TECTONICS AND GEODYNAMICS

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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 if 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^{-1} 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.

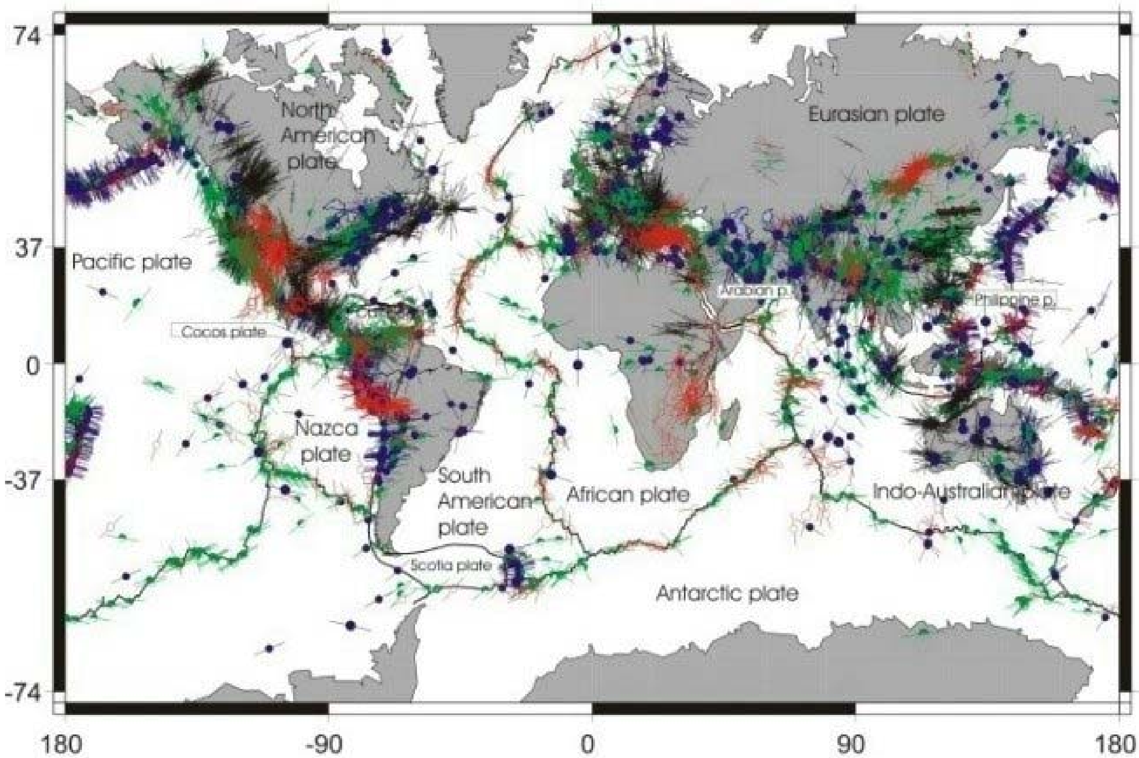

Figure 1. The intraplate stress field of the world superimposed on a rough plate tectonic subdivision of earth. Different symbols indicate different methods of stress determination including earthquake focal mechanisms, borehole breakouts and geological indicators. Different shadings indicate different 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 centercenters 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 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 centercenters (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 Gilbraltar).

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^{-1} 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.

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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.

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