PLATE TECTONICS AND LANDFORM EVOLUTION

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Keywords: plate tectonics, extension, compression, strike-slip faulting, tectonic regimes, mountain building, basin formation.

Contents

Summary

The movement and deformation patterns of the Earth's surface have been successfully explained by the concept of plate tectonics. The Earth's lithosphere layer is divided into several "plates" that move with respect to each other due to thermal convection. Lithospheric plates comprise either only oceanic, or both oceanic and continental crust. New oceanic basins originate by rifting and breakup of continental lithosphere. At the consecutive divergent boundaries, the plates are moving apart and a new oceanic lithosphere is produced by the mechanism of sea floor spreading. The oceans decline at the convergent plate boundaries, where the dense oceanic lithosphere sinks and is recycled back into the mantle in subduction zones. As the lithospheric plates move, continents drift passively. After the diminishing of an oceanic domain, its former continental margins come into collision, since the continental crust is not prone to

subduction. Continental collision is the principal mechanism of orogeny and mountain building. At the transform (conservative) plate boundaries, the lateral strike-slip component of the relative motion of two plates dominates over the convergent or divergent component.

Lithospheric plates are parts of the Earth's convection system and the plates themselves generate the forces that drive their motion. Subduction slab pull is a negative buoyancy force produced by a cold and dense oceanic lithosphere sinking into the mantle. The slab pull is counteracted by collision resistance triggering orogenic deformation along the convergent plate boundaries. Plates are also driven by the ridge push force originating at the divergent boundaries.

Spatial and temporal variability of the qualities and magnitudes of stress fields within the Earth's crust is expressed by changing tectonic regimes that control the surface landscape forms and their evolution. Extensional tectonic regimes are primarily associated with divergent plate boundaries, but can also commonly be found in plate interiors in the form of localized rift zones and extensional basins. Another widespread setting for extensional tectonics are upper plates above subduction zones subjected to back-arc extension. Rifting and extension generates crustal thinning: normal faulting and elevated heat flow that collectively account for the surface subsidence and sedimentary basin formation. Compressional regimes predominantly surround the convergent plate boundaries. The rise of high mountain ranges is triggered by crustal thickening due to thrust stacking. The strike-slip tectonic regime produces wide or localized subvertical fault structures that are marked by high seismic activity.

1. Introduction

The processes that shape the Earth's surface and govern the evolution of landforms are generated by forces classified as either external, or internal with respect to the solid Earth's body. The external (exogenous) forces include weathering of rocks, their erosion, transport by fluid media, and deposition in morphological depressions; that is, they have a tendency to diminish the morphological contrasts on the Earth's surface. The internal (endogenous) forces arise from thermal and gravitational instabilities within the solid Earth that are slowly liberated by mass movements of the Earth's matter. The uppermost stiff layer of the Earth, the lithosphere, is split into large plates that move with respect to each other, sliding on a weak asthenosphere below to produce deformation of the Earth's crust and to create all the positive and negative morphological forms at the Earth's surface.

The present chapter provides an introduction to plate tectonic theory and describes the main deformation patterns of the Earth's crustal material influencing the surface morphology and landforms.

2. Plate Tectonics and Orogeny

The concept of "plate tectonics," or "new global tectonics," was formulated in the 1960s and has since become a tectonic paradigm. In spite of many uncertainties, there is a general belief that it can account for nearly all aspects of the evolution of continents and

oceans during the Earth's history. The main notions that characterize the principles of plate tectonics are continental drift, sea-floor spreading, oceanic crust subduction, and motion of lithospheric plates.

2.1. Birth of the Theory

It was Alfred Wegener, a German-Austrian astronomer and meteorologist, who envisaged the plate tectonic concept by formulating the hypothesis of continental drift at the beginning of the twentieth century. In his notable book *Die Entstehung der Kontinente und Ozeane* (1915), and in its numerous re-editions, he presented a total of 65 lines of evidence in favor of the existence of an ancient continent called Pangaea which split into Laurasia and Gondwana and then into the modern continents. His proofs came from geology, geodesy, biology, paleontology and climatology, and most of them are still valid. He was inspired, like his ancestors F. Bacon, T. C. Lilienthal, A. von Humboldt, A. Snider, W. H. Pickering, and F. B. Taylor, by the remarkable fit of the American and European-African coasts of the Atlantic Ocean. Unfortunately, there was no reasonable dynamic explanation for his views at that time and seemingly little evidence in the geological structure of continents. Therefore, Wegener's ideas were not treated seriously in the subsequent decades, with the exception of A. DuToit's book *Our wandering continents* (1937) and A. Holmes' treatise *Principles of Physical Geology* (1944, 1965). Holmes also found a plausible mechanism for the horizontal movements of the Earth's crust—convection currents in the Earth's interior. Nevertheless, the governing geosynclinal paradigm at that time postulated the Earth's global contraction to be the main driving mechanism for deformation of the Earth's crust, and all hypotheses assuming horizontal extension and continental drift were rejected.

A great impetus to renew Wegener's hypothesis came from investigations of the geological structure of oceanic bottoms and continental margins in the 1950s and 1960s. Through the study of magnetic anomalies in rocks of the oceanic crust, it was confirmed that continents could move apart by the mechanism of sea floor spreading. This means that a new oceanic crust is continuously generated from molten mantle material advecting below mid-oceanic ridges, and progressively ages during its retreat from the ridge, the crust adjacent to continental margins being the oldest. Thus, the portions of the oceanic crust from the opposite margins of, for example, the Atlantic originated at the same time in the past and, consequently, these margins were adjacent to each other at that time. This information confirmed Wegener's ideas, despite the fact that the mechanism generating continental drift appeared to be different.

Because the Earth has had a more or less stable radius throughout its existence, sea floor spreading must be compensated for by the destruction of the crust out of the ridges. By studying focal mechanisms of deep earthquakes, it was found that in places where continental margins are rimmed by deep-sea trenches, the earthquake foci indicate the sinking of oceanic crust below the continental crust. Consequently, trenches are interpreted as areas of sea floor consumption—subduction, maintaining the general balance between the production and reduction of the oceanic crust.
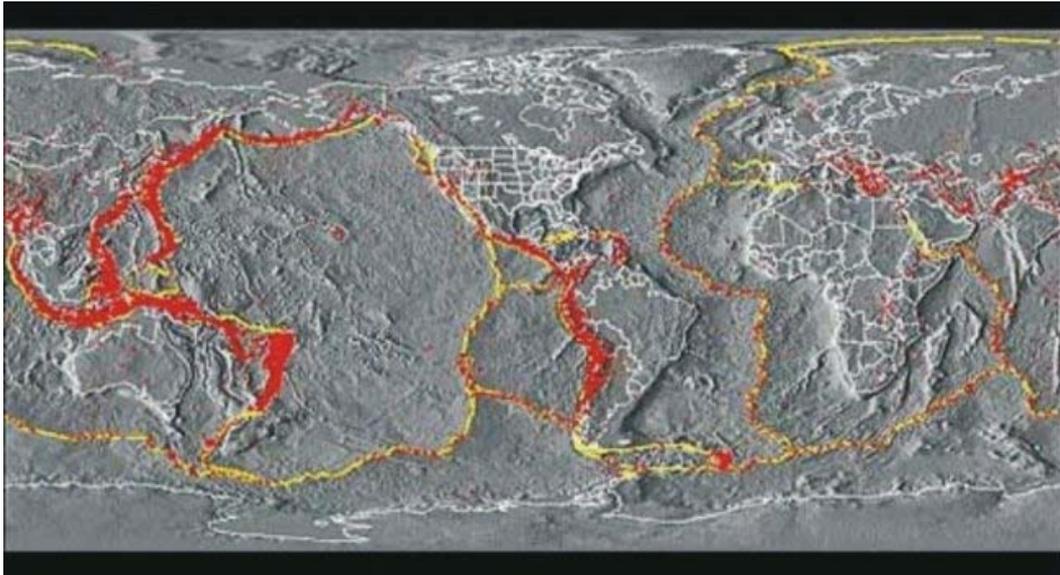
Figure 1. Global land 1 km base elevation (GLOBE) shaded relief with earthquake epicenters delineating the belts of recent seismic activity in the world. Compare to Figures 2 and 3 to see the confinement of active zones to the plate boundaries. Image and data from the National Geophysical Data Center, Boulder, Colorado.

2.2. Lithospheric Plates

The most pronounced consequence of thermally driven mass movements on the Earth is the motion of lithospheric plates. Distinguishing the lithospheric plates was probably the main achievement of the revolution in geosciences in the 1960s, which ultimately led to the formulation of the plate tectonics paradigm. The distribution of lithospheric plates on the Earth's surface is clear from first glance at a world map on which active volcanoes or earthquake epicenters are depicted. These concentrate in long and mostly narrow, more or less continuous strips that irregularly wriggle around the Earth's globe, marking the plate boundaries (see Figures 1 and 3). The large areas with obviously weaker seismic and volcanic activity belong to the plate interiors. Lithospheric plates comprise either only oceanic, or both oceanic and continental crust. There are fifteen principal plates distinguished (Figure 2): Eurasian, African, Arabian, Indian, Australian, Antarctic, North American, Caribbean, South American, Scotia, Nazca, Cocos, Juan de Fuca, Philippine, and Pacific. There are also several smaller plates, or "microplates," whose independence from large plates is limited, however. Some of the plate boundaries are not very sharp and distinct, being diffused into broad zones of deformation (see Figure 3). The number of plates and their dimensions, movement directions, and velocities have been continuously changing throughout the Earth's evolution. Nevertheless, the spatial position of some plate tectonic features, e.g. the circum-Pacific subduction system, appears to be quite stable over long periods of time.
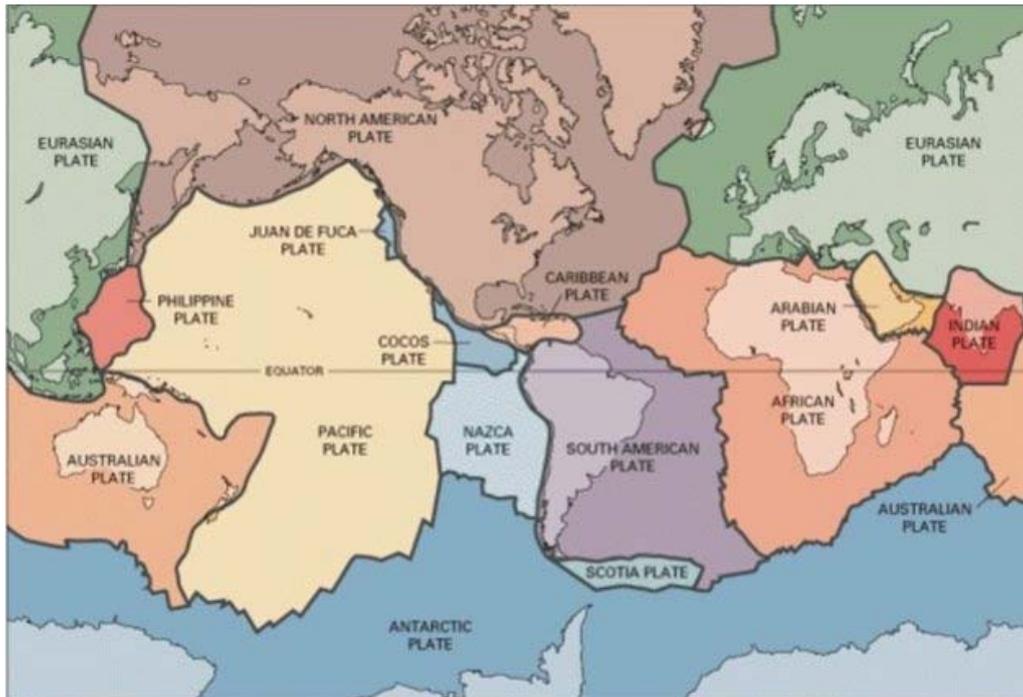
Figure 2: The distribution of the principal lithospheric plates. From the online edition of the book *This Dynamic Earth: The Story of Plate Tectonics,* by W. Jacquelyne Kious and Robert I. Tilling, USGS. Courtesy of USGS, available at http://pubs.usgs.gov/.

Plates are continuously moving with respect to each other with velocities reaching several centimeters per year—which is approximately the growth speed of our hair or nails. The velocity of a particular plate does not depend on its dimensions, but rather on its composition: plates including only oceanic crust move more rapidly compared to plates which also involve continental crust. As the plates are moving in different directions, they produce boundaries of three types: divergent, convergent (both of which are usually oblique), and transform (Figure 3).
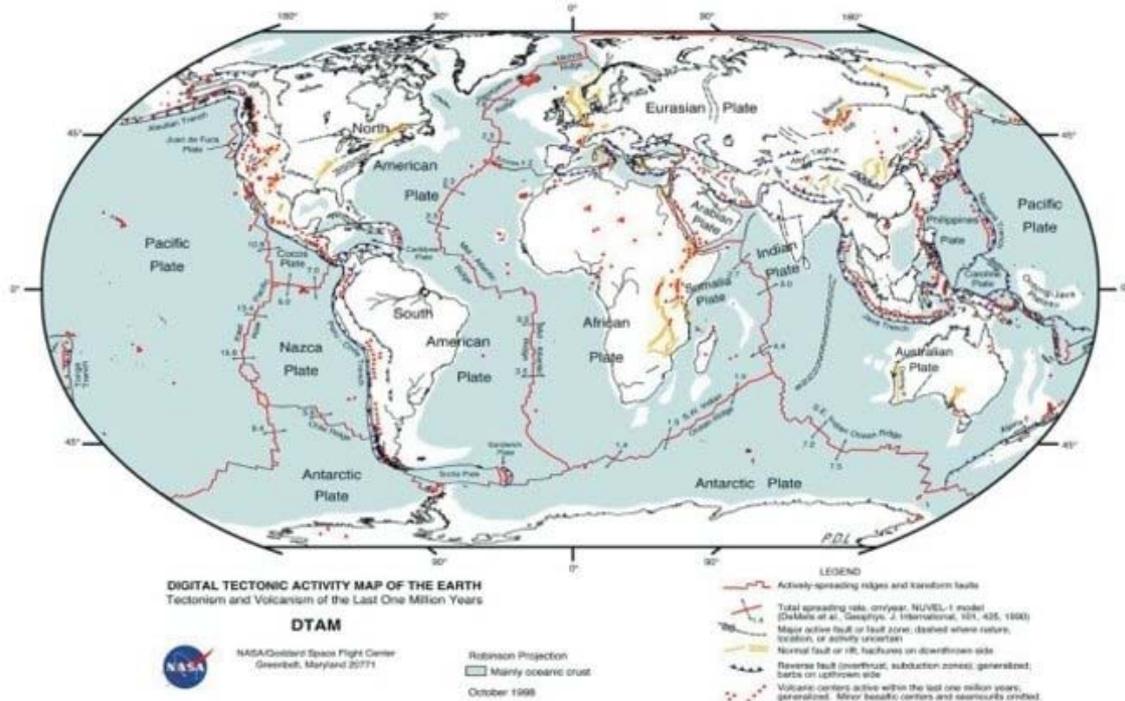
Figure 3: The main tectonic elements of the Earth's surface – lithospheric plates, character of their boundaries, some important intra-plate tectonic elements and recently active volcanoes. After Lowman P., Yates J., Masuoka P., Montgomery B., O'Leary J. and Salisbury D. (1999). A digital tectonic activity map of the Earth. *Journal of Geoscience Education* 47, 428–437. Used with permission. Also available at http://denali.gsfc.nasa.gov/dtam/.

At the divergent (constructive) plate boundaries, plates are moving apart by the mechanism of sea floor spreading. Hot and buoyant asthenospheric melts rise below linear spreading centers, then cool and accrete to either side of plates that split apart (Figure 4). Magma is constantly delivered from the mantle and spreading centers are sites of shallow and weak but frequent seismicity, and widespread though mostly submarine volcanism (see Figures 1. and 3.). This is the principal way in which a new oceanic lithosphere is produced. Because of the buoyancy of magma and young oceanic crust, the spreading centers create positive morphological forms, known as mid-oceanic ridges. As the oceanic lithosphere cools during its movement away from the ridge, it becomes thicker and denser. Consequently, the ocean floor depresses to abyssal depths. This might be well illustrated by the hypsographic map of the Atlantic Ocean—the abysses next to the continental margins of America and Africa reach depths in excess of 6000 meters, while the well-developed mid-Atlantic ridge rises above the sea level in places (e.g. Iceland).

New oceanic basins are generated by the process of rifting of the continental lithosphere (Figure 4). Due to enormous tensional forces, the continental lithosphere may break away at long and narrow rift valleys that progressively develop into young oceans. The Earth provides examples of oceanic basins at various stages of their "life." The East African rift system is just a baby, while the Red Sea is already a teenager. The Atlantic is a well-grown middle aged person, the Pacific is a still powerful whitebeard, but the

Mediterranean lies on its deathbed, and all collisional orogens are cemeteries of ancient oceans. Continental rifting produces plates that involve both the oceanic and continental lithospheres. In this case the intra-plate boundary between the continent (with its shelves) and the ocean is designated as the passive continental margin (or Atlantic type margin).
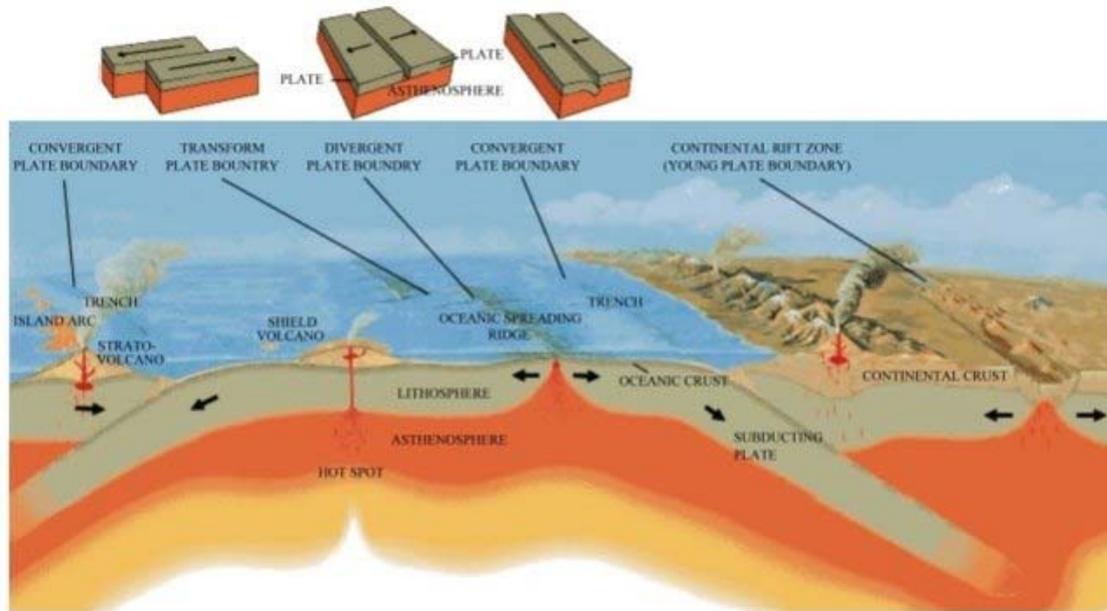

Figure 4: The plate tectonics framework. Cross-section by José F. Vigil from "This dynamic planet". A wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory. Courtesy of USGS.

The oceans decline at convergent (destructive) plate boundaries. The dense oceanic lithosphere is insulated from the Earth's surface; it sinks and is recycled back in the mantle in subduction zones. These are inclined generally in the movement direction of the subducting plate, i.e. under the overriding neighbor plate. Submerged parts of oceanic plates going down into the mantle are called slabs. If the overriding plate consists mostly of continental material, the plate boundary is designated as an active continental margin (or Andean type margin). Active margins are preferred sites of mountain building and active tectonism (Figures 4 and 10).

The subduction process has dramatic consequences for the behavior of convergent plate boundaries. The overriding plate, in particular, is strongly deformed, giving rise to the seismically and volcanically most active belts on the Earth. The well-known circum-Pacific "Ring of Fire" follows the subduction zones of the Pacific and related plates, being a place of severe disasters that constantly jeopardize residential population (Figure 5). The reason is that the sinking oceanic slab frictionally slides along the boundary fault with the upper plate. The friction is temporarily relaxed by earthquakes (see *Internal Forces and Their Influence on the Earth's Surface*). Some of the earthquakes are deep and exceptionally strong, so they can catastrophically affect large areas. Fluids released from the descending plate help to melt the overriding plate and generate extensive volcanism, which occurs in narrow long belts next to the subduction

zones that are known as volcanic island arcs (Figure 9). Some subduction zones are accompanied by extension of the upper plate behind the arc. These are marginal, or back-arc basins usually floored by the oceanic type of crust (e.g. the Japanese Sea).
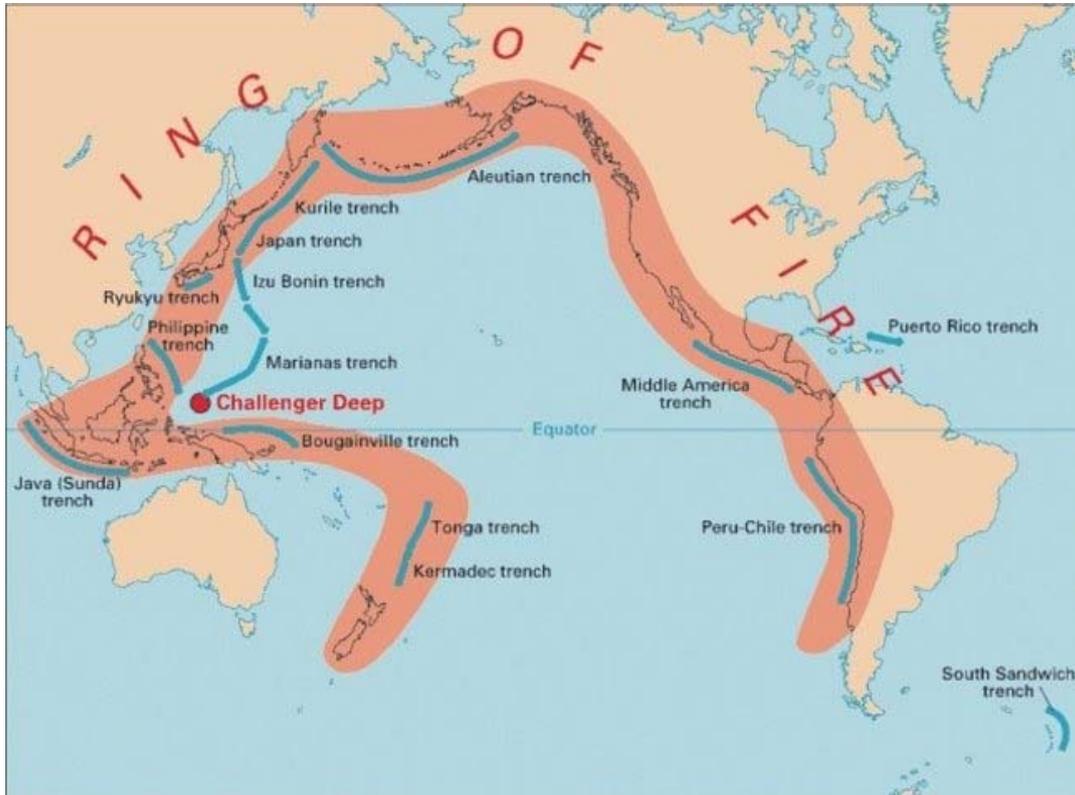

Figure 5: The Ring of Fire. From the online edition of the book *This Dynamic Earth: The Story of Plate Tectonics,* by W. Jacquelyne Kious and Robert I. Tilling, USGS. Courtesy of USGS, available at http://pubs.usgs.gov/.

The convergent plate boundaries are sites of long-term plate interaction. Deformation associated with this interaction leads to the development of long and comparatively narrow mountain belts that follow the destructive plate boundaries (e.g. the American Cordilleras and the Andes—Figures 4. and 10.). This type of orogeny is designated as activation orogeny (or Cordilleran type orogeny). The nature of tectonic forces associated with activation orogeny depends on the degree of locking, or cohesion, along the subduction fault. If the fault is locked, compressive stresses, crustal thickening, and mountain uplift are generated in the upper plate. If the fault is unlocked, tensile stresses prevail, the overthickened crust collapses and mountains of the basin-and-range type develop. (See *Internal Forces and Their Influence on the Earth's Surface.*)

At the transform (conservative) plate boundaries, the lateral strike-slip component of the relative motion of two plates dominates over the convergent or divergent component. Transform boundaries longer than 1000 km are relatively uncommon, with the exception of the transform faults segmenting the mid-oceanic ridges. Nevertheless, large active strike-slip faults, either inter-plate or intra-plate, often generate catastrophic

earthquakes. Examples are the San Andreas Fault in California (see Figure 6), the Alpine Fault of New Zealand, or the North Anatolian Fault in Turkey.
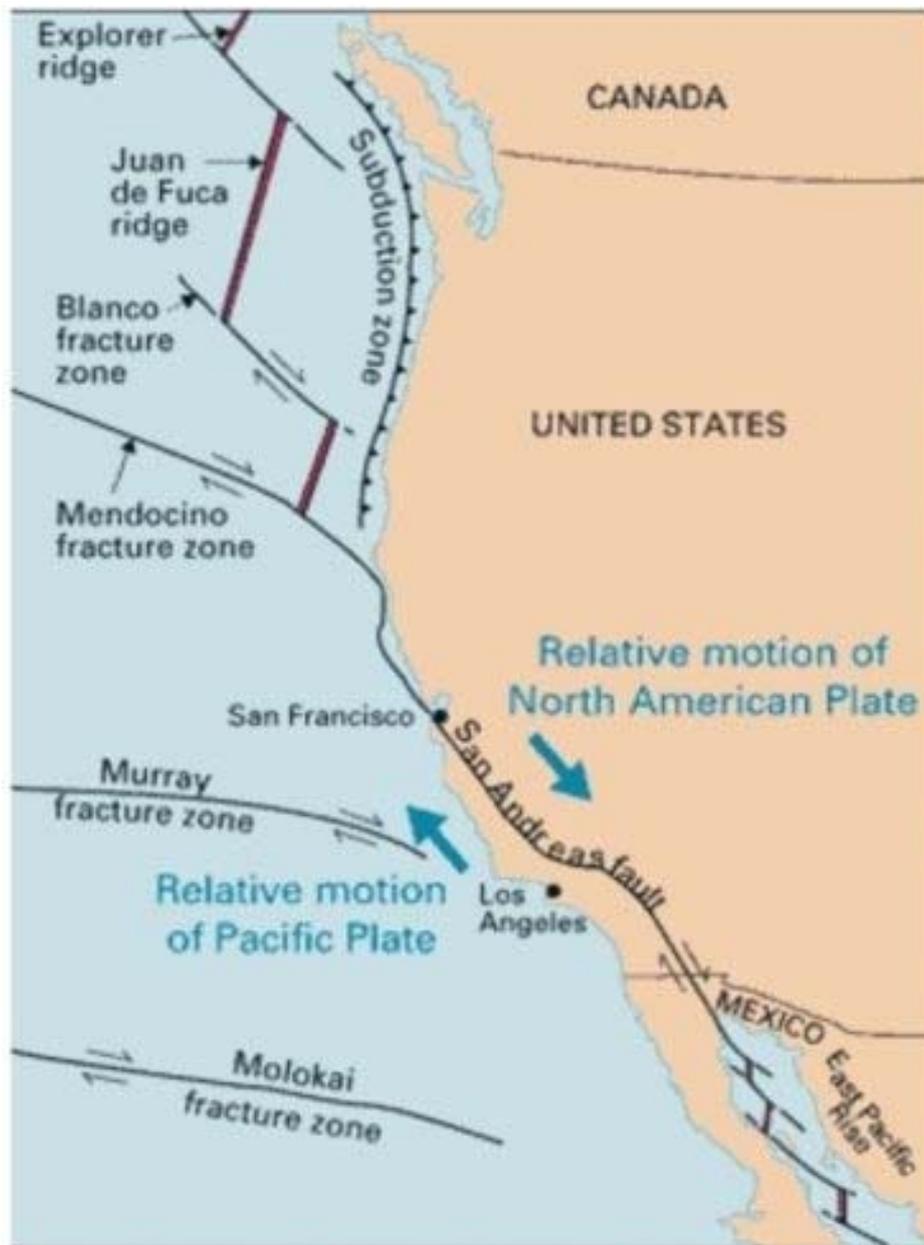

Figure 6: A complex system of plate boundaries along the western coast of North America. The San Andreas transcurrent fault system connects the obliquely spreading Juan de Fuca and Gulf of California ridges segmented by several transform fracture zones. From the online edition of the book *This Dynamic Earth: The Story of Plate Tectonics,* by W. Jacquelyne Kious and Robert I. Tilling, USGS. Courtesy of USGS, available at http://pubs.usgs.gov/.

Three plates meet at a triple junction. Theoretically, ten types of triple junction might exist: RRR, RRF, RRT, RFF, RFT, RTT, TTT, TTF, TFF, FFF, where R stands for ridge (divergent boundary), T for trench (convergent boundary) and F for transform

fault. However, RRR, RTT and TTT are in fact the most common types of triple junctions.

2.3. Driving Forces

As has already been mentioned, all lithospheric plates are in continuous relative movement. Although the kinematics of this movement are comparatively well known, its dynamics, i.e. mechanisms and energetic sources, are not so well understood. The principal question is the nature of plate driving forces. There are two fundamentally different views on the character of these forces. The difference is rooted in two opinions concerning the mechanical relationship between the lithosphere and the sublithospheric mantle. The first opinion suggests effective coupling at the base of the lithosphere; therefore the convection currents in the deeper mantle should directly govern the plate motion through the drag force exerted at the base of the lithosphere. This view is in line with the early concepts of whole-mantle convection, in which the dimensions of convection cells correspond to the extents of lithospheric plates. Thus the divergent plate boundaries occur above hot ascending convection currents, while subduction zones relate to cool descending currents. (See *Internal Forces and Their Influence on the Earth's Surface*)

However, this logic was questioned when the model of layered mantle convection was proposed. The reason behind the latter model is that the convection cells in the upper mantle are substantially smaller than the large plates. This involves decoupling at the base of the lithosphere and allows the possibility that it may move independently with respect to the mantle convection currents. In addition, plate kinematics strongly support the free movement of lithospheric plates. The spreading centers appear to be passive structures, which migrate apart during splitting of continents, and can even be subducted. Trenches migrate as well and the distances between ridges and trenches have been continuously changing during geological history. Partly molten asthenosphere, which enables decoupling, is omnipresent below the oceanic plates and is often missing below the Archean cores of continents. Accordingly, the convection currents should preferably drive the continental plates; yet the plates dominated by oceanic lithosphere in fact move with velocities nearly one order of magnitude higher than plates composed mostly of continental lithosphere (7–10 and 1–3 cm per year, respectively). These observations imply that the basal drag force can even be a negative, i.e. resistive, force that hampers plate movement.

There is now general agreement that no single force can provide an explanation of all the complexities in plate movements and deformation. Plates are parts of the Earth's convection system and the main driving forces are generated by the plates themselves. These are designated as the plate boundary (edge) forces. They fall into two categories—the driving and the resistive forces. We distinguish ridge push, slab pull, and trench suction as the driving forces. Friction at transform faults, and collision and subduction resistances impede the plate motions.

Subduction slab pull is a negative buoyancy force produced by a cold dense oceanic lithosphere sinking into the mantle by its own weight. It acts on a subducting plate and generates tensional stresses, provided that it is not eliminated by the subduction

resistance, which is a viscous opposition of the mantle against the plate penetration. The slab pull, which could effectively drive plates dominated by oceanic lithosphere that have long subduction boundaries, is also counteracted by collision resistance—a force that couples the sinking and overriding plates along the subduction fault. However, if the hinge of the subducted plate retreats from the subduction zone in the direction opposite to the plate movement (a process called roll-back), it decouples from the overriding upper plate and exerts a tensional force on its edge, which is termed trench suction. This suction may drive smaller plates or rifted-off fragments of larger continental plates. It also provides a plausible mechanism for the origin of back-arc basins.

Plates dominated by the oceanic lithosphere are driven also by the ridge push force. This is a net force arising from the positive buoyancy of hot and comparatively light asthenospheric material ascending below the mid-oceanic spreading centers, from the gravitational potential of the topographically elevated ridges and from the negative buoyancy of oceanic lithosphere as it cools, thickens, and weights away from the ridge. The ridge push exerts compressive stresses on both diverging plates and helps to move plates apart from the spreading boundaries. It is reduced by the transform fault resistance—a force caused by frictional drag along the strike-slip faults segmenting the mid-oceanic ridges.

The direction and velocity of movement of every plate is controlled by the net influence of all applied forces. Calculations assuming the dynamic equilibrium of all plate boundary forces indicate that the present global system of plate motions is principally governed by the slab pull force, which is one order of magnitude higher than any other force. However, this force obviously cannot drive plates which are not attached to any subducting slab (e.g. the Eurasian plate). On the other hand, it probably accounts, along with the ridge push, for the high velocities of oceanic plates bounded by both divergent and convergent boundaries with unidirectional polarities. It is quite possible that the plates involving large continents and bounded only by divergent boundaries (or convergent in the upper-plate position) are principally driven by the ridge push, and perhaps also by the mantle drag force.

2.4. Continental Collision

Under special circumstances, the consumption of oceanic lithosphere exceeds its production within a particular plate. This may occur when a spreading center is subducted, or when a new spreading center originates by continental rifting behind a continental fragment that approaches a convergent boundary. In this case, the oceanic lithosphere is diminished and the passive continental margin of the consumed plate gradually advances toward the active margin of the overriding plate. Finally, after complete consumption of the oceanic lithosphere, the two margins come into continental collision (Figure 11). Collisional orogeny (or Himalayan type orogeny) is responsible for the formation of the largest mountain belts in the world, such as the Alps and Himalayas. Likewise, many other ancient mountain belts which are now almost leveled—e.g. the Appalachians or the Urals—are vestiges of old collisional orogens.

Collisional orogens are an expression of continuing convergence after the diminishing of the oceanic domain between two continents. Shortening of the continental crust, which has been detached from the mantle lithosphere, leads to its considerable thickening. Consequently, the light thickened crust isostatically rebounds by surface uplift, and the mountains rise.

The main plate tectonic processes described above occur in a regular succession called the Wilson cycle. The complete Wilson cycle partially corresponds to classically defined Phanerozoic orogenic cycles, such as the Caledonian, Hercynian (Variscan), or Alpine cycles. The cycle starts with a continental rifting (as in the present East African rift, Dead Sea, Baikal rift, Rhine graben), followed by a continental breakup (the Red Sea, Gulf of Aden, Gulf of California), oceanic rifting and spreading (the Atlantic, Arctic, Indian, Pacific Oceans), oceanic subduction (the Indian and Pacific Oceans), and gradual oceanic closure (the Mediterranean Sea), ending with oceanic suturing and continental collision. The greatest continental collisional system of the present begins at the Straits of Gibraltar and ends in New Guinea, comprising tremendous mountain belts, such as the Betic Cordillera, Pyrenees, Apennines, Alps, Carpathians, Dinarides, Balkans, Hellenides, Taurides, Pontides, Caucasus, Zagros, Himalayan system, Indo-Chinese mountains, and the Indonesian archipelago. These mountain belts originated after the closure of an ancient ocean called Tethys. The last relic of the Tethys Ocean is the eastern part of the Mediterranean where it diminishes by subduction beneath the Aegean arc. However, evidence of the Tethys Ocean is also present within the orogens in the form of fragments of its crust, which was not subducted but incorporated amidst the continental material of former oceanic margins. Dismembered oceanic crust remnants are designated as ophiolites and usually occur disconnectedly along a narrow but long belt—an oceanic suture, which marks the position of the former ocean. In places, the ophiolite complexes form large coherent units, which were emplaced by the process of obduction.

The structure of a collisional zone depends on numerous factors. Foremost among these are the proportions of the colliding blocks. The overriding continental block is usually large and comparatively stable, while drifting blocks which collide with the active margin may have various dimensions and compositions. Smaller blocks with dimensions substantially less than the overriding plate include fragments of the continental lithosphere, active or inactive oceanic ridges and plateaus, isolated seamounts, carbonate platforms, faded volcanic island arcs etc. Since these blocks are not usually prone to subduction, they are accreted to the edge of the overriding plate and the subduction zone relocates from their leading to the trailing edges. In cases when the subduction zone is active for a long time, it temporarily brings numerous such blocks to the active margin. Here, they amalgamate with the upper plate to form an accretionary orogen—a type of orogen that bears characteristic features of both activation and collisional orogenies. The extraneous blocks are named suspect terranes (exotic or allochthonous terranes, xenoblocks), as they sometimes cardinally differ from the neighboring blocks in their composition and tectonostratigraphic evolution. Due to permanent compression on an active margin, the suspect blocks prolong their movement past each other along major strike-slip faults after accretion, too (displaced terranes). An accretionary orogen is therefore a complex collage of coherent and dismembered blocks and wrench zones that juxtapose units of various provenances and tectonic histories.

The circum-Pacific orogens are typical examples of accretionary orogens. Figure 7 shows some large suspect terranes that constitute the North American Cordilleras.
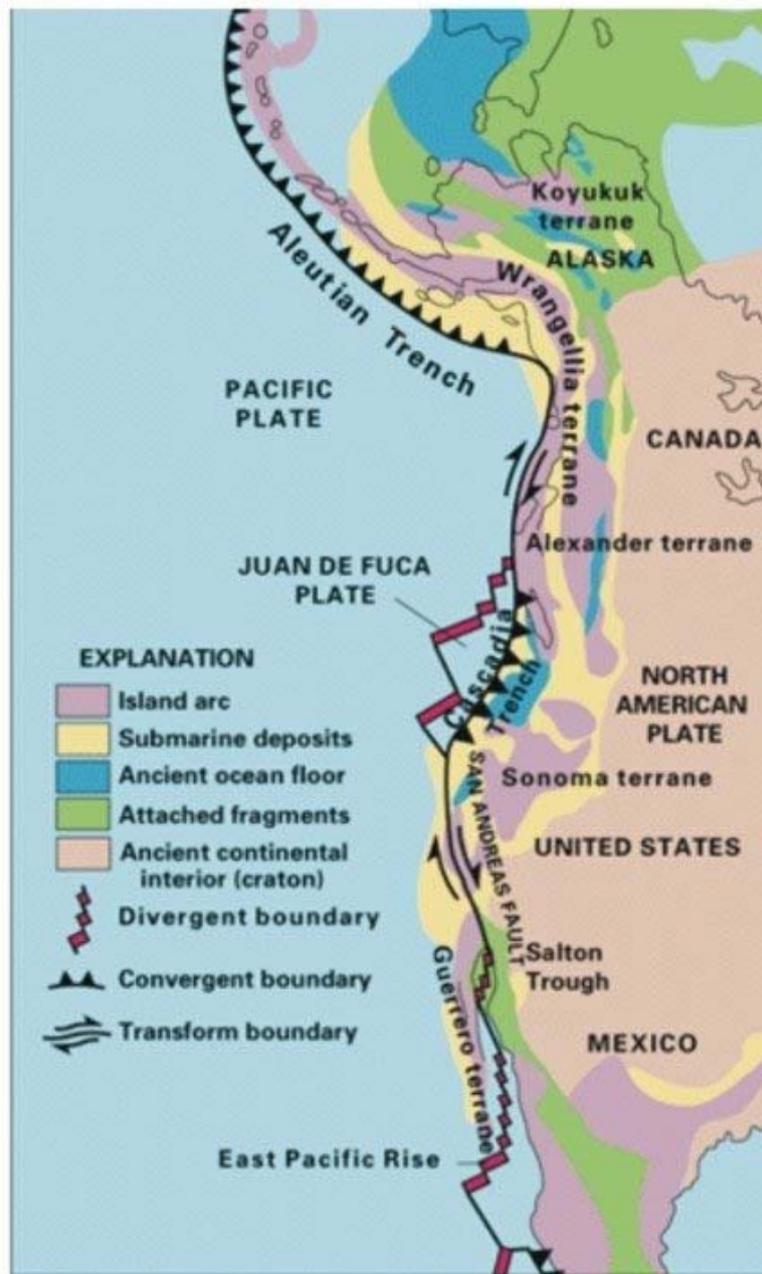

Figure 7: The most important exotic terranes of the North American Cordilleras. Modified from illustration provided by *Oceans* magazine; original figure by Jack Cook, Woods Hole Oceanographic Institution. From the online edition of the book *This Dynamic Earth: The Story of Plate Tectonics,* by W. Jacquelyne Kious and Robert I. Tilling, USGS. Courtesy of USGS, available at http://pubs.usgs.gov/.

The origin of the Alps may exemplify a case history of a mountain belt generated by the collision of two large continental blocks during the Cenozoic. In this case, the lower plate (the North European platform) represents the relatively stable block. The drifting

block that collided with the passive margin of Europe was Adria (or Apulia)—an Africa-related microcontinent. The Penninic oceanic basins between these two continental areas commenced with the rifting of the post-Variscan platform during the Jurassic, and had reached a considerable width by the Late Cretaceous. The structure of this oceanic realm was rather complex. It embraced zones floored by an oceanic lithosphere (Ligurian-Piemont and Valais), separated by a continental ribbon (Briançonnais), and several other splinters of a continental crust within the oceanic domain. During the Late Cretaceous, the Penninic Ocean began to be subducted below the northern Adriatic margin and Adria gradually advanced towards Europe. When the southern, Ligurian-Piemont branch of the Penninic Ocean was diminished, the northern margin of Adria formed by the Austroalpine units collided first with the Briançonnais continental domain, during the earliest Tertiary. At that time, the northern, Valais Penninic branch was still open. During the Eocene the subduction was completed, and the southern passive European margin (represented by the Helvetic units) and the northern active margin of Adria came into collision. Though a large amount of lithospheric material was subducted during the convergence, the rest was not subductable and was instead stacked in a thick nappe complex (composed of the Helvetic, Penninic, and Austroalpine units), which was mechanically weaker than the bounding continental blocks. Consequently, the prolonged northward motion of Adria caused a strong deformation of this weak stack, leading to its uplift and the exhumation of rocks that were previously deeply buried. The mechanical boundary between the Central Alps and Adria, which is now exposed in the Southern Alps, is rather sharp, represented by the so-called Periadriatic lineament, a prominent fault structure of the Alps. Movement along this fault, both orthogonal and lateral, accommodated most of the additional advancement of Adria towards Europe.

The process of the penetration of stiff continental blocks into weak subduction-collision complexes, as described in the Alps, is called indentation. This means that Adria is an indenter. The Himalayas are another example of indentation tectonics. After the elimination of the Tethys Ocean between Asia and the drifting Indian continental block, the Himalayan mountain system resulted from the penetration of India into a collision complex at the Asian margin. However, in this case, the collisional margin of the Indian indenter was much more strongly deformed compared to the Adriatic indenter of the Alps, probably due to a more extensive (and still ongoing) convergence. While the total convergence between Adria and Europe is estimated at about 500 km, it amounted to more than 2000 km in the Himalayas, starting from the commencement of collision during the Early Tertiary only. If the supposed width of the Tethys Ocean is taken into account, the total shortening between Asia and India reaches several thousands of kilometers (Figure 8).
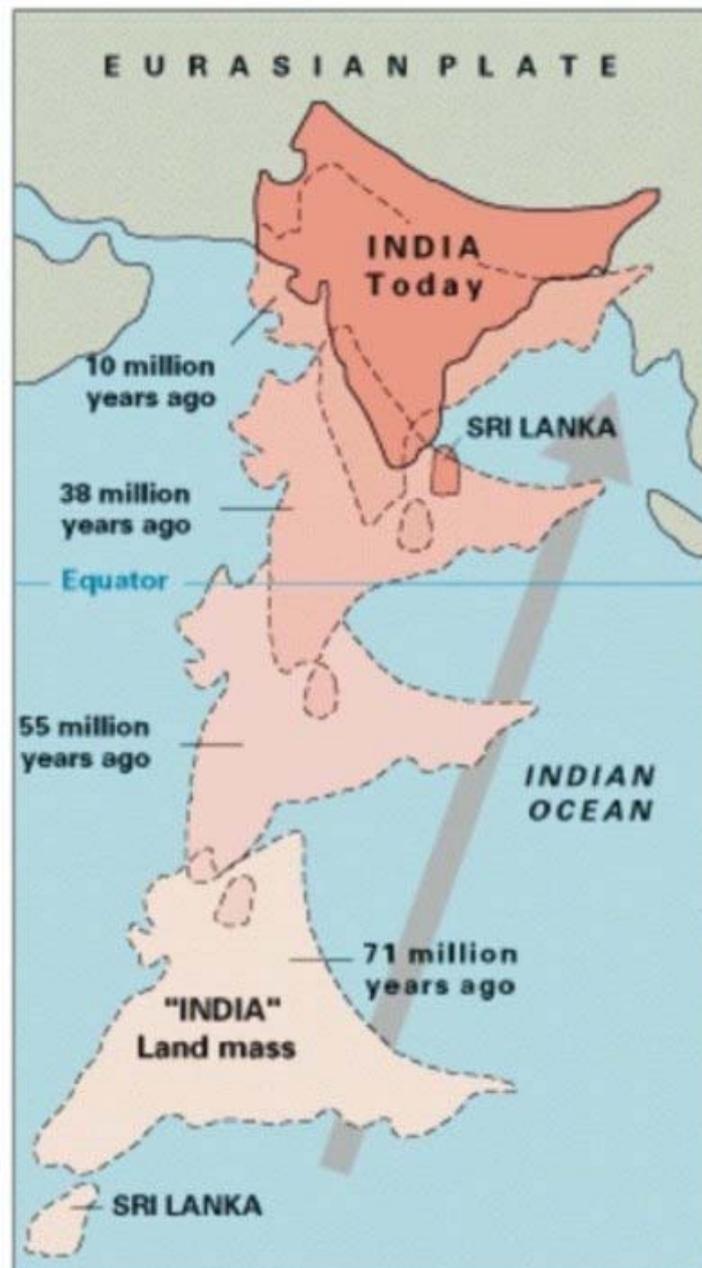
Figure 8: The drift of India towards the Eurasian continent. From the online edition of the book *This Dynamic Earth: The Story of Plate Tectonics,* by W. Jacquelyne Kious and Robert I. Tilling, USGS. Courtesy of USGS, available at http://pubs.usgs.gov/.

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Biographical Sketch

Dušan Plašienka grew up and completed his high school and university studies in Slovakia. He acquired the RNDr. title in 1979 and the CSc. degree (=Ph.D.) in 1981 at the Geological Institute of the Slovak Academy of Sciences in Bratislava, where he is still working as a Senior Scientist. His research interests include structural geology and regional tectonics of the central zones of the Western Carpathians. Since 1991 he has been giving lectures in regional geology of the Western Carpathians at the Comenius University in Bratislava and at the Masaryk University in Brno (Czech Republic). In 1998 he became an Associated Professor at the Comenius University. His international acknowledgements include chairmanship of the Tectonic Commission of the Carpatho-Balkan Geological Association, as well as membership of the International Association of Structural and Tectonic Geologists Committee and of the Editorial Board of the international geological journal Geologica Carpathica. He published one book and over 50 research papers in international and local geological journals and conference volumes.