

Supplementary information

1. Olivine conductivity

The dry olivine conductivity model, SO2, is expressed by the following equation [Constable et al. 1992]:

$$\sigma_{\text{SO}_2} = 2.5 \times 10^2 e^{-\frac{186 \text{ kJ/mol}}{RT}} + 1.5 \times 10^9 e^{-\frac{493 \text{ kJ/mol}}{RT}} \quad (\text{S1})$$

where R is the gas constant and T is the absolute temperature. The first and second terms express the contributions of small polaron and ionic conductions, respectively.

The newer dry olivine conductivity model, SEO3 [Constable 2006], expresses the contributions of small polaron and ionic conductions by the products of the concentration and mobility of $\text{Fe}_{\text{Mg}}^{\cdot}$ and $\text{V}_{\text{Mg}}^{\prime\prime}$ based on the conductivity and thermopower measurements by Constable and Roberts [1997]. Their defect concentrations, $[\text{Fe}_{\text{Mg}}^{\cdot}]$ and $[\text{V}_{\text{Mg}}^{\prime\prime}]$ in m^3 , are expressed by the following formula:

$$[\text{Fe}_{\text{Mg}}^{\cdot}] = b_{\text{Fe}_{\text{Mg}}^{\cdot}}(T) + 3.33 \times 10^{24} \cdot \exp\left(-\frac{2 \text{ kJ/mol}}{RT}\right) \cdot f_{\text{O}_2}^{1/6} \quad (\text{S2})$$

$$[\text{V}_{\text{Mg}}^{\prime\prime}] = b_{\text{V}_{\text{Mg}}^{\prime\prime}}(T) + 6.21 \times 10^{30} \cdot \exp\left(-\frac{177 \text{ kJ/mol}}{RT}\right) \cdot f_{\text{O}_2}^{1/6} \quad (\text{S3})$$

where f_{O_2} is the oxygen fugacity in Pa, and

$$b_{\text{Fe}_{\text{Mg}}^{\cdot}}(T) = 5.06 \times 10^{24} \cdot \exp\left(-\frac{34 \text{ kJ/mol}}{RT}\right) \quad (\text{S4})$$

$$b_{\text{V}_{\text{Mg}}^{\prime\prime}}(T) = 4.58 \times 10^{26} \cdot \exp\left(-\frac{73 \text{ kJ/mol}}{RT}\right) \quad (\text{S5})$$

The functions $b_{\text{Fe}_{\text{Mg}}^{\cdot}}(T)$ and $b_{\text{V}_{\text{Mg}}^{\prime\prime}}(T)$ denote the oxygen-fugacity independent terms of the defect density of $\text{Fe}_{\text{Mg}}^{\cdot}$ and $\text{V}_{\text{Mg}}^{\prime\prime}$, respectively, as a function of temperature. Thus, the SEO3 model includes the effects of oxygen fugacity on conductivity, which is in contrast to the SO2 model. Equations (S26) and (S27) suggest that the electrical conductivity becomes insensitive to f_{O_2} with decreasing f_{O_2} [Constable and Roberts, 1997].

The mobility of these defects, $\mu_{\text{Fe}_{\text{Mg}}^{\cdot}}$ and $\mu_{\text{V}_{\text{Mg}}^{\prime\prime}}$ in m^2/s , is expressed by the simple Arrhenius equations as:

$$\mu_{\text{Fe}_{\text{Mg}}^{\cdot}} = 12.2 \times 10^{-6} \cdot \exp\left(-\frac{101 \text{ kJ/mol}}{RT}\right), \quad (\text{S6})$$

$$\mu_{V_{Mg}''} = 2.72 \times 10^{-6} \cdot \exp\left(-\frac{105 \text{ kJ/mol}}{RT}\right) \quad (S7)$$

The total conductivity, σ_{SEO3} is given by:

$$\sigma_{SEO3} = [Fe_{Mg}'] \cdot \mu_{Fe} \cdot e + [V_{Mg}''] \cdot \mu_{Mg} \cdot 2e \quad (S8)$$

where e is not the exponential function but the elementary charge (1.602×10^{-19} C).

As shown in Eqs (S2) and (S3), the conductivity given by SEO3 increases with increasing oxygen fugacity. Since the oxygen fugacity increases with increasing pressure, the formulation of SEO3 implies that the hopping and ionic conductions would greatly increase with increasing pressure, which is against the experimental results. Here, the hopping and ionic conductions are assumed constant along the IW buffer at a given pressure and temperature, and conductivity is calculated by considering the relative oxygen fugacity from the IW buffer at the same temperature. Namely,

$$f_{O_2,calc}^T = f_{O_2,mantle}^{P,T} \cdot (f_{O_2,IW}^{0,T} / f_{O_2,IW}^{P,T}) \quad (S9)$$

where $f_{O_2,calc}^T$, $f_{O_2,mantle}^{P,T}$, $f_{O_2,IW}^{0,T}$ and $f_{O_2,IW}^{P,T}$ are the oxygen fugacity for conductivity calculation, for the mantle at high pressure and high temperature, of the IW buffer at ambient pressure and high temperature, and of the IW buffer at high pressure and high temperature, respectively.

The proton conduction in olivine is expressed by the following formula:

$$\sigma_P = \sigma_0^P C_{H_2O} \exp\left(-\frac{\Delta H^P - \alpha C_{H_2O}^{1/3}}{RT}\right) \quad (S10)$$

where C_{H_2O} is the H_2O content, σ_0^P is the pre-exponential factor, ΔH^P is the activation enthalpy, α is the parameter to express the water-content dependence of the activation enthalpy, R is the gas constant, and T is the absolute temperature. The parameters in the High Proton model are $\sigma_0^P = 10^{-1.37}$ ($S \text{ m}^{-1}$), $\Delta H^P = 89$ (kJ mol^{-1}) and $\alpha = 1.79$ ($\text{kJ mol}^{-1} \text{ wt.ppm}^{-1/3}$) based on the FT-IR calibration by Bell et al. [2003], and $\sigma_0^P = 10^{-1.17}$ ($S \text{ m}^{-1}$), and $\alpha = 2.08$ ($\text{kJ mol}^{-1} \text{ wt.ppm}^{-1/3}$) based on the calibration by Withers et al. [2012]. The parameters in the Low Proton model are $\sigma_0^P = 10^{-2.10}$ ($S \text{ m}^{-1}$), $\Delta H^P = 89$ (kJ mol^{-1}) and $\alpha = 0.71$ ($\text{kJ mol}^{-1} \text{ wt.ppm}^{-1/3}$) based on the FT-IR calibration by Bell et al. [2003].

2. Melt conductivity

Ni et al. [2011] gave the conductivity of hydrous basalt, σ_{HB} , by the following formula as a function of H₂O content (wt%).

$$\sigma_{\text{HB}} = 8.6 \cdot \exp\left(-\frac{860.82 - 204.46\sqrt{C_{\text{H}_2\text{O}}}}{T - 1146.8}\right) \quad (\text{S11})$$

Sifre *et al.* [2014] gave the conductivity of H₂O- and CO₂-bearing melts as a function of CO₂ and H₂O contents:

$$\sigma_{\text{melt}} = \sigma_0^{\text{H}_2\text{O}} \exp\left[-\frac{E_0^{\text{H}_2\text{O}}}{RT}\right] + \sigma_0^{\text{CO}_2} \exp\left[-\frac{E_0^{\text{CO}_2}}{RT}\right] \quad (\text{S12})$$

where $E_0^{\text{H}_2\text{O}}$ and $E_0^{\text{CO}_2}$ are the activation energy as a function of H₂O and CO₂ contents, respectively, and $\sigma_0^{\text{H}_2\text{O}}$ and $\sigma_0^{\text{CO}_2}$ are the pre-exponential terms. The activation energy is given as a function of the volatile content $C_{\text{H}_2\text{O}}$ in wt% by:

$$E_0^{\text{H}_2\text{O}} = 88.8774 \text{ kJ/mol} \cdot \exp[-0.3880 \cdot C_{\text{H}_2\text{O}}] + 73.029 \text{ kJ/mol} \quad (\text{S13})$$

$$E_0^{\text{CO}_2} = 78.9166 \text{ kJ/mol} \cdot \exp[-0.1708 \cdot C_{\text{H}_2\text{O}}] + 32.820 \text{ kJ/mol} \quad (\text{S14})$$

Their pre-exponential factors are

$$\sigma_0^{\text{H}_2\text{O}} = \exp[4.54 \times 10^{-5} E_0^{\text{H}_2\text{O}} + 5.5607] \quad (\text{S15})$$

$$\sigma_0^{\text{CO}_2} = \exp[5.50 \times 10^{-5} E_0^{\text{CO}_2} + 5.7956] \quad (\text{S16})$$

3. Geotherm

The temperature profile follows the adiabatic geotherm given by Katsura et al. [2010], $T_a(z)$, just below the ridge except for the surface temperature of $T_0 = 1.5^\circ\text{C}$. Temperature distributions under plates with various ages are obtained by solving the equation of thermal diffusion:

$$\partial T / \partial t = \kappa \left(\partial^2 T / \partial z^2 \right) \quad (\text{S17})$$

where T is the temperature at depth z and time after leaving the mid-oceanic ridge, t . The boundary conditions are:

$$\begin{aligned}
T &= T_0 & \text{at} & \quad z = 0 \text{ and } t \geq 0 \\
T &= T_a(z) & \text{at} & \quad z > 0 \text{ and } t = 0 \\
T &\rightarrow T_a(z) & \text{as} & \quad z \rightarrow \infty > 0 \text{ at } t > 0
\end{aligned} \tag{S18}$$

No conductive heat transfer does not occur under the adiabatic geotherm. Therefore, $T_a(z)$ is replaced by a constant temperature to solve Eq. (S1). Then, the solution is:

$$T = T_0 \cdot \operatorname{erfc}(z/2\sqrt{\kappa t}) + T_a(z) \cdot \operatorname{erf}(z/2\sqrt{\kappa t}) \tag{S19}$$

where $\kappa = 8 \times 10^{-7} \text{ m}^2/\text{s}$ is the thermal diffusivity. Temperatures in the plume mantle under a plate with a given age are calculated by adding 200°C to those in the ambient mantle under a plate of the same age.

4. Oxygen fugacity

The standard oxygen fugacity in the mantle is taken from Stagno et al. [2013]. Their values are shown in Table S2 together with the FMQ, EMOG and IW buffers along the adiabatic geotherm.

5. Water storage capacity

We empirically fitted Férot and Bolfan-Casanova's [2012] data to obtain the following formula for the water storage capacity of olivine:

$$X_{\max\text{H}_2\text{O}}^{\text{ol}} = 10^{(-0.004321+0.000104 \cdot P) \cdot (T+273)+8.265} \tag{S20}$$

6. Volatile-free peridotite solidus

The volatile-free peridotite solidus, T_S^{vf} ($^\circ\text{C}$) is taken from Hirschmann [2000], which is

$$T_S^{\text{vf}} = -5.140 \cdot P^2 + 132.899 \cdot P + 1120.661. \tag{S21}$$

7. Carbonated peridotite solidus

The carbonated peridotite solidus is taken from Fig. 1 in Dasgupta et al. [2013], which is shown in Table S1

8. Water partitioning between peridotite and melts

The partition coefficient of water between solid peridotite and melt, $D_{\text{H}_2\text{O}}^{\text{peridotite/melt}}$, is expressed by

$$D_{\text{H}_2\text{O}}^{\text{peridotite/melt}} = X_{\text{ol}}D_{\text{H}_2\text{O}}^{\text{ol/melt}} + X_{\text{opx}}D_{\text{H}_2\text{O}}^{\text{opx/melt}} + X_{\text{cpx}}D_{\text{H}_2\text{O}}^{\text{cpx/melt}} + X_{\text{gt}}D_{\text{H}_2\text{O}}^{\text{gt/melt}} + X_{\text{sp}}D_{\text{H}_2\text{O}}^{\text{sp/melt}}. \quad (\text{S22})$$

where X_{ol} , X_{opx} , X_{cpx} , X_{gt} and X_{sp} are the fractions of olivine, Ca-poor pyroxene, Ca-rich pyroxene, garnet and spinel, respectively, and $D_{\text{H}_2\text{O}}^{\text{ol/melt}}$, $D_{\text{H}_2\text{O}}^{\text{opx/melt}}$, $D_{\text{H}_2\text{O}}^{\text{cpx/melt}}$, $D_{\text{H}_2\text{O}}^{\text{gt/melt}}$ and $D_{\text{H}_2\text{O}}^{\text{sp/melt}}$ are the partition coefficients of H_2O of olivine, Ca-poor pyroxene, Ca-rich pyroxene, garnet and spinel, respectively, to melt.

The formula of the fraction of each mineral is provided by Hirschmann et al. [2009] and given in Table S2.

The partition coefficients are as follows. Olivine: $D_{\text{H}_2\text{O}}^{\text{ol/melt}} = 0.0017$, garnet: $D_{\text{H}_2\text{O}}^{\text{gt/melt}} = 0.003$, spinel: $D_{\text{H}_2\text{O}}^{\text{sp/melt}} = 0$ [Hirschmann et al., 2009]. The $D_{\text{H}_2\text{O}}^{\text{opx/melt}}$ and $D_{\text{H}_2\text{O}}^{\text{cpx/melt}}$ are complicated functions, because they are functions of Al contents in these minerals [Mierdel and Keppler, 2007]. We adopted the formulation by O'Leary et al. [2010]:

$$\ln(D_{\text{H}_2\text{O}}^{\text{opx/melt}}) = 5.66 + 8.4 \cdot X_{\text{IV Al}}^{\text{opx}} + 10 \cdot X_{\text{Ca}}^{\text{opx}}, \quad (\text{S23})$$

$$\ln(D_{\text{H}_2\text{O}}^{\text{cpx/melt}}) = -5.0 + 6.3 \cdot X_{\text{IV Al}}^{\text{cpx}} - 12 \cdot X_{\text{Ca}}^{\text{opx}} + \frac{1600}{T+273.15}. \quad (\text{S24})$$

where $X_{\text{IV Al}}^{\text{opx}}$ and $X_{\text{IV Al}}^{\text{cpx}}$ are the Al fractions in the four-coordinated sites in Ca-poor and Ca-rich pyroxenes, respectively, and $X_{\text{Ca}}^{\text{opx}}$ and $X_{\text{Ca}}^{\text{opx}}$ are the Ca fractions in in Ca-poor and Ca-rich pyroxenes, respectively. We adopt

$$X_{\text{IV Al}}^{\text{opx}} = 0.032 + 0.056 \cdot P \quad \text{at } P < 2.83 \text{ GPa} \quad (\text{S25})$$

$$X_{\text{IV Al}}^{\text{opx}} = 0.40 + 0.20 \cdot \ln(P) \quad \text{at } P > 2.83 \text{ GPa} \quad (\text{S26})$$

$$X_{\text{IV Al}}^{\text{cpx}} = 0.067 + 0.030 \cdot P \quad \text{at } P < 2.6 \text{ GPa} \quad (\text{S27})$$

$$X_{\text{IV Al}}^{\text{cpX}} = 0.26 - 0.12 \cdot \ln(P) \quad \text{at } P > 2.6 \text{ GPa} \quad (\text{S28})$$

$$X_{\text{Ca}}^{\text{opX}} = 0.074 \quad (\text{S29})$$

$$X_{\text{IV Al}}^{\text{cpX}} = 0.70 + 0.23 \cdot \ln(P). \quad (\text{S30})$$

9. Calculation of the melt fraction and concentrations of H₂O, CO₂, K₂O and P₂O₅.

If peridotite partially melts, the temperature must be higher than its solidus temperature. The temperature of partially molten volatile-free peridotite is expressed as a function of the melt fraction:

$$T_{\text{F}}^{\text{vf}}(F) = T_{\text{S}}^{\text{vf}} + \Delta T_{\text{F}}^{\text{vf}}(F) \quad (\text{S31})$$

where T_{S}^{vf} (°C) is the volatile-free solidus temperature, $T_{\text{F}}^{\text{vf}}(F)$ (°C) is the temperature of partially-molten volatile-free peridotite with melt fraction, F (wt%), and $\Delta T_{\text{F}}^{\text{vf}}(F)$ (°C) is the temperature increase causing partial melting.

On the other hand, the solidus temperature is decreased by adding H₂O and CO₂:

$$T_{\text{F}}^{\text{v}}(F, C_{\text{H}_2\text{O}}^{\text{melt}}, C_{\text{CO}_2}^{\text{melt}}) = T_{\text{S}}^{\text{vf}} + \Delta T_{\text{F}}^{\text{vf}}(F) - \Delta T_{\text{H}_2\text{O}}(C_{\text{H}_2\text{O}}^{\text{melt}}) - \Delta T_{\text{CO}_2}(C_{\text{CO}_2}^{\text{melt}}) \quad (\text{S32})$$

Where $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$ are the H₂O and CO₂ contents in the melt (wt%), respectively, $\Delta T_{\text{H}_2\text{O}}(C_{\text{H}_2\text{O}}^{\text{melt}})$ and $\Delta T_{\text{CO}_2}(C_{\text{CO}_2}^{\text{melt}})$ are the depressions of the solidus temperature (freezing point depression) by H₂O and CO₂, respectively, as a function of $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$, respectively, and $T_{\text{F}}^{\text{v}}(F, C_{\text{H}_2\text{O}}^{\text{melt}}, C_{\text{CO}_2}^{\text{melt}})$ is the temperature (°C) at which the peridotite has a partial melt with a fraction of F with $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$. Here, we assume that $\Delta T_{\text{F}}^{\text{vf}}(F)$ is independent from $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$. Eq. (S30) gives the melt fraction at a given temperature $T = T_{\text{F}}^{\text{v}}(F, C_{\text{H}_2\text{O}}^{\text{melt}}, C_{\text{CO}_2}^{\text{melt}})$. Since $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$ are functions of F at a given bulk H₂O and CO₂ contents, F , $C_{\text{H}_2\text{O}}^{\text{melt}}$ and $C_{\text{CO}_2}^{\text{melt}}$ are obtained by iteration.

For the above calculation, we need the formulas of T_{S}^{vf} , $\Delta T_{\text{F}}^{\text{vf}}(F)$, $\Delta T_{\text{H}_2\text{O}}(C_{\text{H}_2\text{O}}^{\text{melt}})$ and $\Delta T_{\text{CO}_2}(C_{\text{CO}_2}^{\text{melt}})$. T_{S}^{vf} is given as Eq. (S20). $\Delta T_{\text{F}}^{\text{vf}}(F)$ is expressed by the linear approximation

$$\Delta T_{\text{F}}^{\text{vf}}(F) = F \cdot (d\Delta T_{\text{F}}^{\text{vf}}/dF) \quad (\text{S33})$$

Hirschmann [2010] gave $d\Delta T_F^{vf}/dF$ as a function of pressure P (GPa):

$$d\Delta T_F/dF = -40 \cdot P + 450, \quad (S34)$$

although the formula shown in Fig 1 of Hirschmann [2010] seems incorrect.

Dasgupta et al. [2013] expressed ΔT_{CO_2} by the following formula:

$$\Delta T_{CO_2} = a \cdot C_{CO_2}^{melt} + b \cdot \ln(1 - c \cdot C_{CO_2}^{melt}) \quad (S35)$$

where a , b and c are the fitting parameters. Dasgupta et al. [2013] provided sets of these parameters of $(a \ b \ c) = (1921 \ 1491.37 \ 0.86)$, $(2704 \ 1490.75 \ 1.18)$, $(3190 \ 1469.92 \ 1.31)$ and $(-501 \ 1514.84 \ 1.23)$ at 2, 3, 4 and 5 GPa, respectively, based on their experimental calibration at pressures of 2 to 5 GPa and $C_{CO_2}^{melt} > 25$ wt%. Since the calibrated parameters are limited to the pressure below 5 GPa, they are extrapolated to 10.6 GPa.

ΔT_{H_2O} is given by

$$\Delta T_{H_2O} = T_F^{vf} \left(1 - \frac{1}{1 - (R/\Delta \hat{S}_{\text{peridotite}}^{\text{fusion}}) \ln(1 - X_{OH^-}^{\text{melt}})} \right) \quad (S36)$$

where R is the gas constant, $\Delta \hat{S}_{\text{peridotite}}^{\text{fusion}}$ (J/K/mol) is the molar entropy of fusion of peridotite, and $X_{OH^-}^{\text{melt}}$ is the mole fraction of OH⁻ in the melt. The $\Delta \hat{S}_{\text{peridotite}}^{\text{fusion}}$ is calculated by the product of the molar weight of the melt, M , and the entropy of fusion of peridotite per weight, $\Delta S_{\text{peridotite}}^{\text{fusion}}$ (J/K/g): $\Delta \hat{S}_{\text{peridotite}}^{\text{fusion}} = M \cdot \Delta S_{\text{peridotite}}^{\text{fusion}}$. We use the values of $M = 59$ g/mol. and $\Delta S_{\text{peridotite}}^{\text{fusion}} = 0.4$ (J/K/g) [Hirschmann et al., 2009]. The $X_{OH^-}^{\text{melt}}$ is calculated by

$$X_{OH^-}^{\text{melt}} = \frac{C_{H_2O}^{\text{melt}}/M_{OH}}{C_{H_2O}^{\text{melt}}/M_{OH} - (100 - C_{H_2O}^{\text{melt}})/M} \quad (S37)$$

where $C_{H_2O}^{\text{melt}}$ (wt%) is the mass concentration of H₂O in the melt, and $M_{OH} = 9$ g/mol is the molar weight of the hydroxyl group.

$C_{CO_2}^{\text{melt}}$ is calculated by assuming that all CO₂ is contained in the melt once melting occurs. The $C_{H_2O}^{\text{melt}}$ is calculated by the partitioning of the solid from the bulk content:

$$C_{\text{H}_2\text{O}}^{\text{melt}} = \frac{C_{\text{H}_2\text{O}}^{\text{bulk}}}{X_{\text{m}}^{\text{melt}} + (1 - X_{\text{m}}^{\text{melt}}) D_{\text{H}_2\text{O}}^{\text{peridotite/melt}}} \quad (\text{S38})$$

where $C_{\text{H}_2\text{O}}^{\text{melt}}$ is the bulk H₂O content, $X_{\text{m}}^{\text{melt}}$ is the mass fraction of melt, and $D_{\text{H}_2\text{O}}^{\text{peridotite/melt}}$ is the partition coefficient of H₂O between peridotite and melt, which is already given in the section 8.

Since Dasgupta et al. [2013] calibrated the melt CO₂ contents as a function of pressure and temperature up to 25 wt% of CO₂, the above calculation was applied to this CO₂ content. On the other hand, the melt composition on the carbonated peridotite solidus is assumed to be of pure dolomite, and therefore the CO₂ contents on this curve is taken as 47.8 wt%. The CO₂ contents in the melt under conditions between 25 and 47.8 wt% was obtained by linear interpolation with temperature. Then, the H₂O component was contained in the carbonate melt using the partition coefficients explained above, and the freezing point depression was estimated using Eqs. (S31) and (S32). The melt fraction was obtained by the ratio of the assumed bulk CO₂ content to the melt CO₂ content.

Then, K₂O and P₂O₅ are added into the melt. These components are assumed to be contained in Ca-rich pyroxene and melt only. The partition coefficients of K₂O and P₂O₅ between melt and Ca-rich clinopyroxene are $D_{\text{K}_2\text{O}}^{\text{cpx/melt}} = 0.02$ [Luth *et al.*, 1997] and $D_{\text{P}_2\text{O}_5}^{\text{cpx/melt}} = 0.08$ [Kozett *et al.*, 2012], respectively. The bulk K₂O and P₂O₅ contents, respectively, are assumed to be 60 and 190 ppm in DMM, respectively, and 290 and 210 ppm in EM, respectively. The addition of these components decreases the CO₂ content in the melt and increases the melt fraction.

The potential H₂O contents in the solid parts of peridotite may exceed the H₂O storage capacity of the solid peridotite in EM. In this case, we assume that all excess H₂O will be accommodated in the melt, and the amount of melt is increased so that the water content in the melt is equilibrated with the solid peridotite based on the H₂O partition coefficient between peridotite and melt. As a result, the CO₂ content in the melt decrease by its inverse proportionality to the melt fraction.

Finally, the limitation of the CO₂ content in the melt by oxygen fugacity is calculated. Stagno et al. [2013] suggested that pure carbonated melt is unstable in regions deeper than 150 km depth, and their diagram (Fig 3a in Stagno [2013]) indicated that the logarithm of the mantle oxygen fugacity linearly decreases with depth at the rate of

$$d \log(f_{\text{O}_2})/dP = -0.0087 \log \text{ Pa/km}. \quad (\text{S39})$$

By assuming ideal mixing, the maximum CO₂ content, $C_{\text{Max CO}_2}^{\text{melt}}$, in the melt should also decrease with depth at this rate. Hence, the maximum CO₂ content in melt is expressed as:

$$C_{\text{Max CO}_2}^{\text{melt}} = 47.8 \cdot 10^{-0.0087(D-150)} \text{ at } D > 150 \text{ km,} \quad (\text{S40})$$

where D is the depth in km. If $C_{\text{CO}_2}^{\text{melt}}$ exceeds $X_{\text{Max CO}_2}^{\text{melt}}$ in the calculation based on Eq. (S34), the melt CO₂ contents are forced to be $C_{\text{CO}_2}^{\text{melt}} = C_{\text{Max CO}_2}^{\text{melt}}$.

10. Bulk conductivity

The contribution of the melt to the bulk conductivity could primarily be assumed proportional to the melt volume fraction, X_V^{melt} :

$$\sigma_{\text{vol}} = X_{\text{melt}}\sigma_{\text{melt}} + (1 - X_{\text{melt}})\sigma_{\text{ol}} \quad (\text{S41})$$

X_V^{melt} is obtained by the following formula

$$X_V^{\text{melt}} = \left[1 + \left(\frac{1}{X_m^{\text{melt}}} - 1 \right) \frac{d_{\text{melt}}}{d_{\text{peridotite}}} \right]^{-1} \quad (\text{S42})$$

where d_{melt} and $d_{\text{peridotite}}$ are the density of melt and peridotite, and are 2.8 and 3.3, respectively, in the present calculation.

According to the Archie's law, the contribution of the melt conductivity is not linear to the melt fraction but proportional to some power of the melt fraction: $\propto X_{\text{melt}}^n$. Yoshino et al. [2010] gave the melt-fraction exponent of $n = 0.89$ for the olivine-basaltic system, whereas Miller et al. [2015] proposed $n = 1.3 \pm 0.3$. Since these studies provided values with opposite tendencies for the power law, we assume the melt-fraction exponent of $n = 1$, namely we use Eq. (S41) in this study.

In addition to the Archie's law, various mixing laws are proposed. Here, we also calculate the bulk conductivity using the mean of a tube:

$$\sigma_{\text{tube}} = \frac{1}{3} X_{\text{melt}}\sigma_{\text{melt}} + (1 - X_{\text{melt}})\sigma_{\text{ol}} \quad (\text{S43})$$

and film:

$$\sigma_{\text{film}} = \left\{ [(1 - X_{\text{melt}})^{2/3} - 1]\sigma_{\text{melt}} - [(1 - X_{\text{melt}})^{1/3} - 1]\sigma_{\text{ol}} \right\}$$

$$\times \{ [1 - X_{\text{melt}} - (1 - X_{\text{melt}})^{2/3}] \sigma_{\text{melt}} + [(1 - X_{\text{melt}})^{2/3} - (1 - X_{\text{melt}}) - 1] \sigma_{\text{ol}} \}^{-1} \sigma_{\text{melt}} \quad (\text{S44})$$

[Sifre *et al.*, 2014]. Then, we take the average of these three estimations.

11. Anisotropy

The conductivity anisotropy is assumed to be made by the alignment of melt tubes in the flow direction. If the melt tubes are perfectly aligned in the flow direction, conductivity parallel to the flow direction is equal to the volume average of melt and solid (Eq. S41), and the conductivity in the normal direction will be approximately equal to the conductivity of the solid. The anisotropy is therefore estimated by the ratio of the conductivity of the melt-aligned peridotite to the melt-free peridotite.

$$\sigma_{\text{aniso}} = \sigma_{\text{vol}} / (\sigma_{\text{SE03}} + \sigma_{\text{P}}) \quad (\text{S45})$$