MOUNTAIN BUILDING – Tutorial Script

Mt Everest, the Grand Tetons, Mauna Kea, Monument Valley
Across planet Earth, we see multiple examples of majestic mountains. The word ***mountain*** applies to any landform that stands taller in elevation than the surrounding land. The shape of the variety of mountains we see across the planet comes from a combination of tectonic forces that push the land up and erosional processes, such as glaciers, gravity, wind, and running water, that carve that land down. In this video we will review the different types of mountains we find on our planet: their causes, similarities, and differences.

Mount Shasta in northern California, Mount Fuji in Japan, Mauna Kea in Hawaii, and Snæfellsjökull in Iceland: what type of mountains are all these? Volcanic. When magmas erupt on Earth's surface, they can produce layers of lavas, ash, or cinders that pile up above the surrounding land. We call these taller landforms volcanoes, volcanic domes, or cones. Volcanoes are found wherever we melt the mantle, which happens at divergent plate boundaries, subduction zones, and hotspots. Volcanoes can be spectacularly steep like Mount Fuji, a stratovolcano towering almost 4 km above its surroundings, or gently sloping giants like Mauna Kea in Hawaii – broad shield volcanos that rise upward just over 9 km above the surrounding seafloor. For more information on volcanoes, plate tectonics, and hotspots, watch the video tutorials on these subjects.

The Himalayas, in Asia, the highest elevation mountain system in the world, the Alps in Europe, and the Olympic mountains in Washington state: what kind of mountains are all these? Fold and thrust mountains. When a region is subjected to compression, which happens daily at convergent plate boundaries, the land is squeezed and thickened, forming mountains. When the leading edge of one converging plate consists of oceanic crust, and the other continental crust, the plate with the ocean crust subducts or sinks under the plate with the continental crust because ocean plate is denser.

Material atop the subducting plate such as islands, sediment, or the crust itself, can get scraped off and attached or accreted to the edge of the continental plate in the zone between the trench and the volcanic arc. These accreted elements, called terranes, are squeezed up against the continent, which gets thicker here, with folds at depth and faults at surface. As discussed in the folds and faults video tutorial the faults that form from compression are called reverse faults, or if very low angle, thrust faults, hence the name of these mountains as fold and thrust mountains.

When the leading edge of both converging plates consist of oceanic crust, the densest one will subduct, and the accretionary fold-and-thrust mountains will form just like in the previous subduction zone example. The main difference is that oceanic crust is on average $1/10^{th}$ the thickness of continental crust so these fold-and-thrust mountains will not be as thick as when formed at the edge of continental crust.

When the leading edge of both converging plates consist of continental crust, neither subducts, as they are both too low in density. The result is some of the highest elevation land in the world, as thick continental crust is thickened even further. As discussed in the isostasy video tutorial, to support high elevation crust and plate atop a plastic asthenosphere, there will be a deep root underneath, like an iceberg in the ocean. So not only are the Himalayas the highest elevation crust, the base of the crust under the Himalayas is also the deepest. Not surprising considering two thick pieces of continent are now sharing the same space – the squeezing pushes rocks up and down. Note: Mount Everest is the highest elevation mountain in the world, at just under 9 km above sea level. To climb Mt Everest, you would have to climb 8.5 km up from its base! Also note that because the Himalayas are so thick with such a deep root (and still growing) it will take hundreds of millions of years after tectonic compression stops, for the mountains to erode away. For each few feet that erodes from the top, removal of weight will cause the land to rise up isostatically to balance itself. This process would have to go on for hundreds of millions of years before the deep root was completely gone. We see this process happening today in the Appalachian Mountains on the east coast of the United States. These mountains were the Himalayas of the past – forming 250 million years ago when all Earth's continents converged on each other and combined into one supercontinent, Pangaea. That collision produced large fold-and-thrust mountains that were later broken up and redistributed when Pangaea broke apart. Today, 250 million years after the Appalachians stopped forming, we see what's left over as erosion tears these mountains down.

The ridges of the East African Rift Zone, the Grand Tetons in Wyoming, and the Sierra Nevada in California: what kind of mountains are these? Fault-block mountains. When a region is subjected to tension, which happens daily at divergent plate boundaries, the land is stretched and thinned. The crust will break into blocks that pull apart along faults. Imagine these books to be continental crust, broken into blocks separated by faults. We apply tension and stretch the blocks apart. Along each fault, the hanging wall slips down and the foot wall rises upward, bringing formerly deep and old rocks up to the surface and creating series of linear mountain ranges separated on both sides by linear valleys. As described in the Folds and Faults video tutorial, tensional faults are called normal faults. Where tension is pulling apart the American Southwest, as a continuation of the divergence in the Gulf of California, we see spectacular examples of the alternating valleys and ridges or basins and ranges produced through tension. Both the Grand

Tetons eastern edge and the Sierra Nevada eastern edge are normal faults along which these mountains rise upwards out of the Earth.

The Bighorn Mountains in Wyoming, Mt. Diablo in the San Francisco Bay Area: what kind of mountains are these? Domes. When less dense material that is buried underground rises upward with a buoyant force, it pushes the rocks above it into a dome. What are some examples of less dense material rising upwards? Certainly we have plenty of lower-density molten rock rising under volcanic centers, but normally those lead to volcanic mountains as already discussed. If, however, the molten rock pushes up and never makes it out, it might lead to the formation of a dome. Some domes form above buried salt beds that have mixed with waters and formed upward-migrating salt mounds. Some domes have cores of serpentinite, which as discussed in the Metamorphic Rocks video tutorial forms when mantle rock at seafloor spreading centers mixes with hot water. The lower density of the serpentinite makes it migrate upward along cracks in the seafloor, up subduction zones, and if no cracks exist, push upward into domes.

Monument Valley in Arizona, Twin Peaks in San Francisco, Ayers Rock in Australia: what kind of mountains are these? Erosional remnants. When erosional forces such as running water remove material from a landscape, they will preferentially remove first the rocks that are softest, leaving behind the most resistant rocks. When the geology of an area has a mixture of soft and hard rocks, after erosion, the hard rock can remain standing above the surrounding terrain. When the geology of an area is made almost entirely of hard rock, erosion will be slow, and concentrated where there are cracks or holes. Erosion will continue in those areas as faster rates than other areas, often eroding downward to softer rocks that might lie underneath. Over time, as more and more material is eroded in these areas, erosional remnants are left behind like islands in the landscape. These types of mountains are generally much smaller than compressional and tensional mountain systems, but they can still be quite spectacular.

In San Francisco, the waves erode the land on three sides and over time have carved out the surrounding rocks leaving a number of mountains or hills behind as remnants of this erosion. These hills have cores of hard sandstone or basalt and chert. In Monument Valley, in Arizona, the layers of rock that sit at the top of the mountains are hard layers that have resisted erosion more than those beneath them. These hard rocks cap and protect the layers underneath them. Eventually as the underlying layers are eroded, the tops are undercut and fall downward, creating spectacular steep-sided peaks with piles of fallen boulders at their base. These erosional remnant mountains are still being attacked by erosional forces such as gravity and running water and will eventually be eroded flat. Until then they remain as testaments in the landscape to the power of erosion.

What happens in the center of plates, in the center of continents, where there are no tectonic forces? Erosion has been at work there for hundreds of millions of years, and the land has been eroded flat. We call these areas of tectonic stability cratons, and often here is where we find some of the oldest best-preserved rocks on the planet. These cratons provide a stark contrast to the dynamic tectonics of subduction zones where new rock is added continually to the continents through volcanism in the arcs and accretion of terranes in the fold-and-thrust mountain ranges in the accretion zone.

In summary, any landform that sits higher than its surroundings, and which we call a mountain can be classified as either volcanic, compressional fold-and-thrust mountains, tensional fault-block mountains, domes, or erosional remnants. The variety of shapes they display comes from a combination of the forces that push the land up, the erosional forces that sculpt it down, and the hardness of the rock that sits within the mountains. Combined, these create the variety of mountains we see across our planet.

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