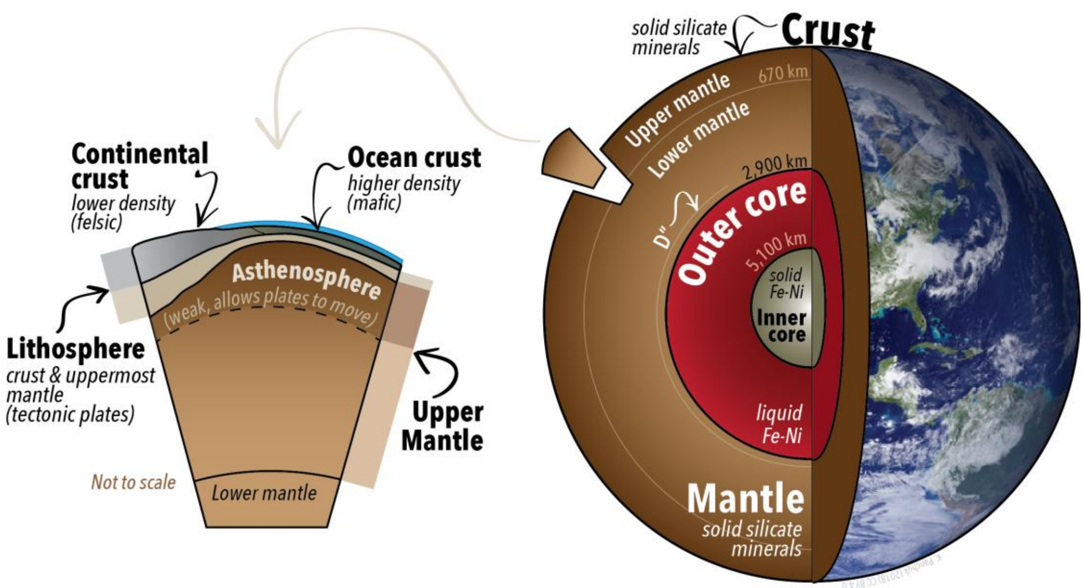
Module 1: Mountain Building

How are mountains formed?

If we want to understand how mountains are formed and raised, we need first to know something about the Earth's structure, and how it continues to evolve

We understand our planet's structure to comprise a solid-iron inner core at the centre, with a liquid-iron outer core circulating around it, and a mantle of hot, 'plastic' rocky material moving very sluggishly around that.



The Earth's crust to inner core by Karla Panchuk (2018) CC BY 4.0. Earth photo by NASA (n.d.) Public Domain *view source*

The outer shell of the Earth – the crust – is the relatively thin layer of solid rock which forms the ocean floor, islands and continents. Oceanic crust is thinner – about 5 km to 10 km thick – than continental crust, which is mostly 30 km to 50 km, sometimes (around high mountain ranges) as much as 80 km, thick. When we look at average crustal thickness in comparison with the Earth's total diameter, it is thinner than a hen's egg-shell in relation to the egg!

We can think of different areas of oceanic and continental crust as being a bit like pieces in a giant jigsaw puzzle, covering the entire planet. These pieces are called ‘plates’. We know that new oceanic crust is formed by volcanic eruptions – almost always under the ocean – along the edges of pairs of oceanic plates, where those parts of the mantle which are less dense, and melt at relatively low temperatures and pressures, ooze out through cracks between the plates.

These oceanic-to-oceanic plate boundaries, identified as sub-oceanic mountain chains formed from young volcanic rocks, are known as ‘constructive plate margins’. A good example of such a ‘mid-oceanic ridge’ can be seen all the way up the centre-line of the Atlantic Ocean: new oceanic crust forms along this line, as the ocean is slowly (at about the rate a finger-nail grows) being pulled apart by global-scale crustal forces, and so grows wider. The ridge, and the margin along its centre, can even be seen above sea-level, in the country of Iceland, and a few other islands along its course.

By tracing a wide variety of different clues back through the geological record, we have come to understand that the continents of North and South America, and Europe and Africa, once formed a continual landmass: even today, we can see that their coasts could more or less fit together. As they were slowly pulled apart – mainly under the influence of the circulating mantle material below – the Atlantic Ocean developed between them.

In other regions, where an oceanic plate and a continental plate are pushed against each other along their edges, one of these must give. The thinner, denser oceanic plate is pushed underneath the edge of the (thicker, more buoyant) continental plate, back down towards the mantle. This is known as ‘subduction’.

Not far offshore the west coast of British Columbia (BC), Canada, there are examples of both a constructive spreading ridge and a destructive subduction zone. While new ocean crust continues to be generated to the west of Vancouver Island, by remnants of what was once the Pacific mid-oceanic ridge (Juan de Fuca Ridge), the oceanic plate to the east of this margin (Juan de Fuca plate) is being subducted beneath continental North America (marked by the Cascadia Trench). (Note that most of the spreading-ridge itself has also already disappeared in this way.)

Magma, lava and volcanoes: igneous mountain-building processes

As the oceanic plate descends beneath the continental margin, it encounters higher temperatures and pressures, and begins to melt. Some parts of the rock forming the oceanic crust melt earlier, at shallower depths: being less dense and more fluid, these partial melts – we can think of them as ‘bubbles’ of magma – tend to move up through the edge of the continental crust, exploiting any lines of weakness in the structure. Some of these pathways are themselves likely to have been formed by stresses driven by the plate-to-plate collision and subduction. As the magma moves, it may also melt surrounding rock, which is added to the mix.

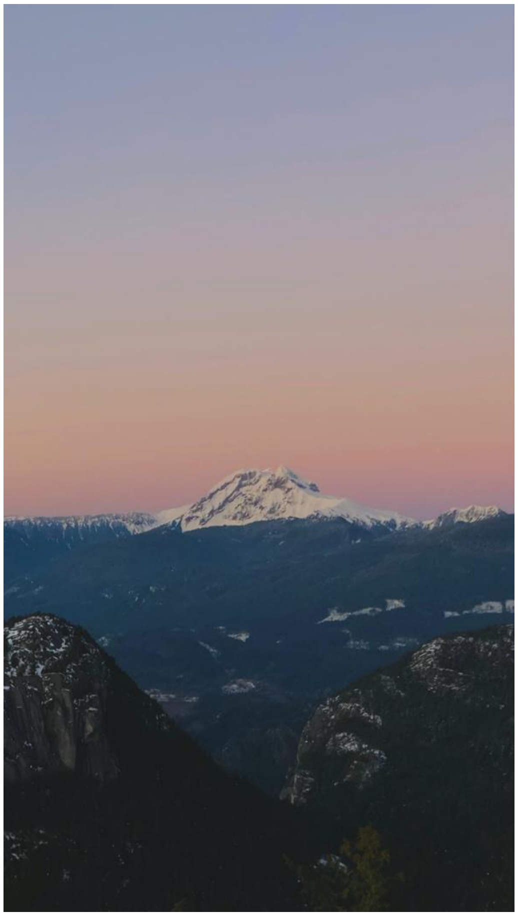
The combination of horizontal pressure along the plate-margins at the surface (folding and faulting,) together with some vertical pressure from magma forcing upward from the regions of melting oceanic crust (doming,) are important mechanisms by which mountains begin to be raised.

If the magma finds its way to the surface, it will erupt as a volcano. Once a route has been forced from deep in the crust all the way to the surface, it tends to be exploited repeatedly by successive pulses of magma. Many of the mountains along British Columbia’s coast were formed in this way:

through long periods of time, repeat eruptions of molten rock (now, when it appears on the Earth's surface, called lava) add more and more material to each vent.

Often, along a boundary between an oceanic and a continental plate, the chemical composition of the melt makes it quite sticky or viscous, so the lava does not flow far before it solidifies. Another result is that it's not easy for gases to escape – until the pressure builds sufficiently for a major explosion.

Volcanoes associated with sporadic explosive eruptions are often found in mountain ranges along coastal margins next to subduction zones – for example in the Cascade, Coast, and Andes ranges. One of the best-known examples of a major explosive eruption of this type was at Mount St Helens (Washington State) in 1980. Because the 'sticky' lava does not flow very far, these volcanoes can eventually build high mountains – such as Mount Meager, Mount Garibaldi, Mount Baker, and Mount Rainier.



Mount Garibaldi, British Columbia, is a volcano formed by sporadic eruptions.
Photo by Olivier Lattaro.

Where the route between the magma's origin and the surface is shorter, in areas where the crust is thinner, or it has been split by other forces, the lava tends to be much more fluid, so it flows further, sometimes forming an extensive plateau. The longest lava flow known from the geological record was over 500 km. Eruptions in Hawaii often provide a good example of fluid lava flows – but examples of these are also found across large areas of British Columbia (e.g. Wells Gray Provincial Park) and in the Columbia River basalts of Washington or Oregon. It's thought that these might have been made possible by crustal thinning occurring behind the coastal mountain ranges.

Regardless of the lava's viscosity – on encountering the much cooler, low-pressure conditions at the surface compared to those deeper in the crust, it solidifies rapidly. This limits the time available for mineral crystals to form and develop, so volcanic rocks tend to be very fine-grain. The most extreme example of this is when the melt cools almost instantly, with no time at all for crystallization, forming volcanic glass. Obsidian is a type of volcanic glass: high-quality obsidian from deposits on Mt Edziza, in northwestern British Columbia, was highly prized by Indigenous peoples for making tools and spear and arrow points and traded extensively – as far as northern Alberta and Alaska.

In contrast, magma which does not reach the surface – despite pushing upward through the lower to middle sections of the crust, quite possibly causing uplift by 'doming' as it does so – never encounters that sudden surface-shock. It cools over much longer durations, giving time for the various chemical constituents of the melt to migrate, organize themselves, and begin to form and develop crystals. The longer the magma takes to cool, the larger the crystals – particularly those which form last in the cooling process – might grow.

Building mountains by folding and faulting

As two plates are pushed against one another, compression forces the rock to change shape: this is known as deformation. At an ocean-continent collision, these forces are limited by the subduction of the oceanic plate – it deflects below the continental crust, rather than colliding with it fully. Nevertheless, appreciable deformation occurs, helping – along with (and in some ways aiding) the volcanic activity – to build the mountains along the continental margin.

More rarely, two units of continental crust might be pushed against one another. In this case, there's no backing-down: it's a full-on collision, and the forces generated are immense. Through time, great chunks of land – known as terranes – formed new additions to British Columbia and the western side of Canada, carried on the subduction-driven conveyor of the Pacific oceanic plate. With each new collision, new mountains were pushed up on the surface. This is also the origin of the Himalayas, formed by the northward collision of the Indian sub-continent (which it really is, in geological terms!) with south-central Asia.

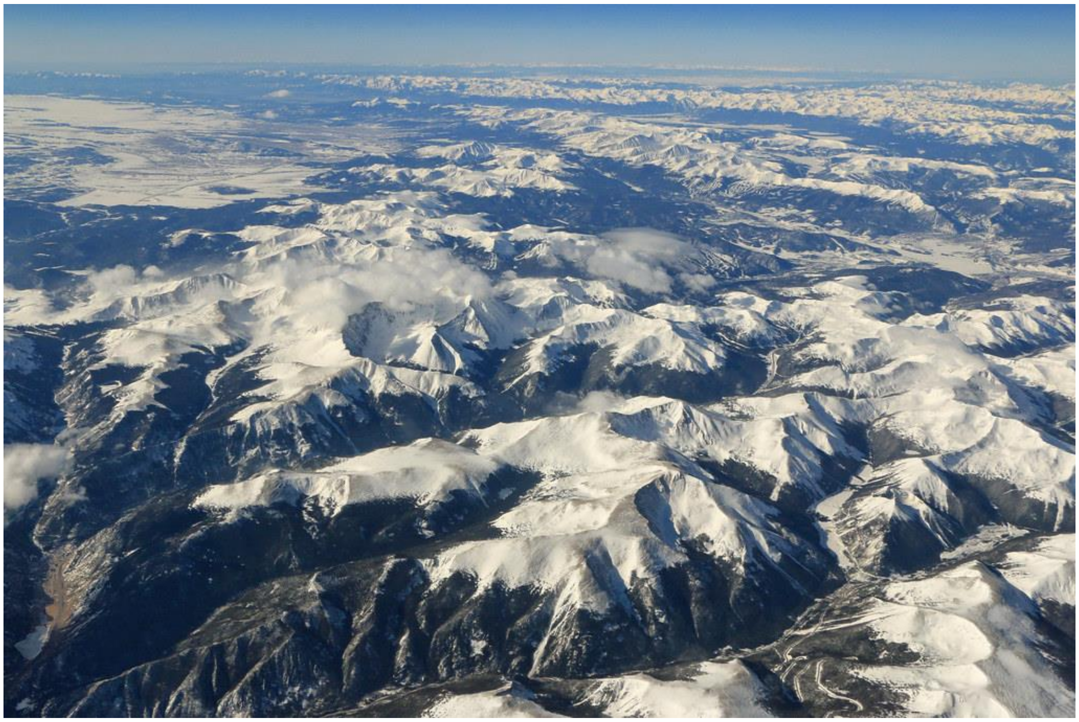
Different rocks respond to compression in different ways under different conditions. Some are relatively brittle, others ductile ('bendable'). Their mechanical response to stress will vary, depending on how this stress is applied in relation to the alignment of the rock units; their physical composition and overall morphometry (form, dimensions); and how deep they are within the crust (and thus the surrounding temperatures and pressures.)

"Himalayas - Aerial view" by Dr. Partha Sarathi Sahana is licensed under CC BY 2.0.

Ductile or plastic deformation results in 'folding'. Depending on the nature and scale of the stress applied, this may affect anything from an individual unit of rock to entire mountains. Generally, small folds are found on larger folds, which in turn are on still larger folds. Although upward folds (anticlines) often form higher land than the downward folds (synclines), sometimes this can be reversed – the initial uplands are more vulnerable to erosion and may be rapidly stripped away: this may in turn expose softer rocks beneath, which are then exploited by major forces such as glaciers and rivers, and thus become lowlands and valleys. In extreme cases, 'over-folding' may completely invert entire geological sequences, turning them upside-down.

Again depending on the physical characteristics of the rock, the nature of the applied stress, and the surrounding conditions of temperature and pressure, a unit of rock may at some point fail, splitting apart: this is 'faulting'. In compressional settings, where major geological units are being squeezed, faults often develop after folding has progressed beyond a particular limit. However, in brittle rock conditions, faulting may occur more rapidly, with no folding involved. As well as through compression, faults may result from extension (pulling apart) and shear (lateral or sideways tearing). The complex rage of stresses and mechanisms arising from mountain-building events may result in all of these being found within the same region. There is no guarantee that rock which moves upward as a result of faulting will continue indefinitely to form higher ground: the combination of exposure, erosion and different rock-unit resistances may in time reverse this relationship.

So far, we have been thinking mainly about subduction zones, where an oceanic plate dives below the edge of a continental plate. However, the greatest compressional stresses in rocks at and near the surface occurs when two units of continental crust are being pushed against one another. These forces tend to generate regional-scale folding and faulting. The planes along which these 'thrust faults' form tend to be at quite shallow angles to the surface: these discontinuities or breaks in major geological units enable enormous sub-units to move horizontally (and also vertically).



"Rocky Mountains" by U.S. Geological Survey is licensed under CC BY 2.0.

If you fly over the Rocky Mountains on a clear day, you will see something like the image above – each ridge is a unit of rock which was folded by compressional stress, before ultimately failing (faulting), and being pushed sideways and upwards over the unit below it. The largest mountain ranges around the world – the Himalayan ranges, Rockies, Andes, European Alps, and much older ranges, of which only the exposed roots are now visible – have all been formed primarily by this process.