Some Issues on the Strength of the Lithosphere

Shun-ichiro Karato*

Department of Geology and Geophysics, Yale University, New Haven, CT 06520, USA

ABSTRACT: The strength of the oceanic and continental lithosphere has important controls on some of the major geological processes on earth including the operation of plate tectonics and the long-term stability of the continental roots. However, explaining these major geological features from the experimental and theoretical studies on the strength of rocks is challenging and some of the existing models for the strength of the lithosphere do not explain these main geological observations. A brief review is provided to summarize recent progress in these areas with the emphasis on experimental studies.
KEY WORDS: lithosphere, plate tectonics, continent.

INTRODUCTION

The strength of the lithosphere has strong influence on the dynamics of the earth. There are two major geological observations that need to be explained in terms of the strength of the lithosphere. First, the subduction of the oceanic lithosphere that is a key element in plate tectonics, is possible only when the oceanic lithosphere is reasonably weak: otherwise so called "stagnant-lid" mode of convection would occur on the earth. Second, according to geochemical studies, the continental roots (~200–300 km) have undergone little deformation for ~3 Ga. This requires high viscosity of the continental roots relative to the surrounding mantle.

However, the explanation of these two major observations in terms of the rheological properties is not straightforward, and a commonly held assumption of "dry" olivine-dominated rheology of the oceanic lithosphere with homogeneous deformation in the ductile regime, and a model of "wet" continental lithosphere (e.g., Kohlstedt et al., 1995, see Fig. 1) cannot explain two of the most important aspects of earth's dynamics, i.e., operation of plate tectonics and the long-term survival of the deep continental roots. It is the purpose of this review to summarize some key results. For more extensive discussion on the strength of the continental lithosphere, a reader is referred to Karato (2010), and for the oceanic lithosphere to Ohuchi et al. (2011).

THE STRENGTH OF THE OCEANIC LITHOSPHERE

The strength of the oceanic lithosphere must be modest in order for plate tectonics to operate (e.g., Richards et al., 2001; Tackley, 2000; Solomatov and Moresi, 1997, for the estimate of the strength of the oceanic lithosphere and its implications to plate tectonics, see also Zhong et al. (1998)). The critical strength of the oceanic lithosphere that allows plate tectonics may be estimated by the energy considerations where the energy dissipation by plastic deformation and gravitational energy release by subduction is balanced (e.g., Conrad and Hager, 1999). With plausible parameter values for gravitational energy release, the critical strength (average strength) of the oceanic lithosphere to allow plate tectonics is ~200 MPa. If the
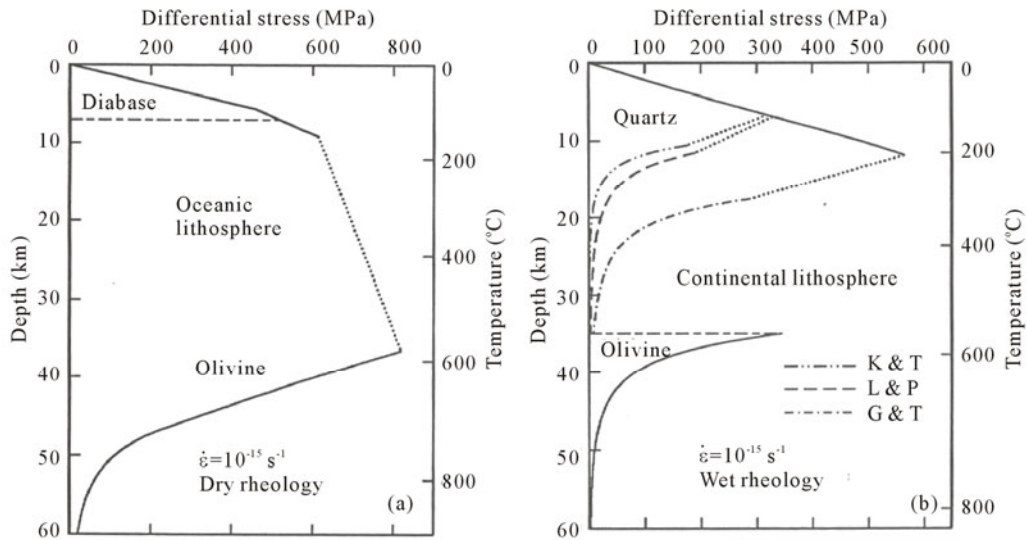
Figure 1. Models of the strength-depth profiles proposed by Kohlstedt et al. (1995). Note that in this model, the peak strength in the oceanic lithosphere exceeds ~600 MPa, while the continental lithosphere is assumed to be "wet" and has weak strength in its deep portion. These two features are inconsistent with the known operation of plate tectonics and the long-term survival of the deep continental roots.

strength of the oceanic lithosphere exceeds this value, the style of convection would be "stagnant-lid convection", a convection style that is considered to operate on many other terrestrial planets such as Venus, Mars and the Moon.

Various attempts have been made to estimate the strength of the lithosphere. The pioneering work by Goetze and Evans (1979) introduced the concept of strength envelope incorporating both brittle failure in the shallow part and plastic flow in the deep part. Following this guideline, Kohlstedt et al. (1995) provided models of the strength of the oceanic and continental lithosphere. In this model, the mantle part of the lithosphere is modeled assuming that its strength is basically controlled by olivine, and the oceanic lithosphere is considered to be "dry" (water-free). In this model, deformation is localized (concentrated on the fault panes) in the brittle regime, but deformation is assumed to be homogeneous in the ductile regime. Consequently, the strength profiles are calculated based on the friction law (Beyrlee's law) for the brittle regime and the ductile creep strength for steady-state deformation in the ductile regime. Their model for the oceanic lithosphere shows the maximum strength of ~600 MPa or higher. Note that their model contains arbitrary "cut-off" strength near the peak and if this cut-off is removed, the peak strength will exceed

1 000 MPa. Even with a cut-off strength, the maximum strength in this model is too high for plate tectonics to operate.

A number of studies have been published to explain the operation of plate tectonics on earth. The key question is why the actual oceanic lithosphere is much weaker than such a simple model predicts. Bercovici and his group, for example, conducted an extensive study to model shear localization using a "damage" model (e.g., Bercovici and Ricard, 2005; Bercovici, 2003). However, some of the physical processes of "damage" are not clearly modeled in their work. A particularly important aspect is the role of small grains during dynamic recrystallization. A preliminary model of deformation of such a two-phase mixture is developed by Karato (2008), but the details need to be worked out including the role of the kinetics of recrystallization and the role of stress-strain distribution. Korenaga (2007) suggested that thermal cracking could penetrate deep into the oceanic lithosphere (~20 km or so) and create a weak zone. However, the validity of deep cracks is unclear because most of the earthquakes in the oceanic lithosphere show compressional stress state (Sykes and Sbar, 1973).

In the recent study by Ohuchi et al. (2011), they showed that orthopyroxene, the second most abundant mineral in the upper mantle, has much smaller

strength under low-temperature conditions. This finding is for nearly "dry" (water-free) orthopyroxene. As discussed by Karato (2008), the weakening effect of water is expected to be stronger for orthopyroxene than for olivine (this point has not been confirmed by experiments yet, however). When the oceanic lithosphere is formed at mid-ocean ridges, most part of it is depleted with water due to the effect of partial melting (Karato, 1986). The degree of water depletion by partial melting depends on mineral, and based on the thermodynamic model of water dissolution, we expect that orthopyroxene likely contains a substantially higher water content than olivine after partial melting (for a detailed discussion see Dai and Karato (2009)). Consequently, in the cold oceanic lithosphere, or-

thopyroxene (at least for those favorably oriented ones) is expected to be much weaker than olivine. If orthopyroxene triggers localized deformation in the upper mantle, the average strength of the oceanic lithosphere will be considerably smaller than the model of homogeneous deformation dominated by olivine would predict. In order to explain the weak strength of the oceanic lithosphere by this model, one needs to investigate the role of weak phase in the deformation of a mixture of weak and strong phases. In particular, the role of a weak phase to promote localized deformation needs to be developed. A cartoon to illustrate the possible role of weak orthopyroxene is shown in Fig. 2. The validity of such a model is currently investigated in my laboratory.
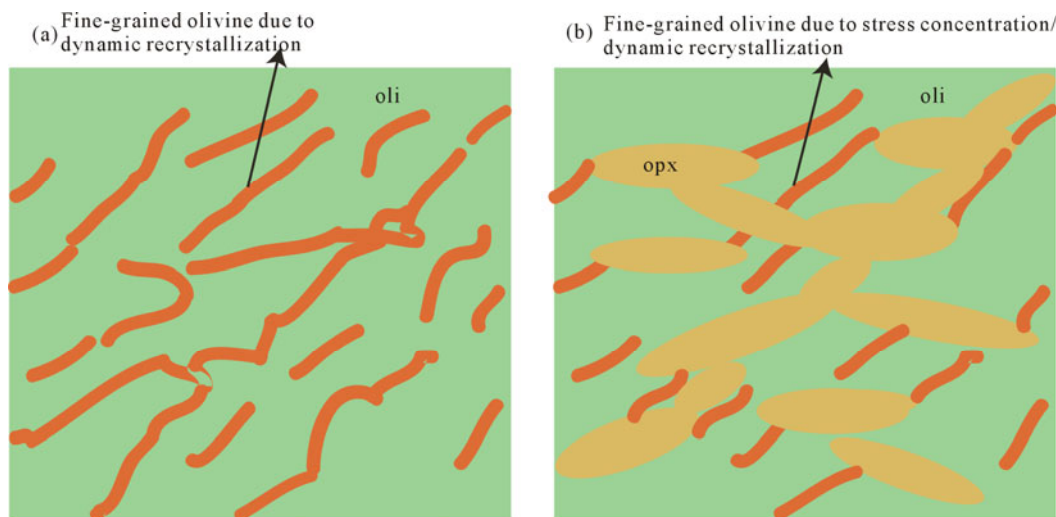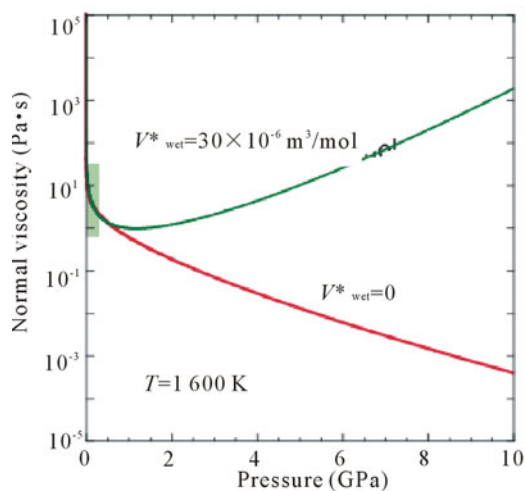

Figure 2. Cartoon showing the mechanisms of shear localization in (a) an olivine-dominated case, and (b) a case where weak orthopyroxene promotes connection of weak regions. Weak orthopyroxene might help shear localization thereby the operation of plate tectonics possible. Experimental studies are underway in Karato's lab to test this hypothesis. oli. Olivine; opx. orthopyroxene.

An opposite problem arises as to the strength of the continental lithosphere by the model of Kohlstedt et al. (1995). In this model, the deep continental lithosphere is considered to be "wet", i.e., water-saturated. Under these conditions, the deep continental roots (200 km or deeper) where temperature is not much different from the surrounding mantle will have lower viscosity than the surrounding mantle, and consequently, the deep continental roots will not survive against convective erosion (e.g., Lenardic and Moresi, 1999; Shapiro et al., 1999), which is not consistent with geochemical observations (e.g., Carlson et al.,
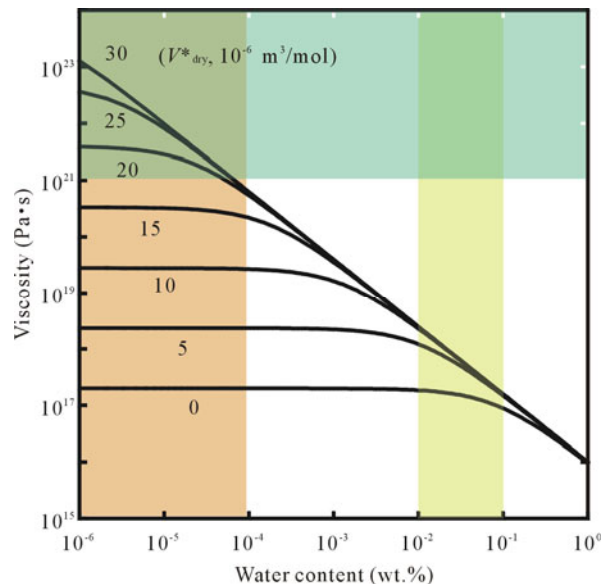
2005).

Under the deep upper mantle conditions, localization of deformation is unlikely, and one can focus on the creep strength of rocks under nearly steady-state conditions. Also, at high temperatures, orthopyroxene becomes stronger than olivine. Consequently, the strength of the deep upper mantle is well represented by that of olivine at steady-state conditions. Two issues are the key to understand the deep upper mantle rheology. These are the influence of pressure and of water on rheological properties. Karato (2010) reviewed recent experimental studies of the role of

water and pressure on olivine rheology and discussed the key issues on the survival of the deep continental roots. One model to explain the long-term stability of the deep continental roots is to suppose that when the continental lithosphere was formed, it was depleted with water by extensive partial melting. If this is the case, the continental roots will be strong (relative to the surrounding water-rich mantle) because of the contrast in water content. In fact, there is rich evidence of extensive partial melting and resultant depletion in hydrogen (water) and other incompatible elements as reviewed by Carlson et al. (2005). However, quantifying the role of water on deformation is not trivial, and the results that can be applied to the deep upper mantle were obtained only recently (Kawazoe et al., 2009; Karato and Jung, 2003). The key is that experimental results on the role of water and pressure

that can be extrapolated to the deep upper mantle (>50 km) must be performed at high- pressures exceeding at least ~1 GPa (Karato and Jung, 2003). Results from high-resolution Paterson apparatus below 0.5 GPa, such as Mei and Kohlstedt (2000a, b), cannot be extrapolated to the main part of the lithosphere or the asthenosphere because of the change in the thermodynamic properties of water at around 0.5 GPa (Fig. 3). Hirth and Kohlstedt (2003) discussed the upper mantle rheology down to ~300 km depth based on the experimental data obtained at low pressure (<0.5 GPa), and the extrapolation of these data to higher pressures was made by using arbitrary chosen values of activation volumes. As emphasized by Karato (2010),

Figure 3. A diagram illustrating the range of uncertainties if only low-pressure data are used to estimate the viscosity of the deep upper mantle under "wet" conditions (from Karato, 2010) (V^*_{wet} is the activation volume of wet olivine). At low pressures (<0.5 GPa), the fugacity effect dominates and viscosity is reduced with pressure. At high pressures (>1 GPa), the activation volume term can also be important for a reasonably large activation volume. Both effects need to be characterized, but the activation volume effect can be determined only from data at pressures exceeding ~1 GPa. If only data below ~0.5 GPa are used, activation volume (V^*_{wet}) is unconstrained that leads to large uncertainties in estimating the viscosity in the deep upper mantle.

Figure 4. The influence of water-depletion on the change in viscosity (from Karato, 2010). The yellow region shows the likely water contents in the typical oceanic asthenosphere in the continental margin. V^*_{dry} is the activation volume of dry olivine. If V^*_{dry} is larger than ~10×10^{-6} m^3/mol, and if the water content in the continental roots is as low as shown by an orange region in this figure, the viscosity contrast between the continental roots and the surrounding deep upper mantle is large enough to maintain the deep continental roots undeformed for billions of years. The recent experimental study by Kawazoe et al. (2009) showed that $V^*_{dry}=(15–20)\times10^{-6}$ m^3/mol, but the water content in the deep continental root is controversial. For more detailed discussion, see Karato (2010).

the values of activation volume were not well constrained before Kawazoe et al. (2009) (values ranging from ~0 to ~27 cm^3/mol were published for "dry" olivine) and consequently the arguments by Hirth and Kohlstedt (2003) have very weak physical basis). In evaluating the role of water depletion on the strength of rocks in the deep upper mantle, the role of pressure to change the strength of water-depleted rocks needs to be evaluated. Such a study requires new techniques for the quantitative studies of rheological properties under high-pressure and temperature conditions equivalent to the deep upper mantle. Due to the recent development of new technologies using RDA (rotational Drickamer apparatus) operated at a synchrotron X-ray facility, Kawazoe et al. (2009) determined the rheological properties of "dry" olivine to P ~10 GPa and T ~2 000 K and combined with the study by Karato and Jung (2003) on "wet" olivine, the quantitative model for the rheological properties of the deep upper mantle was proposed (Karato, 2010) (Fig. 4).

These studies showed the importance of development of new techniques to explore the rheological properties of the deep interior of the earth (e.g., Karato and Weidner, 2008). It must be emphasized that although high-precision data are obtained at low pressures (<0.5 GPa), data from low-pressure (<0.5 GPa) cannot be extrapolated to the upper mantle below ~50 km because of the change in the thermodynamic behavior of water at around 0.5 GPa. Also, some minerals, such as orthopyroxene, are stable only at pressures exceeding 0.5 GPa (at relatively high temperatures). In addition to these technical developments, we also need a better theoretical model for shear localization to understand the strength of the oceanic lithosphere, where localized deformation likely determines its strength.

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