

Wide distribution and partial melting of eclogite indicated by the X-discontinuity in the upper mantle

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Key Points:

- The enrichment of 30% orthopyroxene is required to explain the X-discontinuity.
- Both the coesite-stishovite transition and the OPX-HPCPX transition are dominant mechanisms for the genesis of the X-discontinuity.
- The X-discontinuity provides an effective approach to assess the melt situation of eclogite in the deep earth.

Abstract

Whether and where recycled oceanic crusts melt in the deep mantle are fundamentally important questions for understanding the evolution and dynamics of the Earth's mantle, and they currently remain unclear. Here, we find compelling evidence for the wide distribution of eclogite melting around a depth of 300 km by investigating the origins of the X-discontinuity. We show that both the transformation of orthopyroxene into high-pressure clinopyroxene and the coesite-stishovite transition are dominant mechanisms. The degree of partial melting of oceanic crust is crucial for the X-discontinuity mechanisms since melting promotes the enrichment of orthopyroxene by consuming solid silica. The silica phase transition dominates in the relatively low-temperature region, while the orthopyroxene phase transition in the high-temperature region results in the indistinguishable seismological Clapeyron slope of the X-discontinuity, with both transitions presenting a large positive Clapeyron slope. The X-discontinuity provides a key method for identifying partial melting of recycled oceanic crust.

Plain Language Summary

The genesis of the X-discontinuity, which is characterized by wide depth variations and indistinguishable seismological Clapeyron slopes, is not well understood. The coesite-stishovite transition has been proposed as the mechanism underlying the X-discontinuity; however, previous seismic studies frequently excluded the transformation of orthopyroxene (OPX) to high-pressure clinopyroxene (HPCPX) because of its small impedance contrasts. In this study, we performed first-principle calculations to obtain the elasticity of high-pressure clinoenstatite at high pressure and high temperature. Our results show that impedance contrasts caused by the OPX-HPCPX transition are two times larger than previously thought and hence cannot be ignored. Furthermore, we emphasize the role of eclogite melt and propose that both the coesite-stishovite transition and OPX-HPCPX transition are dominant mechanisms for the X-discontinuity, with the former dominating where eclogite is hard to melt and the latter dominating where partial melting of eclogite occurs. Thermal state analysis and seismological observations support the important role of the OPX-HPCPX transition in the X-discontinuity and wide distribution of partial melting of eclogite. The new interpretation not only well explains the indistinguishable Clapeyron slope of the X-discontinuity but also provides an approach for identifying partial melting of eclogite in the deep earth.

1 Introduction

Seismic discontinuities with impedance contrasts of 2%~8% in depth ranges of 250 km~350 km were initially designated the X-discontinuity by Revenaugh and Jordan (1991), and they have been detected beneath various tectonic settings, such as stable continents and hotspots and near subduction zones (Bagley and Revenaugh, 2008; Arwen Deuss and Woodhouse, 2002; Revenaugh and Jordan, 1991; Schmerr, 2015; Srinu et al., 2021). The origin for the X-discontinuity is still debated. Several mechanisms have been proposed, including the formation of phase A ($\text{Mg}_7\text{Si}_2\text{O}_8(\text{OH})_6$) (Revenaugh and Jordan, 1991), the reaction of forsterite and periclase to anhydrous phase B ($5\text{Mg}_2\text{SiO}_4 + 4\text{MgO} \rightarrow \text{Mg}_{14}\text{Si}_5\text{O}_{24}$) (Ganguly and Frost, 2006), the phase transition from coesite to stishovite (Chen et al., 2015; Williams and Revenaugh, 2005), and the phase transition from orthopyroxene (OPX, $(\text{Mg,Fe})\text{SiO}_3$) to high-pressure clinopyroxene (HPCPX) (Akashi et al., 2009; Alan B. Woodland, 1998). Phase A is only stable in the pressure

and temperature (PT) range of hydrated cold slabs (Kawamoto, 1996; A B Woodland et al., 1997), indicating that the formation of phase A can only provide an explanation for the X-discontinuity observed within cold subduction zones. The formation of anhydrous phase B requires the local enrichment of periclase, which would consume OPX first before reacting with olivine to form anhydrous phase B. The mechanisms for generating substantial amounts of periclase remain unclear and need to be answered in further studies (Chen et al., 2015).

The phase transition from coesite to stishovite (Chen et al., 2015; Williams and Revenaugh, 2005) generates very large wave impedance contrasts, and only 4~8 wt% free silica is required to cause the observed X-discontinuity. Although the pyrolite model consists of no free silica, the subducted oceanic crust contains certain amounts of silica in both the MORB and sediment layers (Trønnes, 2009). Therefore, the silica transition has become a popular mechanism to explain the X-discontinuity. However, the large Clapeyron slope of the transition is inconsistent with seismological studies indicating that a clear Clapeyron slope was not observed for the X-discontinuity (A. Deuss and Woodhouse, 2004).

The phase transition from OPX to HPCPX, which was first proposed by Angel et al. (1992), has been considered to explain the formation of the X-discontinuity (Akashi et al., 2009; Alan B. Woodland, 1998). The transition is completed within 5 km intervals (Alan B. Woodland, 1998). However, impedance contrasts of the transition under mantle conditions have had a serious impact on previous results regarding the possibility of the OPX-HPCPX transition for the X-discontinuity, and they remain unclear because of the lack of elasticity of HPCPX at high PT. Thus, high-quality elastic data of HPCPX at high PT are necessary to quantitatively evaluate the relationship between the OPX-HPCPX transition and the occurrence of X-discontinuities.

In this study, we investigated the elasticity of high-pressure clinoenstatite (HPCEN, MgSiO_3), a Mg endmember of HPCPX, at high PT via first-principle calculations based on density functional theory and combined it with the elasticity of orthoenstatite (OEN, MgSiO_3), a Mg endmember of OPX (Qian et al., 2018), to obtain impedance contrasts caused by the OEN-HPCEN transition. We discussed the contribution of the OPX-HPCPX transition to the genesis of the X-discontinuity by considering the effect of eclogite melt on OPX enrichment.

2 Methods and calculation details

According to *Barron and Klein* (1965), isothermal elastic constants can be obtained by

$$c_{ijkl}^T = \frac{1}{V} \left(\frac{\partial^2 F}{\partial e_{ij} \partial e_{kl}} \right) + \frac{1}{2} P (2\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj} - \delta_{ik}\delta_{jl}) \quad (1)$$

where F and e_{ij} ($i, j=1, 2, 3$) represent the Helmholtz free energy and the infinitesimal strains, respectively. In the quasi-harmonic approximation (QHA), F is expressed as

$$F(e_{ij}, V, T) = U(e_{ij}, V) + \frac{1}{2} \sum_{q,m} \hbar \omega_{q,m}(e_{ij}, V) + k_B T \sum_{q,m} \ln \left\{ 1 - \exp \left[-\frac{\hbar \omega_{q,m}(e_{ij}, V)}{k_B T} \right] \right\} \quad (2)$$

where T , V , K_B , and \hbar represent the temperature, volume, Boltzmann and reduced Planck constants, respectively; and ω and its subscripts q and m denote vibrational frequencies, the phonon wave vector and the normal mode index. The first, second, and third terms on the right-hand side of Eq. (2) are the static internal energy, zero-point energy, and vibrational energy

contributions at a given strain ϵ_{ij} and volume V , respectively. Based on Eq. (1), to obtain thermal elastic constants, the vibrational density of states (VDos) of many strained configurations must be calculated using conventional methods, which are computationally expensive. *Wu and Wentzcovitch* (2011) developed a semianalytical method where only the VDos of the unstrained configuration is needed to obtain high-T elasticity, and this method has lowered the computational workload to less than ten percent that of conventional methods. This method has been applied successfully to MgO (*Wu and Wentzcovitch*, 2011), ringwoodite (*Valdez et al.*, 2012), olivine and wadsleyite (*Núñez-Valdez et al.*, 2013), ferropericlase (*Wu et al.*, 2013), stishovite and CaCl_2 -type silica (*R Yang and Wu*, 2014), bridgmanite (*Shukla et al.*, 2015), pyrope (*Hu et al.*, 2016), superhydrous phase B (*D P Yang et al.*, 2017), orthoenstatite (*Qian et al.*, 2018), diopside (*Zou et al.*, 2018), corundum (*Wang and Wu*, 2018), magnesite (*Yao et al.*, 2018), and akimotoite (*Hao et al.*, 2019). *Zou et al.* (2018) further generalized the method to monoclinic crystal systems. Similarly, we use the developed method to calculate the elastic properties of HPCEN.

The open-source Quantum ESPRESSO package (*Giannozzi et al.*, 2009) based on density functional theory was used to perform all calculations in this study. Local density approximation (LDA) was chosen to handle the exchange correlation energy. The pseudopotentials for oxygen and silicon were generated by the norm-conserving Troullier-Martins method (*Troullier and Martins*, 1991). The pseudopotential for magnesium was generated by the method of von Barth and Car (*Karki et al.*, 2000). The crystal structure was optimized by the variable cell-shape damped molecular dynamic method (*Wentzcovitch*, 1991), and the dynamical matrices were calculated based on density-functional perturbation theory (*Baroni et al.*, 2001) with a $2 \times 2 \times 2$ q-point mesh. The cutoff energy of plane wave expansion was 70 Ry. Elastic constants in static conditions were calculated according to the stress-strain relationship, and 1% strain was imposed.

3 Results

3.1 Equation of states of HPCEN

The calculated equation of states of HPCEN (MgSiO_3) is consistent with the available experimental results up to the highest measured temperature of 1273 K (Fig. 1a and Table S1-S2) (*Angel and Hugh-Jones*, 1994; *Angel et al.*, 1992; *J. Kung et al.*, 2005; *Jennifer Kung et al.*, 2004; *Lazarz et al.*, 2019; *Li et al.*, 2014; *Shinmei et al.*, 1999; *Yu and Wentzcovitch*, 2009). The differences between the calculated and experimental volumes are less than 0.5% for almost all experimental results except for those of *Lazarz et al.* (2019), which gradually deviated from the calculated results to a value of 1.42% at 30 GPa with increasing pressure.

3.2 Elasticity of HPCEN at high PT

With space Group $C2/c$, the elastic tensor of HPCEN is fully determined by thirteen independent single-crystal elastic constants C_{11} , C_{22} , C_{33} , C_{12} , C_{13} , C_{23} , C_{44} , C_{55} , C_{66} , C_{15} , C_{25} , C_{35} , and C_{46} . Experimental data for elastic constants are still not available. *Li et al.* (2014) provided static GGA results, and after pressure correction, their results match our LDA static results very well (Fig. S1 and Table S3).

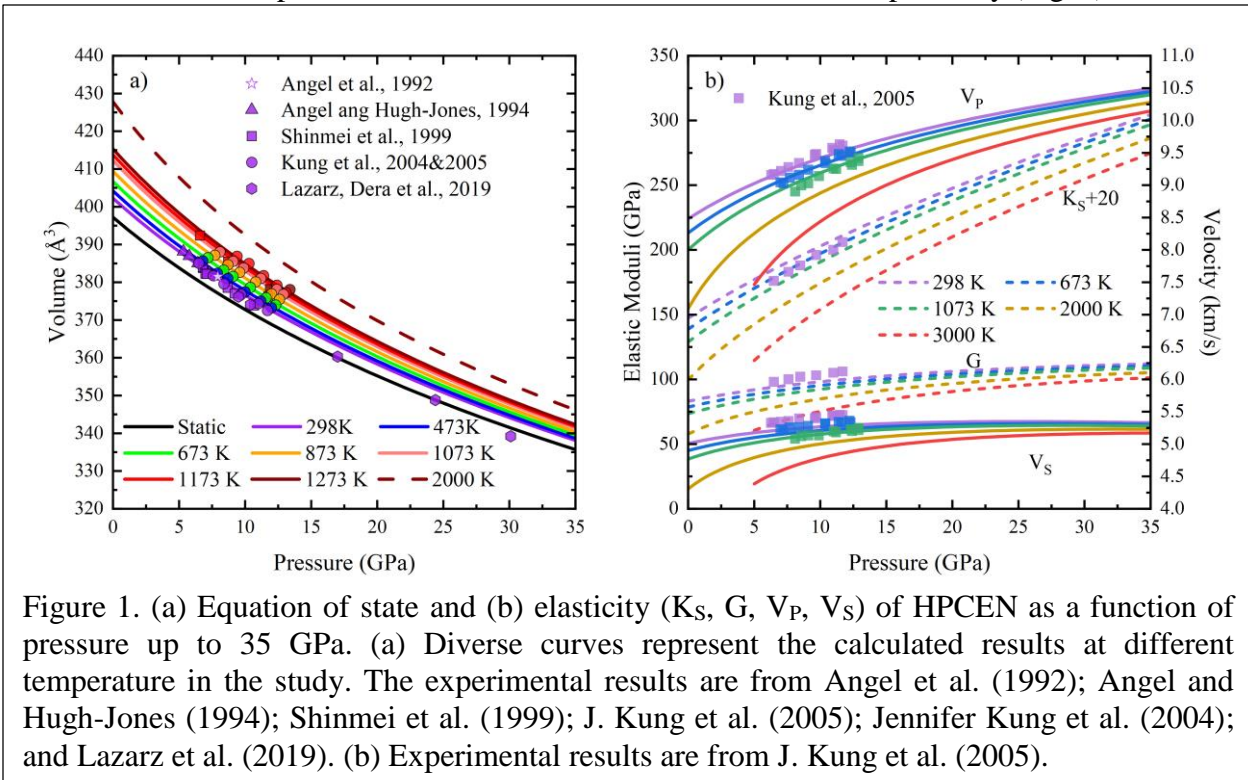
The adiabatic bulk modulus (K_S) and shear modulus (G) were obtained via the Voigt-Reuss-Hill averaging method (Hill, 1952). The calculated K_S and G of HPCEN are consistent with ultrasonic measurements (Fig. 1b). Both K_S and G have nonlinear relationships with pressure in the range of 0-35 GPa, especially for G . For example, at ambient temperature, $\frac{\partial K_S}{\partial P}$ and $\frac{\partial G}{\partial P}$ change from 6.53 and 2.14 at 0 GPa to 4.89 and 1.06 at 10 GPa, respectively. The compressional wave velocity (V_P) and shear wave velocity (V_S) can be derived from the density and elastic moduli K_S

and G as $V_P = \sqrt{\frac{K_S + \frac{4}{3}G}{\rho}}$, $V_S = \sqrt{\frac{G}{\rho}}$. The calculated results are well in line with the results of J.

Kung et al. (2005) for V_P , regardless of temperature, whereas there are some discrepancies for V_S , with a maximum of ~2-2.5% at ambient temperature and gradual shrinkage with increasing temperature (Fig. 1b). The fitting parameters of elastic moduli and velocities as a function of pressure and temperature are reported in Table S4.

3.3 Property contrasts caused by the OEN-HPCEN transition

Combined with the elasticity of the OEN at high PT from Qian et al. (2018), we evaluated the property contrast caused by the OEN-HPCEN transformation expressed as $\delta M = \frac{2 \times (M_{HPCEN} - M_{OEN})}{M_{HPCEN} + M_{OEN}} \times 100\%$, where M denotes different properties, including density, V_P , V_S , P wave impedance, and S wave impedance. At room temperature, OEN transforms into HPCEN with ~2.7%, ~2.9%, and ~4.1% jumps for density, V_P , and V_S , respectively, which is consistent with the results of Jennifer Kung et al. (2004). The OPX-HPCPX transition should have similar impedance contrasts due to the similar Fe partitioning behavior between OPX and HPCPX (A Woodland et al., 1997). Under the PT conditions of the X-discontinuity, the transition accompanies ~5.7% and ~6.9% impedance contrasts for the P wave and S wave, respectively (Fig. 2). In addition,

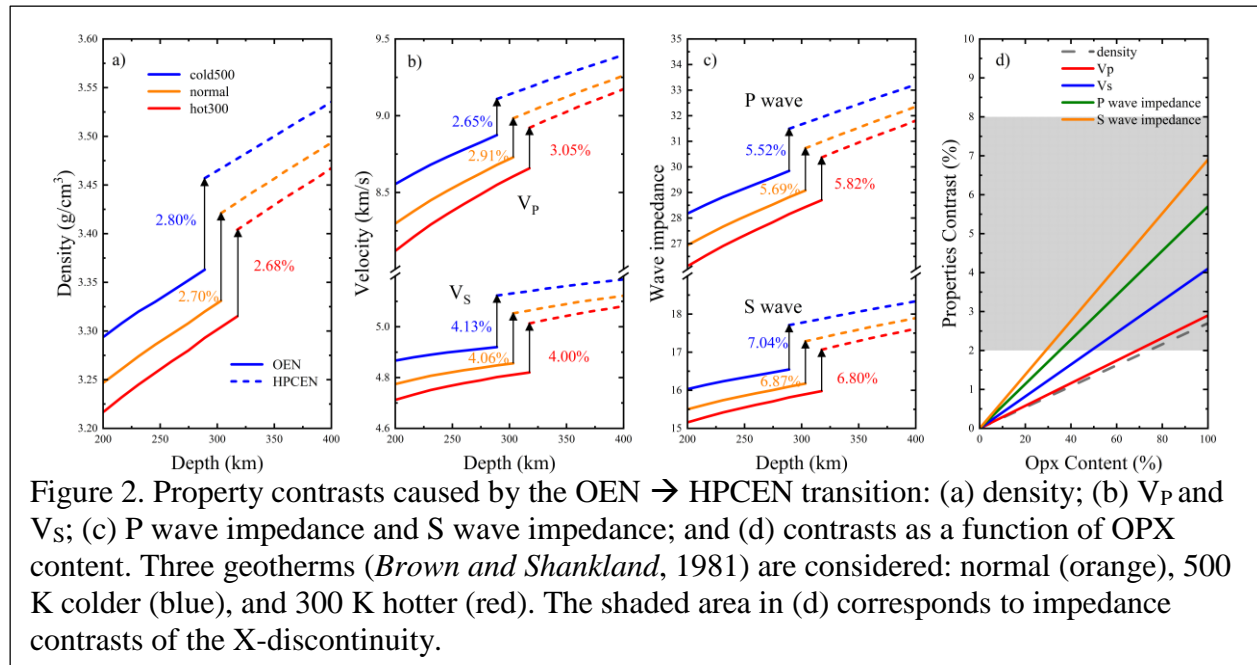


20% OPX corresponds to 1.2% P wave and 1.4% S wave impedance contrasts. These values are two times larger than those of Alan B Woodland and Angel (1997), which were assumed from Birch's law without direct wave speed measurements. Since Kemp et al. (2019) and Pugh et al. (2021) adopted underestimated impedance contrasts of Alan B Woodland and Angel (1997), they inappropriately ruled out the OPX-HPCPX transition in advance. According to our results, the OPX-HPCPX transition has the ability to generate seismically detected X-discontinuities as long as the OPX content exceeds 30% (Fig. 2d).

4. Discussion

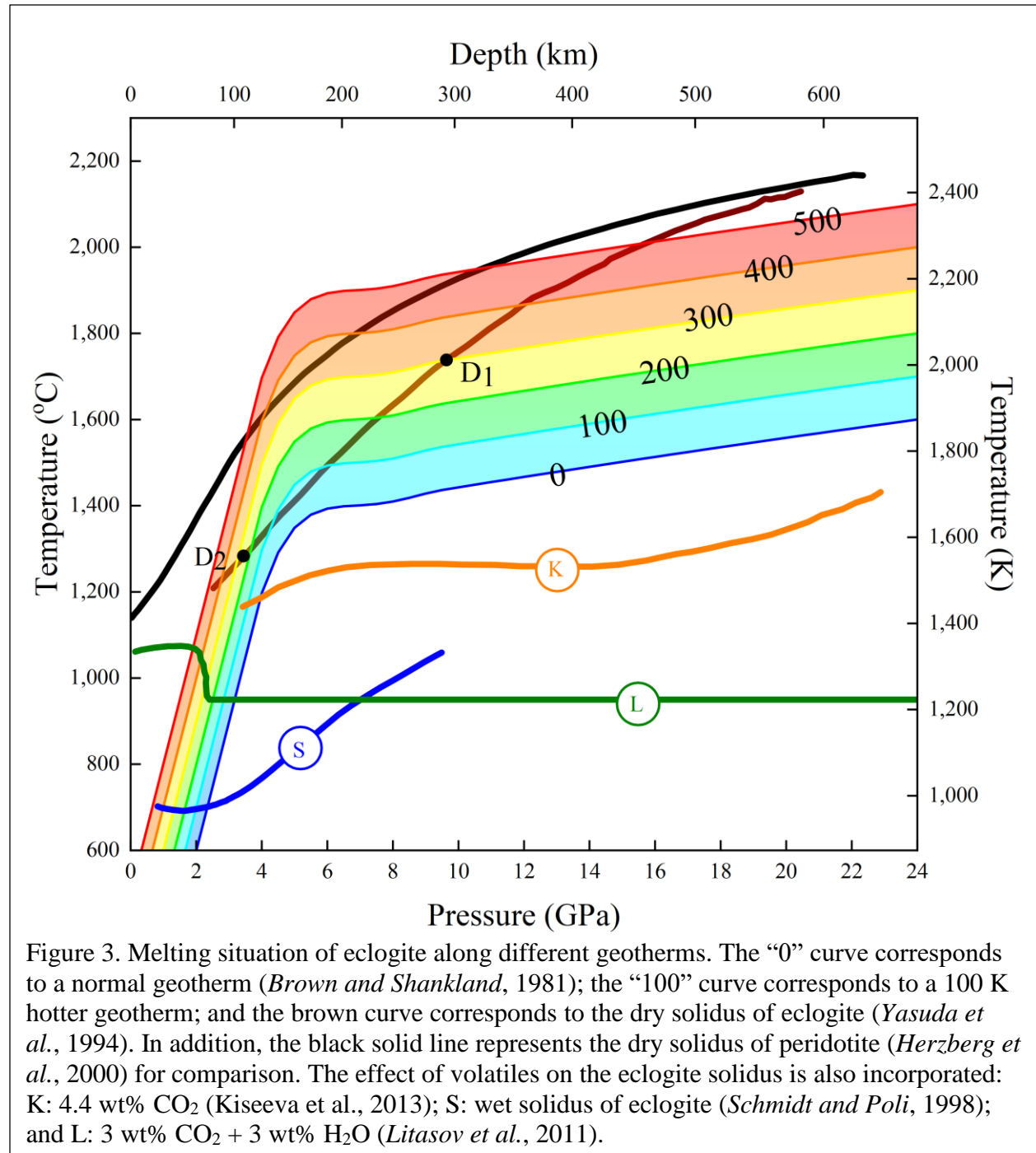
4.1 OPX enrichment and partial melting of eclogite

OPX is an important major mineral in the upper mantle, occupying ~10% of the pyrolite model and gradually dissolving into garnet. Therefore, the OPX in the pyrolite model is insufficient to generate visible X-discontinuities (Frost, 2008), and greater amount of OPX is required for the formation of the X-discontinuity. Within subduction zones, the harzburgite layer, which is the mantle residual part after MORB extraction, is more depleted and contains ~13% OPX on average (Matsukage et al., 2005). In addition, the enrichment of OPX is mainly achieved by melt/rock reactions between silica-rich melts generally derived from eclogite and surrounding peridotite at the expense of olivine. Although experimental studies have widely demonstrated the OPX-enrichment mechanism (Gervasoni et al., 2017; Mallik and Dasgupta, 2012; Rapp et al., 1999; Yaxley and Green, 1998), whether eclogite melts around the depth range of the X-discontinuity,



which has comprehensive implications for the processes of Earth's interior, remains uncertain. Here, we show compelling evidence for the OPX-HPCPX transition as one of the dominant mechanisms of the X-discontinuity and the wide distribution of melting of eclogite around the depth range of the X-discontinuity.

The estimates of the melting situation of eclogite based on a volatile-free dry solidus of eclogite (Yasuda et al., 1994) and a relatively low geotherm (Brown and Shankland, 1981) are conservative compared to that using other reported geotherms (Katsura et al., 2010). The



estimations clearly suggest that eclogite is subject to partial melting in high-temperature regions. Taking eclogite entrained by the upwelling plume as an example, it starts to melt at depth D_1 and then crystallizes at shallower depth D_2 ($D_1 > D_2$) along the hot geotherm. As shown in Fig. 3, the depth interval where eclogite will partially melt (D_1 , D_2) broadens quickly with increasing temperature. D_1 approaches 300 km, and OPX can be locally enriched at a depth of 300 km under 300 K hotter conditions. When the geotherm is 500 K hotter, eclogite starts to melt at a depth of ~450 km and has a larger melting degree at 300 km, suggesting that there is less solid-state silica but more OPX enrichment. Thus, OPX enrichment is likely to be achieved in hot regions. The presence of H_2O or CO_2 dramatically decreases the solidus of eclogite (Kiseeva et al., 2013; Litasov et al., 2011; Schmidt and Poli, 1998) (Fig. 3) and further promotes the partial melting of volatile-bearing recycled oceanic crust. Thus, the OPX-HPCPX transition likely plays an important role in the origin of the X-discontinuity in hot or wet areas.

4.2 Seismological support

Although precisely determining the mechanism underlying the observed X-discontinuity is difficult, there are indeed some special seismological signals to help us discriminate the origin of the X-discontinuity. We noted that several recent seismological studies on the X-discontinuity (Kemp et al., 2019; Pugh et al., 2021; Rein et al., 2020) support our view.

4.2.1 X-discontinuity and disappearance of 410 beneath the Hawaii hotspot

Kemp et al. (2019) found that the X-discontinuity, with an average depth of 296 km, exists throughout the entire area beneath Hawaii. The X-discontinuity becomes deeper and stronger, while the 410 discontinuity becomes deeper but weaker and even vanishes in the eastern part of the Big Island. Kemp et al. (2019) simply excluded the OPX-HPCPX transition based on the results of Alan B Woodland and Angel (1997) and proposed that the X-discontinuity results from the coesite-stishovite transition in eclogite. In fact, our calculation shows that the OPX-HPCPX transition can cause X-discontinuities with a large impedance contrast (Fig. 2d). Moreover, the coesite-stishovite transition for the X-discontinuity beneath Hawaii (Kemp et al., 2019) faces several fundamental challenges. As shown in Fig. 4a, the depth of the X-discontinuity (~300 km) is significantly shallower than the coesite-stishovite transition considering the high temperature beneath the Hawaii hotspot. Furthermore, the deeper depths of the X-discontinuity and 410 in the eastern part of Big Island (Kemp et al., 2019) indicate that the eastern part has a higher temperature and larger melting degree of eclogite than other areas, which means a weaker X-discontinuity signal. This finding conflicts with the observed stronger X-discontinuity signal in the eastern part. Finally, an accumulation of eclogite >60%, which is required to explain the disappearance of 410 according to synthesis tests (Kemp et al., 2019), will be >3% denser than ambient mantle and generate gravitational instability (Maxim D Ballmer et al., 2015; Maxim D. Ballmer et al., 2013). In contrast, these challenges become strong arguments for the X-discontinuity resulting from the OPX-HPCPX transition. Beneath Hawaii, Si-rich melts derived from eclogite carried by the upwelling plume react with surrounding peridotite to enrich OPX at the expense of olivine. The OPX-HPCPX transition, which occurs at a much shallower depth than the coesite-stishovite transition (Fig. 4a), is consistent with the depth of the X-discontinuity. A larger degree of melting, which means a larger degree of enrichment of OPX and consumption of olivine, can well explain the stronger X-discontinuity and the weaker and even vanished 410 in the hotter east part. High-Ni and high-Si parental Hawaiian magmas also indicate that their source is not peridotite but olivine-free pyroxenite formed by consuming olivine (Sobolev et al., 2005; Sobolev et al., 2007).

4.2.2 Double X-discontinuities beneath Southwest Morocco

The X-discontinuity beneath Southwest Morocco (SW Morocco) (Rein et al., 2020) provides more cogent evidence on the important role of the OPX-HPCPX transition in the X-discontinuity. According to local tectonic settings and the relationship between temperature and lithospheric thickness, Rein et al. (2020) found that the temperature in the study area rises successively from the west, southeast, and northeast regions. Receiver function results show that from west to southeast, the X-discontinuity signal weakens and the depth of the X-discontinuity increases from 310~340 km to 330~350 km. The situation is the most complicated in the northeast. Double weak X-discontinuities are detected, with one at 285~295 km and the other at 330~350 km. In the northernmost part, the deeper part disappears, leaving the shallow part untouched (see Figure 5 in Rein et al. (2020)). The scenario is completely consistent with our point of view. The free solid-state silica is preserved to the largest extent and generates the strongest X-discontinuity in the coldest west. The higher temperature in the southeast results in a deeper X-discontinuity because of the positive Clapeyron slope of the silica transition and weaker signal because more eclogite melts to reduce solid-state silica. Although the melting of silica promotes the enrichment of OPX, the OPX in the southeast is still less than 30%, and its phase transition cannot produce a detectable discontinuity. With further increases in temperature in the northeast, the enrichment of OPX is eventually enough to be detected and results in relatively weak double X-discontinuities, which are shallower for the OPX-HPCPX transition and deeper for the coesite-stishovite transition. With higher temperatures, silica-induced X-discontinuities cannot be detected and OPX-induced X-discontinuities become stronger, corresponding to the single 290-km X-discontinuity in the northernmost part. Such double X-discontinuities demonstrate that the OPX-HPCPX transition can indeed cause X-discontinuities in hot areas.

By combining these studies together, we found further evidence to support our view on the cause of the X-discontinuity beneath Hawaii. It is acceptable that the Hawaii hotspot should be hotter than SW Morocco, which is also supported by seismological results: the 410 in Hawaii depresses by ~20 km (Kemp et al., 2019) while the 410 in SW Morocco depresses by only ~10 km (Lawrence and Shearer, 2006; Spieker et al., 2014). If the X-discontinuity beneath Hawaii is caused by a silica phase transition, it should be deeper than the X-discontinuity associated with the silica transition beneath SW Morocco due to the strong positive Clapeyron slope of the coesite-stishovite transition. However, the average depth of the Hawaiian X-discontinuity (296 km) is significantly shallower than those of even the coldest part of SW Morocco (310~330 km). Similarly, all robust X-discontinuities beneath 15 hotspots except Tahiti reported by Pugh et al. (2021) occur at depths less than 280 km (pink area in Fig. 4a) and thus should also result from the OPX-HPCPX transition rather than the coesite-stishovite transition suggested by Pugh et al. (2021).

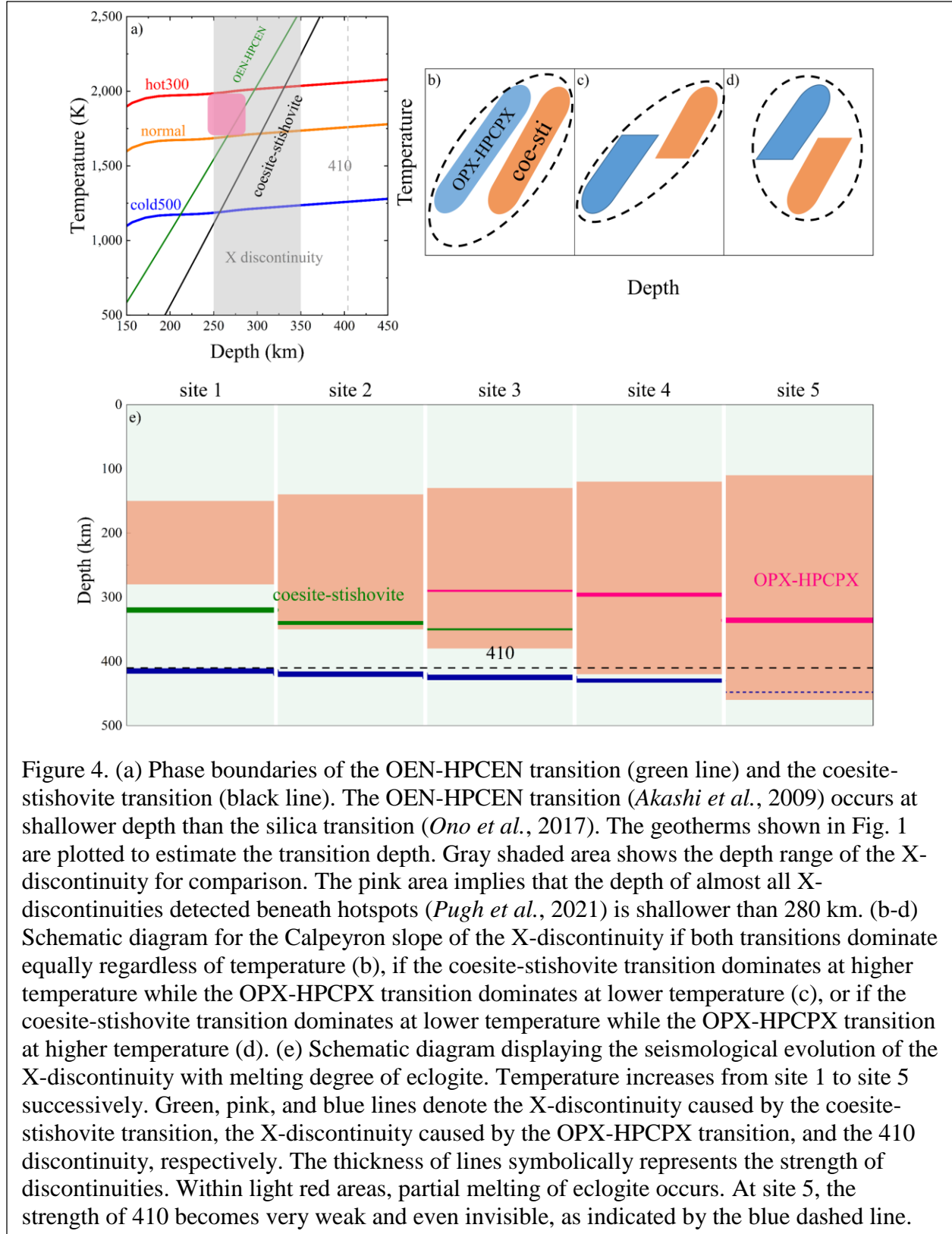


Figure 4. (a) Phase boundaries of the OEN-HPCEN transition (green line) and the coesite-stishovite transition (black line). The OEN-HPCEN transition (Akashi *et al.*, 2009) occurs at shallower depth than the silica transition (Ono *et al.*, 2017). The geotherms shown in Fig. 1 are plotted to estimate the transition depth. Gray shaded area shows the depth range of the X-discontinuity for comparison. The pink area implies that the depth of almost all X-discontinuities detected beneath hotspots (Pugh *et al.*, 2021) is shallower than 280 km. (b-d) Schematic diagram for the Calpeyron slope of the X-discontinuity if both transitions dominate equally regardless of temperature (b), if the coesite-stishovite transition dominates at higher temperature while the OPX-HPCPX transition dominates at lower temperature (c), or if the coesite-stishovite transition dominates at lower temperature while the OPX-HPCPX transition at higher temperature (d). (e) Schematic diagram displaying the seismological evolution of the X-discontinuity with melting degree of eclogite. Temperature increases from site 1 to site 5 successively. Green, pink, and blue lines denote the X-discontinuity caused by the coesite-stishovite transition, the X-discontinuity caused by the OPX-HPCPX transition, and the 410 discontinuity, respectively. The thickness of lines symbolically represents the strength of discontinuities. Within light red areas, partial melting of eclogite occurs. At site 5, the strength of 410 becomes very weak and even invisible, as indicated by the blue dashed line.

4.3 Evolution of the X-discontinuity with the melting degree of eclogite

The X-discontinuity beneath SW Morocco and hotspots actually well represent the variations in the X-discontinuity with the melting degree of eclogite (Fig. 4e). Site 1 in Fig. 4e, which indicates the western part of SW Morocco, has temperatures close to the normal mantle, and there is enough solid-state silica to produce strong X-discontinuities. At site 2, eclogite melts at depths deeper than 300 km but the OPX enrichment is not enough to produce detectable discontinuities. In this case, one weaker but deeper X-discontinuity is observed in the seismology that represents the southeastern part of SW Morocco. At site 3, a larger melting degree leads to OPX enrichment that exceeds 30%. The relevant X-discontinuity can be detected, while the silica-induced X-discontinuity can still be observed, although its strength diminishes, resulting in double X-discontinuity, as found beneath the northeastern part of SW Morocco (Rein et al., 2020) and the following hotspots: Marquesas, Samoa, and St. Helena (Pugh et al., 2021). When temperatures continue to increase at site 4, which is also observed at the hottest part in SW Morocco (Rein et al., 2020), at most hotspots (Pugh et al., 2021), and at the Hawaii site investigated by Kemp et al. (2019) except for the eastern part of Big Island, the silica-relevant X-discontinuity eventually disappears while the OPX-related X-discontinuity becomes stronger. Thus, there is only one shallow X-discontinuity appearing in the seismology results. When the temperature increases to a certain degree, olivine near the 410 discontinuity is also consumed by the eclogite melt and the strength of the 410 is thus affected more or less and even disappears, as shown at site 5 (represented by the eastern Big Island (Kemp et al., 2019)).

4.4 Indistinguishable seismological Clapeyron slope of the X-discontinuity

Among the mechanisms causing the X-discontinuity, the OPX-HPCPX transition and the coesite-stishovite transition are the most plausible. Partial melting of eclogite is crucial for both mechanisms since it promotes the enrichment of OPX by reducing the solid-state silica content. In relatively low-temperature and volatile-poor regions, where eclogite is hard to melt, the coesite-stishovite transition is dominant. In contrast, in regions where a large degree of partial melting of eclogite occurs, the OPX-HPCPX transition is dominant. The interpretation of the genesis of the X-discontinuity is also supported by the indistinguishable seismological Clapeyron slope of the X-discontinuity (A. Deuss and Woodhouse, 2004). Their findings indicate that a single mineralogical mechanism is insufficient since these transitions have a large positive Clapeyron slope. If both transitions dominate equally regardless of temperature (Fig. 4b) or if the coesite-stishovite transition dominates at higher temperatures while the OPX-HPCPX transition dominates at lower temperatures (Fig. 4c), then an obviously positive Clapeyron slope will be detected. In contrast, when the coesite-stishovite transition dominates at lower temperatures while the OPX-HPCPX transition dominates at higher temperatures (Fig. 4d), there is no strong relationship between temperature and depth, which naturally provides an explanation for the indistinguishable seismological Clapeyron slope of the X-discontinuity (A. Deuss and Woodhouse, 2004). Consequently, the dominance of the OPX-HPCPX transition together with the coesite-stishovite transition for the X-discontinuity suggests ubiquity of partial melting of recycled oceanic crust around a depth of 300 km. The X-discontinuity provides a key method of identifying partial melting of recycled oceanic crust.

Acknowledgments

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Data Availability Statement

The authors comply with the AGU's data policy, and the datasets in this paper are available on zenodo via <https://doi.org/10.5281/zenodo.5515367>

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