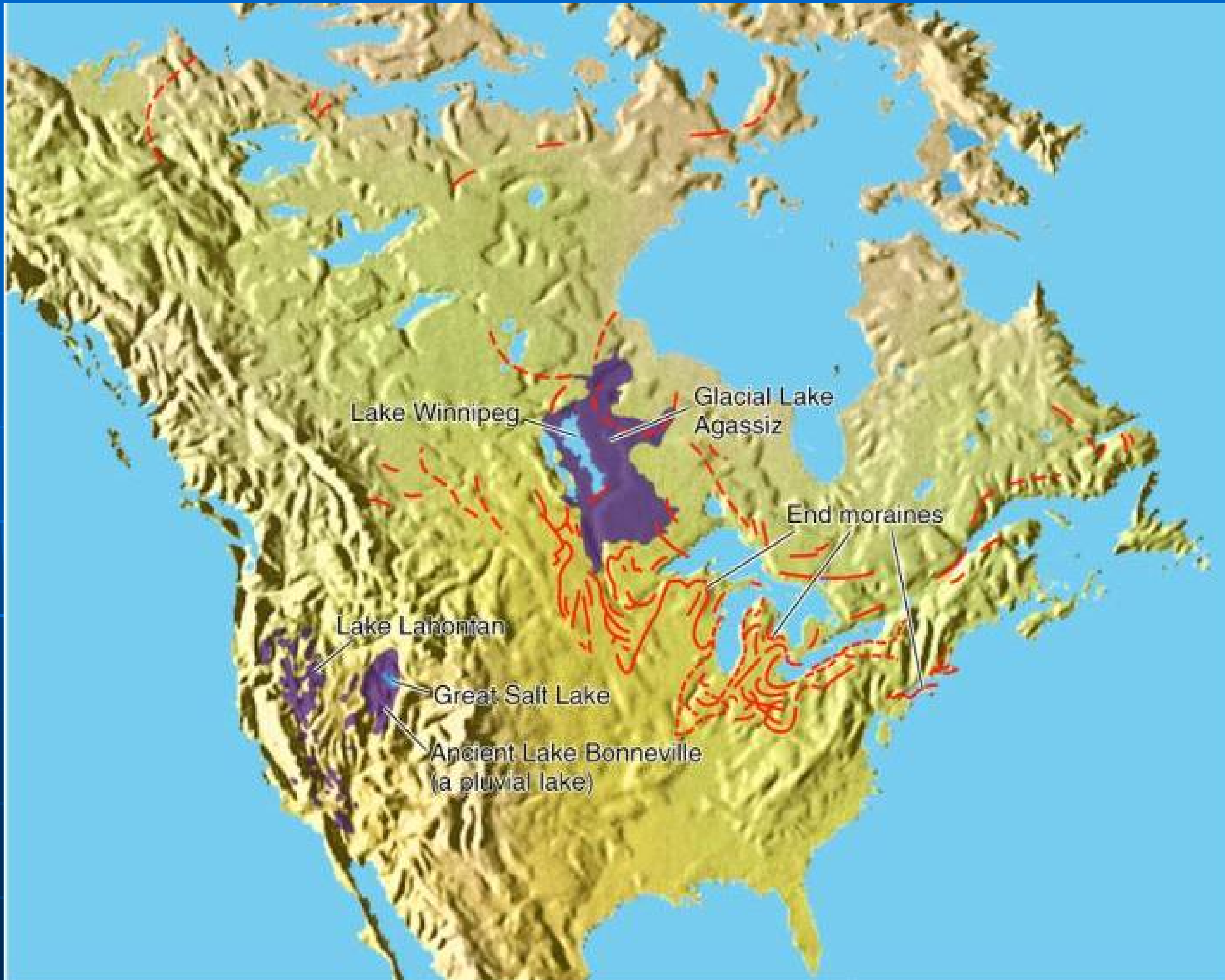
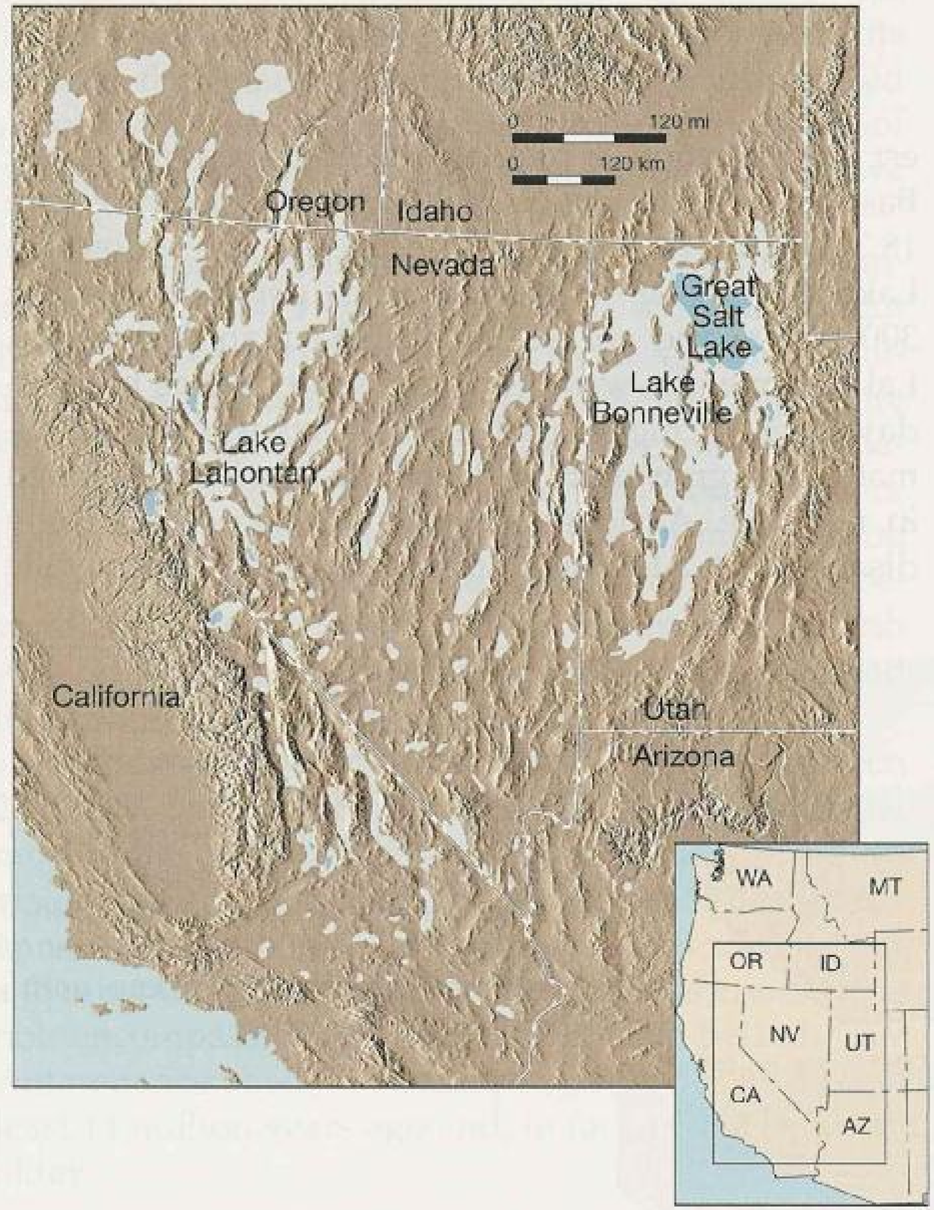


FIGURE 13-43 Curve reflecting variations in the global volume of ice (and, indirectly, paleotemperatures) during the past 500,000 years. Data are from radiometric dating and isotope measurements of cores from the Indian Ocean. (*Data from Hays, J. D., and Shackleton, N. J. 1976. Science 194:1121–1132.*)


Glacial Lake
Agassiz
Lake Winnipeg
End moraines
Lake Lahontan
Great Salt Lake
Ancient Lake Bonneville
(a pluvial lake)

Pluvial – lakes in the West

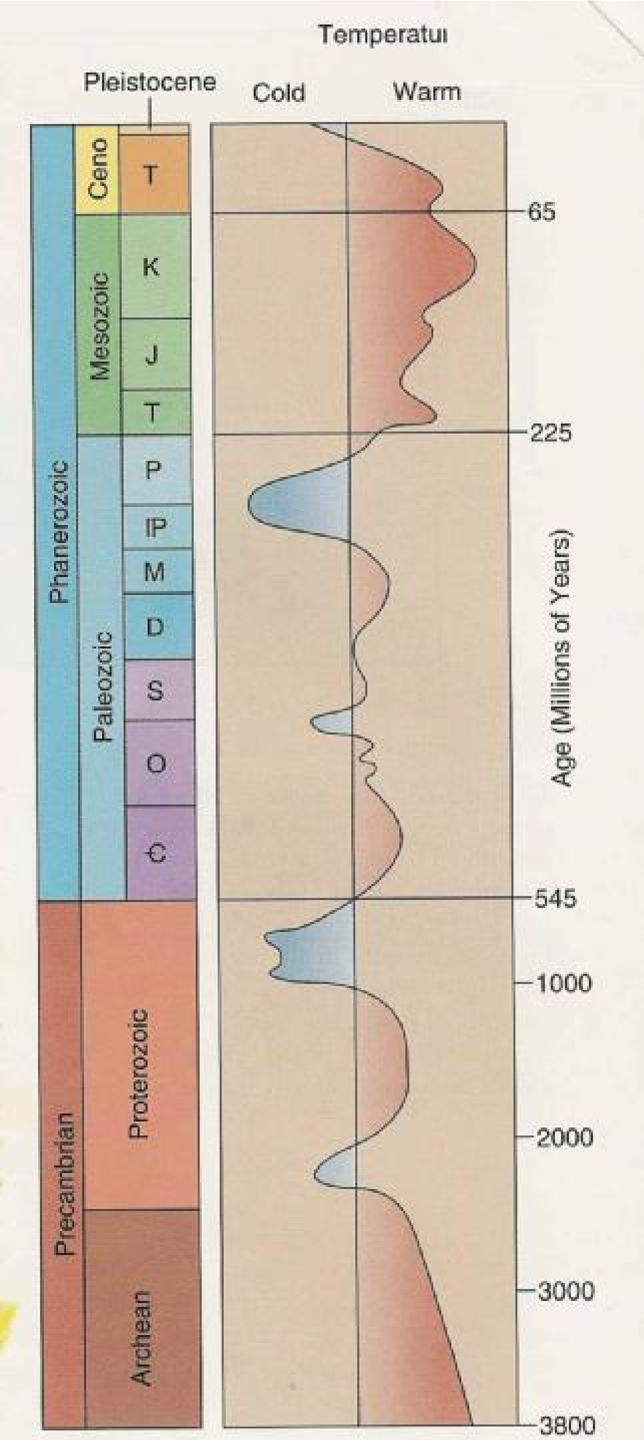


▲ **FIGURE 18.30** Pluvial lakes of the Western United States. (After R. F. Flint, *Glacial and Quaternary Geology*, New York: John Wiley & Sons)

Willcox Playa

Glaciation through Geologic time

Figure 14.37 Several periods of glaciation have been identified in Earth's long history that may record changes in the surface temperature. The graph shows one estimate of relative temperature changes with time. The curve shows when temperatures were higher (to the right) or lower (to the left) than today.



Carbon dioxide, last 100,000,000 years

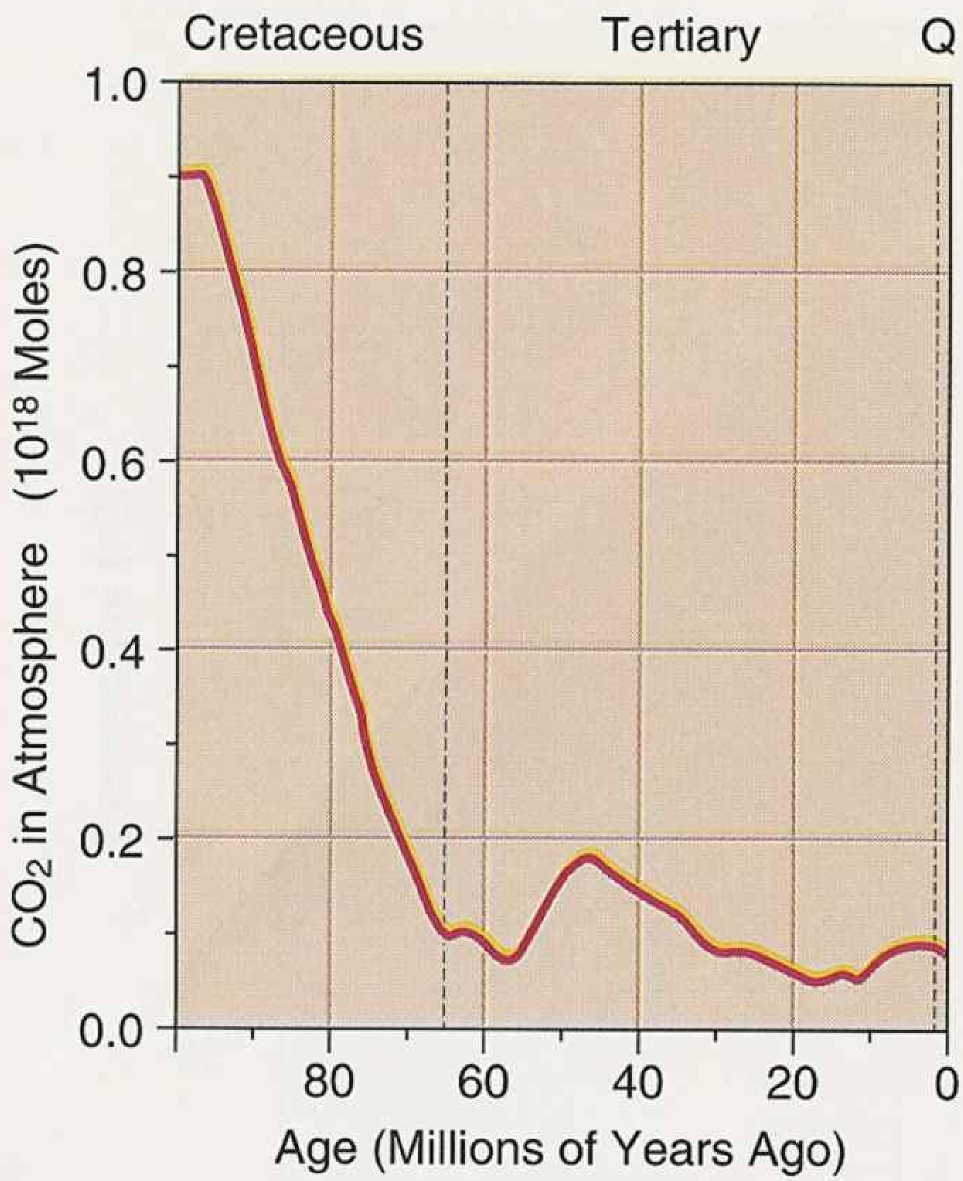


Figure 14.40 The abundance of carbon dioxide in Earth's atmosphere has declined dramatically during the last 100 million years. Loss of this important greenhouse gas may have allowed Earth to cool enough for glaciers to accumulate.

1,000,000 years temperature change

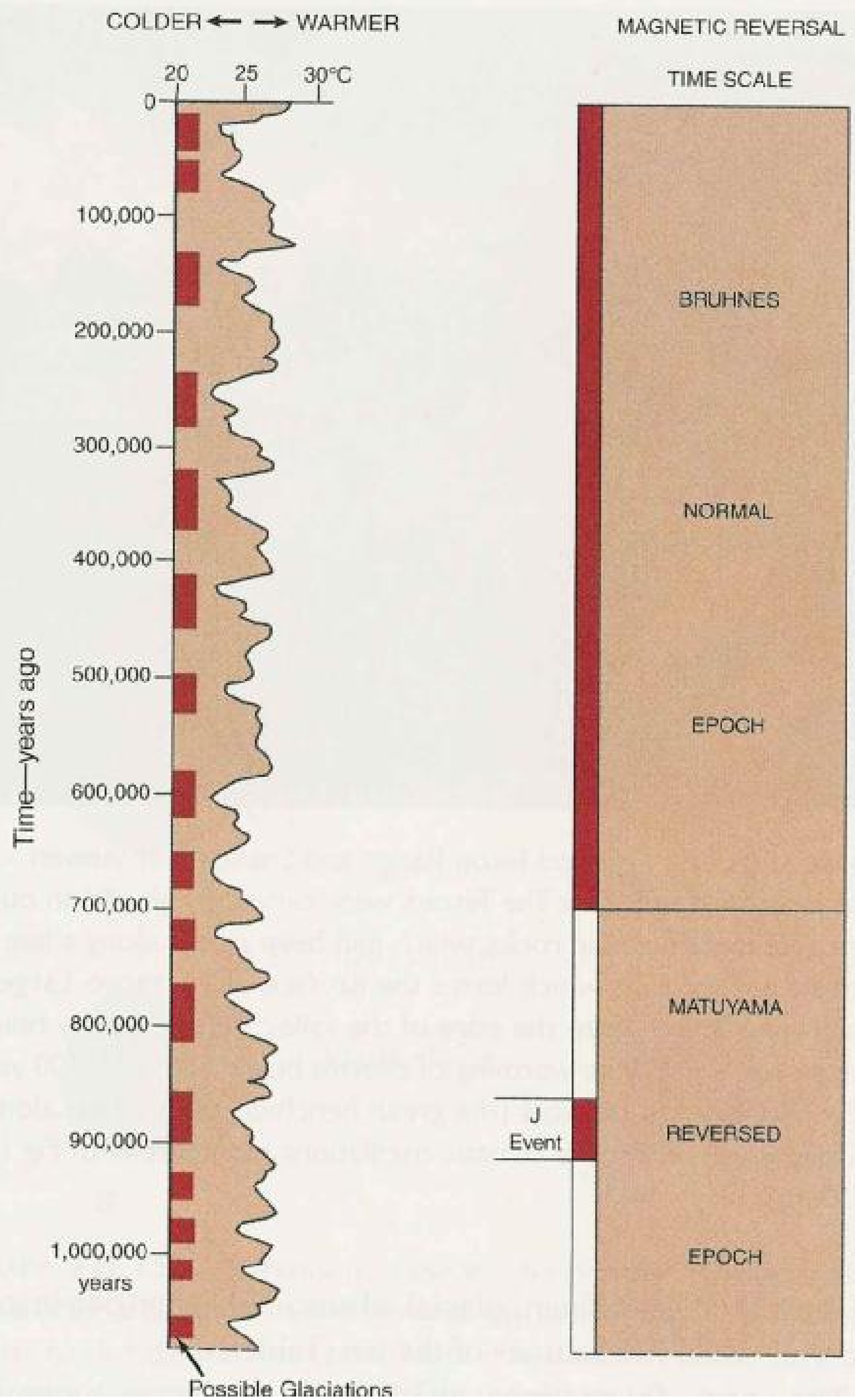


Figure 16.16 Late Pleistocene standard marine paleotemperature curve *(left)* based upon oxygen-isotope analyses of calcium carbonate in microfossil shells from deep-sea cores of three oceans. Magnetic polarity measurements on the same cores *(right)* and limited isotopic dating of cores provide a time 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

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

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

In North America, the glacial stages are Nebraskan, Kansan, Illinoian, and Wisconsinian. These terms correspond approximately to the Günz, Mindel, Riss, and Würm in Europe.

Climate Change 160,000 yrs

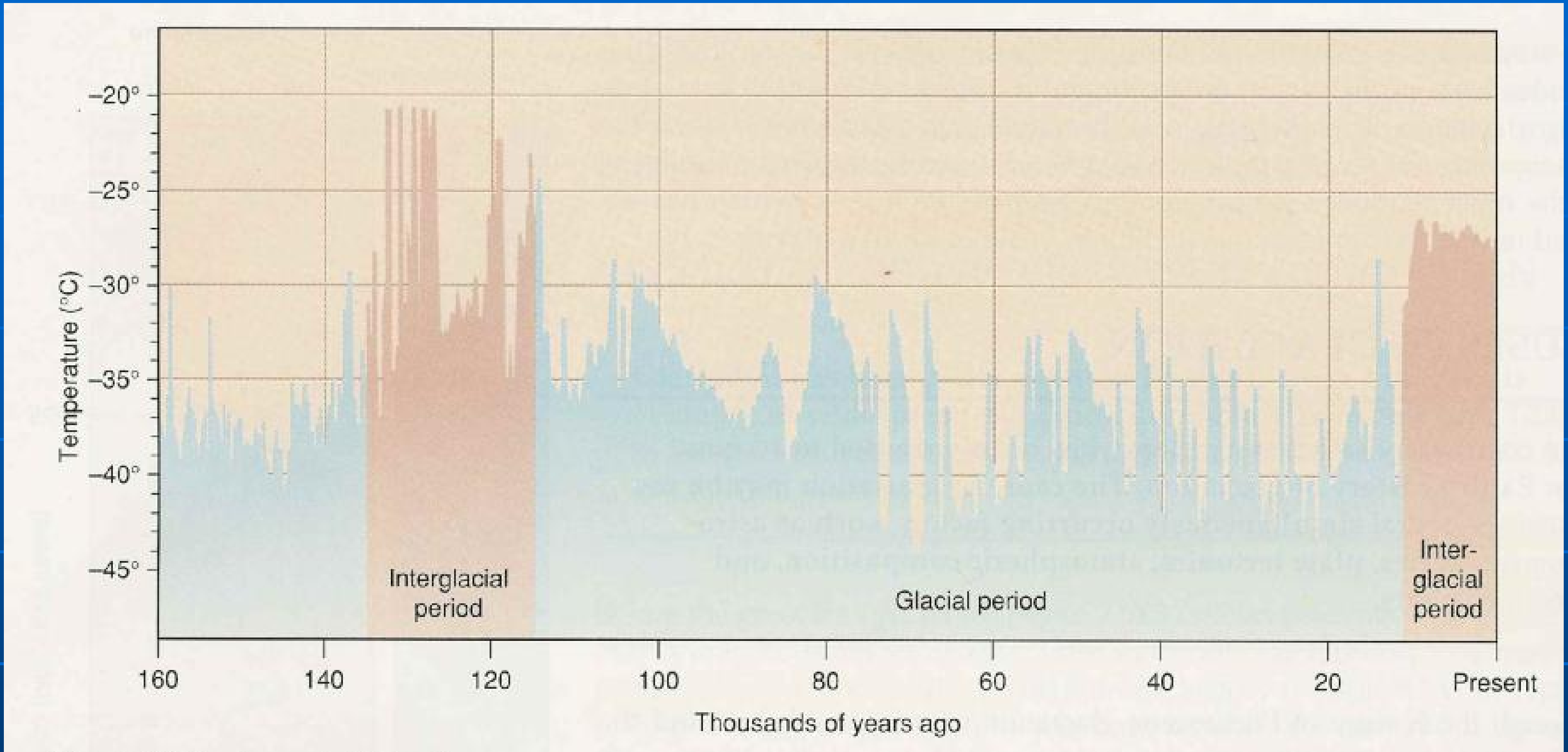
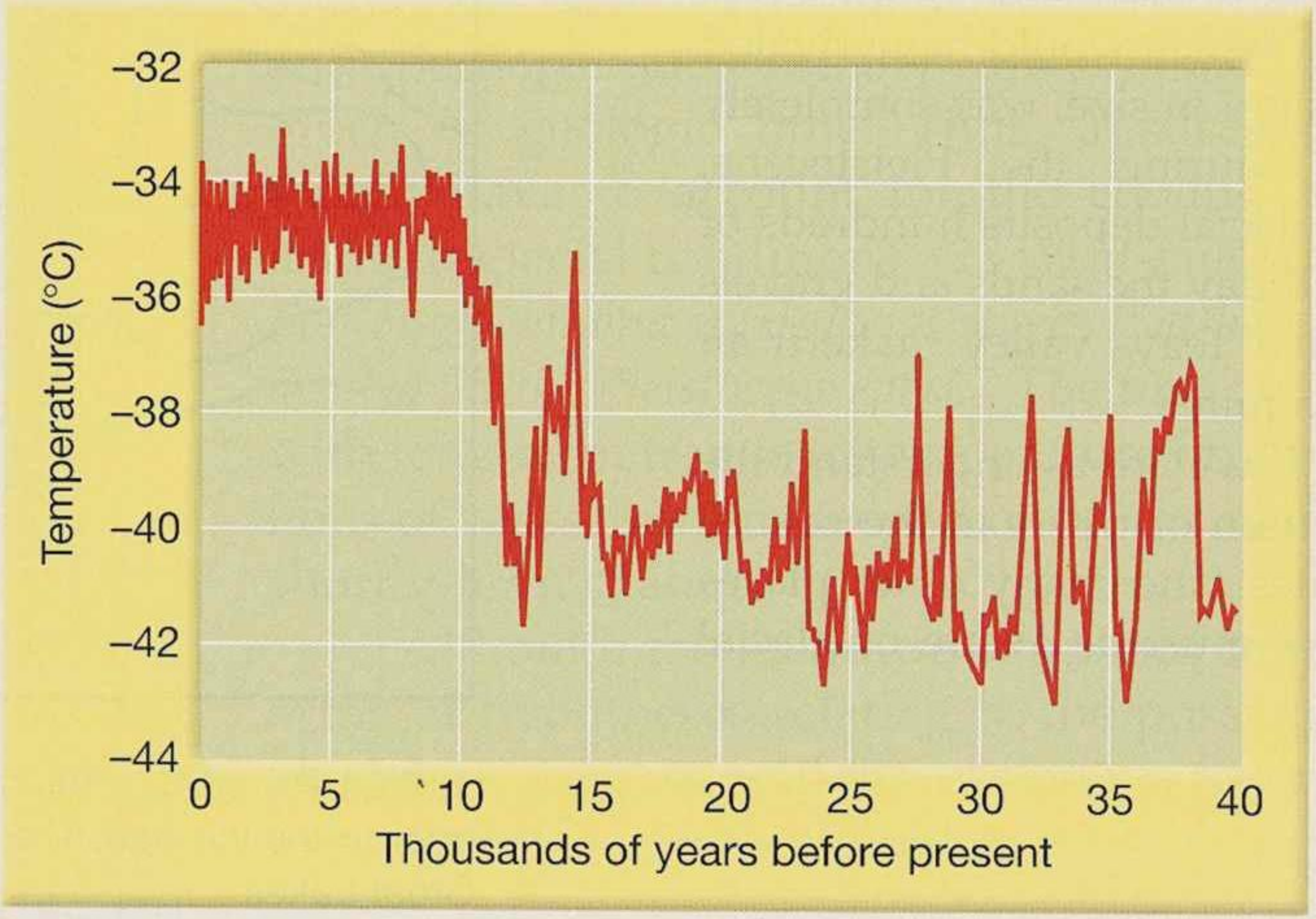


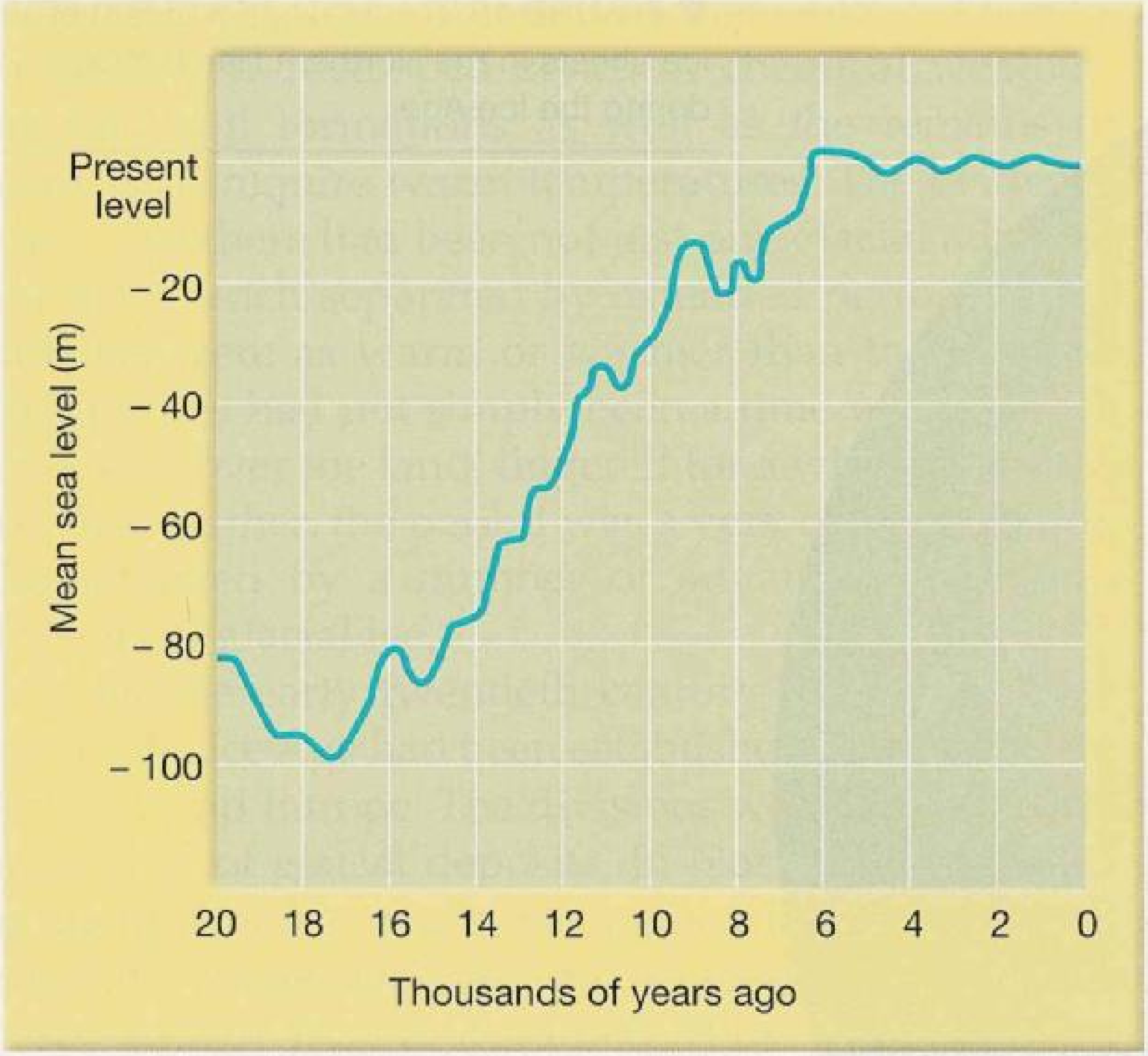
Figure 14.38 A record of climatic change during the last 160,000 years was assembled from studies of ice cores from Greenland's glacier. It shows that the normal pattern of change involves numerous rapid fluctuations in temperature—not only during glacial periods, but throughout interglacial periods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

40,000 yrs temp 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)*

Temperature 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

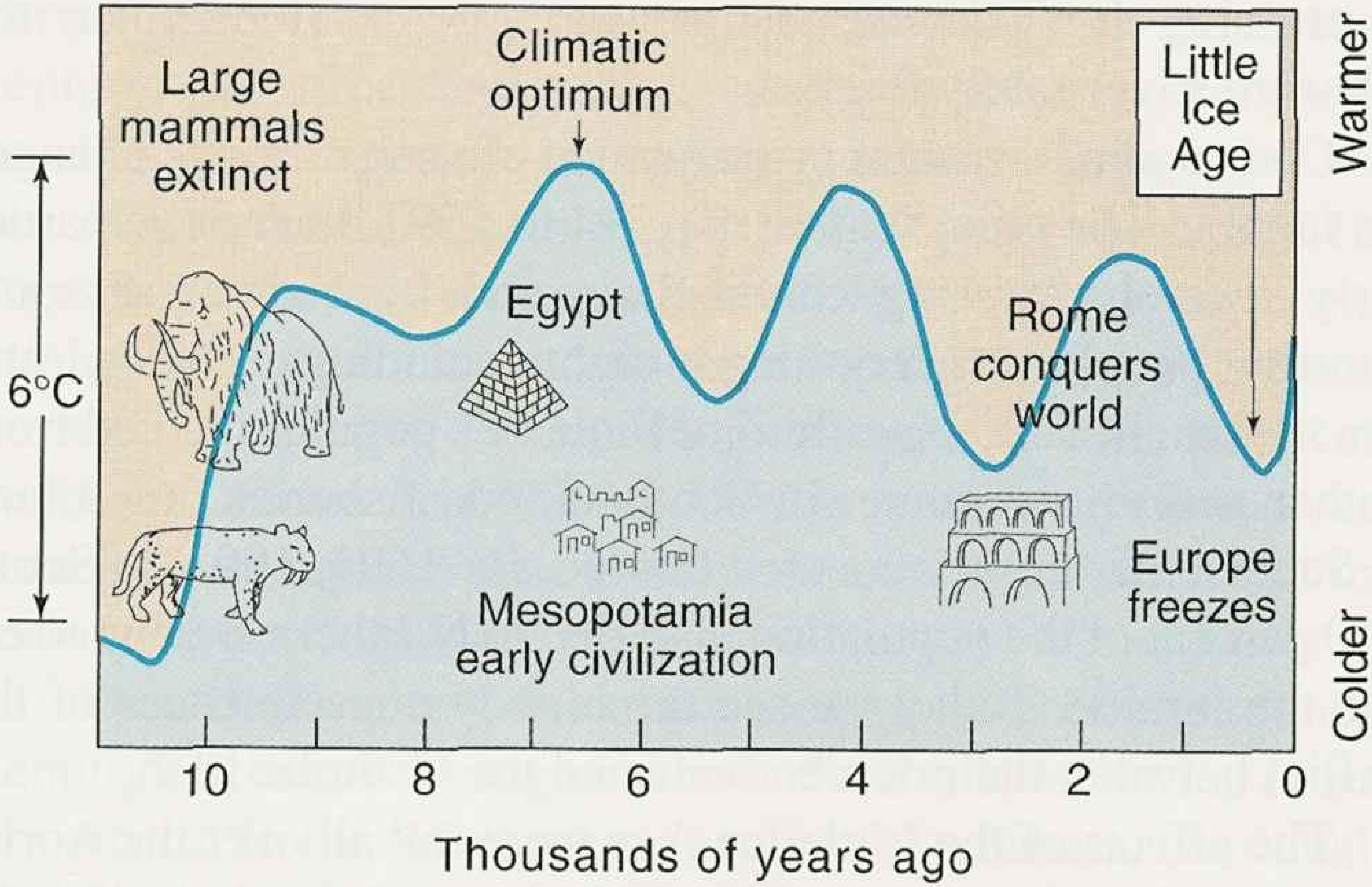


Figure 16.35 The effects of climatic cycles on the past 10,000 years of human history.

Temperature change, 5500 years

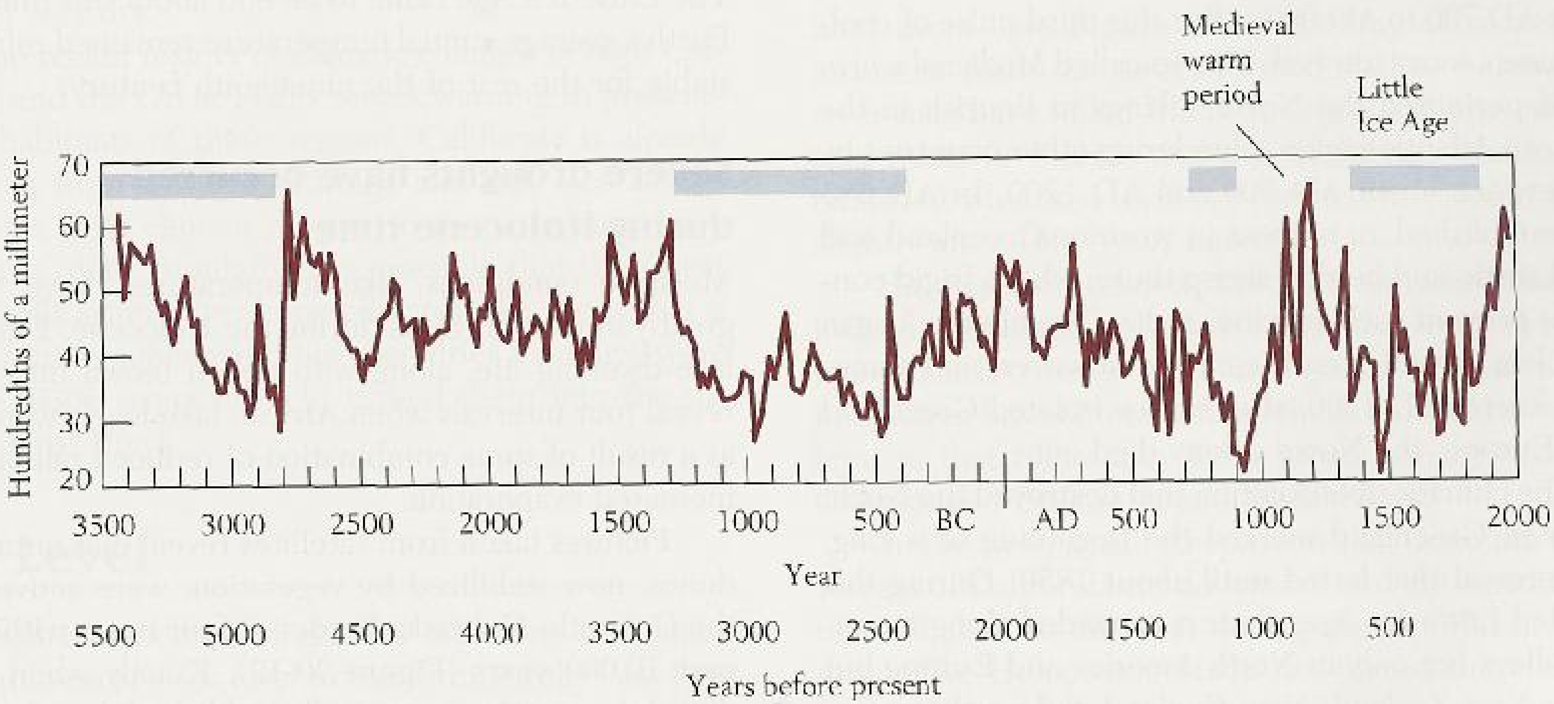


Figure 20-10 **Cold intervals of the past 5500 years recorded by widths of annual growth rings in bristlecone pines near the upper tree line of the White Mountains of California.** (Data from V. C. La Marche, in H. H. Lamb, *Climate History and the Modern World*, Routledge, London, 1995.)

LaBrea tarpits, L.A.

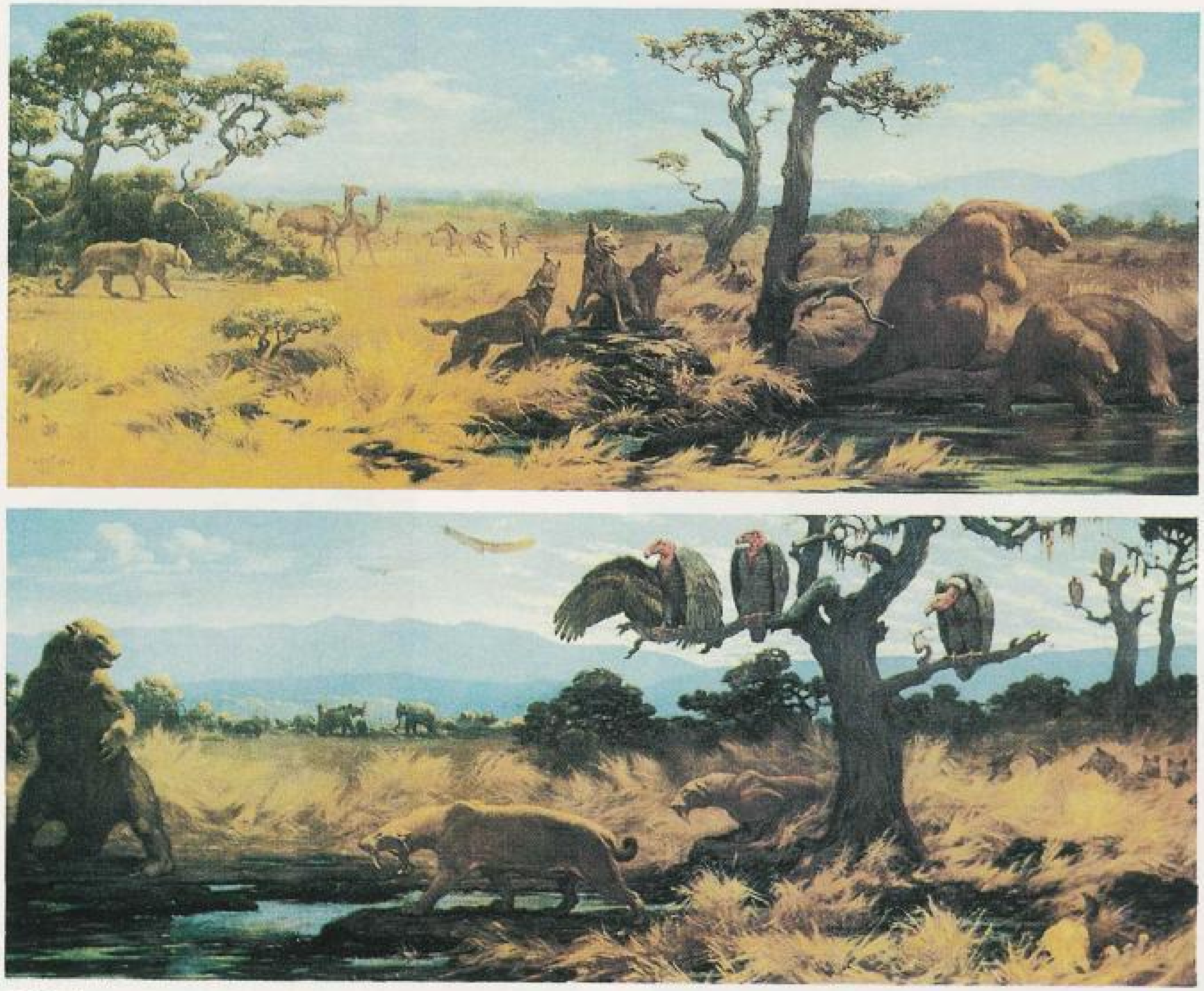


Figure 16.26 Reconstruction of life in Los Angeles about 40,000 years ago, as preserved in the famous tar pits of Rancho La Brea. The tar came from oil seeping up from the Miocene rocks in the Los Angeles Basin and forms natural ponds, which are typically covered by rainwater. Thirsty animals waded into the water and became trapped by the sticky tar. Typically the panicked cries of a single trapped animal would attract many predators and scavengers, so the tar pits have many more fossils of saber-toothed cats, dire wolves, lions, bears, and vultures than they have bison, camels, horses, ground sloths, or mammoths and mastodonts. However, in nature there is much more biomass of prey species than endothermic predators (see Fig. 14.51), so the tar pits were a selective death trap that preserves a biased sample of life. In this famous reconstruction by Charles R. Knight, prey species (such as the ground sloth, camels, horses, and mammoths) are in the background relative to the predators and scavengers (saber-toothed cats, lions, dire wolves, and giant vultures). *(Mural by Charles Knight. Courtesy of George C. Page Museum.)*

Cratonic sequences

Unconformity bounded

Continental assembly

Erosion & uplift

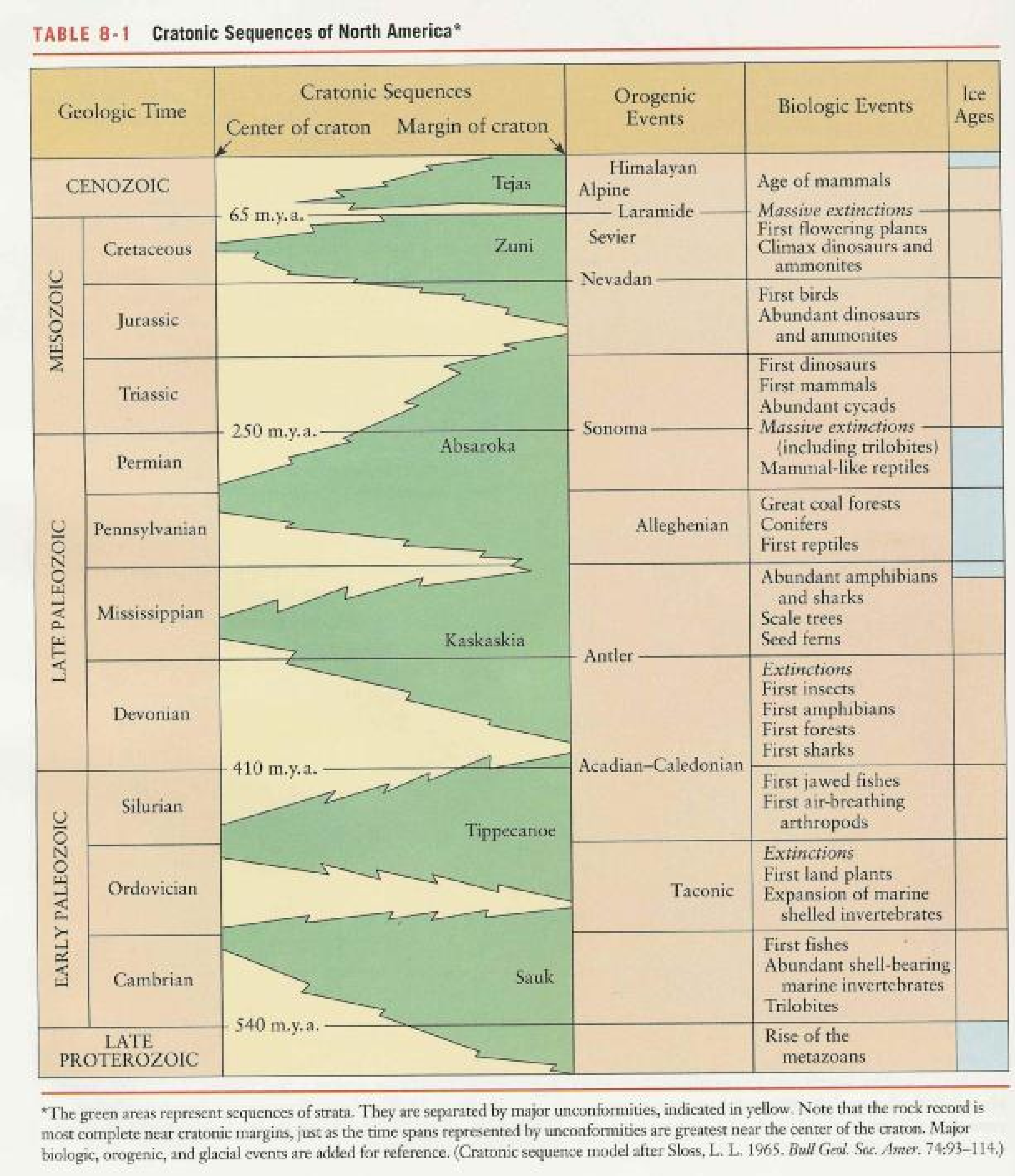


TABLE 8-1 Cratonic Sequences of North America*

Geologic Time		Cratonic Sequences (Center of craton → Margin of craton)	Orogenic Events	Biologic Events
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
	Triassic			First dinosaurs; First mammals; Abundant cycads
		250 m.y.a.	Sonoma	*Massive extinctions* (including trilobites)
LATE PALEOZOIC	Permian	Absaroka		Mammal-like reptiles
	Pennsylvanian		Alleghenian	Great coal forests; Conifers; First reptiles
	Mississippian	Kaskaskia		Abundant amphibians and sharks; Scale trees; Seed ferns
			Antler	
	Devonian			*Extinctions*; First insects; First amphibians; First forests; First sharks
		410 m.y.a.	Acadian–Caledonian	
EARLY PALEOZOIC	Silurian	Tippecanoe		First jawed fishes; First air-breathing arthropods
	Ordovician		Taconic	*Extinctions*; First land plants; Expansion of marine shelled invertebrates
	Cambrian	Sauk		First fishes; Abundant shell-bearing marine invertebrates; Trilobites
		540 m.y.a.		
LATE PROTEROZOIC				Rise of the metazoans

*The green areas represent sequences of strata. They are separated by major unconformities, indicated in yellow. Note that the rock record is most complete near cratonic margins, just as the time spans represented by unconformities are greatest near the center of the craton. Major biologic, orogenic, and glacial events are added for reference. (Cratonic sequence model after Sloss, L. L. 1965. *Bull Geol. Soc. Amer.* 74:93–114.)