

## Earth Through Time

### Revisiting Plate Tectonics

- Details using more concepts and vocabulary
- “How” we know as well as “what” we know

## Summary

- An understanding of global tectonics evolved during the 20<sup>th</sup> century. Continental Drift Theory (1911-1930) was based on geologic, paleontological, and paleoclimate observations. No compelling causal mechanism was accepted. The Plate Tectonic revolution (1950s-1970) involved both new observations from paleomagnetism and seismology and a compelling causal mechanism (sea floor spreading).
- The lithosphere is broken into six large and many small plates, each about 100 km thick and each slowly moving over the top of the weak asthenosphere beneath it.
- Three kinds of margins are possible between plates. Divergent margins (spreading centers) are those where new lithosphere forms; plates move away from them. Convergent margins (subduction zones) are lines along which plates compress each other and along which lithosphere capped by oceanic crust is subducted back into the mantle. Transform fault margins are lines where two plates slide past each other.
- Plate movement can be described in terms of rotation across the surface of a sphere. Each plate rotates around a spreading axis. The spreading axis does not necessarily coincide with the Earth's axis of rotation.
- Because plate movement is a rotation, the velocity varies from place to place on the plate. Each segment of oceanic ridge that marks a divergent margin between two plates lies on a line of longitude passing through the spreading pole. Each transform fault margin between two plates lies on a line of latitude of the spreading pole.

- Two major structural units can be discerned in the continental crust. Cratons are ancient portions of the crust that are tectonically and isostatically stable. Separating and surrounding the cratons are orogens of highly deformed rock, marking the site of former and current mountain ranges
- An assemblage of cratons and deeply eroded orogens that forms the core of a continent is a continental shield.
- There are five kinds of continental margins: passive, convergent, collision, transform fault, and accreted terrane.
- Passive margins develop by rifting of the continental crust. The Red Sea is an example of a young rift; the Atlantic Ocean is a mature rift.
- Continental convergent margins are the locale of paired metamorphic belts, chains of stratovolcanoes (magmatic arc), and linear belts of granitic batholiths.
- Collision margins are the locations of fold-and-thrust mountain systems.
- Transform fault margins occur where the edge of a continent coincides with the transform fault boundary of a plate.
- Accreted terrane margins arise from the addition of blocks of crust brought in by subduction and transform fault motions.

## Tracking Plate Motions

- **Global Positioning System (GPS) measurements confirm current (instantaneous) plate motions.**
- **History of past movements of plates requires geologic evidence.**
  - **Paleomagnetic data**
  - **Reconstructions based on**
    - ≡ **Geology (continuity of strata, metamorphic and structural trends)**
    - ≡ **Paleoclimate indicators**
    - ≡ **Paleontological data**
- **Plates have existed for 2 billion years!**
  - **But record is fragmentary before 175 my**

## Historical Notes

- Sixteenth century mapping first suggested a jigsaw puzzle fit of the Americas to Africa
- Nineteenth century idea: Earth is cooling from molten mass.
  - Contraction explains crust being compressed to make mountains
  - Hard to reconcile with continents moving apart
- Beginning of twentieth century: Earth's interior is kept hot by radioactive decay.
  - The Earth might not be cooling but heating up (and therefore expanding).
  - Heating would cause the Earth to expand and the continental crust would then crack into fragments.

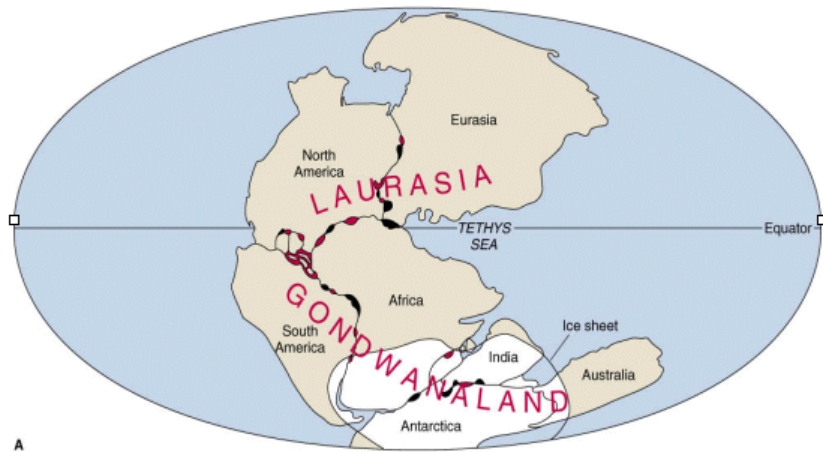


Figure 20.1 A

## Continental Drift Debate (1911-1930)

- Scientific case made by Alfred Wegener
  - Meteorologist who was initially intrigued with coastline match
  - Wrote book in 1911 "Origin of Oceans and Continents"
    - Assembled arguments based on geology, paleoclimate indicators, paleontology, and geophysics
    - Coined terms: Pangea, Laurasia, Gondwanaland
  - Ideas evaluated and rejected by North American scientists, supported by some European and South African scientists
  - Wegener died in 1930 on a meteorological expedition to Greenland

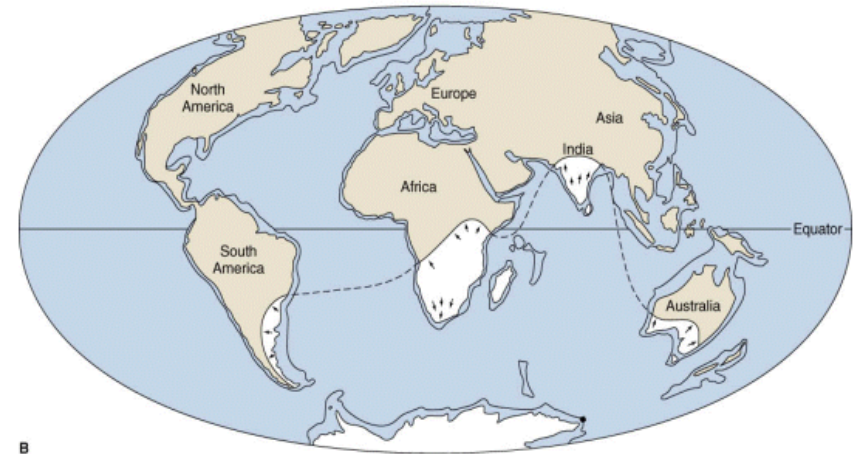


Figure 20.1B



## Objections to Continental Drift

- Geological evidence:
  - Circumstantial, perhaps other plausible explanations
- Paleoclimate:
  - Perhaps the observations are misinterpreted
- Paleontological:
  - Which are more mobile animals or continents?
- Geophysics:
  - Wegener gave no plausible mechanism to move continents

## Plate Tectonic Revolution (1950-1970)

- New observations from paleomagnetism
  - Rocks record orientation of Earth's magnetic field
  - Earth's magnetic field aperiodically reverses
- New observations from seismology
  - Earthquake locations and depth distribution
  - First-motion studies
- New theoretical idea
  - Mantle convection and sea floor spreading

## The "Fossil" Magnetic Record

- Earth's magnetic polarity history
  - normal or reversed at the time of rock's formation.
- Direction to the magnetic pole at the time of formation
- Magnetic inclination
  - indicating how far away the magnetic poles lay

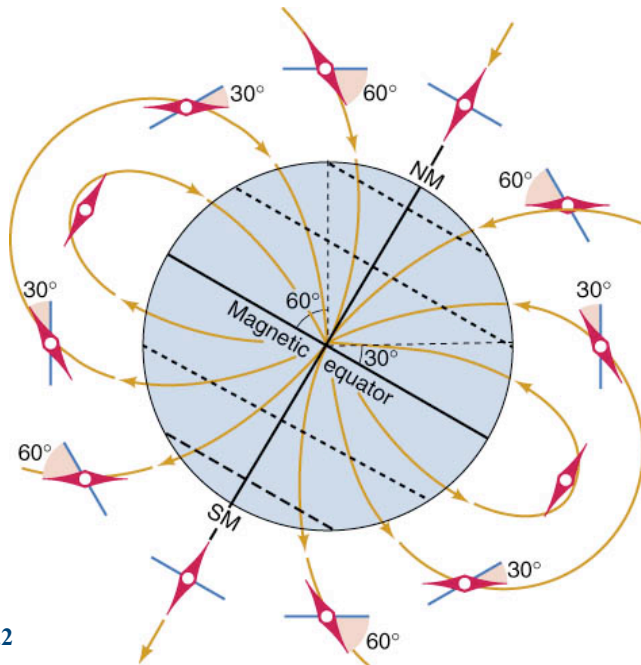
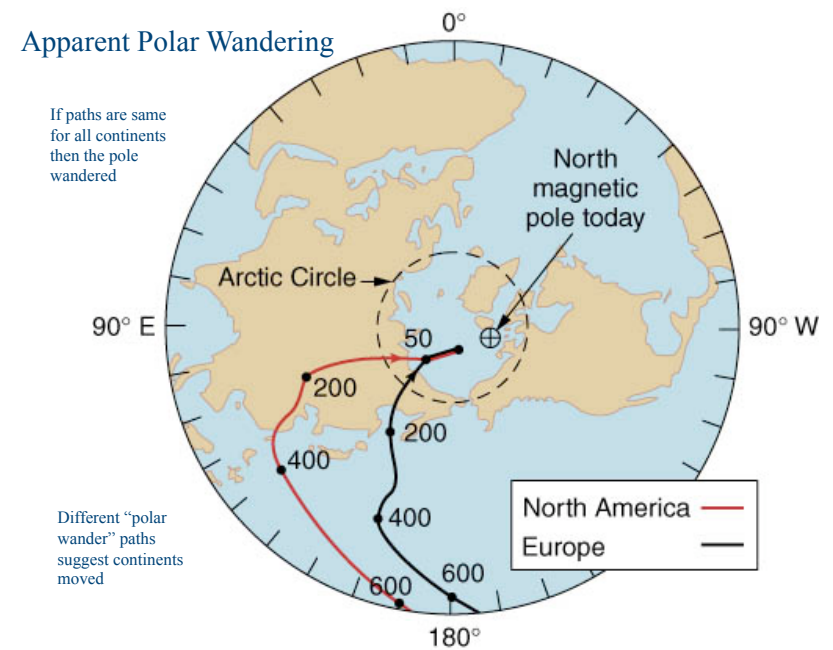


Figure 20.2



## Seafloor Spreading

- In 1962, Harry Hess hypothesized that the topography of the seafloor could be explained if the seafloor moves sideways, away from the oceanic ridges.
  - Hypothesis called “seafloor spreading”
  - Initially viewed skeptically
    - ⇒ One authority suggested that it was “cocktail conversation” not science
    - ⇒ Hess referred to it as “geopoetry”
- In 1963, Vine and Mathews (& Morley) combined sea floor spreading with magnetic reversals to explain ocean magnetic surveys

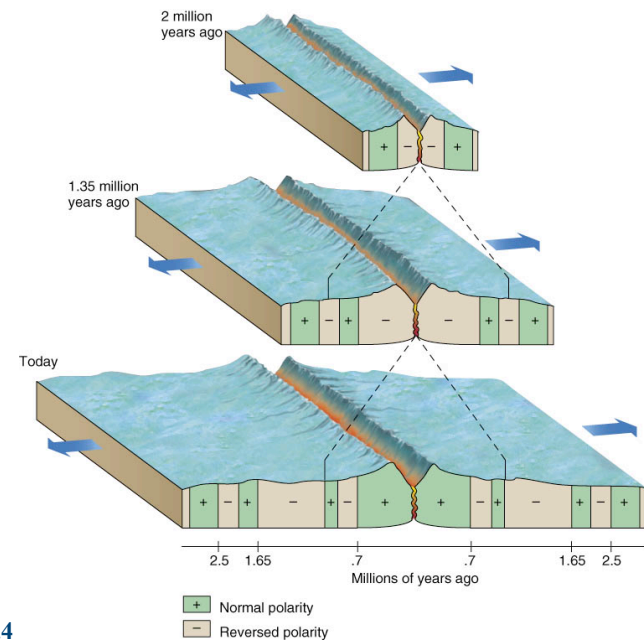
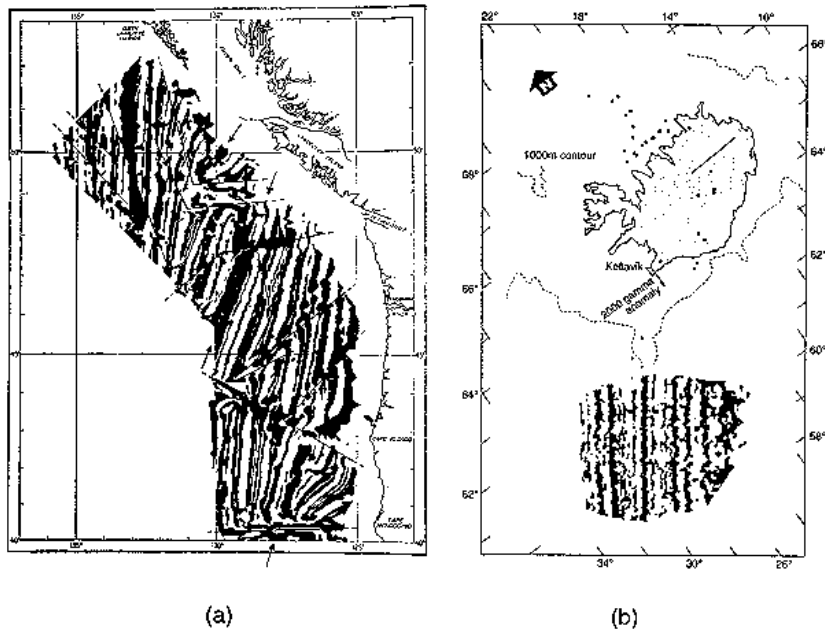


Figure 20.4





## Magnetic Record And Plate Velocities

- The most recent magnetic reversal occurred 780,000 years ago.
- The oldest reversals so far found date back to the middle Jurassic, about 175 million years ago.
- From the symmetrical spacing of magnetic time lines it appears that both plates move away from a spreading center at equal rates.

## Magnetic Record And Plate Velocities

- All that can be deduced from magnetic time lines is the relative velocity of two plates.
- Absolute velocities requires information from GPS measurements (for present-day plate motions), or hot spot tracks, or past plate motions;
  - Plates with only oceanic lithosphere tend to have high relative velocities (Pacific and Nazca plates).

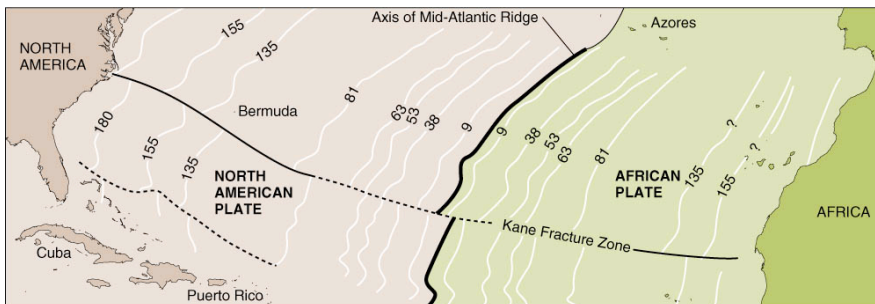


Figure 20.5

## Magnetic Record And Plate Velocities

- Plates with a great deal of thick continental lithosphere, such as the African, North American, and Eurasian plates, have low relative velocities.
- Plate velocities vary with the geometry of motion of a sphere.
  - ⇒ Plates of lithosphere are pieces of a shell on a spherical Earth.

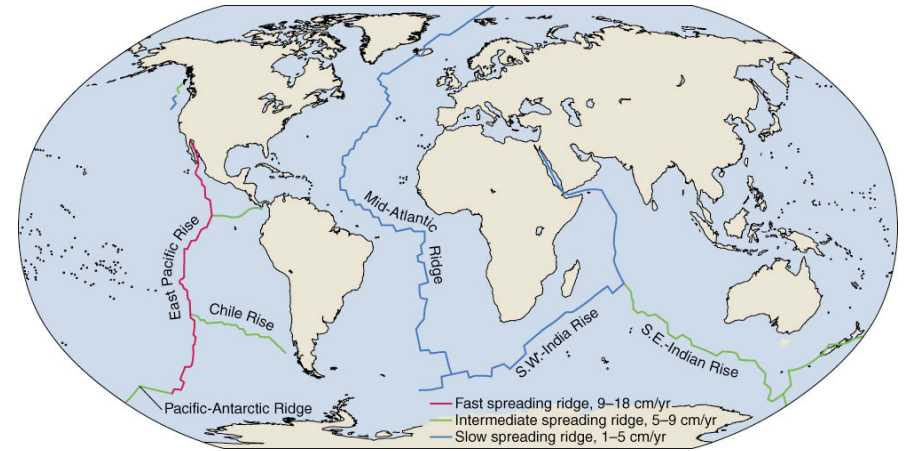


Figure 20.6

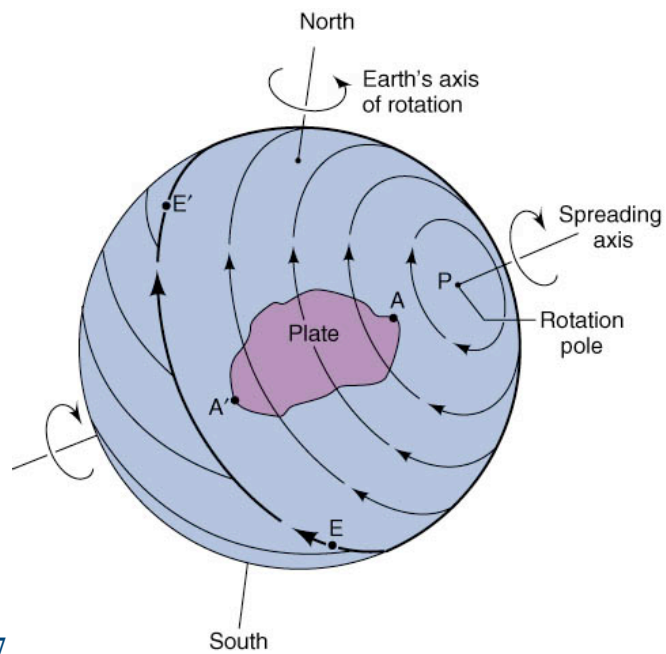


Figure 20.7

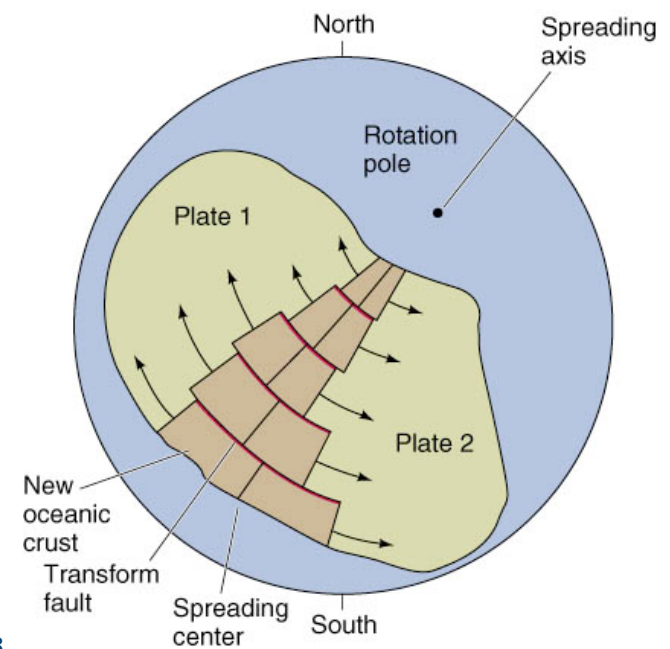


Figure 20.8

## Relict Plate Boundaries In The Geologic Record

- Seafloor magnetic strips help us reconstruct plate motion only as far back in time as the Jurassic, some 175 million years ago.
- All large expanses of older oceanic crust have been subducted back into the mantle at convergent plate boundaries.

## Relict Plate Boundaries In The Geologic Record

- Paleomagnetism of continental rock can be used to follow plate motion further back in time,
  - but without the breadth and continuity of seafloor data.
- Today's continents were assembled from many distinct plates or plate fragments.
- Small fragments of continental crust that have drifted as a single unit in the Earth history are called terranes.

## Ophiolites

- The igneous rock formed at a spreading center, known as midocean ridge basalt (MORB), has a distinctive chemistry
- When MORB is found on land, it usually lies within a body of rock that appears to be a fragment of oceanic crust caught up in a continental collision.

## Ophiolites

- The minerals that characterize peridotites, if transform into a assemblage dominated by a distinctive green fibrous mineral called serpentine.
- These serpentine-dominated fragments of oceanic crust found on continents are called ophiolites, from the Greek word for serpent, ophis.

## Ophiolites

- Their structure matches well the crustal structure expected at a midocean ridge:
  - At the top is a thin veneer of sediment that was deposited on the ocean floor.
  - Beneath the sediment is a layer of pillowed basalt.
  - Still deeper are sills of gabbro, the plutonic equivalent of basalt.

## Subduction Mélange

- **Mélange:** chaotic mixture of broken, jumbled, and thrust-faulted rock found at convergent boundaries
  - A sinking plate drags the sedimentary rock downward beneath the overriding plate.
  - Low-temperature metamorphism to blueschists facies.

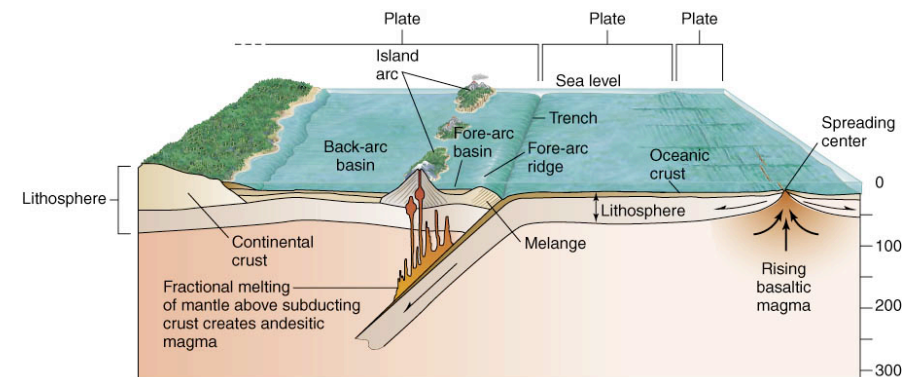
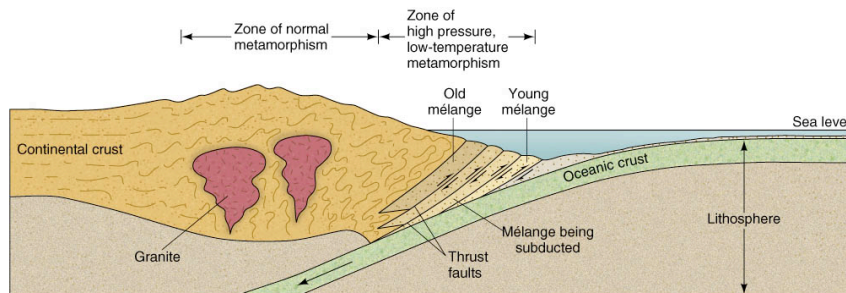


Figure 20.10

Figure 20.11



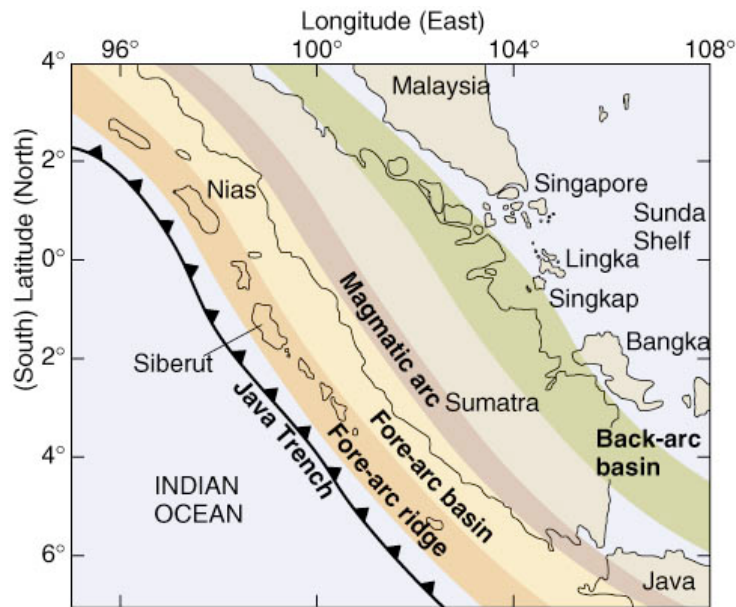


Figure 20.12

## Supercontinents And Vanished Oceans

### ■ Two supercontinents existed in the past:

- Pangaea, formed roughly 350 million years ago,
- Rodinia, an earlier Proterozoic continent formed roughly 1100 million years ago and split apart roughly 750 million years ago.

### ■ The sutures between continental fragments can be found in the many mountain ranges and belts of ophiolites that formed in the late Paleozoic period, roughly between 450 and 350 million years ago.

## Supercontinents And Vanished Oceans

### ■ Examples include:

- The Appalachian mountains in eastern North America.
- The Atlas mountains in Morocco.
- The Ural mountains in Russia.
- The Hercynian mountains in Europe.

### ■ Each of these mountain ranges is heavily eroded now.

## Supercontinents And Vanished Oceans

### ■ Pangaea lasted as a supercontinent for at least 150 million years.

### ■ New oceans formed when Pangaea separated:

- The Atlantic.
- Southern Oceans.

Rodinia

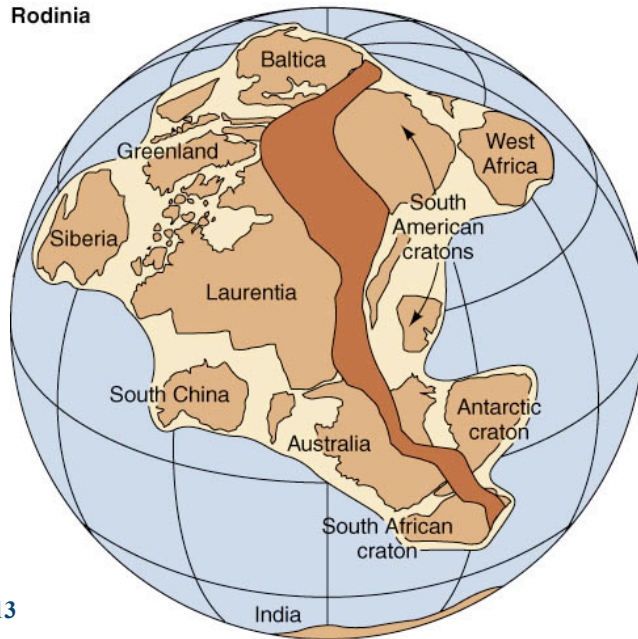


Figure 20.13

## Structures Of Continents

### ■ Two structural units:

- Cratons are ancient cores of continents
- Orogens are elongate regions of crust that have been intensely folded and faulted during continental collision.
  - ⇒ Young orogens remain mountainous today.
  - ⇒ Ancient orogens reveal their history through the kinds of rock they contain and the kind of deformation present.

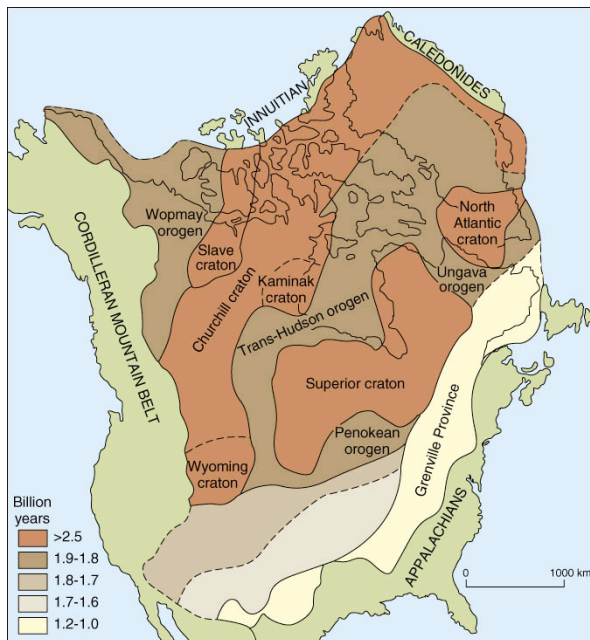


Figure 20.15

## Structures Of Continents

### ■ Continental Shield: assemblage of cratons and ancient orogens that has reached isostatic equilibrium

- Because it is a stable platform, a continental shield is covered by a thin layer of little-deformed sediments.
- North American (Canadian) shield surrounded by orogens younger than 600 my
  - ⇒ Western Cordilleran, Appalachian, ...



## Continental Margins

■ The fragmentation, drift, and welding together of pieces of continental are responsible for the five types of continental margins we know of today:

- Passive.
- Convergent.
- Collision.
- Transform fault.
- Accreted terrane.

## Passive Continental Margins

- A passive continental margin occurs in the stable interior of a plate.
  - Eastern coast of North America.
- Develop when a new ocean basin forms by the rifting of continental crust
  - the Red Sea

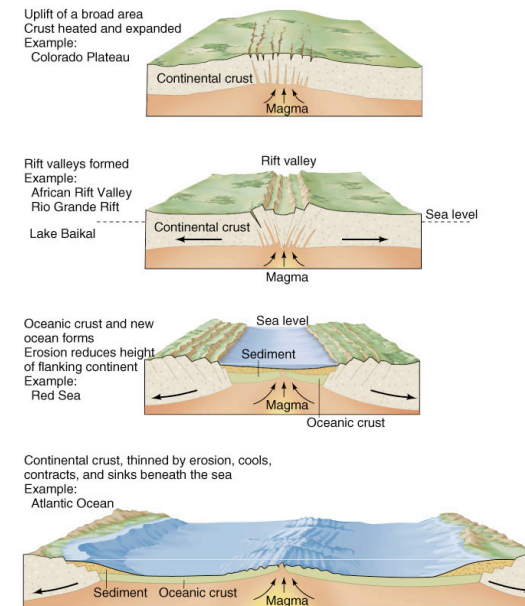


Figure 20.16

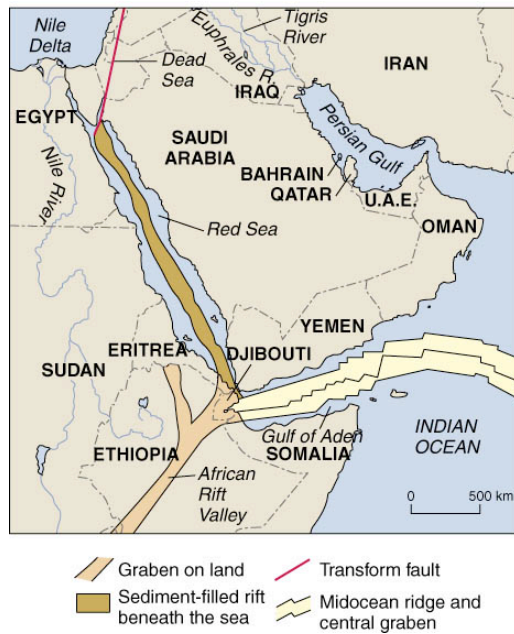


Figure 20.17

## Passive Continental Margins

- Passive continental margins are places where a great thickness of sediment accumulates.
- Formation of three-armed rifts with one of the arms not developing into an ocean is a characteristic feature of passive continental margins.



Figure 20.18

## Continental Convergent Margins

- Oceanic lithosphere subducted beneath continental lithosphere.
- Sediment forms a *mélange*.
  - Sediments subjected to high-pressure and low-temperature metamorphism.
  - Adjacent and parallel to the belt of *mélange*, the crust beneath the continental volcanic arc is metamorphosed
    - Distinctive feature of a continental convergent margin is a pair of parallel metamorphic belts.





Figure 20.19

## Continental Collision Margins

- The edges of two continents, each on a different plate, come into collision at a continental collision margin.
  - This results in intense folding and thrust faulting.
    - ⇒ The Himalayan Mountain chain.
- Within a fold-and-thrust mountain system, strata are compressed, faulted, folded, and crumpled, commonly in an exceedingly complex manner.

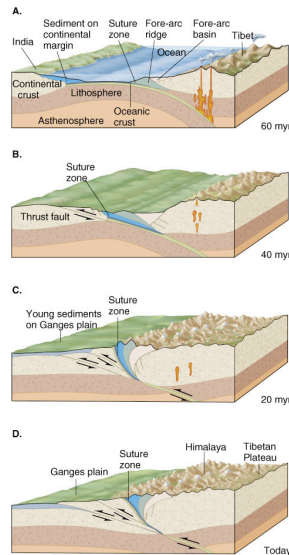


Figure 20.20

## Continental Collision Margins

- Metamorphism and igneous activity are always present.
  - The Alps and Himalayas are young fold-and thrust mountain systems formed during the Mesozoic and Cenozoic eras.
- The Appalachians and Urals are older, Paleozoic-aged, examples.

## Transform Fault Margins

- A transform fault continental margin occurs when the margin of a continent coincides with a transform fault boundary of a plate.
  - The San Andreas Fault.
- The San Andreas Fault apparently arose when the westward-moving North American continent overrode part of the East Pacific Rise.
  - The San Andreas is the transform fault that connects the two remaining segments of the old spreading center.

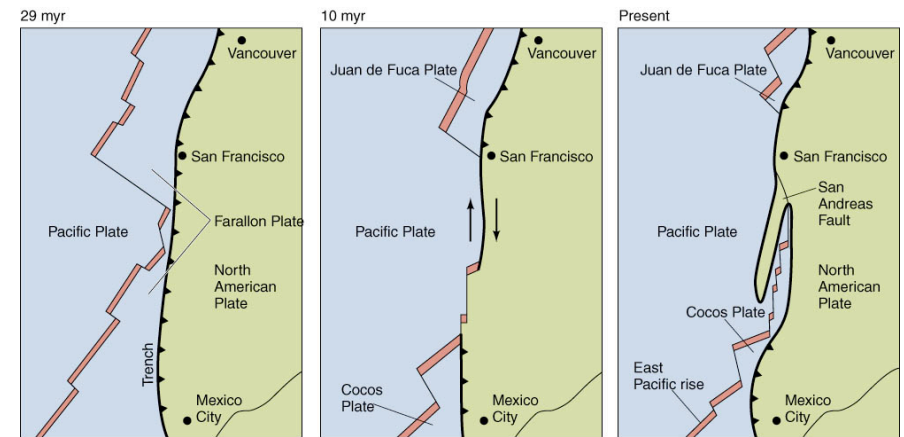


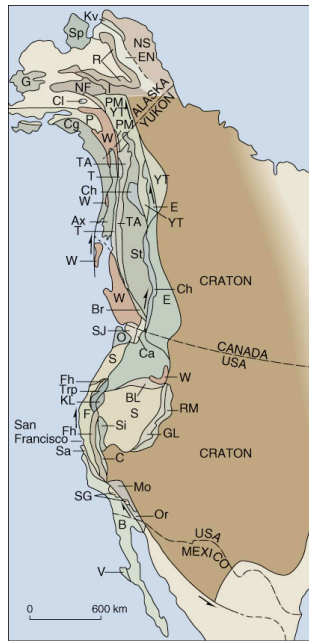
Figure 20.21

## Accreted Terrane Margins

- A former convergent or transform fault margin modified by the addition of rafted-in, exotic fragments of crust.
- Western margin of North America, from central California to Alaska and from coast to Wyoming and Montana is an accreted terrane margin.

## Accreted (Suspect) Terranes

- Geologic entities characterized by a distinctive stratigraphic sequence and structural history.
- Always fault-bounded and differs in its geologic features from adjacent terranes
- Some terranes have moved 5000 km or more.



Symbol	Name
Ax	Alexander
B	Baja
BL	Blue Mountains
BR	Bridge River
C	Calaveras
Cg	Chugach
Ch	Cache Creek
Cl	Chulitna
E	Eastern assemblages
En	Endicott
F	Franciscan and Great Valley
Fh	Foothills Belt
Gl	Golconda
I	Innoko
KI	Klamath Mountains
Kv	Kagvik
Mo	Mohave
NF	Nixon Fork
NS	North Slope
O	Olympic
P	Peninsular
PM	Pingston and McKinley
R	Ruby
RM	Roberts Mountains
S	Siletzia
Sa	Salinian
SG	San Gabriel
Si	Northern Sierra
SJ	San Juan
Sp	Seward Peninsula
St	Stikine
T	Taku
TA	Tracy Arm
Trp	Western Triassic and Paleozoic of Klamath Mountains
V	Vizcaino
W	Wrangella
YT	Yukon-Tanana

Figure 20.22

## Mountain Building

- Today's fold-and-thrust ranges are the orogens that formed during the last few hundred million years.
- Examples include:
  - The Appalachians.
  - The Alps.
  - The Canadian Rockies.

## The Appalachians

- Paleozoic fold-and-thrust mountain system
- Contain mud cracks, ripple marks, fossils of shallow-water organisms, and, in places, fresh water materials such as coal.
- The sedimentary strata thicken from west to east.

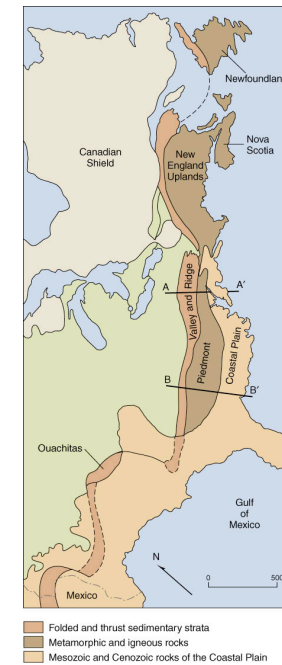


Figure 20.23

■ Folded and thrust sedimentary strata  
 ■ Metamorphic and igneous rocks  
 ■ Mesozoic and Cenozoic rocks of the Coastal Plain

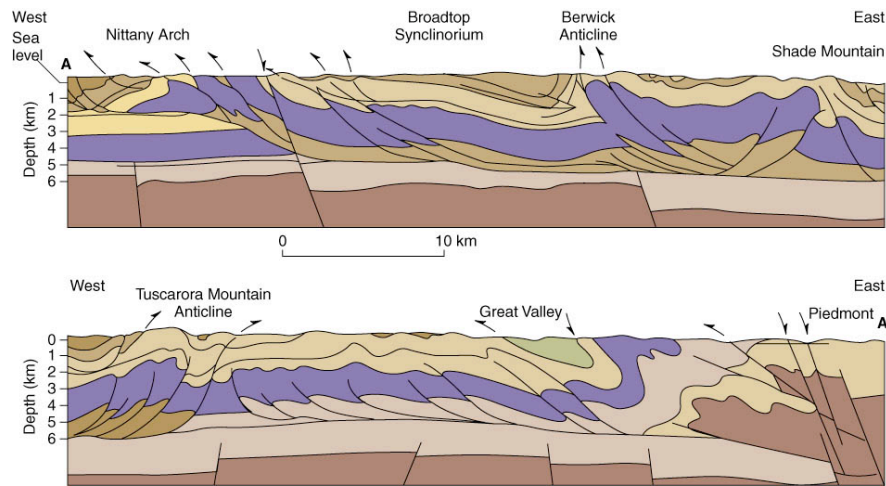


Figure 20.24

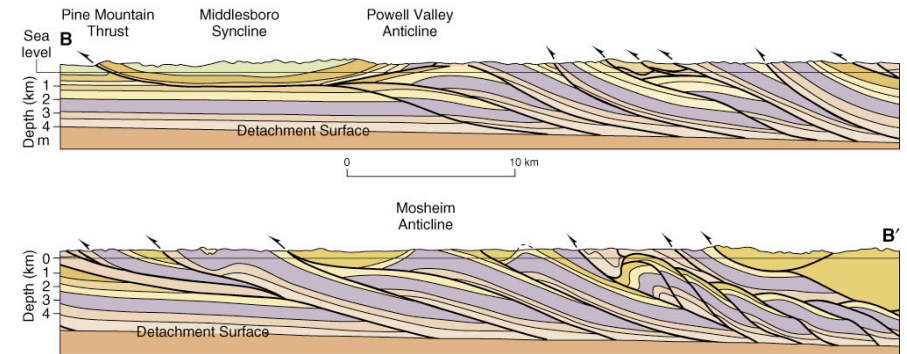


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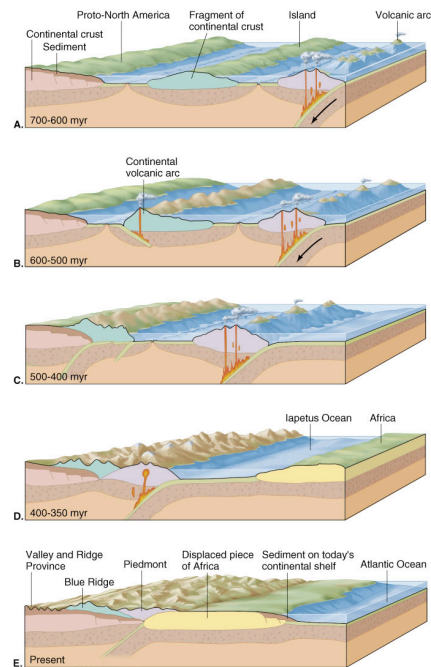


Figure 20.26

## The Alps

- Formed during the Mesozoic and Cenozoic eras, as a consequence of a collision between the European and African plates.
- The Jura Mountains, which mark the northwestern edge of the Alps, have the same folded form and origin as the Valley and Ridge Province in North America.



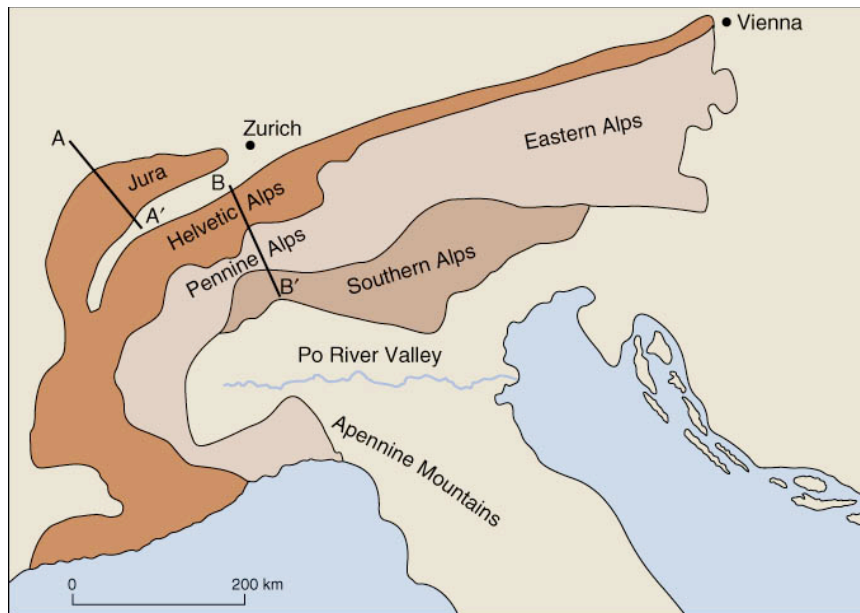


Figure 20.27

## The Alps

- The Jura Mountains were formed from shallow-water sediments deposited on an ancient continental shelf.
- In the high Alps, thrusting appears to have developed on a much grander scale than in the Appalachians.
- The high Alps are composed of deeper-water marine strata.

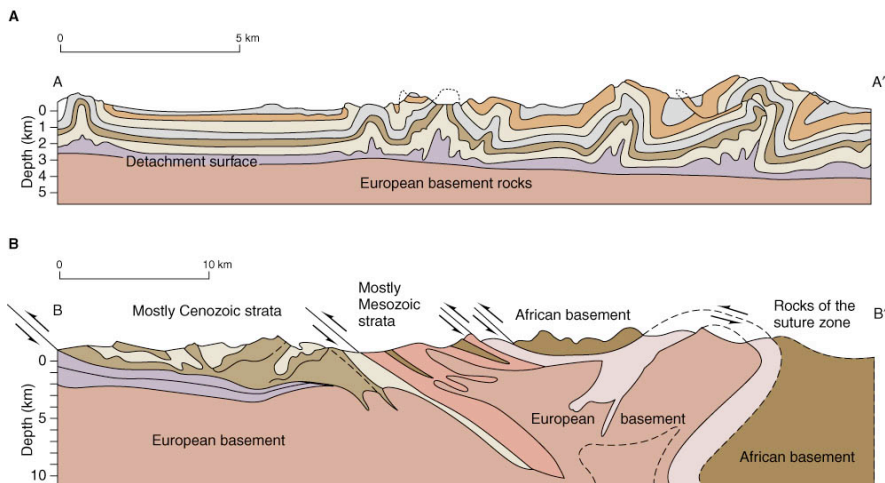


Figure 20.28

## The Canadian Rockies

- A central zone has been intensely metamorphosed.
- The thrust sheets in the Canadian Rockies moved eastward away from the core zone.
- Each sedimentary unit becomes thinner from west to east.

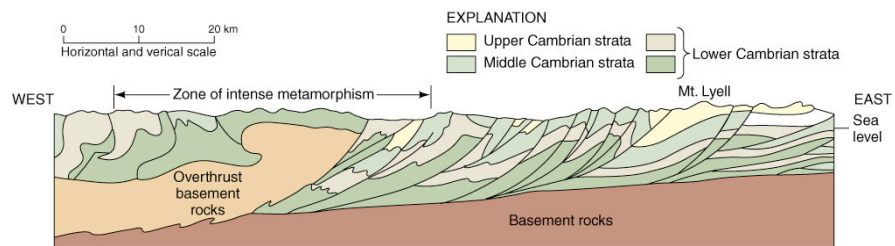


Figure 20.29

