TECTONIC PROCESSES

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Summary

Plate tectonics is responsible for most geographical and geological features of Earth, in particular, those that are associated with natural hazards such as volcanoes and seismic zones. First, we classify the three main relative movements that rule plate tectonics. Major geological features and processes associated with specific movements, plate interactions, and geological settings are then summarized. A few examples illustrate how the concept of plate tectonics has revolutionized earth sciences, and linked many separate observations into a single, complex system controlled by the internal activity of the planet. Lithospheric responses to these movements, and subsequent forces both at the plate boundaries and within the plates, lead to different features that evolve at different rates. The understanding of the tectonic framework, based on the descriptive approach, opens new perspectives in terms of short and long term predictions concerning the life of the outer surface of Earth.

1. Introduction

Tectonic is derived from τεχτονικη which designated in ancient Greek the art of building. After its appearance in the geological literature of the mid-nineteenth century, it was mainly used to describe the study of Earth's structures on every scale, including those that are too large to be examined on the outcrop. It was only in the 1960s that mapping of the sea floor and mid-oceanic ridges conferred to the term tectonics its modern definition. Knowledge of the nature and age distribution of the oceanic crust provided a complete theory of Earth's dynamics, unifying earth sciences by pulling together diverse concepts and explaining many independent observations. The theory comprises four basic tenets.

a) The outer layer of Earth (its *lithosphere*) is relatively strong compared to the deeper *asthenosphere*; it is fragmented into pieces called *plates*.
b) The plates move independently relative to one another as rather rigid mechanical entities.
c) Earthquakes and volcanic eruptions are concentrated in narrow belts that correspond to linear topographic anomalies. This distribution of both the seismic and topographic disturbances indicates severe tectonic activity at or near the boundaries of the plates.
d) The interior of plates is relatively quiet, with far fewer earthquakes than occur at plate boundaries, and little volcanic activity.

Plate tectonics represents the simplest paradigm to relate superficial, geological, and geophysical structures with quantified movements attributed to deep processes of Earth. Plate tectonics permit in particular a dynamic interpretation of the present-day, large-scale features of Earth. Processes that opened oceanic basins through continents, and closed oceans to produce mountains and new continents, are collectively known as *tectonic cycles*. Since Earth is not expanding significantly, the rate of lithosphere destruction at convergent boundaries is virtually the same as the rate of creation at divergent boundaries.

2. Relative Plate Movements

Using the distribution of mountain ranges to define belts of continental shortening, and fold orientations to determine the force directions, large motions between *continental blocks* were envisioned by a few geologists who embraced the idea of *continental drift*, developed by the meteorologist Alfred Wegener in the early 1900s. Despite the work of some visionary scientists, geologists have not been able to document *plate movements*, because they needed to explore the oceans rather than the continents to find convincing arguments and demonstrate a mechanism for continental drift. This mechanism can be established for the past 200 million years, about the age of the oldest oceanic crust.

The lithosphere, which is the cool outer shell of Earth's convective system, includes both the *crust* and part of the *upper mantle*. The thickness of the lithosphere is thus controlled by the geotherm. It is defined on seismological criteria that reflect relatively gradual changes in various physical properties. As a metaphor, the lithospheric plates move over the asthenosphere a bit like ice-sheets on the sea. The asthenosphere is animated by the convection motions that drag the plates on the surface of the Earth, as fast as fingernails grow.

The edges of the plates are called *plate boundaries*. Points where three plates meet are *triple junctions*, which are succinctly classified in terms of the types of plate boundaries that join each other at the junction. Quadruple junctions are unstable configurations that immediately devolve into paired triple junctions.

The relative, horizontal movements of the rigid plates produce space problems at the contacts between adjacent plates. Because lithospheres are relatively rigid, their space problems produce forces that act on rocks. The response of the rocks is a deformation that creates secondary structures. These relative motions and their consequences are called *plate tectonics*.

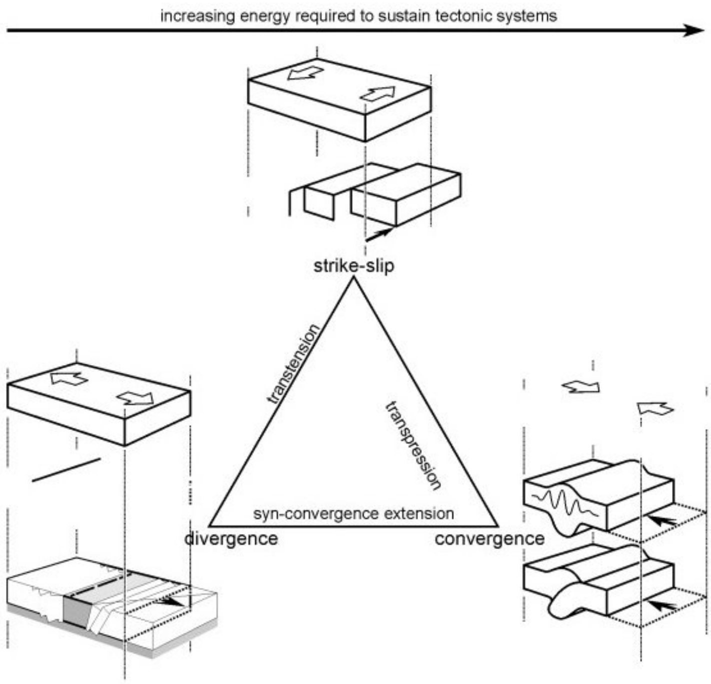

Figure 1. Ternary classification of plate movements and associated tectonic regimes

Horizontal velocities are up to nearly 20 cm yr $^{-1}$, and relative plate motions are described in terms of convergence, divergence, and strike-slip (Figure 1).

- *Divergence* is due to adjoining plates moving away from one another. Crustal area extends, new ocean crust is formed at such boundaries, and plates grow.
- *Convergence* brings adjacent plates towards each other. The bulk crustal area diminishes, and plates even disappear down into the mantle along *subduction zones*. If Earth remains the same size, then the amount of crust consumed in a convergent zone must equal the amount of new crust that is formed in a divergent zone.
- *Strike-slip* consists of lateral shifting of one plate past another horizontally, without diverging or converging.

Plate movements may combine in many ways, depending on the kind of plate interaction that must be accommodated. The actual relative movement may be perpendicular or oblique to the plate boundary. An oblique convergence of plates produces *transpressive deformation*. An oblique divergence is termed *transtension*.

Any horizontal motion on a spherical Earth is necessarily a rotation about an axis through the center of the globe. Moving plates are rigid spherical caps that rotate around axes, each axis cutting Earth's surface at two antipodal points: the *poles of rotation*. The location of these poles depends on the reference used. Therefore, each pole pair corresponds to the relative rotation of one plate with respect to another, considered as fixed. These poles are the only points on the surface of Earth that do not move with respect to either of the two considered plates. Rotation poles are also called Euler poles, to honor the Swiss mathematician who established the basic geometry of movements on a sphere. The angular velocity between two plates is constant along the whole length of their boundary. Consequently, the linear velocity—that is, the relative displacement per unit time—increases away from the pole to accommodate larger and larger circumferences (Figure 2).

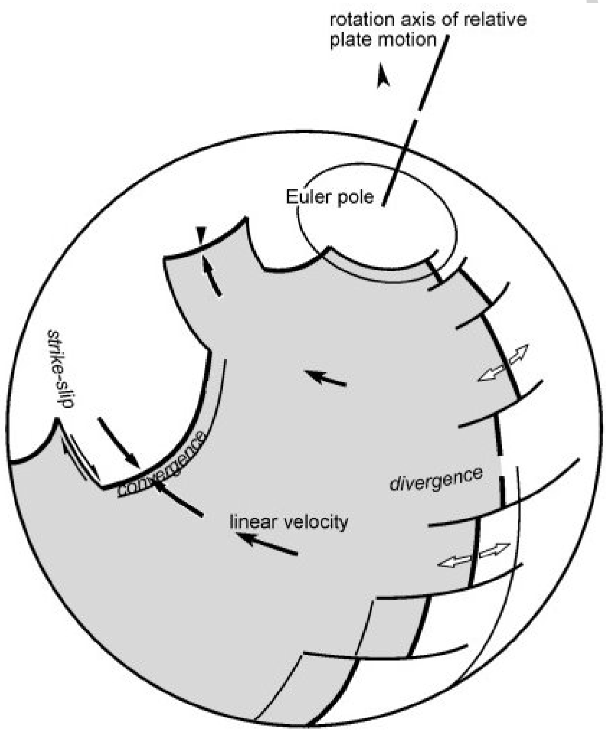

Figure 2. Description of a plate movement (shaded) with respect to an arbitrarily fixed plate (white) by an angle of rotation about a pole of rotation on a simplified two-plate planet, with one convergent, one divergent, and strike-slip boundaries. The angular rotation is the same everywhere, but the linear displacement increases according to the size of the sphere. Attention: the Euler pole is not the geographical pole or the planet's rotation pole.

Divergent boundaries usually run along segments of great circles that intersect at the Euler poles. Therefore, divergent boundaries strike mostly orthogonal to the divergence direction. The orientation of convergent boundaries varies, because rigid shells on a sphere normally have arcuate boundaries. Ideal strike-slip boundaries are segments of small circles concentric about the Euler poles. Thus, they lie along the direction of relative motion between plates. A change of rotation pole between two plates requires a change in relative movement direction and, consequently, a change in the character of plate boundaries. Plate boundaries are not permanent features throughout their geological history. However, case studies suggest that poles for any two plates remain rather stable for long periods of times, pointing to some inertia in plate movements.

On the present Earth, the plate organization has formed two networks: one chain of divergent boundaries, and one chain of convergent boundaries, are segmented and connected by strike-slip boundaries (Figure 3). This simple organization reflects the mantle convection pattern, which is stable on a long term.

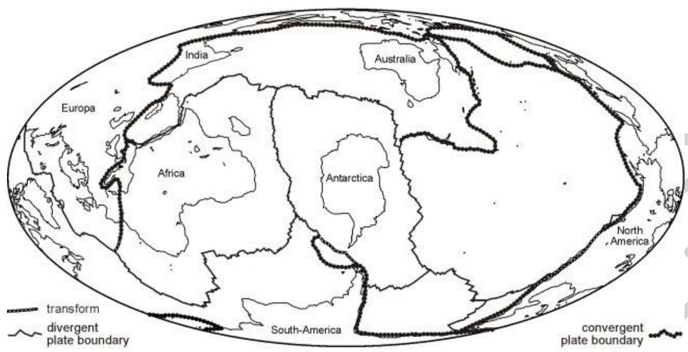

Figure 3. Framework of plate boundaries on Earth. Divergent and convergent boundaries pertain to two continuous belts connected through transform, strike-slip boundaries.

2.1 Plate Divergence

Divergent plate boundaries are zones of tension where plates split into two or more smaller plates that move apart, and the dominant stress field is extension. To accommodate the separation, dominantly normal faults and even open fissures form where crustal rocks undergo stretching, rupture, and lengthening coeval with lithosphere thinning. Because the lithosphere is thinned, there is *upwelling* of the mantle below the necked crust. Decompression of the mantle results in partial melting, and basaltic magma is injected into the fissures or extruded as fissure eruptions. Basaltic magmatism at the axis of a *ridge* creates new oceanic lithosphere as plates diverge from one another. Divergent plate boundaries are some of the most active volcanic areas on Earth. Magma filling the space opened between divergent plates is a process so important that more than half of Earth’s surface has been created by volcanic activity along and within divergent boundaries during the past 200 million years. With sustained opening, continental edges move further and further from the mid-oceanic ridge. The whole process is known as *seafloor spreading*.

2.1.1 Rifts: Plate Divergence in Continental Settings

The break up of a continent is accomplished by normal faulting and produces *rift systems*. One of the best examples comprises the Read-Sea, the African Great Rift Valley, and the Gulf of Aden, which meet in a triple junction in the Afar region. Rifting produces long and linear crustal depressions whose characteristics are:

- An area where the crust has been arched upward.
- A relatively narrow width which is about the thickness of the rifted continental crust, irrespective of the length of the rift valley.
- Steep margins that are as much as 3–4 km high normal-fault scarps. Some of these faults are very long, but most of them relay each other, eventually in an en échelon manner.
- Huge down-dropped blocks, which are sites of continental basins that are filled by thick (more than 1 km) clastic debris derived from adjacent high-standing blocks. Thinning of the continental crust has usually occurred on a series of listric faults.
- Parallel dyke swarms and outpouring flows of tholeiitic and alkaline basalts that accompany normal faults along which the crust is pulled apart. Mounts Kenya and Kilimanjaro are big volcanoes that exemplify this magmatism. Rhyolitic magma may be produced by partial melting of the granitic crust. The *bimodal* association of acid and basic volcanic rocks is characteristic of within-continent rift systems.

Continental rifts may represent the initial stages in the evolutionary cycle that further separates the older rifted segments, and finally leads to a *continental break-up* and ocean basin formation between two separated pieces of continental lithosphere. A rift that did not lead to continental separation remains preserved within the continent as a failed rift or *aulacogen*.

Two rifting modes have been envisioned, which refer to the role of the asthenosphere (Figure 4). The “mantle-activated” or “active” mechanism considers rifts to be initiated by mantle *plumes* or diapirs. The rising asthenosphere bends the lithosphere about a large dome, on top of which radial fractures bound rifts. The alternative “lithosphere-activated” or “passive” mode attributes rifts to lithosphere extension under tectonic forces. These two modes are distinguished in their initial stage, plume-generated rifts beginning with doming and abundant volcanism, while passive rifts begin with narrow grabens of clastic sedimentation and younger, limited volcanism. In addition, active rifts tend to be symmetric above the vertically rising asthenosphere, whereas the mechanical response of a stretched lithosphere generates rather asymmetric systems. The East African rift has been considered to be typically mantle-activated, and the Baikal and Rhine Grabens to be lithosphere-activated. Passive rifts may evolve into active rifts by the upward intrusion of the asthenosphere into the necked lithosphere.

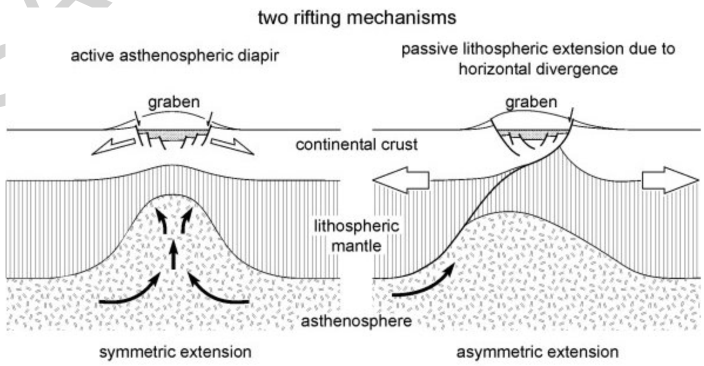

Figure 4. Extension mechanisms based on the active or passive role of the asthenosphere. Half arrows in the active mode point to outward plate movement

imposed by the intruding asthenosphere. Large arrows in the passive mode represent far-field tectonic forces.

2.1.2 Passive Continental Margins

The natural evolution of a divergent plate boundary is recorded along the rifted, split, and spread apart margins of an original continent.

Stretching and thinning of the continental lithosphere at the margins of the two new continents results from initial rifting followed by extensive and continued normal faulting, often on listric faults in asymmetric systems (Figure 5). These concave, upward faults merge into or are cut by a flat *detachment*, on which extreme extension takes place. In the hanging wall of this master fault, sediments are generally deposited directly on tilted and eroded basement blocks, forming a profound unconformity. Synsedimentary faulting is common. Distance from the earth's surface to the top of the asthenosphere is steadily reduced as stretching proceeds. Alkaline igneous intrusions are common at that stage. Ultimately, the lithosphere is stretched and thinned to a point of rupture, permitting break-up of the continent, along with intrusion and extrusion of basaltic magma through the stretched lithosphere, creating new oceanic lithosphere. Oceanic lithosphere continues to crystallize in the developing separation zone between the adjacent diverging plates. Hence, a new and continually enlarging ocean basin forms at the site of the initial rift zone. Oceanic crust is welded directly onto continental crust. The mixture of original continental rocks and the added oceanic component at the continental edge produces a hybrid *transitional* crust. The thermal input is so important during the initial rifting stage that margins of the rifted continent are buoyantly uplifted.

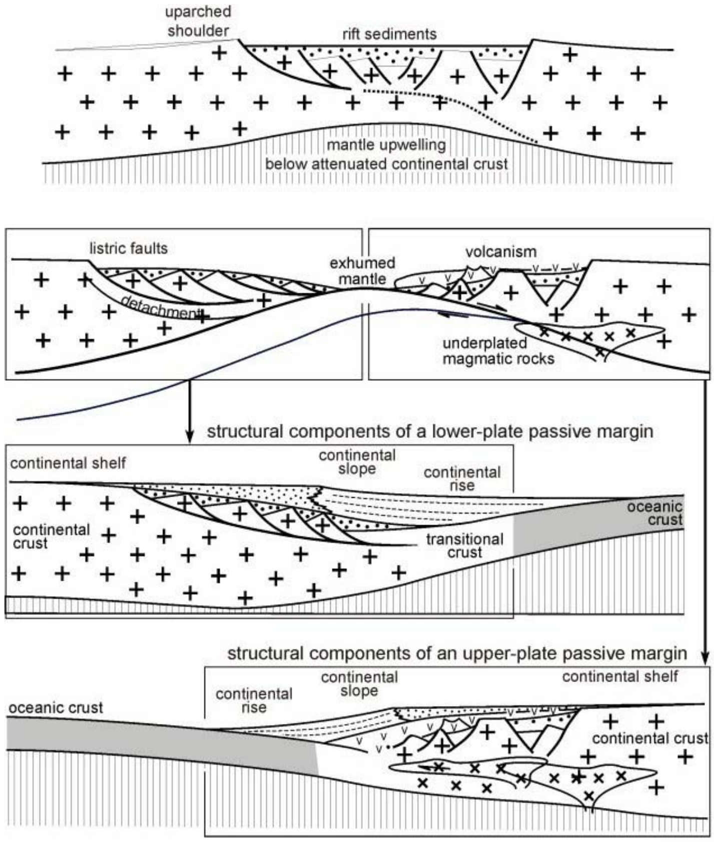

Figure 5. Structural components of extensional systems and idealized evolution from continental rifting to passive margin

The edge of the continent is a *passive margin* in that stresses are no longer deforming it (reference examples are the Atlantic margins). Structures and rock associations of the rifting phase are frozen into rocks of the continental margin, and they are passively conveyed laterally along with the rest of the plate to which they belong. The two continental margins become further away from the hot spreading center, and they cool down. Colder crust is denser, so the edges of the continental crust gradually subside below sea level; a non-mechanical process termed *thermal subsidence*. A *pericontinental sea* forms on the continental shelf. Shallow marine conditions may spread far over the continent to form an *epicontinental sea* (for example, the North Sea).

Passive margins include three main parts (Figure 5):

- A coastal plain and a submarine *continental shelf* of variable width (from a few kilometers—for example, Corsica—to over 1000 km—as in north-western Europe). They are generally underlain by a thick sequence of shallow-water mature clastic or biogenic sediments.
- The *continental slope*, at the edge of the continental shelf, which is generally present at the point where the shelf passes into a steeper topographic slope (3–5°) towards the basin.

- The *continental rise***,** which links the ocean basin to the continental slope. A relatively thick sequence of sediments is generally present along the continental rise and slope.

Massive subsidence (up to 10–15 km) of the passive continental margin takes place as the attached oceanic lithosphere cools off. Most sediments on Earth lie on passive margins, which, therefore, contain more than half the world's oil reserves.

2.1.3 Ridges: Plate Divergence in Oceanic Settings

The present day divergent plate boundaries reside mainly in oceans where they form broad, fractured swells, generally more than 1000 km wide. The prominent physiographic expression is a world-encircling, approximately 100 km wide, and symmetrical topographic relief that rises up to 3000 m higher than the average ocean floor. It does so because the young lithosphere is hot and, therefore, less dense than the older and colder adjacent oceanic lithosphere. It is called the *ocean ridge system*. The dynamically active part of the system is restricted to a prominent axial rift valley that actually marks the plate boundary. Within a rift no wider than 20–30 km, the opening between diverging plates is continuously filled in by igneous intrusions of olivine tholeiite magma. New oceanic lithosphere is created by the combination of intrusion of mafic igneous rocks, extrusion of basaltic lavas interlayered with oceanic sediments, and extensional faulting. When cooled and crystallized, the intrusions and freshly accumulated *mid-ocean-ridge-basalts* (so called MORB) and sediments become part of the moving plates. They constitute new additions to the lithosphere. Accordingly, plate boundaries along oceanic ridges are also called *constructive boundaries*. As new crust forms, it continually spreads away from the ridge. This is termed *accretion*. The characteristics of a mid-oceanic ridge depend on its spreading rate. Slow ridges (such as the Atlantic) are higher and have more rugged topography than the fast ones (for example, the East Pacific Rise).

In response to changing tectonic conditions, a ridge may grow or propagate into an adjacent plate. Whole sections of a ridge may "jump" to form a new rift parallel to the existing ridge.

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Biographical Sketch

Jean-Pierre Burg ,has been full Professor (ETH/University of Zurich) at the Institute of Geology of the ETH Zurich since September 1, 1993.Prof. Burg was born on April 25, 1953 in Meknès, Morocco, and is of French nationality. He received a scholarship from the British Council, which enabled him to study as a graduate student at Imperial College of Science, Technology, and Medicine in London from October 1975 to July 1976. From 1979 to 1983 he did scientific research at the French CNRS. His dissertation was honored with great distinction by the USTL Montpellier in May 1983. In November 1983 he assumed a post as research fellow at Melbourne University. In March 1986 he was appointed Research Director at the CNRS Center for Geology and Geophysics in Montpellier—a post he held until he was called to the ETH. Prof. Burg has many editorial responsibilities. He has been chief editor of Geodinamica Acta and Géologie de la France, and is now one of the chief editors of Tectonophysics. His dedication merited the Australian Society of Educational Technology Award in 1986. He was awarded the Prix Henri Becquerel from the Academy of Sciences in Paris on November 26, 1990. On the decision of the Sofia University Council, Prof. Burg received the Blue Ribbon award from Sofia University in May 1995. In 1999 he was offered a Japan Society for the Promotion of Science fellowship for research.