U3A Geology

Orogenesis

Orogenesis (mountain building)

- Orogenesis describes the processes involved in the formation of mountain belts
- mountain belts are formed at convergent tectonic plate boundaries by compressive forces resulting from plate collision
- orogenesis involves subsidence followed by uplift
- mountains therefore provide a record of the Earth's dynamics

Factors important in orogenesis

Factors that are important in the process of orogenesis are:

1. Rock sequences that form the mountains
2. structural deformation
3. metamorphism
4. igneous activity
5. erosion and isostatic uplift of the crust that occur after orogenesis until the mountain is eroded to sea level

Orogenic belts

- Most mountain belts are elongated zones of the Earth's crust
- they begin as troughs in which accumulated sediments were abnormally thick compared to those of the same age on adjoining platforms
- the strata and any igneous rocks were eventually compressed, intruded by granitic plutons, folded, overthrust and intensely metamorphosed
- associated uplift made it possible for long sections of orogenic belts to become mountain ranges like the Alps, Himalayas, Andes and American Cordillera

Orogenic belts

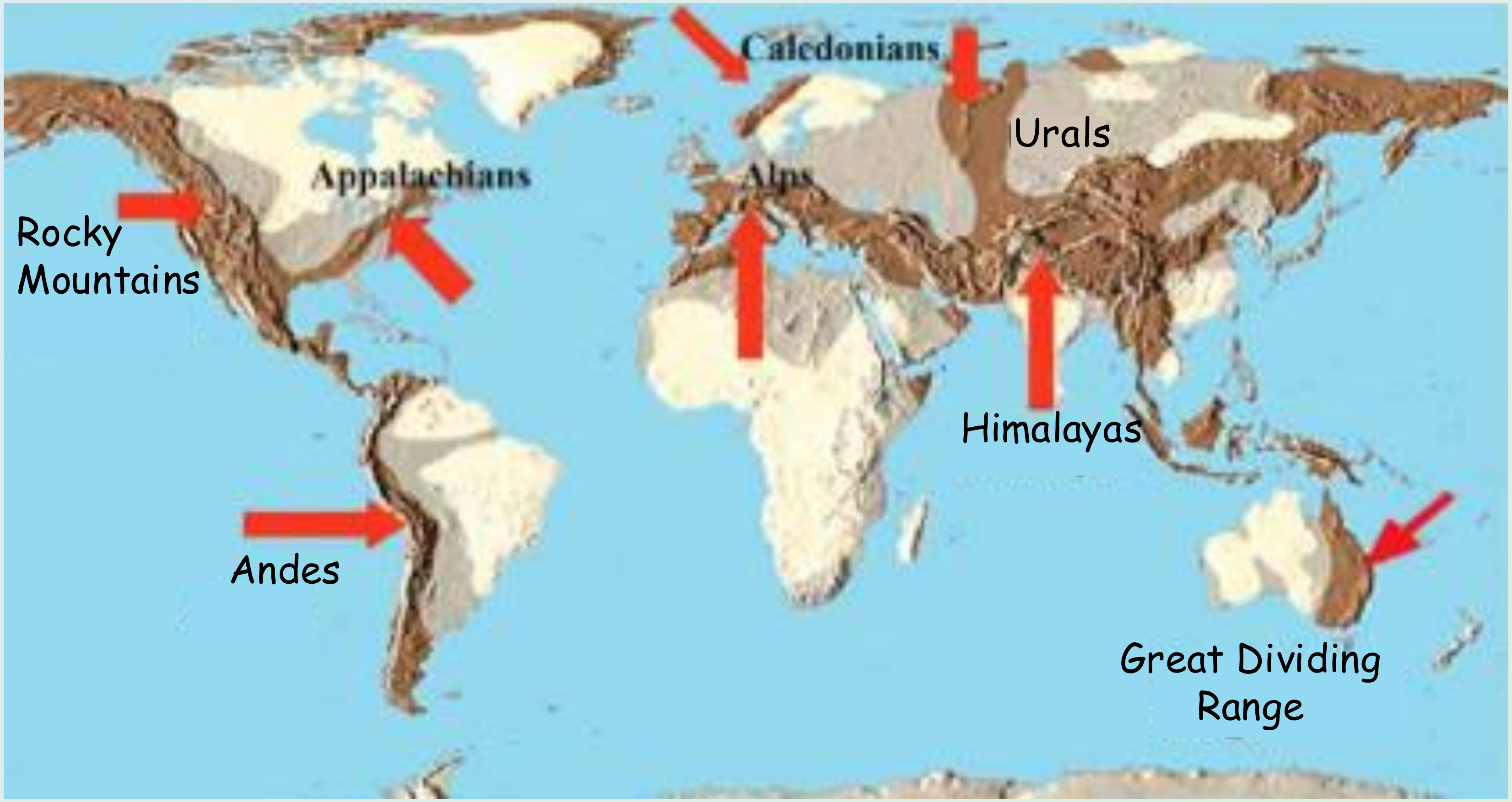


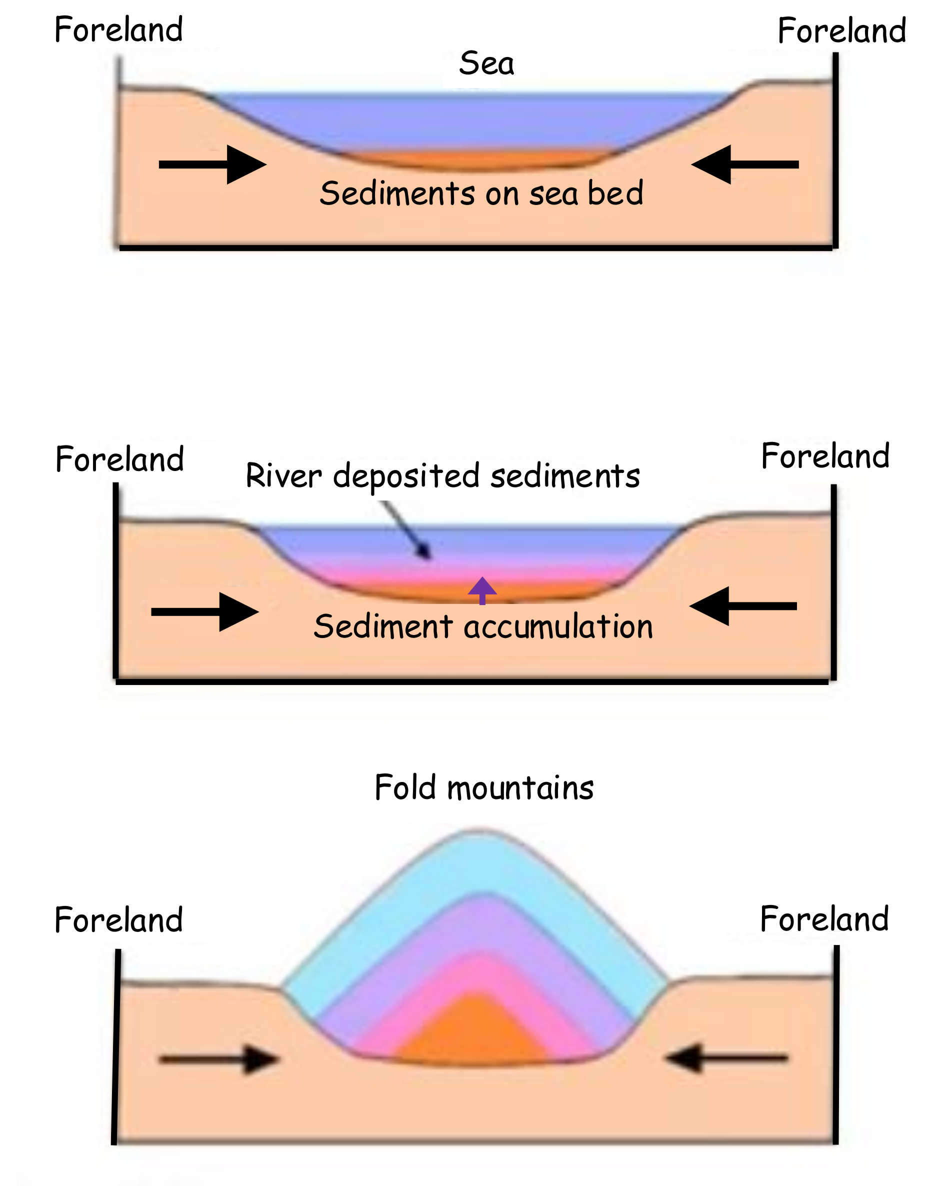
Plate tectonic theory and orogenesis

- Modern theories of geosynclinal sedimentation and mountain building relate formation to plate tectonics theory
- the theory of plate tectonics proposes that orogenesis occurs along convergent plate margins
- it does not require specific rock types and events to occur in the same order in all orogenic belts
- when deformed at convergent plate margins, different sequences produce different styles of mountain belts

Geosyncline

- More than 100 years ago, American geologist James Hall suggested → mountain ranges were a region of the crust that initially subsided more than the rest of the continent
- gradual subsidence permitted great thickness of shallow marine sediments to accumulate
- accumulation rates → roughly equivalent to rates of subsidence
- an elongate subsiding trough is called a geosyncline
- after receiving a critical thickness, the geosyncline was compressed and uplifted into a mountain range

Geosyncline



James Dana

Another American geologist called James Dana proposed that mountain building involved a three phase cycle consisting of:

(1) Geosynclinal sedimentation and contemporaneous subsidence

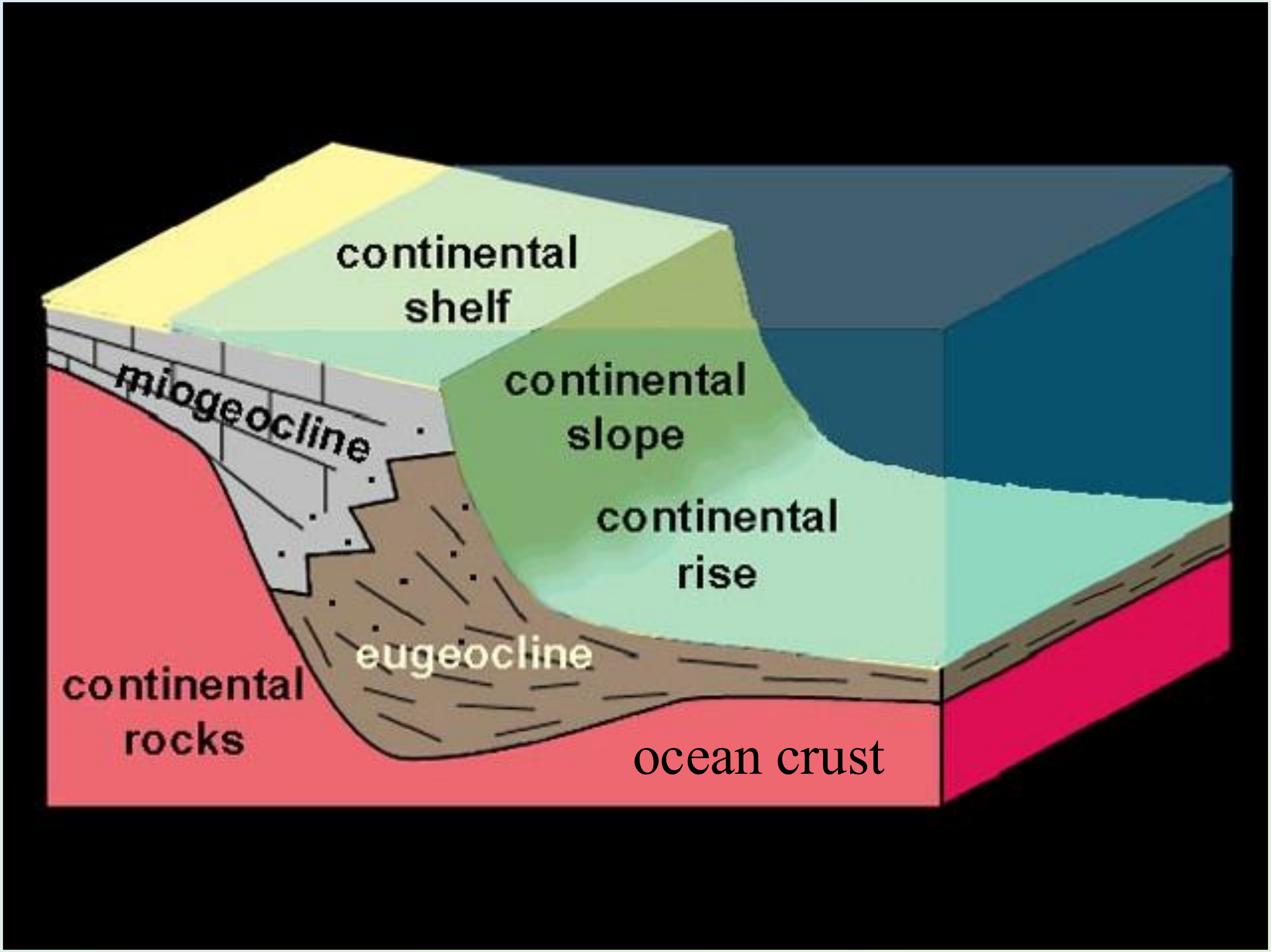
(2) compression and deformation

(3) uplift and erosion

Contrasting geosynclines

- Studies of mountain belts in different parts of the world have shown Hall-Dana geosyncline theory to be too simple
- instead of a single belt, parallel belts of different types of geosynclinal sedimentation exist
- one belt called the miogeocline is adjacent to a stable platform underlain by continental crust
- the other belt is called a eugeocline and consists of sediments deposited in deep marine environments and typically includes volcanic rocks

Contrasting geosynclines (Phyllis Newbill 2014)



Sedimentation at convergent plate boundaries

- In miogeoclines that lie in shallow water along coastal margins, the sequence consists of clean, well-sorted sandstone, shale and limestone derived from erosion of continents
- in eugeoclines in deep water off continental margins, the sequence consists of poorly-sorted sandstone and shale, submarine slump blocks and rock debris from submarine land slides
- a third rock assemblage common in some mountain belts consist of peridotite, gabbro, pillow basalt and deep marine sediments that form in ocean crust
- these rocks have been scraped off a subsiding plate and plastered against the over-riding plate → forms accretionary wedge

Structural deformation

- The single most distinctive feature of a mountain belt is structural deformation of the rocks
- scale of deformation ranges from wrinkled grains to folds tens of km wide
- structure of the Alps features overturned folds called nappes that show enormous amounts of crustal shortening
- rocks are so intensely deformed → spherical pebbles have been stretched to 30 times their original length
- in each mountain belt, internal structures result from strong horizontal forces

Metamorphism

- In deeper parts of an orogenic belt, intensive plastic deformation and recrystallization at elevated temperature and pressure metamorphose original rocks
- schists and gneisses are formed
- metamorphism may be intense enough to produce migmatite

Igneous activity

- Partial melting of ocean crust along subduction zone forms a silica-rich magma that is emplaced in a mountain belt

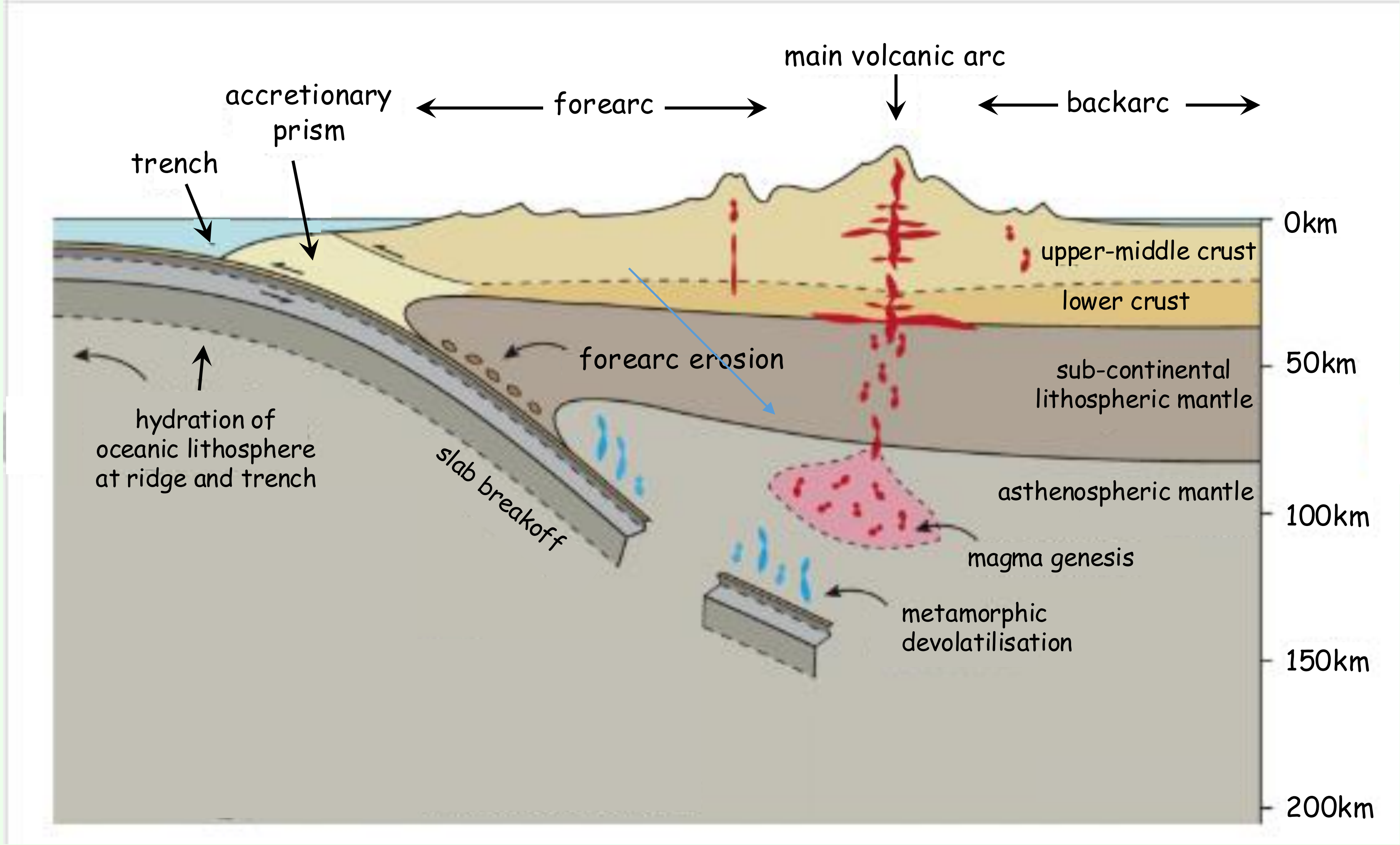
- Magma can result from partial melting in three regions of the subduction zone:

  (1) in subducting oceanic crust

  (2) in overlying mantle, as hot fluids percolate upwards

  (3) near base of continental crust

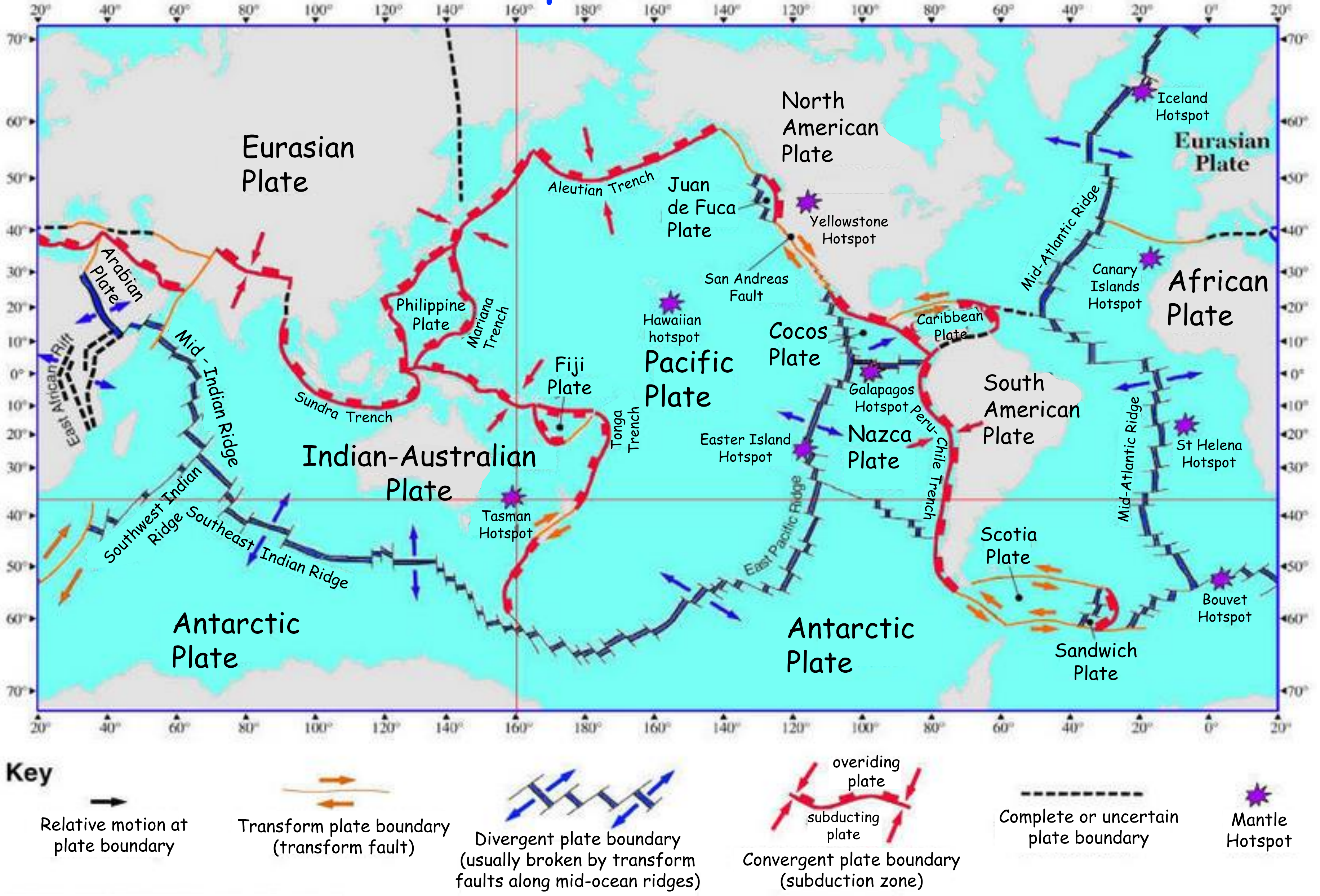
Magma genesis at convergent plate margins



The evolution of a mountain belt

- In the evolution of a mountain belt, folding and thrusting occur at relatively shallow depth
- metamorphism occurs deeper and partial melting occurs at still greater depths
- much of the magma migrates upward forming tear-shaped bodies that collect into larger and larger masses
- the magma can be emplaced and cool within a few km of surface or be extruded at the surface

Tectonic plate boundaries



Types of orogenic activity

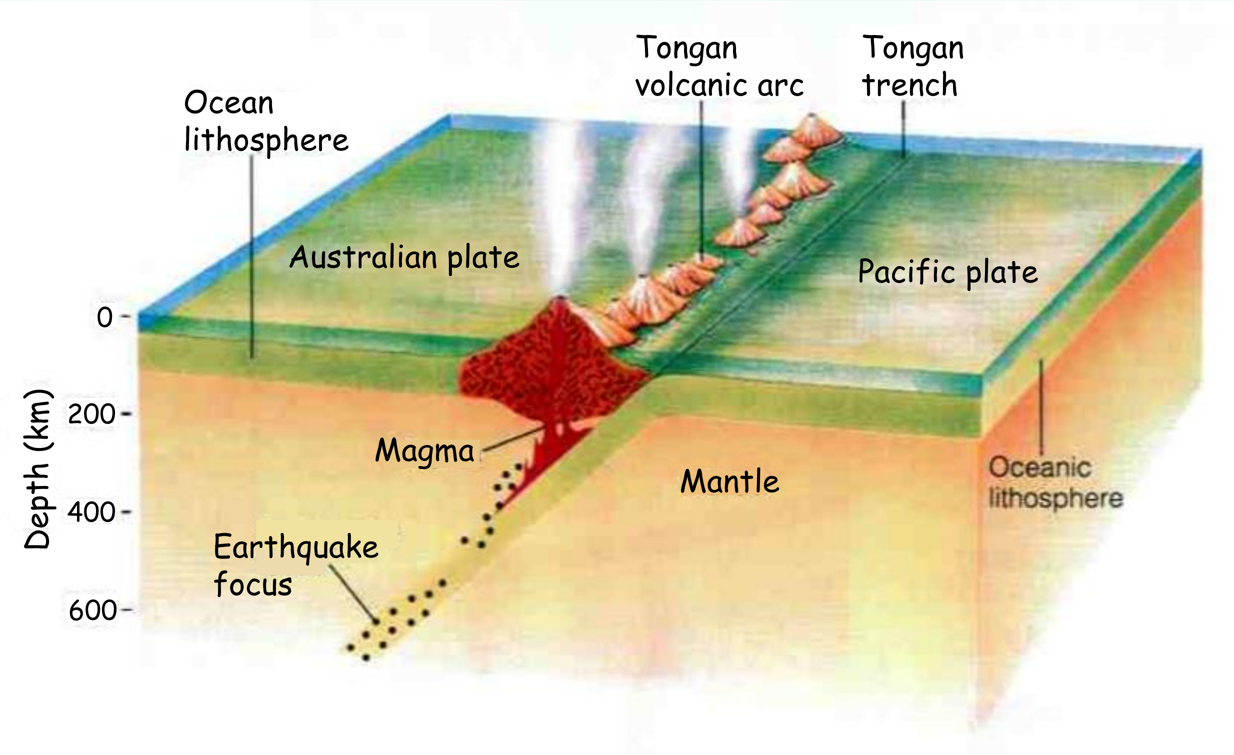
- Mountain belt building (orogenesis) is the result of tectonic plate convergence
- it involves intensive deformation, metamorphism and igneous activity
- there are three different types of convergence:
  - (1) Convergence of two oceanic plates
  - (2) convergence of continental and oceanic plates
  - (3) convergence of two continental plates

Convergence of two oceanic plates

- Where two oceanic plates converge, an arc of volcanic islands is formed above the subduction zone
- the first stage in development is restricted to volcanic activity on overriding plate
- it does not involve widespread metamorphism or granitic intrusion
- the Tongan islands are an example of a primitive island arc
- in more mature complex island arcs (e.g. Indonesia, Japan, Aleutian Islands) crustal deformation, metamorphism and granitic intrusion produce distinctive rock associations

Convergence of two oceanic plates

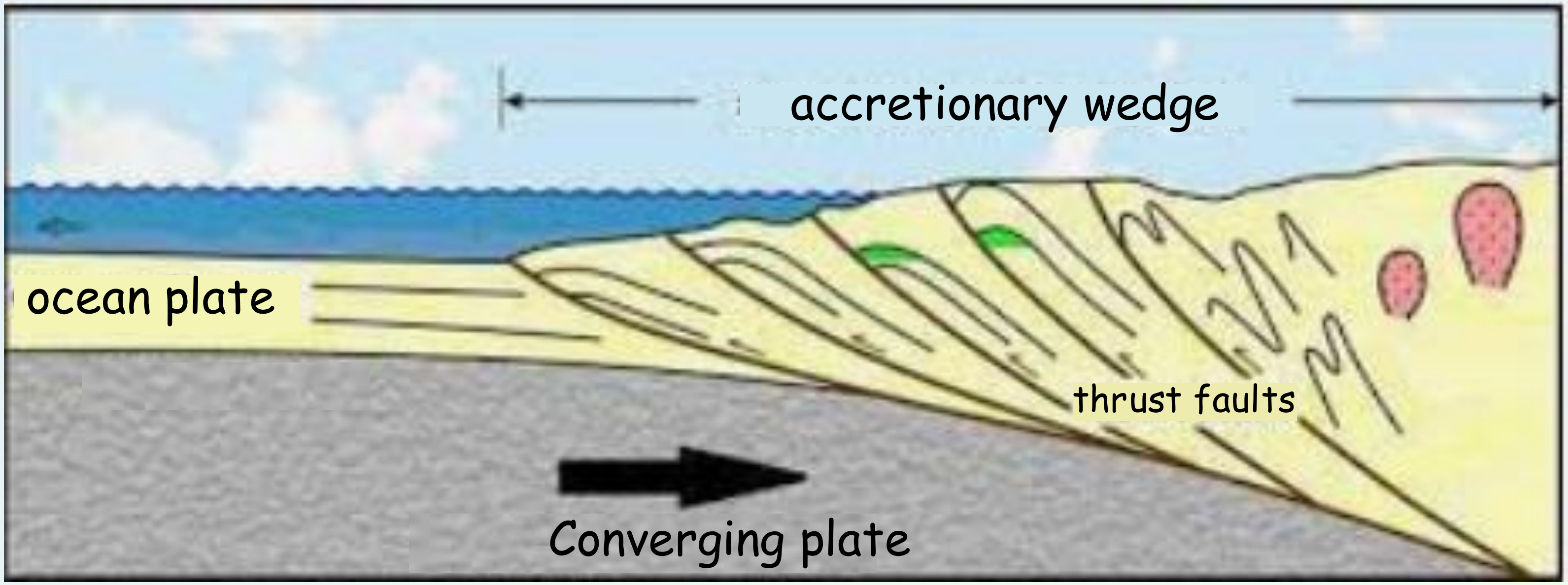
- One plate is pushed under the other → subduction zone
  → subducted plate triggers melting in the mantle
- magma erupts at surface forming island arc e.g. Tongan volcanic arc
- the principal volcanic rock type is andesite



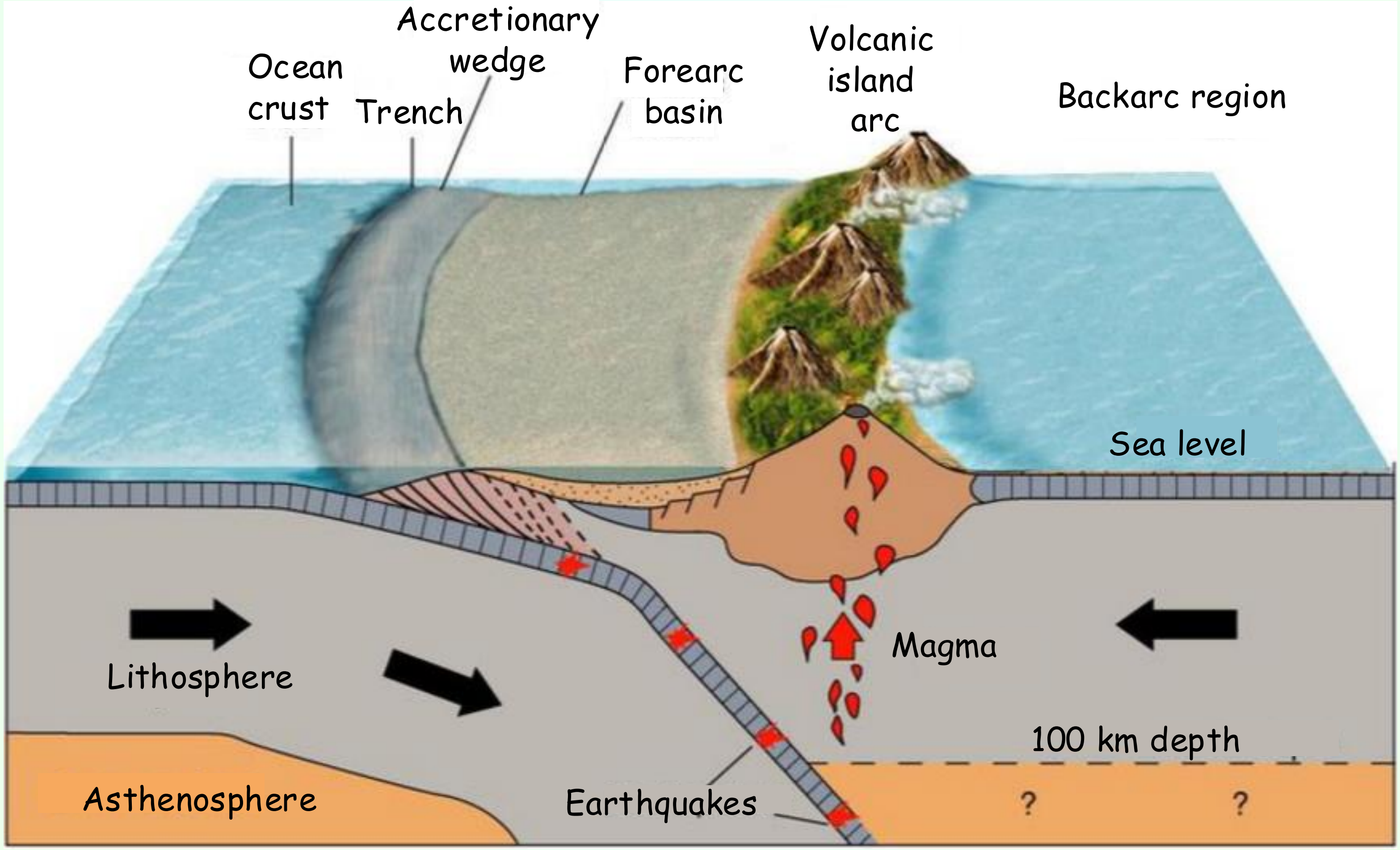
Ocean plate-ocean plate convergence, Tongan-Kermadec trench

Accretionary wedge

- Accretionary wedge → composed mostly of sedimentary material
- accumulates on edge of tectonic plates where oceanic and continental plates collide
- sediments scraped off the top of a subducting oceanic plate → added to margin of the overriding plate



Convergence of two oceanic plates



Island arcs

The major features of mature island arcs are:

(1) Rock sequences consisting of ocean sediments and pillow basalts of ocean crust.

(2) Partial melting of rocks in subduction zone produces a silica-rich magma that rises to form granite intrusions and volcanic products

(3) a zone of high pressure, low temperature metamorphism develops on outer margins of overriding plate

(4) inner zone of high temperature metamorphism develops with associated granite intrusion

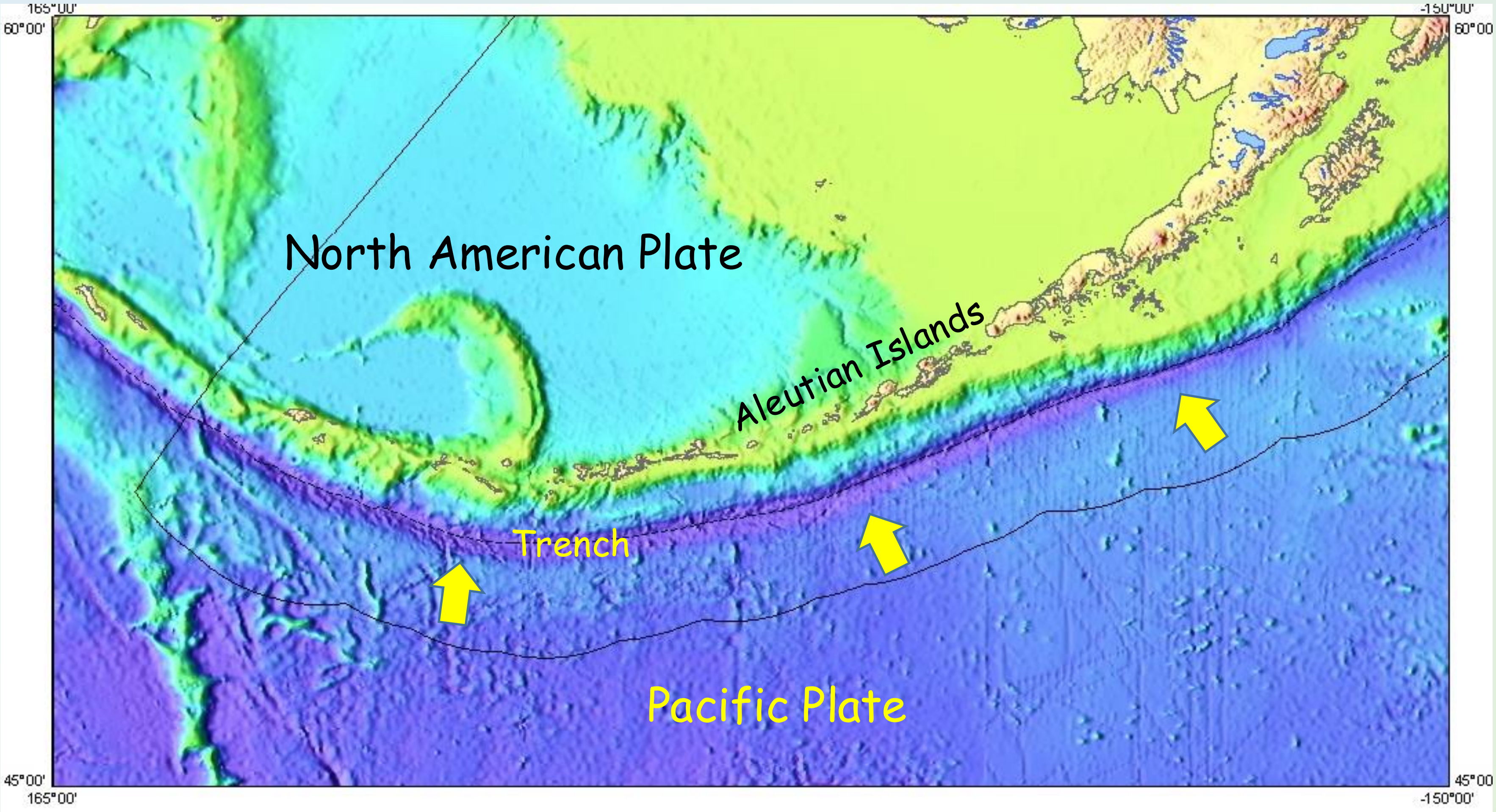
(5) crustal deformation of the volcanic arc results from converging plates and granite intrusion

Indonesian island arc

Aleutian Islands

- Aleutian Islands → 300km volcanic arcuate arrangement of mountain ranges and submerged plate margins
- formed by subduction of Pacific tectonic Plate beneath the North American Plate
- the islands represent the top of a massive submerged ridge (cordillera) formed of volcanoes
- the upper crust consists mainly of basaltic andesite with trace amounts of Palaeozoic rocks intruded by batholiths
- the batholiths contain plutonic rock types (diorite, granodiorite)

Aleutian Islands – plate convergence



Aleutian Islands

Volcanoes in the Islands of Four Mountains, Aleutian Islands, Alaska

Convergence of continental and oceanic plates

The style of mountain building produced by convergence of continental and oceanic plates resembles that produced by ocean plate convergence but is distinctive in two main respects

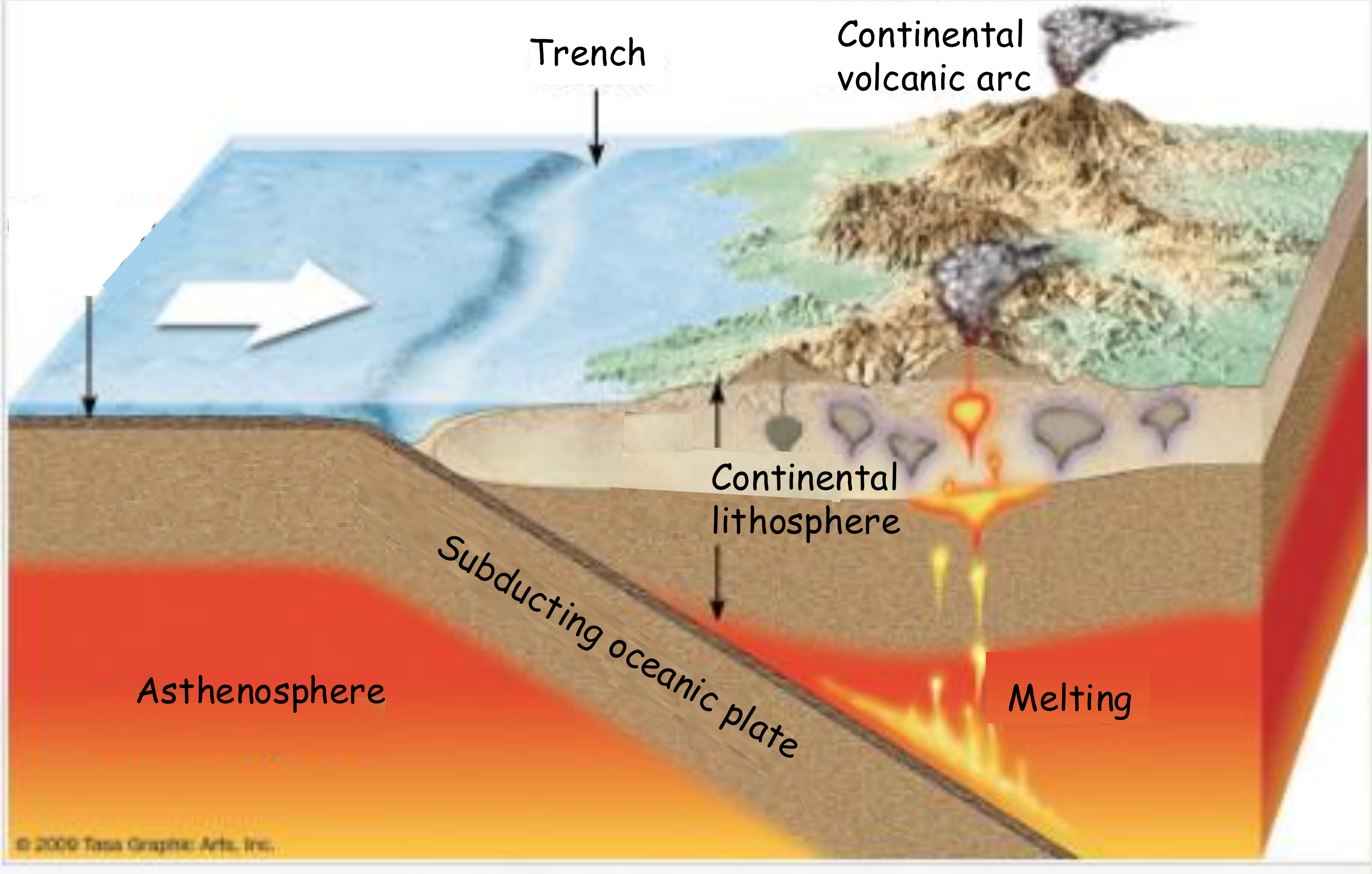
(1) thick sequences of geosynclinal sediments derived from the continents commonly occur along the continental margins, different to rock sequences deposited around a volcanic arc

(2) silica-rich magma generated by the partial melting of descending oceanic crust is formed upon or within the continental crust, rather than on the ocean floor. Volcanic material is soon stripped off mountain range exposing granitic batholiths

Convergence of continental and oceanic plates

- Before the subduction of the oceanic plate, a considerable thickness of shallow marine sediments accumulate in the miogeocline along the continental margin
- during this same period deep marine sediments accumulate in the ocean basin
- as the oceanic plate approaches subduction zone some deep marine sediments can crumple and be deformed
- slabs of oceanic crust shear off and are incorporated in chaotic mass

Convergence of continental and oceanic plates



Convergence of continental and oceanic plates

- The thick sequence of geoclinal sediments along the continental margin is compressed and deformed
- intense metamorphism occurs within deeper zones where temperatures and pressures are relatively high
- partial melting of descending lithosphere generates silica-rich magma that rises to form granitic intrusions or erupts as volcanic material at surface

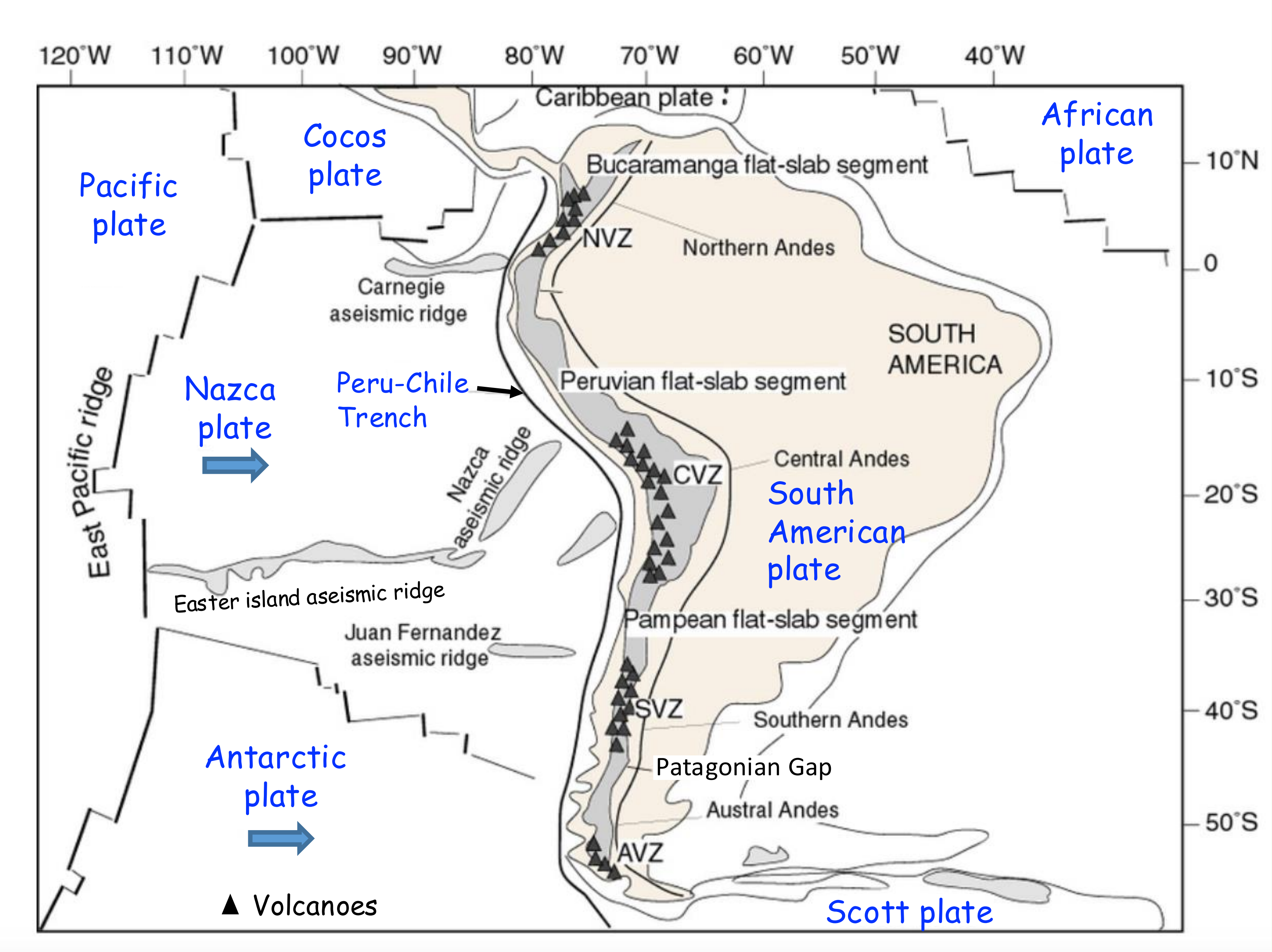
Convergence of continental and oceanic plates

- With continued compression, deformation of geoclinal sediments and the resulting crust thickens landwards and edge of deformed continental margin rises above sea level
- there are many excellent examples of orogenic belts formed by the convergence of oceanic and continental plates e.g. the Rocky Mountains of western North America, the Andes of South America and the Appalachians of the eastern USA.

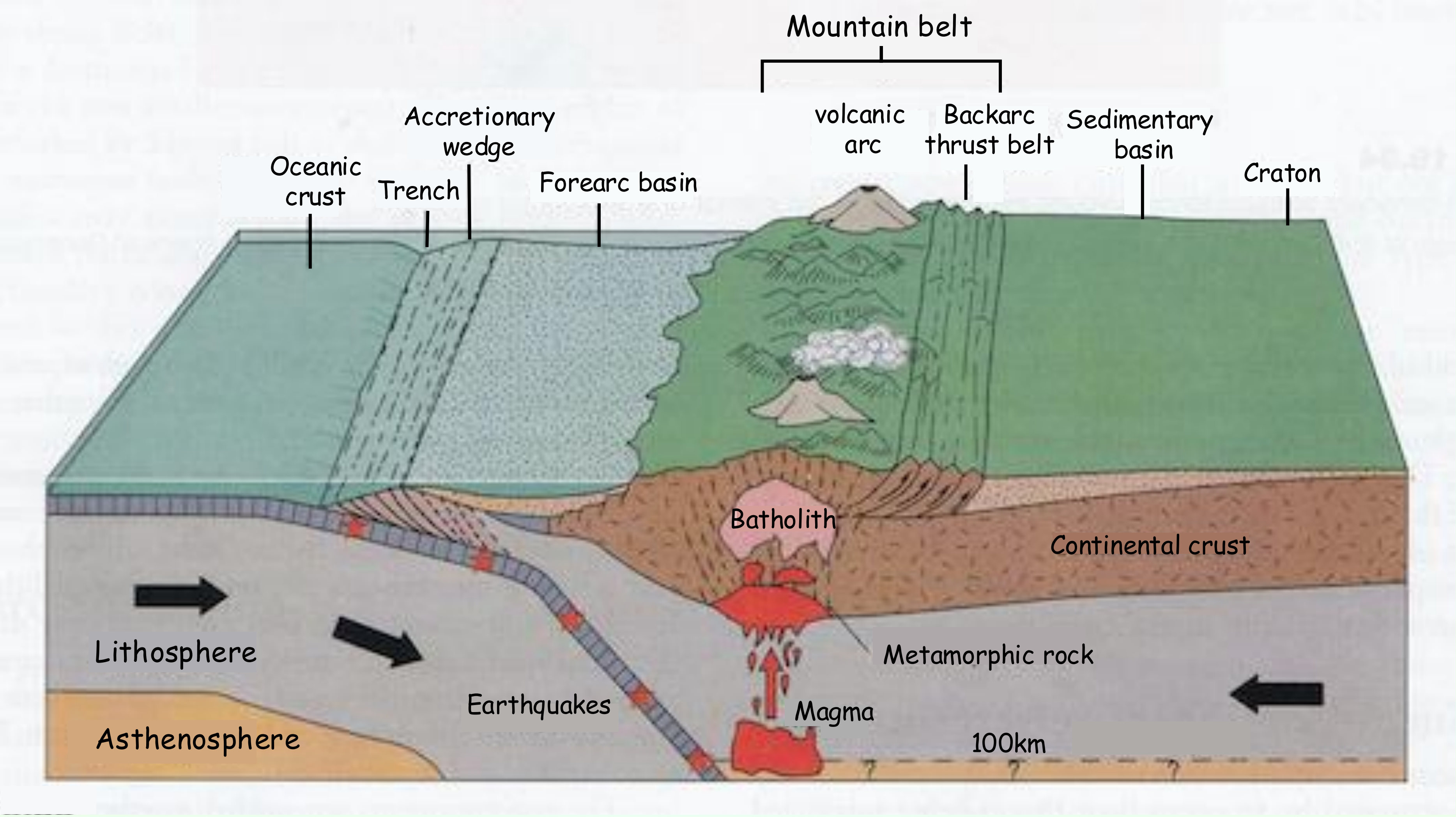
Andes

- The Andes mountains are a 7,000km long active continental arc formed by the subduction of the Nazca and Antarctic plates beneath the South American plate
- the orogeny involves intense folding, thrust faulting and volcanism
- volcanoes are mostly andesitic with much lesser rhyolite
- intrusions that form the core of the Andes cordillera are primarily composed of granodiorites and tonalites

Tectonic setting of the Andes



Ocean-continent convergence



Andes

Aerial view of Valle Carbajal in the Andes, Tierra del Fuego, South America

Convergence of two continental plates

- In the tectonic system, virtually all oceanic crust is destined to descend into the mantle by subduction
- as continents are carried by plates towards subduction zones, the ocean basin is continuously reduced in size
- the basin is eliminated completely if two continents collide
- the collision of two predominantly continental plates generates an orogenic belt different from those of other types of orogeny

Convergence of two continental plates

(1) Before continental collision, the wedge of sediments along the margin of the continent above the subduction zone is deformed

(2) as continents approach collision, segments of remaining oceanic crust are deformed and eventually squeezed between converging plates

(3) as continental crust moves into the subduction zone, its buoyancy prevents it from descending into the normal mantle, it can be thrust under the over-riding plate

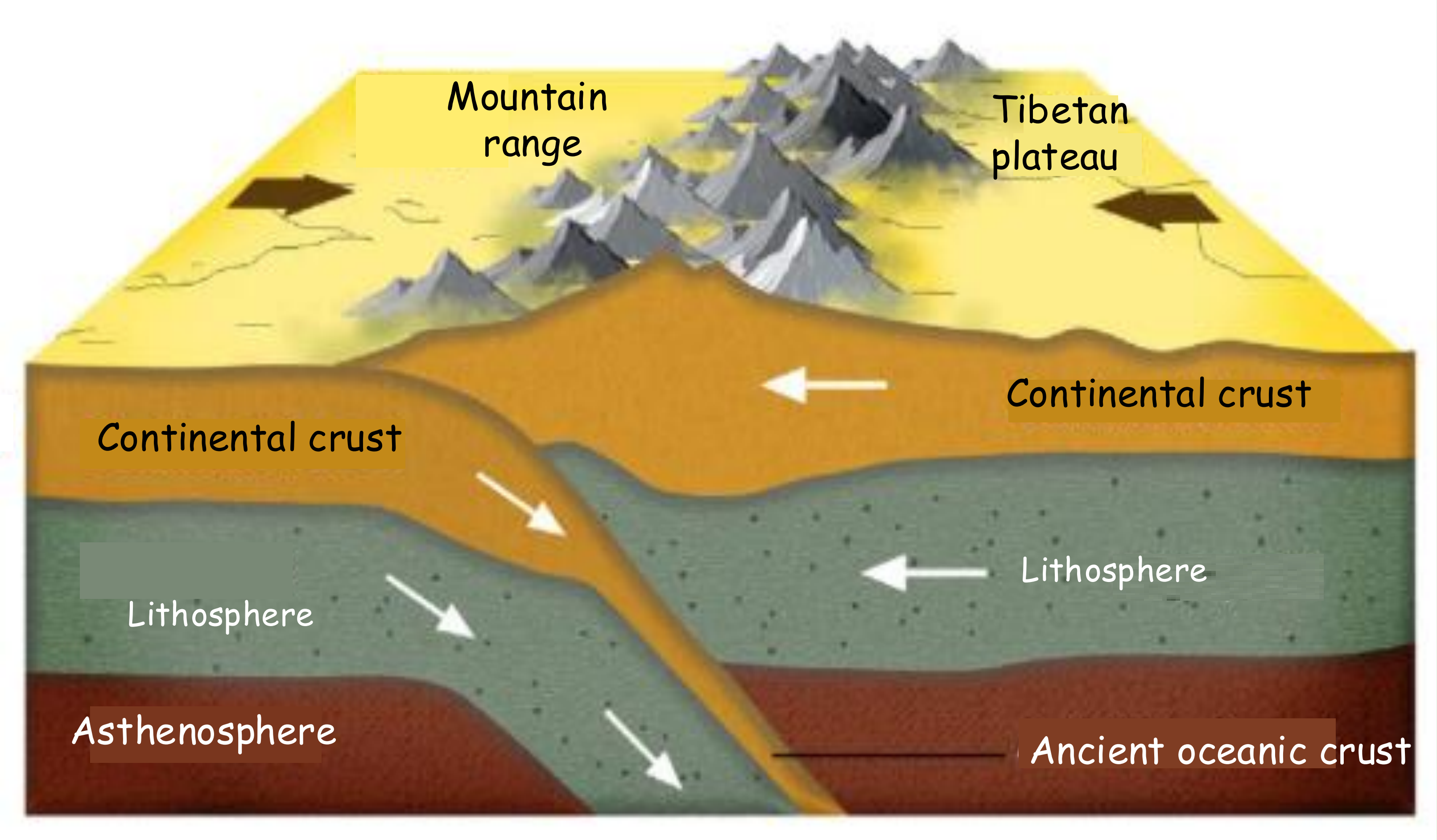
(4) alternatively, continental masses can become welded together and fragments of ophiolite (oceanic crust) can be caught between them and move upwards

Convergence of two continental plates

(5) the oceanic slab of the lithosphere descending into the mantle, ultimately becomes detached and sinks independently. Slab is consumed with volcanic activity ceasing

(6) the welding of the two continents produces a single large continental mass with an internal mountain range

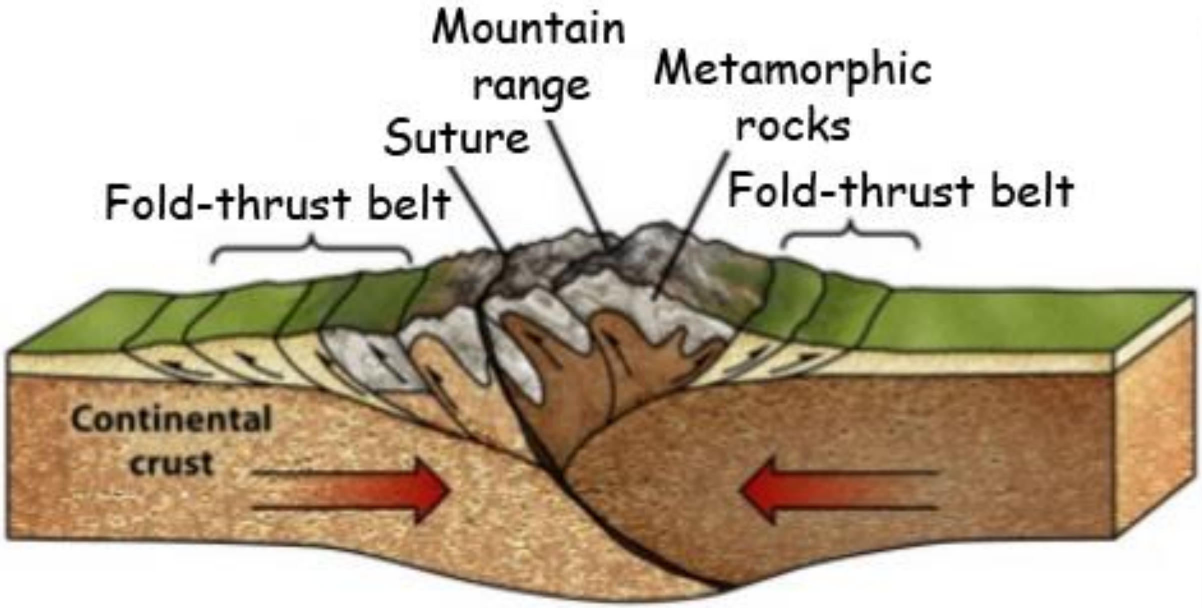
Convergence of two continental plates



Himalayan Mountains

- Himalayan Mountains → example of orogenesis due to continental collision
- formed in last 100Myrs as India moved northwards and destroyed oceanic lithosphere that formerly separated it from Asia
- as the two continents collided, India was thrust under the Asia plate and the Himalayas of the Tibetan plateau were formed
- earthquakes are frequent in the region but they are shallow and occur in a broad, diffuse zone because of no descending oceanic plate

Formation and structure of Himalayan mountains

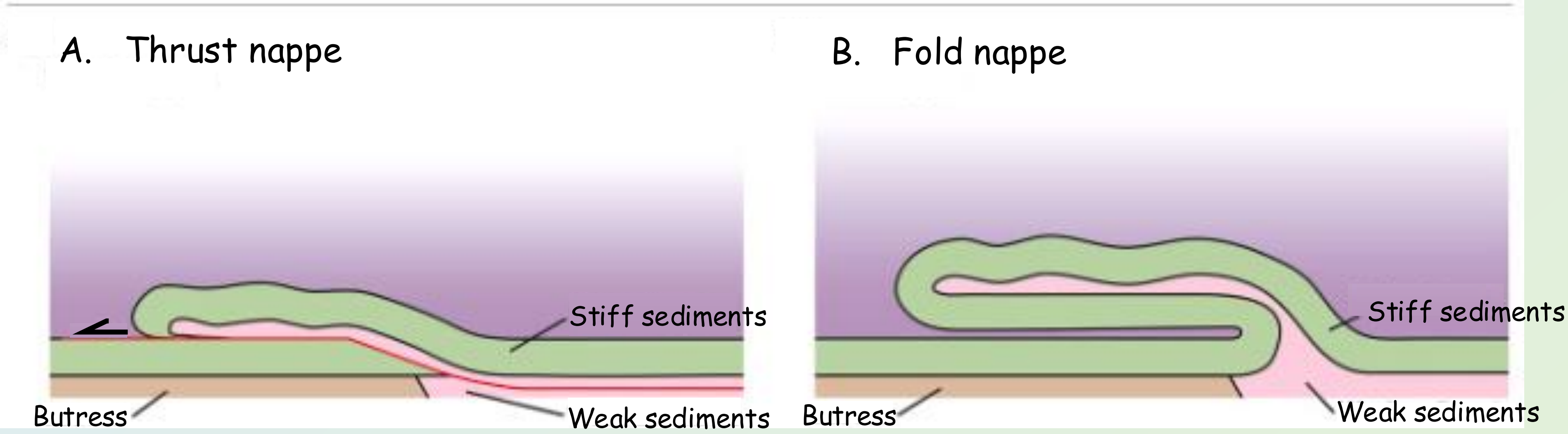


European Alps

- European Alps result from convergence of the African and Eurasian tectonic plates
- Africa is moving northwards against Eurasia but not to the point at which the oceanic plate is completely consumed
- the pressure of the collision formed great recumbent folds (nappes)
- crystalline basement rocks are the rocks forming Mont Blanc and the Matterhorn

Nappe formation

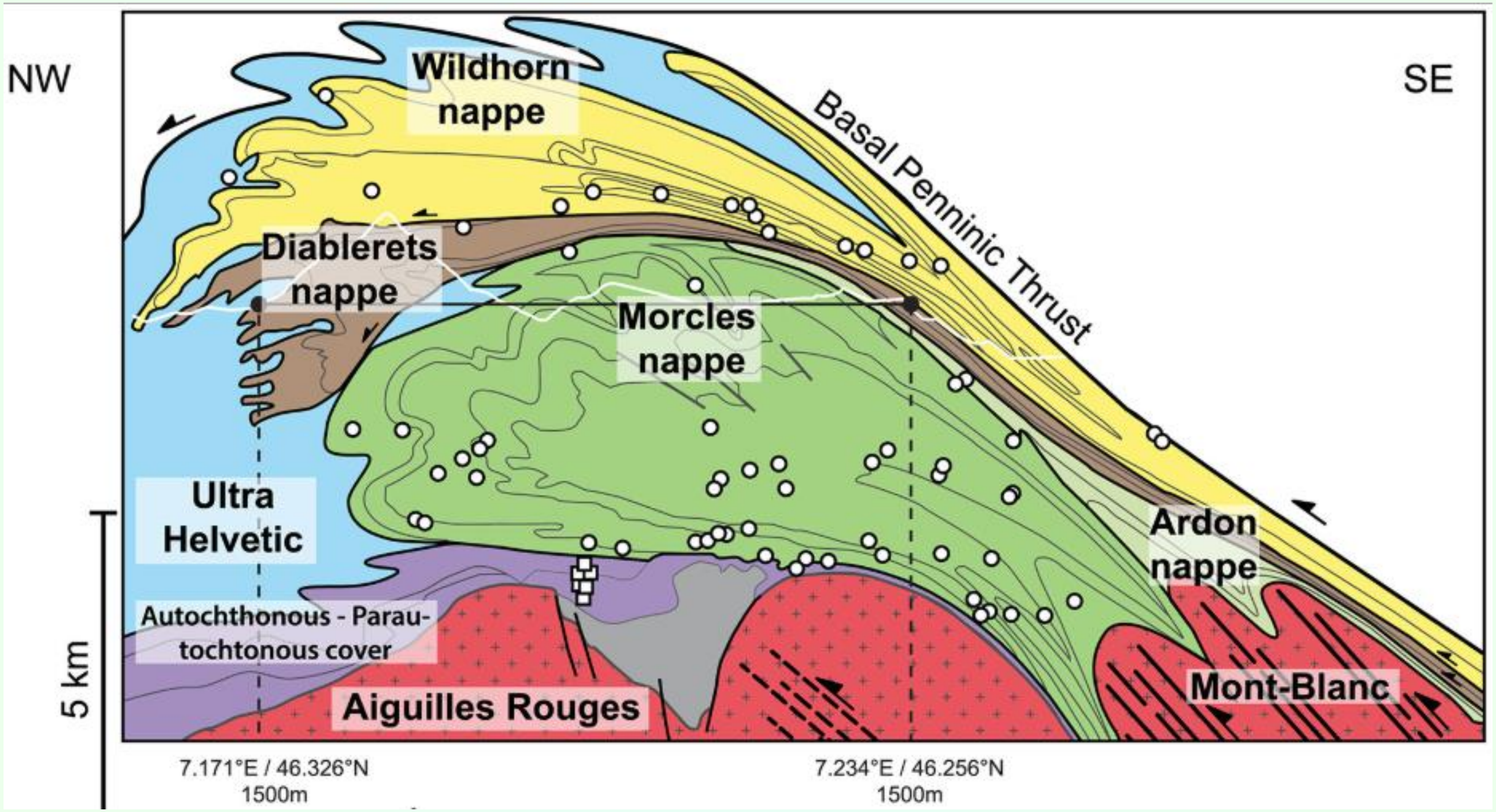
Nappes are sheet-like rock bodies thrust over long distance (often >2km) via thrust faults or folds in compressional tectonic zones like the European Alps



Morcles nappe, Switzerland

Helvetic nappes of the European Alps

(Girault et al. 2020)



Recumbent fold, Teruel, Spain

Summary of plate convergence

- Orogenesis is a fundamental process in the differentiation of the Earth
- processes of compressional deformation, metamorphism and igneous activity are involved in mountain building
- the style of orogenesis can vary depending on interactions occurring along convergent plate boundaries
- the three types of convergence produce their own style of mountain building

Isostasy

- Isostasy → concept that relates elevation of Earth's surface to the downward displacement of the lithosphere
- the asthenosphere is relatively weak → plastic flow
- lithosphere basically 'floats' on the underlying denser asthenosphere
- lithosphere varies significantly in density and thickness due to heterogeneity of the crust
- gravity pulls different segments of the lithosphere to various levels
- gravitational equilibrium between the lithosphere and the asthenosphere is called isostasy

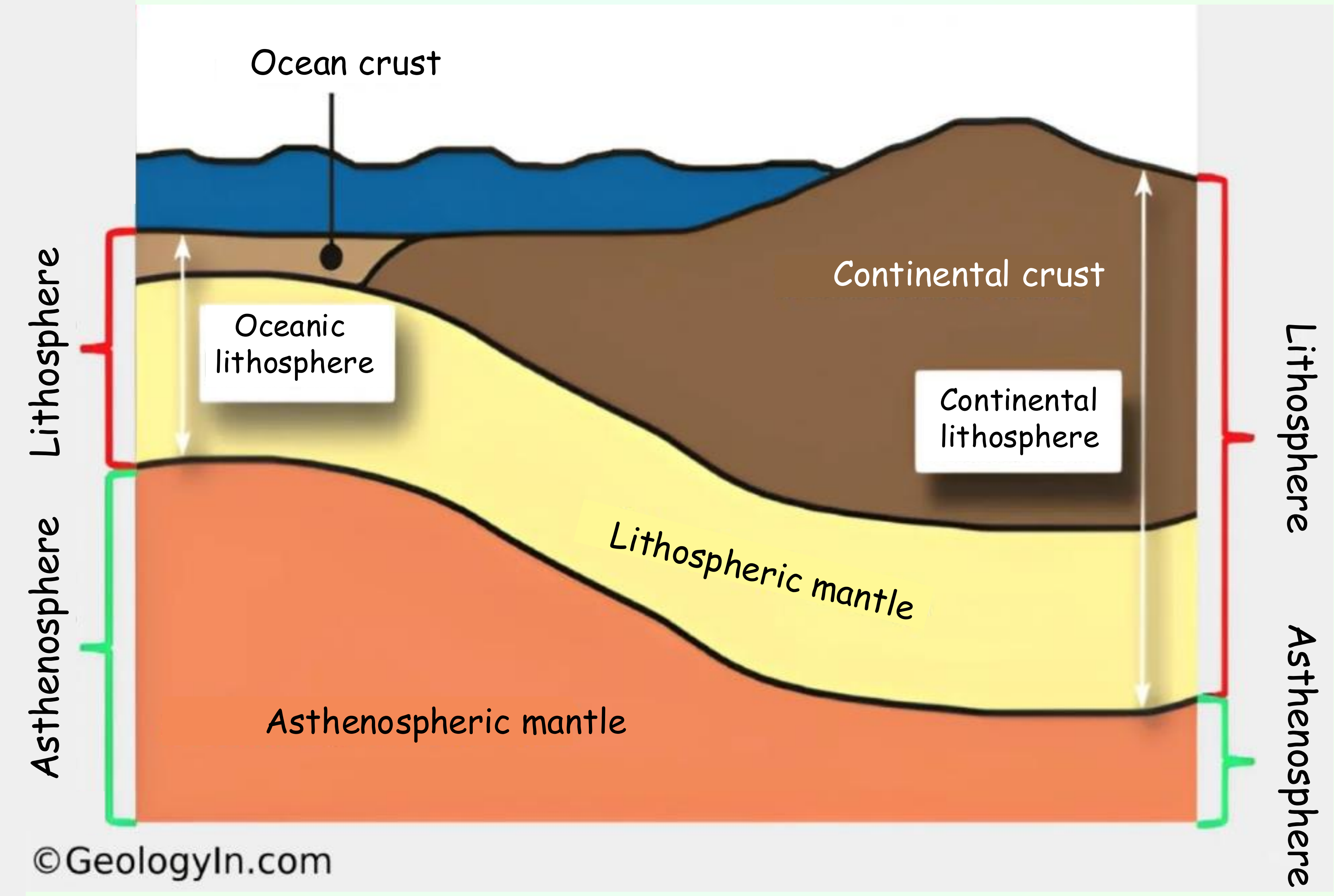
Characteristics of crust

- Crust varies greatly in composition, density, structure and thickness
- there is a fundamental difference and strong contrast between continental crust and oceanic crust
- oceanic crust is composed of dense mafic rocks (basalt, gabbro) continental crust → less dense mostly lighter coloured rocks
- very large range in elevations within the crust:
  → tops of Himalayas 7km above sea level
  → deepest sea trenches 11km below sea level

Characteristics of lithosphere

- Density of lithosphere varies a lot because the density and thickness of the crust is variable
- gravity acts on the lithosphere similar to how it acts on a boat → if you add more weight to the boat, it will sink further into the water (Archimedes Principle)
- different segments of the lithosphere sink into the asthenosphere to a depth depending on the density and thickness of the lithosphere → this behaviour is called isostasy

Cross-section through crust and mantle



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Isostasy

- Isostasy → response of outer shell of Earth (lithosphere) to the imposition or removal of large loads
- although the lithosphere is strong, it is unable to support huge stresses imposed by mountain ranges without deforming
- isostasy first recognised in the Andes in 18th century by the French scientist Pierre Bouguer
- the presence of sub-surface compensation is confirmed by a variation in the Earth's gravitational field over broad areas

Effects of isostasy

- Isostasy is a dynamic process
- if the load on the crust increases e.g. by ice, sediments or lavas, the base of the lithosphere will subside → affect isostasy
- if load is removed e.g. by erosion of rocks or melting of ice, the lithosphere will rise
- this rebound is due to plastic flow in the asthenosphere

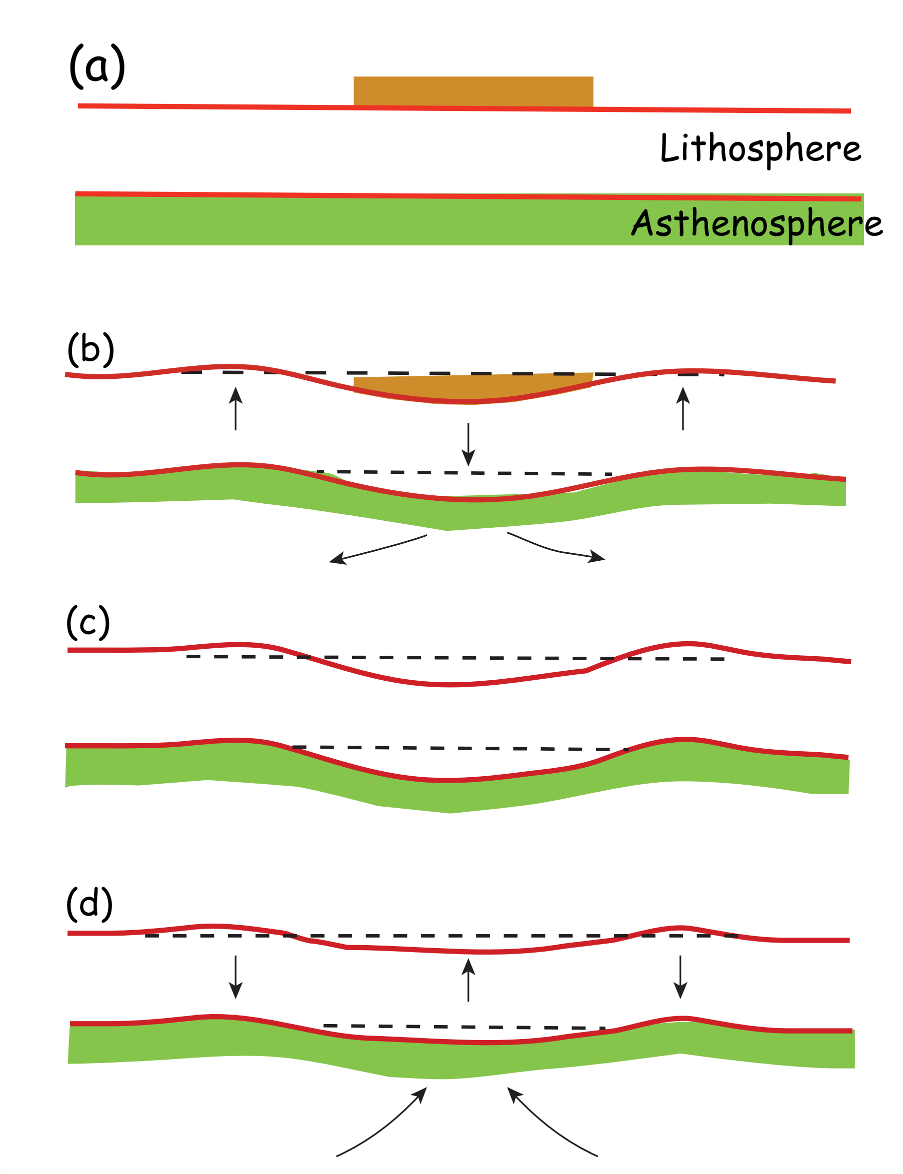
Isostatic rebound

(a) lithosphere with load

(b) load on lithosphere causes bending with peripheral uplift and lateral flow in asthenosphere

(c) removal of load

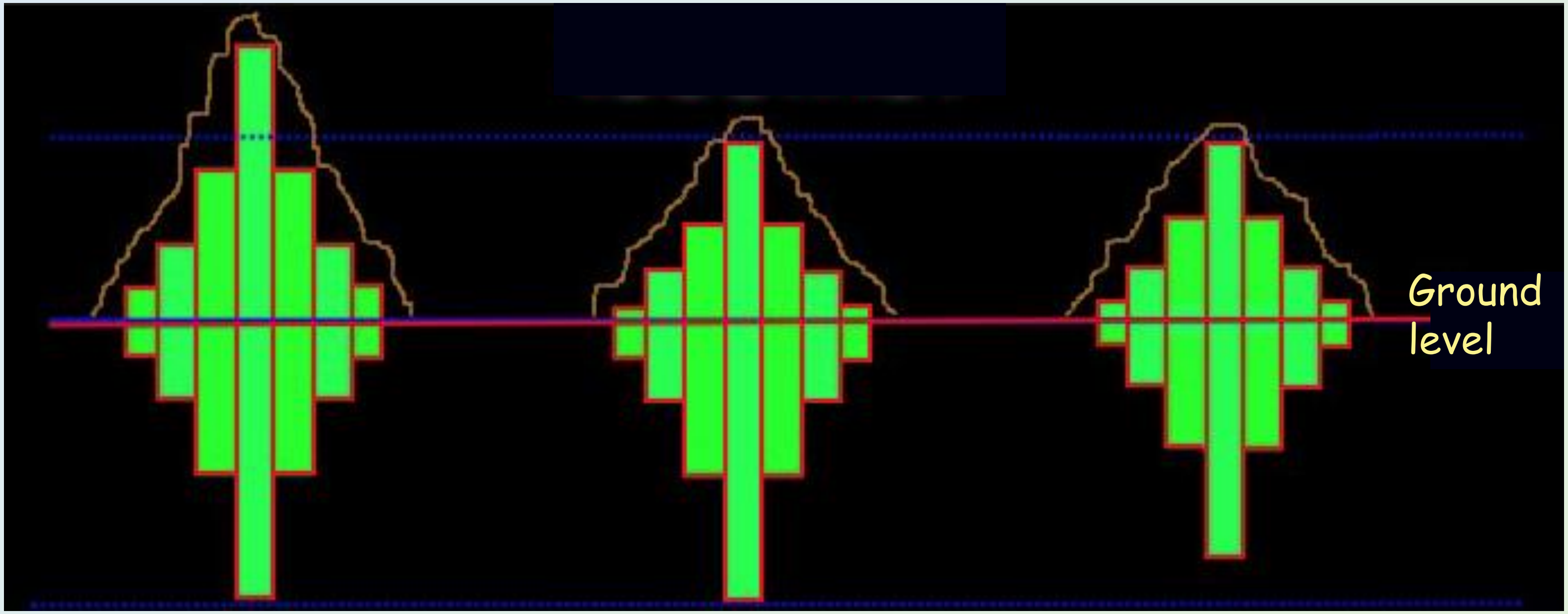
(d) isostatic equilibrium regained by reversed flow in asthenosphere and sinking of peripheral bulges



Crustal loading in mountain belts

- As mountain range builds up → pushes down lithosphere
- eventually mountain building ceases
- top of mountain range erodes over a long period of time → reduces load on lithosphere → base of lithosphere rises up
- rocks in core of ancient mountain range → originally were deeply buried → exposed at the Earth's surface

Isostatic adjustment



Young mountain
Below ground the mountain has roots as deep as mountain is high

Erosion
Creates imbalance → more mountain below ground than above

Equilibrium
Entire mountain rises → ongoing process