

INTERNAL FORCES AND THEIR INFLUENCE ON THE EARTH'S SURFACE

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Summary

Earth works like a heat machine, in which heat is transported from its interior towards the surface. This is the principal way Earth cools. The internal thermal and gravitational instabilities vanish due to mass movements that transport heat by thermal convection, mainly within Earth's mantle. Increasing temperature lowers the rock strength so that rocks in Earth's interior are able to flow in a viscous manner. Convection currents in the mantle ultimately induce various kinds of deformation and movements of the Earth's upper layers. The stiff outer shell of Earth, the lithosphere, has a different composition and properties in oceanic and continental areas. The oceanic lithosphere is relatively uniform and strong, while the continental lithosphere, and especially its crust, is weak due to compositional and rheological layering. Consequently, the continental crust is prone to extensive deformation expressed by mountain building and seismicity.

The system of driving and resistive forces produces various stress fields in the lithosphere. Provided the rock strength is overcome, the stress is relaxed by deformation. Faulting, folding, and ductile creep are the main processes by which crustal rocks are deformed. Ductile flow in deeper parts of the crust initiates stress amplification in the brittle upper crust that is transiently relieved by seismic slipping along active faults, generating sometimes catastrophic earthquakes.

1. Introduction

Earth's surface, on which humankind lives, exhibits an endless variability in morphological forms. The continental exteriors vary from mountain belts and volcanic chains to hilly areas and flat lowlands, the oceanic bottom rises from large abyssal plains to seamounts and ridges and falls to narrow trenches. All this variability is an expression of the ever-present competition of two classes of energetic sources. The first class is the heat production in Earth's interior that generates forces known in geology as internal or endogenous. The internal forces drive all the vertical and horizontal movements of Earth's crust and are responsible for some severe disasters such as earthquakes or volcanic eruptions. The second class—the external or exogenous forces—is generated by energetic input from the Sun. They trigger motions in Earth's hydrosphere and atmosphere and tend, through weathering, erosion, and sedimentation, to decrease the morphological expressiveness created by internal forces. This is an expression of the second theorem of thermodynamics predicting dissipative exchange of energy between systems that are in mutual disequilibrium. Generally, if there were no atmosphere and hydrosphere on Earth, the internal forces would produce extremely rugged surface morphology with any kind of steep positive or negative forms that could sustain gravitational forces. On the other hand, if there were no internal forces, erosion would quickly diminish all morphological variations and Earth would become a boringly flat spheroid body.

The purpose of this article is to outline how the internal forces are generated, distributed, and dissipated, and how they influence the composition, structure, movements, and deformation within the upper layers of the solid Earth.

2. The Earth's Interior—Thermal and Compositional Structure

2.1. Internal Heat

The degree of surface instability of every planet in the Solar System is proportional to its internal mobility (i.e., to the ability of masses in the planetary interiors to move due to accommodation of thermal and gravitational instabilities). This can be expressed by the ratio of volume (V) to the surface area (S) as being proportional to radius (R) in the equation:

$$\frac{V}{S} = \frac{\frac{4}{3}\pi R^3}{4\pi R^2} = \frac{R}{3}$$

This means that this ratio is high for large planets and they cool slowly due to their smaller surface area per volume compared to small planets and moons, which have a

comparatively low heat capacity and a large surface area per volume to cool out. Accordingly, large planets are hot and mobile, depending on their compositions. Among the terrestrial planets composed mostly of silicates, only those with large radii are able to store enough thermal energy to reduce the strength of rock masses in their interiors. Increasing temperature lowers the rock strength exponentially and every rock begins to flow at a certain temperature. This holds for Earth and Venus in particular, which are hot enough for their interiors to be highly mobile. In the case of Earth, the internal thermal and, consequently, gravitational instabilities vanish due to mass movements that are transferred towards the surface and expressed by various kinds of deformation and movements of the upper, seemingly stiff layers of Earth. Accordingly, Earth may be regarded as a heat engine, though Earth's internal thermal input power is rather low (approximately 1×10^7 MW, which is comparable to the energetic production of the whole of humankind).

The principal sources of internal heat are considered to be twofold: (1) the heat inherited from the early accretionary period of Earth and (2) the radiogenic heat produced by decay of radioactive elements presently involved in Earth's crust and mantle. During the earliest stages of Earth's history (some 4.7–4.5 billion years ago), its internal heat rose gradually, being generated by transformation of the kinetic energy of incident particles forming the early Earth and by the thermal energy released during the gravitational collapse, adiabatic compression and an increase of the density of Earth's body. Later on, the temperature in Earth's interiors reached the melting point, which enabled the gravitational differentiation of rock masses producing additional heat. However, the **radiogenic heat production** has been the most important input power during the whole of Earth's history. It is generated by the breakdown of radioactive isotopes, which had originally been randomly distributed within the early Earth's body but, being comparatively light, became concentrated in Earth's upper layers after the gravitational differentiation. (**See Early Earth**).

Earth's body is thermally inhomogeneous. The temperature in its core reaches 6000 °C, while the surface temperature approaches 0 °C. Obviously the temperature increases with depth. This downward increase (directed to Earth's center) is known as the **geothermal gradient**, a measure of rise in temperature per unit length. Surface and subsurface measurements in deep wells and mines indicate this gradient to be in the range of 10–40 °C km⁻¹, most typically 20–25 °C km⁻¹. However, an extrapolation of this value to Earth's interiors would mean unrealistically high temperatures, therefore the thermal gradient has to decrease with depth. This is in line with the observation that the radioactive elements as the main sources of Earth's heat production are concentrated in the crust. Nevertheless, Earth is hottest in its center and coldest on its surface, which indicates that a great deal of its thermal energy is being dissipated on the surface. In fact, this and other losses only slightly exceed the internal heat production, which means that the Earth as a whole cools very slowly, negligibly with respect to the length of human existence.

Variations in the near-surface geothermal gradient are an expression of a changing heat flow, a measure of the thermal input from Earth's interiors towards its surface. The heat flow density indicates the amount of heat that is released from Earth's surface per unit area and per unit time. Within Earth's body, the heat is transported in two principal

ways—by conduction and convection. Thermal conduction differs for various rocks, and prevails in the stiff upper layers of Earth. Thermal convection means heat transport by moving matter, and prevails in Earth's interior. However, many large positive heat flow anomalies on Earth's surface are dominantly produced by thermal convection, for example by ascending magmatic melts or aqueous and other fluids in active volcanic areas. But also in nonvolcanic areas with thinned crust, which are usually overlain by large and deep sedimentary basins, the heat primarily conveyed from the depths by conduction is then distributed by meteoric waters circulating within the upper crustal rocks.

Geothermal energy might be, thanks to its apparent inexhaustibility, one of the most important energy sources for humankind in the future. Nowadays, this energy is only widely utilized in certain areas with high heat flow, to produce electric power and to heat various objects such as buildings or greenhouses. However, the energetic potential of areas with normal and even with lowered heat flow is considerable as well.

2.2. Geospheres

The long-term gravitational differentiation within Earth's body, which was enabled by the temperatures in its inner parts having been elevated beyond the limit of plastic behavior of rocks and minerals, led to the concentration of dense rocks, minerals, and elements in Earth's interior and of light ones in its outer layers. With regard to various physical properties and composition, Earth may be viewed as an onion composed of several spherical layers—geospheres (Figure 1). The innermost sphere (with a radius of about 1300 km) is the solid inner core composed mainly of iron and nickel. The liquid metallic outer core, composed predominantly of iron and sulfur, is a layer some 2200 km thick. Earth's mostly solid (from the point of view of instantaneous properties) mantle, about 2800–2870 km thick, is composed mainly of ferrous and magnesian oxides and silicates. The crust that we live on is only a few tens of kilometers thick. It is composed of rocks that can commonly be found on Earth's surface. During the gravitational differentiation, the radius of the core gradually increased and the radius of the whole solid Earth decreased—but only insignificantly, by some 25 km from the time of Earth's origin.

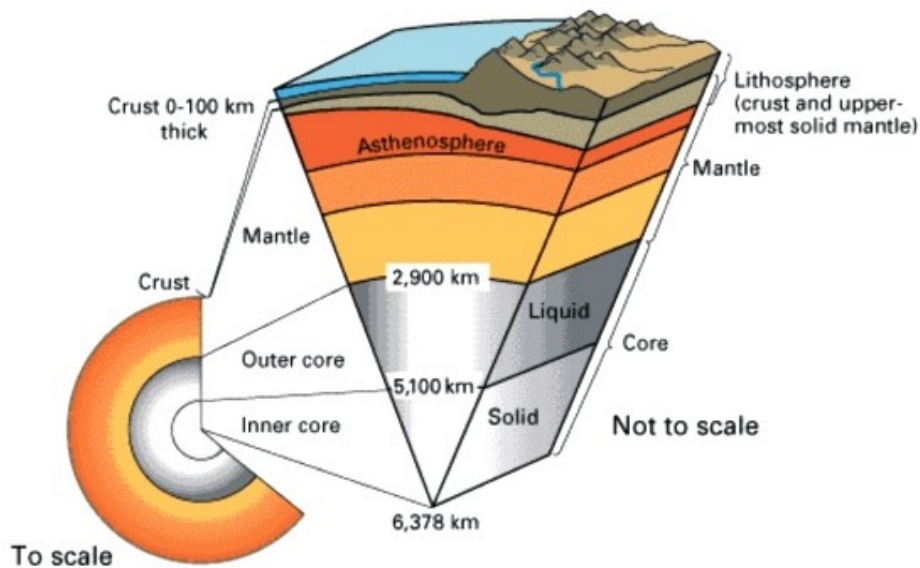


Figure 1. Earth's layers

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/>

From the point of view of mechanical properties, two other important outer layers of Earth are distinguished. The lithosphere comprises the crust and the stiff uppermost part of the mantle. The asthenosphere below is partly molten and forms a layer of irregular thickness (in some places missing altogether) from a depth of 100 to 350 km, but approaching the surface below the mid-oceanic ridges. The boundary between the asthenosphere and lithosphere is thermally defined and corresponds to a temperature of slightly above 1300 °C, at which the mantle rocks begin to melt to some extent. Due to the viscous behavior of the asthenosphere and the rigidity of the lithosphere, the two are at least partly mechanically decoupled. The outer lithospheric shell of Earth is only seemingly stable; in fact it is split into several lithospheric plates which move slowly with respect to one another (see *Plate Tectonics and Landform Evolution*). This relative movement is an expression of the global, thermally driven mass movement of Earth's matter. Larger parts of lithospheric plates, apart from the continental crust, are involved in the deep circulation of Earth's matter. This means that circulating parts of lithospheric plates are born from and then recycled back into the mantle.

The lithospheric plates carry Earth's crust, of which there are two types. The oceanic crust, rather like the upper mantle, consists mainly of dense mafic rocks and minerals and is, together with a thin sedimentary layer, at maximum 10 km thick. It always floors the large oceanic basins and only exceptionally participates in the structure of continental areas. The latter are composed of continental crust, a complex mixture of various rocks 20 to 70 km, but mostly around 35 km thick. The base of the crust is geophysically defined as a boundary of abrupt downward increase in the velocities of seismic waves, known as the Mohorovicic, or *Moho discontinuity*. Due to its composition from less dense rocks, the continental crust is buoyant and does not take

part in the deep circulation of the lithospheric matter. The continental crust began to be formed by gravitational differentiation in the early stages of Earth's history and is still growing due to this process, though negligibly. The oldest parts of the continental crust, the shields or cratons, contain rocks that record processes forming the ancient crust on the juvenile Earth (**See *The Geosphere: Structure and Properties***).

3. The Mantle Engine

All expressions of endogenous processes on Earth's surface depend on the way that heat, as the energy source for movement, is transferred out from Earth's interior. Thanks to the viscous behavior of matter in Earth's interior, heat can be conveyed by the most effective process—convection. But how do we know the physical properties of matter in the inner Earth, which is beyond the reach of direct observations?

3.1. Short-Term Mantle Properties

Most of our knowledge about the inner structure of Earth comes from measurements of the velocities of elastic *seismic wave* propagation. The measured velocities are compared with laboratory data and calculated theoretical velocities of rocks that likely occur in Earth's interior. At certain depths the velocities change quite abruptly, or the waves can be reflected or refracted, which is interpreted as a result of their passage into an environment with different composition and/or rheological behavior. The velocities are considerably higher in solid rocks than in partly molten rocks of the same composition, which accounts for the decrease of the seismic wave rates from the lower lithosphere down to the asthenosphere. Thus, seismologically, the asthenosphere is termed the low velocity zone. Another low velocity zone occurs in the outer core.

The seismic velocities also vary in response to the chemical and mineral composition of the rock medium, being higher in dense rocks enriched in heavy siderophile elements and mafic minerals (e.g., basalt, gabbro) and in rocks that crystallized at considerable depths and high pressures (eclogite, granulite). On the other hand, rocks that are composed mainly of light lithophile elements (e.g., granite, gneiss), or that originated at the surface (porous sediments) exhibit comparatively decelerated velocities. Generally, the rate of seismic wave propagation constrains well the composition and thermal structure of Earth's body.

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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 (PhD) 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 Associate 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.