MANTLE DYNAMICS AND PLATE KINEMATICS

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Contents

Summary

Plates move at the surface of Earth, but we still do not know what energy source accounts for plate tectonics. Mantle tomography, studies on the viscosity of Earth's interior, and geological, geophysical, and geodetic analysis of plate tectonics are rapidly contributing to an understanding of why plates describe a sinusoidal flow and why there is a westward delay of the lithosphere relative to the mantle, creating strong asymmetries in the structure of subduction zones and rift zones.

The main energy seems to come from Earth's cooling and associated mantle convection. Earth's rotation however seems to contribute as well, both in terms of direction of plate motions, and possibly also in terms of energy.

1. Introduction

Life on Earth is dependent on its atmosphere, which formed mainly as a result of mantle degassing through volcanoes and other forms. Volcanism on Earth is primarily a consequence of plate tectonics, and therefore the motion of crustal plates is a foundation of life on Earth. Plate tectonics lead to disasters such as earthquakes, volcanic eruptions, and landslides, but are also the engine for natural resources, from hydrocarbons to geothermy, mineral resources, water, and the spectacular landscapes that enhance our lives. In other words, we cannot live without plate tectonics, and it is very helpful to better understand the mechanisms and the structures associated with the movements of the lithosphere.

The lithosphere is subdivided in a number of plates; a plate is an element of the lithosphere characterized by its own independent velocity relative to the neighboring sections of the lithosphere. These differential velocities among plates generate plate tectonics. Approaching or separating plates are controlled by their relationship with the underlying mantle. There is a close link between what happens in Earth's mantle and what is going on at the surface. In this article we briefly describe what is understood about mantle dynamics and plate kinematics, and link the two.

2. Techniques to Sample the Interior of the Earth

Nowadays, together with the study of magmatic rocks (that is, rocks formed deep in the Earth, but now found in its crust), satellite geodesy and seismic tomography are major tools for sampling the interior of Earth, to retrieve its innermost structure in terms of its density, and its elastic and rheological properties. "Rheology" covers a wide field of studies related to the creep and flow properties of metals, ice, or in this case, Earth's mantle. The term "rheology" can be used to indicate not only the field of study but also the property of flowing and creeping of materials, so that it is possible to speak of the rheology of ice or the rheology of the mantle. Rocks have the ability to "flow" under the impact of the stresses that originate from geodynamic processes. The major region of the Earth where geodynamic processes originate is the mantle, the portion of our planet between the rigid outer lithosphere, which is about 100 km thick, and the core, at a depth of 2890 km. Figure 1 is a sketch showing schematically the interior of our planet, with the mantle characterized by the fundamental property of creep, which means that the mantle rocks are able to flow when subject to shear stresses applied for time intervals typical of geological processes, from thousands to million years. In Figure 1, the two layers embedded between the elastic lithosphere and the core denotes the mantle. The mantle itself is subdivided into the upper and lower mantle, with the transition zone located at a depth of 670 km.

A key issue in geodynamics is the determination of the viscosity of the upper and lower mantle; the viscosity is higher in the lower mantle. The importance of the viscosity stands on the fact that the dynamics of the mantle and the kinematics of the plates are ultimately controlled by this parameter, which characterizes the flow properties of Earth's interior. The innermost portion of Earth is the core, as indicated in Figure 1, which differs substantially from the mantle in terms of rheological properties: the external core is in fact an inviscid fluid, whereas the internal core is solid and is the densest part of the planet. The outermost layer of Earth is called the "lithosphere," and in contrast to the mantle, its viscosity is so high that it can be assumed to behave as an elastic body.

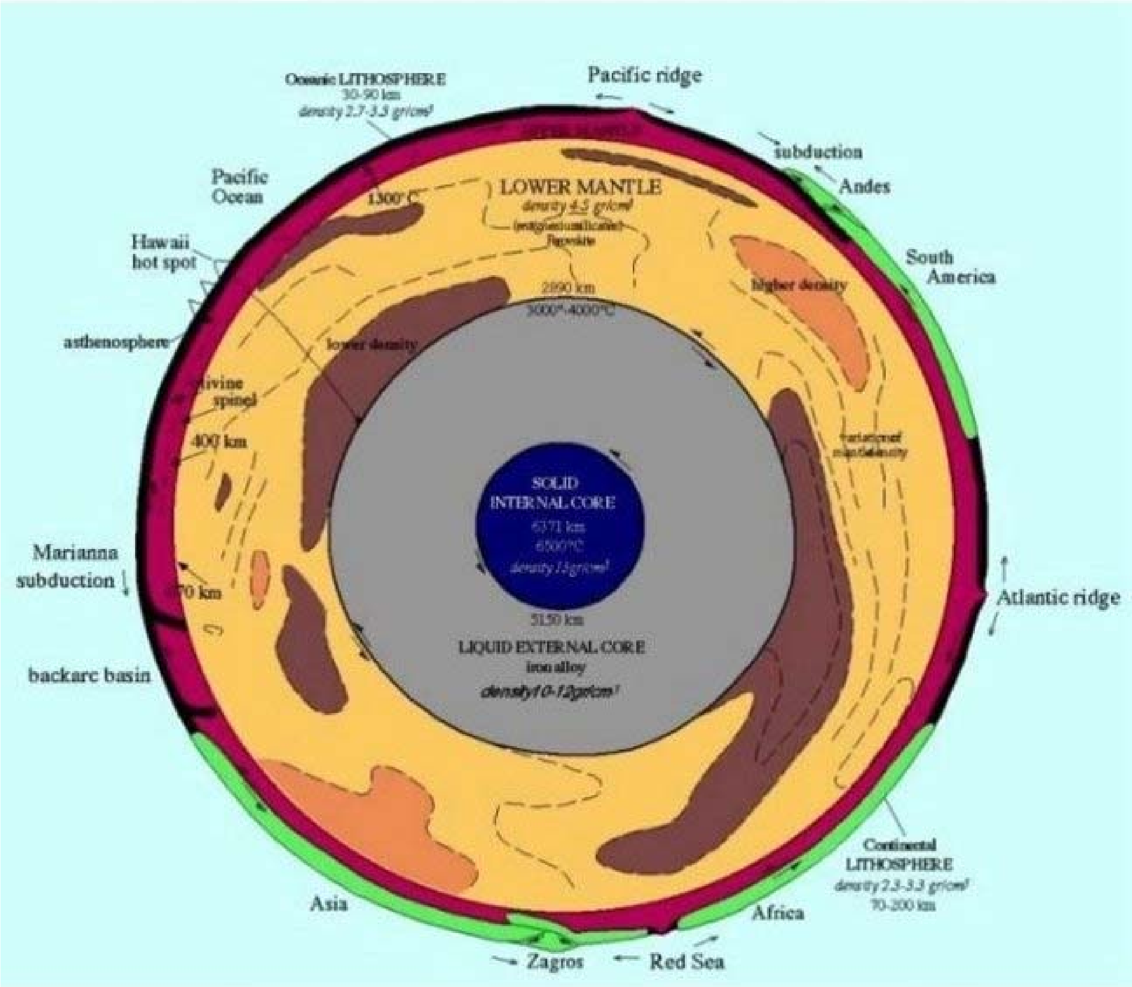

Figure 1. Model of Earth. The lithosphere is both oceanic and continental, and includes the crust. It is the outermost layer, and it behaves mainly as an elastic body. The upper and lower mantle are viscoelastic, which means that mantle rocks creep under the action of long-standing shear stresses, while the external core is an inviscid fluid. Variations in density in the mantle are inferred by seismic tomography, and they refer to variations relative to similar depths. Boundaries between the different layers represent changes in density and viscosity. Note that the different shells are interpreted to be shear zones. In particular the lithospheric movement is delayed westward relative to the mantle, determining a relative eastward mantle flow.

The five-layer model in Figure 1 (lithosphere, upper mantle, lower mantle, external core, and internal core) shows all the fundamental ingredients of Earth in terms of its rheological and dynamic properties.

3. Seismic Tomography

Seismic tomography is the technique of inverting seismological data to retrieve a three-dimensional image of the anomalies in seismic wave velocity within the media they cross. It is based on the physical phenomenon that the velocities of seismic waves (that is, waves triggered by earthquakes) are subject to change as they cross regions of Earth's mantle with different densities and elastic properties. The availability of a large amount of data from the well-recorded global seismicity thus makes it possible today to retrieve a picture of the structure of Earth's mantle, in terms of thermal and compositional anomalies.

Both surface wave and body waves can be used to detail the image of Earth's interior. Body waves are those that have the ability to cross the whole mantle, while surface ones propagate in proximity to the interfaces where the density or elastic properties of the Earth are discontinuous. The surface waves thus provide information on Earth's structure in the upper mantle, down to the depth of 670 km, where the interface between the upper and lower mantle is located. The body waves give information on the whole mantle and on Earth's core.

Seismic tomography provides a snapshot, an instantaneous picture today of a slowly, geologically evolving mantle. In principle, in order to use seismic tomography in a self-consistent way it is necessary to compare the tomographic images of recent seismic movements with those obtained from mathematical models of the evolution of Earth's geological structures since the beginning of its formation.

Figure 2 provides an Equatorial cross-section of velocity anomalies through the mantle. The section through the upper mantle is the middle diagram, while the section through the lower mantle is the lower diagram. The diagrams show velocity anomalies, quantified in terms of percentage variations from a normal velocity, which corresponds to the velocity of a wave crossing a "normal" (not anomalous) region of the mantle. The velocity anomalies in the upper mantle correlate well with the Precambrian shields and mid-ocean ridges. Underneath the shields the velocity is higher (positive anomalies as high as 3% and 0.75% for S-and P-wave velocities), while in the hot regions of the mantle, corresponding to the mid-ocean ridges, the velocity is lower because of dissipative effects. This equatorial tomographic section shows a limited correlation between velocity anomalies in the lower mantle and those of the upper mantle.

The most noticeable feature in the lower mantle is the high velocity around the Pacific, which correlates with the Pacific subduction complex. Since velocity anomalies are related to elastic parameters and density, and therefore to the composition and temperature of mantle material and its fluid content, they can be considered as an instantaneous image of the thermal and compositional anomalies of the mantle. The effects of temperature and composition cannot be separated, and it could be that the seismic waves move more rapidly in the subcratonic upper mantle not only because it is cooler but also because it is compositionally different from the suboceanic mantle. In the interpretation of tomographic studies, problems related to error limitations and the resolution powers of the technique are important. The resolution in global studies, such as that portrayed in Figure 2, is limited to features with minimum horizontal and vertical dimensions of 2000–3000 km and 150–400 km respectively. More accurate resolution can be obtained today, particularly in regional tomographic studies.

Two main areas of low velocity occur in the mantle, in the central-south Pacific, and underneath southern Africa, providing a sort of bi-polarity. They correspond to the areas of positive anomalies of the geoid. They do not coincide with significant plate boundaries and occur beneath both oceanic and continental lithosphere, showing no apparent relationship with surface tectonics.

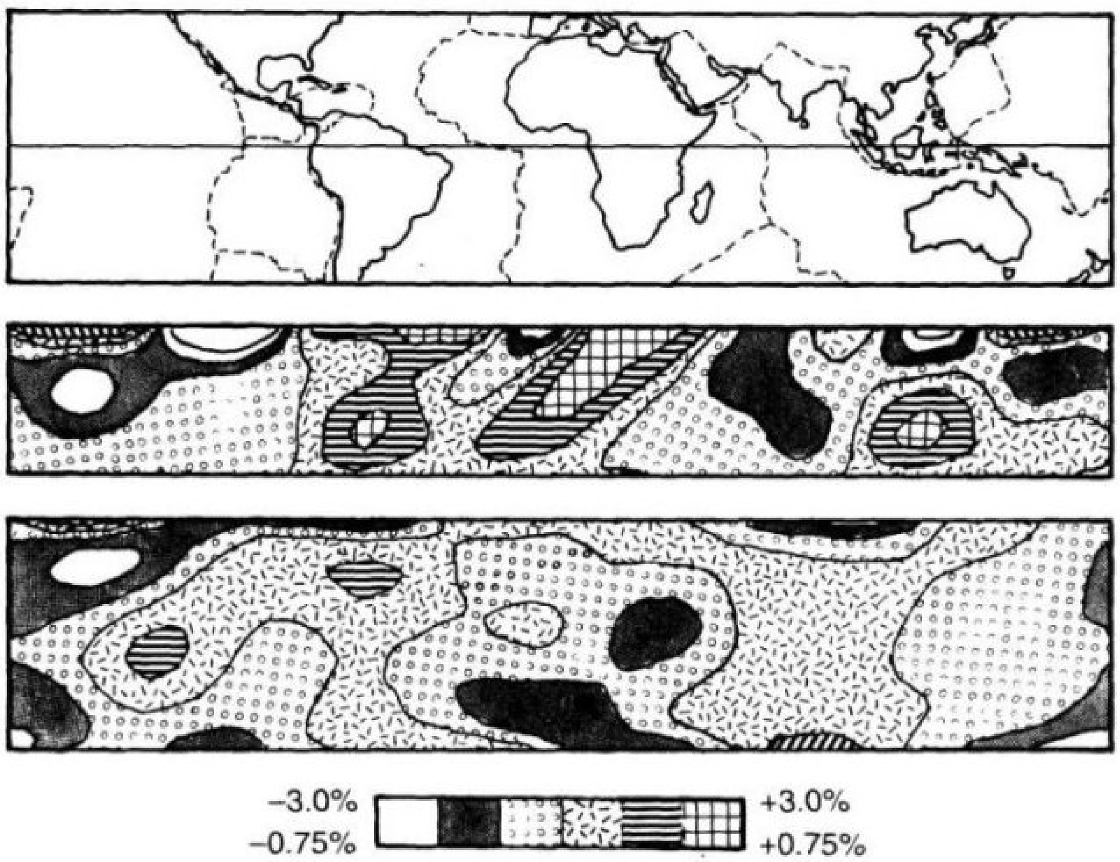

Figure 2. Equatorial cross-sections of seismic wave velocity anomalies, for shear waves (in the upper mantle, middle panel) and compressional waves (in the lower mantle, bottom panel). Source: Woodhouse and Dziewonski, 1984.

4. Changes in Earth's Gravity Field and their Implications for Mantle Dynamics

Satellite geodesy is today undergoing rapid development, because of new technologies such as laser tracking of satellites and gradiometry (measurements of gradients of the gravity field), which make it possible to detect the gravity field, and in particular its time variations, with high accuracy and spatial resolution. A constellation of geodetic satellites, orbiting around the Earth at different altitudes, is sensitive to time variations in the gravity field, which cause perturbations in their orbits. These perturbations can be monitored by means of laser tracking from laser stations located at different sites on the surface of Earth. Laser beams are shot from a station to the satellite, and reflectors mounted on the satellite send back the beam to the station: from the fly time of the laser beam it is possible to measure accurately the position of the satellite with respect to the station, and thus with respect to the Earth. After years of data sampling it is possible to measure the modification of the orbit of the satellite with respect to the Earth, and from the orbit perturbations the changes in the gravity field can be retrieved on the global spatial scale. Changes in the gravity field on a smaller scale are measured nowadays by means of instruments on board the satellites, which are sensitive to the local gradient of gravity.

The anomalies in the gravity field are ultimately caused by mass anomalies embedded inside the Earth, and their variation over time is related to the ongoing redistribution of mass inside and on the surface of the Earth. Thus it is clear that satellite techniques are today the most powerful tool available for gaining a deep insight into mantle dynamic processes. Seismic tomography presents an essentially static picture, but satellite geodesy has the capability to sample the ongoing changes in gravity. In order to understand the physics, the gravity data need to be compared with results from simulations of the processes thought to be involved, carried out using appropriate mathematical models. Comparison between the two sets of data makes it possible to invert the key parameters that control the geodynamic processes. The mathematical models can be fine-tuned after this data crosscheck, and in principle it should ultimately be possible to use them to predict the evolution over time of the geodynamic processes.

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Biographical Sketches

Carlo Doglioni is full Professor of Geology at the University La Sapienza of Rome, Italy. He was formerly at the Universities of Basilicata, Bari, and Ferrara, where he did his thesis. He has visited as researcher the Universities of Basel, Oxford, and Rice University of Houston. He works mainly on the geodynamics of subduction zones and on the structural geology of the Alps, Apennines, and other areas of the Mediterranean area. He has been AAPG distinguished lecturer.

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