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Influence of phase transformations on lateral heterogeneity and dynamics in Earth's mantle

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Abstract

Using a self-consistent computation of phase equilibria and physical properties, we determine isobaric velocity–temperature and velocity–density scalings as a function of depth, focusing on the upper 800 km. The scalings contain an isomorphic part due to the influence of temperature on the physical properties of individual phases, and a metamorphic part due to variation of phase abundances and compositions with temperature. We show that the contribution from phase transformations is comparable in magnitude to that of temperature alone, and has important consequences for mantle structure. Both scalings are highly non-linear functions of temperature and depth even in the elastic limit due to the influence of phase transitions: near sharp phase transitions seismic velocities become much more sensitive to temperature. We expect the magnitude of lateral variations in seismic velocity to vary rapidly with depth. This result has important implications for the interpretation of smoothed tomographic models, particularly in the upper 1000 km, and possibly the bottom few hundred km, where phase transformations have a large influence on the structure. It will be important to include the metamorphic contribution of the scalings in geodynamical studies relating seismic structure to thermal structure or the gravity field. We find that the combined phase buoyancy of transitions near 520 km depth is equal in magnitude to that of the olivine to wadsleyite transition and should be included in future dynamical studies.

Keywords: mantle; thermodynamics; high pressure

1. Introduction

Below the lithosphere, Earth structure is approximately spherically symmetric and physical properties depend most strongly on depth. Deviations from radial structure, that is variations in physical properties with latitude and longitude at a given depth, while small, are disproportionately important in our understanding of Earth's dynamics and evolution. For example, lateral variations in density drive mantle flow and plate motions and produce dynamic topography and the non-hydrostatic part of the geoid and gravity field. Seismic wave velocities vary laterally and the results of seismic tomography are providing us with an increasingly clear and robust view of three-dimensional mantle structure.

With advances in seismic tomography and mineral physics, particularly knowledge of the elastic properties

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of mantle phases at high pressure and temperature, has come an increasing interest in the origins of lateral heterogeneity. Much of the lateral variations seen in seismic tomography are likely to be related to lateral variations in temperature. Quantifying this relationship has proved difficult, in part because of the non-uniqueness of tomographic models (e.g. damping) and remaining uncertainties in key mineralogical properties. Because the magnitude of lateral variations is small, consideration of second-order effects such as attenuation and dispersion are important, if still ill-constrained experimentally, particularly at mantle pressures. Lateral variations in chemical composition almost certainly contribute as well, for example associated with depletion of the continental lithospheric mantle. In the deep mantle, the relationship between lateral variations in S- and P-wave velocities cannot be explained by lateral variations in temperature alone, although what other causes might be responsible is still a matter of debate.

Here we demonstrate another important contributor to lateral heterogeneity that has so far received little attention: that due to lateral variations in phase proportions and compositions (Anderson, 1987). We will argue that the contribution from phase transformations is reasonably well constrained experimentally, is comparable in magnitude to that of temperature alone in a monophase aggregate, and should be included in future analyses of three-dimensional structure. We first outline the thermodynamic theory and illustrate the effect of phase transformations with examples. We then explore the influence of phase transformations on the temperature variation of velocity and density in a realistic mantle composition. Finally we draw some conclusions regarding the likely importance of phase transformations in the interpretation of mantle structure.

2. Theory

Consider the seismic wave velocity in the vicinity of a phase transformation (Fig. 1). Because the mantle is a multi-component system, phase transformations generally occur over a finite depth interval, ΔP. Assume that the velocity contrast between the two phases is ΔV. It is generally assumed that the passage of the seismic wave is sufficiently rapid and the stresses generated sufficiently small, that no phase transformation is induced. In this case, the velocity increases monotonically with increasing depth across the phase transformation interval. The details of the shape of the transition, i.e. whether the velocity depends linearly or non-linearly on depth within the phase transformation interval (Stixrude, 1997) are not important for the present argument.

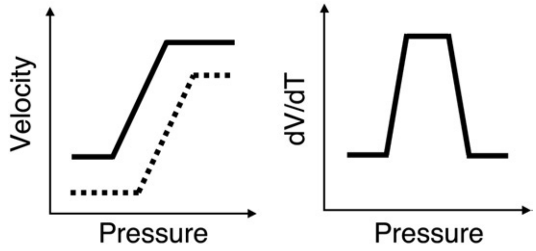

Fig. 1. Schematic illustration of (left) the seismic wave velocity in the vicinity of a phase transformation in a colder (solid) and hotter (dashed) portion of the mantle and (right) the temperature derivative of the velocity.

Assume for purposes of illustration that the phase transformation has a positive Clapeyron slope. The Clapeyron slope is not uniquely defined for multi-component phase transformations. For the purposes of illustration we may take the effective Clapeyron slope to be, for example, $\Gamma = (\mathrm{d}P_{1/2}/\mathrm{d}T)_{\mathrm{eq}}$, where $P_{1/2}$ is the pressure at temperature T at which the phase transformation is half completed.

Now consider the same depth interval but at a different geographic location where the temperature is greater by δT (Fig. 1). The difference in velocity between colder and hotter mantle at the same depth represents the lateral variation in the velocity. The hotter mantle differs in two ways. First, the velocity is generally lower everywhere, in accord with the experimental observation that the velocity decreases with increasing temperature. Second, the phase transformation occurs at a greater depth. The difference in velocity is relatively small above and below the phase transformation interval and is governed by the temperature dependence of the velocity in the low and high-pressure assemblages, respectively. Within the phase transformation interval, the difference in velocity is much greater and is a function of the difference in velocity between the two transforming phases. Because the difference in velocity between phases is generally much larger than the influence of temperature on the velocity of a single phase, the contribution from phase transformations can be large.

Formally, we may write

$$\left(\frac{\partial \ln X}{\partial T}\right)_P = \left(\frac{\partial \ln X}{\partial T}\right)_{P,\vec{n}} + \left(\frac{\partial \ln X}{\partial \vec{n}}\right)_{P,T}\left(\frac{\partial \vec{n}}{\partial T}\right)_P \qquad (1)$$

for the variation of the velocity or density with lateral variations in temperature where X is some physical property of the assemblage, such as the longitudinal, shear, or bulk sound velocity or the density, and $\vec{n}$ is the vector specifying the amounts of all end-member species of all phases. The first term on the right hand