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Short communication

Bulk attenuation in the earth's mantle due to phase transitions

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ABSTRACT

The calculated bulk attenuation due to phase transition from mineral physics data is reported here. With relaxation time less than 1 s, the calculated value for a pyrolite mantle is consistent with the inverted bulk attenuation of the upper mantle from seismic observations. The two important mechanisms of phase transitions, diffusion-controlled and kinetics-controlled, have different relaxation time as indicated by the models here. The diffusion controlled is more likely to contribute to the observed seismic bulk attenuation than the kinetic-controlled process based on the available diffusivity and kinetics data. The correlation between the bulk attenuation and relaxation time emphasizes the importance of a number of parameters in the mineral physics database such as Fe–Mg diffusivity and kinetics in olivine–wadsleyite–ringwoodite–perovskite, Mg–Ca–Al–Si diffusivity and kinetics in pyroxene–garnet–Ca perovskite, some of which are still unknown.

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1. Introduction

Finite bulk attenuation has been agreed to be required to explain the observed damping of radial modes (Anderson, 1980; Durek and Ekstrom, 1995; Sailor and Dziewonski, 1978) even though the dissipation of seismic energy is dominated by shear losses. Bulk attenuation should occur somewhere in the Earth such as the upper mantle (Durek and Ekstrom, 1995; Sailor and Dziewonski, 1978; Widmer et al., 1991); the inner core (Anderson, 1980; Anderson and Hart, 1978a; Dziewonski and Anderson, 1981) or the outer core (Anderson and Given, 1982; Widmer et al., 1991). The plausible mechanisms of attenuation, based on the mineral physics studies (Budiansky and O'Connell, 1980; Budiansky et al., 1983; Heinz et al., 1982), have been proposed as thermoelastic heterogeneity of composite materials for the upper mantle or presence of partial melt or fluid for the core. However, an important mechanism, i.e. phase transitions, has been ignored even though kinetics near equilibrium phase boundaries may be the limiting factor in seismic normal modes (Tamisiea and Wahr, 2002). Moreover, phase transition can contribute to the bulk attenuation due to its volume variation during the process. Table 1 listed the reported compressional attenuation of the mantle from inverted radial models and mineral physics models. In general, the upper mantle, where major minerals transform to denser phases, has higher bulk attenuation than the lower mantle. The mineral physics models (see later in the text) show strong dependence on the relaxation time and seismic period. The Q_K with relaxation time of 1 s and seismic period of 300 s is comparable with major seismic studies.

The relaxation theory of bulk attenuation (Anderson, 1980) defines $Q_k^{-1}(\omega) = (\Delta K/K)(\omega\tau_v/1 + (\omega\tau_v)^2)$, in which $(\Delta K/K)$ is the fractional difference between the high frequency and low frequency moduli, ω is the seismic frequency, τ_v is the volume relaxation time. The materials undergoing phase transitions may have a relaxed bulk modulus (K_0) lower than its unrelaxed bulk modulus (K_∞) due to the extra volume reduction (ΔV), as defined by $(1/K_0) = -(V/\delta V) = -(1/\Delta P)(\Delta V/V)_{\text{tran}} + (1/K_\infty)$.

Fig. 1 shows the calculated inverse Q_K for the mantle due to phase transitions alone. Q_K was calculated using previously reported the volume changes (ΔV) and width of the binary loop (ΔP) for the phase transitions (e.g. olivine–wadsleyite–ringwoodite (Katsura and Ito, 1989; Navrotsky, 1995), ringwoodite–post spinel (Ito and Takahashi, 1989), pyroxene–garnet–perovskite (Gasparik, 2003). The model uses pyrolite composition and a geotherm (Brown and Shankland, 1981). The corresponding unrelaxed and relaxed velocities were calculated using software (TR410 and TR660) as used by previous study (Wang et al., 1998; Li and Weidner, 2008). The used wave period ranges from 100 to 500 s, since the high frequency radial modes are most sensitive to the upper mantle structure and have period from 100 to 500 s (Durek and Ekstrom, 1995). The dispersion of Q_K from 100 s to 500 s is found to be about a factor

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Table 1
Compressional attenuation of mantle. Depth at 410 km represents the region in the middle of 410 km phase loop for olivine.

Q_K, upper mantle	Depth, km	References
10,000	24.4–2891	Anderson (1980)
400	24.4–670	Sailor and Dziewonski (1978)
15,200	24.4–2891	Durek and Ekstrom (1995)
1060	24.4–670	Durek and Ekstrom (1995)
27,700	220–2891	Durek and Ekstrom (1995)
175, 213	80–220	Durek and Ekstrom (1995)
780	24.4–670	Dziewonski and Anderson (1981)
1050	24.4–670	Widmer et al. (1991)
1029, 943	24.4–670	Durek and Ekstrom (1996)
939	24.4–670	Li (1990)
1.1–10	410	Ricard et al. (2009), T = 300 s
74,000	Mantle[a]	This study, $\tau_v = 0.01$ s, T = 300 s
740	Mantle[a]	This study, $\tau_v = 1$ s, T = 300 s
62,244	410	This study, $\tau_v = 0.01$ s, T = 300 s
622	410	this study, $\tau_v = 1$ s, T = 300 s

[a] Represents regions of the mantle where phase transitions occur. $\tau_v = 0.01$ s, T = 300 s represent a relaxation time of 0.01 s, a 300 s (period) seismic wave.

of 10. Fig. 1 has relaxation time τ_v for phase transition as 0.01 s (Li and Weidner, 2008). Also plotted in Fig. 1 is the result from a previous study (Ricard et al., 2009) which has larger relaxation time. The difference between these two studies will be discussed in Section 2.

Fig. 2 illustrates the bulk attenuation versus depth as inverted from the radial free oscillation data (Anderson and Hart, 1978b; Durek and Ekstrom, 1995; Sailor and Dziewonski, 1978). The bulk attenuation scatters among these studies but is generally less than 2×10^{-3}. In addition, the bulk attenuation is illustrated for two relaxation times: 1 s and 0.01 s. However, the calculated $1/Q_K$ due to these phase transitions can exceed the Q_K^{-1} from the free oscillation data, depending on the relaxation time of the phase transition. Fig. 3 illustrates the calculated bulk attenuation due to these phase transitions evaluated for 300 s oscillations as a function of the relaxation time. Also illustrated here is the inferred maximum attenuation from the free oscillation data(Durek and Ekstrom, 1995). Since the phase transformation kinetics will account for only a portion of the bulk attenuation, Fig. 3 indicates that the characteristic time for the phase transformation must be either less than 1 s or greater than 10^5 s. In between these values, the bulk attenuation due to the phase transformation will exceed the maximum allowed attenuation in the seismic frequency band. Since most laboratory determinations of phase boundaries require less than a day (10^5 s), the appropriate kinetic time for mantle phase transitions should be less than 1 s.

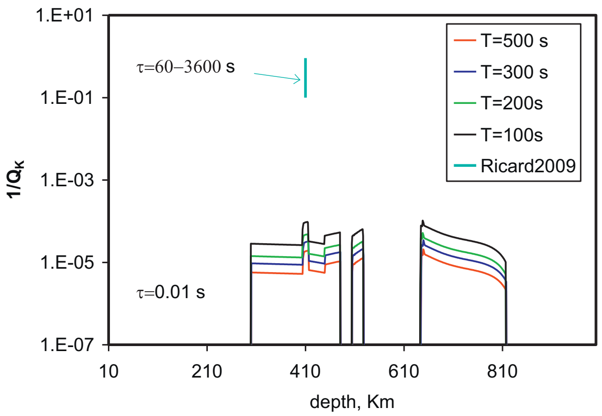

Fig. 1. Bulk attenuation due to phase transitions alone. The bulk attenuation is $Q_k^{-1}(\omega) = (\Delta K/K)(\omega\tau_v/1 + (\omega\tau_v)^2)$, in which $\Delta K/K = (K_0 - K_\infty)/K_\infty$. The relaxation time of phase transition is 0.01 s. The four periods of 100–500 s represent the period of the sampling seismic wave. Also plotted are Q_K from a previous study (Ricard et al., 2009).

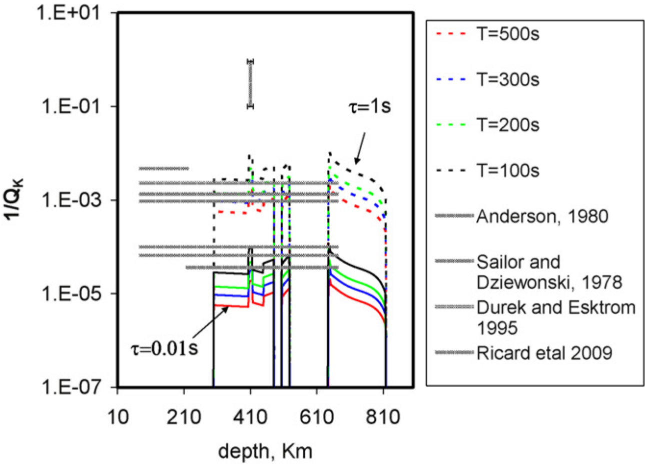

Fig. 2. Bulk attenuation due to phase transitions as in Fig. 1. Added are the plots for relaxation times of 1 s. Also plotted are Q_K inverted from the spheroidal free oscillation data (Anderson and Hart, 1978b; Durek and Ekstrom, 1995; Sailor and Dziewonski, 1978).

As indicated in Figs. 1–3, the estimation of bulk attenuation highly depends on the relaxation time. There has been reported relaxation time (Anderson, 1980; Bukowinski and Knopoff, 1976; Zener, 1948) ranging from 10^{-9} to 1 s for the Earth's core. However, the relaxation time for the mantle due to phase transitions has not been modeled quantitatively despite the recognition of its importance (Anderson, 1989, 1980; Jackson, 2007; Li and Weidner, 2008; Ricard et al., 2009; Tamisiea and Wahr, 2002). Below we explore two distinctive models for phase transforming aggregates to define the relaxation time of the mantle.

2. Dissipation mechanism of phase transitions

The materials undergoing phase transitions are uniquely governed by kinetic processes. At least two factors can limit the kinetics of a reconstructive phase transition. One is the velocity that the reconstruction interface can move. The second is the rate that the composition of the region that is transforming can adjust to the new equilibrium conditions. For the major phase transition occurring at 410 km depth of the Earth, olivine to wadsleyite, the relaxation processes are dominated by: (1) Nucleation and growth

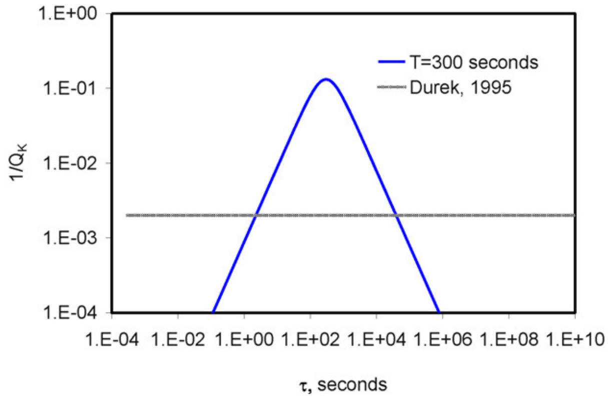

Fig. 3. Bulk attenuation for the upper mantle as a function of relaxation time. The sampling wave has a period of 300 s. Also plotted are the inverted results from the radial free oscillation (Durek and Ekstrom, 1995). The attenuation due to phase transition must be less than the seismically observed value thus the relaxation is either shorter than 1 s or longer than 10^5 s.

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