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Rheology of the Earth's mantle: A historical review

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ABSTRACT

Historical development of our understanding of rheological properties of the Earth's mantle is reviewed. Rheological properties of the Earth's mantle control most of the important geological processes such as the style of mantle convection (e.g., stagnant lid versus plate tectonics) and the nature of thermal evolution. However, inferring the rheological properties of the Earth's mantle is challenging because of the presence of multiple mechanisms of deformation that have different dependence on time-scale (strain-rate), stress levels and other parameters. Through the integration of a broad range of observations including the elastic stiffness from tidal deformation and the viscosity from the concept of isostasy, a gross picture of rheological stratification of the Earth's mantle (a strong lithosphere, a weak asthenosphere and a strong layer below) was proposed in the mid-19th century. However, not only the physical basis for such a model was weak due to the lack of proper understanding of some materials science issues such as the interplay between elastic and viscous deformation but also the lack of understanding of temperature–depth relation associated with convection prevented our understanding of the rheological structure of the Earth's interior. Major progress occurred in the first half of the 20th century in our understanding of the atomistic mechanisms of plastic deformation in solids, and much of the theoretical framework on the plastic deformation of solids was established by late 1960s. Those developments provided a basis for scaling analyses that are critical to the applications of laboratory results to the Earth's interior. Major progress in laboratory studies on rheological properties occurred in the mid-1960s to the early 1970s in Griggs' lab using a new type of solid-medium high-pressure deformation apparatus to pressure ~2 GPa and temperature ~1600 K. The basic concepts such as the water weakening, non-linear rheology and deformation-induced lattice-preferred orientation were identified by their studies. However, large uncertainties in the stress measurements with this type of apparatus were recognized in the late 1970s and high-resolution experimental studies using synthetic samples were initiated in Paterson's lab in the mid-1980s using a high-resolution gas-medium deformation apparatus. However, experimental studies with such a gas-medium deformation apparatus can be conducted only at low pressures (<0.5 GPa) and it is difficult to apply these low-pressure data to the Earth's interior deeper than ~20 km. New experimental techniques to study rheological properties in Earth's deep interior have been developed during the last a few years. These techniques allow us to quantitatively study the rheological properties of Earth materials down to the lower mantle condition (~24 GPa, ~2000 K). Some geodynamic issues related to rheological properties are discussed including (i) the strength of the lithosphere and the origin of plate tectonics, (ii) the origin of the asthenosphere, and (iii) the deep mantle rheology and its influence on thermal history of Earth. Existing models on these topics are reviewed and new alternative models are discussed.

1. Introduction

In his classic articles "History and Current Status of Earth Science" published in 1965–1966 (reproduced as Miyashiro, 2009), Miyashiro emphasized the importance of understanding the historical development of geological sciences. After the in-depth analyses of the logical structure of geological sciences, he discussed that because geological science has intricate, multifaceted nature compared to physics, understanding the history of geological science is critical in order to understand various controversies or models in the proper context. In fact, in his textbook (Miyashiro, 1965, see also Miyashiro, 1973; Kushiro, 2010 —this issue), Miyashiro described the historical development of study of metamorphic rocks and metamorphism. This point was further expanded in his later book (Miyashiro, 1998) where he analyzed the differences in the logical structure between physics and geological sciences taking examples such as Bowen's model of origin of volcanic rocks.

In this article, I present a historical review of studies of rheological properties of Earth's mantle (and crust) following the spirit of Miyashiro. The intention is to identify some of the intriguing but potentially confusing issues in this area through the analysis of the history of this area. Therefore, those topics that have important relevance to some of the currently controversial issues were chosen.

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Importance of understanding rheological properties of the mantle is obvious. Mantle convection controls most of the geological processes in terrestrial planets and the rheological properties of the mantle have the first-order influence on the nature of mantle convection. Some of the fundamental questions of Earth science such as “why does plate tectonics occur on Earth but not on other planets?”, “how do the materials inside of Earth circulate and how are they mixed to control the evolution of this planet?” or “how has Earth evolved thermally?” can be addressed only when we understand the rheological properties of the Earth's mantle. However, the studies of rheological properties of the Earth's mantle are challenging and there have been many controversies in this area. Understanding the history of development in this topic will help appreciate the nature of controversies in this important area of research. Indeed, as discussed in this paper, the historical development of research on this area is complicated and interesting. When rheological properties are studied only from the material science point of view, the approach is straightforward and not much different from typical physical sciences. However, when studies of rheological properties of mantle are conducted to solve some geological problems, the multifaceted aspect of this area becomes immediately clear. Not only does one need to integrate a broad range of observations to come up with plausible models of rheological properties and related geological processes, but also considerations of geological problems often lead one to investigate deep into the materials science basis of deformation of materials. Some examples of the multifaceted nature of this area of science will be described.

This paper addresses the following topics:

- Mechanical properties of solids
- A brief history of studies of the mechanical properties of Earth
- Mineral and rock physics studies on rheological properties
- Mechanical properties of Earth's interior
- Mechanical properties and mantle convection
- Concluding remarks

2. Mechanical properties of solids

2.1. Time-dependent deformation of solids

When stress is applied, materials will be deformed. Deformation can be classified into *elastic* and *non-elastic*. When a small stress is applied for a short time, then a material will be deformed instantaneously, and when the stress is removed, the material goes back to the initial state. This instantaneous and recoverable deformation is called *elastic deformation*. Material properties responsible for elastic deformation are characterized by elastic constants. In contrast, when a large stress is applied or a small stress is applied for a long time, then deformation occurs gradually and, in most cases, after the removal of the stress, the material does not revert to the initial state. Such time-dependent and often non-recoverable deformation is called *non-elastic deformation*. A typical non-elastic deformation is viscous deformation that is characterized by viscosity. The essence of elastic and viscous deformation was known from a study of Hooke in the 17th century (see Timoshenko, 1953). However, the first paper to discuss the operation of two modes of deformation in solids was by Kelvin (Thomson, 1865) where he demonstrated finite energy loss by the observation of amplitude decay of vibrating metals (Al, Cu, Zn).

How does elastic and viscous deformation operate together in a material? There are two fundamentally different models of mechanical properties of matter involving both elastic and viscous component: the Maxwell and the Kelvin–Voigt models (Fig. 1). In both models, the mechanical response of a matter changes across a characteristic time defined by

$$\tau_M = \frac{\eta}{\mu} \tag{1}$$

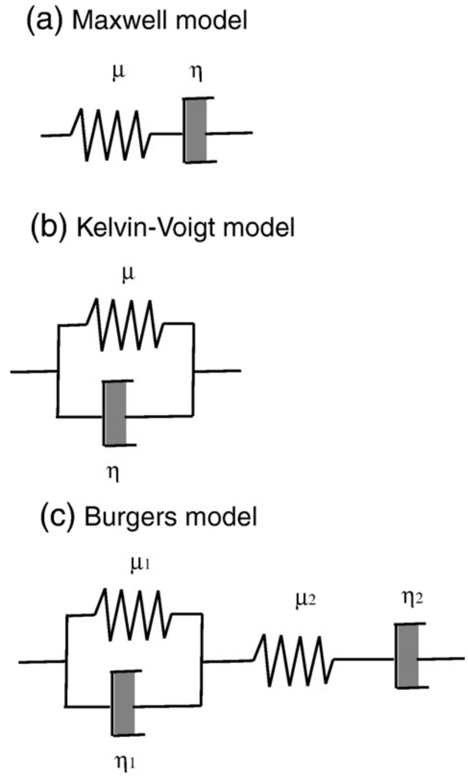

Fig. 1. (a) Maxwell, (b) Kelvin–Voigt model and (c) Burgers model of visco-elastic or anelastic behavior. For the Maxwell model, a material will behave like an elastic solid if the time-scale of deformation is much shorter than the Maxwell time, $\tau_M = \frac{\eta}{\mu}$. In contrast, for the Kelvin–Voigt model, a material will behave like an elastic solid for the time-scale larger than $\tau_M = \frac{\eta}{\mu}$. The Burgers model is a combination of the Maxwell and the Kelvin–Voigt model. The burgers model explains (i) the instantaneous elastic response, (ii) long-term viscous response, and (iii) the intermediate time anelastic response of a material.

where η is viscosity and μ is shear modulus. For the Maxwell model, a material will behave like a viscous material at a long time-scale ($t >> \tau_M$). In contrast, in the Kelvin–Voigt model, a material will behave like a viscous material at the short time-scale ($t = \tau_M$). Therefore choosing either of these models is critical in the interpretation of time-dependent deformation. However from the purely *phenomenological approach*, we cannot make any conclusions as to which model is more appropriate for a particular case. However, neither Maxwell (1867) nor Thomson (1865) provided microscopic mechanisms to justify their models in any detail (for instance, the model by Maxwell was discussed only in a passing reference in his paper on the dynamical theory of gases). In order to understand the physical basis for these models, we need to go one step further into the *microscopic physics* of deformation. But the microscopic physics of plastic deformation of solids was not understood in the 19th century, and in order to understand the microscopic physics of plastic deformation, one needs a concept of crystalline “defects” that was developed in the 20th century.

The Maxwell model describes mechanical behavior of a solid in which viscous deformation can occur indefinitely without any threshold strain (or stress). This corresponds to a case, where some “defects” including melt inclusions or crystal dislocations can move indefinitely. The Kelvin–Voigt model, in contrast, corresponds to a mechanical behavior in which the viscous motion of “defects” creates a “back-stress” and is eventually terminated when the back-stress balances with the applied stress. At sufficiently high-temperatures, any processes creating the back-stress are removed by thermally activated motion of atoms, and consequently, the Maxwell model provides a good description of mechanical behavior from elastic to