2.3: Convergent Boundaries

Convergent boundaries, also called destructive boundaries, are places where two or more plates move toward each other. Convergent boundary movement is divided into two types, subduction and collision, depending on the density of the involved plates. Continental lithosphere is of lower density and thus more buoyant than the underlying asthenosphere. Oceanic lithosphere is denser than continental lithosphere, and, when old and cold, may even be denser than asthenosphere.

Figure: Geologic provinces of Earth. Orogenies are labeled light blue.

When plates of different densities converge, the higher density plate is pushed beneath the more buoyant plate in a process called subduction. When continental plates converge without subduction occurring, this process is called collision.

2.3.1: Subduction

Video showing continental-oceanic subduction, causing volcanism. By Tanya Atwater and John Iwerks.
Subduction occurs when a dense oceanic plate meets a more buoyant plate, like a continental plate or warmer/younger oceanic plate, and descends into the mantle [45]. The worldwide average rate of oceanic plate subduction is 25 miles per million years, about a half-inch per year [46]. As an oceanic plate descends, it pulls the ocean floor down into a trench. These trenches can be more than twice as deep as the average depth of the adjacent ocean basin, which is usually three to four km. The Mariana Trench, for example, approaches a staggering 11 km [47].

Figure: Diagram of ocean-continent subduction.

Within the trench, ocean floor sediments are scraped together and compressed between the subducting and overriding plates. This feature is called the accretionary wedge, mélange, or accretionary prism. Fragments of continental material, including microcontinents, riding atop the subducting plate may become sutured to the accretionary wedge and accumulate into a large area of land called a terrane [48]. Vast portions of California are comprised of accreted terranes [49].
When the subducting oceanic plate, or slab, sinks into the mantle, the immense heat and pressure push volatile materials like water and carbon dioxide into an area below the continental plate and above the descending plate called the mantle wedge. The volatiles are released mostly by hydrated minerals that revert to non-hydrated minerals in these higher temperatures and pressure conditions. When mixed with asthenospheric material above the plate, the volatile lower the melting point of the mantle wedge, and through a process called flux melting it becomes liquid magma. The molten magma is more buoyant than the lithospheric plate above it and migrates to the Earth’s surface where it emerges as volcanism. The resulting volcanoes frequently appear as curved mountain chains, volcanic arcs, due to the curvature of the earth. Both oceanic and continental plates can contain volcanic arcs.
How subduction is initiated is still a matter of scientific debate [50]. It is generally accepted that subduction zones start as passive margins, where oceanic and continental plates come together, and then gravity initiates subduction and converts the passive margin into an active one [51]. One hypothesis is gravity pulls the denser oceanic plate down [52] or the plate can start to flow ductility at a low angle [53]. Scientists seeking to answer this question have collected evidence that suggests a new subduction zone is forming off the coast of Portugal [54]. Some scientists have proposed large earthquakes like the 1755 Lisbon earthquake may even have something to do with this process of creating a subduction zone [55], although the evidence is not definitive. Another hypothesis proposes subduction happens at transform boundaries involving plates of different densities [56].

Some plate boundaries look like they should be active, but show no evidence of subduction. The oceanic lithospheric plates on either side of the Atlantic Ocean for example, are denser than the underlying asthenosphere and are not subducting beneath the continental plates.

One hypothesis is the bond holding the oceanic and continental plates together is stronger than the downward force created by the difference in plate densities.
Figure: Earthquakes along the Sunda megathrust subduction zone, along the island of Sumatra, showing the 2006 Mw 9.1-9.3 Indian Ocean Earthquake as a star.

Subduction zones are known for having the largest earthquakes and tsunamis; they are the only places with fault surfaces large enough to create magnitude-9 earthquakes. These subduction-zone earthquakes not only are very large but also are very deep. When a subducting slab becomes stuck and cannot descend, a massive amount of energy builds up between the stuck plates. If this energy is not gradually dispersed, it may force the plates to suddenly release along several hundred kilometers of the subduction zone [57]. Because subduction-zone faults are located on the ocean floor, this massive amount of movement can generate giant tsunamis such as those that followed the 2004 Indian Ocean Earthquake and 2011 Tōhoku Earthquake in Japan.
All subduction zones have a forearc basin, a feature of the overriding plate found between the volcanic arc and oceanic trench. The forearc basin experiences a lot of faulting and deformation activity, particularly within the accretionary wedge [58].

In some subduction zones, tensional forces working on the continental plate create a backarc basin on the interior side of the volcanic arc. Some scientists have proposed a subduction mechanism called oceanic slab rollback creates extension faults in the overriding plates [59]. In this model, the descending oceanic slab does not slide directly under the overriding plate but instead rolls back, pulling the overlying plate seaward. The continental plate behind the volcanic arc gets stretched like pizza dough until the surface cracks and collapses to form a backarc basin. If the extension activity is extensive and deep enough, a backarc basin can develop into a continental rifting zone. These continental divergent boundaries may be less symmetrical than their mid-ocean ridge counterparts [60].

In places where numerous young buoyant oceanic plates are converging and subducting at a relatively high velocity, they may force the overlying continental plate to buckle and crack [61]. This is called back-arc faulting. Extensional back-arc faults pull rocks and chunks of plates apart. Compressional back-arc faults, also known as thrust faults, push them together.

The dual spines of the Andes Mountain range include an example of compressional thrust faulting. The western spine is part of a volcanic arc. Thrust faults have deformed the non-volcanic eastern spine, pushing rocks and pieces of a continental plate on top of each other.

There are two styles of thrust fault deformation: thin-skinned faults that occur in superficial rocks lying on top of the continental plate and thick-skinned faults that reach deeper into the crust. The Sevier Orogeny in the western U.S. is a notable thin-skinned type of deformation created during the Cretaceous Period. The Laramide Orogeny, a thick-skinned type of deformation, occurred near the end of and slightly after the Sevier Orogeny in the same region.
Flat-slab, or shallow, subduction caused the Laramide Orogeny. When the descending slab subducts at a low angle, there is more contact between the slab and the overlying continental plate than in a typical subduction zone. The shallowly-subducting slab pushes against the overriding plate and creates an area of deformation on the overriding plate many kilometers away from the subduction zone [62].

**Oceanic-Continental Subduction**

Oceanic-continental subduction occurs when an oceanic plate dives below a continental plate. This convergent boundary has a trench and mantle wedge and frequently, a volcanic arc. Well-known examples of continental volcanic arcs are the Cascade Mountains in the Pacific Northwest [63] and the Western Andes Mountains in South America [64].

**Oceanic-Oceanic Subduction**

Oceanic-oceanic subduction occurs when an oceanic plate dives below another oceanic plate, forming a trench and an island arc.
The boundaries of oceanic-oceanic subduction zones show very different activity from those involving oceanic-continental plates. Since both plates are made of oceanic lithosphere, it is usually the older plate that subducts because it is colder and denser. The volcanism on the overlying oceanic plate may remain hidden underwater. If the volcanoes rise high enough the reach the ocean surface, the chain of volcanism forms an island arc. Examples of these island arcs include the Aleutian Islands in the northern Pacific Ocean, Lesser Antilles in the Caribbean Sea, and numerous island chains scattered throughout the western Pacific Ocean [65].

2.3.2: Collisions

When continental plates converge, during the closing of an ocean basin, for example, subduction is not possible between the equally buoyant plates. Instead of one plate descending beneath another, the two masses of continental lithosphere slam together in a process known as collision [66]. Without subduction, there is no magma formation and no volcanism. Collision zones are characterized by tall, non-volcanic mountains; a broad zone of frequent, large earthquakes; and very little volcanism.

When oceanic crust connected by a passive margin to continental crust completely subducts beneath a continent, an ocean basin closes, and continental collision begins. Eventually, as ocean basins close, continents join together to form a massive accumulation of continents called a supercontinent, a process that has taken place in ~500 million-year-old cycles over earth’s history.
The process of collision created Pangea, the supercontinent envisioned by Wegener as the key component of his continental drift hypothesis. Geologists now have evidence that continental plates have been continuously converging into supercontinents and splitting into smaller basin-separated continents throughout Earth’s existence, calling this process the supercontinent cycle, a process that takes place in approximately 500 million years. For example, they estimate Pangea began separating 200 million years ago. Pangea was preceded by an earlier supercontinents, one of which being Rodinia, which existed 1.1 billion years ago and started breaking apart 800 million to 600 million years ago.

A foreland basin is a feature that develops near mountain belts, as the combined mass of the mountains forms a depression in
the lithospheric plate. While foreland basins may occur at subduction zones, they are most commonly found at collision boundaries. The Persian Gulf is possibly the best modern example, created entirely by the weight of the nearby Zagros Mountains.

Figure: Pillow lavas, which only form underwater, from an ophiolite in the Apennine Mountains of central Italy.

If continental and oceanic lithosphere are fused on the same plate, it can partially subduct but its buoyancy prevents it from fully descending. In very rare cases, part of a continental plate may become trapped beneath a descending oceanic plate in a process called obduction. When a portion of the continental crust is driven down into the subduction zone, due to its buoyancy it returns to the surface relatively quickly.

As pieces of the continental lithosphere break loose and migrate upward through the obduction zone, they bring along bits of the mantle and ocean floor and amend them on top of the continental plate. Rocks composed of this mantle and ocean-floor material are called ophiolites and they provide valuable information about the composition of the mantle.

The area of collision-zone deformation and seismic activity usually covers a broader area because the continental lithosphere is plastic and malleable. Unlike subduction-zone earthquakes, which tend to be located along a narrow swath near the convergent boundary, collision-zone earthquakes may occur hundreds of kilometers from the boundary between the plates.

The Eurasian continent has many examples of collision-zone deformations covering vast areas. The Pyrenees mountains begin in the Iberian Peninsula and cross into France. Also, there are the Alps stretching from Italy to central Europe; the Zagros mountains from Arabia to Iran; and Himalaya mountains from the Indian subcontinent to central Asia.

References


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