

## TECTONICS AND GEODYNAMICS

**Grasmann, Bernhard**

*University of Vienna, Vienna, Austria*

**Stüwe, Kurt**

*Karl Franzens University of Graz, Graz, Austria*

**Keywords:** Tectonics, geodynamics, geophysics, rheology, mechanics

### Contents

1. Introduction
2. The Theory of Plate Tectonics
  - 2.1. The Geodynamic Concept of Plate Tectonics
  - 2.2. Global Seismicity in the Concept of Plate Tectonics
3. The Description of Geodynamic Processes
  - 3.1. Energetic Descriptions of Geodynamic Processes
  - 3.2. Kinematic Description of Geodynamic Processes
  - 3.3. Dynamic description of geodynamic processes
4. Important Concepts in Geodynamics and Tectonics
  - 4.1. Rheology of the Lithosphere
  - 4.2. Gravity and Isostasy
5. Outlook and Perspectives
  - 5.1. Alternative Concepts ?
  - 5.2. The Future of Geodynamics

Acknowledgements

Glossary

Bibliography

Biographical Sketches

### Summary

The science of geodynamics and tectonics includes the description and interpretation of a large variety of geological processes that operate in the earth. However, we generally think of geodynamic processes of those that act on the scale of the whole lithosphere. This contribution summarizes some fundamental concepts of geodynamics and tectonics, and serves as an introduction to articles on specific subjects within the topic. Among the methods of describing geodynamic processes we discern between energetic, kinematic and dynamic descriptions. Energetic descriptions are those that consider the production, distribution and redistribution of thermal energy in the lithosphere. Kinematic descriptions are those used to describe the movement and geometry of rocks units and surfaces. Dynamic descriptions are those that use force balance considerations to describe orogenic processes. The application of these methods to the description of geodynamic processes is illustrated simple model concepts of the rheology of the lithosphere and the principle of isostasy as examples. The contribution is rounded off with an outlook on the future of geodynamics.

## 1. Introduction

Geodynamics is the science describing the dynamic processes that govern the large scale structure of earth. Geodynamic processes have operated throughout the billions of years of the earth's history to create, destroy and recreate continents and oceans, geological provinces and terranes, mountain chains and basins, and all the mineral and hydrocarbon deposits so essential to our society. Thus, "geodynamic processes" are understood to include a large variety of processes and earth scientists use the term quite loosely. Nevertheless, when discussing "geodynamics and tectonics" we generally think of processes that act on the scale of lithospheric plates or plate boundaries, rather than on the scale of a single outcrop. In the past decade the term "geodynamics" has often been used as a fashionable synonym to "tectonics", which traditionally has only been understood to be the science of the kinematics of rocks on a large scale, e.g., in the context of terms like "thrust tectonics", "extensional tectonics", "subduction tectonics" and so on. However, geodynamics also includes the conceptual description of physical processes governing tectonics, the combination of thermal and mechanical descriptions for integrated physical interpretation of the earth and more. In general, it may be said that geodynamic processes are described using energetic, kinematic and dynamic descriptions. While these three methods of description cannot be separated strictly, they each use some characteristic variables: Energetic descriptions are involved with the distribution of thermal energy using variables like heat or temperature. Kinematic descriptions are those using parameters like velocity and strain. Dynamic descriptions are those using variables like stress and force. Each of these three descriptions is discussed in this contribution with some applications to some geodynamic processes on the lithospheric scale. We therefore begin with a brief summary of the concept of plate tectonics.

## 2. The Theory of Plate Tectonics

### 2.1. The Geodynamic Concept of Plate Tectonics

The earth's outermost rigid layer is called lithosphere and it consists of a rigid upper mantle and a crust. The crust may be either of oceanic or crustal type. The theory of plate tectonics states that this lithosphere is broken into 7 major plates (African, North American, South American, Eurasian, Australian, Antarctic, and Pacific plates) and several minor plates (e.g., Arabian, Nazca, Cocos, Juan-de-Fuca and Philippines plates) sliding over the plastic asthenosphere, which is the upper layer of the mantle (Figure 1). The lithospheric plates are all moving in different directions and at different velocities between 1 to more than 10 cm a<sup>-1</sup> relative to each other. The place where the two plates meet is called a plate boundary. Where they interact, along these margins, important geological processes take place, such as the formation of mountain belts, earthquakes, and volcanoes. These plate boundaries have different names depending on how the two plates are moving in relationship to each other: (i) convergent, (ii) divergent and (iii) transform boundaries. Before discussing these plate boundaries in some more detail, we also note that some important mountain belts, for example the Tien Shan, have also formed inside continental plates, and that other important geological processes like Hot Spot volcanism also occur inside oceanic plates.

### 2.1.1. Convergent Boundaries

If the size of the earth has not changed significantly during the last 200 Ma (which is about the age of the oldest oceanic lithosphere) this implies that the lithosphere must be destroyed at about the same rate as it is being created. This recycling of lithospheric material takes place along convergent boundaries or collision zones (destructive plate boundary). Collision can occur:

- between an oceanic and a continental plate
- between two oceanic plates, or:
- between two continental plates.

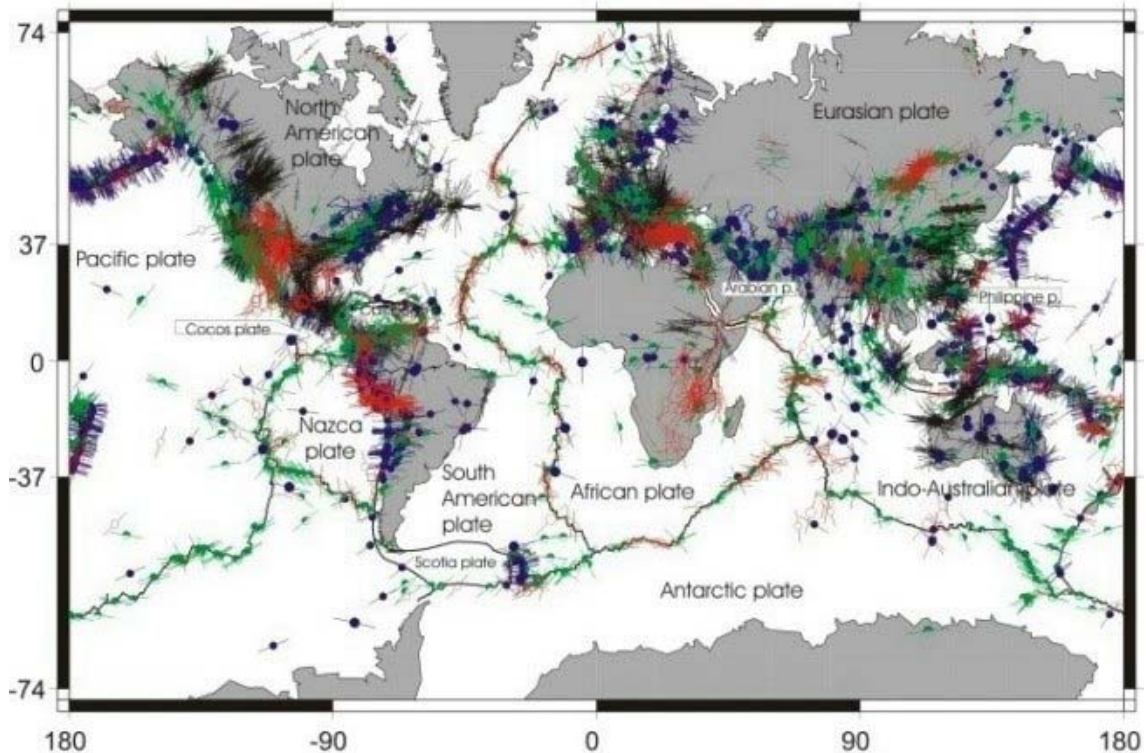


Figure 1. The intraplate stress field of the world superimposed on a rough plate tectonic subdivision of earth. Different symbols indicate different methods of stress determination including earthquake focal mechanisms, borehole breakouts and geological indicators. Different shadings indicate different deformation regimes: darkest are thrust faults, medium grey are normal faults and light shading are strike slip faults. This map was created using the CASMO facility on the world stress map project home page. The map is also modified after Stüwe (2002).

Oceanic-continental convergence is associated with up to 10 km deep trenches, where the oceanic lithosphere is subducted beneath the continental plate (e.g., the Nazca Plate beneath the South American Plate). Subduction is frequently associated with eruptive volcanic activities where the magma is either generated by the partial melting of the subducted oceanic slab, or the overlying continental lithosphere, or both.

When two oceanic plates converge, one is subducted beneath the other, and similar to

oceanic-continental subduction a deep trench is formed (e.g., Mariana Trench). Subduction processes in oceanic-oceanic plate convergence also result in the formation of volcanoes, which are called, because of their parallel arrangement to the generally curved trenches, island arcs.

Continental-continental convergence is the result of the collision of two continents forming a collision orogen (e.g., the Himalayas after collision of India with Asia some 55 Ma ago). Generally, the continental collision followed an oceanic-continental subduction zone. Such collisional orogens are characterized by fold-and-thrust belts, regional metamorphism, igneous activities, exhumation of high-grade and ultra-high-pressure rocks and surface uplift and erosion of huge rock masses.

### **2.1.2. Divergent Boundaries**

Divergent plate boundaries occur along spreading center centers where plates are moving apart and new lithosphere is created by magma pushing up from the mantle (constructive plate boundary). One of the best-known examples is the Mid-Atlantic Ridge, which is one segment of the global mid-ocean ridge system that encircles the earth and has a total length of some 60000 km. The rate of spreading along the Mid-Atlantic Ridge averages about  $2.5 \text{ cm a}^{-1}$ . This seafloor spreading over the past 200 Ma has caused the Atlantic Ocean to grow from narrow rift between the continents of Europe, Africa, and the Americas into the vast ocean that exists today. However, divergent plate boundaries like the Mid-Atlantic Ridge never start out as boundaries between two oceanic plates. They always commence as rifts in side the continents. The causes for such rifting remain unclear, but it is fiercely debated if they initiate in response to hot spots underneath the continents or in response to gravitational potential energy differences. A new spreading center probably forming the earth's next major ocean may be developing under Africa along the East African Rift Zone. A further stage of divergent plate boundary development may be observed in the Red Sea where the first oceanic lithosphere begins to form.

### **2.1.3. Transform Boundaries**

The zone between two plates sliding horizontally past one another is called a transform-fault boundary, or simply a transform boundary. Transform faults connect either two spreading center centers (divergent plate boundaries) or, less commonly, trenches (convergent plate boundaries). Therefore most transform faults are found on the ocean floor where they produce the offset appearance of mid ocean ridges. However, transform boundaries may also occur on land (e.g., San Andreas fault zone in California connecting two divergent boundaries).

It is important to note that not all plate boundaries on earth are as simple as the main types discussed above, especially if plate-movement deformation occurred over a long time span with changing kinematics and extends over a broad belt (i.e., plate-boundary zone). Such plate-boundary zones frequently involve at least two large plates and one or more micro-plates resulting in complicated geological structures and earthquake patterns (e.g., Mediterranean-Alpine region between the Eurasian and African Plates).

## 2.2. Global Seismicity in the Concept of Plate Tectonics

The theory of plate tectonics furthermore explains four types of seismic zones:

Seismic zones along rift systems

Seismic zones along transform boundaries

Seismic zones related to subduction zones

Seismic zones associated with collision tectonics

The first type of seismic zone follows the mid ocean rift system and is associated with the volcanic activity along the axis of the ridges (e.g., Island). The seismic activity is generally low, and it occurs at very shallow depths because the lithosphere is very thin and weak at these divergent boundaries.

The second type of seismic zone is associated with transform plate boundaries or large strike slip faults causing friction between neighboring plates (e.g., North Anatolian Fault or San Andreas Fault). Earthquakes are shallow-focus events generally without any volcanic activity. As large strike slip faults are always bend and segmented in several sections activity does not always occur along the entire length of the fault during any one earthquake.

The third type of earthquake is related to subduction zones along convergent plate margins. One plate is thrust or subducted under the other plate so that a deep ocean trench is produced (e.g., Peru - Chile trench, where the Pacific plate is being subducted under the South American plate). Earthquakes associated with subduction zones can be shallow, intermediate, or deep, according to its location on the down going lithospheric slab (Wadati-Benioff zone).

The fourth type of seismic zone is associated with collision tectonics where shallow earthquakes are associated with intense shortening and formation of high mountain ranges (e.g., broad swath of seismicity from Burma to the Mediterranean, crossing the Himalayas, Iran, Turkey, to Gibraltar).

Numerous processes, such as for example, climate change, earthquakes, volcanism or erosion are of major concern for human life. The motion at plate tectonic boundaries is only in the order of a few mm – cm a<sup>-1</sup> and can therefore only be observed by means of high-resolution geodetic methods over a time span of years (e.g., Global Positioning System). However, within seconds an earthquake or volcanic eruption can unleash bursts of energy far more powerful than anything we can generate. Besides all these hazards, people also benefit from the forces and consequences caused by plate tectonics (e.g., geothermal energy, generation of natural resources).

Due to the importance of plate tectonic processes for our life, separate articles of this encyclopedia are dedicated to the plate tectonic processes: *Plate Tectonics of Continents and Oceans* by Martin Meschede (Ernst-Moritz-Arndt-Universität Greifswald, Germany), which covers many aspects of the earth's composition and age, plates, plate boundaries, triple junctions and hot spots; *Neotectonics* by Manfred Strecker and co-workers (Potsdam University, Germany) which emphasizes all features of active

tectonic processes including geomorphological, paleoseismological, geodetical and geophysical methods. A special emphasis is given on neotectonic movements and climate patterns.

### 3. The Description of Geodynamic Processes

The following sections discuss some fundamental concepts in geodynamics and serve as a basis for other articles covering important subjects related to the dynamics of the earth. Excellent, detailed mathematical and physical introductions to this topic are given in the Bibliography. *Geodynamics of compressional orogens* by Jean Braun (Australian National University, Australia) shows an application of the fundamentals of geodynamics by demonstrating the use of complex numerical methods in order to investigate the geodynamic evolutions and processes of past and present orogens.

-  
-  
-

TO ACCESS ALL THE 27 PAGES OF THIS CHAPTER,  
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

#### Bibliography

Anderson, D. L., (2002). How many plates? *Geology*, v. 30, p. 411–414. [The planform of a freely convecting spherical shell may have little to do with the size, shapes and number of plates. The plates may self-organize and serve as the template that organizes mantle flow].

Argand, E. (1916). Sur l'arc des alpes occidentales. *Eclogae geologicae Helvetiae* **14**, 145 – 191 [Revolutionary idea that continental collision is the best explanation for the folded and buckled strata observed in Alpine-type orogens].

Byerlee, J. D. (1978). Friction of Rocks: *Pure and Applied Geophysics*, v. 116, p. 615-626. [Pioneering work about laboratory studies of rock friction showing that the coefficient of friction of almost every type of crustal rock falls within the surprisingly narrow range of 0.6 - 1.0].

Belousov, V. (1990a). Critical aspects of the plate tectonics theory Vol. 1: Criticism on the plate tectonics theory. *Theophrastus* (Athens), 435 pp. [Collection of provocative ideas, that plate tectonics was a premature generalization of still very inadequate data on the structure of the ocean floor and is far removed from geological reality].

Belousov, V. (1990b). Critical aspects of the plate tectonics theory Vol. 2: Alternative theories. *Theophrastus* (Athens), 444 pp. [Collection of provocative ideas that plate tectonics was a premature generalization of still very inadequate data on the structure of the ocean floor and is far removed from geological reality].

Dietz, R.S. (1961). Continental ocean basin evolution by spreading of the sea floor. *Nature* 190, S. 854-857. [Original paper about the spreading theory, suggesting that the sea floor moves out in opposite directions from the mid-ocean rises and that the gap is filled by new strips of sea floor created from the

ultrabasic mantle].

Grasemann, B., Ratschbacher, L., and Hacker, B. R., (1998). Exhumation of ultrahigh-pressure rocks: thermal boundary conditions and cooling history. in: Hacker, B. R., and Liou, J. G., eds., *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Structural Geology and Petrology*, 10, Dordrecht, Kluwer Academic Publishers, p. 117-139. [Thermal modeling of the first order boundary conditions influencing the cooling history of rocks].

Hess, H. H. (1962). History of Ocean Basins. In: Engle, A. E. J., James, H. L. and Leonard, B. F. (eds.), *Petrologic Studies: A Volume in Honor of A. F. Buddington*, 599-620. Geological Society of America (New York). [Hess proposed that the seafloor was created at mid-ocean ridges, spread out toward the trenches, and descended beneath them into the mantle. He argued that the process was driven by convection currents in the mantle. In this model, the continents are passively carried along in the process].

Meyerhoff, A. A., Taner, I., Morris, A. E. L., Martin, B. D., Agocs, W. B., & Meyerhoff, H. A., (1992). Surge tectonics: a new hypothesis of earth dynamics. in: Chatterjee, S., & Hotton, N., eds., *New Concepts in Global Tectonics*, Lubbock, Texas, Texas Tech University Press, p. 309-409. [Introduction of a new alternate theory called Surge Tectonics explaining many geodynamic processes conservatively explained by plate tectonics].

Mohr, O. (1882). Über die Darstellung des Spannungszustandes und des Deformationszustandes eines Körperelementes und über die Anwendung derselben in der Festigkeitslehre. *Der Civilingenieur* 28, 113-156. [Borrowing upon earlier work by Karl Culmann, this paper expanded the graphical representation of stress about a point to three dimensions. The "circles of stress" is now commonly called Mohr Circle and helped to develop the first theory of strength based on shearing stresses].

Oertel, G., (1996). *Stress and Deformation: A Handbook on Tensors in Geology*: Oxford, Oxford University Press, 292 p [Textbook introducing the concept of tensor with applications to geodynamic problems].

Ortelius, A. (1587). *Abrahami Ortelij Antverpiani thesaurus geographicus*. Plantin (Antwerpen), 368 pp. [First modern atlas combining maps of uniform size and style with comprehensive text crediting the original cartographers].

Pitman, W.C. & Heirtzler, J.R. (1966): Magnetic anomalies over the Pacific-Antarctic ridge. *Science* 154, S.1164-1171. [This work was the basis of the first magnetic polarity timescale based on marine magnetic anomalies].

Ramberg, H. (1981). *Gravity, deformation and the Earth's crust*. 2nd Edition, Academic Press, London 452 pp. [Profuse illustrations of beautiful analogue, analytical and numerical models reproducing tectonic and structural patterns having a profound influence during the early days of plate tectonics].

Ranalli, G. (1994). *Rheology of the Earth*. 2nd Edition: London, Chapman & Hall, 413 p. [Complete treatment of deformation and flow of earth materials from both the continuum mechanics and the microphysical viewpoint].

Slater, J.G. & Wixon L. (1986) The relationship between depth and age and heat flow and age in the western North Atlantic. In: Vogt P.R. & Tucholke B.E. (eds.) *The western North Atlantic region*, AGU monograph, M, 257-270. [Summary paper on the classic work of Slater and coworkers defining the age-depth-heat flow relationship of oceanic lithosphere].

Schidegger, A. E. (1982). *Principles of Geodynamics*. 3rd Edition, Berlin, Springer, 395 pp. [Compilation of important principles of geodynamics including physiogeographic, geologic and geophysical data].

Stüwe, K. & Barr, T.D. (2000) On the relationship between surface uplift and gravitational extension. *Tectonics* **19**, 1056-1064. [The second of two review papers of these authors on vertical reference frames and their implications to potential energy contrasts].

Stüwe, K. (2002). *Geodynamics of the Lithosphere. An Introduction*. Springer, Berlin, 450 pp. [The book provides an understanding of basic concepts of map projections, plate tectonics, heat flow, isostasy, geomorphology, kinematics stress, strain and rheology. These concepts are integrated to examine a variety of geodynamic problems].

Turcotte, D. L. & Schubert, G. (2002). *Geodynamics - Applications of continuum physics to geological problems*. John Wiley & Sons, New York, 450 pp. [The classical book about geodynamics providing the fundamentals necessary for an understanding of the workings of the solid earth, describing the mechanics of earthquakes, volcanic eruptions, and mountain building in the context of the role of mantle convection and plate tectonics. Observations such as the earth's gravity field, surface heat flow, distribution of earthquakes, surface stresses and strains, and distribution of elements are discussed].

Twiss, R. J. & Moores, E. M. 1992. *Structural Geology*. W.H. Freeman and Company, New York, 532 pp. [Excellent text book for advanced undergraduate structural geology courses including brittle-, ductile deformation, rheology and tectonics].

Wegener, A. (1912): Die Entstehung der Kontinente. *Geologische Rundschau* **3**, 276-292 [The concept of the continental drifts based on the shape of continents, fossils and other geological evidences].

Wilson, J. T. (1966b): Did the Atlantic close and then re-open? *Nature* (London), **211/5050**, 676-681. [Wilson Cycle suggests that supercontinent formation, intracontinental rifting, breakup and dispersal of individual continental cratons, is followed by assembly of these cratons to form a new supercontinent].

### **Biographical Sketches**

**Bernhard Grasemann** is an associate Professor for structural geology at the University of Wien in Austria. He special expertise is the coupling of fieldwork with numerical modeling. He is currently working in the Himalayas, the Aegean region and the Alps and has widely published on theoretical questions in structural geology and tectonics.

**Kurt Stüwe** is an associate Professor for geodynamics at the University of Graz in Austria. He has been educated at the Universities of Melbourne and previously held positions at Monash University and Adelaide University in Australia. His specialty is interdisciplinary research between petrology and structural geology, and he is particularly interested in numerical modeling. He has worked in all continents and has written two textbooks on geodynamics.