

Continental Drift

James Hutton—concept of a “World Machine” that renews itself. Erosion tears at mountains, creating sediments that pile up in the ocean, eventually melt, and are uplifted becoming new mountains. A cycle with no end; a static world of vertical movements but no moving continents

Alfred Wegner: Recognized the fit of continents around the Atlantic (Pangea) and showed detailed similarity of their geology and fossils; but had no mechanism to explain how they could ‘drift’ apart—the theory was widely ridiculed since continental crust could not plow through the oceans.

Continental crust: mostly granitic rocks, sediments and their metamorphic equivalents
Oceanic crust: mostly basalt and its plutonic equivalent, gabbro, and sediments.

Vertical motion not so hard to accept--Isostasy

Principle of Isostasy = (From the Greek = “Equal standing”): Gravitational balance maintained by different parts of the crust with different thickness and density

Earth’s lithosphere (Crust and rigid mantle) floats on the asthenosphere and finds the level at which its mass is buoyantly balanced.

Low density rocks (like the continents) float high relative to high density rocks (like the ocean floors) given equal volumes and thick crust sinks farther into the mantle than thin crust.

Removal of some crust by erosion is partly “compensated” by isostatic uplift; likewise addition of material (by sedimentation or volcanic eruption) depresses the crust compensating for the addition of material.

Two examples:

1. the depression of the oceanic crust around the Hawaiian Islands creates a ‘moat’ on the ocean floor
2. The loading of ice on North America and Europe pushed many areas of what is now land below sea-level, the gradual return flow of the mantle under the continents after melting the ice results in gradual (up to 5 cm/year) uplift of the crust)

Isostasy results in a “hysometric” curve that shows that there are pretty much two densities: (1) oceanic crust (composed of basalt) with a density of XX and (2) continental crust (composed of granites) with a density of ~2.6 g/cm³—hence the hysometric curve has two levels.

Distribution of tectonic plates

Looking at the bathymetry map, where are the plates? Take North America, for example, what defines the boundaries of this plate? Is the division at the ocean-continent boundary, within the continent, within the ocean basins, where?

Look at the distribution of volcanoes, now what?

Plates are not defined by the type of crust, but by the areas of principal tectonic activity; includes the rigid upper mantle and crust (= lithosphere)

GPS tells us the plates move

Global Positioning system satellites can be used to detect motions of the plates over time (the GPS system has been around since the 1960's but used for GPS studies of plate motions since the 1980's)

GPS studies show that the Pacific and Indian Plates are moving along at about 10 cm/year, North America is moving gradually SW at about 3-4 cm/year (gradually to warmer climes) and S. Calif is moving with the Pacific plate (alas to the chilly N. Pacific!); Africa is not moving much at all, but is slowly spinning counter clockwise

Also show that the plates are mostly rigid and have the same sense and amount of motion everywhere—a notable exception is California which shows much variation in motion, probably because it straddles two plates.

What causes this motion? In a word: “Convection”

Convection – transfer of heat by rise of buoyant hot material and sinking of cool, dense material

Convection works owing to **Thermal Expansion**—hot rock expands so that for an equivalent mass of cold rock, hot rock takes up more space and has less density per given volume

The lower density of a given amount of hot versus cold rock causes the hot rock to float higher than the cold rock; the rock need not melt to do this but they flow faster at higher temperature or if they have a lot of gas or water trapped in them (which lowers the melting point)

The fluid mantle has a temperature above $\sim 1300^{\circ}\text{C}$ which happens to be the temperature at the base of the lithosphere and hence, the boundary between the cool, rigid lithosphere and the plastic, flowing asthenosphere

Convection driven from the top :

Could imagine that plate motion is driven by convection in the mantle with areas of upwelling being areas where plates split apart and down welling areas being places where plates are pulled into the mantle.

A better analogy is a cooling vat of metal: a skin forms from cooled metal and this eventually becomes denser than the underlying hot metal and sinks allowing new molten metal to rise to the surface.

Return to Tectonic forces:

Slab pull = the pull on a plate as it cools and sinks into the hot, buoyant mantle

Ridge push = the gravitational sliding as a plate slides downhill off a buoyant (and high standing ridge) where new mantle is exposed at the surface.

Also consider **Slab friction**: since there is significant friction between the top of the slab and the overlying plate

Types of Plate Boundaries

There are three main types:

1. **divergent**: where new crust is created and plates are moving away from each other
2. **convergent**: where plates are in collision and bumping into each other
3. **transform**: where plates are sliding past each other

Because the Earth is a sphere, creation of a plate at a divergent margin must be balanced by destruction (slab sinking) somewhere else.

Divergent Margins:

Can start in both oceanic and continental crust, but always involves the creation of oceanic crust

Have few earthquakes focused on an axial ridge

Ridge is ~2-3 km higher than the oldest (and coldest) seafloor owing to thermal expansion in the hot asthenosphere rising to replace the spreading crust.

Spreading varies from 2-4 cm/year (Atlantic) to ~20 cm/year (East Pacific Rise)

Structure consists of (top to bottom) sediments, pillow basalts (erupted onto the seafloor), sheeted dikes, gabbro intrusions, and partially melted mantle.

Seawater circulates through all these rocks extracting metals which precipitate out in hot vents to form 'black smokers' and also become bound up in clay minerals, serpentine, and other water-bearing minerals. This water plays a key role in convergent margins

Convergent Margins

Three main types:

1. **Ocean-Ocean**,
2. **Ocean Continent**, and
3. **Continent-continent** convergent margins

All involve a “subduction zone” where old, cool oceanic crust sinks back into the mantle in a ‘Trench’

Subduction heats the down-going “slab” and the water trapped in clays, serpentine and other trapped gases help lower the melting temperature of the overlying mantle creating magma bodies

These magma bodies may intrude the overlying plate creating a chain of volcanoes—a “Volcanic arc”

In Ocean-Ocean and Ocean-continent convergent margins, the volcanic arc is underlain by intrusive/plutonic rocks that can cool and form large masses of igneous “plutons” or “batholiths”

Because the volcanic arc forms above the point at which volatiles are released, the distance of the arc from the trench can vary depending upon the angle of descent of the slab (which in turn is related to the age and density of the slab).

Volatile release typically happens at a depth of ~100 km (probably because at this depth some process happens to drive off the water trapped in the down-going slab).

The slab itself seems not to melt very much.

Benioff Zone: The zone from the trench to a depth of ~670 km in which earthquakes are associated with the subducting slab; deeper than this, flow between the slab and surrounding rocks is probably too plastic to generate earthquakes.

In Continent-continent convergent margins, two continents collide. Since both are made of buoyant continental crust neither can be subducted into the mantle.

The resulting collision forms large mountain ranges that mark the location of vanished oceans. Other mountain chains form above subducting ocean plates by a complex process of formation of plutons and back-arc rifting.

Transform Margins

Plates slide past each other on “Strike-Slip” faults

Transforms typically connect other types of plate boundaries and allow plate movement on a sphere.

For example, the San Andreas Fault (a transform between N. America and the Pacific) connects spreading centers in the Gulf of California and the Pacific Northwest.

These can be very long—100’s of km and may not be discrete zones of slippage (as in the San Andreas)

Hotspots

Believed to represent mantle plumes arising from near the core-mantle boundary.

The plume spreads out on the underside of the lithosphere and can feed a long-lived series of volcanoes on the overlying plate.

As the plate moves over the plume, the volcanoes die out as they move away from the plume head; the result is a chain of volcanoes whose age increases away from the location of the plume head.

An Example is the Hawaiian chain whose oldest volcano (now sunk beneath the surface ocean) is >60 Ma, and whose volcanoes get steadily younger toward the modern island of Hawaii.

Not all plumes form hotspot tracks—for example African plumes in many cases form clusters, rather than chains of volcanoes—reinforcing the evidence from GSP studies that the African plate is not moving very fast in any direction.

Why do plates move at different speeds?

In all cases a plate will move faster if it has some place to go: Slab pull may explain why plate motion in the Pacific Plate and Indian plate is very fast whereas it is slow on the African Plate. The African plate is surrounded by divergent margins, whereas the Pacific Plate is surrounded by subduction zones.