# INTRODUCTION TO TECTONICS

The Earth is composed of layers of different composition and physical properties, principally the solid central core, the fluid peripheral core, the viscous mantle, and the solid **lithosphere**. The lithosphere is comprised of the upper mantle and the crust, the outer shell of the Earth. There are two types of lithosphere, according to the crust resting on the solid mantle lithosphere (**lithospheric mantle**): the oceanic lithosphere has a 5 to 8km thick oceanic crust (with a basaltic composition) and the continental lithosphere has a 30km to 40km thick granitic-dioritic crust. The lithosphere is fragmented into pieces of variable shape and size, the **plates**. The edges of the plates are called **plate boundaries**. The Earth has 7 major plates (Africa, Antarctica, Australia, Eurasia, North America, South America and Pacifica) and several minor ones (Adria, Arabia, Caribbean, Nazca, Philippines and others). Most of the plates are composed of continental and oceanic lithosphere. These plates move independently relative to one another, with a restricted independence from the 7 large plates, however. The relative, horizontal movements are ideally described as rigid body motions that produce space and friction problems at the contacts between adjacent plates. Plate boundaries are not fixed; they also move and change shape. The global mosaic of plates periodically reorganizes itself and new plate boundaries form while others close up. **Plate tectonics**, the study of such relative motions and their consequences, allows relating surface, geological and geophysical structures with quantified movements attributed to deep processes of the Earth's heat engine: The interior is hot, space is cold; the second law of thermodynamics states that this gradient will drive spontaneous convection processes in pursuit of equilibrium. The motion of lithospheric plates is a considerable consequence of thermally-driven mass movements on the Earth.
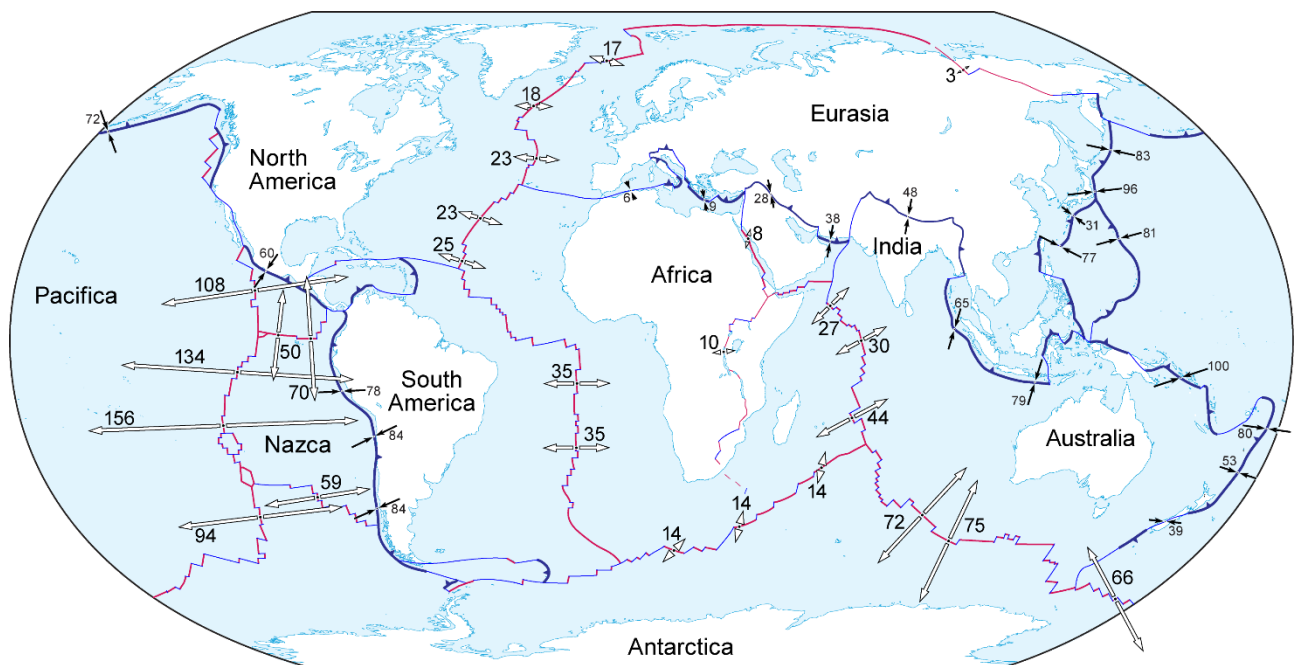
relative rates (in mm/a) and directions of present-day plate movements (world Robinson projection)
scale convergence = 50% scale divergence

The Earth is the only planet known to currently have plate tectonics. This suggests that Earth possesses a unique combination of heat budget (probably a matter of size; compare with Mars, about half size of the Earth) and rheology: the surface is rigid enough to make plates (compare with Jupiter

  made up almost entirely of gases) but weak enough to localize strain (compare with Venus, similar size and composition as Earth, but possibly stronger lithosphere).

Geodynamics is the discipline of Earth Sciences that attempts to explain observations about the recent large-scale features of the globe in terms of mechanical (dynamic) principles. It becomes accepted that repeated **amalgamation** and subsequent **breakup** of continental lithosphere along with repeated creation and subduction of oceanic lithosphere have profoundly affected Earth's evolution since the Archaean. In this plate-tectonic framework, large-scale deformation is the local response of the lithosphere to induced stresses.

Plate relative motions

The large-scale features of the Earth are geographic (map distribution and topography) and result from both horizontal movements that may reach up to >20 cm/year and vertical components of up to 10 mm/year. This is an order of magnitude difference. This is why also, on a structural / geodynamic point of view, the horizontal, relative movements between plates (as fast as nails grow!) will dominate the structures of interest to geologists, keeping in mind that at some stage (an order of magnitude less) vertical movements will also have to be taken into consideration.

Plates may:
> - move apart (**divergent boundaries**),
> - glide horizontally along each other (**wrench** and **transform boundaries**) or
> - move toward one another (**convergent boundaries**).

These relative plate movements may combine in varying degrees, depending on the overall plate interactions. An oblique convergence of plates produces **transpressive deformation.** An oblique divergence produces **transtension**. The descent of one plate beneath the other and deep into the asthenosphere is the most common response to the space problem posed by convergence.

Plate organisation of the present-day Earth
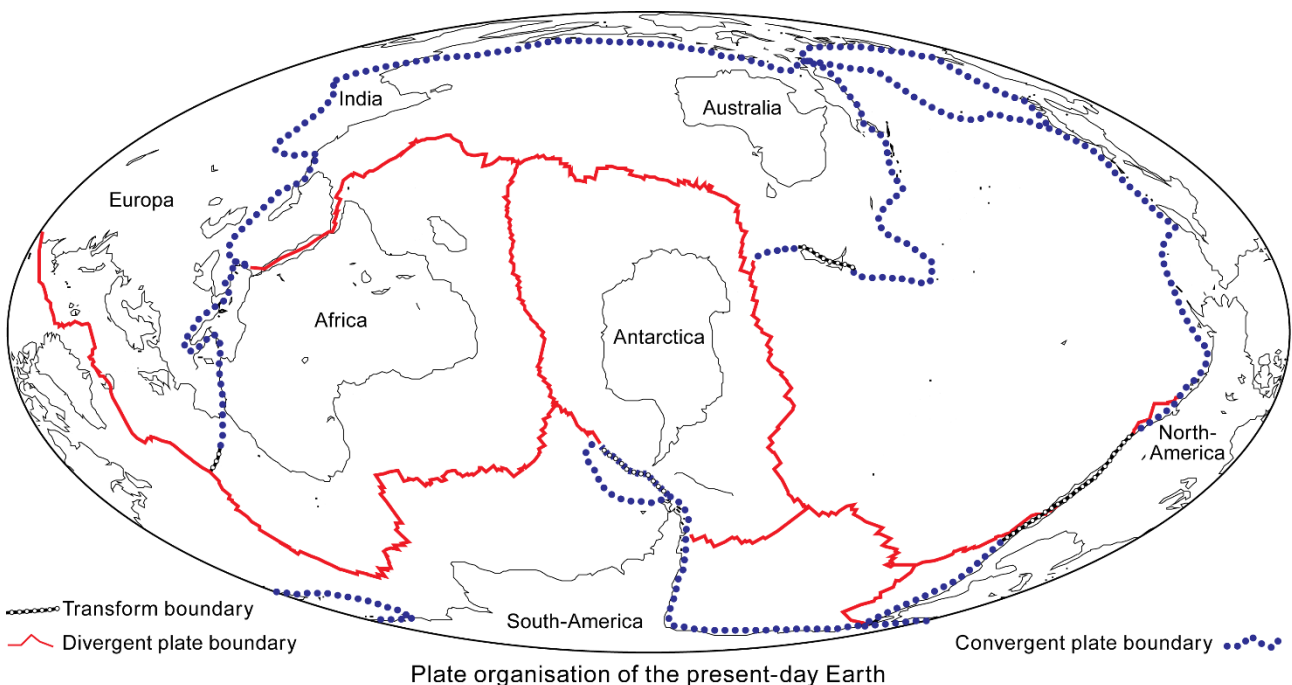
On the present earth, the plate organization has formed two networks: (1) an about 70000 km long chain of divergent boundaries and (2) an about as long chain of convergent boundaries. Both are segmented and connected by strike slip boundaries. This simple organization results from the patterns of plate motions and mantle convection, which are stable on a long term. In fact, the stresses that drive lithospheric motion arise from two sources:

(1) gravity acting on density variations within the lithosphere

(2) gravity acting on density variations deeper than the lithosphere.

The latter gives rise to tractions (radial and tangential) that act on the base of the lithosphere, affecting the stress field of the lithosphere and producing dynamic topography. The former involves density variations associated with support of non-dynamic components of topography.

Structure systems

A system is a group of individual yet interdependent components that interact to form a unified entity and are under the influence of related forces. Systems have real or arbitrary boundaries. Any change in a system occurs in order to maintain **equilibrium**, which is the condition of the lowest possible energy. Equilibrium is also the condition in which the net result of the forces acting on the system is zero.

A geologic system is a group of related natural features, objects and forces that can be isolated completely and arbitrarily from the rest for consideration of the changes that may occur within it under varied conditions until equilibrium is reached. Geologic systems may be short-lived or may persist over millions of years.

Two types of systems are important in geology.
- closed systems exchange only heat with their surroundings (e.g. a cooling lava flow).
- open systems can exchange heat and matter (e.g. a hydrologic system that can receive rains and loose flowing water).

Most geologic systems are open systems in which energy and material are rearranged towards a state of equilibrium. Therefore, these changes occur in a predictable (i.e. **systematic**) way. Because all components are interconnected, any small change in any component causes change in the rest of the system. Predicting and understanding these changes is the key to understanding natural geological laws.

A major geological system is the **tectonic system** that involves the movement of lithospheric plates. The plates move seemingly independently, which indicates that the system is **dynamic**, i.e. material and energy move and change from one form to another. Regional stresses in lithospheres generate particular deformation **subsystems** with characteristic geometry, attitudes and organisation, in particular at plate boundaries. Six fundamental structure subsystems (3 end members and 3 intermediate) are identified:

End member tectonic subsystems	Intermediate tectonic subsystems
Compressive system	Transpression system
Extension system	Transtension system
Strike-slip system	Syn-convergence extension systems

These subsystems, which contain structures of the same geological age, in response to the same tectonic processes, may cover enormous regions, e.g. 10 to 100 km in width for some 1000 km in length in orogens or passive margins.

One can understand the relationship between these structure subsystems with a simple model, taking the round cover of a bin as a plate. It is strong and rigid. Place all around the bin-cover sand, which represents the weak ranges and/or sedimentary basins. Sand reacts to stress in a brittle manner like upper crustal rocks. What happens in sand when moving the bin cover?

(1) A brittle compression system with thrusts develops in front of this experimental plate.

(2) A brittle extension system with normal faults develops behind the plate.

(3) Strike-slip systems develop on both sides of the bin cover, one clockwise (dextral) and the other anticlockwise (sinistral).

Ternary classification of plate movements
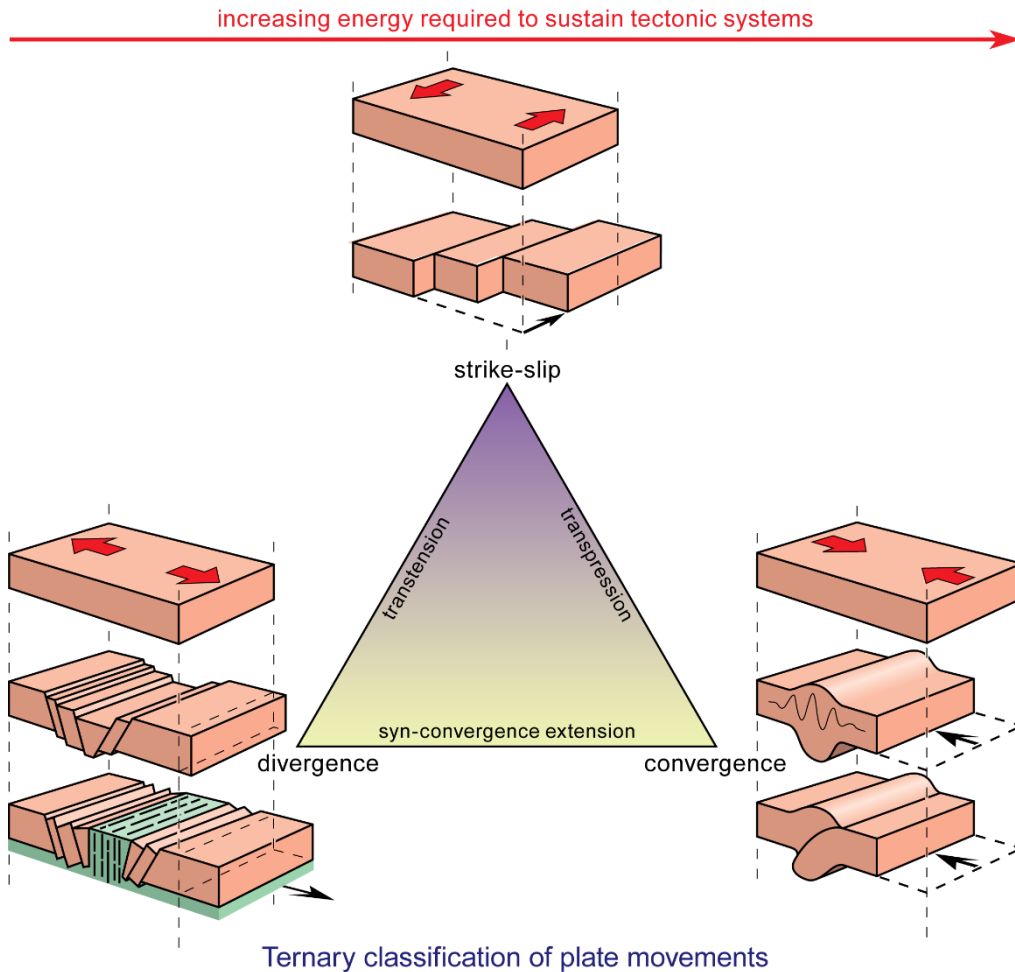
In this experimental approach one considers only horizontal deformation components. Regional-scale deformation may also be associated with vertical mass transfers such as anatectic and plutonic domes. Such regional systems are usually controlled by gravity-dominated forces and produce structures comparable to those formed in the compression, extension and strike-slip systems.

Tectonic regime - Fault systems

Regional **stress fields** control active fault systems. One assumes a Cartesian system of coordinate axes parallel to the principal stresses σ_1, σ_2 and σ_3, with the (x, y) plane horizontal. Any of the principal stresses can be vertical. This vertical component σ_{zz} is the overburden i.e. the lithostatic pressure:

$$\sigma_{zz} = \rho \, g \, z$$

with ρ the average density of the overlying rocks, z the depth and g the gravitational acceleration. There is no tectonic contribution (deviatoric stress) in the vertical direction.

Orientation of principal stresses

compression

thrusts

extension

normal faults

strike slip faults
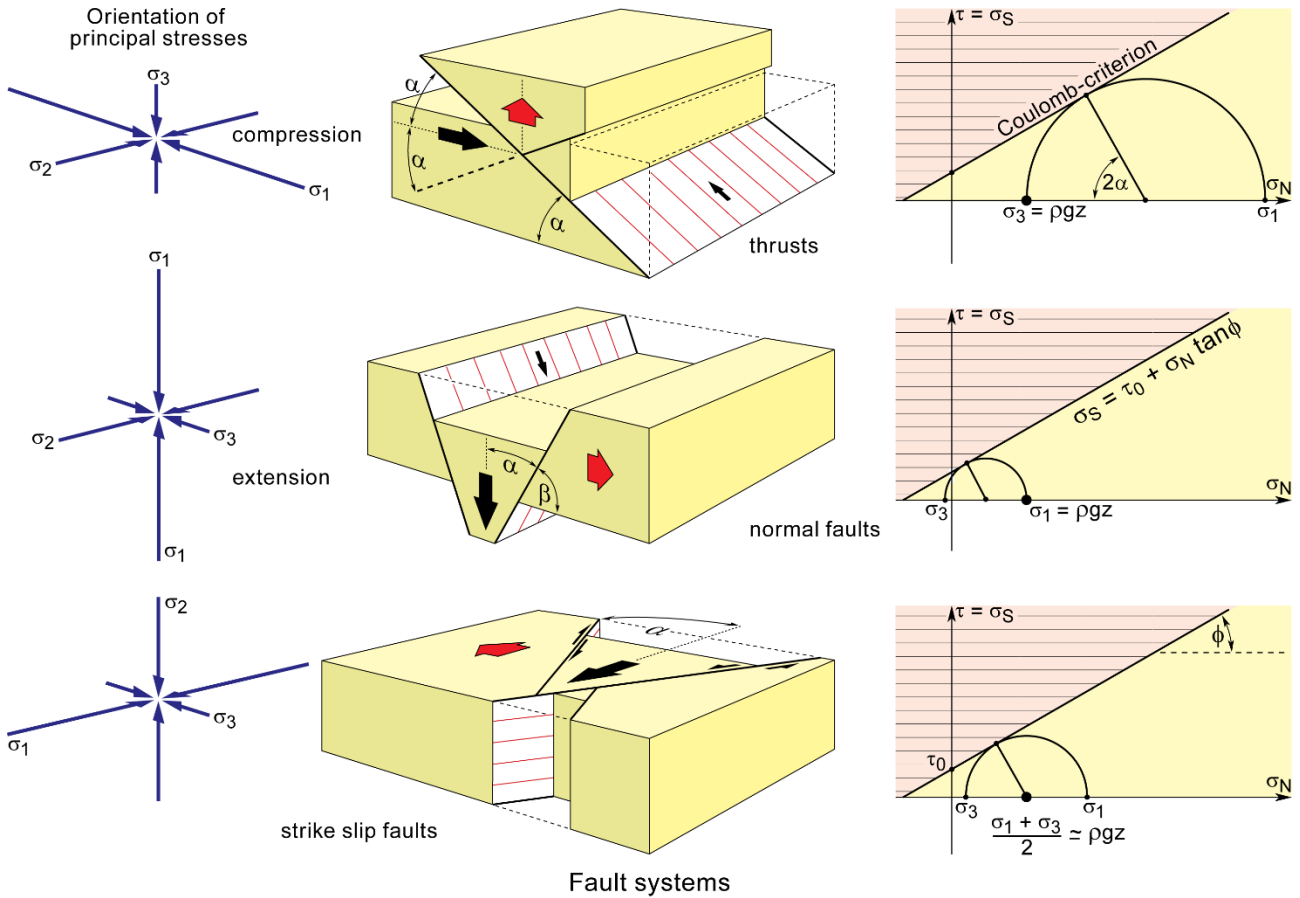
Fault systems

Compression – Thrust systems

Upward movement of the hanging wall on a thrust fault indicates that the compressional deviatoric stress $\Delta\sigma_{ii}$ is applied in one horizontal direction (for instance x) and exceeds the smallest principal stress component, which is vertical while the intermediate principal stress is large enough to contain deformation. The horizontal compressional stress is:

$$\sigma_1 = \rho gz + \Delta\sigma_{xx} = \sigma_{xx}$$

Assuming elastic deformation and no strain in the intermediate y-direction, (in this case parallel to σ_2), the Poisson ratio ν (defined in the Rheology chapter) relates the deviatoric stress component $\Delta\sigma_{yy}$ to $\Delta\sigma_{xx}$:

$$\Delta\sigma_{yy} = \nu.\Delta\sigma_{xx}$$

The horizontal principal stress σ_2 parallel to y is therefore:

$$\sigma_2 = \rho gz + \nu.\Delta\sigma_{xx}$$

The general, triaxial tectonic condition $\sigma_1 \geq \sigma_2 \geq \sigma_3$ becomes:

$$\left(\rho gz + \Delta\sigma_{xx}\right) \geq \left(\rho gz + \nu.\Delta\sigma_{xx}\right) \geq \rho gz$$

with all principal stresses positive in compression; the vertical, least compressive stress is σ_3. Conjugate thrusts dip 30°.

Extension – Normal fault systems

Horizontal extension on normal faults implies that the smallest deviatoric stress $\Delta\sigma_{ii}$ is applied in one horizontal direction (for instance x). Since this direction is tensional:

$$\Delta\sigma_{xx} < 0$$

The horizontal principal stresses are expressed in the same way as for thrusting:

$$\sigma_3 = \rho gz - \Delta\sigma_{xx} = \sigma_{xx}$$
$$\sigma_2 = \rho gz + \nu\left(-\Delta\sigma_{xx}\right)$$

The condition $\sigma_1 \geq \sigma_2 \geq \sigma_3$ becomes:

$$\left(\rho gz - \Delta\sigma_{xx}\right) \leq \left(\rho gz - \nu.\Delta\sigma_{xx}\right) \leq \rho gz$$

The vertical stress is the most compressive stress σ_1. Note that the deviatoric $\Delta\sigma_{xx}$ remains smaller than overburden and σ_3 remains positive. Conjugate normal faults dip 60°.

Transcurrent tectonics - Strike slip systems

Strike slip faulting describes horizontal displacements. Following the same reasoning as for compression and extension, the vertical direction z is the no strain, intermediate stress axis σ_2 (the no-strain direction). The horizontal deviatoric stresses are compressive in one direction and tensional in the other.

Either $\hspace{3em}$ $\Delta\sigma_{xx} > 0$ $\hspace{2em}$ and $\hspace{3em}$ $\Delta\sigma_{yy} < 0$

or $\hspace{3.5em}$ $\Delta\sigma_{xx} < 0$ $\hspace{2em}$ and $\hspace{3em}$ $\Delta\sigma_{yy} > 0$

One is larger than the lithostatic pressure while the other is smaller.
The condition $\sigma_1 \geq \sigma_2 \geq \sigma_3$ becomes:

$$\left(\rho gz + \Delta\sigma_{xx}\right) \geq \rho gz \geq \left(\rho gz - \nu.\Delta\sigma_{xx}\right)$$

Conjugate faults intersect along the vertical σ_2 axis, which implies that strike slip faults are vertical.

Mantle dynamics

The Earth is a heat engine through radioactive decay, primordial heat, latent heat of crystallization and tidal heating. Heat flow drives internal **convection** in the liquid outer core and the asthenosphere. **Conduction** of heat occurs through the lithosphere. Earth's cooling and the associated mantle convection provide the main energy that maintains the tectonic engine. Creation (freezing) and subduction (sinking and melting) of the oceanic lithosphere vitally contribute to mantle convection. The relationship of plates with the underlying mantle largely controls whether they approach or separate.

Mantle

The mantle is embedded between the lithosphere and the core. The mantle itself is subdivided into the upper and lower mantle (asthenosphere and mesosphere, respectively), with the transition zone located at a depth of ca. 670 km. This seismically reflective boundary is attributed to changes in density and viscosity subsequent to compositional and mineral changes, the lower mantle having higher density and viscosity because the extremely high pressure at this depth tightens the atomic packing of crystalline structures.

The mobility of the lithospheric plates is a surface manifestation of larger and deeper movements in the mantle. Energy considerations based on measurements of heat flow and the amount (and

disintegration) of radioactive elements in mantle rocks lead to theoretical estimates of enough energy to generate whole mantle convection.

hypothetic flow lines in the convective mantle
with lithospheric plates, fragments and mantle plumes
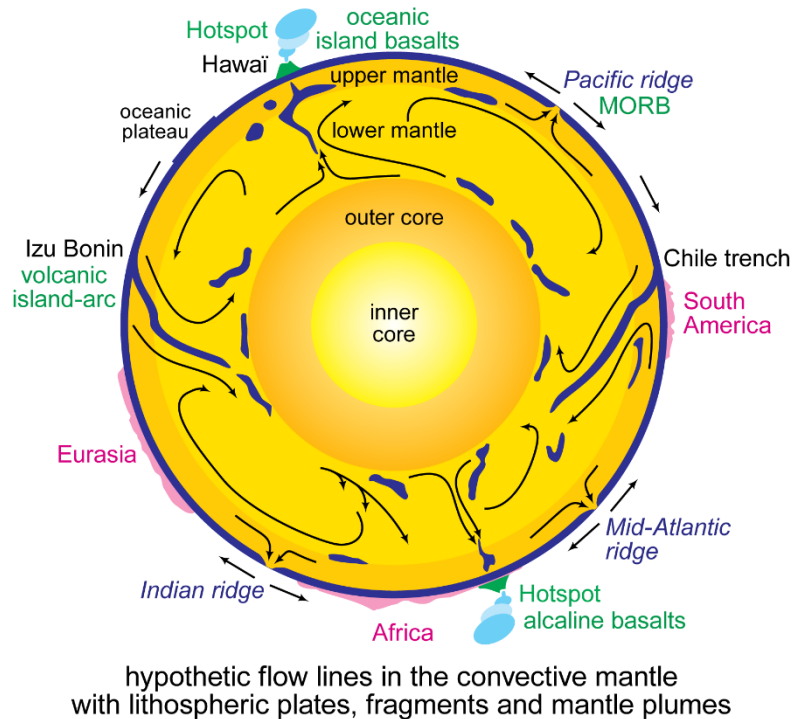
Seismic tomographic images and progress in numerical modelling suggest that three modes of flow dominate the structure of the Earth's mantle: (1) Subducting plates, some of which penetrating into the deeper lower mantle (e.g. Circum-Pacific region), attest for descending currents; (2) Large-scale, broad upwelling-plumes like beneath mid oceanic ridges (e.g. South Pacific), attesting for ascending currents; (3) Small-scale upwelling-plumes.

Continents move, ridges and subduction zones move or disappear. Therefore, the distribution of convection cells varies with time, which implies that mantle convection is not-stationary.

## *Hot-spot reference frame: Westward drift of the lithosphere*

Hot spots are stationary, intraplate and long-lived volcanic centres whose origins were speculated to be in particularly hot source regions, deep in the mantle. Their surface traces are long, narrow, time-progressive volcanic chains used to infer that the lithosphere is moving on top of such spatially restricted and supposedly fixed sources, which deliver magma through rising **plumes**. Plumes are considered to be heat- and melt-transporting columnar diapirs rising from the core–mantle boundary because of their thermal buoyancy.

Hot spots are independent of, and usually remote from plate boundaries. However they are an important element of mantle convection. About 10% of heat flow across the mantle is apparently carried by plumes, which are driven by basal heating rather than surface cooling and subduction of cold lithosphere. The related, volcanic centers have huge lava production rates and provide a reference point for anchoring measurements of plate kinematics, provided the hotspots are maintained over sufficiently long times. If hot spots are relatively fixed and nearly punctual surface terminations of narrow plumes, then they constitute a framework for calculation of absolute plate motions. On the basis of such a **hot-spot reference frame**, an average >50 mm.a–1 westward drift of the lithosphere relative to the asthenospheric mantle has been assessed. This drift is an average delay of the lithosphere with respect to the hot spots but, conversely, is also a relative eastward flow of the asthenosphere with respect to the lithosphere. The Earth's rotation may contribute to this bulk flow (the asthenospheric "wind") and mantle dynamics.
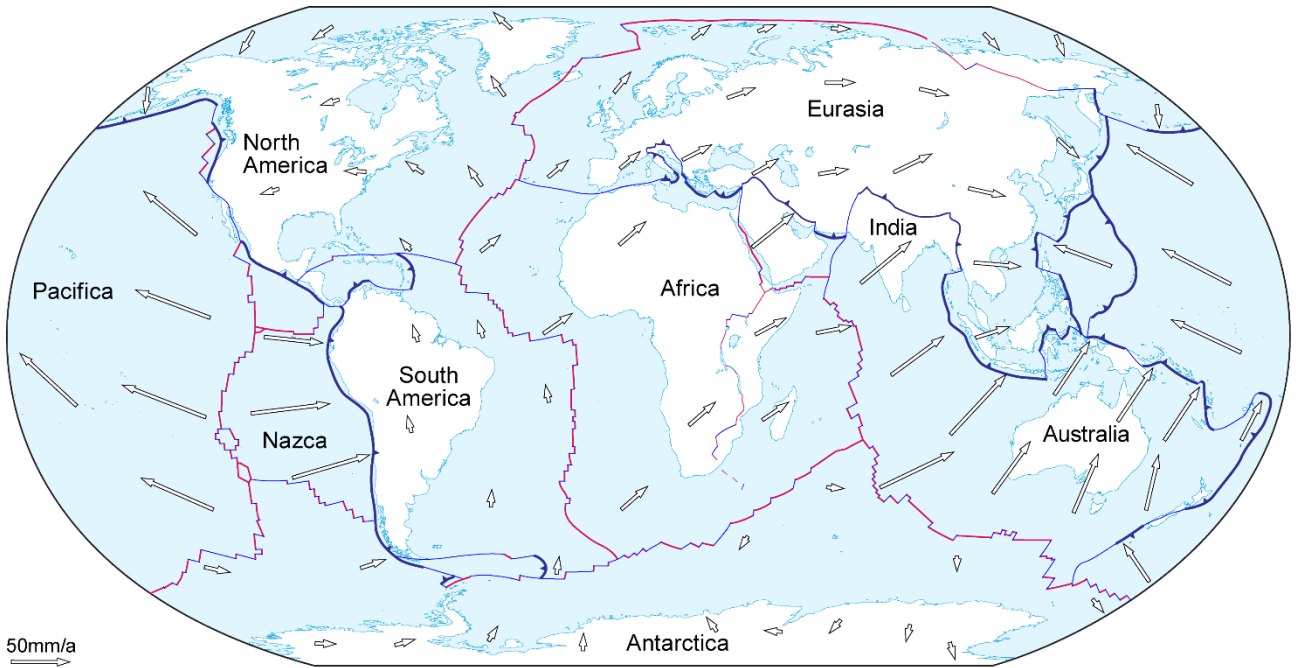
Current absolute plate motion from GPS information (world Robinson projection)

Westward drift implies that plates have a general sense of motion, and are not moving randomly. Geophysical and geodetic analyses suggest that plates move along sinusoidal flow lines with different velocities, yet with the general westward direction. Therefore plates are more or less mechanically detached from the mantle.
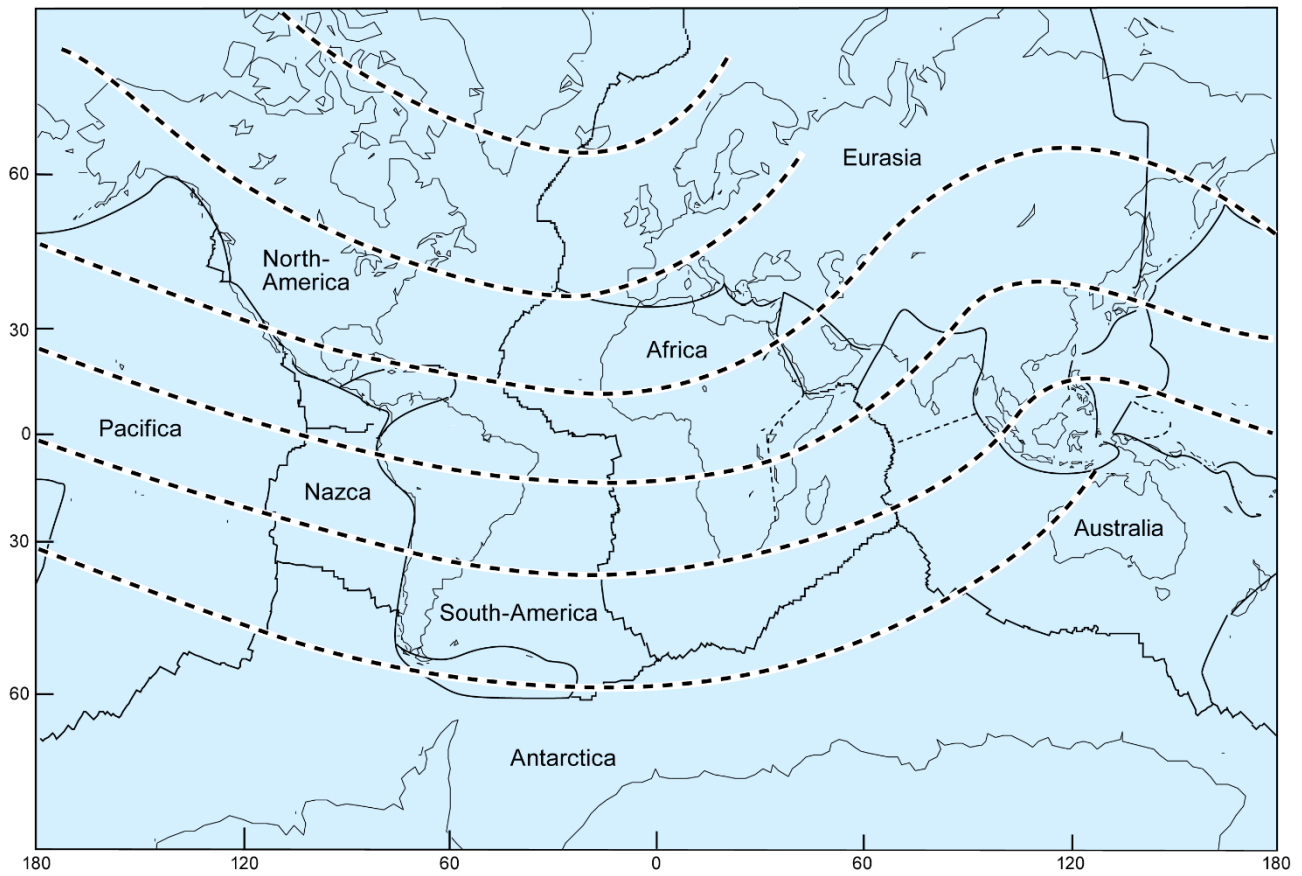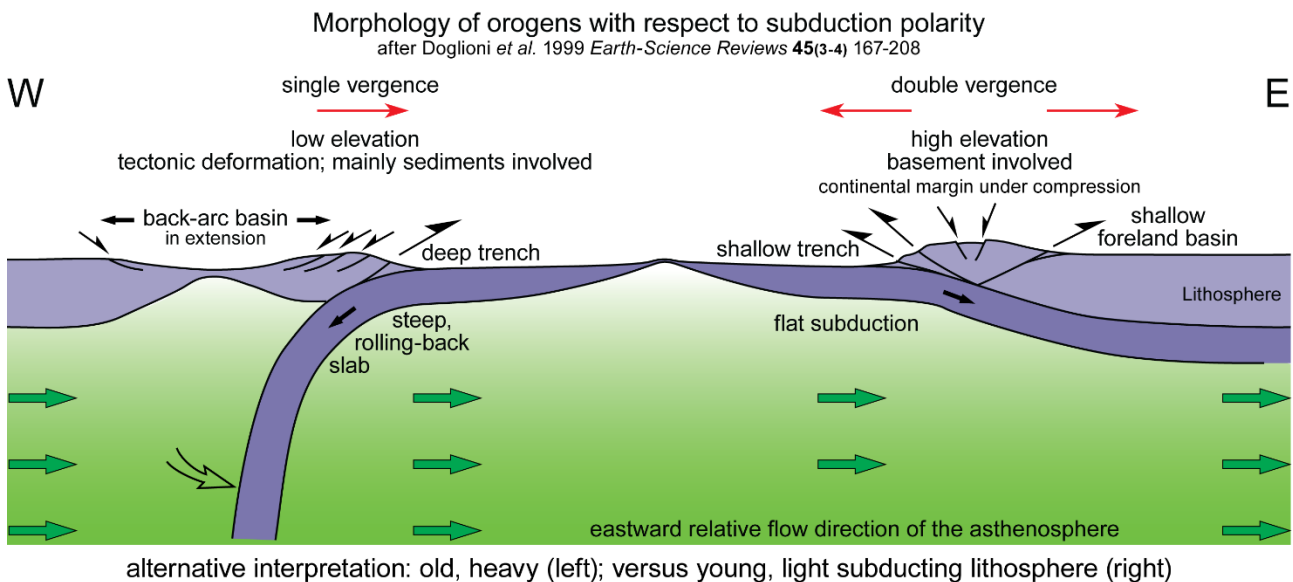

Sinusoidal shape of the mainstream of absolute, present-day plate motion
after Doglioni *et al.* 1999 *Earth-Science Reviews* **45(3-4)** 167-208

The degree of decoupling is controlled by lithospheric thickness and composition, and/or the thickness and viscosity of the underlying asthenosphere, and the lateral variations of these parameters. Where a plate moves faster toward west than its adjacent plate behind, to the east, the plate margin is divergent; conversely, if this plate moves faster to the west than its preceding plate, to the west, their boundary is convergent.

The lithosphere delay with respect to the mantle may create strong structural asymmetries in subduction and rift zones. The asthenospheric flow may influence steepening or shallowing of slabs:
- the slab will steepen where it is oriented against the asthenospheric wind, which pushes the slab upper boundary;
- the slab will become shallower where it is supported by the asthenospheric wind, which opposes the slab pull by pushing on the slab lower boundary.

Morphology of orogens with respect to subduction polarity
after Doglioni *et al.* 1999 *Earth-Science Reviews* **45(3-4)** 167-208

alternative interpretation: old, heavy (left); versus young, light subducting lithosphere (right)

However, there is an apparent contradiction between the idea of hot spot fixity (their motion at the surface is negligible compared to plate motions) and their proposed plume origin implying active, dynamic mantle convection. In fact, the on-going recognition of hot spot mobility and that some hot spots are linked to shallow plumes leads to new absolute reference frames such as GPS data.

Fate of slabs and other deep processes

Subduction describes how a part of the lithosphere, the **slab**, plunges and falls down into the mantle. Slabs have a wide range in material age, thickness and density. They therefore reach a position of neutral buoyancy at different depths. Old, cold slabs are likely to sink deeper than younger and warmer slabs. Whatever their age, slabs are cold where they enter the asthenosphere but immediately begin being warmed up from both sides towards temperatures of the surrounding mantle. Sediments, crustal lavas and magmatic rocks and the subducted mantle reach at some depth their melting temperature. Dehydration, melting and recycling through the mantle, and their contribution to mantle heterogeneity are likely different. Melting and recycling are considered to be responsible for hotspot and island arc volcanism.

The geological information yields a mean life span of > 2Ga for the continental crust, only less than 185 Ma for the oceanic crust. This significant discrepancy is taken as evidence that the continental crust tends to avoid recycling in subduction. Taken in the same reference frame, subducting plates move 3−4 times faster than their overriding plates. This difference is likely caused by **slab pull**, giving further evidence that body forces are important and that the lithosphere is part of the actors that animate plate tectonics.

Rollback

When the negatively buoyant slab (compared to the asthenosphere) is long and heavy, or anchored in the mantle, it can sink more rapidly than the rate of plate convergence. The gravitationally unstable slab becomes steeper, which produces a migration of the hinge zone and the bulge, where the slab bends, away from the arc. **Rollback** describes the oceanward retreat of the trench due to the gravitational pull of the slab. Slab rollback and consequent trench retreat play two important roles: (1) It inserts extensional episodes in an overall convergent regime and (2) it triggers changes in plate boundary patterns.

Syn-convergence extension

The asthenosphere of the overriding plate must flow towards the retreating slab to compensate the space left by the slab that sweeps back through the mantle like a paddle.
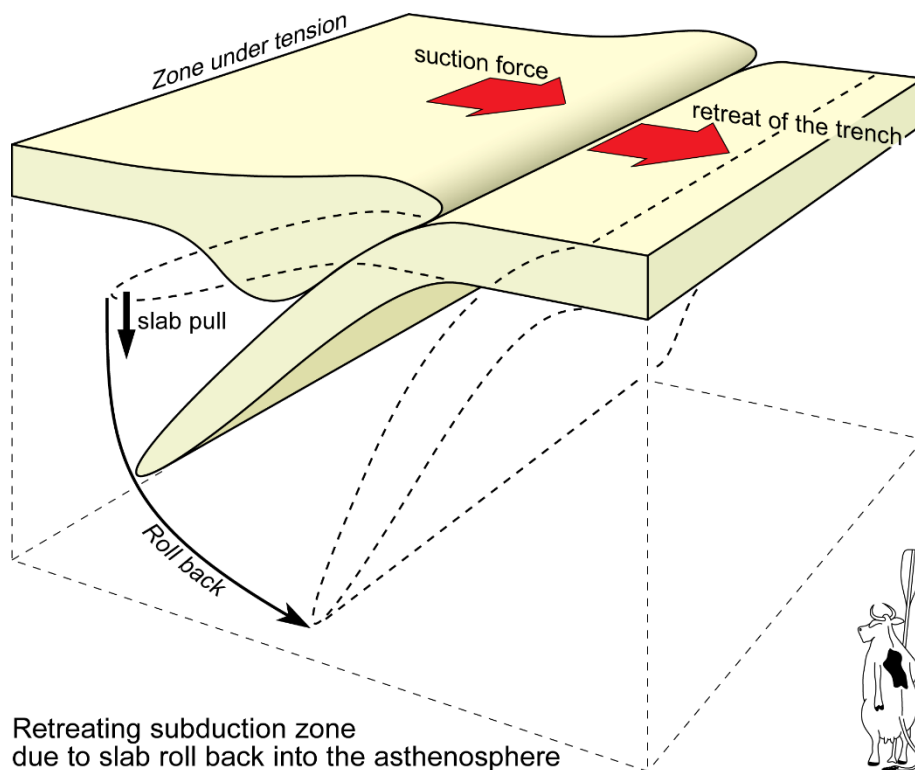

This passive flow produces a suction force that pulls the overriding plate, where it induces extension. Accelerated rollback may thus produce a switch from compression to extension tectonic modes in an overall convergent setting (back-arc extension is a classic example). The overriding plate tends to split at the active arc, while the forearc tends to adhere to the migrating trench. Indeed, the strength of the hanging wall plate is smallest at the arc, due to thermal weakening and high potential energy in the thicker arc crust.

Rollback is particularly evident for west-directed subduction zones such as the Marianas, Barbados, and the Apennines, where it is associated with back-arc opening.

Toroidal flow

Obviously, the asthenosphere below the rolling-back slab has to flow out of the way. This may be accomplished by along strike flow and evacuation around the slab edges or through slab windows (a gap opened in the slab). Toroidal flow describes the swirling transfer of mantle material from below to above the slab region.
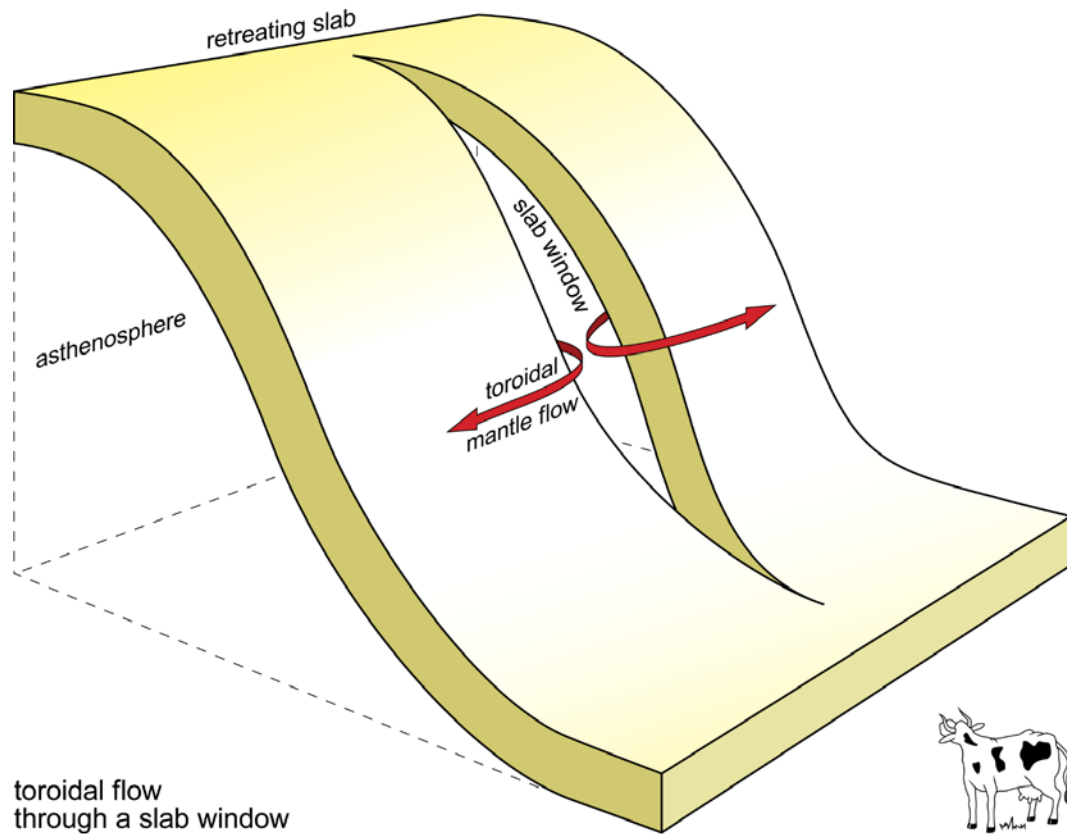
toroidal flow
through a slab window

Realignment of plate boundaries

Rollback is essential in changing the orientation of plate boundaries. Paleomagnetic measurements on the Fiji Islands show that the latter have rotated by 90° over the last 40 Ma, which implies that the trench line near the Tonga-Kermadec arc has pivoted by about the same angle about the North Island of New-Zealand. Such rotations suggest that rollback is effective between a rotation axis and a tear fault in the slab. The process might be able to generate curved orogens.
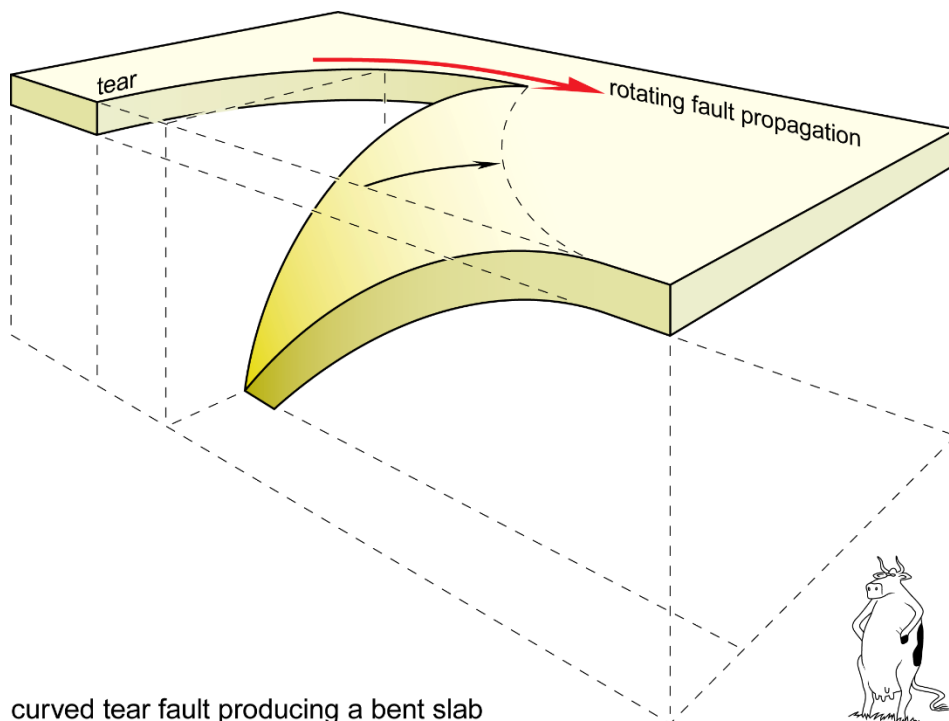
curved tear fault producing a bent slab

Slab fragmentation

After long convergence, the slab can be long enough to reach a weight larger than the lithospheric tensile strength. The slab breaks where the tensile strength is reached and slab segments separate from the buoyant part of the lithosphere at the surface. Then these slab segments sink more rapidly and come to float within the asthenosphere where they eventually dissolve thermally and become gradually absorbed. Gaps in earthquake distribution along slabs were taken as evidence for slab rupture. Seismic and tomographic information documents two major ways slabs can break: along nearly horizontal tears and along down-dip tears.


Slab breakoff
(e.g. Vrancea, Romania)
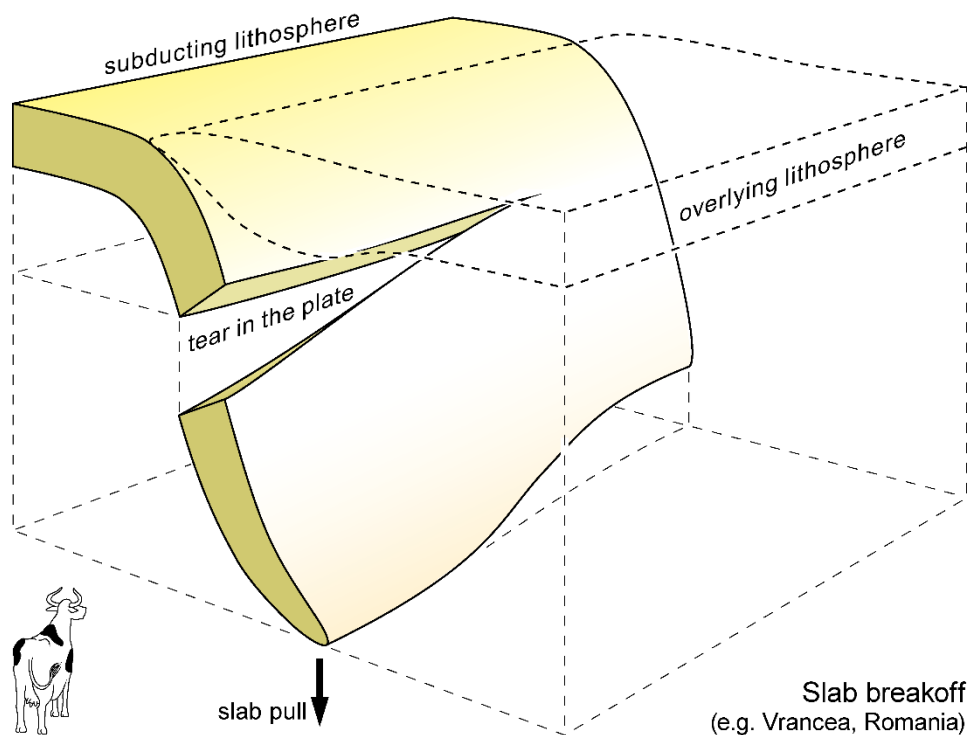
Slab break-off

The slab (usually oceanic lithosphere) can detach from the surface (often continental) part of the plate along a fracture propagating horizontally, along-strike of the trench, probably after and along necking of the descending lithosphere. This event is known as **slab break-off**, which has severe consequences for the development of collisional zones.

With slab break-off there is cessation of slab pull. Termination of this downward force brings about a general uplift of the collision zone due to both the elastic unbending of the subducting plate and **isostatic rebound** of the buoyant thickened crust. Asthenospheric material replaces the dense slab and elevates the heat flow, which may lead to partial melting of both the mantle and crustal material and produce voluminous magmatism and volcanism. These processes have been proposed to account for the Late Eocene - Oligocene magmatism in the Alps (Periadriatic intrusions, Adamello, Bergell).

Slab vertical tear

Vertical tear of slabs (mostly oceanic lithosphere) likely occurs along fracture zones (ancient transform faults?) and might be due to horizontal extension required by the arcuate shape of subducting slabs, which creates some sort of divergence at depth. Asthenospheric toroidal flow may accommodate further slab rollback if the slab is still attached to the plate.

Slab vertical tear
(e.g. Izu-Bonin slab)
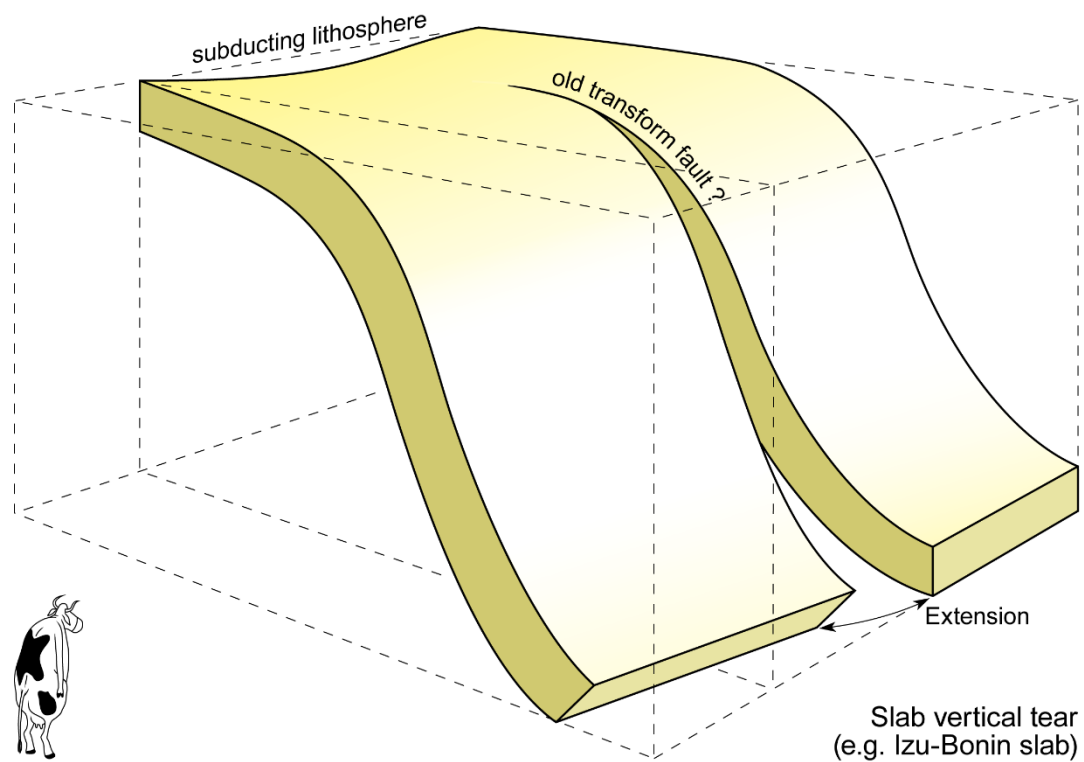
Slab fragmentation

Combined horizontal and vertical fracturing produces extensive slab fragmentation into disconnecting pieces of variable sizes.

Subduction flip

If an oceanic plate overrides a continental lithosphere, the less dense continental material resists to sinking. Slab breakoff and subsequent isostatic rebound of the previously subducted continent may induce the sense of subduction to be reversed so that the previously upper plate becomes the subducting one. Subduction is **flipped**. After break-off or flip, the abandoned slab is absorbed into the asthenosphere. This could explain why most ocean trenches are found along the edges of continents.

Subduction flip
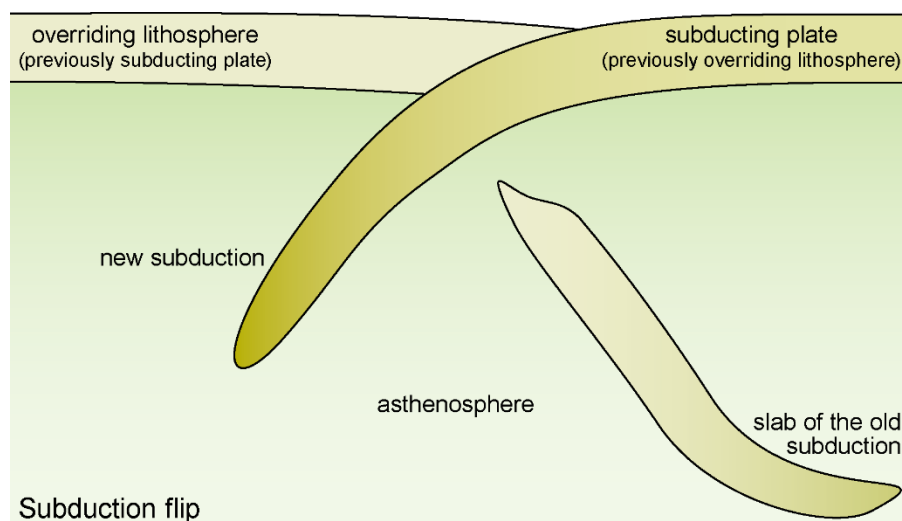
Removal of the lithospheric mantle

The mantle lithosphere has higher density than both the overlying crust and underlying fluid asthenosphere. Therefore the buoyancy of the 5-8 km thick oceanic crust compensates no more than a 35-56 km thick mantle lithosphere. Similarly the 30-40km thick continental crust does not compensate more than 250 km of mantle lithosphere to float on the asthenosphere. The mantle lithosphere is therefore an unstable layer in the plate construction. It does not sink because the positive buoyancy of the crust holds it up unless the bonds between crust and mantle are broken. Four main mechanisms have been envisioned to remove continental lithospheric mantle (i.e. ungluing the crust from its mantle lithosphere):
(1) mantle subduction,
(2) delamination
(3) convective thinning,
(4) foundering of dense layers.
In all cases, the asthenosphere flows to replace lithosphere.

Exercise:

Calculate and plot the crustal thickness / mantle lithosphere thickness required for neutral buoyancy

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Density layering of a cratonic plate above its asthenosphere
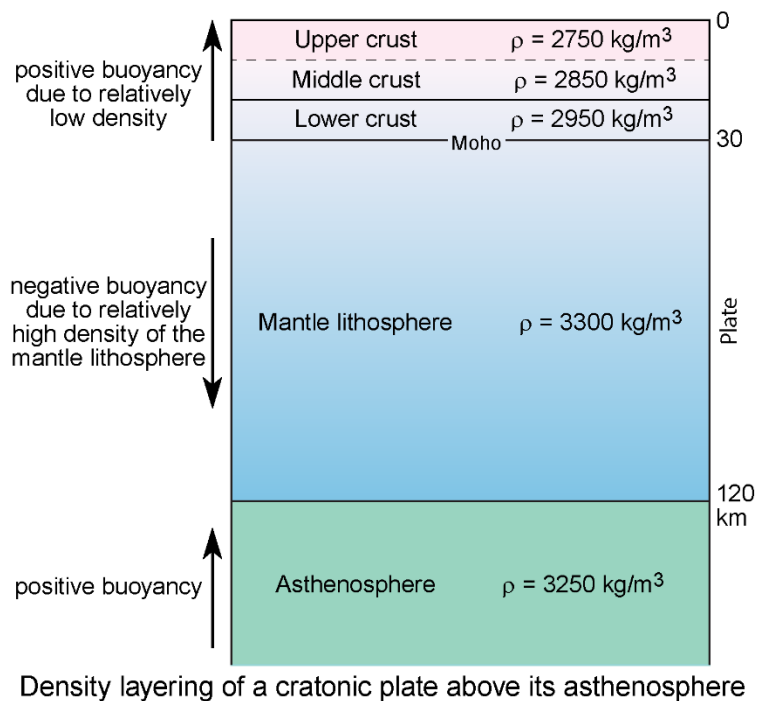
Mantle subduction

Mantle subduction is assumed to follow an earlier subduction of oceanic lithosphere. The overlying lithosphere acts as a wedge-shaped scraper that splits the subducting lithosphere. The crust is sheared off the mantle lithosphere at a point of discontinuity (called singular point). The lithospheric mantle carrying no more crust sinks into the less-dense asthenosphere while a crustal sheet (**flake**) of the split lithosphere may override the other lithosphere. **Flake tectonics** refers to this collision process.
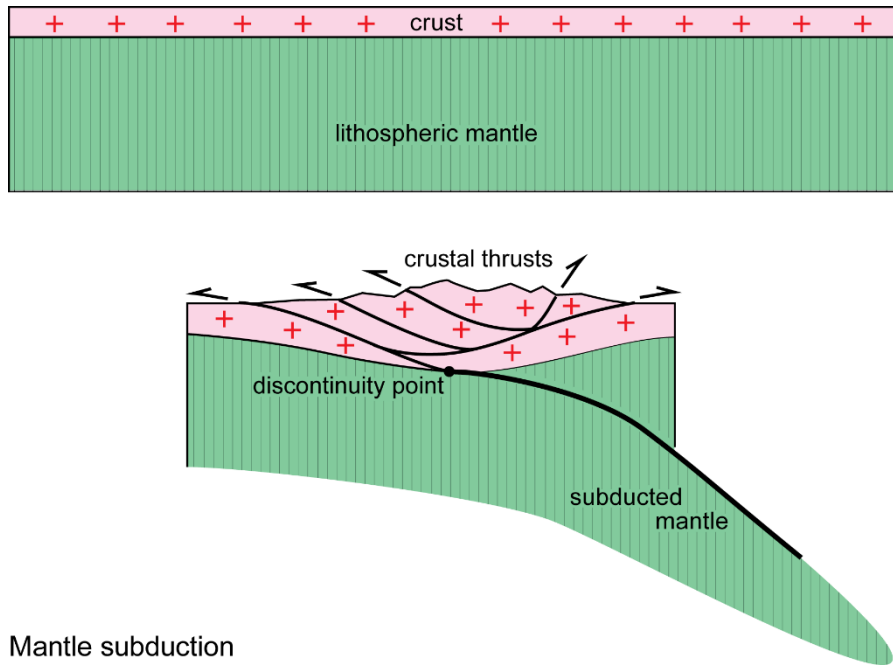
Mantle subduction

Delamination

Delamination is a generic term for separation of two initially bonded layers. Tectonic delamination is favoured by the presence of relatively weak crustal layers provided by major changes in composition and thus rheology.
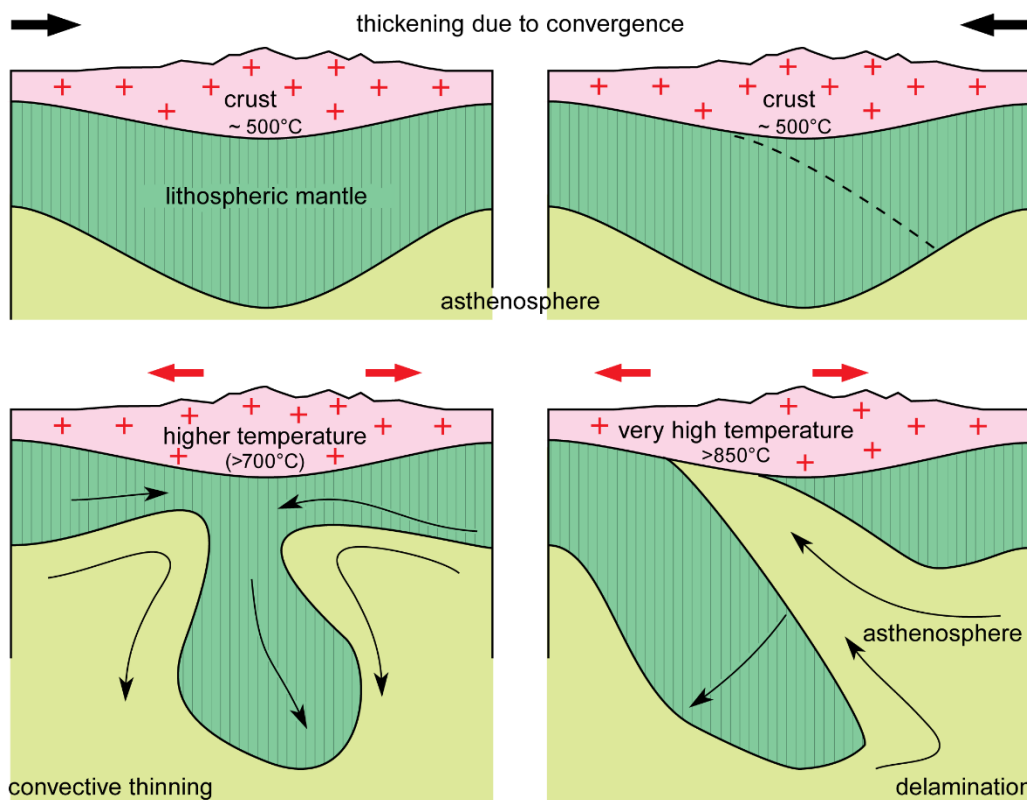
Two possible mechanisms to remove the sub-crustal lithosphere

Earth scientists have envisioned two possibilities: layer division and convective thinning. In both cases, the asthenosphere flows to replace the lithosphere. Subsequent heating may cause partial melting and magma generation. Magma may intrude the upper crust as post-orogenic plutons. In addition, the hot asthenosphere replacing the heaviest lithosphere triggers isostatic uplift. Geographical and time propagation of magmatism and uplift might help differentiating these delamination modes.

Layer separation

Dense crustal and/or mantle layers are ripped away from the layers atop. The negatively buoyant, detached layers or portions of dense layers sink into the deeper mantle and asthenosphere. While mantle lithosphere progressively peels away from crust as a coherent sheet, the delamination point migrates away from its starting point and the region of thinned lithosphere enlarges. Hot asthenosphere invades the gap as it opens between the descending mantle and the crust.

Convective thinning

Lithospheric shortening in orogenic belts is isostatically accommodated by the formation of a thick lithospheric root. Convective thinning is then driven by the negative buoyancy of the mantle lithosphere thickened by shortening. The mantle lithosphere from adjoining regions flows into the downwelling as this Rayleigh-Taylor instability grows. Eventually, upwelling asthenosphere replaces the mantle lithosphere as it is thinned and stretched. The downwelling lithosphere drops into the asthenosphere, which substantially increases the gravitational potential energy of the overlying continental crust. Conductive warming reduces the strength of the orogen. As a result the orogen may be thrown into extension, as the isostatically uplifted crust attempts to spread laterally (post-collisional collapse of orogens).

Thermal erosion

The boundary between lithosphere and asthenosphere is thermally controlled, since it is the same material (peridotite) in solid and liquid forms. Convective thinning occurs as heat is advected to the base of the lithosphere at a rate larger than normal basal flux, and conducted within the lithosphere. Convection in the liquid asthenosphere is a process of heat transfer much more efficient than conduction in the solid shell. In that case, temperature is increased and the melting point can be exceeded at the bottom of the mantle lithosphere. Then the mantle lithosphere thins down as it is transformed into asthenosphere.


Thermal erosion of the lithosphere
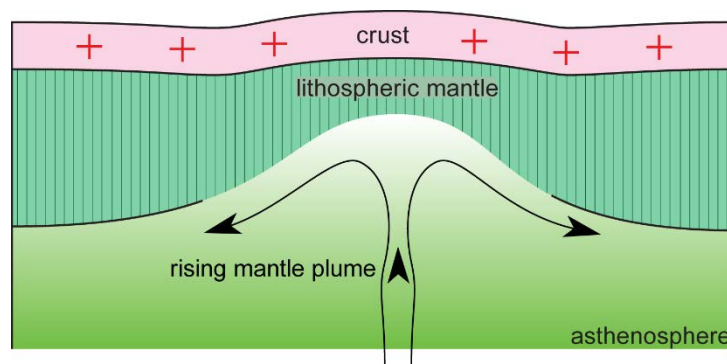
The heat excess can be carried to the lithosphere by mantle plumes that cause the lithosphere to thin with isotherms progressively rising through. Uplift in large swells is due to thermal expansion more than dynamic overpressure of the impinging plume. Delamination could start once the asthenosphere has cut the mantle lithosphere and reached the crust.

Foundering of dense layers

Dense mafic/ultramafic layers of the crust and portions of mantle lithosphere fall down as viscous chunks into the less dense asthenosphere. The upwelling asthenosphere replaces the removed lithospheric pieces but the region of thinned lithosphere keeps the same size and areal limits as at the division time.

Slab graveyard

Seismic observations show a shear velocity discontinuity and a density jump at 660 km depth and several slow anomalies just underneath. This seismic discontinuity is the boundary between the upper and the lower mantle and is attributed to a phase change from spinel at low pressure to much stiffer perovskite at higher pressure. Earthquakes occur all the way down to this boundary, but not below. The seismic tomography supportively images lithospheric slabs subducting through the upper mantle. They are either deflected along the upper-mantle/lower-mantle transition zone and/or penetrate into the lower-mantle down to the core-mantle boundary. Tomographic results suggest piling of gigantic recumbent folds laying at this boundary, similar to buckles of honey poured on a slice of bread (e.g. beneath the Caribbean). Laying (**stagnant**) slabs and buckle folds both indicate that subducted lithosphere experiences resistance to further penetration when they encounter the 660 km deep discontinuity.
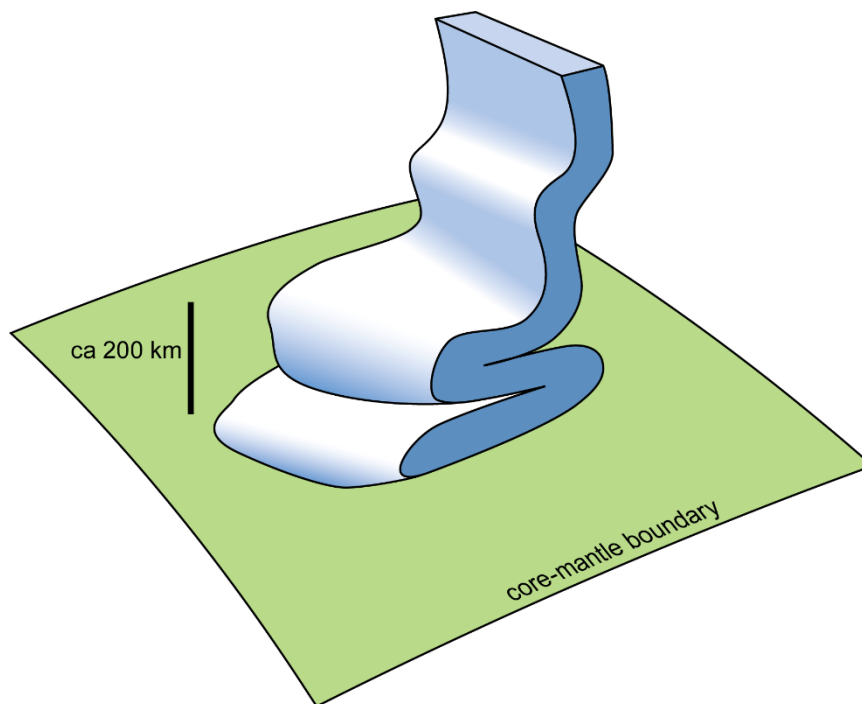
cold, buckled "slab" beneath the Cocos plate (Central America)
after Hutko, Lay, Garnero & Revenaugh 2006 *Nature* **441** 333- 336

The lowermost lower mantle, known as the D''-layer (depth between ca 2700 and 2900 km), has been postulated to be the ultimate destination of slabs. This layer may reflect a change in mineral structure from the relatively low-temperature magnesium silicate perovskite to a post-perovskite form at the core-mantle boundary. High seismic velocities and reflections from just above the anomalously high wave speed core image relatively cold slab material laying and accumulated on the core-mantle boundary but the evidence is disputed.

   Slow melting of slab material may source plumes from both "graveyard" levels, the core-mantle boundary and the 660km discontinuity. Thus, the two main elements of the earth engine, sinking subduction and raising mantle plumes, are chemically and physically related, deep in the mantle.

Aims of the lecture

The problem of the growth and evolution of the continental crust is an important subject in Earth Sciences. The continental crust is distinguished from the oceanic crust by its more evolved and differentiated nature. It consists mainly of rocks of granitoid compositions, accompanied by subordinate amounts of mafic and ultramafic rocks. On one hand, continents are known to grow:
   - by **lateral accretion** of arc complexes in active continental margins and
   - by **vertical underplating** of mantle-derived magma.

These processes may be followed by a series of complex processes leading to production of granitoid rocks.

On the other hand, continents are progressively destroyed:
   - through chemical and physical erosion from the surface
   - **delamination** of the lower crust from the bottom, and even
   - limited **subduction** to mantle depths, as evidenced from ultrahigh-pressure metamorphic terranes.

Thus, much of the continental mass has gone through recycling in a perpetually dynamic Earth since its earliest formation in the early Archean. As such, continents are the only record of old (pre-Jurassic) plate geometries.

Since the quantified geodynamic setting is identified in the oceanic crusts, it is important to describe the modern continental deformation first, i.e. the recent mountain systems such as the **Alpine-Himalayan orogenic system**, which stretches from Spain and North Africa to Indochina. This orogenic system results from the closure of a Mesozoic ocean (**Tethys**) between Europe + Asia (Eurasia) and various blocks derived from Gondwana (in simple terms Greater-Africa). Note that although the orogenic system presumably results from important horizontal movements, its best expression is the elevation of the ranges, i.e. the result of subsequent vertical movements.

This general lecture on tectonics will describe and compare some young mountain chains on the earth's surface. They are collision zones of different age and therefore with different erosion stages. One may speculate that similarities and differences in their evolution and present tectonics represent collisional processes at different stages of maturity. These examples will be used to study the crustal consequences of important converging systems. The word crustal should be emphasised since plate tectonics imply movement of lithospheric plates, whereas geologists can study only the crustal part of lithospheres. However, this is the upper-part that dominates the visible Earth, and which geologists have to deal with.

This lecture will concentrate on the geodynamic control of large-scale deformations involving the continental crust, in order to describe some fundamental differences with the oceanic lithospheres. These differences are expressed by parameters that are intensive in the development of the structures studied.

Relative movements of Gondwana-derived microplates with respect to Eurasia since the Early Jurassic (190 Ma) after Savostin *et al.* (1986) *Tectonophysics* **123**, 1-35

The course will be organised around a description of reference examples such as Oman because knowledge of geological data documenting a specific geodynamic phenomenon is the only way to understand more difficult areas. Indeed, one of the fundamental principles in geology is to assume that similarity is not coincidence. Hence, identifying similar geological data is used to infer similar geodynamic processes in more different areas. Comparative geology is a scientific approach in itself.

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