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Key Points:

- Electrical conductivity (EC) of amorphous and liquid CaCO_3 has been studied up to 15 GPa and 2,100 K
- Amorphization of CaCO_3 does not enhance the ionic diffusivity. EC of amorphous CaCO_3 is comparable to that of hydrous minerals
- Amorphization of CaCO_3 is an unlikely mechanism to explain the EC anomalies in the upper mantle

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

T. Yoshino,
tyoshino@misasa.okayama-u.ac.jp

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Author Contributions:

Conceptualization: Takashi Yoshino

Data curation: Bin Zhao

Formal analysis: Bin Zhao,

Takashi Yoshino, Qi Chen, Tony Yu, Yanbin Wang

Funding acquisition: Bin Zhao, Takashi Yoshino

Investigation: Bin Zhao, Takashi Yoshino, Qi Chen, Dongzhou Zhang, Bin Chen, Yanbin Wang

Methodology: Bin Zhao, Takashi Yoshino

Project administration: Takashi Yoshino

Resources: Qi Chen, Tony Yu, Yanbin Wang

Supervision: Takashi Yoshino

Validation: Bin Zhao, Takashi Yoshino, Tony Yu

Visualization: Bin Zhao

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Electrical Conductivity of Amorphous and Molten CaCO_3 at High Pressures and Its Implications for Mantle Conductivity Anomalies

Bin Zhao^{1,2} , Takashi Yoshino¹ , Qi Chen³ , Tony Yu³ , Dongzhou Zhang³ , Bin Chen² , and Yanbin Wang³

¹Institute for Planetary Materials, Okayama University, Misasa, Japan, ²School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI, USA, ³Center for Advanced Radiation Sources, The University of Chicago, Chicago, IL, USA

Abstract Impedance spectrometry experiments have been conducted on CaCO_3 up to 15 GPa and 2,100 K to identify its state under high pressure. The melting temperature of CaCO_3 was also determined by the falling of a Re sphere observed via X-ray radiography. The phase transition from aragonite to the amorphous phase does not cause a leap in the Electrical conductivity (EC), while a drastic increase in the EC, by 1.5–2.0 log units, only occurs with the onset of melting. The EC of amorphous CaCO_3 is comparable to other hydrous mantle minerals at similar pressure and temperature conditions. The required fraction of amorphous CaCO_3 implies that it can be excluded from the potential origins responsible for the observed high EC anomalies in the upper mantle. If the conductivity anomalies are induced by the presence of carbonate, a low-degree melting of carbonate-bearing peridotite is anticipated.

Plain Language Summary The observed electrical conductivity (EC) anomalies in Earth's mantle are often explained by the presence of hydrous minerals or a small fraction of silicate/carbonate melts. CaCO_3 , as one of the main carbon carriers that transport surface carbon to the Earth's interior, has been demonstrated to exist as a stable amorphous phase in the upper mantle above the 410-km discontinuity if not forming a solid solution with other carbonates. The amorphization which induces structural disorder and imperfections, may enhance the ionic self-diffusion in CaCO_3 , and subsequently increase the EC, while this mechanism has not yet been proposed to explain the observed EC anomalies. In this study, we experimentally investigate the EC of amorphous and liquid CaCO_3 at mantle pressure and temperature conditions, and examine if the results can explain the conductivity anomalies in terms of the proposed budget of CO_2 of the upper mantle.

1. Introduction

The carbon (C) cycling of the Earth is achieved by subductions that transfer the surface carbon into depth, followed by deep incipient melting, mantle upwelling, and volcanism that bring deep carbon back to the surface. This process sustains or regulates the climate on the time scale of millions to billions of years (Hoffman et al., 1998; Isson et al., 2020; Kelemen & Manning, 2015; Plank & Manning, 2019). During subduction, the main C carriers are carbonates/carbonatites in mantle peridotite, oceanic crusts and the overlying sediments (Dasgupta and Hirschmann, 2006, 2010; Kelemen & Manning, 2015), among which siderite and ankerite-rich phases are readily fusible or dissociated at shallower depth (Kang et al., 2015; Tao et al., 2013). Although a part of the more refractory counterparts (magnesite, calcite, or dolomite) can survive at deeper mantle pressure (P)—temperature (T) conditions (Zhu & Ogasawara, 2002) and transport C through the transition zone (Ague & Nicolescu, 2014; Thomson et al., 2016), a global mantle melting introduced by carbonates was favored by melting experiments of mantle peridotites (Dasgupta et al., 2013), and was later supported by a sound velocity study on dolomite melts that suggested an extremely low degree of melting can account for the global seismic models (Xu et al., 2020).

High electrical conductivity (EC) anomalies have been observed by magnetotelluric (MT) sounding studies from subsurface (~50 km beneath the ocean floors, Key et al., 2013) through the lower mantle (e.g., Kelbert et al., 2009). Hydrous minerals, silicate/carbonate melts, and supercritical fluids have been widely employed to explain the high EC anomalies in the Earth's mantle (Manthilake et al., 2009; Sifré et al., 2014; Yoshino et al., 2009). In particular, carbonate-rich silicate melt produced by incipient mantle melting has been used to explain the observed EC anomalies from the lithosphere-asthenosphere boundary to the transition zone (Gaillard

Writing – original draft: Bin Zhao
Writing – review & editing: Bin Zhao,
Takashi Yoshino, Qi Chen, Tony Yu,
Dongzhou Zhang, Bin Chen, Yanbin Wang

et al., 2008; Sifré et al., 2015; Yoshino et al., 2012). It has been shown that 5 wt% of CO₂ incorporated in peridotite will decrease the melting temperature by ~600 K for the same P – T condition (Litasov and Ohtani, 2007, 2009), causing incipient slab melting that extracts CaCO₃ (Litasov and Ohtani, 2009; Thomson et al., 2016). Indeed, calcite inclusions have been found in natural diamonds (Wirth et al., 2009; Zedgenizova et al., 2016), suggesting that CaCO₃ may be present as a pure phase in certain regions of the mantle. To investigate CaCO₃ as a potential cause for EC anomalies, previous experimental studies on the EC of CaCO₃ mainly focused on low-temperature phases calcite and aragonite (Bagdassarov & Slutskii, 2003; Ter Heege & Renner, 2007), as well as their solid solution, dolomite (Ono & Mibe, 2015). Transport properties of liquid CaCO₃ have been studied by atomistic simulations (Vuilleumier et al., 2014).

However, CaCO₃ is known to form an amorphous phase (also called “disordered CaCO₃”) right below the melting point in the pressure range of 4–15 GPa by both experiments and calculations (Gavryushkin et al., 2020; Hou et al., 2019; Litasov et al., 2017; Suito et al., 2001). The stability field of amorphous CaCO₃ determined by in situ X-ray diffraction makes it the most plausible solid form in the depth of 70–400 km if it does not form solid solutions with other carbonates. Also, the expected low density of amorphous CaCO₃ allows higher mobility with the mantle flows compared to crystalline CaCO₃ (Hou et al., 2019). To our knowledge, there has no report on these properties of amorphous CaCO₃. In this study, we measured the EC of amorphous and liquid CaCO₃ in the pressure range of 6–15 GPa and temperatures up to 2100 K to investigate the validity of amorphous and liquid CaCO₃ as the source of EC anomalies in the upper mantle.

2. Results

2.1. Melting Curve of CaCO₃

The melting of CaCO₃ was monitored by the falling of a Re sphere placed at the center of the capsule (Figure S1 in Supporting Information S1). The melting temperature determined by the falling sphere technique at GSECARS beamline of the Advanced Photon Source is shown by the magenta symbols in Figure 1. Accompanied by the fall of the sphere, we observed that the EC of the sample largely increased by ~1.5 orders of magnitude to 1.7–2.0 S/m, consistent with the results obtained from the Institute for Planetary Materials (IPM) (Figure 2). We attribute such increase in the EC to melting. The melting points determined by an abrupt conductivity change observed at IPM are also shown in Figure 1 (red symbols). The main discrepancy in temperature comes from the distance between the thermocouple (TC) and the sample in the high-pressure cell assembly, that is, the relative position to the hot-spot of the heater. Such discrepancy is usually less than 100 K. However, the discrepancy at 6 GPa was found to be up to 200 K. Combined with low-pressure data in previous studies, the low melting point at 6 GPa was probably due to a larger displacement of the TC junction. While the melting curve is almost flat from 5 to 15 GPa, a slight dip can be seen around 12 GPa, similar to the trend defined by Li et al. (2017), although the melting temperature is overall 70–100° lower than that in Li et al. (2017) throughout the pressure range of interest. It is noted that their experiments show a large temperature interval of resistance change just below the melting point. The conductivity measurement cell they used exhibit a large temperature gradient by metal heater, which may require an apparently higher temperature for complete melting.

2.2. Electrical Conductivity of CaCO₃

The impedance spectra collected at 8 GPa upon cooling from 1,900 K are shown in Figure S4 in Supporting Information S1 as an example. The inductive semicircle at low frequencies, which follows the capacitive semicircle at high frequencies, are usually attributed to the electrode surface processes which mathematically resemble inductance (Hampson et al., 1980; Yoshino et al., 2012). Electrical conductivity is defined as follow:

$$\sigma = l/RS \quad (1)$$

where R is the resistance, l the length along the cylindrical axis, and S the cross-sectional area of the sample. The sample dimension was determined by the recovered sample from off-line experiments at IPM, and by X-ray radiography during in situ experiments at 13-ID-D under pressure. The uncertainties in length and cross-sectional area do not result in discernible differences in σ when plotted in logarithmic scale.

Figure 2 shows the calculated EC of CaCO₃ from 6 to 15 GPa. The uncertainty in temperature is typically less than ± 25 K above 1,500 K, indicated by previous experiments with two sets of TC placed at both ends of the sample

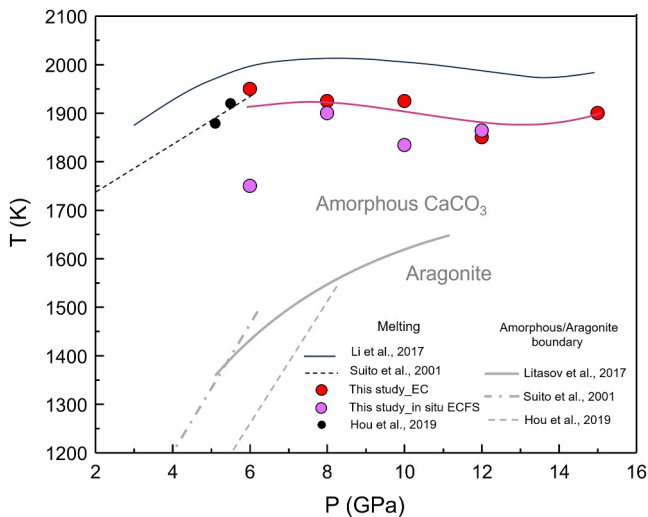


Figure 1. The melting point/curve of CaCO_3 defined in different studies. Red circle: This study, by increase in electrical conductivity (EC). Magenta circles: This study, by in situ falling sphere and increase in EC. Solid line: Li et al. (2017), by decrease in resistance and falling sphere. Black symbols: Hou et al. (2019), by falling sphere. Dash line: Suito et al. (2001), by in situ X-ray diffraction and quenched phases. The aragonite/amorphous phase boundary from literature is displayed with gray curves (Hou et al., 2019; Litasov et al., 2017; Suito et al., 2001).

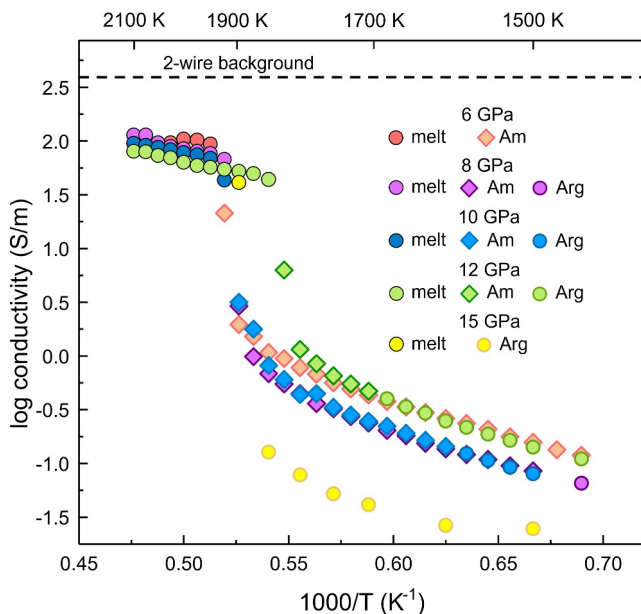


Figure 2. Log electrical conductivity (EC) of aragonite, amorphous CaCO_3 , and molten CaCO_3 in the pressure range of 6–15 GPa. The temperature range of aragonite (circles at low T) and amorphous CaCO_3 (diamonds) at each pressure is assigned by literature data or its extrapolation (Hou et al., 2019; Litasov et al., 2017; Suito et al., 2001). The slot for amorphous CaCO_3 at 15 GPa is considered closed according to the extrapolation. The dashed line shows the short-circuit conductivity using the two-wire experimental setup (Yoshino et al., 2018). Note that the range of the measured EC is sufficiently low.

(e.g., Zhao et al., 2025). The measurements span the temperature range of transformations from aragonite to amorphous to liquid at 8–12 GPa and from amorphous to liquid at 6 GPa. The aragonite to amorphous phase boundary is defined as an average value of literature data or its extrapolation (Hou et al., 2019; Litasov et al., 2017; Suito et al., 2001), that is, 1,350, 1,500, 1,600, and 1,700 K at 6, 8, 10, and 12 GPa, respectively. The EC above the melting point shows a negative pressure dependence, consistent with the experimental results on silicate and carbonate melts (Pommier et al., 2008; Sifré et al., 2015; Yoshino et al., 2018), as well as numerical simulations (Vuilleumier et al., 2014). However, there is no clear pressure dependence of the conductivity of aragonite nor the amorphous phase. In addition, there is no inflection point at the phase boundary between aragonite and the amorphous phase, implying that there is no major change in the conduction mechanism that controls the EC between these two phases.

Electrical conductivity above liquidus can be fitted to the following arrhenian equation

$$\sigma = \sigma_0 \exp\left(-\frac{\Delta E + P\Delta V}{kT}\right) \quad (2)$$

where σ_0 is a pre-exponential factor in S/m, ΔE the activation energy in J/mol, P the pressure in Pa, ΔV the activation volume in m^3/mol , k the Boltzmann constant, and T the temperature in K. The fitting yields a σ_0 of 1.094×10^4 S/m, ΔE of 0.72 eV, and ΔV of $1.28 \text{ cm}^3/\text{mol}$. Our fitting yields a higher activation energy and a lower activation volume compared to those of $[\text{Na}_2]_{0.7}[\text{Mg}]_{0.3}\text{CO}_3$ melt (Yoshino et al., 2018), whose ΔE and ΔV are 0.22 eV and $1.81 \text{ cm}^3/\text{mol}$, respectively. The higher activation volume is related to the greater pressure dependence of slope of log conductivity versus reciprocal T , which originates from the nature of different cations. However, the numerical simulation on liquid CaCO_3 yielded a fitted ΔV of 2.19–2.35 cm^3/mol in 6–15 GPa (Vuilleumier et al., 2014), almost twice the value of this study. We note that such large difference is mainly from the fitting uncertainties, as only one or two datapoints were available for fitting at each pressure in Vuilleumier et al. (2014). Despite the large discrepancy in the activation volume, the experimentally determined EC in this study is highly consistent with the numerical simulations ($\sim 2,070$ K, 8–15 GPa), with the differences essentially less than 20% (Figure 3).

3. Discussion

3.1. Conduction Mechanisms of CaCO_3

In crystalline CaCO_3 , that is, calcite or aragonite, the conduction mechanism is limited self-diffusion of Ca^{2+} and CO_3^{2-} which creates cation and anion vacancies. Previous studies have demonstrated that, at same temperatures, the diffusion coefficient of C and O are 4–5 orders of magnitude higher than that of Ca (Anderson, 1969; Fisler & Cygan, 1999). Furthermore, the diffusivity of O is up to 4 times higher than that of C (Anderson, 1969), making the self-diffusion of O the most significant contributor to bulk EC. Above 3 GPa, CaCO_3 transforms to the amorphous phase at high temperature, and the transformation triggers a decrease in density (Hou et al., 2019). Molecular dynamics simulation shows that a key feature of the amorphous phase is freely rotating CO_3 groups (Gavryushkin et al., 2020). However, our EC data

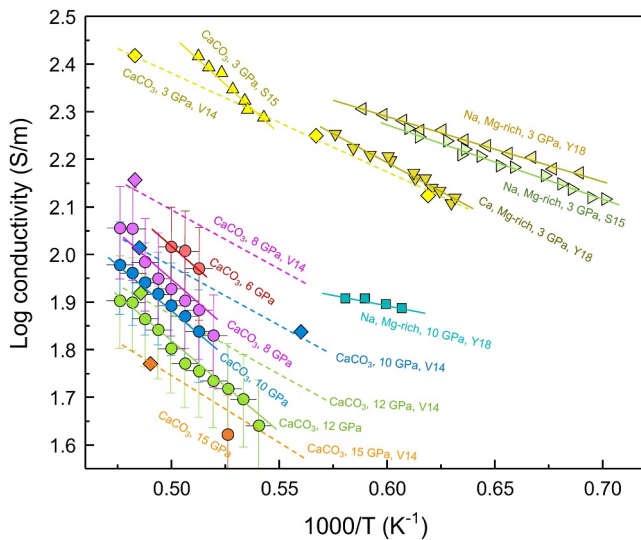


Figure 3. Comparison of the electrical conductivity among carbonate melts from 3 to 15 GPa. Experimental results include: Ca-rich melt and Na, Mg-rich melt at 3 GPa (Sifré et al., 2015: S15), Ca, Mg and Na, Mg-rich melt at 3 GPa and Na, Mg-rich melt at 10 GPa (Yoshino et al., 2018: Y18), CaCO_3 melt from 6 to 15 GPa (this study). Numerical simulation results: CaCO_3 melt from 3 to 15 GPa (Vuilleumier et al., 2014: V14).

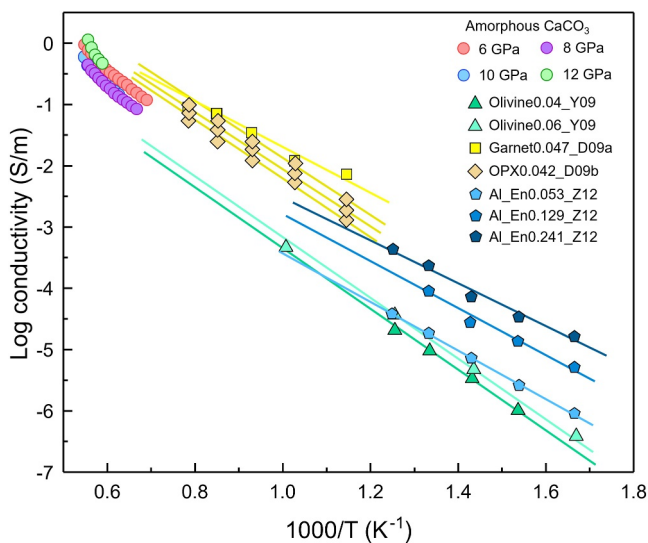


Figure 4. Comparison of the electrical conductivity of amorphous CaCO_3 and hydrous minerals at similar P – T conditions. Circles: results of amorphous CaCO_3 from this study; Squares: hydrous garnet with 0.047 wt% water at 8 GPa (Dai & Karato, 2009a); Diamonds: hydrous orthopyroxene with 0.042 wt% water at 8 GPa (Dai & Karato, 2009b); triangles: hydrous olivine with 0.04 and 0.06 wt% water at 10 GPa (Yoshino et al., 2009); Pentagons: hydrous aluminous enstatite with 0.053, 0.129, and 0.241 wt% water at 3 GPa (Zhang et al., 2012).

do not exhibit an inflection point at the proposed phase transition boundary as reported in the literature. This suggests that the amorphization is an unlikely mechanism to enhance self-diffusion of the ions.

Once the melting point is reached, ionic diffusion is drastically enhanced in liquid CaCO_3 , with the EC elevated by 1.5–2.0 log units. Similar to other carbonate melts, the EC is contributed from all the charge species, that is, metallic cations and CO_3^{2-} anions that follow the Nernst-Einstein relationship (Yoshino, 2010). At the same P – T condition, the EC is affected by the sort of cations: Carbonate melts with monovalent cations, mainly Na^+ , are more conductive due to the high diffusivity of the alkaline cations (Jambon, 1982), which can be readily seen with the results of Na, Mg-rich (Sifré et al., 2015) and Ca-Mg-rich (Yoshino et al., 2018) samples at 3 GPa, and Na, Mg-rich sample (Yoshino et al., 2018) and CaCO_3 at 10 GPa in Figure 3. On the other hand, the overall negative pressure effect on the EC is consistent with previous experimental studies and Molecular dynamics simulations, implying that the diffusion channels for the charge species become narrower with increasing pressure. The conductivity of liquid CaCO_3 in a pressure range from 8 to 12 GPa determined from our experiments is in good agreement with the high-temperature datapoints from simulations, differing by less than 0.1 log unit (Figure 3).

3.2. Geophysical Implications

Hydrous minerals are often used to explain the observed high conductivities in the upper mantle, because migration of H^+ (proton conduction) considerably elevates bulk EC of minerals by a few orders of magnitude. Figure 4 compares EC between amorphous CaCO_3 and several hydrated nominally anhydrous upper-mantle minerals. Amorphous CaCO_3 possesses conductivity comparable to hydrous garnet and orthopyroxene with 0.04–0.05 wt% H_2O at similar P – T conditions, while hydrous olivine and aluminous enstatite are less conductive when extrapolated to the same temperature. CaCO_3 as one of the main carbonates in the subduction slabs, will likely transform from calcite to aragonite at shallow mantle depth and subsequently transform to the amorphous phase below 100 km in a descending slab (Bayarjargal et al., 2018; Hou et al., 2019). As shown in Figure 5b and 5 wt% of CO_2 incorporate in peridotite will decrease the melting temperature by ~ 600 K for the same P – T condition (Litasov and Ohtani, 2007, 2009), causing incipient slab melting that extracts CaCO_3 (K. Litasov and Ohtani, 2009; Thomson et al., 2016). The enrichment of water and monovalent cations such as Na^+ and K^+ will pose a similar impact so that CaCO_3 is extracted by the melt (Chen et al., 2014; Li et al., 2017; Litasov and Ohtani, 2007). Thus, the formation of pure CaCO_3 requires the slab to be depleted in water and monovalent cations (at least locally), and the bulk CO_2 content should be less than 5%. In regions of the mantle where these requirements are met, amorphous CaCO_3 will be a stable phase above the 410-km discontinuity due to its high melting temperature. Since Yoshino et al. (2009) have demonstrated that many conductive regions in oceanic and continental mantle can be readily addressed by the existence of hydrous olivine with water content less than 0.1 wt%, the higher conductivity of amorphous CaCO_3 may serve as another candidate for the medium-conductive zones, especially considering its low density and low strength, which make it more likely to escape from the descending slabs and diffuse into the overlying mantle (Hou et al., 2019).

The melting curve of CaCO_3 intersects the mantle adiabat in the upper mantle transition zone (Figure 5b). If a piece of sediment or oceanic crust is

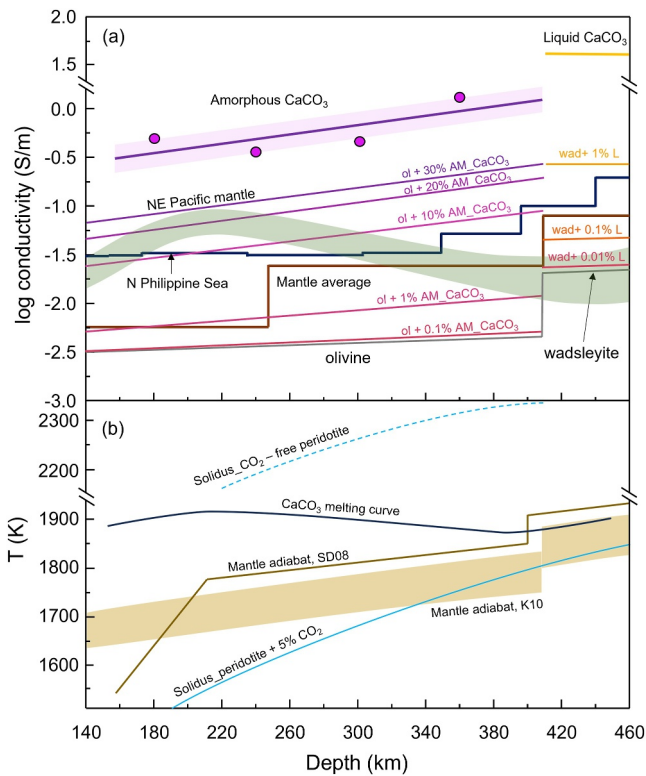


Figure 5. (a) Electrical conductivity-depth profile for the mantle average (Kelbert et al., 2009), N Philippine Sea (Baba et al., 2010), and NE Pacific mantle (Lizarralde et al., 1995). Gray lines on the bottom are the data of dry olivine and wadsleyite (Yoshino et al., 2008). Colored curves are data of amorphous liquid CaCO₃ (top) and mixing models with minerals and certain amount of CaCO₃ using HS⁺. (b) Solidus of CO₂-free peridotite and carbonated peridotite (Litasov and Ohtani, 2007, 2009), and mantle adiabats from different models (Katsura et al., 2010; Stacey & Davis, 2008) compared with the melting curve of CaCO₃.

detached from a subducting slab, it will be heated by the mantle wedge and CaCO₃ may melt based on the mantle adiabats by both models (Katsura et al., 2010; Stacey & Davis, 2008). Following the above considerations, here we examine whether the presence of amorphous and liquid CaCO₃ can explain the EC anomalies observed in subduction zone and the surrounding mantle. The mantle EC involving CaCO₃ is modeled by the Hashin-Shtrikman upper bound (HS⁺, Hashin and Shtrikman, 1962) to calculate the EC of multi-phase mixtures where the grains or melt form interconnections:

$$\sigma(HS^+) = \sigma_M + \left(\sum_{i=1}^n \frac{\phi_i}{(\sigma_i - \sigma_M)^{-1} + (3\sigma_M)^{-1}} \right) / \left[1 - (3\sigma_M)^{-1} \left(\sum_{i=1}^n \frac{\phi_i}{(\sigma_i - \sigma_M)^{-1} + (3\sigma_M)^{-1}} \right) \right] \quad (3)$$

where σ_M is the EC of the most conductive component, σ_i the EC of the i th component, and ϕ_i the volumetric fraction of the i th components of the mixture. HS⁺ correlates to the minimum volume fraction of the highly conductive phase (amorphous or liquid CaCO₃) in the mixture, and thus the calculated fraction of CaCO₃ can be directly compared to the CO₂ budget in the mantle. For simplification, the model is established with two components, olivine with amorphous CaCO₃ above the 410-km discontinuity, and wadsleyite with liquid CaCO₃ in the upper transition zone. Accordingly, Equation 3 simplifies to:

$$\sigma(HS^+) = \sigma_{CaCO_3} + (1 - \phi_{CaCO_3}) \left[\frac{1}{\sigma_s - \sigma_{CaCO_3}} + \frac{\phi_{CaCO_3}}{3\sigma_{CaCO_3}} \right]^{-1} \quad (4)$$

where σ_s is the EC of olivine or wadsleyite. Figure 5a shows the EC profile of mantle average (Kelbert et al., 2009), beneath the Northeast Pacific mantle (Lizarralde et al., 1995), and beneath the North Philippine Sea (Baba et al., 2010). Also shown are the EC of dry olivine and wadsleyite (Yoshino et al., 2008) on the bottom, the conductivity of amorphous and liquid CaCO₃

following the upper bound of the mantle adiabat by Katsura et al. (2010) on the top, and the mixing models in between. Above the 410-km discontinuity, our mixing model indicates that up to 30 vol % interconnected amorphous CaCO₃ is required to account for the conductivity of the subduction zone in the NE Pacific mantle if CaCO₃ acts as the source of the conductivity anomaly. Even for the less conductive mantle, ~1 vol % of CaCO₃ will be required, corresponding to ~3,600 ppm CO₂, a value nearly 30 times higher than the CO₂ budget in the mid-ocean ridge basalt (MORB) source mantle estimated by Le Voyer et al. (2017). Such high CO₂ budget required excludes the amorphous CaCO₃ as the source of the observed conductivity anomalies. On the other hand, forming solid solutions with other carbonates will dramatically lower the melting point, making it possible a low-degree global pervasive melting, as has been favored by a sound velocity study of dolomite melt (Xu et al., 2020), which is also a preferred mechanism for the observed conductivity anomalies.

In the upper transition zone, the temperature in some hot regions is above the melting point of CaCO₃. Considering the carbonatite melts derived from slab melting is usually Ca, Mg, and Fe rich (e.g., Thomson et al., 2016), their melting point should be well below the mantle geotherm. The current data set of CaCO₃ can serve as proxy for general (Ca, Mg, Fe)CO₃ melts based on the following facts: While Mg²⁺ has a slightly smaller effective radius (0.72 Å, Shannon, 1976) and larger diffusivity than Ca²⁺ (1.00 Å, Shannon, 1976), the difference in EC between CaCO₃ and MgCa(CO₃)₂ melts is less than 0.02 log unit at 1850 K up to 12 GPa, indicated by a atomistic calculation (Desmaele et al., 2019). With the effective radius of Fe²⁺ in between (0.78 Å, Shannon, 1976), it can be foreseen that the (Ca, Mg, Fe)CO₃ melts can keep a nearly constant EC at a fixed P - T condition.

With the above assumptions, if carbonate melts exist, an overall 0.01–0.2 vol % (Ca, Mg, Fe)CO₃ forming melt interconnection can explain the value of mantle average and NE Pacific mantle, although it is difficult to detect such a small amount of melt. Considering the region beneath the N. Philippine Sea, where the temperature is lower than the average mantle geotherm, a significant amount of melt, close to 1 vol %, is required. However, since the temperature in such a region does not reach the melting temperature of CaCO₃, alkali elements such as Na are required for carbonate melt to cause the EC anomaly. We note that these melt fractions estimated with conductivity of CaCO₃ melt correlate to the Na⁺ depleted cases, and thus higher limit of carbonate melt fraction. If the subducted slab is locally enriched in monovalent (Na⁺ and K⁺) components, or the melts are derived at greater depth (especially larger than 20 GPa), the Na⁺ and K⁺ components will substantially dissolve into the melt (Thomson et al., 2016; Zhang et al., 2020), producing much more complicated carbonate compositions. Such carbonatite melts generated by incipient slab melting have actually higher conductivity than the CaCO₃ melt due to the higher ionic diffusivity of alkaline species and therefore a slightly lower necessary melt fraction can be foreseen.

An additional mechanism for carbonate melt generation involves the incorporation of CaCO₃ components into mantle plume sources, such as those formed in ancient subduction zones. Some ocean island basalts from Hawaii and Pitcairn Islands exhibit Mg and Sr isotopic anomalies that indicate plume sources containing recycled carbonate-rich sediments (Huang et al., 2009; Wang et al., 2018). However, carbonatite melts in the plume are not likely to pond at depth due to its low density compared to the surrounding peridotite. Density of liquid (Mg, Ca) CO₃ was calculated to be 3.05–3.10 g/cm³ at 14 GPa and 1,900 K (Desmaele et al., 2019), which is ~11% and ~15% less dense than forsterite and wadsleyite (#Mg = 100) at same conditions (Dorogokupets et al., 2015). If similar Fe content is expected in both melts and surrounding mineral matrix, the melts are supposed to be less dense than the surroundings. Superimposed by the upwelling force of the mantle plume, carbonatite liquids could be dragged toward the surface and decarbonate below 3 GPa (e.g., Thomson et al., 2016), and therefore are unlikely responsible for the predicted EC anomalies atop of the 410 km seismic discontinuity (Toffelmier & Tyburczy, 2007).

4. Conclusions

The EC of amorphous and liquid CaCO₃ has been studied up to 15 GPa and 2100 K. The phase transition from aragonite to the amorphous phase does not cause a leap in the EC, indicating that the self-diffusion does not undergo a major enhancement during the amorphization. A drastic increase in the EC only occurs at the onset of melting, accompanied by the largely enhanced charge diffusivity. Although the amorphous CaCO₃ is a stabilized phase above the 410-km discontinuity, it can be excluded from the origin of the EC anomalies because the required CO₂ content largely exceeds the budget in the MORB source mantle. Instead, a low-degree melting of multi-carbonates is preferred. In the upper transition zone, the required fraction of XCO₃ melt (X = Ca, Fe, Mg) is overall less than 1 vol% to explain the high EC anomalies of mantle average, NE Pacific mantle, and beneath the N. Philippine Sea, and the required melt fraction would be further reduced by the presence of other alkaline cations in the melt.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The impedance spectra data are available in the online data repository Zenodo (Zhao, 2025).

Acknowledgments

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References

- Ague, J. J., & Nicolescu, S. (2014). Carbon dioxide released from subduction zones by fluid-mediated reactions. *Nature Geoscience*, 7(5), 355–360. <https://doi.org/10.1038/ngeo2143>
- Anderson, T. F. (1969). Self-diffusion of carbon and oxygen in calcite by isotope exchange with carbon dioxide. *Journal of Geophysical Research*, 74(15), 3918–3932. <https://doi.org/10.1029/JB074i015p03918>
- Baba, K., Utada, H., Goto, T. N., Kasaya, T., Shimizu, H., & Tada, N. (2010). Electrical conductivity imaging of the Philippine Sea upper mantle using seafloor magnetotelluric data. *Physics of the Earth and Planetary Interiors*, 183(1–2), 44–62. <https://doi.org/10.1016/j.pepi.2010.09.010>
- Bagdassarov, N. S., & Slutskii, A. B. (2003). Phase transformations in calcite from electrical impedance measurements. *Phase Transitions*, 76(12), 1015–1028. <https://doi.org/10.1080/0141159031000098233>

- Bayarjargal, L., Fruhner, C. J., Schrod, N., & Winkler, B. (2018). CaCO_3 phase diagram studied with raman spectroscopy at pressures up to 50 GPa and high temperatures and DFT modeling. *Physics of the Earth and Planetary Interiors*, 281, 31–45. <https://doi.org/10.1016/j.pepi.2018.05.002>
- Chen, C., Tran, T., Olivares, R., Wright, S., & Sun, S. (2014). Coupled experimental study and thermodynamic modeling of melting point and thermal stability of Li_2CO_3 - Na_2CO_3 - K_2CO_3 based salts. *Journal of Solar Energy Engineering*, 136(3), 031017. <https://doi.org/10.1115/1.4027264>
- Dai, L., & Karato, S. I. (2009a). Electrical conductivity of pyrope-rich garnet at high temperature and high pressure. *Physics of the Earth and Planetary Interiors*, 176(1–2), 83–88. <https://doi.org/10.1016/j.pepi.2009.04.002>
- Dai, L., & Karato, S. I. (2009b). Electrical conductivity of orthopyroxene: Implications for the water content of the asthenosphere. *Proceedings of the Japan Academy, series B*, 85(10), 466–475. <https://doi.org/10.2183/pjab.85.466>
- Dasgupta, R., & Hirschmann, M. M. (2006). Melting in the earth's deep upper mantle caused by carbon dioxide. *Nature*, 440(7084), 659–662. <https://doi.org/10.1038/nature04612>
- Dasgupta, R., & Hirschmann, M. M. (2010). The deep carbon cycle and melting in earth's interior. *Earth and Planetary Science Letters*, 298(1–2), 1–13. <https://doi.org/10.1016/j.epsl.2010.06.039>
- Dasgupta, R., Mallik, A., Tsuno, K., Withers, A. C., Hirth, G., & Hirschmann, M. M. (2013). Carbon-dioxide-rich silicate melt in the Earth's upper mantle. *Nature*, 493(7431), 211–215. <https://doi.org/10.1038/nature11731>
- Desmaele, E., Sator, N., Vuilleumier, R., & Guillot, B. (2019). The MgCO_3 - CaCO_3 - Li_2CO_3 - Na_2CO_3 - K_2CO_3 melts: Thermodynamics and transport properties by atomistic simulations. *The Journal of Chemical Physics*, 150(21), 214503. <https://doi.org/10.1063/1.5099015>
- Dorogokupets, P. I., Dymshits, A. M., Sokolova, T. S., Danilov, B. S., & Litasov, K. D. (2015). The equations of state of forsterite, wadsleyite, ringwoodite, akimotoite, MgSiO_3 -perovskite, and postperovskite and phase diagram for the Mg_2SiO_4 system at pressures of up to 130 GPa. *Russian Geology and Geophysics*, 56(1–2), 172–189. <https://doi.org/10.1016/j.rgg.2015.01.011>
- Fisler, D. K., & Cygan, R. T. (1999). Diffusion of Ca and Mg in calcite. *American Mineralogist*, 84(9), 1392–1399. <https://doi.org/10.2138/am-1999-0917>
- Gaillard, F., Malki, M., Iacono-Marziano, G., Pichavant, M., & Scaillet, B. (2008). Carbonatite melts and electrical conductivity in the asthenosphere. *Science*, 322(5906), 1363–1365. <https://doi.org/10.1126/science.1164446>
- Gavryushkin, P. N., Sagatov, N., Belonoshko, A. B., Banaev, M. V., & Litasov, K. D. (2020). Disordered aragonite: The new high-pressure, high-temperature phase of CaCO_3 . *Journal of Physical Chemistry C*, 124(48), 26467–26473. <https://doi.org/10.1021/acs.jpcc.0c08309>
- Hampson, N. A., Karunatilaka, S. A. G. R., & Leek, R. (1980). The impedance of electrical storage cells. *Journal of Applied Electrochemistry*, 10(1), 3–11. <https://doi.org/10.1007/BF00937331>
- Hashin, Z., & Shtrikman, S. (1962). A variational approach to the theory of the effective magnetic permeability of multiphase materials. *Journal of Applied Physics*, 33(10), 3125–3131. <https://doi.org/10.1063/1.1728579>
- Hoffman, P. F., Kaufman, A. J., Halverson, G. P., & Schrag, D. P. (1998). A Neoproterozoic snowball Earth. *Science*, 281(5381), 1342–1346. <https://doi.org/10.1126/science.281.5381.1342>
- Hou, M., Zhang, Q., Tao, R., Liu, H., Kono, Y., Mao, H. K., et al. (2019). Temperature-induced amorphization in CaCO_3 at high pressure and implications for recycled CaCO_3 in subduction zones. *Nature Communications*, 10(1), 1963. <https://doi.org/10.1038/s41467-019-09742-5>
- Huang, S., Abouchami, W., Blichert-Toft, J., Clague, D. A., Cousens, B. L., Frey, F. A., & Humayun, M. (2009). Ancient carbonate sedimentary signature in the Hawaiian plume: Evidence from mahukona volcano, Hawaii. *Geochemistry, Geophysics, Geosystems*, 10(8), Q08002. <https://doi.org/10.1029/2009GC002418>
- Isson, T. T., Planavsky, N. J., Coogan, L. A., Stewart, E. M., Ague, J. J., Bolton, E. W., et al. (2020). Evolution of the global carbon cycle and climate regulation on Earth. *Global Biogeochemical Cycles*, 34(2), e2018GB006061. <https://doi.org/10.1029/2018GB006061>
- Jambon, A. (1982). Tracer diffusion in granitic melts: Experimental results for Na, K, Rb, Cs, Ca, Sr, Ba, Ce, Eu to 1300 °C and a model of calculation. *Journal of Geophysical Research*, 87(B13), 10797–10810. <https://doi.org/10.1029/JB087iB13p10797>
- Kang, N., Schmidt, M. W., Poli, S., Franzolin, E., & Connolly, J. A. (2015). Melting of siderite to 20 GPa and thermodynamic properties of FeCO_3 melt. *Chemical Geology*, 400, 34–43. <https://doi.org/10.1016/j.chemgeo.2015.02.005>
- Katsura, T., Yoneda, A., Yamazaki, D., Yoshino, T., & Ito, E. (2010). Adiabatic temperature profile in the mantle. *Physics of the Earth and Planetary Interiors*, 183(1–2), 212–218. <https://doi.org/10.1016/j.pepi.2010.07.001>
- Kelbert, A., Schultz, A., & Egbert, G. (2009). Global electromagnetic induction constraints on transition-zone water content variations. *Nature*, 460(7258), 1003–1006. <https://doi.org/10.1038/nature08257>
- Kelemen, P. B., & Manning, C. E. (2015). Reevaluating carbon fluxes in subduction zones: What goes Down, mostly comes up. *Proceedings of the National Academy of Sciences*, 112(30), E3997–E4006. <https://doi.org/10.1073/pnas.1507889112>
- Key, K., Constable, S., Liu, L., & Pommier, A. (2013). Electrical image of passive mantle upwelling beneath the northern east Pacific rise. *Nature*, 495(7442), 499–502. <https://doi.org/10.1038/nature11932>
- Le Voyer, M., Kelley, K. A., Cottrell, E., & Hauri, E. H. (2017). Heterogeneity in mantle carbon content from CO_2 -undersaturated basalts. *Nature Communications*, 8(1), 14062. <https://doi.org/10.1038/ncomms14062>
- Li, Z., Li, J., Lange, R., Liu, J., & Militzer, B. (2017). Determination of calcium carbonate and sodium carbonate melting curves up to earth's transition zone pressures with implications for the deep carbon cycle. *Earth and Planetary Science Letters*, 457, 395–402. <https://doi.org/10.1016/j.epsl.2016.10.027>
- Litasov, K. D., & Ohtani, E. (2007). Effect of water on the phase relations in the earth's mantle and deep water cycle. In E. Ohtani (Ed.), *Advances in high-pressure mineralogy* (Vol. 421, pp. 115–156). Geological Society of America. [https://doi.org/10.1130/2007.2421\(08](https://doi.org/10.1130/2007.2421(08)
- Litasov, K. D., & Ohtani, E. (2009). Solidus and phase relations of carbonated peridotite in the system CaO - Al_2O_3 - MgO - SiO_2 - Na_2O - CO_2 to the lower mantle depths. *Physics of the Earth and Planetary Interiors*, 177(1–2), 46–58. <https://doi.org/10.1016/j.pepi.2009.07.008>
- Litasov, K. D., Shatskiy, A., Gavryushkin, P. N., Bekhtenova, A. E., Dorogokupets, P. I., Danilov, B. S., et al. (2017). PVT equation of state of CaCO_3 aragonite to 29 GPa and 1673 K: In situ X-ray diffraction study. *Physics of the Earth and Planetary Interiors*, 265, 82–91. <https://doi.org/10.1016/j.pepi.2017.02.006>
- Lizarralde, D., Chave, A., Hirth, G., & Schultz, A. (1995). Northeastern Pacific mantle conductivity profile from long-period magnetotelluric sounding using Hawaii-to-California submarine cable data. *Journal of Geophysical Research*, 100(B9), 17837–17854. <https://doi.org/10.1029/95JB01244>
- Manthilake, G., Matsuzaki, T., Yoshino, T., Yamashita, S., Ito, E., & Katsura, T. (2009). Electrical conductivity of wadsleyite as a function of temperature and water content. *Physics of the Earth and Planetary Interiors*, 174(1–4), 10–18. <https://doi.org/10.1016/j.pepi.2008.06.001>
- Ono, S., & Mibe, K. (2015). Influence of pressure and temperature on the electrical conductivity of dolomite. *Physics and Chemistry of Minerals*, 42(9), 773–779. <https://doi.org/10.1007/s00269-015-0761-x>
- Plank, T., & Manning, C. E. (2019). Subducting carbon. *Nature*, 574(7778), 343–352. <https://doi.org/10.1038/s41586-019-1643-z>

- Pommier, A., Gaillard, F., Pichavant, M., & Scaillet, B. (2008). Laboratory measurements of electrical conductivities of hydrous and dry Mount Vesuvius melts under pressure. *Journal of Geophysical Research*, 113(B5), B05205. <https://doi.org/10.1029/2007JB005269>
- Shannon, R. D. (1976). Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. *Foundations of Crystallography*, 32(5), 751–767. <https://doi.org/10.1107/S0567739476001551>
- Sifré, D., Gardés, E., Massuyeau, M., Hashim, L., Hier-Majumder, S., & Gaillard, F. (2014). Electrical conductivity during incipient melting in the Oceanic low-velocity zone. *Nature*, 509(7498), 81–85. <https://doi.org/10.1038/nature13245>
- Sifré, D., Hashim, L., & Gaillard, F. (2015). Effects of temperature, pressure and chemical compositions on the electrical conductivity of carbonated melts and its relationship with viscosity. *Chemical Geology*, 418, 189–197. <https://doi.org/10.1016/j.chemgeo.2014.09.022>
- Stacey, F. D., & Davis, P. M. (2008). *Physics of the Earth*. Cambridge University Press.
- Suito, K., Namba, J., Horikawa, T., Taniguchi, Y., Sakurai, N., Kobayashi, M., et al. (2001). Phase relations of CaCO₃ at high pressure and high temperature. *American Mineralogist*, 86(9), 997–1002. <https://doi.org/10.2138/am-2001-8-906>
- Tao, R., Fei, Y., & Zhang, L. (2013). Experimental determination of siderite stability at high pressure. *American Mineralogist*, 98(8–9), 1565–1572. <https://doi.org/10.2138/am.2013.4351>
- Ter Heege, J. H., & Renner, J. (2007). In situ impedance spectroscopy on pyrophyllite and CaCO₃ at high pressure and temperature: Phase transformations and kinetics of atomistic transport. *Physics and Chemistry of Minerals*, 34(7), 445–465. <https://doi.org/10.1007/s00269-007-0162-x>
- Thomson, A. R., Walter, M. J., Kohn, S. C., & Brooker, R. A. (2016). Slab melting as a barrier to deep carbon subduction. *Nature*, 529(7584), 76–79. <https://doi.org/10.1038/nature16174>
- Toffelmier, D. A., & Tyburczy, J. A. (2007). Electromagnetic detection of a 410-km-deep melt layer in the Southwestern United States. *Nature*, 447(7147), 991–994. <https://doi.org/10.1038/nature05922>
- Vuilleumier, R., Seitsonen, A., Sator, N., & Guillot, B. (2014). Structure, equation of state and transport properties of molten calcium carbonate (CaCO₃) by atomistic simulations. *Geochimica et Cosmochimica Acta*, 141, 547–566. <https://doi.org/10.1016/j.gca.2014.06.037>
- Wang, X. J., Chen, L. H., Hofmann, A. W., Hanyu, T., Kawabata, H., Zhong, Y., et al. (2018). Recycled ancient ghost carbonate in the Pitcairn mantle plume. *Proceedings of the National Academy of Sciences*, 115(35), 8682–8687. <https://doi.org/10.1073/pnas.1719570115>
- Wirth, R., Kaminsky, F., Matsyuk, S., & Schreiber, A. (2009). Unusual micro- and nano-inclusions in diamonds from the juina area, Brazil. *Earth and Planetary Science Letters*, 286(1–2), 292–303. <https://doi.org/10.1016/j.epsl.2009.06.043>
- Xu, M., Jing, Z., Bajgain, S. K., Mookherjee, M., Van Orman, J. A., Yu, T., & Wang, Y. (2020). High-pressure elastic properties of dolomite melt supporting carbonate-induced melting in deep upper mantle. *Proceedings of the National Academy of Sciences*, 117(31), 18285–18291. <https://doi.org/10.1073/pnas.2004347117>
- Yoshino, T. (2010). Laboratory electrical conductivity measurement of mantle minerals. *Surveys in Geophysics*, 31(2), 163–206. <https://doi.org/10.1007/s10712-009-9084-0>
- Yoshino, T., Gruber, B., & Reinier, C. (2018). Effects of pressure and water on electrical conductivity of carbonate melt with implications for conductivity anomaly in Continental mantle lithosphere. *Physics of the Earth and Planetary Interiors*, 281, 8–16. <https://doi.org/10.1016/j.pepi.2018.05.003>
- Yoshino, T., Matsuzaki, T., Shatskiy, A., & Katsura, T. (2009). The effect of water on the electrical conductivity of olivine aggregates and its implications for the electrical structure of the upper mantle. *Earth and Planetary Science Letters*, 288(1–2), 291–300. <https://doi.org/10.1016/j.epsl.2009.09.032>
- Yoshino, T., McIsaac, E., Laumonier, M., & Katsura, T. (2012). Electrical conductivity of partial molten carbonate peridotite. *Physics of the Earth and Planetary Interiors*, 194, 1–9. <https://doi.org/10.1016/j.pepi.2012.01.005>
- Yoshino, T., Nishi, M., Matsuzaki, T., Yamazaki, D., & Katsura, T. (2008). Electrical conductivity of majorite garnet and its implications for electrical structure in the mantle transition zone. *Physics of the Earth and Planetary Interiors*, 170(3–4), 193–200. <https://doi.org/10.1016/j.pepi.2008.04.009>
- Zedgenizov, D. A., Ragozin, A. L., Kalina, V. V., & Kagi, H. (2016). The mineralogy of Ca-rich inclusions in sublithospheric diamonds. *Geochemistry International*, 54(10), 890–900. <https://doi.org/10.1134/S0016702916100116>
- Zhang, B., Yoshino, T., Wu, X., Matsuzaki, T., Shan, S., & Katsura, T. (2012). Electrical conductivity of enstatite as a function of water content: Implications for the electrical structure in the upper mantle. *Earth and Planetary Science Letters*, 357, 11–20. <https://doi.org/10.1016/j.epsl.2012.09.020>
- Zhang, Y., Wang, C., & Jin, Z. (2020). Decarbonation of stagnant slab in the mantle transition zone. *Journal of Geophysical Research: Solid Earth*, 125(7), e2020JB019533. <https://doi.org/10.1029/2020JB019533>
- Zhao, B. (2025). Dataset for 'electrical conductivity of amorphous and molten CaCO₃ at high pressures and its implications for mantle conductivity anomalies [dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.17028458>
- Zhao, B., Zhu, J., He, J., & Yoshino, T. (2025). Electrical conductivity of carbonated hydrous basaltic melt: Implications for the conductivity anomaly beneath the ocean floors. *Journal of Geophysical Research: Solid Earth*, 130(10), e2025JB032215. <https://doi.org/10.1029/2025JB032215>
- Zhu, Y., & Ogasawara, Y. (2002). Carbon recycled into deep Earth: Evidence from dolomite dissociation in subduction-zone rocks. *Geology*, 30(10), 947–950. [https://doi.org/10.1130/0091-7613\(2002\)030<0947:CRIDEE>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0947:CRIDEE>2.0.CO;2)