Mountain Building (Orogeny)

Eric Lin

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1 Introduction

Orogeny, or mountain building, is a series of processes where the collision of plates generates one or more mountain ranges. The newly-formed mountains make an almost linear range of mountains parallel to the plate margin, which we call an orogenic belt. These areas can also be called orogens, contractional regimes, or thrust and fold belts (which is a less precise term discussed later). This handout will examine the structures and mechanisms of a normal orogenic belt, as well as the relation between orogeny and plate tectonics.

2 Structures and mechanisms

2.1 Cross-section of an orogeny belt

This is a cross-section of an oceanic-continental orogeny belt, and from left to right three main structures can be observed on the hinterland (i.e. the part that is behind you when you stand on the land facing the trench) : the accretion wedge, the craton, and the fold-and-thrust belt. They will be discussed further in the following subsections.

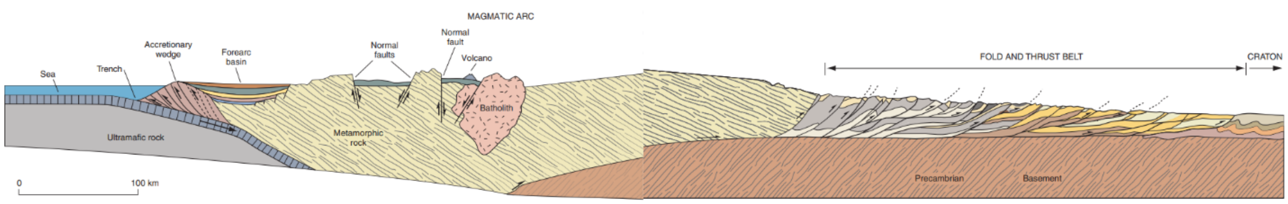


Figure 1: Cross-section of a Continental-oceanic orogeny belt.
(Source: Plummer et at., Physical Geology)

2.1.1 Fore and Backarc basins in island mountain ranges

- Backarc basins are geologic basins that form behind (landward of) volcanic arcs at some convergent plate boundaries, where an oceanic plate subducts beneath another oceanic or continental plate.
- Backarc basins are typically long and narrow, and result from tensional forces caused by the rollback of the subducting plate, which creates a gap between the arc and the trench.
- Backarc basins are filled with oceanic crust that forms by seafloor spreading at spreading ridges within the basins. The crust is often rich in water, which is released from the subducting plate into the mantle wedge above it.
- Forearc basins are geologic basins that form in front of (seaward of) volcanic arcs at convergent plate boundaries, between the arc and the trench.
- Forearc basins are usually associated with an accretionary wedge, which is a pile of sediments scraped off the subducting plate and added to the overriding plate. The accretionary wedge may form a ridge called an outer arc ridge that parallels the arc.

- Forearc basins are filled with sediments that accumulate in the depression between the accretionary wedge and the arc. The sediments may come from the trench, the arc, or the continental margin.

- Both backarc and forearc basins are influenced by the dynamics of subduction, such as the age, speed, angle, and direction of the subducting plate, as well as the mantle flow and magmatism in the mantle wedge.

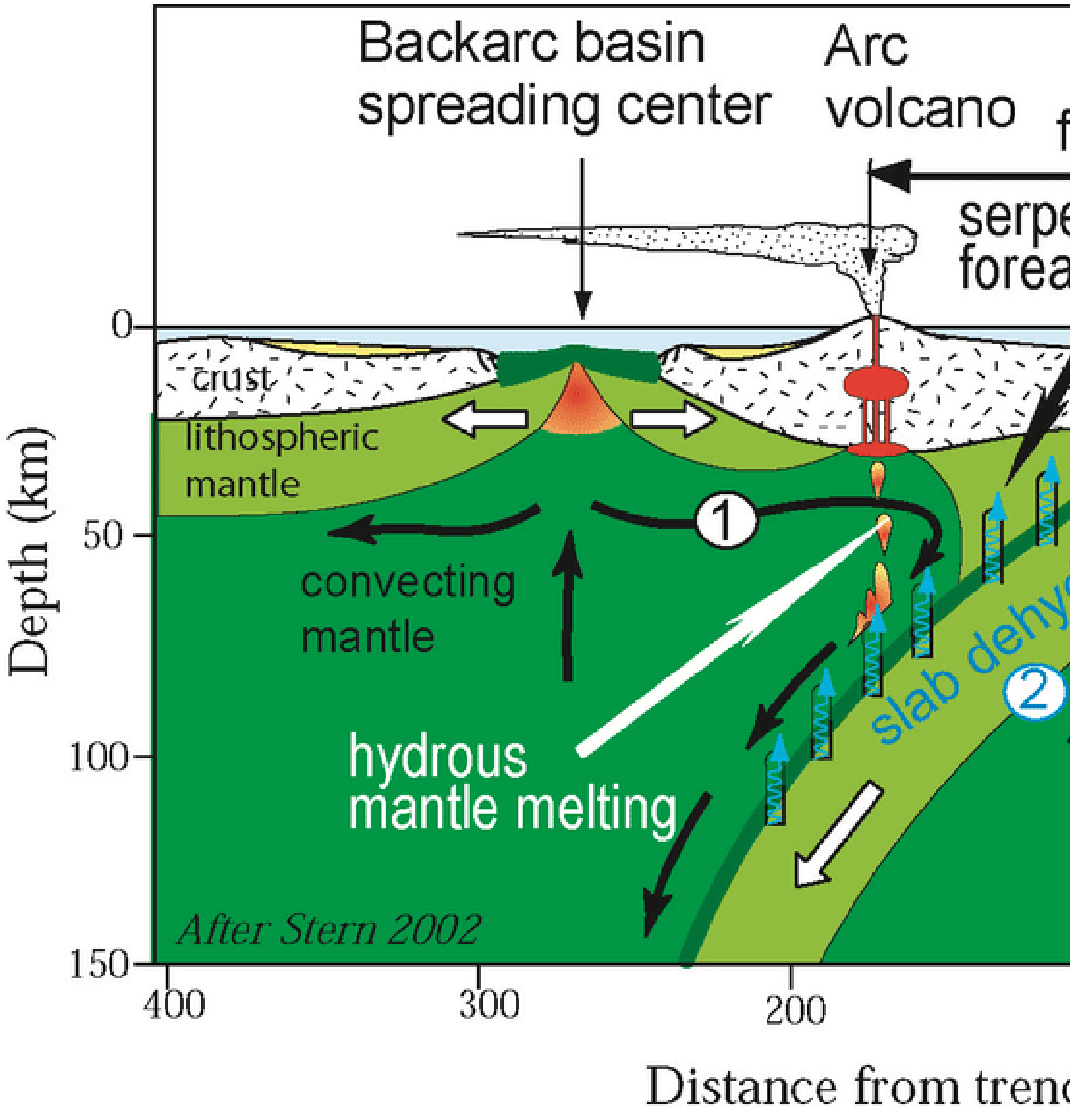


Figure 1: Back and Fore arc

2.1.2 thrust-and-fold belt (fold-and-thrust belt)

When convergence occurs, layers of formations tend to shorten, which leads to buckling (forming folds) or thrusting (forming thrusts). However, some layers or formations are denser or firmer than others, making them deform less than the overlying layers. As strain accumulates, softer rock layers (usually sedimentary formations or sediments closer to the surface) begin to buckle or thrust, leading to a plane where the shear between them and the basement accumulates. When this plane finally cannot withstand the shear, the force rips out a surface of sliding between sediments and the basement, which we call the décollement or the detachment.

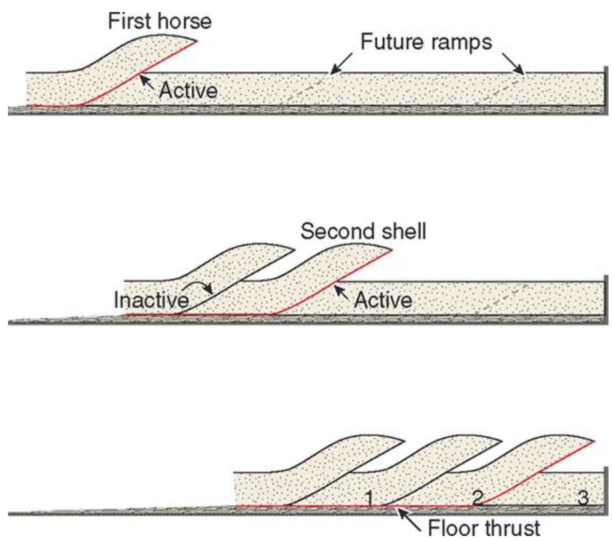


Figure 2: Thrusting. (Source: Hassan Elmeknassi, Pinterest)

Therefore, a typical fold-and-thrust belt has several components:

- A series of thrust faults and uplifted areas. They mostly form at the layers of sedimentary formations and are usually less dense compared to the basement.
- The basement. These rocks are less deformable and usually much denser. Common basement components include Cratonic platforms or crystalline basements.
- Décollement (detachment).

2.1.3 Thin-Skinned vs Thick-Skinned deformation

From the previous definitions, you may probably wonder about the scale of a fold-and-thrust belt. In fact, the term "fold-and-thrust" is occurring so commonly on our planet in almost any region of convergence stress, from microplates to the entire lithosphere. We thus need a more precise description to tell them apart. "Skin" here is a simile of the nappe (the transported sediments), or the thrusted layers.

	Thin-Skinned	Thick-Skinned
"skin"	mainly sediments or weakly-cemented sedimentary formations	the entire crust
where thrusts form	weak parts	weak parts
basement	usu. crystalline basements	mantle
décollement	relatively weak strata	MOHO or not obvious
required stress	low	high
commonly found in	almost any contractional regime	convergence boundaries

2.1.4 orogenic wedges

Let's zoom out our camera a little to view the thrust-and-fold belt as a whole. What shape should it look like? The bulldozer model suggests imagining a bulldozer or loader shoving the snow on the ground. The shoved snow should be wedge-like, or triangular if viewed from the side. If you live in a place that doesn't snow, put some water in a bathtub (fish tank, food container, or whatsoever) and move your hand perpendicular to the water surface to observe the same phenomenon. The wedge has the sharper side in the same direction of the movement, and this is mainly what happens in a fold-and-thrust belt.

2.1.5 metamorphism and plutonism in the hinterland

The fold-and-thrust belts mark the regions of tectonic forces not yet intense enough to create intense strain or temperature that changes the properties of rocks. However, things change when we view the hinterland, where the tectonic force that drives the whole orogeny system is in charge. The hinterland is the most deformed part of the large-scale orogenic belts, thus metamorphism and plutonism may occur due to the stress by convergence or burying, or the high temperature as a result of tectonic forces. Migmatites (a mixture of granitic and metamorphic rocks) or xenoliths may be found under relatively lower temperatures, while under extreme temperatures, zones of metamorphic rock or magmatic structures such as batholiths and magma diapirs may form.

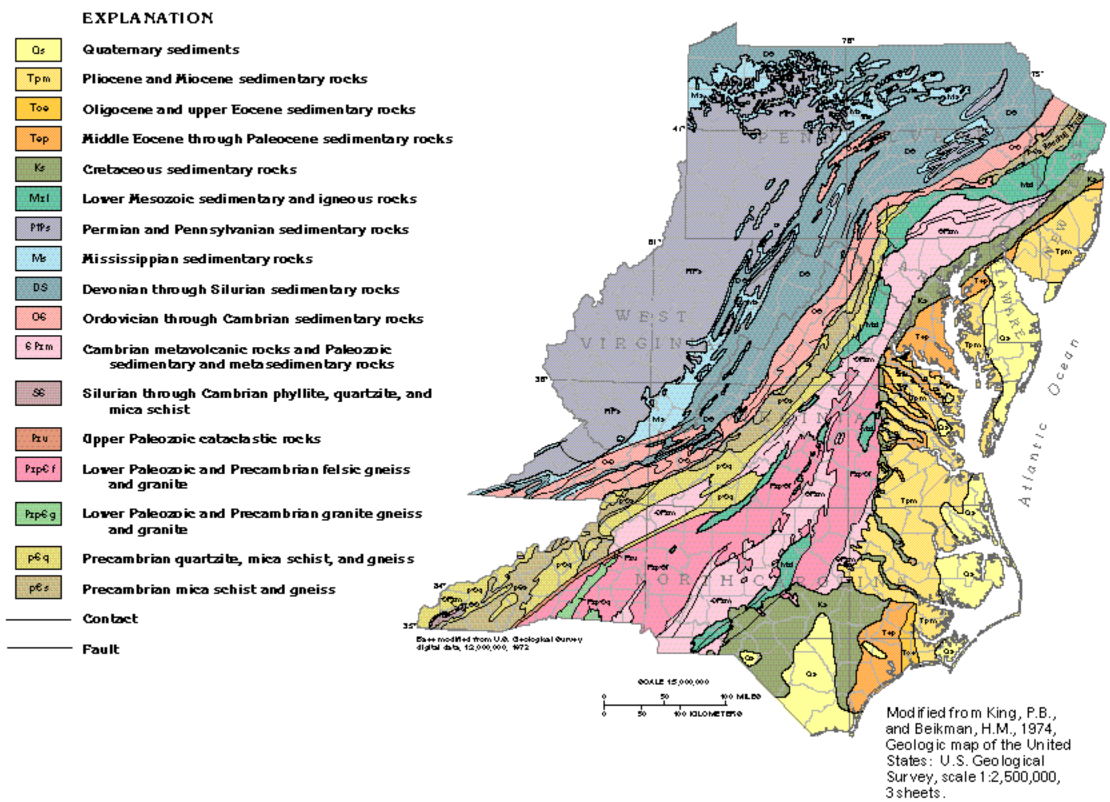


Figure 3: Gneiss and granite at the Appalachians shown in darker pink. Hinterland is the blue and salmon color.
(Source: Wikipedia, modified from King and Beikman)

2.2 Isostasy, post-orogenic uplift and extension

2.2.1 Isostasy

Before we examine what may happen to an orogenic belt after the most intense collision, we have to go through the theory of Isostasy. The theory suggests that the crust is ”floating” on the mantle, or in more precise terms, the lithosphere is floating on the asthenosphere. This may be difficult to imagine this as the lithospheric mantle is slightly ductile, so let’s just imagine wood blocks, representing the crust, floating on water, or the mantle. Pascal’s law suggests equal pressure everywhere of the same depth, so we can infer the following:

- **Blocks (crust) of the same density have the same *proportion* of height above the water.** That is, if block A is 4cm above and 2cm under the water surface, then block B of the same density and height of 9 would be 6cm above and 3cm under the water surface.
- **Blocks (crust) of greater density tend to have a greater portion of height below the surface**

Geologist thus use the inferences to explain why there are thicker and higher mountains as well as thinner and lower plains on our planet. Three models are now commonly accepted:

- **The Airy–Heiskanen model (Airy’s model).** The density of all crusts are assumed to be the same. Thus according to Rule 1, mountains are regions of crust with greater thickness.
- **The Pratt–Hayford model (Pratt’s model).** The root (parts of crust under the average mantle surface) of all crusts are assumed to be the same. Thus according to Rule 2, mountains are regions of crust with greater density.
- **The Vening Meinesz model (flexural model).** Considering the rigidness of the asthenosphere, the lithosphere’s weight can be supported by a considerable region of the mantle. In this model the asthenosphere bends like a sponge rather than behaving totally like a fluid. This is also the most realistic model.

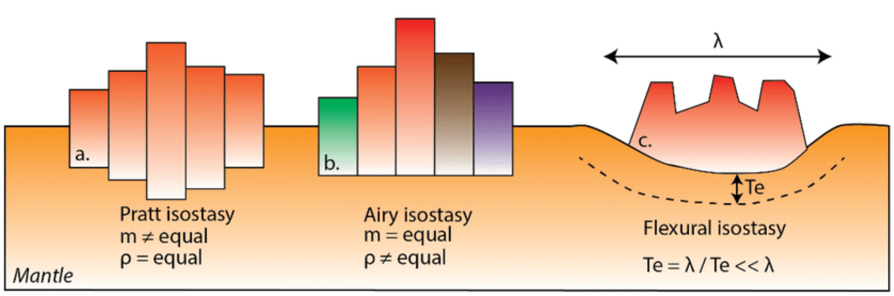


Figure 4: Models of isostasy. (Source: Anouk Beniest, ResearchGate)

2.2.2 Post-orogenic uplift and extension

After the orogeny, high mountains form as a result of the collision. However, please be noticed that erosion is always occurring. Therefore, when the converging force decreases or comes to a halt, the erosion of the crustal materials causes the entire orogenic belt to lift under the control of buoyancy. Meanwhile, the previously constrained metamorphic or plutonic rocks are lifted to the surface. This causes the extension of the whole system, and normal faults may form as a consequence.

3 Orogeny and plate tectonics

Orogeny leads to the formation of many mountains in the world, including the Andes, the Alps, the Himalayas, and the Appalachians; along with lifting islands, including Taiwan, Japan, and New Zealand. In this section, we'll go through the results caused by orogeny and tectonic forces, from the scale of a continent to the formation of some typical convergence belts.

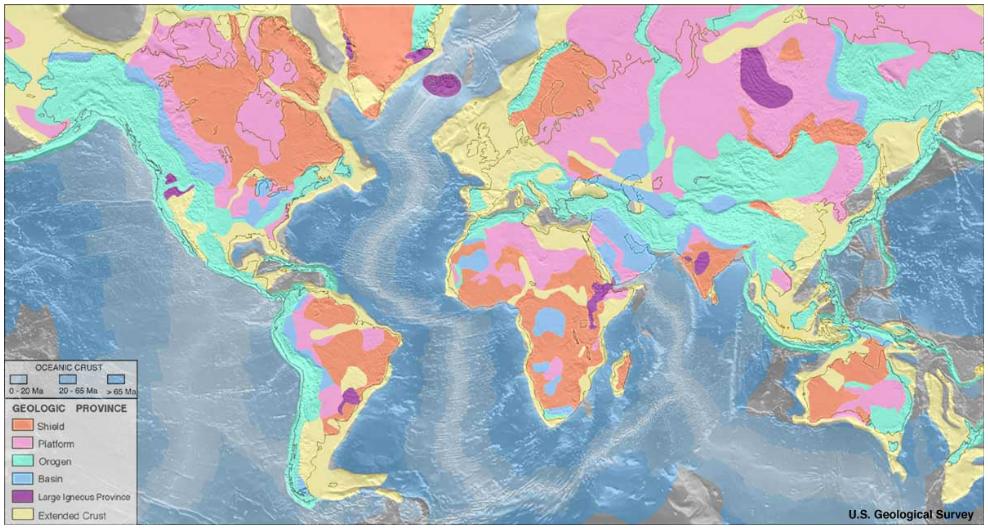


Figure 5: Orogenic belts in the world shown in cyan. (Source: USGS)

3.1 The Wilson Cycle

The Wilson Cycle was first proposed to describe the life and death of the major oceans and served as one of the strong pieces of evidence of the plate tectonic theory. The complete cycle is divided into six stages:

- **The embryonic stage.** This is when the craton starts to separate due to extensional forces (mainly caused by the uplift mentioned in the previous section). Large-scale normal faults may further lead to the birth of valleys and rifts. Examples: The East African rift valley.
- **The juvenile stage.** The craton separates further due to extensional forces (mainly caused by divergence now). On appearance, it differs from the embryonic stage in the presence of narrow waters. Examples: The Red Sea.
- **The mature stage.** The ocean basin is now large enough to be an ocean. Before the next stage, the prior three stages are called the **growing (divergence) stages**. Examples: The Atlantic.
- **The declining stage.** When the divergence force no longer pushes apart the ocean basin but rather makes the plate subduct below the other marks the beginning of this stage. Because of the convergence force on the boundaries, orogens of small islands form and the typical arc-trench system may be found. Examples: The Pacific.

- **The terminal stage.** The ocean becomes increasingly small while more orogenic activities occur. Islands may not come in an arc, but in groups instead. Examples: The Mediterranean Sea.

- **The suturing stage.** The converging force leads to massive orogeny, thus high and young mountains are mostly formed within this stage. The characteristics mentioned in the last section are almost guaranteed to be found here, while no water will exist at all. The last three phases are referred to be the **dying (convergence) stages**. Examples: The Alps and the Himalayas.

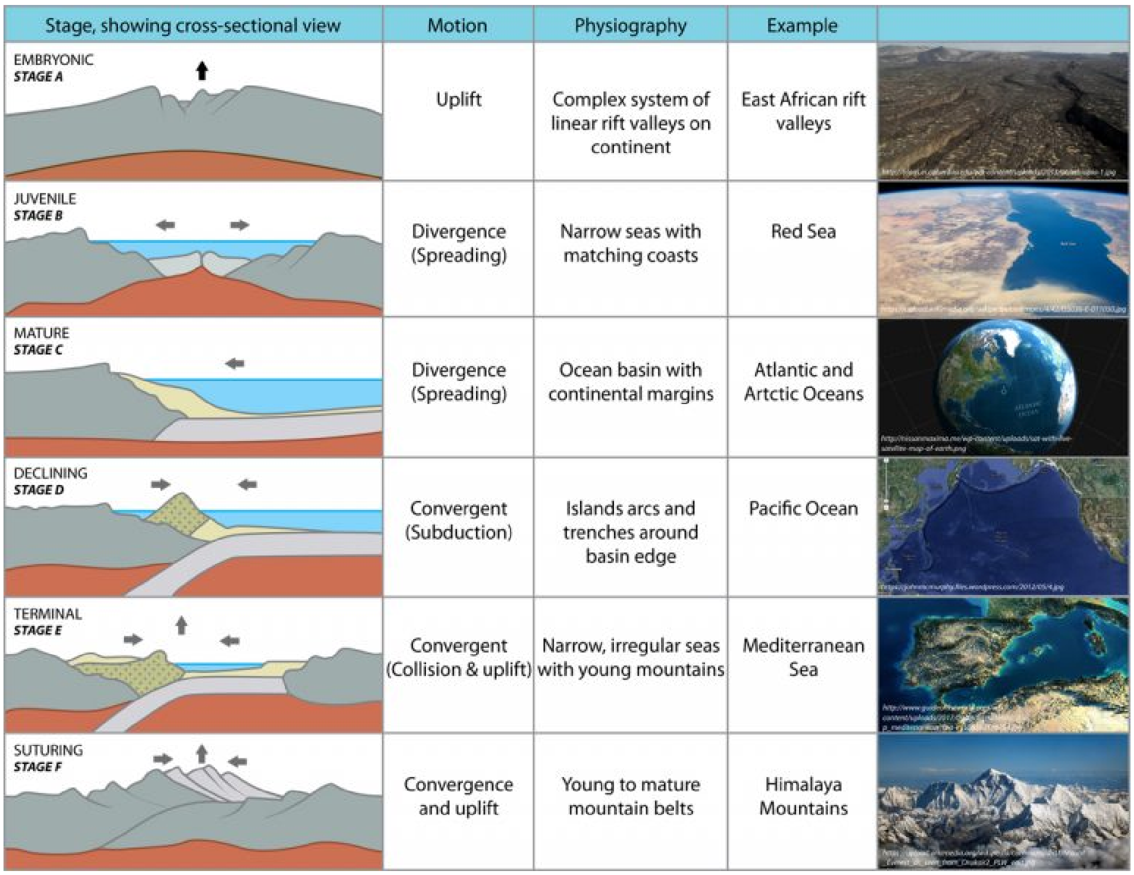


Figure 6: Wilson Cycle. (Source: Polarpedia)

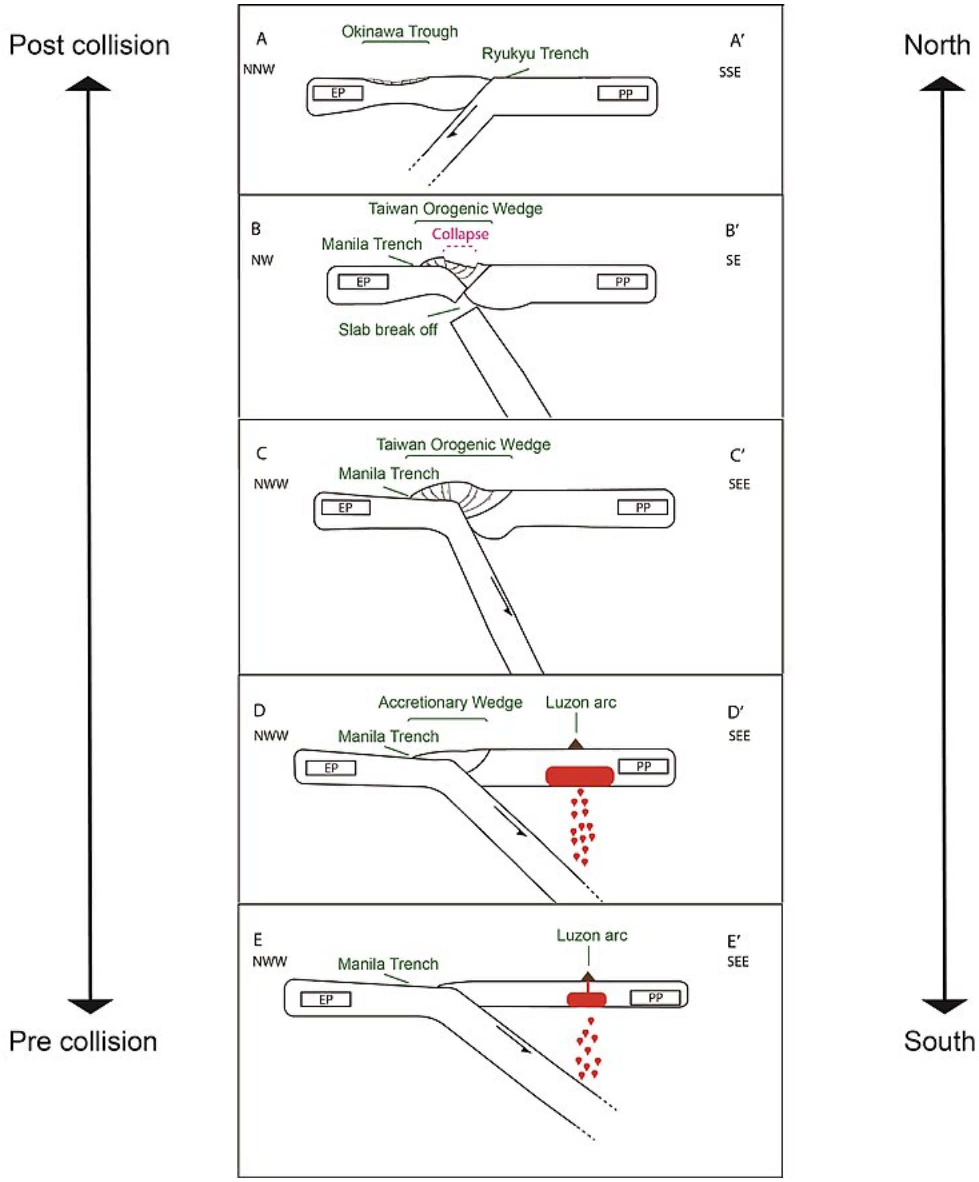
Practice 3.1 (USESO Training Camp Exams 2019, Geosphere Section Q6) The Wilson Cycle describes the cyclic process of the opening and closing of ocean basins through tectonic activity. Order the following events according to this cycle.
(1) Sediment accumulates at passive margins.
(2) Accretion welds terrain onto continents.
(3) The continent undergoes rifting.
(4) Subduction creates volcanic mountain belts.
(5) Erosion dominates, thinning mountains.

Solutions or Suggested Answer: 31425.

3.2 Convergence belts

According to the last subsection, plate convergence is a common way to create orogenic belts. However, not all convergent boundaries generate mountain belts. To make mountains, one of the plates that collide must be a continental plate, which provides a stiff basement and a great number of sediments. The situation can further be divided into three types, each creating a unique pattern of mountain belts.

- **Ocean-Continent convergence.** This is the most common type of convergence, and its structure is shown in Figure 1. This type of movement also contributes to the declining stage of the Wilson cycle and makes the Andes on our planet. (Thus, this type of mountain belt is often referred to as Andean-type).
- **Arc-Continent convergence.** The one eventually leads to the collision and fusion of the pre-existing arc and the continental crust. One typical characteristic is the presence of *the flipping subduction zone*. That is, due to the increasing pushing force from the arc to the continent, the subducting crust may switch from the continental-carrying plate to the arc-carrying one. This type of convergence is believed to play a significant role in building the Appalachians during Paloezoic.
- **Continent-Continent convergence.** This type is commonly seen at the suturing stage of the Wilson cycle and accounts for the highest mountains on Earth, including the Alps, the Appalachians (late paleozoic and early Mesozoic), and the Himalayan. Intense fold-and-thrust belts accompanied by high while rugged terrains are their main characteristic.


Post collision
Pre collision
North
South
A
NNW
Okinawa Trough
Ryukyu Trench
A′
SSE
EP
PP
B
NW
Taiwan Orogenic Wedge
Collapse
Manila Trench
Slab break off
B′
SE
C
NWW
Taiwan Orogenic Wedge
Manila Trench
C′
SEE
D
NWW
Accretionary Wedge
Luzon arc
Manila Trench
D′
SEE
E
NWW
Luzon arc
Manila Trench
E′
SEE

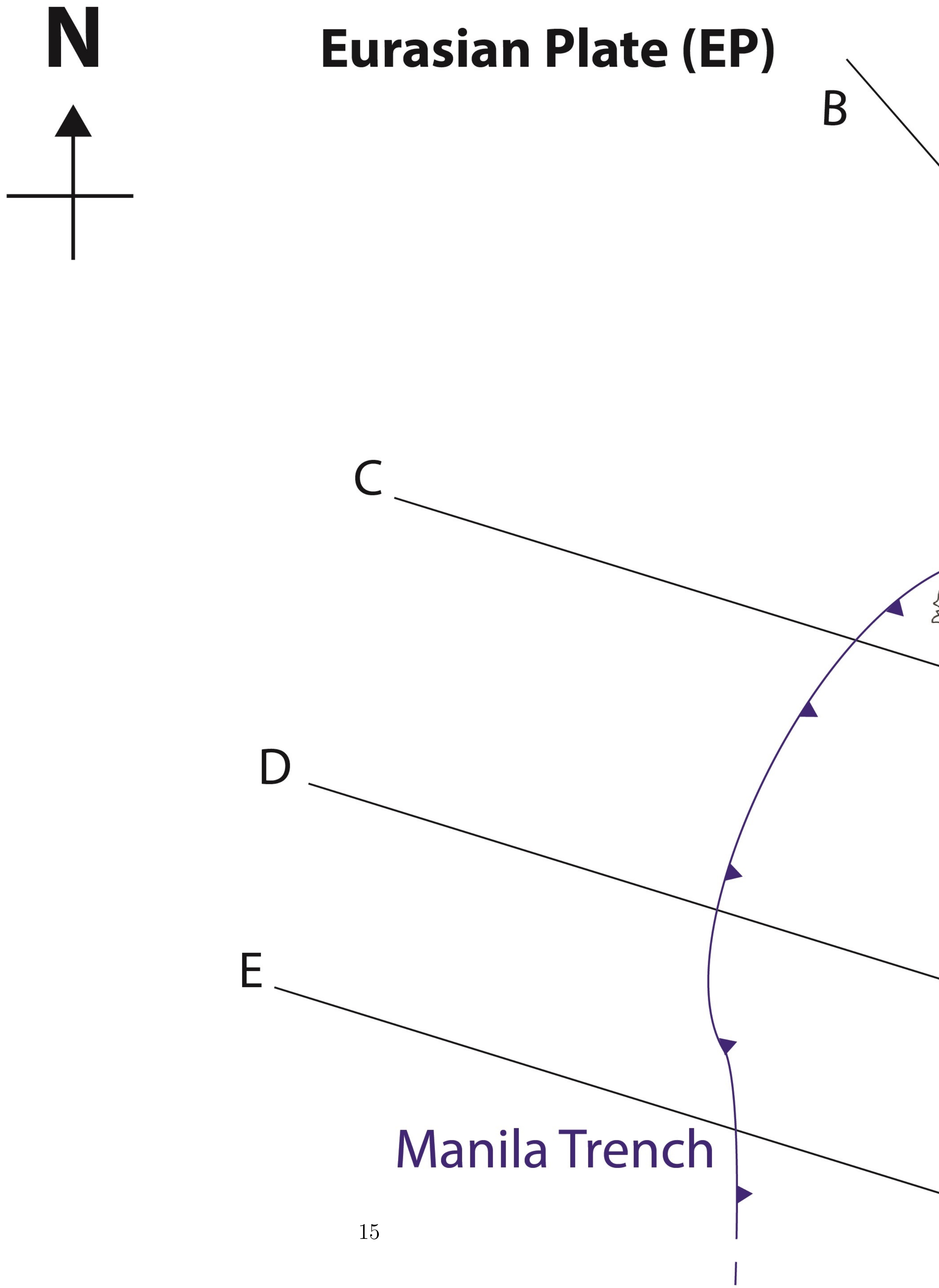

N
Eurasian Plate (EP)
B
C
D
E
Manila Trench

Figure 7: Flipping Subduction Zone on Taiwan island and an areal view. (Source: Wikipedia)

General Practice (USESO Training Camp Exams 2022, Geosphere Section II Q2) The Himalayas form the longest mountain range in Asia. This problem explores its crustal deformation in a cross section and the Main Himalayan Thrust.

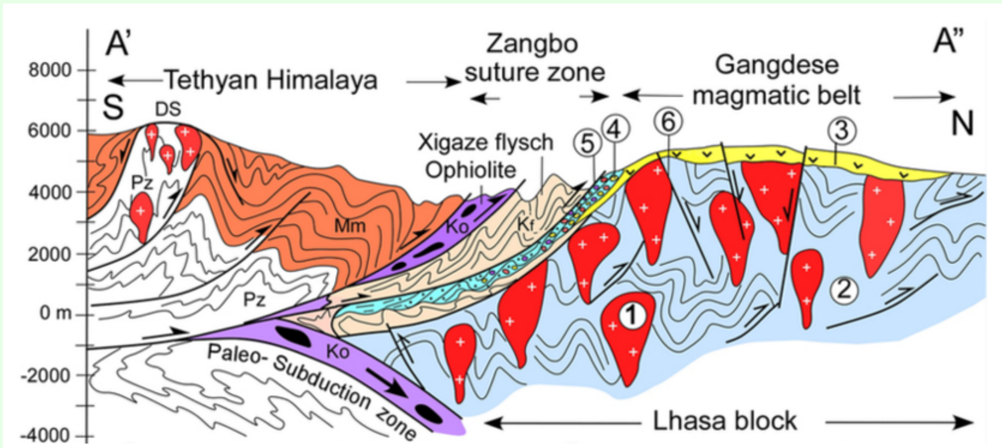


Figure: Cross section of Himalayas. (Wang et al., 2015)

1. Contemporary sinking near the Zangbo suture zone is causing the Gangdese magmatic belt to rise. Explain how this motion is an example of isostatic adjustment.
Editor hint: Consider the flexural model.

2. Around 20 million years ago, monsoons around the Himalayas intensified. How might this have affected the vertical movement of the Himalayas?
Editor hint: Consider the isostasy equilibrium.

3. A geologist finds pillow basalt in the Himalayas. In which region(s) of this cross-section could the geologist potentially be in? (May have more than one answer.)
(A) Tethyan Himalayas
(B) Zangbo Suture Zone
(C) Gangdese Magmatic Belt
Key: Pillow basalt indicates an underwater eruption of mafic lava.
Editor hint: Consider the structure of a orogenic belt. Which part is lifted?

Solutions or Suggested Answer:
1. The Tethyan Himalaya places a large vertical load on underlying lithosphere. Because the asthenosphere behaves as a liquid beneath the lithosphere, the downward bending from the weight of the mountain is accommodated by a nearby upward bend to approach isostatic equilibrium. This is sometimes known as lithospheric flexure.
2. Intensification of monsoons increases erosion, which is especially true of high-relief topography such as the Himalayas. A decrease in mass causes the lithosphere to isostatically rebound.
3. Pillow basalts are indicative of basalt erupting underwater. They are often found in ophiolites, in which fragments of the oceanic crust are sutured onto continental crust instead of

being subducted.