Kinetics of melting in peridotite from volume strain measurements

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ABSTRACT

Partial melting in the Earth's mantle involves a combination of processes such as ionic diffusion and solid–liquid transition. These processes yield an array of characteristic times for the melting kinetics. Both the magnitude and time constant of melt-induced volume strain affect seismic velocity, attenuation, and buoyancy. In situ monitoring of samples during melting are enabled by multi-anvil high-pressure devices coupled with synchrotron X-ray radiation. In this study, the volume strain induced in a sample from melting is measured as a function of time using X-ray images. We find a doubling of the effective thermal expansion for only 2% melt both from our data and from thermodynamic models of peridotite. The characteristic time of melting is determined to be less than one second. These findings have a direct impact on the effect of melting on seismic velocities.

1. Introduction

Melting is a profound phase transformation that is accompanied by significant changes in strength, volume, and viscosity. Because of the chemical complexity, most rocks melt over a wide temperature range. Changes in pressure, temperature, or stress will promote a change in the amount of melt. Since the melt is inherently less dense than the solid, these changes in pressure, temperature, or stress will result in an enhanced effective compressibility, thermal expansion, or elastic compliance and, ultimately affect sound velocity and buoyancy.

This effect is simply illustrated for changes in pressure or temperature as they are accompanied by a change in the amount of melt in the system. Melting induces a volume change of the sample because the melt volume is generally significantly different from that of the host crystals. The volume change, in turn, affects both the effective thermal expansion and the effective compressibility as the fraction of melt (F) changes due to changes in P and T. The resulting thermal expansion α and the compressibility β are:

$$\alpha_{\text{effective}} = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_X + \left(\frac{\Delta V}{V}\right)_{\text{melting}}\left(\frac{\partial F}{\partial T}\right)_X \tag{1}$$

$$\beta_{\text{effective}} = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_X - \left(\frac{\Delta V}{V}\right)_{\text{melting}}\left(\frac{\partial F}{\partial P}\right)_X \tag{2}$$

where $(\Delta V/V)_{\text{melting}}$ is the relative volume change associated with melting. X represents the P–T path of the perturbation. These terms are typically isothermal (T), adiabatic (S), or constant pressure (P), or, as in a realistic high pressure experiment, is a combination of these. The first term on the right is the intrinsic thermal expansion (compressibility). This term includes the properties of all of the phases present as a mechanical ensemble. The case where this term is defined for a solid–liquid mixture has been studied in depth e.g. (Hammond and Humphreys, 2000a,b; Mavko and Nur, 1975; Sato et al., 1989; Spetzler and Anderson, 1968) and it has been concluded that the compressibility is relatively insensitive to the presence of a small amount of melt, while the shear modulus can vary significantly as a function of the amount of melt present (F) but the magnitude of this effect also depends on the geometry of the melt.

The second term on the right side of these equations is the volume strain resulting from melting as P or T change. It depends on the melt productivity ($\partial F/\partial T$ or $\partial F/\partial P$) and is independent of the amount of melt present (F). The effective thermal expansion (compressibility) defined in Eqs. (1) and (2) are the zero frequency value of the variables as they represent thermodynamic equilibrium. The kinetics of the melting process will make these terms time dependent.

Thermodynamic calculations with the MELTS program (Smith and Asimow, 2005) for a peridotite composition suggest that melting will double the thermal expansion or the compressibility for about 2% melt. The impact of melting on seismic velocities (Anderson, 1989; Li and Weidner, 2013) or mantle convection and post-glacial uplift (O'Connell, 1976) depends on the time that is required for significant melting to occur, that is, the kinetics of melting.

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Several processes can control the kinetics of melting. In order for the equilibrium portion of melt to form, atoms must diffuse. The construction/deconstruction of crystal structures must occur and can create a delay between the time of the change in state and the attainment of equilibrium. Understanding the process will assist us in relating laboratory measurements to planetary-scale issues. Indeed, melting will impact the density even before equilibrium is attained. Thus, it is important to know the time dependence of the density change in order to define the impact of melting on these Earth issues.

The relaxation time τ of an activated process is generally represented by $\tau(P,T) = \tau_0 \exp\left[\frac{(E^* + PV^*)}{RT}\right]$ (Anderson, 1989), where E^* and V^* are activation energy and volume, τ_0 is a reference characteristic time, P and T are the pressure and temperature departure from the reference state. For partial melting, τ_0 has multiple values. In the case for the bulk sample to reach compositional equilibrium, the ionic diffusion is rate-limiting, yielding a τ_0 that depends on a characteristic length and the diffusion coefficients. On the other hand, the atomic level process of moving the crystal–liquid interface could be characterized with a different τ_0, where this latter characteristic time is probably shorter than the diffusion characteristic time. τ impacts the seismic velocity by:

$$c^2(\omega) = c_0^2 \left(1 + \frac{\omega^2 \tau^2 c_\infty^2}{c_0^2}\right) \Big/ \left[(1 + \omega^2 \tau^2)^2 + 2\omega^2 \tau^2 Q_{max}^{-1}\right]^{1/2} \qquad (3)$$

where $2Q_{max}^{-1} = \frac{c_\infty^2 - c_0^2}{c_0 c_\infty}$, c is the phase velocity, ω is seismic frequency. c_∞ and c_0 are velocities at infinite and zero frequency (Anderson, 1989). The goal of this study is to define the time scale for significant volume change associated with melting.

Seismic velocities $V_p = \sqrt{(K + \frac{4G}{3})/\rho}$ and $V_s = \sqrt{G/\rho}$ depend on elastic moduli, where K and G are bulk modulus (or inverse of compressibility) and shear modulus and ρ is density. Both bulk and shear moduli are affected by melting due to the transformation volume as discussed elsewhere (Li and Weidner, 2013). The crucial factor concerning the effect of melting on seismic velocities is the value of $\omega\tau$. If $\omega\tau \ll 1$, the seismic wave will experience a media with reduced elastic moduli, resulting in a slowing of the seismic velocity. For $\omega\tau \gg 1$, maximum values of seismic propagation will occur. If $\omega\tau \approx 1$, then the velocity will be frequency dependent and seismic attenuation will result.

In our previous study (Li and Weidner, 2013), we probed the significance of Eq. (2) on the effective elastic moduli. The results indicate a significant melting-induced softening caused by a non-negligible $\partial F/\partial P$ (Young's modulus softened to less than half of the intrinsic value). That study (Li and Weidner, 2013) measured the modulus at a period of 720 s to mimic seismic frequency. The study reported here is designed to measure the time scale of melting though the viewpoint of Eq. (1) by varying temperature to investigate the time response of the system, i.e. the term $\partial F/\partial T$. The experiment uses X-ray images of the sample from a CCD camera that can capture sample images at tens of frames per second in which we can resolve volume strain at 10^{-4} precision. The uniqueness of this study is to use image-resolved volume strain a at sub-second time scale to yield effective thermal expansion during melting in situ at high P–T. This study by changing $\partial F/\partial T$, is complementary to the study varying $\partial F/\partial P$ (Li and Weidner, 2013), both provide strong arguments to support a short characteristic time and softened elastic modulus of peridotite in partially molten regions of the Earth's mantle.

2. Experimental methods

Our measurement of thermal expansion centers on measuring sample dimensions (Li et al., 2003; Li and Weidner, 2007, 2013) using synchrotron X-ray absorption images of the sample in the D-DIA high pressure device. Details of the experimental setup are further described in (Li and Weidner, 2014).

The sample, fine ground KLB1 peridotite powder (Takahashi, 1986) (~5 micron grain size), was cold pressed to 1.5 GPa, then heated to subsolidus conditions (c.a. 850 °C) and annealed for 30 min. The melting relations of this peridotite have been thoroughly studied as a function of pressure (Herzberg et al., 1990; Takahashi, 1986; Takahashi and Scarfe, 1985) as a model mantle composition. Rather than a conventional cell assembly as used in (Li and Weidner, 2007), a rhenium capsule is used to wrap the cylindrical sample (1 mm diameter, 1.5 mm long) to serve as the lateral strain marker, as illustrated in Fig. 1. The sample, S, is located between two dense corundum rods, A1 and A2, also decorated with Re foils above and below. In our experiment, the thermocouple is placed outside of the capsule, yielding a measured temperature that could be 100 °C lower than the sample temperature.

In the DIA geometry, the X-ray beam passes between two of the anvils on it is entrance and two more on it is exit from the sample. Tungsten carbide anvils truncate the beam width to less than one millimeter, thereby obscuring the lateral dimension of the sample. Thus, we used sintered diamond as the lateral anvils as they are
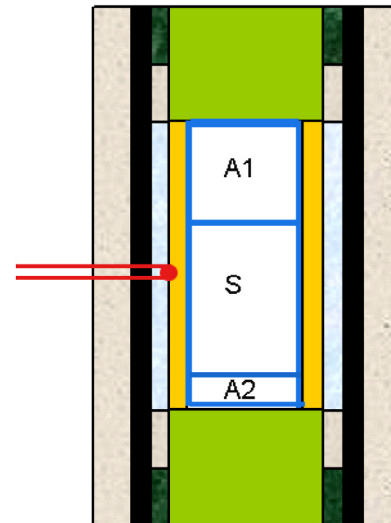
	Material
	Al2O3
	carbon U5
	carbon UF4S
	Al2O3
	Boron Nitride
	carbon U5
	crushable al2o3
	Re foil
	Thermocouple

Fig. 1. Cell assembly for thermal expansion experiments. The diagram indicates the inner cylinder that is located within an amorphous boron-epoxy cube with 6 mm edge lengths. A1 and A2 are dense corundum rods; S is the KLB1 sample.