Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 255 (2007) 357 – 366
EPSL
www.elsevier.com/locate/epsl

Possible density segregation of subducted oceanic lithosphere along a weak serpentinite layer and implications for compositional stratification of the Earth's mantle

Cin-Ty Aeolus Lee [a,*], Wang-Ping Chen [b]

[a] *Department of Earth Sciences, MS-126, Rice University, 6100 Main St., Houston, Texas, United States*
[b] *Department of Geology, University of Illinois, Urbana-Champaign, United States*

Received 2 November 2006; received in revised form 15 December 2006; accepted 22 December 2006
Available online 8 January 2007
Editor: C.P. Jaupart

Abstract

There is growing evidence that the top part of the oceanic mantle is pervasively serpentinized prior to subduction. Because the interior of a subducting slab heats up slowly, the serpentinized layer can be preserved for tens of Myr, thereby forming a weak zone that allows for mechanical decoupling between the oceanic crust and underlying lithospheric mantle. Once the crust is eclogitized, a shear stress would be induced by a compositionally-driven buoyancy difference between the crust and the lithospheric mantle. By simple force balance, we show that the downward slip velocity of the crust relative to the lithospheric mantle is similar to subduction velocities themselves; hence, conditions necessary for segregation of eclogitized crust from lithospheric mantle are generally met well before the slab approaches the lower mantle. The segregated components are predicted to journey to different resting grounds. Depleted lithospheric mantle, being slightly less dense than the ambient mantle, would eventually rise upward and congregate in the upper mantle while eclogitic crust would settle in a neutrally buoyant state near the bottom of the transition zone or at the base of the lower mantle. We speculate that this process gradually leads to the irreversible compositional stratification of the Earth's mantle.

Keywords: eclogite; subduction; serpentine; decoupling; slab segregation; mantle convection

1. Introduction

There seems to be little doubt that the upper part of the mantle, as sampled by mid-ocean ridge basalts (MORBs), is on average depleted in highly incompatible trace elements (large ion lithophile elements, Ti, Nb, light rare-earth elements, noble gases, U and Pb) as well as in some moderately incompatible elements, such as Al [1–9]. Much of this depletion can be accounted for by the continental crust, which is enriched in these same elements and hence exhibits a trace-element signature complementary to that of the upper mantle [3]. However, if the entire mantle was depleted, the sum of trace elements in the mantle and in the continental crust does not add up to that expected for the Earth's primitive mantle. This discrepancy has led to the long-held view

* Corresponding author. Tel.: +1 713 348 5084.
E-mail addresses: ctlee@rice.edu (C.-T.A. Lee), wpchen@uiuc.edu (W.-P. Chen).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2006.12.022

among geochemists that the upper mantle is depleted and relatively isolated from more enriched reservoirs in the lower mantle.

The problem at hand is that a number of geodynamic models [10,11] and interpretations of seismic tomography [12–14] seem to suggest that convection occurs on a whole-mantle scale, making it difficult to preserve trace-element and isotopic stratification in the mantle. The discordance between geochemical and geophysical perspectives has led to a series of attempts to generate models that allow for whole-mantle convection while preserving isolated geochemical reservoirs [15–17]. However, most geodynamic models do not explicitly consider the intimate link between mantle convection and chemical differentiation, a coupled process that gives rise to both trace and major element heterogeneities. An example of such coupling is the process of melting at mid-ocean ridges: adiabatic decompression of the mantle beneath the ridges leads to partial melting and the making of new oceanic crust and an underlying residual mantle within the oceanic lithosphere. This residuum is depleted in Ca, Fe, and Al, and thus is compositionally buoyant with respect to ambient mantle.

Over geologic time, could the cumulative effect of repeated melting and generation of basaltic oceanic crust and depleted mantle residuum provide a way to generate compositional stratification in the mantle? If subducted lithosphere is assimilated into the mantle wholesale, then no long-term stratification of the mantle would result because, except for modification in trace elements due to dehydration or to small amounts of partial re-melting during subduction, wholesale subduction of oceanic lithosphere is essentially an isochemical process. If, on the other hand, the oceanic crust can physically segregate from the lithospheric mantle during subduction, important implications may follow because the two components of the oceanic lithosphere have very different major-element compositions and therefore will result in disparate mineral assemblages and hence different densities at depth [18]. These differences in density between subducted crust and mantle lithosphere could provide a driving force for stratification of the mantle.

Until now, the general view seems to be that oceanic crust and lithospheric mantle remain tightly coupled during subduction [19]. However, as we will discuss below, there is now enough evidence to prompt a close re-examination of this issue. In this paper, we use simple, proof-of-concept scaling analyses to explore the plausibility (i.e., can it happen?) of segregating oceanic lithosphere into a crustal component and a mantle residuum during subduction. We then explore the logical consequences of slab segregation and test our hypothesis by examining a collection of somewhat circumstantial but independent evidence (i.e., has it happened?).

2. A weak serpentine layer between oceanic crust and lithospheric mantle

A necessary condition for separating oceanic crust from the underlying lithospheric mantle is a mechanically weak zone of intervening material. Prior to subduction, profiles of maximal strength for the oceanic lithosphere typically do not include such a weak zone because the oceanic crust is thin (5–10 km) and, as a consequence, the entire crust is in the brittle regime [19–22]. However, if the top of the lithospheric mantle has been serpentinized, then a weak zone is expected to exist because of serpentine's exceedingly low strength when compared with unaltered peridotite and basalt [23,24].

Several lines of evidence suggest that at the onset of subduction, the uppermost part of the oceanic lithospheric mantle may indeed be serpentinized. First, near the outer-rise region of the trench where the curvature of the downgoing lithosphere increases rapidly, seismic reflection profiles have revealed that normal-faulting extends down to depths of at least 15–20 km into the subducting slab, suggesting that serpentinization is likely at these depths in the interior of the lithosphere [25]. Second, large earthquakes associated with normal-faulting frequently occur near the outer-rise, and their focal depths reach at least 30 km below the sea-floor [26,27], providing geologically active examples of deep-penetrating normal faults. Third, in a recent study of an ophiolite believed to have undergone in situ serpentinization beneath the seafloor, paleo-depth estimates of the peridotitic bodies suggest serpentinization depths extending down to at least 30–40 km [28]. Finally, earthquakes within subducting slabs often define a double seismic zone, a pattern that seems to follow the 600 to 700 °C isotherm predicted by thermal models [29,30]. When taken together, all these independent observations suggest the existence of a weak serpentinite layer just beneath the oceanic crust even though alternative explanations may exist for any individual observation (Fig. 1A).

The question that follows is whether a hydrated core within the downgoing slab can survive for a sufficiently long time after subduction into the mantle. Hydrous minerals in the oceanic crust will undoubtedly breakdown quickly because the top of the slab will heat up first. In contrast, heating up the interior of the slab takes

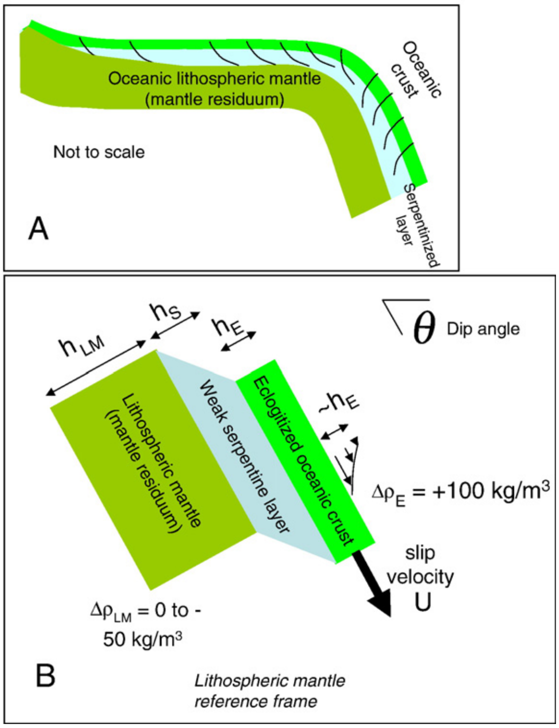

Fig. 1. (A) A cartoon showing features of the oceanic lithosphere relevant to this study. The lithospheric mantle consists of the mantle residuum from which basaltic partial melt (which forms the oceanic crust) has been extracted. The region in blue represents a zone of pervasive serpentinization caused by the infiltration of water through ridge-and trench-parallel normal faults. (B) A schematic of force-balance analysis, which forms the basis of calculating slip rates across a weak serpentinite layer between the dense, eclogitized oceanic crust and the lithospheric mantle. An additional contribution from positive buoyancy of the serpentinite layer is ignored.

much longer because thermal diffusion is slow [31–33]. As a proof of concept, we show in Fig. 2A the results of a simple 1-D model for conductive heating of a cold slab in the mantle (more details appear in the caption). Assuming an initial serpentinized layer of 20 km in thickness (possibly a conservative estimate), a 7.5-km thick crust is sufficient to insulate the entire hydrous core below 600 °C for about 20 Myr after subduction.

Even after 50 Myr, about 10 km of hydrous core remains (Fig. 2A). In 20 Myr, 1000 km of slab would have been subducted at a typical rate of 50 mm/yr. With a dip angle of 60°, common for most modern subduction zones [34], such a slab would surely have entered the mantle transition zone or even possibly the lower mantle. Thus, if serpentinization can extend ~20–30 km into the oceanic lithosphere, a hydrated zone, made up of serpentine (at low pressure) or hydrous phase A (at high pressure), can persist in the core of subducting slabs for tens of millions of years. Above the serpentinite layer, the basaltic oceanic crust would have dehydrated and eclogitized as it heats up quickly (Fig. 1B) [35].

3. Separation along the serpentinite layer by compositionally induced buoyancy forces

Owing to the presence of garnet and omphacitic clinopyroxene, eclogitized oceanic crust would be 2–4% more dense (3400–3500 kg/m^3) than fertile peridotite (3350 kg/m^3) at a given pressure and temperature (Fig. 1B). In contrast, were it not for a difference in temperature, the mantle residuum portion of the subducted oceanic lithosphere should be only slightly less dense than the fertile peridotite of the ambient mantle through which the slab is passing (maximum difference in density is 2% for the most depleted residuum [36]). Thus, while the sinking slab as a whole is negatively buoyant because of its low overall temperature (Fig. 1B), stronger negative buoyancy forces act on the eclogitized oceanic crust than on the lithospheric mantle, because each of these slab components has a different contrast in density relative to the ambient fertile mantle. As the dipping slab sinks, the differential buoyancy across the weak serpentinite layer would drive relative slip between the oceanic crust and lithospheric mantle, provided that the serpentinite layer is weak enough to allow decoupling. Next, we explore the conditions under which decoupling will occur.

Because we are primarily interested in the relative slip between the crust and lithospheric mantle, we use the latter as the frame of reference in the following formulation, eliminating the need to consider the overall sinking of the lithospheric mantle. The shear force F_{COMP} caused by differential buoyancy between the eclogite and lithospheric mantle across the weak serpentinite layer is (Fig. 1B)

$$F_{\mathrm{COMP}} = (\Delta\rho_{\mathrm{E}} h_{\mathrm{E}} A - \Delta\rho_{\mathrm{LM}} h_{\mathrm{LM}} A) g \sin\theta \quad (1)$$

where the compositional density difference $\Delta\rho_i$ between a given layer (i) and the reference ambient mantle (o) is given by $\Delta\rho_i = \rho_i - \rho_o$, g is the gravitational acceleration, h_i the thickness of a given layer, A the surface area of the slab, and θ the local slab dip.

This buoyancy-induced shear force must be balanced by viscous resisting forces from the serpentinite layer and ambient mantle. The total viscous resisting force on the eclogite slab is then

$$F_{\mathrm{drag}} \propto (\eta_o \, \dot{\varepsilon}_{\mathrm{mantle}} + \eta_{\mathrm{S}} \, \dot{\varepsilon}_{\mathrm{serp}}) A \quad (2)$$

where η_o is the viscosity of the ambient mantle, η_{S} the viscosity of the serpentinite layer, $\dot{\varepsilon}_{\mathrm{mantle}}$ the strain rate in

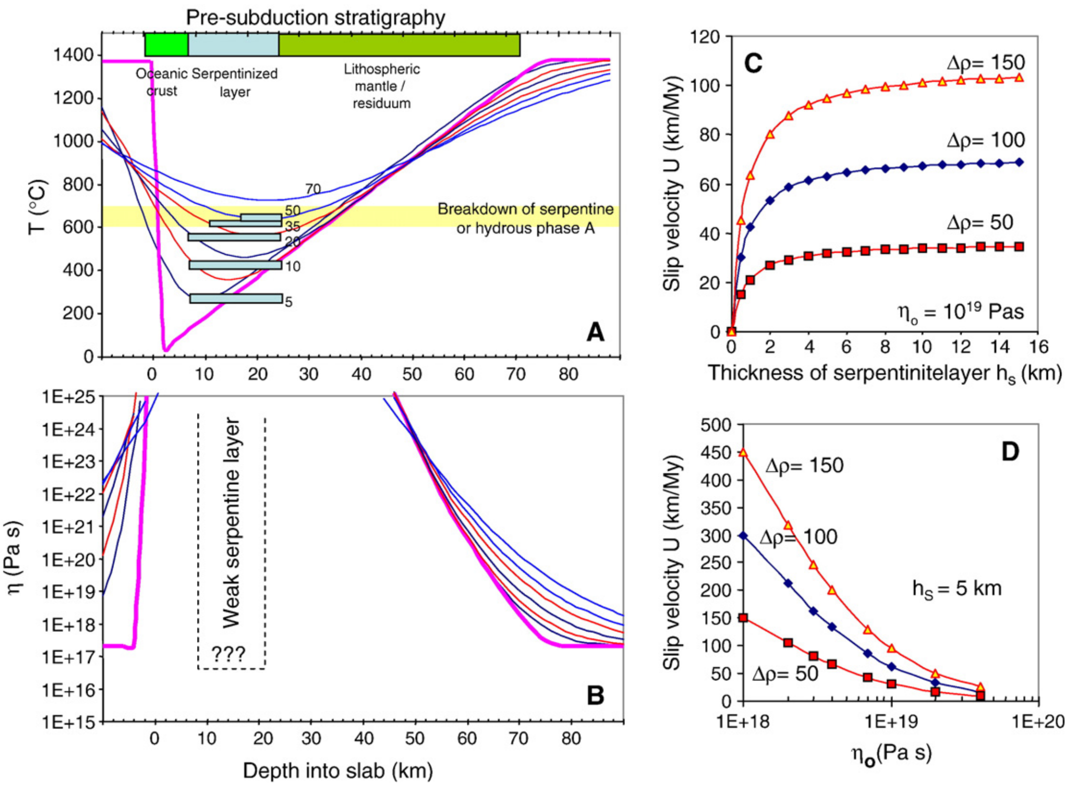

Fig. 2. (A) Thermal profile of an oceanic lithosphere as a function of time since subduction. Pure conductive cooling is assumed (the initial thermal profile corresponds to a 50 Myr old slab with its top and bottom held at 1400 °C). The colored bar at the top of the figure refers to the pre-subduction structure of the oceanic lithosphere. The long horizontal bar (in beige) represents the approximate temperature (600–700 °C) above which serpentine or its equivalent high pressure hydrous phases break down (effect of pressure is ignored here). Short horizontal bars (in light blue) denote how the thickness of the serpentinite layer evolves with time due to progressive warming of the slab's interior (numbers mark Myr since subduction). (B) Effective viscosity of the subducted slab and surrounding mantle as a function of time, following temperatures estimated in panel A. We used known non-Newtonian rheology of wet olivine [38] and assumed a background differential stress of 0.3 MPa). The region outlined by dashed lines denotes a weak serpentine layer. (C) Calculated slip velocity U between eclogitic crust and the lithospheric mantleas a function of the thickness of the serpentinite layer (h_S) for three different density contrasts (kg/m^3) between eclogite and ambient mantle (as a conservative estimate of slip velocity, we assume that there is no compositional density contrast between the residual mantle layer and the ambient mantle). Viscosities of the ambient mantle and the serpentinite layer are set at 10^{19} Pa s and 10^{18} Pa s, respectively. Thickness of lithospheric mantle (excluding serpentinite layer) and eclogitized oceanic crust are assumed to be 50 and 10 km, respectively. (D) Effects of varying viscosity of the ambient mantle on slip-velocity (U). Values of other parameters are the same as those for panel C.

the ambient mantle, and $\dot{\varepsilon}_{\mathrm{serp}}$ the strain rate in the serpentinite layer. Here, we assume a Newtonian (linear dependence of strain rate on stress) rheology for simplicity and for lack of a precise flow law for serpentine, thus η_o and η_S are effective viscosities [20,37]. In any case, the assumption of a Newtonian rheology leads to conservative estimates of strain rates as a power-law dependence on stress would result in a dynamic increase in strain rates.

Once normalized by appropriate deformation length-scales (i.e., the thickness of the boundary layers over which deformation occurs), strain rates scale with the slip velocity, U, so Eq. (2) becomes

$$F_{\mathrm{drag}} \propto \left(\eta_o \frac{U}{h_{\mathrm{E}}} + \eta_{\mathrm{S}} \frac{U}{h_{\mathrm{S}}}\right) A \tag{3}$$

where the lengthscales of deformation in the ambient mantle and the serpentinite layer scale as h_{E} and h_{S}, respectively. Notice that we have used h_{E} as the deformation lengthscale in the ambient mantle rather than the half-width of the entire slab, $(h_{\mathrm{L}}+h_{\mathrm{E}}+h_{\mathrm{S}})/2$. This is because we are looking at only the relative motion between the eclogitized oceanic crust and the lithospheric mantle — a motion superimposed on the overall background deformation associated with the thermally induced sinking of the slab. In any case, using any lengthscale greater than h_{E} in the ambient mantle would only decrease the calculated drag force, resulting in even higher estimates of slip velocity as shown in Eq. (4) below.

By Eqs. (2) and (3), the velocity at which the eclogite slab slides *relative* to the lithospheric mantle scales as

$$U \propto \frac{(\Delta\rho_{\mathrm{E}} h_{\mathrm{E}} - \Delta\rho_{\mathrm{LM}} h_{\mathrm{LM}}) g \sin\theta}{\eta_o / h_{\mathrm{E}} + \eta_{\mathrm{S}} / h_{\mathrm{S}}} \tag{4}$$

The viscosity ratio between the ambient mantle and the serpentinite layer, η_o/η_{S}, is probably at least 10 because the addition of ppm levels of water to nominally anhydrous minerals can decrease viscosities by a factor of 10 or more [38], hence the presence of enough water to stabilize hydrous minerals, such as serpentine, might be expected to decrease viscosity even further. This leads to the following general condition, $\eta_o/h_{\mathrm{E}} \gg \eta_{\mathrm{S}}/h_{\mathrm{S}}$, because the thickness of the serpentinite layer is likely to be at least 2 km [39]. In other words, with the weak serpentinite layer as a zone of mechanical decoupling, the slip velocity, U, is controlled mainly by the viscous resisting forces of the ambient mantle and not by that within the serpentinite layer. In this limit, the velocity approaches about twice the terminal value (e.g., the Stoke's settling velocity) for an isolated slab of eclogite immersed in the ambient mantle (a factor of two comes from the neglible viscous drag of the serpentinite layer).

We now consider a vertically dipping slab ($\sin\theta = 1$; the average dip of a typical slab is about 60° or $\theta = 0.87$; [34]). For three eclogite density contrasts $\Delta\rho_{\mathrm{E}}$ of 50, 100, and 150 kg/m^3 (for a conservative estimate of slip velocity, $\Delta\rho_{\mathrm{LM}}$ is assumed to be zero), Fig. 2C and D show values of calculated slip velocity as a function of serpentinite thicknesses and ambient mantle viscosities. At an ambient mantle viscosity of 10^{19} Pa s (see Fig. 2C), appropriate for the upper mantle near subduction zones, the slip speed ranges from 20–80 mm/yr as long as the serpentinite layer is thicker than ~1 km. These differential velocities are comparable to overall subduction velocities, so relative sliding across the serpentinite layer is significant. Using a higher viscosity of $>10^{20}$ Pas would decrease the slip velocities, but such viscosities are more relevant to the mantle transition zone or the lower mantle than the upper mantle near subduction zones where slab segregation could occur at shallow depths as discussed below.

A key to this point lies in the nature of normal faults near the outer-rise region of the trench where significant bending of the lithosphere occurs just before subduction. Recently, active-source seismic studies showed that the bending zone of subducting slabs is indeed cut by numerous normal faults extending well into the oceanic lithospheric mantle. Moreover, these normal faults are closely spaced at 5–10-km intervals [25].

Judging from our estimated slip velocities (Fig. 2C and D), even at a low rate of 10 mm/yr, it takes only 0.5 Myr for the eclogitized oceanic crust to slip a distance comparable to the spacing of normal faults. We speculate that these crust-penetrating normal faults, being weak and oblique to the surface of the subducting slab, serve as ready launch points for down-sliding eclogitized oceanic crust to deflect off and eventually segregate from the underlying lithospheric mantle. Thus, as long as there is a layer of serpentinite between the oceanic crust and underlying mantle residuum, the key conditions necessary for separation of eclogitized oceanic crust from lithospheric mantle are met well before the slab enters the transition zone of the mantle which lies below (depths of about 410–660 km). This analysis is clearly not an air-tight proof that separation of eclogitized crust occurs at all subduction zones, but by virtue of satisfying all requisite conditions, it does provide strong impetus for pursuing more sophisticated models and for gathering additional evidence in the future to test this hypothesis. Numerical studies of mantle convection that consider low viscosity channels would thus be of interest [40].

4. The fate of segregated lithospheric components: generating a stratified mantle

Accepting, as a working hypothesis, that oceanic crust and lithospheric mantle can be separated during subduction, speculating on the ultimate fates of segregated components could lead to new insights regarding mass fluxes in the mantle. Owing to opposing compositional buoyancies, the crust and the mantle residuum should eventually journey to different resting places in the mantle.

Once thermal re-equilibration is near complete, the oceanic lithospheric mantle, being slightly lower in Fe (due to basalt extraction), will be slightly less dense (on average, up to 1%) than the ambient mantle at all depths [36]. Given the large volume of oceanic mantle residuum, even a slightly lower density would result in significant buoyancy, allowing it to eventually rise to the upper mantle or possibly even initiate thermal upwellings.

The eclogitized oceanic crust, on the other hand, has two potential fates. Above the 660-km seismic discontinuity, eclogite is considerably denser than pyrolite. Between depths of 660 and 800 km, eclogite is close to neutrally buoyant, but regains negative buoyancy at greater depths [41]. Interpretations of seismic tomography and a number of other observations, such as patterns in deep seismicity and fault plane solutions, lateral variations in the amplitude of the 660-km discontinuity, and seismic anisotropy, indicate that many slabs may stall in the transition zone [42–45]. In this case, one would expect segregated eclogite to eventually find a resting place centered near or slightly below the 660-km discontinuity, where the buoyancy of eclogite is close to neutral [42,46,47] (case A in Fig. 3).

If subduction extends into the lower mantle [13,14,42], this scenario does not change provided that segregation of eclogite is largely complete above the lower mantle. On the other hand, if a substantial amount of eclogitic crust accompanies deep-penetrating lithospheric mantle, eventual segregation of eclogite blocks might leave them indefinitely in the lower mantle if the lower mantle has a largely peridotitic composition [41,48].

Either way, eclogitic crust and mantle residuum have intrinsically opposite buoyancies. Once separated, each component would tend to have different resting grounds. Could segregation of subducting oceanic lithosphere lead to an upper mantle that is slightly depleted in Ca, Al, and Fe compared to the bulk silicate Earth and a transition zone (or lower mantle) that is correspondingly enriched in such elements?

Rough estimates suggest that mass fluxes associated with this process could indeed be significant. Starting with the modern oceanic crust production rate of ~3.4 km^2/yr [49], an average thickness of 7 km for oceanic crust and 50 km for the residual mantle lithosphere (all these quantities may have been higher in the past), 2.7×10^{23} and 2.3×10^{24} kg of oceanic crust and lithospheric mantle, respectively, would have been subducted over the last 4 Gyr. For perspective, these values equate with 7 and 56 wt.%, respectively, of the entire mantle. The total mass of lithospheric mantle subducted is equivalent to the mass of the mantle above ~1000 km in depth. If all subducted eclogite was stored between the depths of 400 and 1000 km, it would make up 26 wt.% of this region. Alternatively, if all the eclogite was stored in the lower mantle beneath 1000 km, it would make up 11% of this region.

The foregoing calculations, however, are upper bounds as they ignore the possibility that a certain fraction of subducted materials might have been efficiently homogenized on short lengthscales (comparable to the thickness of oceanic crust) and remixed back into the mantle. Thus, a lower bound of the amount of stored oceanic crust is also desirable. This quantity can be extracted from recent estimates of the composition of the upper mantle from which modern mid-ocean ridge basalts (MORB) are extracted [5]. This depleted mantle reservoir is often referred to as the "Depleted MORB Mantle". Workman and Hart [5] estimated that the DMM presently has 3.98 wt.% Al_2O_3, which is less than the 4.44 wt.% expected for bulk silicate Earth [50]. Although formation of the continental crust is likely to be the dominate cause of trace-element depletion in the DMM, the mass of the continental crust is too small to

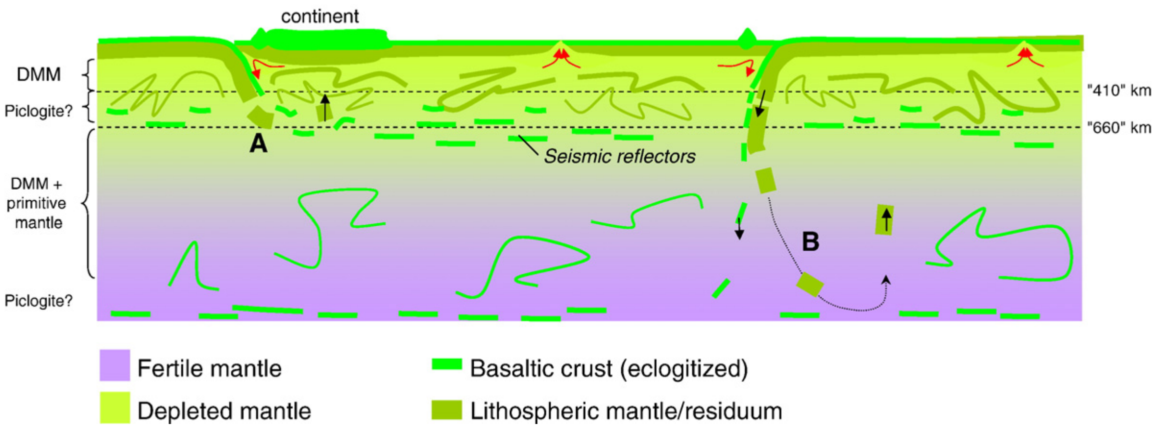

Fig. 3. Cartoon of a subtly stratified mantle envisioned in this paper. Two possible scenarios are considered for subducted oceanic lithosphere: A) a slab stagnates near the bottom of the mantle transition zone, and B) a slab penetrates into the lower mantle. In both cases, eclogitic crust segregates from peridotitic lithospheric mantle well before reaching the 660-km discontinuity. Eclogitic crust eventually settles near the base of the transition zone and uppermost lower mantle or near the base of the lower mantle for cases (A) and (B), respectively. Depleted mantle residua making up much of the oceanic lithospheric mantle should eventually rise and accumulate in the uppermost mantle. The transition zone of the mantle may become slightly enriched in eclogite, yielding a bulk composition of peridotite mixed with eclogite ("piclogite"). Our prediction of concentrated eclogite blocks near the bottom of the transition zone is consistent with abundant seismic reflectors and scatterers in the Mariana and Izu-Bonin subduction zones where conditions for eclogite segregation are optimal. DMM denotes depleted MORB mantle.

account for the degree of Al depletion [3]. Thus, we take the low Al_2O_3 content of DMM as circumstantial evidence for the preferential return of at least some parts of the deeply subducted residual lithospheric mantle to the uppermost parts of the Earth's mantle.

If one then assumes that most of the missing Al lies in subducted oceanic crust sequestered elsewhere, it can be shown that DMM would represent the residual after extracting about 3.8% of a basaltic melt that has ~16 wt.% Al_2O_3. If the mass of the DMM makes up the bulk of the mantle above depths of ~400 km, the amount of sequestered eclogitic crust is equivalent to 0.6% of the entire mantle deeper than 400 km or 2% of the mantle between depths of 400 and 1000 km or a region in and around the transition zone. These estimates are about an order of magnitude less than those calculated above from subduction rates alone, but the smaller values are only minimum estimates as the collective size of DMM may be larger than assumed here. Nevertheless, even this lower bound implies a significant amount of sequestered oceanic crust.

The above discussions build upon many previous studies. For example, significant amounts of sequestered oceanic crust have been deemed necessary in order to remediate various imbalances in trace elements [4,51–53]. What we have done differently here is to provide a physical mechanism, whereby separates oceanic lithospheric mantle from the crust during subduction, thus allowing the former to eventually return to the upper mantle and the latter to concentrate near the bottom of the transition zone or at the base of the lower mantle.

5. Predictions and implications

We hypothesize that segregation of subducting oceanic lithosphere results in the formation of a subtly stratified mantle as depicted schematically in Fig. 3. Insofar as not all slabs subduct deep into the lower mantle, the region above the 660-km discontinuity, being the final resting place for a significant fraction of buoyant, depleted lithospheric mantle (e.g., [43]), would progressively become more depleted throughout Earth's history. The lowermost mantle and the region near the 660-km discontinuity (mid-mantle) are predicted to become populated by eclogite, so that the bulk composition of this region might be a mixture of eclogite and fertile peridotite, tending toward a "piclogite" composition [46].

In general terms, the notion of widespread, small-scale heterogeneities in the mantle are consistent with short-wavelength seismic scatterers observed on a global scale. Statistical approaches show that above the 660-km discontinuity, the dominant length-scale of scatterers is about 4 km with amplitudes of about 3–4% in rms speed of seismic waves; the corresponding estimates for the lower mantle are 8 km and 0.5%, respectively [54,55]. Although the exact properties and origin of seismic scatterers remain uncertain, their lengthscales are comparable to the thickness of the oceanic crust and the spacing of deep-penetrating normal faults near the outer-rise (5 to 10 km; [25]).

More importantly, observations along modern subduction zones support several key steps leading to the separation of crust and lithospheric mantle. Currently, fast subduction of old (thus cold) oceanic lithosphere occurs mainly along the western Pacific and Indonesia where conditions are most favorable for preserving low temperatures in the down-going slab. In particular, a near-vertical slab is outlined by deep seismicity between the depths of 200 to 600 km beneath the Mariana trench where the subducting plate abruptly bends downward [56]. Such geometry is ideal for generating deep-penetrating normal faults near the outer-rise, providing ready pathways for sea-water to hydrate mantle peridotite. As expected, a layer of serpentinite surely exists along the subduction zone because pervasive serpentine diapers are present near the Mariana trench [57] and subducted serpentinite has been proposed as part of source materials for arc volcanism [58]. While there is no direct observation of eclogitized crustal blocks peeling off from the lithospheric mantle, Eq. (4) predicts that the steep dip would produce a high relative slip velocity between the two components of the subducting Pacific lithosphere. The confluence of factors favoring eclogite segregation may be the reason why the best cases for anomalous reflectors/scatterers near the transition zone of the mantle are observed in the Mariana and Izu Bonin regions [59–62]. Indeed, most anomalous scatterers in the mantle are found along subduction zones of the western Pacific and Indonesia at depths just below the mantle transition zone (approximately 800 to 1200 km) [60,62–64].

The segregation of oceanic lithosphere during subduction proposed here leads to several implications. Preferential retention of eclogite near the bottom of the transition zone could help explain why the observed radial-gradient of seismic wave speeds is higher than those predicted for individual mineral phases [65]. Addition of eclogite into the transition zone would dilute the influence of olivine. Instead, the higher Al and Ca content of the resulting mixture could enhance the effects of Ca-perovskite (which has a higher radial-gradient of seismic-wave speeds) and/or the effects of orthopyroxene transformation to majorite [46,65]. Quantitative testing of this hypothesis, however, is beyond the scope of this paper.

Considering that depleted mantle is intrinsically less dense than more fertile mantle, over geologic time, even a slight density difference may lead to gradual compositional stratification of the mantle, which in turn could affect the nature of mantle convection. One current view is that the whole mantle is involved in convection: some slabs seem to penetrate the 660-km discontinuity [13] and some hotspots seem to be connected to deep plumes, which presumably rise from the deep lower mantle [66]. However, the existence of a driving force for chemical and density stratification, as suggested here, would compete against the convective mass and heat transfer across the transition zone or mid-mantle. We speculate that this segregation process should eventually lead to irreversible stratification of the Earth's mantle [67].

The next question is whether this stratification has been an ongoing process. As discussed above, the observed depletion of aluminum in the upper mantle is not fully compensated by the present mass of the continental crust and hence requires segregated basaltic oceanic crust to reside somewhere deep in the mantle. While these geochemical observations hint that this segregation process has been operating over a significant period of Earth's history, we are still left with the question of when segregation processes began. In this context, we note that in Earth's early history, the average temperature of the mantle, although not well-constrained, could have been hotter [68]. As such, formation and preservation of serpentinized lithosphere, a temperature-dependent process, would have been reduced, minimizing the importance of slab segregation back in the Archean.

Finally, we speculate that rising of segregated oceanic lithospheric mantle driven by its slight chemical buoyancy may help initiate thermal upwellings or even cause chemical upwellings without the need of associated thermal anomalies. For a coefficient of thermal expansion of about 3×10^{-5} °C^{-1}, a 1% chemical buoyancy associated with a harzburgite composition is equivalent to $\sim$+300 °C of a thermal anomaly, underscoring the potential impact of compositional buoyancies. Unfortunately, finding evidence for ancient depleted mantle residua in the source regions of ocean island basalts is very difficult. Nonethelesss, recent studies of osmium and hafnium isotopes suggested that such components may exist beneath Hawaii and the Azores [69–71]. In addition, re-evaluations of helium partition coefficients suggest that, under some conditions, helium may be slightly more compatible than its radioactive parent uranium [72]. If so, could the high $^3He/^4He$ ratios in ocean island basalts derive from ancient, *depleted* mantle rather than primordial undegassed mantle as traditionally thought [72]? At any rate, a better understanding of element partitioning in harzburgitic lithologies seems necessary in order to identify depleted source components in ocean island basalts [73].

Acknowledgments

This paper was conceived during the last week of the 2006 Cooperative Institute for the Study of the Deep Earth (CIDER) at the Kavli Institute for Theoretical Physics, University of California, Santa Barbara. Special thanks go to the CIDER community and especially to Barbara Romanowicz, Stan Hart, Adam Dziewonski and Louise Kellogg, who organized the sessions. Discussions with Marc Hirschmann, Adrian Lenardic, Jessica Warren, Magali Billen, Matthew Jackson, Mark Reagan, Stephen Marshak, Amber Harris, Arnaud Agranier and Zheng-xue A. Li, and review comments by Thorsten Becker and an anonymous reviewer are appreciated. We acknowledge support from the NSF (grants EAR-0209121 and 0440033 to Lee and EAR-0551995 and 990932 to Chen) and the Packard Foundation (Lee), but any opinions and recommendations expressed here are those of the authors and do not necessarily reflect those of the NSF.

References

[1] A. Zindler, S. Hart, Chemical geodynamics, Annu. Rev. Earth Planet. Sci. 14 (1986) 493–571.
[2] S.B. Jacobsen, G.J. Wasserburg, A two-reservoir recycling model for mantle-crust evolution, Proc. Natl. Acad. Sci. 77 (1980) 6298–6302.
[3] A.W. Hofmann, Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust, Earth Planet. Sci. Lett. 90 (1988) 297–314.
[4] A.W. Hofmann, Mantle geochemistry: the message from oceanic volcanism, Nature 385 (1997) 219–229.
[5] R.K. Workman, S.R. Hart, Major and trace element composition of the depleted MORB mantle (DMM), Earth Planet. Sci. Lett. 231 (2005) 53–72.
[6] C.J. Allegre, Limitation on the mass exchange between the upper and lower mantle: the evolving convection regime of the Earth, Earth Planet. Sci. Lett. 150 (1997) 1–6.
[7] R.K. O'Nions, N.M. Evensen, P.J. Hamilton, Geochemical modeling of mantle differentiation and crustal growth, J. Geophys. Res. 84 (1979) 6091–6101.
[8] R.W. Carlson, Mechanisms of Earth differentiation, Rev. Geophys. 32 (1994) 337–361.

[9] C.B. Agee, D. Walker, Mass balance and phase density constraints on early differentiation of chondritic mantle, Earth Planet. Sci. Lett. 90 (1988) 144–156.
[10] P. Puster, T.H. Jordan, How stratified is mantle convection? J. Geophys. Res. 102 (1997) 7625–7646.
[11] P.E. van Keken, E. Hauri, C. Ballentine, Mantle mixing: the generation, preservation, and destruction of mantle heterogeneity, Annu. Rev. Earth Planet. Sci. 30 (2002) 493–525.
[12] S.P. Grand, R. van der Hilst, S. Widiyantoro, Global seismic tomography; a snapshot of convection in the Earth, GSA Today 7 (1997) 1–7.
[13] R. van der Hilst, Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench, Nature 374 (1995) 154–157.
[14] R. van der Hilst, S. Widiyantoro, E.R. Engdahl, Evidence for deep mantle circulation from global tomography, Nature 386 (1997) 578–584.
[15] T.W. Becker, J.B. Kellog, R.J. O'Connell, Thermal constraints on the survival of primitive blobs in the lower mantle, Earth Planet. Sci. Lett. 171 (1999) 351–365.
[16] L.H. Kellogg, B.H. Hager, R.D. van der Hilst, Compositional stratification in the deep mantle, Science 283 (1999) 1881–1884.
[17] I. Tolstikhin, A.W. Hofmann, Early crust on top of the Earth's core, Phys. Earth Planet. Inter. 148 (2005) 109–130.
[18] U.R. Christensen, A.W. Hofmann, Segregation of subducted oceanic crust in the convecting mantle, J. Geophys. Res. 99 (1994) 19867–19884.
[19] P. van Keken, S. Karato, D.A. Yuen, Rheological control of oceanic crust separation in the transition zone, Geophys. Res. Lett. 23 (1996) 1821–1824.
[20] D.L. Kohlstedt, B. Evans, S.J. Mackwell, Strength of the lithosphere: constraints imposed by laboratory experiments, J. Geophys. Res. 100 (1995) 17587–17602.
[21] G. Ranalli, D.C. Murphy, Rheological stratification of the lithosphere, Tectonophysics 132 (1987) 281–295.
[22] Z.-M. Jin, J. Zhang, H.W. Green II, S. Jin, Eclogite rheology: implications for subducted lithosphere, Geology 29 (2001) 667–670.
[23] J. Escartin, G. Hirth, B. Evans, Strength of slightly serpentinized peridotites: implications for the tectonics of oceanic lithosphere, Geology 29 (2001) 1023–1026.
[24] J. Escartin, G. Hirth, B. Evans, Nondilatant brittle deformation of serpentinites: implications for Mohr–Coulomb theory and the strength of faults, J. Geophys. Res. 102 (1997) 2897–2913.
[25] C.R. Ranero, J. Phipps Morgan, K. McIntosh, C. Reichert, Bending-related faulting and mantle serpentinization at the Middle America trench, Nature 425 (2003) 367–373.
[26] D.W. Forsyth, Determinations of focal depths of earthquakes associated with the bending of oceanic plates at trenches, Phys. Earth Planet. Inter. 28 (1982) 141–160.
[27] D.H. Christensen, L.J. Ruff, Seismic coupling and outer rise earthquakes, J. Geophys. Res. 93 (1988) 13421–13444.
[28] Z.-X.A. Li, C.-T.A. Lee, Geochemical investigation of serpentinized oceanic lithospheric mantle in the Feather River Ophiolite, California: implications for the recycling rate of water by subduction, Chem. Geol. 235 (2006) 161–185.
[29] B.R. Hacker, S.M. Peacock, G.A. Aber, D. Holloway, Subduction factory 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions? J. Geophys. Res. 108 (2003), doi:10.1029/2001JB001129.
[30] T. Igarashi, T. Matsuzawa, N. Umino, A. Hasegawa, Spatial distribution of focal mechanisms for interplate and intraplate earthquakes associated with the subducting Pacific plate beneath the northeastern Japan arc: a tripled-planed deep seismic zone, J. Geophys. Res. 106 (2001) 2177–2191.
[31] G.A. Abers, P.E. van Keken, E.A. Kneller, A. Ferris, J.C. Stachnik, The thermal structure of subduction zones constrained by seismic imaging: implications for slab dehydration and wedge flow, Earth Planet. Sci. Lett. 241 (2006) 387–397.
[32] S.M. Peacock, Thermal and petrologic structure of subduction zones, in: G.E. Bebout, D.W. Scholl, S.H. Kirby, J.P. Platt (Eds.), Subduction Top to Bottom, vol. 96, American Geophysical Union, 1996, pp. 119–133.
[33] L.H. Rupke, J. Phipps Morgan, M. Hort, J.N. Connelly, Serpentine and the subduction zone water cycle, Earth Planet. Sci. Lett. 223 (2004) 17–34.
[34] S. Lallemand, A. Heuret, D. Boutelier, On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones, Geochem. Geophys. Geosyst. 6 (2005), doi:10.1029/2005GC000917.
[35] S. Poli, M.W. Schmidt, Petrology of subducted slabs, Annu. Rev. Earth Planet. Sci. 30 (2002) 207–235.
[36] C.-T.A. Lee, Compositional variation of density and seismic velocities in natural peridotites at STP conditions: implications for seismic imaging of compositional heterogeneities in the upper mantle, J. Geophys. Res. 108 (2003) 2441, doi:10.1029/2003JB002413.
[37] G. Hirth, D.L. Kohlstedt, Rheology of the upper mantle and the mantle wedge: a view from the experimentalists, in: J. Eiler (Ed.), Inside the Subduction Factory, Geophysical Monograph Series, vol. 118, Am. Geophys. Union, (2004), pp. 83–106.
[38] G. Hirth, D.L. Kohlstedt, Water in the oceanic upper mantle; implications for rheology, melt extraction and the evolution of the lithosphere, Earth Planet. Sci. Lett. 144 (1-2) (1996) 93–108.
[39] L. Hopkinson, J.S. Beard, C.A. Boulter, The hydrothermal plumbing of a serpentinite-hosted detachment: evidence from the west Iberia non-volcanic rifted continental margin, Mar. Geol. 204 (2004) 301–315.
[40] A. Lenardic, M.A. Richards, F. Busse, Depth-dependent rheology and the horizontal length scale of mantle convection, J. Geophys. Res. 111 (2006), doi:10.1029/2005JB003639.
[41] K. Hirose, Y. Fei, Y. Ma, H.K. Mao, The fate of subducted basaltic crust in the Earth's lower mantle, Nature 397 (1999) 53–56.
[42] Y. Fukao, S. Widiyantoro, M. Obayashi, Stagnant slabs in the upper and lower mantle transition zone, Rev. Geophys. 39 (2001) 291–323.
[43] W.-P. Chen, M.R. Brudsinzski, Evidence for a large-scale remnant of subducted lithosphere beneath Fiji, Science 292 (2001) 2475–2479.
[44] W.-P. Chen, M.R. Brudsinzski, Seismic anisotropy in the mantle transition zone beneath Fiji-tonga, Geophys. Res. Lett. 30 (2003) 1682, doi:10.1029/2002GL016330.
[45] Y.J. Gu, A. Dziewonski, G. Ekström, Simultaneous inversion for mantle shear wave velocity and topography of transition zone discontinuities, Geophys. J. Int. 154 (2003) 559–583.
[46] D.L. Anderson, Theory of the Earth, (1989) 366 pp.
[47] D.L. Anderson, Chemical stratification of the mantle, J. Geophys. Res. 84 (1979) 6297–6298.
[48] A.E. Ringwood, Role of the transition zone and 660 km discontinuity in mantle dynamics, Phys. Earth Planet. Inter. 86 (1994) 5–24.
[49] D.B. Rowley, Rate of plate creation and destruction: 180 Ma to present, Geol. Soc. Amer. Bull. 114 (2002) 927–933.

[50] W.F. McDonough, S.-S. Sun, The composition of the Earth, Chem. Geol. 120 (1995) 223–253.
[51] M.G. Barth, W.F. McDonough, R.L. Rudnick, Tracking the budget of Nb and Ta in the continental crust, Chem. Geol. 165 (2000) 197–213.
[52] R.L. Rudnick, M.G. Barth, I. Horn, W.F. McDonough, Rutile-bearing refractory eclogites; a missing link between continents and depleted mantle, Science 287 (2000) 278–281.
[53] W.F. McDonough, Partial melting of subducted oceanic crust and isolation of its residual eclogitic lithology, Philos. Trans. R. Soc. Lond. Ser. A: Math. Phys. Sci. 335 (1991) 407–418.
[54] O. Gudmundsson, J.H. Davies, R.W. Clayton, Stochastic analysis of global travel time data, mantle heterogeneity and random erros in the ISC data, Geophys. J. Int. 102 (1990) 25–43.
[55] P.M. Shearer, P.S. Earle, The global short-period wavefield modelled with a Monte Carlo seismic phonon method, Geophys. J. Int. 158 (2004) 1103–1117.
[56] D.A. Levitt, D.T. Sandwell, Lithospheric bending a subduction zones based on depth soundings and satellite gravity, J. Geophys. Res. 100 (1995) 379–400.
[57] R.D. Hyndman, S.M. Peacock, Serpentinization of the forearc mantle, Earth Planet. Sci. Lett. 212 (2003) 417–432.
[58] R. Stern, J. Kohut, Subduction factory processes beneath the Guguan cross-chain, Mariana Arc; no role for sediments, are serpentinites important? Contr. Min. Petr. 151 (2006) 202–221.
[59] J.C. Castle, K.C. Creager, A steeply dipping discontinuity in the lower mantle beneath Izu-Bonin, J. Geophys. Res. 104 (1999) 7279–7292.
[60] H. Kawakatsu, F. Niu, Seismic evidence for a 920-km discontinuity in the mantle, Nature 371 (1994) 301–305.
[61] F. Kruger, M. Branumann, F. Scherbaum, M. Weber, Mid-mantle scatterers near the Mariana slab detected with a double array method, Geophys. Res. Lett. 28 (2001) 667–670.
[62] F. Niu, H. Kawakatsu, Y. Fukao, Seismic evidence for a chemical heterogeneity in the mid-mantle: a strong and slightly dipping seismic reflector beneath the Marian subduction zone, J. Geophys. Res. 108 (2003) (12 pp.).
[63] S. Kaneshima, G.R. Helffrich, Subparallel dipping heterogeneities in the mid-lower mantle, J. Geophys. Res. 108 (2003), doi:10.1029/2001JB001596.
[64] Y. Shen, J. Blum, Seismic evidence for accumulated oceanic crust above the 660-km discontinuity between Southern Africa, Geophys. Res. Lett. 30 (2003) (4 pp.).
[65] T.S. Duffy, D.L. Anderson, Seismic velocities in mantle minerals and the mineralogy of the upper mantle, J. Geophys. Res. 94 (1989) 1895–1912.
[66] R. Montelli, G. Nolet, F.A. Dahlen, G. Masters, E.R. Engdahl, S.-H. Hung, Finite-frequency tomography reveals a variety of plumes in the mantle, Science 303 (2004) 338–343.
[67] D.L. Anderson, The case for irreversible chemical stratification of the mantle, Int. Geol. Rev. 44 (2002) 97–116.
[68] E.G. Nisbet, M.J. Cheadle, N.T. Arndt, M.J. Bickle, Constraining the potential temperature of the Archean mantle: a review of the evidence from komatiites, Lithos 30 (1993) 291–307.
[69] V.J.M. Salters, J. Blichert-Toft, Z. Fekiacova, A. Sachi-Kocher, M. Bizimis, Isotope and trace element evidence for depleted lithosphere in the source of enriched Ko'olau basalts, Contrib. Mineral. Petrol. 151 (2006) 297–312.
[70] B.F. Schaefer, S. Turner, I.J. Parkinson, N.W. Rogers, C.J. Hawkesworth, Evidence for recycled Archaean oceanic mantle lithosphere in the Azores plume, Nature 420 (2002) 304–307.
[71] J.C. Lassiter, E.H. Hauri, P.W. Reiners, M.O. Garcia, Generation of Hawaiian post-erosional lavas by melting of a mixed lherolite/pyroxenite source, Earth Planet. Sci. Lett. 178 (2000) 269–284.
[72] S.W. Parman, M.D. Kurz, S.R. Hart, T.L. Grove, Helium solubility in olivine and implications for high $^{3}He/^{4}He$ in ocean island basalts, Nature 437 (2005) 1140–1143.
[73] C.-T.A. Lee, A. Harbert, W.P. Leeman, Extension of lattice strain theory to mineral/mineral rare-earth element partitioning: an approach for assessing disequilibrium and developing internally consistent partition coefficients between olivine, orthopyroxene, clinopyroxene, and basaltic melt, Geochim. Cosmochim. Acta (2007), doi:10.1016/j.gca.2006.09.014.