

Global Tectonics

Summary

- Earth's mantle loses its internal heat with a combination of heat conduction and convection. As part of this process, the upper 100-200 km layer of Earth cools and stiffens to form the lithosphere. Internal heat conducts through the lithosphere to the Earth surface. Beneath the lithosphere, internal heat is transported with moving rock in a convective circulation.
- Earth lithosphere is currently composed of roughly twelve large distinct fragments that, owing to their stiffness, behave as rigid plates. The description of the motions and interactions of these lithospheric fragments is called plate tectonics.
- Since the 1990's direct evidence for the slow drift of all continental landmasses has been available from GPS satellite geodesy data. GPS data confirm that the plates are approximately rigid, with little relative motion in their interiors. In the 1960's, plate tectonics theory was proposed and verified using indirect geologic evidence.
- The interaction between plates at their shared boundaries determines the overall pattern of mantle convection, and accounts for most of the earthquakes and volcanic activity on Earth.
- Continental crust is thicker (25-70 km) and less dense, on average, than oceanic crust (8 km). This difference leads to greater buoyancy for continental lithosphere. The Principle of Isostasy predicts that continental lithosphere will float higher on the viscous asthenosphere, and the oceanic lithosphere lower.

- Plates diverge at mid-ocean ridges, and the underlying asthenosphere rises to fill the gap. Rising asthenosphere melts partially, and the resulting melt rises to the seafloor and forms oceanic crust with an average thickness of 8 km. The residual asthenosphere cools and stiffens to form the mantle portion of oceanic lithosphere, reaching a mature thickness near 100km after roughly 70 Ma. As the young oceanic lithosphere cools, it grows denser and subsides to form the abyssal seafloor.
- The cooling of young oceanic plate is enhanced by seawater, which circulates convectively within crack networks in the upper 10 km of the lithosphere. Water leaches metals from the rock, but also is consumed to form hydrated minerals within the plate. Water and carbon compounds join the plate in sediments that accumulate on the seafloor. This accumulation reduces the supply of the important greenhouse gases CO₂ and water vapor to the atmosphere.
- Where plates converge and at least one plate is oceanic, dense oceanic lithosphere on one side of the plate margin sinks into the asthenosphere in a subduction zone. The convergent boundary between two such plates is marked by an ocean trench.

- Large earthquakes on thrust faults occur at the boundary between down-going and overriding plates. As it sinks, water, CO₂ and other volatile substances escape the descending lithosphere and lower the melting temperature of the surrounding asthenosphere. This mantle rock melts partially, and the melt rises to form an arc of volcanoes in the overriding plate parallel to the trench. Water vapor and CO₂ return to the atmosphere by means of volcanic activity.
- Continental lithosphere is too buoyant to subduct. When two continental plates converge, therefore, a collision zone forms, characterized by thickened crust and high mountains.
- At transform boundaries, plates slide laterally past each other. Strike-slip earthquakes are common along such boundaries.
- Mantle convection is induced by the thermal expansion of relatively warm rock, which leads to a lower density and a tendency to rise. Conversely, the thermal contraction of relatively cool rock leads to a higher density and a tendency to sink. Convective motions are resisted by rock viscosity, and limited by the ability of excess heat to conduct away from warm buoyant regions into cooler, less buoyant regions.
- In plate tectonics, the slow descent of relatively cold, dense oceanic lithosphere in subduction zones is the primary driver of convective flow. Most upward motion of hot buoyant mantle rock occurs passively, induced by plate

- Some upward motion of hot buoyant mantle rock occurs in plumes that rise from the deep mantle. These plumes form persistent hot spots at Earth's surface. Volcanism from a mantle plume can form a chain of volcanoes in a plate, formed sequentially as it drifts over the hot spot.
- Mantle plumes within other terrestrial planets appear to be fixed relative to their lithospheres, confirming the absence of plate motion on other planets.
- Although physical considerations and direct observations suggest that all terrestrial bodies either convect now or have convected in the past, only Earth convection expresses itself in the form of plate tectonics. Without oceanic sediments to accumulate and retain carbon compounds and water, the greenhouse effect on Venus lacks an important regulatory mechanism. This may help explain why Venus has a runaway greenhouse effect.

Earth's Surface and Isostasy

- Buoyant bodies rise to their own level
 - Ice is only slightly less dense than water, 9/10 of the iceberg is below the water line
 - Styrofoam is much less dense than water, only a small amount under water is needed
- Earth's surface is in "isostatic equilibrium"
 - Continents rise high relative to ocean basins because the underlying rock differs in density and thickness
 - Earth has equatorial "bulge"

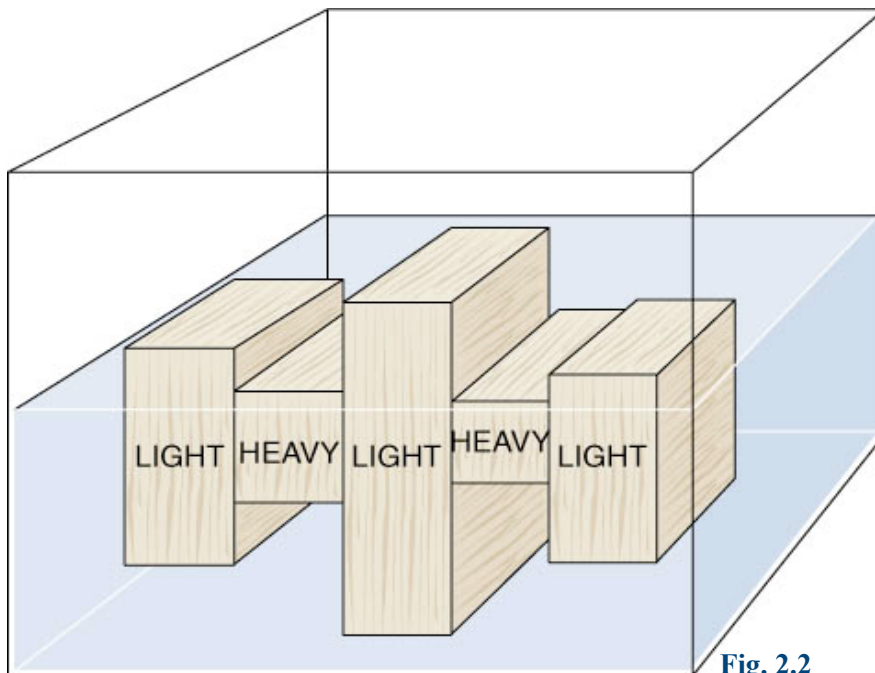


Fig. 2.2

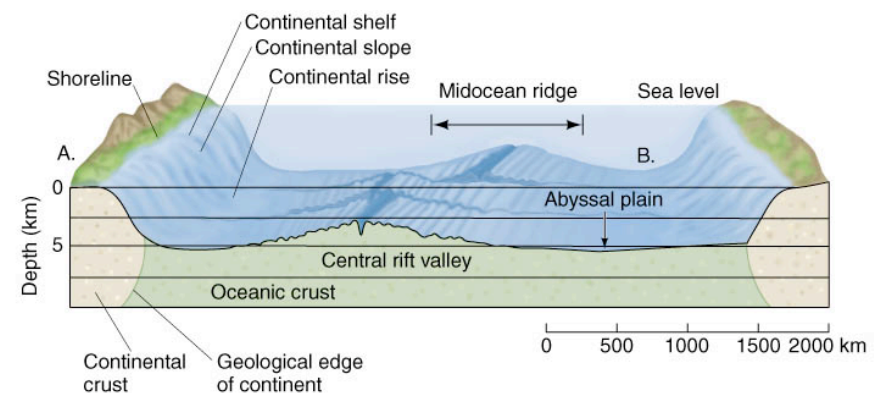


Fig. 2.5

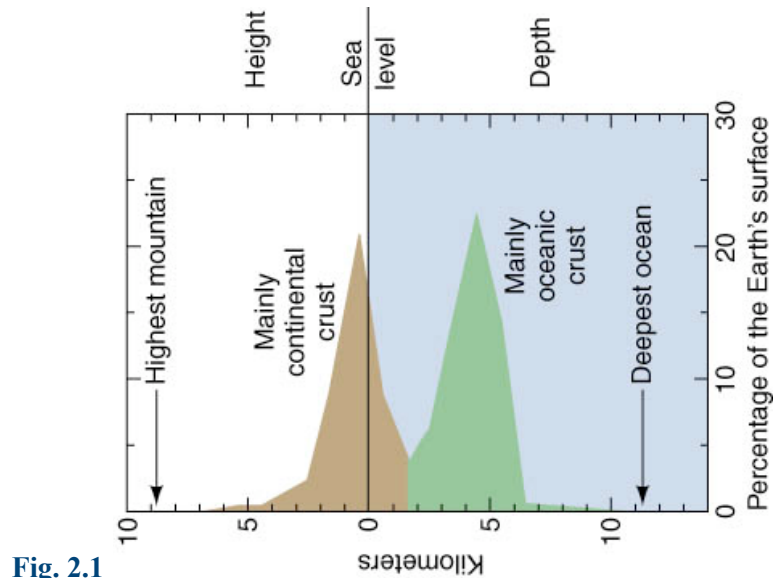


Fig. 2.1

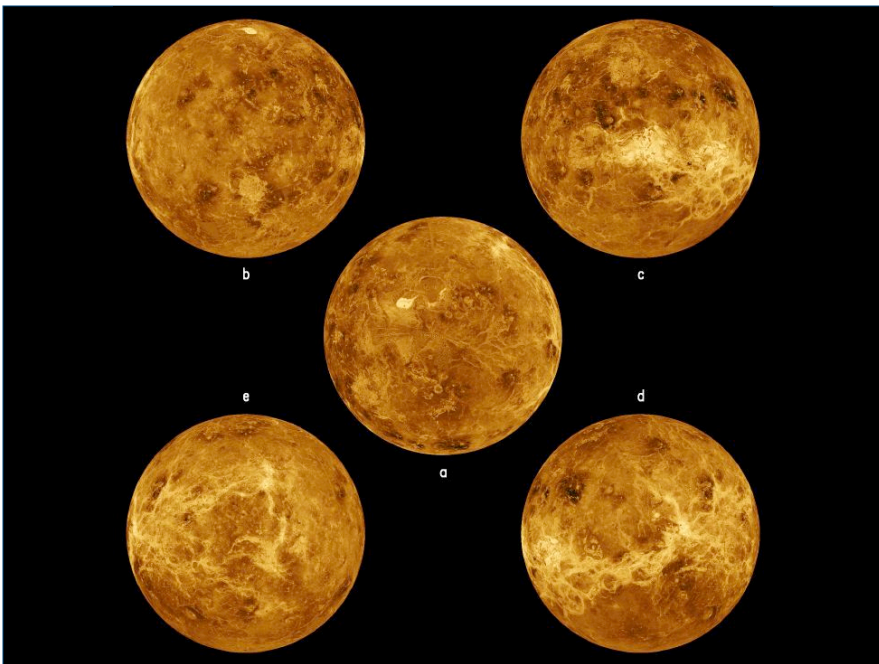
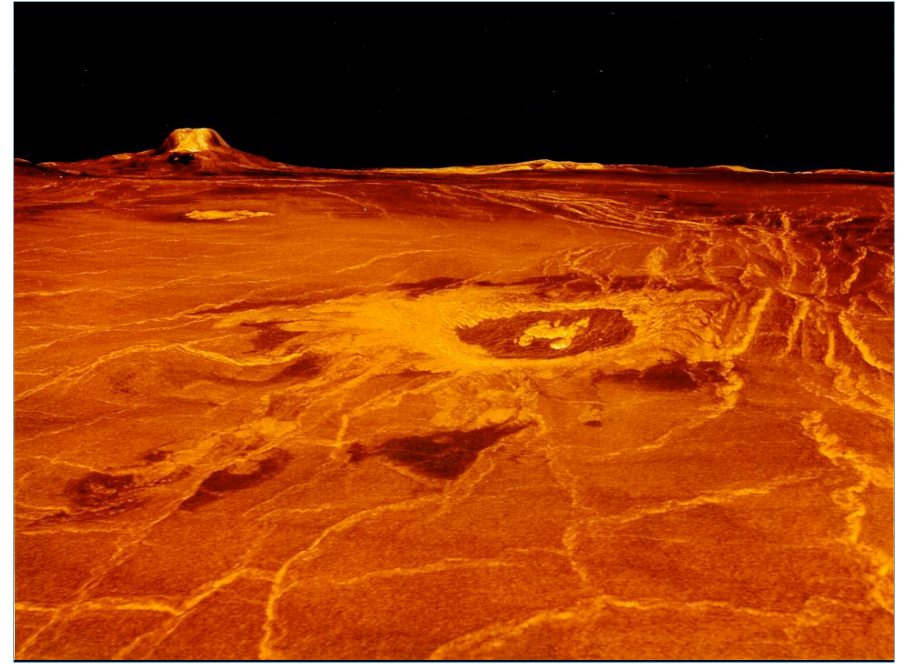
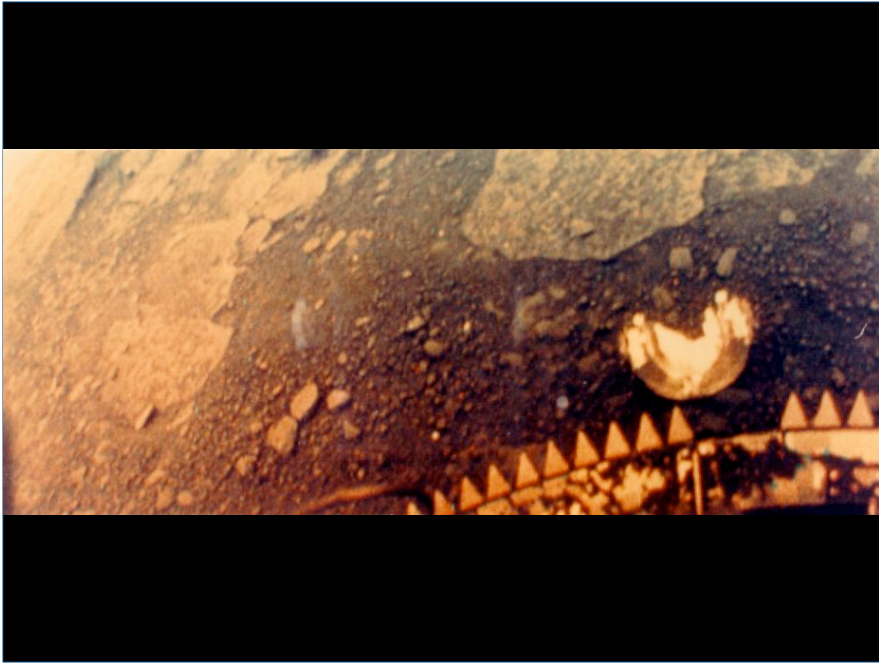
How do Planets Work?

- Heat flows from interior
 - via conduction and convection
- Convection is inevitable for planetary processes
 - Higher temperatures ->
 - thermal expansion -> lower density-> buoyancy
 - Increased ductility -> low viscosity -> flow
 - Rayleigh number is ratio of buoyant forces to viscous forces -
 - any system with R greater than about 1000 convects
 - R for Earth's mantle is greater than a million!

Convection Demo

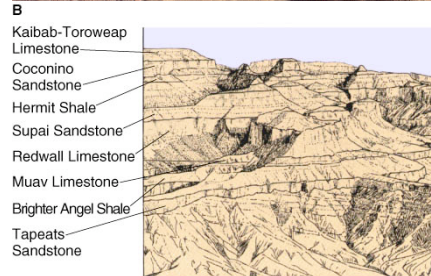
A Tale of Two Planets (plus a couple more)

- Venus and Earth (Moon, Mars)
 - All have evidence of geologic activity
 - All have (or had) adequate internal heat
 - Why are they so geologically different?
 - Why "Plate Tectonics" only on Earth?



- **Venus and Earth are almost twins**
 - Size
 - Composition
- **What happened?**
 - 100 times higher air pressure (mostly CO₂)
 - 500 °C surface temperature
 - Episodic “resurfacing” not plate tectonics
- **Best explanation – different connection between rock cycle and water and carbon cycles**

- Water and carbon are cycled with rocks on Earth
 - both have enormous impact on properties of rock
- Likely that water and carbon are essential for plate tectonics on Earth
- Life on Earth changed the carbon cycle
 - speculative idea – is life another necessary ingredient for plate tectonics



Limestone (CaCO_3)
widespread on Earth – most
with biologic origin

Contains as much carbon as
the atmosphere of Venus

Plate Tectonics: From Hypothesis to Theory to Observational Fact

- Plate tectonics is an observational fact.
- Continents are drifting across the face of our planet.

Global Positioning System

- It is accurate within a few millimeters.
- Two measurement methods:
 - A GPS campaign: researchers establish a network of fixed reference points on Earth's surface, often attached to bedrock. The position is re-measured every few months or years.
 - Continuous GPS measurement: the receivers are attached permanently to monuments, and position is estimated at fixed intervals of a few seconds or minutes.

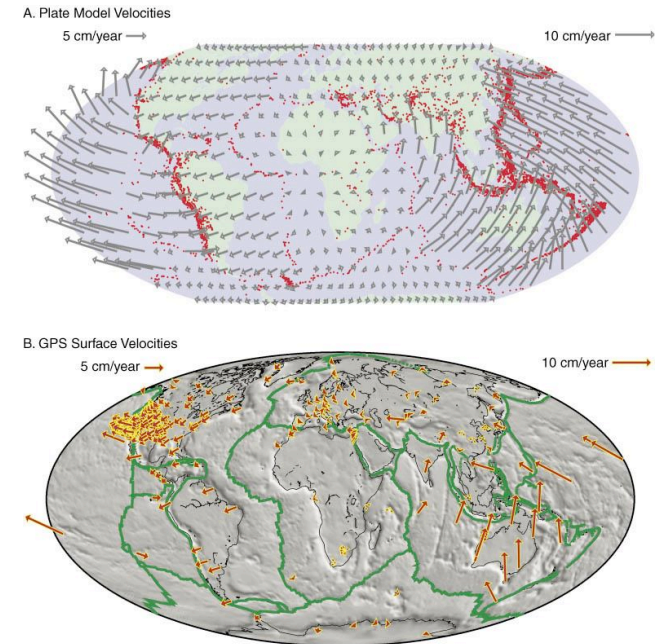
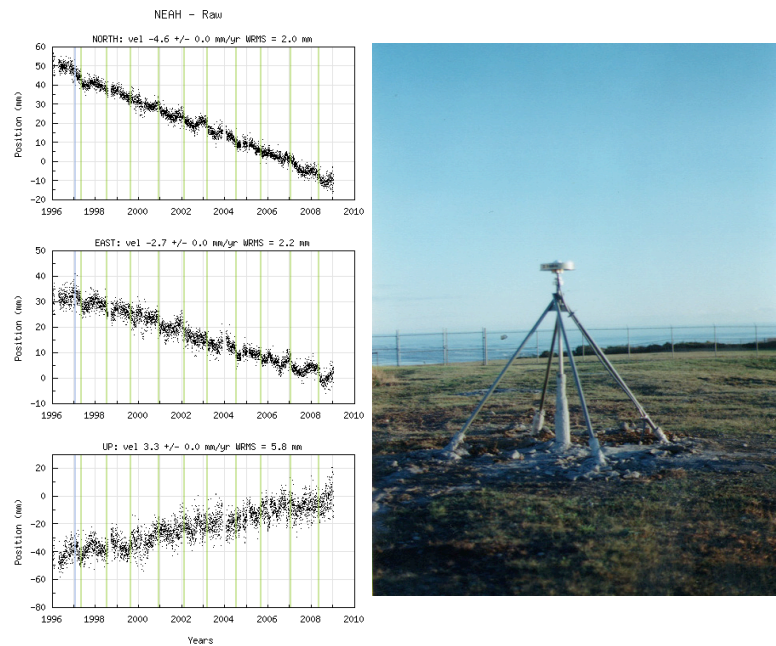
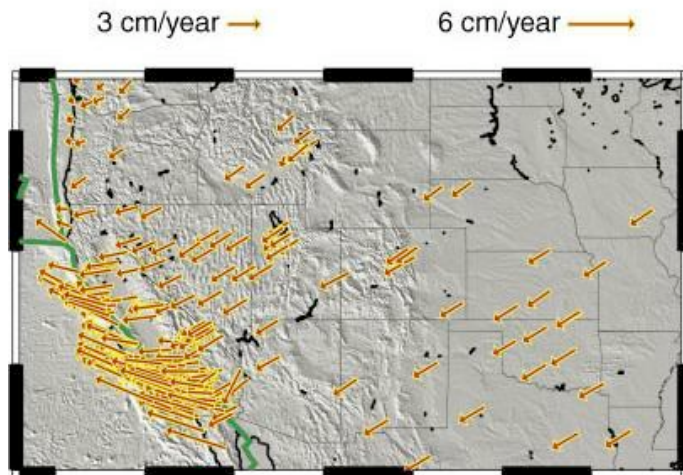


Fig. 2.9

Fig. 2.9 c

C. GPS in Western USA



Four Types Of Plate Margins And How They Move

- The lithosphere currently consists of 12 large plates.
- The seven largest plates are:
 - North American Plate.
 - South American Plate.
 - African Plate.
 - Pacific Plate.
 - Eurasian Plate.
 - Australian-Indian Plate.
 - Antarctic Plate.
- All are moving at speeds ranging from 1 to 12 cm a year.

Plates have four kinds of boundaries or margins

- **Divergent margin (also called a spreading center):** magma rises to form new oceanic crust between the two pieces of the original plate.
- **Convergent margin/subduction zone:** two plates move toward each other and one sinks beneath the other.
- **Convergent margin/collision zone:** two colliding continental plates create a mountain range.
- **Transform fault margin:** two plates slide past each other, grinding and abrading their edges.

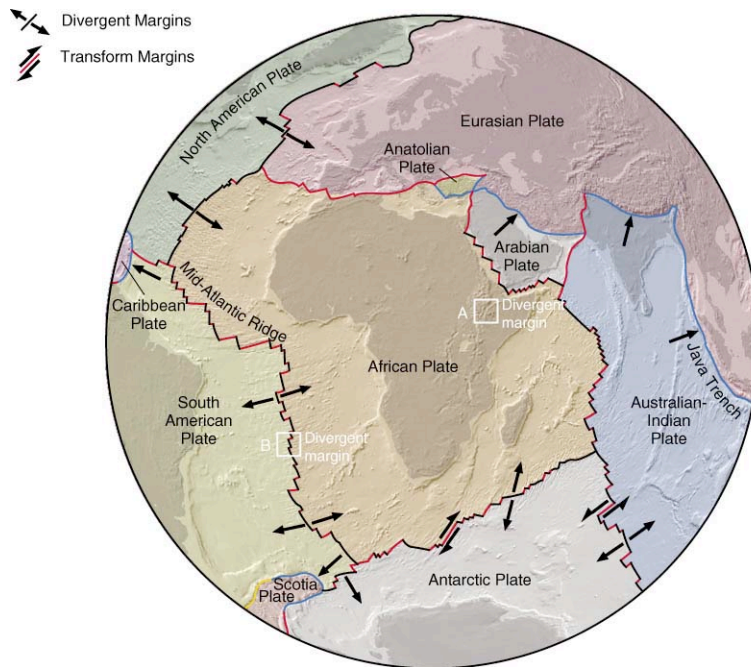
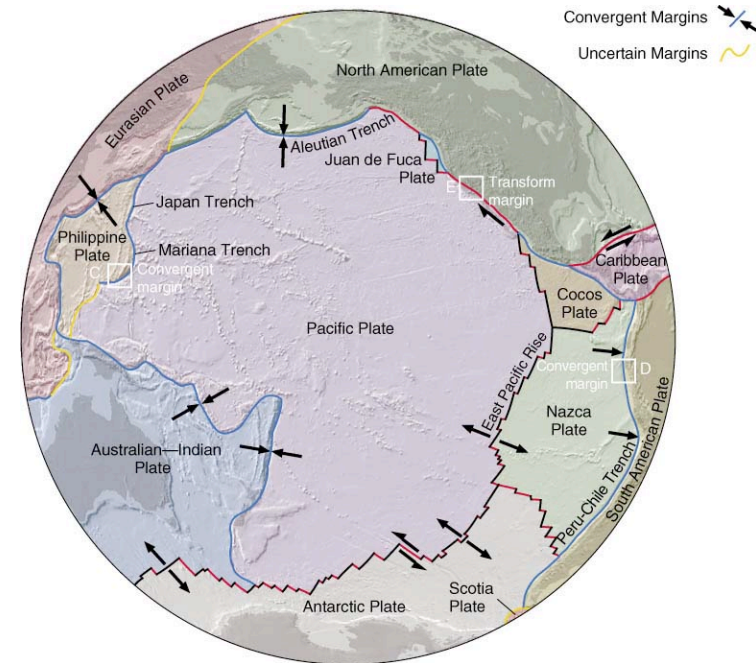


Plate Tectonics: From Hypothesis to Theory

- **Fit of Africa to South America** noticed when the earliest maps were made
- **Robust observations suggested a different arrangement of continents in past**
 - Similar fossils of extinct animals on separate continents in past eras, different animals now
 - Glacial deposits in equatorial regions, coal in Antarctica
 - Geologic strata that lined up when continents were assembled like jigsaw puzzle pieces

Plate Tectonics: From Hypothesis to Theory

- Alfred Wegener proposed the most comprehensive early hypothesis for “Continental Drift” in 1912.
- His theory was widely considered and (not completely) rejected because:
 - Rock is too strong to be plowed aside.
 - no plausible force that could induce the continents to drift was offered
 - Alternate explanations for observations

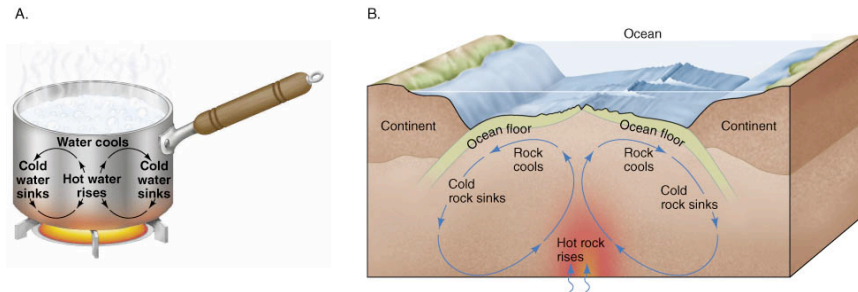


Fig. 2.6

Plate Tectonics: From Hypothesis to Theory

- In the 1960s, the Theory of Plate Tectonics was born.
 - New idea – thermal convection
 - horizontal motions of surface were necessary
 - Explained old data and circumvented earlier objections
 - Continents now “had to move”!!

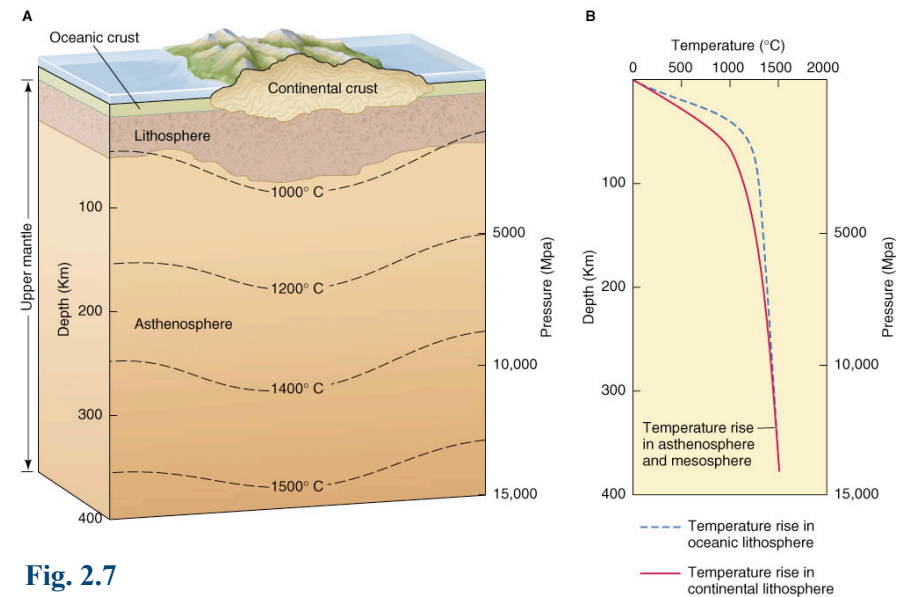


Fig. 2.7

Mantle Convection

- Rock expands as its temperature increases.
- Its density thereby decreases slightly.
- The hot rock is buoyant relative to cooler rock in its immediate neighborhood.
- A 1 percent expansion requires an increase of 300-400°C and leads to a 1 percent decrease in density.
- Viscosity is the propensity of rock to ductile flow.

Mantle Convection

- Rock does not need to melt before it can flow.
- The presence of H₂O encourages flow in solid rock.
- Convection currents bring hot rocks upward from Earth's interior.
- The rock in the lithosphere is too cool for convection to continue.
- Heat moves through the lithosphere primarily by conduction.
- The lithosphere-asthenosphere boundary is about 1300°C

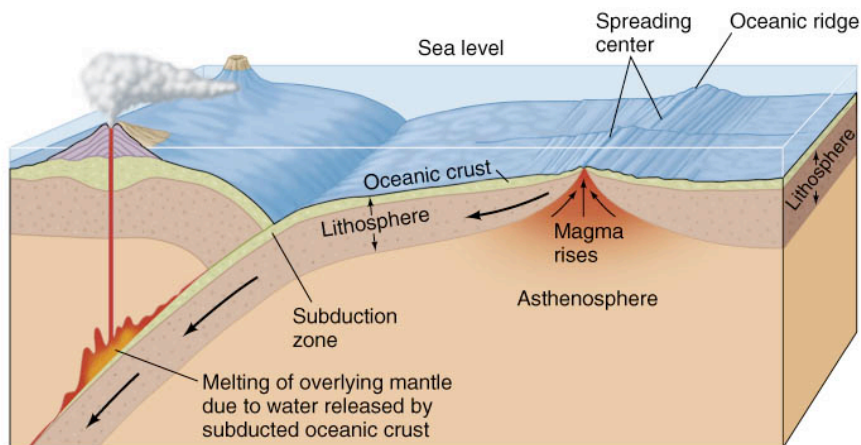


Fig. 2.8

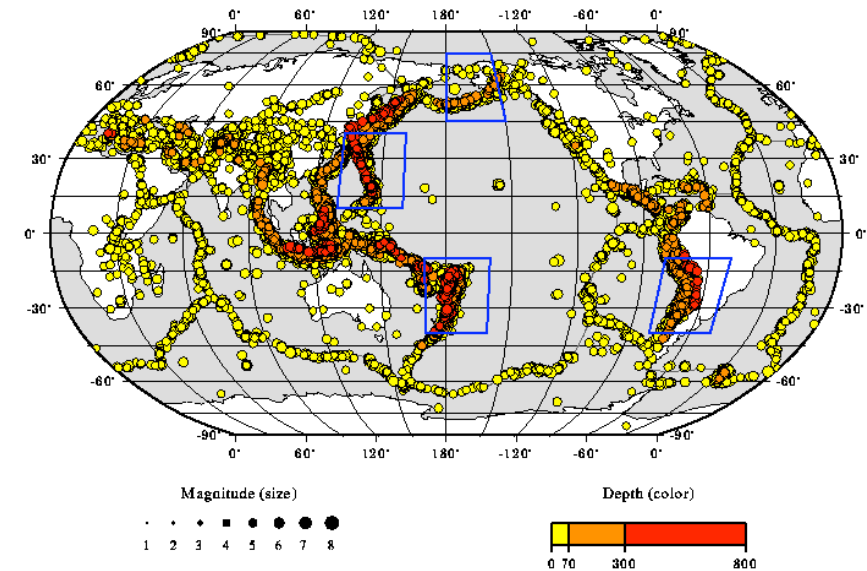
Plates and Mantle Convection

- When continents split apart, a new ocean basin forms.
 - The Red Sea was formed this way 30 million years ago.
- Subduction: the old lithosphere sinks beneath the edge of an adjacent plate.

Seismology and Plate Margin

- Earthquakes occur in portions of the lithosphere that are stiff and brittle.
- Earthquakes usually occur on pre-existing fracture surfaces, or faults.
- Distinctive types of earthquakes correlate nicely with motion at plate boundaries.

01/01/1991 - 12/31/1996 M > 4.5



Three Types of Faults and Their Earthquakes

- Strike-slip faults are vertical or near vertical fracture surfaces (at a plate boundary these are also known as transform faults).
 - Motion is entirely horizontal.
- Thrust faults are fracture surfaces that dip at an angle between the horizontal and the vertical (convergent motion within a volume of rock).
 - Motion is partly horizontal, partly vertical.
- Normal faults are fracture surfaces that also dip (divergent motion with and between bodies of rock).
 - Motion is partly horizontal, partly vertical, but opposite to the motion on a thrust fault.

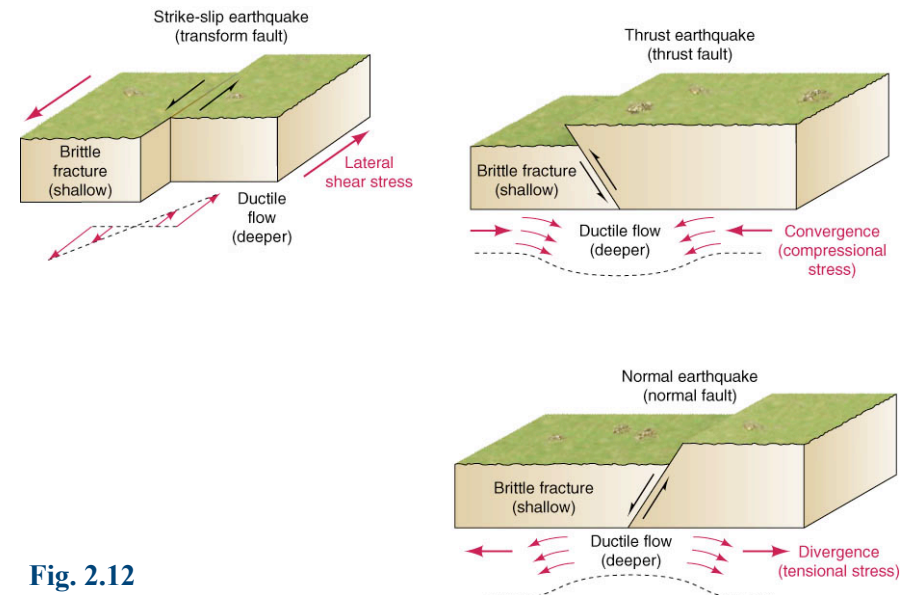


Fig. 2.12

Type I: Divergent Margin

- Where two plates spread apart at a divergent boundary, hot asthenosphere rises to fill the gap.
- As it ascends, the rock experiences a decrease in pressure and partially melts.
- The molten rock is called magma.

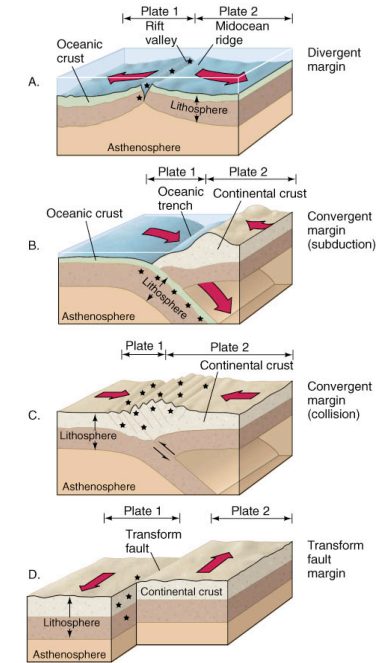


Fig. 2.11

Type I: Divergent Margin

- Midocean ridges occur in oceanic crust.
 - Found in every ocean.
 - Form a continuous chain that circles the globe.
- Oceanic crust is about 8 km thick.

Birth of the Atlantic Ocean

- When a spreading center splits continental crust:
 - A great rift forms (such as the African Rift Valley).
 - As the two pieces of continental crust spread apart:
 - The lithosphere thins.
 - The underlying asthenosphere rises.
 - Volcanism commences.
 - The rift widens and deepens, eventually dropping below sea level. Then the sea enters to form a long, narrow water body (like the Red Sea).

Birth of the Atlantic Ocean

- The Atlantic Ocean did not exist 250 million years ago.
- The continents that now border it were joined into a single vast continent that Alfred Wegener named Pangaea.
- About 200 million years ago, new spreading centers split the huge continent.
- The Atlantic continues to widen today at 2-4 cm/yr.

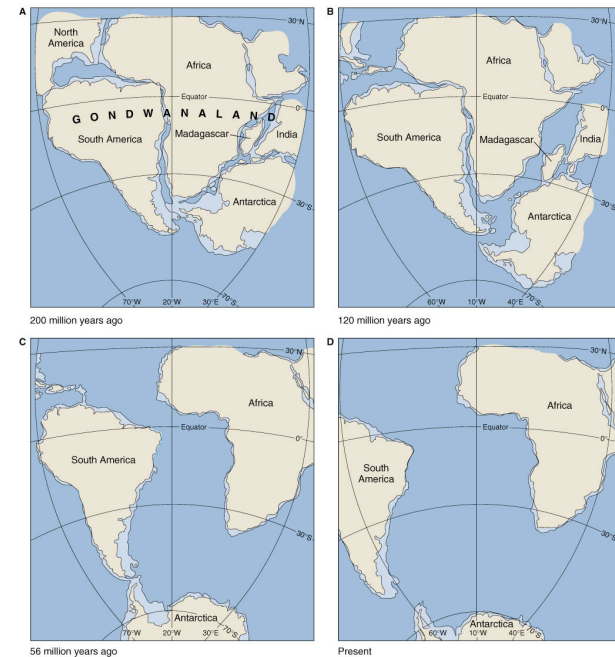


Fig. 2.13

Characteristics of Spreading Centers

- Earthquakes at midocean ridges occur only in the first 10 km beneath the seafloor and tend to be small.
- Normal faults form parallel lines along the rifted margin.
- Volcanic activity occurs at midocean ridges and continental rifts (along narrow parallel fissures).
- The midocean ridges rise 2 km or more above surrounding seafloor.

Characteristics of Spreading Centers

- The principle of isostasy applies: lower-density rock rises to form a higher elevation.

Characteristics of Spreading Centers

- If the spreading rate is fast:
 - A larger amount of young warm oceanic lithosphere is produced.
 - The ridge will be wider.
- A slow-spreading ridge will be narrower.
- The Atlantic Ocean spreads slowly, growing wider at 2-4 cm/yr.
- The Pacific spreading center is fast by comparison: 6-20 cm/yr.

Role of Seawater at Spreading Centers

- Seawater circulates through cracks beneath the ocean floor.
- Cold water percolates through these cracks, warms in contact with subsurface rock, and rises convectively to form undersea hot springs.

Role of Seawater at Spreading Centers

- Seawater reacts chemically with lithospheric rock, leaching many metallic elements from it.
 - Many ore bodies originated in undersea hydrothermal regions
- A small fraction of the seawater remains in the rock, chemically bound within hydrous (water-bearing) minerals like serpentine and clays.

Show Videos

The CO₂ Connection

- As oceanic lithosphere ages, it accumulates a thick layer of sediments such as clay and calcium carbonate (CaCO₃) from the shells and internal skeletons of countless marine organisms.
- The formation of calcium carbonate consumes carbon dioxide (CO₂) that is dissolved in seawater.
- Seafloor sediments remove CO₂ from the atmosphere, and thus have a long-term influence on the greenhouse effect and Earth's climate.

Type II: Convergent Margin/ Subduction Zone

- Over 70 million years, oceanic lithosphere can drift 1500 to 3000 km from the spreading center.
- As the plate cools, it grows denser.
- The principle of isostasy demands that the plate subsides as it grows denser.
- The process by which lithosphere sinks into the asthenosphere is called subduction.

Type II: Convergent Margin/ Subduction Zone

- The margins along which plates are subducted are called subduction zones.
 - These are active continental margins.
- The sinking slab warms, softens, and exchanges material with the surrounding mantle.

Type II: Convergent Margin/ Subduction Zone

- Under elevated temperature and pressure, the crust expels a number of chemical compounds.
 - Water (H₂O).
 - Carbon dioxide (CO₂).
 - Sulfur compounds.
- A small addition of these volatile substances can lower the melting point of rock by several hundred degrees Celsius.

Type II: Convergent Margin/ Subduction Zone

- The hot mantle rock immediately above the sinking slab starts to melt.
 - Magma rises to the surface to form volcanoes.
 - Subduction zones are marked by an arc of volcanoes parallel to the edge of the plate.

The CO₂ Connection, Again

- Water, carbon dioxide, and sulfuric gases like sulfur dioxide (SO₂) and hydrogen sulfide (H₂S) return to the atmosphere.
- Subduction zone volcanic activity raises the carbon dioxide level in the atmosphere, exerting a strong influence on the greenhouse effect and Earth's climate.

The CO₂ Connection, Again

- Volcanism tends to replace the CO₂ that is lost from the atmosphere into the ocean and stored in the seafloor.
- Warmer or cooler episodes in past climates can be deduced from the fossils of ancient plants and animals.

Volcanoes At Subduction Zones

- At a plate boundary, the plunging plate draws the seafloor down into an ocean trench, often 10 km deep or more.
 - If the overriding plate is oceanic lithosphere, volcanoes form a series of islands called a volcanic island arc.
 - Mariana Islands.
 - Aleutian Islands.

Volcanoes At Subduction Zones

- If the overriding plate is continental lithosphere, a continental volcanic arc forms, while sediment washed from the continent tends to fill the offshore trench.
 - Cascade Range of the Pacific Northwest.
 - The Andes of South America.

Volcanoes At Subduction Zones

- Most subduction-arc volcanoes occur roughly where earthquakes indicate that the top of the slab is 100 km deep.

Earthquakes in Subduction Zones

- The largest and the deepest earthquakes occur in subduction zones.
- The location of most earthquakes define the top surface of a slab as it slides into the mantle (the surface to as deep as 670 km)

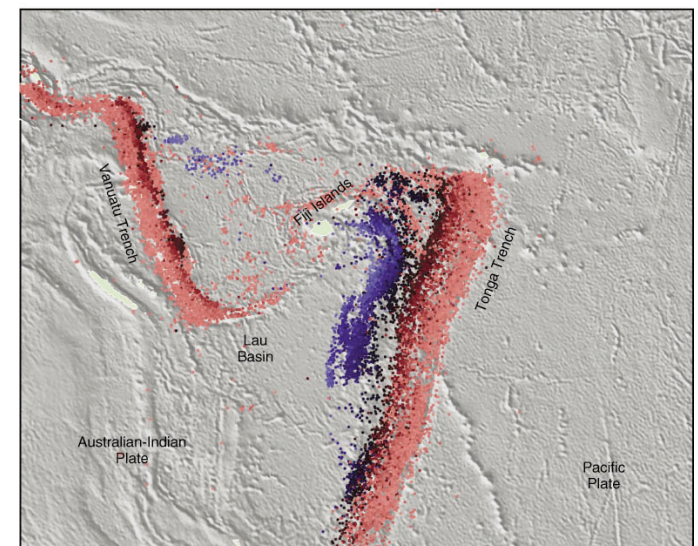
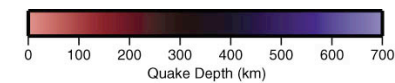


Fig. 2.15

Type III: Convergent Margin/Collision Zone

- Continental crust is not recycled into the mantle.
- Continental crust is lighter (less dense) and thicker than oceanic crust.
- When two fragments of continental lithosphere converge, the surface rocks crumple together to form a collision zone.

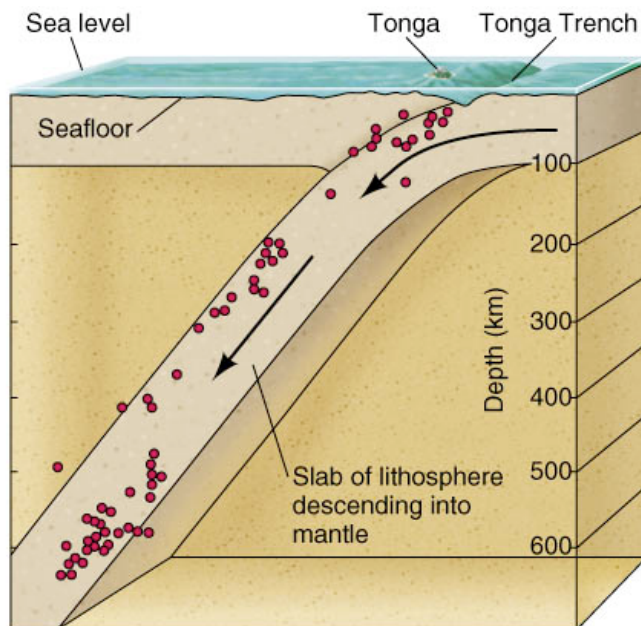


Fig. 2.16

Type III: Convergent Margin/Collision Zone (2)

- Collision zones that mark the closure of a former ocean form spectacular mountain ranges.
 - The Alps.
 - The Himalayas.
 - The Appalachians.

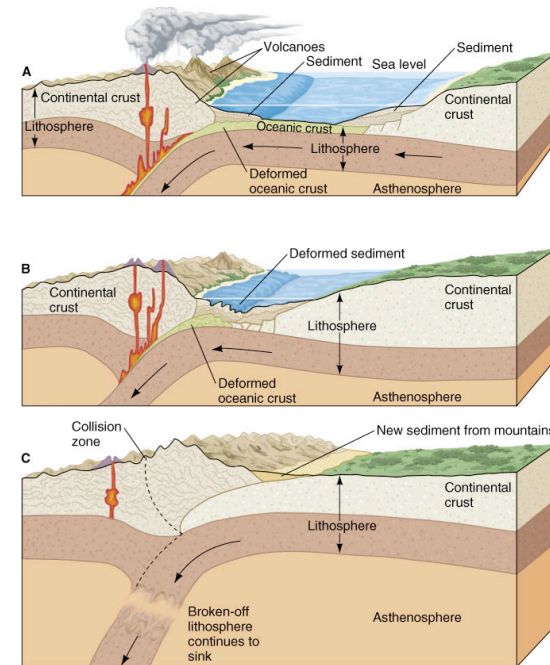


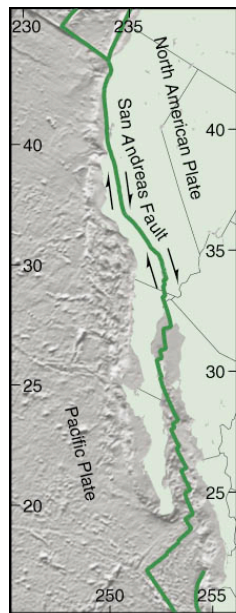
Fig. 2.17

Type IV: Transform Fault Margin

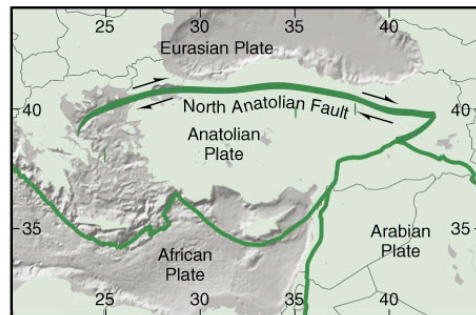
- Along a transform fault margin, two plates grind past each other in horizontal motion.
- These margins involve strike-slip faults in the shallow lithosphere and often a broader shear zone deeper in the lithosphere.
- Most transform faults occur underwater between oceanic plates.

Type IV: Transform Fault Margin

- Two of Earth's most notorious and dangerous transform faults are on land.
 - The North Anatolian Fault in Turkey.
 - The San Andreas Fault in California.



A.



B.

Fig. 2.18

Topography of the Ocean Floor

- Two main features:
 - Mid-ocean ridges.
 - Some 64,000 km in length.
 - The spreading centers separate plates.
 - The oceanic ridge with its central rift reaches sea level and forms volcanic islands.
 - Iceland.
 - The oceanic trenches.

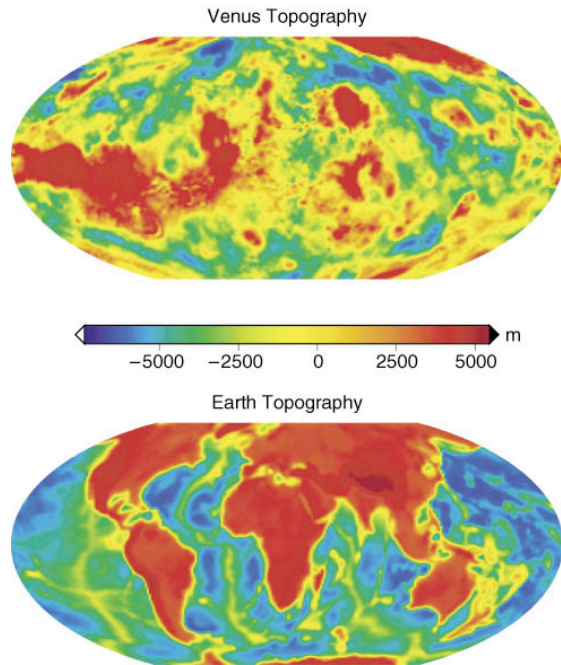


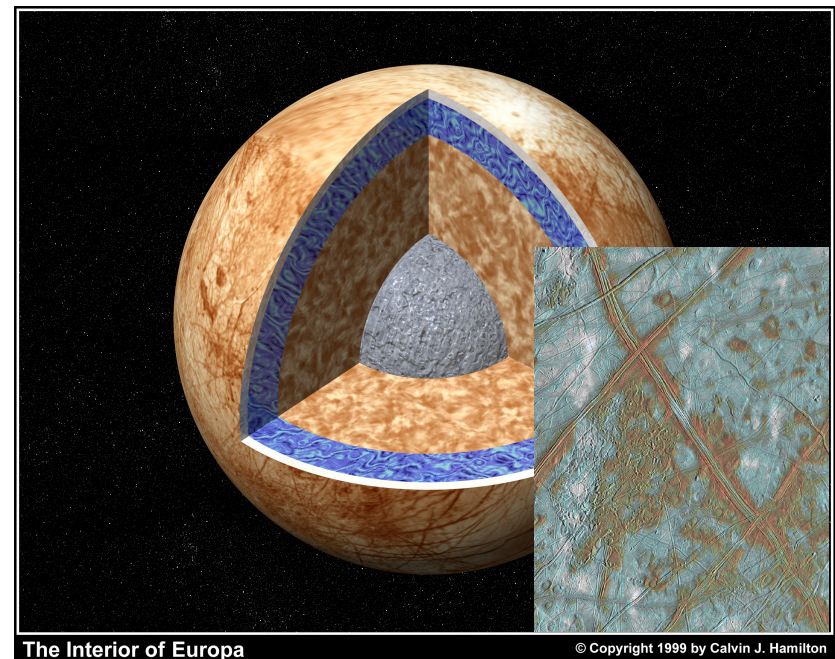
Fig. 2.19

An Icy Analogue to Earth Tectonics

- The closest approximation to Earth tectonic in our solar system is found on Europa (one of Jupiter's four largest moons).
 - Europa is 3138 km in diameter, large enough to be discovered in 1610 by Galileo with his early telescope.
- Europa's interior has rocky composition with density similar to Earth.

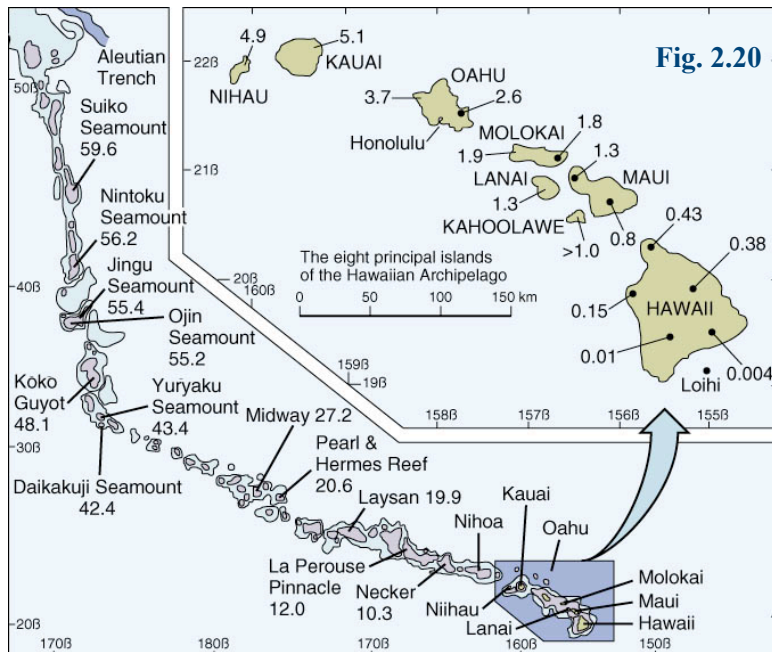
An Icy Analogue to Earth Tectonics

- Its surface layer consists mainly of water ice, at least 100 km deep.
- Large fragments of the icy surface appear to be rigid.
- Plates on Europa are much smaller than Earth's plates.
- Topography at Europa's plate margins suggests convergence, divergence, and transform-fault motion, just as with Earth's plate margins.



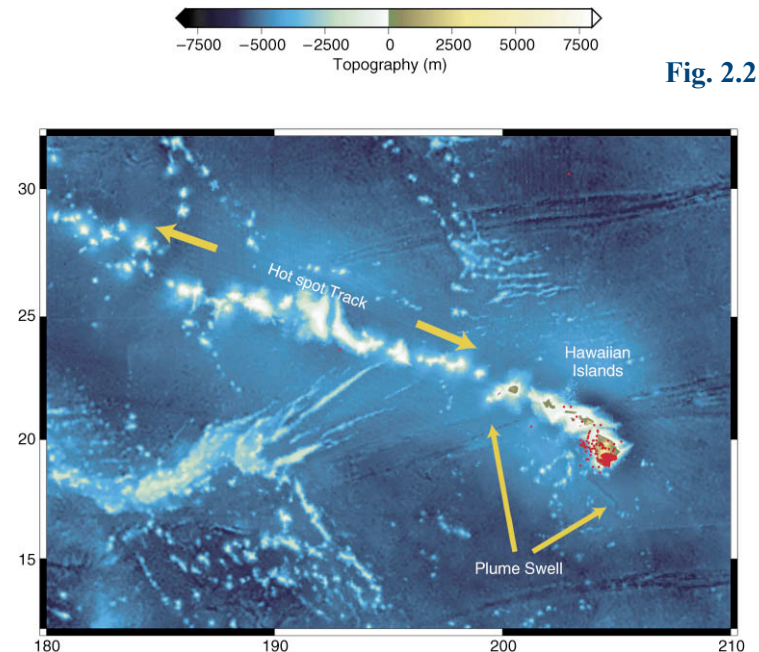
Hot Spots And Absolute Motion

- During the nineteenth century, American geologist James Dwight Dana (1813-1895) observed that the age of extinct volcanoes in the Hawaiian Island chain increases as one gets farther away from the active volcanoes on the “big island.”
- The only active volcanoes are at the southeast end of the island chain, and the seamounts to the northwest are long extinct.
- Earthquakes occur only near the active volcanoes.



Hot Spots And Absolute Motion

- In the 1960's, J. Tuzo Wilson proposed that a long-lived hot spot lies anchored deep in the mantle beneath Hawaii.
- A hot buoyant plume of mantle rock continually rises from the hot spot, partially melting to form magma at the bottom of the lithosphere—magma that feeds Hawaii's active volcanoes.
- If the seafloor moves over the mantle plume, an active volcano could remain over the magma source only for about a million years.



Hot Spots And Absolute Motion

- As the plate moves, the old volcano would pass beyond the plume and become dormant.
- A new volcano would sprout periodically through the plate above the hot spot, fed by plume magma.
- The Hawaiian Islands connect with a chain of seamounts to the northwest.
 - These are dormant seafloor volcanoes that have sunk below the sea surface by erosion and isostasy.

The World's Hot Spots

- Several dozen hot spots have been identified worldwide.
- Hot spot volcanoes do not form tracks on the African Plate -> plate must be very nearly stationary.
- Hot spots transport roughly 10 percent of the total heat that escapes Earth.

The World's Hot Spots

- Mantle plumes were probably more numerous 90-110 million years ago than today, because extinct seamount volcanoes of that age crowd together in the central Pacific.

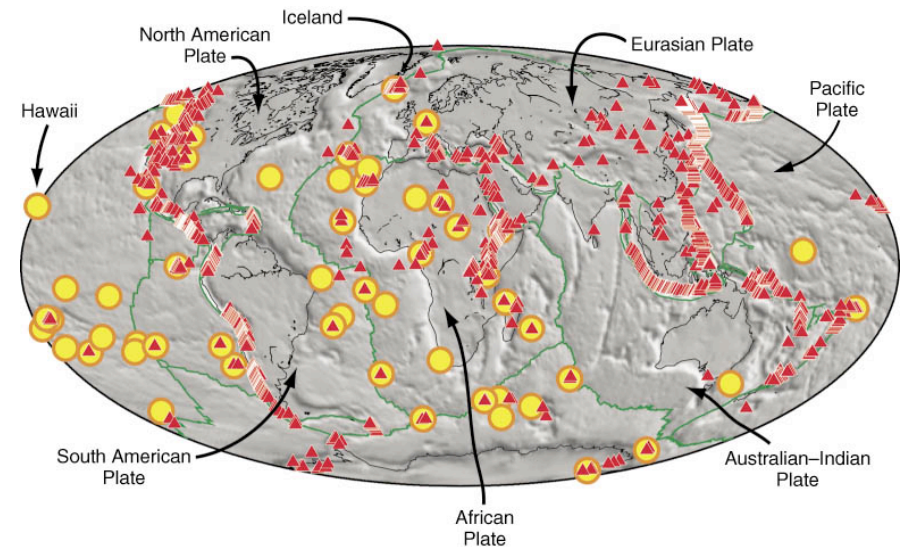


Fig. 2.22

Hot spots and volcanoes

Plume Volcanism on Mars

- Other rocky bodies in the solar system, such as Mars, Mercury, and our Moon have also had volcanism in the past.
- Their small size has limited their tectonic histories.
- Too small to retain internal heat for billions of years, the Moon, Mercury, and Mars now have thick immobile lithospheres.

Plume Volcanism on Mars

- The moon's lithosphere may encompass the Moon's entire mantle.
- At least 20 huge volcanoes and many smaller cones have been identified on Mars.
 - The largest is Olympus Mons (27 km high).
 - It is a complex caldera that is 80 km across.
- Mauna Loa in Hawaii, the largest volcano on Earth, has a similar shape, but it is only 9 km high.

Plume Volcanism on Mars

- The presence of a huge volcanic edifice such as Olympus Mons implies:
 - A long-lived mantle plume.
 - The plume must have remained connected to the volcanic vent for a very long time.
 - The Martian lithosphere has been stationary (no plate tectonics).
 - The Martian lithosphere must be thick and strong.

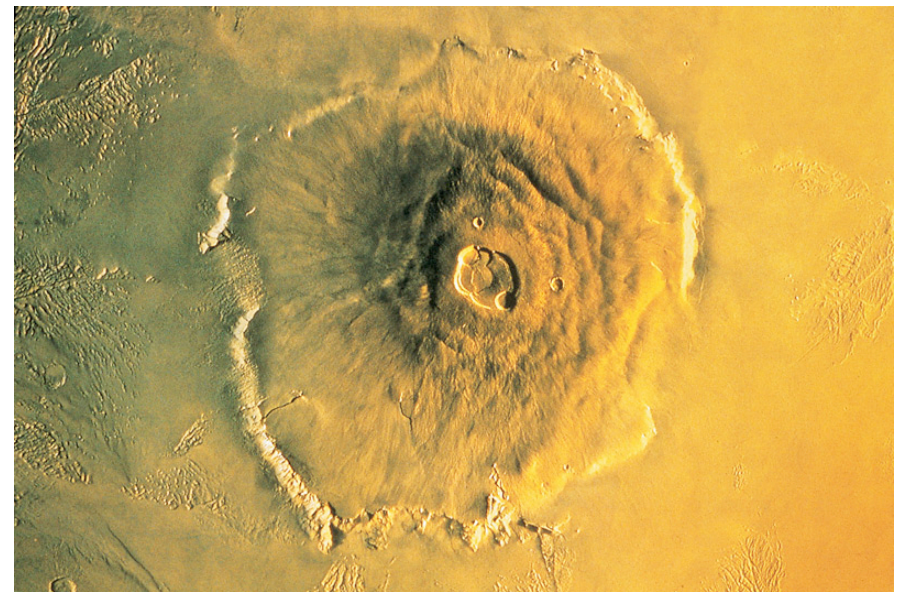


Figure 2.24

What Causes Plate Tectonics?

- More agreement on how plate tectonics works than on why it works.
- Numerical Simulations show:
 - Mantle convection can occur in a variety of patterns, large-scale and small-scale.
 - Low-viscosity material rises in narrow columns that resemble hot spot plumes.
 - Cooler, stiffer material from the surface sinks into the mantle in sheets

What Causes Plate Tectonics?

- Three forces seem likely to have a part in moving the lithosphere:
 - Ridge push: the young lithosphere sits atop a topographic high, where gravity causes it to slide down the gentle slopes of the ridge.
 - Slab pull: at a subduction zone, as the cold, dense slab is free to sink into the mantle, it pulls the rest of the lithosphere into the oceanic trench behind it.

What Causes Plate Tectonics?

- Friction:
 - Slab friction drags the top, the bottom, and the leading edge of descending lithosphere in the subduction zone.
 - Plate friction drags elsewhere at the base of the plate.

Why Does Plate Tectonics Work?

- The theory of plate tectonics does not explain why the plates boundaries exist.
- Water is likely the important ingredient in the plate tectonics.
 - Water molecules can diffuse slowly through solid rock.
 - Water can weaken rock in several ways.

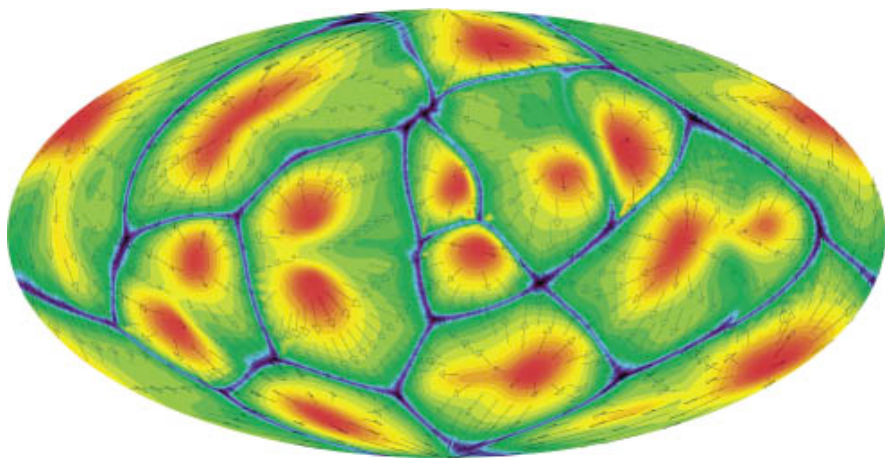


Fig. 2.25

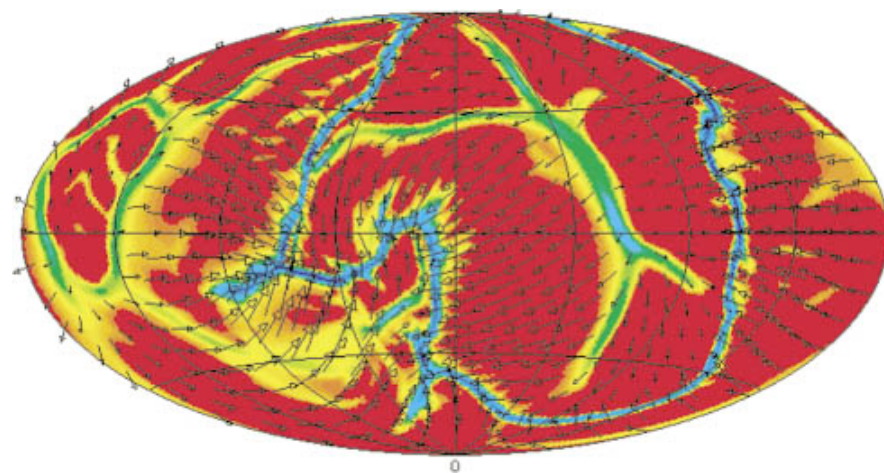


Fig. 2.26