Electrical conductivity during incipient melting in the oceanic low-velocity zone

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The low-viscosity layer in the upper mantle, the asthenosphere, is a requirement for plate tectonics. The seismic low velocities and the high electrical conductivities of the asthenosphere are attributed either to subsolidus, water-related defects in olivine minerals or to a few volume per cent of partial melt, but these two interpretations have two shortcomings. First, the amount of water stored in olivine is not expected to be higher than 50 parts per million owing to partitioning with other mantle phases (including pargasite amphibole at moderate temperatures) and partial melting at high temperatures. Second, elevated melt volume fractions are impeded by the temperatures prevailing in the asthenosphere, which are too low, and by the melt mobility, which is high and can lead to gravitational segregation. Here we demonstrate that incipient melting of the mantle can also trigger high electrical conductivities there. Electrical conductivity increases modestly with moderate amounts of water and carbon dioxide, but it increases drastically once the carbon dioxide content exceeds six weight per cent in the melt. Incipient melts, long expected to prevail in the asthenosphere, can therefore produce high electrical conductivities there. Taking into account variable degrees of depletion of the mantle in water and carbon dioxide, and their effect on the petrology of incipient melting, we calculated conductivity profiles across the asthenosphere for various tectonic plate ages. Several electrical discontinuities are predicted and match geophysical observations in a consistent petrological and geochemical framework. In moderately aged plates (more than five million years old), incipient melts probably trigger both the seismic low velocities and the high electrical conductivities in the upper part of the asthenosphere, whereas in young plates, where seamount volcanism occurs, a higher degree of melting is expected.

The lithosphere is a chemically depleted and mechanically strong region of the uppermost mantle, overlying the chemically enriched and mechanically weak asthenosphere. Volatile enrichments in the asthenosphere have long been known to trigger incipient melting (that is, a small degree of partial melting due to small amounts of CO2 and H2O) in the upper part of the asthenosphere, and a link between incipient melting and the seismic low-velocity zone has also long been suggested. Here we demonstrate that incipient melting of the mantle can also trigger high electrical conductivities. We assume that the low-viscosity layer, the seismic low-velocity zone has also long been suggested, and in most cases the temperature may not be sufficiently high to produce such amounts of melt.

However, incipient CO2- and H2O-rich melts, which are stable under the pressure (P)–temperature (T)–fugacity (fCO2) conditions of the asthenosphere, allow melting in both warm and cold regions of the asthenosphere. Low-temperature carbonatite melts, composed of almost 50% CO2, are characterized by high electrical conductivities, but their stability is restricted to the coldest and driest regions of the asthenosphere. Increasing temperature or H2O content changes the composition of the prevailing melts to intermediates between basalts and carbonatites, often described as carbonatized basalts. Very little is known about the physical properties of such intermediate volatile (CO2 and H2O)-rich melts. In particular, their electrical properties have never been measured because melt would unavoidably tend to rise if present at such high amounts. Second, the lithosphere–asthenosphere boundary (LAB) occurs at a near-constant depth of 50–75 km for both warm, young lithospheres and cold, ancient lithospheres, and in most cases the temperature may not be sufficiently high to produce such amounts of melt.

![Figure 1](image-url)  
**Figure 1** Electrical conductivity of hydrous carbonated basalts, hydrated basalts and hydrous olivine. The conductivities of the hydrous carbonated basalts experimentally measured in this study are by far the highest, reaching up to 200 S m−1 and being about one and four order of magnitude higher than hydrated basalts and hydrous olivine, respectively. The fitting curves are calculated according to our conductivity model for CO2- and H2O-bearing melts (equation (1)).
been measured. To address the issues regarding onset of partial melting at the LAB, and to permit a test of the incipient melting model suggested by petrological studies\textsuperscript{15,17}, we performed electrical conductivity measurements on CO\textsubscript{2}- and H\textsubscript{2}O-rich melts.

We developed an experimental set-up specifically adapted for liquids with high conductivities (Extended Data Fig. 1). A high-performance four-wire method was used under high-pressure and high-temperature conditions in a piston–cylinder apparatus (Methods and Extended Data Figs 1, 2 and 3a). Five melts, with CO\textsubscript{2} and H\textsubscript{2}O contents ranging from 10 to 48 wt% and 0 to 10 wt%, respectively, were analysed by impedance spectroscopy in the temperature range 900–1,500 °C at a confining pressure of 3 GPa. We tested the reproducibility of the measurements by taking measurements during both cooling and heating of the samples (Extended Data Fig. 3a), and we verified that decarbonation and dehydration of samples at high temperature did not affect the conductivity results. Figure 1 reports the measured electrical conductivities as a function of reciprocal temperature. For similar H\textsubscript{2}O contents, the electrical conductivity of carbonated basalts is higher than that of hydrated basalts, and the difference increases with an increase in the CO\textsubscript{2} content of the melt to a maximum of nearly one log unit (a factor of ten). The most CO\textsubscript{2}-rich melt has conductivities higher than 200 S m\textsuperscript{-1}. We develop a semi-empirical model that takes into account the two parallel conductive processes operating in carbonated basalts: conduction by covalent, polymer-like hydrous silicate melts and ionic conduction by carbonate melts\textsuperscript{14}. The corresponding conductivity is given by

\[
s_{\text{model}} = \sigma_{\text{H}_2\text{O}} + \sigma_{\text{CO}_2}
\]

\[
= \sigma_{\text{H}_2\text{O}} \exp \left( -\frac{E_{\text{H}_2\text{O}}}{RT} \right) + \sigma_{\text{CO}_2} \exp \left( -\frac{E_{\text{CO}_2}}{RT} \right)
\]

Here \(T\) is the temperature, \(R\) is the gas constant, and \(\sigma_0\) and \(E\) respectively stand for the pre-exponential and the activation energy terms of the two Arrhenius laws defining the electrical contributions of the hydrous silicate (\(\sigma_{\text{H}_2\text{O}}\)) and the carbonate (\(\sigma_{\text{CO}_2}\)). The conductivities calculated using equation (1), as shown in Fig. 1, reproduce our measurements and those of ref. 7 on CO\textsubscript{2}-free hydrated basalts with an average precision of 5% (Methods). The effect of CO\textsubscript{2} on melt conductivity predicted by equation (1) is negligible at low CO\textsubscript{2} content, but increases sharply for CO\textsubscript{2} content higher than 6 wt%. Such a change is most probably caused by an abrupt transition in the melt structure and properties from silicate type to carbonate type.

We calculate the mantle electrical conductivity for variable amounts of bulk H\textsubscript{2}O and CO\textsubscript{2} contents in a partially molten peridotite. We assume that the interconnected melt is equally distributed between grain-edge tubules and grain-boundary melt films\textsuperscript{26–28} (Methods). The conductivity of hydrated olivine was calculated from ref. 25, and equation (1) was used on CO\textsubscript{2}- and H\textsubscript{2}O-bearing melts. We assume that carbon is exclusively soluble in the melt\textsuperscript{29} (carbonate units) and computed the partitioning of H\textsubscript{2}O between carbonated melt, pargasite, olivine and peridotite, combining refs 9, 10 and 22. We report results for partially molten peridotite containing only H\textsubscript{2}O (Fig. 2a) and both CO\textsubscript{2} and H\textsubscript{2}O (Fig. 2b, c). In all simulations, partitioning constraints for CO\textsubscript{2} and H\textsubscript{2}O between solids and melts require that CO\textsubscript{2}- and H\textsubscript{2}O-rich melts can be produced only at the onset of mantle partial melting and that small melt fractions always contain much more CO\textsubscript{2} than H\textsubscript{2}O (Fig 2, top axis). If melting of more than 1% is attained, the melt volatile contents drop to values that modestly affect their electrical conductivity.

The CO\textsubscript{2}-free depleted mantle, containing about 200 p.p.m. H\textsubscript{2}O (refs 26–28), cannot be conductive at temperatures below 1,350 °C (that is,
conductivity is strongly correlated to CO2 contents (grey dashed lines labelled from 100 to 500 p.p.m. CO2). This discontinuity can be shallower than the previously described discontinuity for young (23.5-Myr-old) plates and deeper for old (70-Myr-old) plates. For 35-Myr-old plates, the two discontinuities occur at the same depth (60 km). The lowest discontinuity shown in Fig. 3 occurs in the depth interval 120–150 km and is described as the region of redox melting, which triggers conductive region of the asthenosphere, is therefore permitted between the redox-melting lower boundary and the decarbonation upper boundary, and this agrees well with electromagnetic observations in oceanic domains, although ref. 29 indicates slightly deeper ranges.

The increase in conductivity in the incipient melting region is major, being half a log unit for the depleted mantle (200 p.p.m. CO2) and more than one log unit for the mantle containing 500 p.p.m. CO2. High conductivities of 0.1 S m\(^{-1}\) or more can be reached for CO2 contents as low as 300 p.p.m. in the case of young plates. We note the surprising effect of H2O (Fig. 3): incipient melting in a mantle with 500 p.p.m. H2O and 500 p.p.m. CO2 induces lower conductivities than in a mantle with

\[ \sigma \geq 0.1 \text{ S m}^{-1} \] unless it contains more than \( -5 \text{ vol\% basaltic melt (Fig. 2a).} \]

Only unreasonably high temperatures for the LAB (>1,450 °C) can make the mantle conductive with small amounts of melt (<1 vol%). Moreover, at high melt percentage, H2O has almost no effect on mantle conductivity, because its content in the melt remains small (that is, less than 1 wt% H2O negligibly affects basalt conductivity). If an H2O-enriched (500 p.p.m.) mantle is considered then a reasonably low melt content (1 vol%) can cause high conductivity, but it still requires a high temperature (>1,325 °C; Extended Data Fig. 4) and the enriched mantle is also CO2 rich.

In the presence of CO2, the formation of incipient CO2-rich melts (<0.5 vol%) disproportionately increases the effective electrical conductivity of the mantle (Fig. 2b, c). For example, in the depleted mantle, containing 200 p.p.m. H2O and 200 p.p.m. CO2 (ref. 26) and fuelling the dominant part of mid-ocean-ridge basalts, 0.1–0.15 vol% of melt at 1,325 °C can explain the existence of a layer of high electrical conductivity reported in oceanic domains. The melt is a carbonated basalt, typically containing 15–35 wt% CO2 and about 2–3 wt% H2O (Fig. 2b). Remarkably, the enriched mantle with 500 p.p.m. H2O and 500 p.p.m. CO2 can produce high conductivities at temperature and melt fractions as low as 1,050 °C and 0.2 vol%, respectively. We also notice that incipient melting of the enriched mantle triggers conductivities that are 2.5 times greater than those in the depleted mantle, making variations in electrical conductivity a powerful probe of the chemical enrichment in the upper mantle.

The stability of incipient melts in the upper part of the asthenosphere is expected as a result of petrological constraints (not considered in Fig. 2). The P–T region of incipient melting in peridotite is shown in Extended Data Fig. 5 together with the stability domain of pargasite, which is the main solid host for H2O in peridotite containing more than 150–200 p.p.m. H2O (ref. 10). We calculate that the presence of pargasite restricts the amount of H2O to 40–50 p.p.m. in olivine, according to partition coefficients among peridotite minerals. Pargasite is, however, stable at temperatures less than 1,070 °C (ref. 10) and for the enriched mantle (>200 p.p.m. H2O). On the basis of the P–T phase diagram of Extended Data Fig. 5, and considering oceanic geotherms at 23.5, 35 and 70 Myr ago, we have calculated one-dimensional conductivity profiles illustrating the impact of several petrological discontinuities (Fig. 3). We have considered the depleted mantle (200 p.p.m. H2O and 100–500 p.p.m. CO2) and the enriched mantle (500 p.p.m. H2O and 500 p.p.m. CO2). Variable CO2 contents in the depleted mantle account for the fact that mid-ocean-ridge basalts have degassed their CO2 with the result that the carbon contents of their sources are highly uncertain.

The upper discontinuity (Fig. 3) predicted by our model is the beginning of incipient melting at ~50–km depth for young, warm plates and at ~70 km for colder, older plates. This discontinuity marks the thermodynamic boundary between CO2-rich melt and CO2-rich vapour, the melt being stable at greater depth. In the case of an enriched mantle, an additional discontinuity occurs owing to the pargasite dehydration melting reaction (producing CO2-rich and H2O-rich, low-SiO2 melt). This discontinuity can be shallower than the previously described discontinuity for young (23.5-Myr-old) plates and deeper for old (70-Myr-old) plates. For 35-Myr-old plates, the two discontinuities occur at the same depth (60 km). The lowest discontinuity shown in Fig. 3 occurs in the depth interval 120–150 km and is described as the region of redox melting; this is the boundary separating diamonds from CO2-rich melts, the melt being stable at shallower depth. Incipient melting, which triggers the conductive region of the asthenosphere, is therefore permitted between the redox-melting lower boundary and the decarbonation upper boundary, and this agrees well with electromagnetic observations in oceanic domains, although ref. 29 indicates slightly deeper ranges.

The increase in conductivity in the incipient melting region is major, being half a log unit for the depleted mantle and more than one log unit for the mantle containing 500 p.p.m. CO2. High conductivities of 0.1 S m\(^{-1}\) or more can be reached for CO2 contents as low as 300 p.p.m. in the case of young plates. We note the surprising effect of H2O (Fig. 3): incipient melting in a mantle with 500 p.p.m. H2O and 500 p.p.m. CO2 induces lower conductivities than in a mantle with...
Incipient melting has long been described as a key petrological process operating in the seismic low-velocity region marking the upper asthenosphere\(^1\) and the mantle geochemistry and petrology in this region argue for production of incipient CO\(_2\)-enriched melts\(^5\) (Extended Data Fig. 3). We demonstrate that these melts have conductivities of hundreds of Siemens per metre, much higher than CO\(_2\)-free hydrated melts or hydrated minerals. Our modelling, despite unavoidable simplifications, incorporates geochemical and petrological constraints and indicates that mantle with small fractions of CO\(_2\)-rich melts at 50–150 km reproduces both the electrical properties and the depth of the LAB quite well, whereas CO\(_2\)-free systems yield too poor or no agreement with geophysical observations. The presence of CO\(_2\)-rich incipient melts in the asthenosphere has important implications for radiogenic heat production because such melts are enriched in heat-producing elements such as potassium, uranium and thorium\(^6\). Moreover, the involvement of CO\(_2\)-rich incipient melts is also recognized in petrological processes occurring in the continental and in the cratonic LAB\(^30\). The association between the asthenosphere and incipient melting that we suggest here can therefore be extended to geodynamic settings other than the oceanic domains. However, it remains to be defined how the mechanical strength of the asthenosphere can be affected by small amounts of CO\(_2\)- and H\(_2\)O-rich melts and how this can be connected to tectonic plate motion.

**METHODS SUMMARY**

Starting materials were mixtures of basaltic glass and hydrated calcium and magnesium carbonates, such that H\(_2\)O and CO\(_2\) were introduced into our sample with a constant molar CO\(_2\)/H\(_2\)O ratio of 2 (Extended Table 1a). Two dry carbonate melts were also investigated. The extent of dehydration and decarbonation of our samples during high-temperature, high-pressure experiments was shown to be small (compare Extended Table 1a with Extended Table 1b). The effect of H\(_2\)O was distinguished from that of CO\(_2\) by using published experimental conductivity measurements on hydrated basalts\(^8\) and the empirical equation (1). This empirical simplification is in line with the effect of H\(_2\)O on the conductivity of carbonated melts that we determined here (compare circle data points with square data points in Extended Data Fig. 3a). It is moderate and almost similar to that recently determined for basalts\(^8\). For simulations in Figs 2 and 3, equation (1) was used within a range of H\(_2\)O and CO\(_2\) contents that required no extrapolation from our experiments.

Figures 2 and 3 were constructed on the assumption that incipient melts are well connected\(^20\). Reference 24 is the only work specifically tackling the connectivity of incipient carbonated melts in olivine, and it shows interconnection at the small melt fractions we are considering. Reference 20 confirmed the good connection for melt contents of ~1%. Mixtures of melt tubes and melt films have been considered...
in our plots; the difference between these geometries implies conductivities differing by about 0.2 log units.

The isotherms in Fig. 4 were obtained using a model of sudden half-space cooling with similar parameters to those in ref. 8. The use of more complicated models, such as the plate model (see ref. 17, where, unlike here, the thickness of the lithosphere is decided a priori), yields similar isotherms for the moderate depths we discuss here.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 9 October 2013; accepted 6 March 2014.

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Acknowledgements This work, part of the ElectroLith project, benefited from funding by the European Research Council (ERC project #279790) and the French agency for research (ANR project #2010 BLAN62101). S.H.-M. acknowledges support from the US NSF grant EAR1215800 and a grant from the University of Orleans. We thank David H. Green for comments.

Author Contributions F.G. led the project and wrote the first draft. All authors contributed equally to the writing of subsequent drafts. D.S. and F.G. developed the experimental set-up, and D.S. performed the conductivity measurements. S.H.-M. contributed to the discussion and provided editorial assistance with the manuscript. D.S. and L.H. produced Fig. 1, E.G. and L.H. produced Fig. 2, D.S. produced Fig. 3, and L.H. and M.M. produced Fig. 4.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to F.G. (fabrice.gaillard@cnrs-orelans.fr).
METHODS

Starting materials. Electrical measurements were performed on six mixtures: two dry carbonated melts (CO₂ = 44–48 wt%), one hydrous carbonated melt (CO₂ = 25.9 wt%; H₂O = 10.2 wt%) and three hydrous carbonated basalts (CO₂ = 10.39–23.32 wt%; H₂O = 4.43–9.22 wt%). Starting materials used to obtain these mixtures were natural dolomite (MgCaCO₃), a natural basalt (popping rock)³⁵, salt (NaCl), sodium carbonate (Na₂CO₃) and brucite (Mg(OH)₂). See Extended Data Table 1a.

Experiments. All experiments were performed at 3 GPa in piston–cylinder apparatus (using half-inch graphite–Pyrex–talc assemblages), which were connected to a 1260 Solartron Impedance/Gain-Phase Analyzer for electrical conductivity measurements. The temperature was measured with a B-type thermocouple localized on top of the sample (Extended Data Fig. 1a). Oxygen fugacity (fO₂) was not controlled during the measurements, but the presence of graphite (furnace) and molten carbonates (sample) should imply an oxygen fugacity close to FMQ-2 (ref. 23).

We developed a new protocol specifically adapted for electrical conductivity measurements on highly conductive molten materials (Extended Data Fig. 1). The new design employs a pseudo-four-wire configuration, which removes the electrical contribution of the electrical cell itself (Extended Data Fig. 2a). Such a configuration, previously used at 1 atm (refs 19, 32), is necessary for our measurements at pressure. Cold pressed pellets (5-mm outer diameter) were cored to insert an inner Pt electrode (1 mm). A Pt foil surrounding the sample was used as outer electrode. An alumina jacket isolated the entire electrical cell from the graphite furnace. The sample impedance was measured between the two electrodes arranged in a coaxial geometry³³–³⁴. The inner electrode was connected to the impedance spectrometer via the two wires of the thermocouple³⁴. The outer electrode was connected to a nickel cylinder (located 5 mm above the sample) that was mounted in series with two additional wires (B-type thermocouples) (Extended Data Fig. 1a).

Impedance spectra, conductivity calculations and uncertainties. The impedance spectra were collected during heating and cooling cycles (Extended Data Table 2a) at different temperature plateaus in the frequency range 1 Hz–1 MHz. Unlike the spectra collected at low temperatures (that is, solid samples showing impedance arcs), high-temperature spectra (that is, molten samples) had vertical lines (Extended Data Fig. 2b). These spectra correspond to induction-dominated signals, and the intercept of each spectrum with the x axis yielded the resistance of the sample.

Reproducibility of electrical measurements was validated by performing the measurements during heating and cooling cycles. For the experiments on hydrated samples (HC and HCB-9, -7, -4), a step of about 10 min was performed at 700°C before brucite dehydration, and the temperature was then rapidly raised (<10 s) to 1,300–1,410°C (that is, the temperature of the molten state), which limited sample dehydration.

Data reductions and uncertainties. The electrical conductivities of the samples were calculated from the measured resistances using the following relationship²²,²³:

\[ \sigma = \frac{\ln(r_{\text{true}}/r_p)}{2\pi R \rho} \]  

(2)

with \( \sigma \) being the electrical conductivity in S m⁻¹; \( r_{\text{true}} \) and \( r \) respectively being the outer radius, the inner radius and the height of the samples in metres; and \( R \) being the resistance of the sample in \( \Omega \) (Extended Data Figs 1b and 2b).

Uncertainties in \( \sigma \) were calculated considering geometrical factors of the samples (Extended Data Fig. 1b) and propagated errors of each measured resistance. The uncertainties in \( \sigma \) are ±7% on average for all measurements and reach a maximum of 16% in HCB-4.

Sample characterization. Scanning electron microscope (SEM) imaging and electron microprobe analyses (EMPA)s were systematically performed after each experiment. Determination of \( r_{\text{true}} \) and \( h \) by SEM imaging showed an average decrease of 20% compared with the initial geometry, most probably due to porosity loss during melting (Extended Data Fig. 1b). No melt leak was observed, and the entire sample remained sandwiched between the MgO plugs and the electrodes. EMPAs were conducted at 15 keV and 10 nA with 10-s counting on peak elements. The beam size (100 µm × 100 µm) was adapted to obtain average chemical compositions, smoothing the heterogeneities due to quartz crystallizations. Compositions before and after experiments indicate no contamination by the MgO surrounding the sample and no considerable volatile loss from the sample (Extended Data Table 1b). Carbon dioxide contents were determined using the by-difference method²⁵ and indicate negligible decarbonation.

A Flash 2000 elemental analyser (Thermo Scientific) was used to measure the H₂O content of samples before and after experiments. Samples were heated to >1,500°C and the released H₂O was reduced into elemental H₂ which was detected by a highly sensitive thermal conductivity detector. This gave the H₂O content with a precision of ±0.5 wt%. We observed negligible dehydration during conductivity measurements.

Conductivity results. Extended Data Fig. 3a shows the good reproducibility of the electrical measurements during heating and cooling cycles. The conductivity-temperature relationship for each sample was fitted using an Arrhenius law

\[ \sigma = \sigma_0 e^{-E_A/RT} \]  

with \( \sigma_0 \), \( E_A \), \( R \), and \( T \) as defined in equation (1).

Calculated pre-exponential factors and activation energies are presented in Extended Data Table 2b.

Increasing the CO₂ concentration in the melt drastically increases its conductivity. Furthermore, we observed that CO₂ tends to decrease both activation energies and pre-exponential factors.

Conductivity modelling. The semi-empirical law that we have developed can be considered the sum of two conductive processes occurring in carbonated basalts: conduction in the hydrous silicate melts by interstitial sodium mobility³³,³⁴ and conduction in CO₂-rich melts caused by the motion of all species in ionic liquids³³ (equation (1)).

The pre-exponential factor, \( \sigma_0 \), and the activation energy, \( E_A \), for both H₂O and CO₂ are related by a compensation law²²,²³ (Extended Data Fig. 3b):

\[ \ln(\sigma_0^\text{volatile} / \sigma_0^\text{CO}_2) = b \]  

(3)

\[ E_A^\text{volatile} = a \exp \left( -b \frac{E_m^{\text{CO}_2}}{E_m^{\text{H}_2\text{O}}} \right) + c \]  

(4)

\( C_m^{\text{volatile}} \) is the CO₂ or H₂O content in wt%.

Thus, equations (1), (3) and (4) directly relate melt conductivities to melt H₂O and CO₂ contents. We have determined the Arrhenius parameters for the melt composition as a function of H₂O content using data in ref. 7 in the temperature range 1,200–1,500°C. Parameters \( a, b, c, d \) and \( e \) for H₂O were obtained by fitting these data with equations (3) and (4) (Extended Data Table 3). The best parameters for CO₂ were obtained by minimizing the differences between our measured conductivities and the CO₂-free values returned by equation (1) (Extended Data Table 3). In doing so, we assumed that the effect of H₂O on electrical conductivity is similar and modest in both silicate and carbonate melts, which is indeed what our measurements show (compare samples C and HC in Extended Data Fig. 3a). Our model reproduces the experimental measurements of \( \sigma \) (ours and that of ref. 7) with an average error of 5% (maximum 10%).

Figures 2 and 3. The bulk rock is considered a peridotite containing a fraction of interconnected melt, where volatiles partition between the solid and the melt phase. The bulk H₂O content is related to H₂O in melt and in peridotite by

\[ C_m^{\text{H}_2\text{O}} = \frac{X_m^{\text{H}_2\text{O}} + (1 - X_m^{\text{H}_2\text{O}}) X_{\text{perid}}^{\text{melt}}}{X_m^{\text{H}_2\text{O}} + X_{\text{perid}}^{\text{melt}}} \]  

\[ C_{\text{perid}}^{\text{melt}} = \frac{X_{\text{perid}}^{\text{melt}}}{X_m^{\text{H}_2\text{O}} + X_{\text{perid}}^{\text{melt}}} \]  

where \( X_m^{\text{H}_2\text{O}} \) is the mass fraction of melt and \( C_{\text{perid}}^{\text{melt}} \) is the partition coefficient of H₂O between peridotite and melt (0.007, the average partition coefficient over the pressure range 1.5–4 GPa: refs 9, 37).

The concentration of H₂O in olivine is

\[ C_{\text{ol}}^{\text{H}_2\text{O}} = C_{\text{perid}}^{\text{melt}} C_{\text{perid}}^{\text{melt}} / C_{\text{perid}}^{\text{melt}} \]  

which differs from that of peridotite because \( C_{\text{perid}}^{\text{melt}} \) is about 0.002 (ref. 9). (See also fig. 6 of ref. 9 for the modal proportion of mineral phases in peridotite Opx, Grt, Cpx, Sp, Amph.)

Pargasite amphibole was considered to affect the distribution of H₂O for bulk H₂O content exceeding 200 p.p.m. (enriched mantle in Figs 2c and 3 and Extended Data Fig. 4). We computed that the H₂O content exceeding 200 p.p.m. in bulk goes in pargasite and computed the partitioning of H₂O among NAMs following ref. 9. If temperatures exceed ~1,070°C (Extended Data Fig. 5), then pargasite dehydration melting occurs and H₂O partitions between melt and the solids as described above.

CO₂ distributes exclusively in the liquid phase²²,²³; that is, \( C_{\text{perid}}^{\text{melt}} = 0 \). Therefore

\[ C_{\text{CO}_2}^{\text{perid}} = C_{\text{perid}}^{\text{melt}} X_m^{\text{CO}_2} \]  

\[ C_{\text{CO}_2}^{\text{melt}} = 0 \]

At small melt fractions, this can lead to CO₂ concentrations higher than that of carbonate (45 wt%) or, in other words, to CO₂ saturation. Calculations performed at saturated concentrations are mentioned in Fig. 2b, c.
Conversion from mass to volume fraction of melt is done considering volume properties of silicate melts and carbonate melts:

\[ X_{\text{melt}} = \left( 1 + \frac{1}{X_{\text{melt}}^{\text{basalt}}} - 1 \right)^{-1} \]

Here, \( d_{\text{peridot}} \) is the density of peridotite, that is, 3, and \( d_{\text{melt}} \) is the density of melt. Because there are no data for the density of hydrous carbonated basalts, we estimate the density of these melts using a simple mixing law:

\[ d_{\text{melt}} = \frac{C_{\text{H}_2\text{O}}^{\text{melt}} d_{\text{H}_2\text{O}}}{{100}} + \frac{C_{\text{CO}_2}^{\text{melt}} d_{\text{CO}_2}}{100} + \frac{(1 - C_{\text{H}_2\text{O}}^{\text{melt}} - C_{\text{CO}_2}^{\text{melt}})}{100} \]

where concentrations are expressed as wt% and \( d_{\text{H}_2\text{O}} = 1.4 \) (considering 12 cm\(^3\) mol\(^{-1}\) for H\(_2\)O partial volume in melts). The mass per cent of carbonate (M-CO\(_3\)), was set to 2.4 according to the density of carbonates at 1 bar (ref. 39).

The conductivity of the melt, \( \sigma_{\text{melt}}(C_{\text{H}_2\text{O}}^{\text{melt}} C_{\text{CO}_2}^{\text{melt}} T) \), was calculated using equation (1). The conductivity of the peridotite was assumed to be controlled by that of hydrous olivine.

The bulk conductivity was calculated using the mean of tube and film:

\[ \sigma_{\text{bulk}}(X_{\text{melt}} C_{\text{H}_2\text{O}}^{\text{melt}} C_{\text{CO}_2}^{\text{melt}} T) = \frac{\sigma_{\text{tube}} + \sigma_{\text{layer}}}{2} \]

This equation returns values almost the same as those reported in refs 20, 46. The bulk conductivity of partial molten peridotite reported in Figs 2 and 3, as well as in the text, was calculated using equation (5).

The melt fraction in Fig. 3 was approximated as \( X_{\text{melt}} = 2.5\text{CO}_2^{\text{bulk}} + 6\text{H}_2\text{O}^{\text{bulk}} \) (Extended Data Fig. 6).

### Buoyant basalts versus incipient melts.

An impermeable layer has been suggested to prevent the melt prevailing in the LAB from rising to the surface. The rate of melt ascent due to buoyancy is otherwise expected to be of the order of several cm yr\(^{-1}\) (refs 11, 12) if melt content is 3–5 vol%. Our model of incipient melting implies an impermeable boundary that is caused by phase relationships, that is, a thermodynamic boundary through which melt cannot rise. We further more emphasize the limited melt mobility at the small melt fraction of interest because, in particular, surface tensions would unavoidably tend to retain the buoyant melt. To conclude, if basalts, being anyway not thermodynamically stable in the asthenosphere, tend to migrate out of the asthenosphere, small melt fractions may in contrast be mechanically stable in the LAB.

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Extended Data Figure 1 | Set-up of electrical conductivity measurement using four wires. a, Modified piston–cylinder assembly for electrical conductivity measurements using a four-wire configuration. The cored sample (in green) contains in its centre an inner electrode in platinum (in blue). A platinum foil (in blue) surrounds the sample, which extends upwards and downwards from the sample and corresponds to the outer electrode. The sample is sandwiched by machined MgO ceramics (in white). The electrode-sample assemblage is isolated from the graphite furnace by an Al₂O₃ jacket (in yellow). The four-electrode wires are emplaced using a four-hole Al₂O₃ tube (in orange). Two of these wires, that is, the thermocouple, are in contact with the inner electrode, whereas the outer electrode is in contact with two other wires by means of a top Ni plug (in red). b, SEM image of the assemblage of sample C after experiments (up to 1,463 °C and 3 GPa). We observed an average decrease of 20% compared to the initial cell geometry (corresponding to the porosity loss during melting). Cell geometry parameters ($h$, $r_{in}$ and $r_{out}$ in equation (2)) are determined from SEM images for each sample.
**Extended Data Figure 2 | Measured resistance of molten carbonate versus nickel.**

**a**, The electrical cell resistance versus temperature. We show the resistance of a sample made of nickel measured using either a two-wire set-up (empty diamond) or a four-wire set-up (red diamond). There are several orders of magnitude of difference between the two measurements, showing that the two-wire setup is not suitable at all for conductive materials. We also show the resistance of carbonate in a four-wire set-up (sample C, molten at \( T > 1,230 \) °C; green triangle).

**b**, Impedance spectra obtained on molten carbonate (sample C) at 3 GPa as a function of temperature. Impedance spectra show vertical lines, indicating an inductance-dominated signal for all temperatures. The resistance is taken from the intercept with the horizontal axis. Data are obtained at frequencies ranging from 19,905 to 315,479 Hz. The black line represents an impedance spectrum of a nickel sample (blank) obtained with a four-wire configuration at 1,464 °C.
Extended Data Figure 3 | Electrical conductivity measurements.
a, Electrical conductivity versus reciprocal temperature measured on carbonated melts and hydrous carbonated basalts. Samples: a carbonated melt (C), a hydrous carbonated melt (HC), and three hydrous carbonated basalts with H₂O contents ranging from 4.43 to 9.22 wt% (HCB-9, HCB-7 and HCB-4) and CO₂ contents ranging from 10.39 to 23.32 wt%. To complete Fig. 1, we distinguished heating–cooling temperature cycles and reported error bars. Large solid symbols, heating cycle (H1); open symbols, cooling cycle (C1); small solid symbols, second heating cycle (H2) (compare with Extended Data Table 2a). The error bars include uncertainties in the geometrical factors of the samples and in the measured resistance. b, Compensation plots showing the correlation between activation energy, E_a, and pre-exponential terms, ln(σ₀). Hydrous basalts (HB) are from the experimental data set of ref. 7 between 1,200 and 1,500 °C, and the data point for the dry basalt (B) is from ref. 32. The dry carbonated melt (C), the hydrous carbonated melts (HC) and the hydrous carbonated basalts (HCB) are from this study (see Extended Data Table 2b for the Arrhenius parameters).
Extended Data Figure 4 | The incipient melt effect on the electrical conductivity of an H$_2$O-enriched, CO$_2$-free peridotite. This figure completes the scenarios illustrated in Fig. 2. The conductivity of partially molten peridotite, in which H$_2$O partitions between minerals and melt (Methods), is reported as a function of melt content and temperature for CO$_2$-free peridotite with 500 p.p.m. H$_2$O (log values; conductivity increases from cold to warm colours). The discontinuity at $T = 1,070$ °C is due to pargasite amphibole breakdown (Extended Data Fig. 5) that redistribute H$_2$O between NAMs and the melt as explained in the Methods. Melt H$_2$O contents (blue if pargasite out, green if pargasite in) are tabulated above the panel.
Extended Data Figure 5 | Melting curves for different bulk peridotitic systems as functions of temperature and depth. The solidus of dry peridotite (black curve) is calculated from ref. 53. The dehydration solidus of nominally anhydrous peridotite at 200 p.p.m. H₂O (blue curve) is modelled from ref. 9. The dehydration solidus of pargasite lherzolite is based on ref. 10. The nominally anhydrous carbonated, fertile peridotite solidus is based on ref. 54 and references therein (green curve). The H₂O-undersaturated carbonated, fertile peridotite curve (purple curve) corresponds to the solidus of a pyrolite with 0.5–2.5 wt% CO₂ and 0.3 wt% H₂O (ref. 14). For pressures ≤1.7 GPa, carbonated melts are unstable and gaseous CO₂ prevails. We connected the melting curve of CO₂-bearing peridotite to that of the dry peridotite at low pressures, which slightly differs from previously published phase diagrams. We considered that, for P ≤ 1.7 GPa, gaseous CO₂ must have a negligible influence on the peridotite solidus due to the small solubility of CO₂ in basaltic melts55. Similarly, at low pressures, the H₂O-undersaturated carbonated, fertile peridotite solidus was connected to the dehydration solidus of nominally anhydrous peridotite (considering peridotite with 200 p.p.m. H₂O), neglecting the presence of pargasite owing to the NAM’s H₂O capacity storage.
Extended Data Figure 6 | Phase equilibria control on H₂O–CO₂ partitioning, ultimately resulting in a change in conductivity as shown in Fig. 3. We show changes in H₂O content in olivine (left), melt fraction (centre) and melt CO₂/H₂O (right) for the 70-Myr age used for calculation in Fig. 3. We use two illustrative compositions: bulk with 200 p.p.m. H₂O and 500 p.p.m. CO₂ and bulk with 500 p.p.m. H₂O and 500 p.p.m. CO₂.
Extended Data Table 1 | Chemical composition of samples before and after electrical conductivity measurements

**a**

| Sample | C | C+ | C | H | H  | HCB-9 | HCB-7 | HCB-4 | Dolomite | Basalt |
|--------|---|----|---|---|----|-------|-------|-------|----------|--------|
| SiO₂    | 0.24 | 0.24 | 0.22 | 5.23 | 15.67 | 31.32 | 0.27 | 52.18 |          | 0.15 |
| TiO₂    | 0.03 | 0.03 | 0.02 | 0.20 | 0.56 | 1.10 | 0.03 | 1.81 |          | 0.15 |
| Al₂O₃   | 0.02 | 0.02 | 0.01 | 1.52 | 4.54 | 9.07 | 0.02 | 15.11 |          | 0.15 |
| FeO     | 0.20 | 0.20 | 0.02 | 0.82 | 2.41 | 4.80 | 0.22 | 7.99 |          | 0.15 |
| MgO     | 18.68 | 18.68 | 23.79 | 22.16 | 18.90 | 14.01 | 20.76 | 7.49 |          | 0.15 |
| CaO     | 26.50 | 26.50 | 32.19 | 30.01 | 25.66 | 19.13 | 29.44 | 10.42 |          | 0.15 |
| Na₂O    | 0.02 | 5.87 | 0.01 | 0.31 | 0.91 | 1.82 | 0.02 | 3.02 |          | 0.15 |
| K₂O     | 0.03 | 0.03 | 0.01 | 0.07 | 0.21 | 0.41 | 0.03 | 0.67 |          | 0.15 |
| MnO     | 0.03 | 0.03 | 0.01 | 0.03 | 0.06 | 0.11 | 0.03 | 0.17 |          | 0.15 |
| P₂O₅    | 0.33 | 0.33 | 0.33 | 0.36 | 0.38 | 0.41 | 0.37 | 0.49 |          | 0.15 |
| NaCl    | 10.00 | - | 7.50 | 6.75 | 5.25 | 3.00 | - | - |          | 0.15 |
| Total   | 56.07 | 51.92 | 63.91 | 67.46 | 74.55 | 85.18 | 51.19 | 0.00 |          | 0.15 |

**b**

| Sample | C | C+ | C | H | H  | HCB-9 | HCB-7 | HCB-4 |
|--------|---|----|---|---|----|-------|-------|-------|
| SiO₂    | 0.4  | 0.32 | 0.26 | 5.49 | 15.83 | 32.12 |       |       |
| TiO₂    | 0.03 | 0.03 | 0.01 | 0.29 | 0.22 | 1.05 |       |       |
| Al₂O₃   | 0.07 | 0.02 | 0.35 | 1.25 | 4.82 | 10.43 |       |       |
| FeO     | 0.01 | 0.03 | 0.03 | 0.04 | 0.29 | 3.98 |       |       |
| MgO     | 17.76 | 18.02 | 23.39 | 22.94 | 20.69 | 14.52 |       |       |
| CaO     | 26.63 | 26.74 | 32.05 | 30.29 | 26.16 | 19.25 |       |       |
| Na₂O    | 5.32 | 5.65 | 3.75 | 3.95 | 3.54 | 3.02 |       |       |
| K₂O     | 0.05 | 0.03 | 0.01 | 0.08 | 0.05 | 0.48 |       |       |
| MnO     | 0.04 | 0.03 | 0.05 | 0.08 | 0.03 | 0.1  |       |       |
| P₂O₅    | 0.33 | 0.33 | 0.04 | 0.38 | 0.27 | 0.51 |       |       |
| NaCl    | 6.12 | - | 4.51 | 4.02 | 3.11 | 1.92 |       |       |
| Total   | 56.76 | 51.19 | 64.45 | 68.83 | 75.01 | 87.38 |       |       |

C, carbon; C+, carbonates; H, hydrous; HCB-9, HCB-7, HCB-4, hydrous carbonated basalt compositions 9, 7, 4 wt%.

**Footnotes:**

a. Bulk chemical composition of the starting materials (wt%).

b. Analysed chemical compositions (wt%) of the bulk systems after each experimental run. 

H₂O contents were analysed using an elemental analyser (Flash 2000). Carbon dioxide contents were obtained by difference on EMPA.

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**Extended Data Table 2 | Temperature range of electrical conductivity measurements and adjusted Arrhenius parameters**

|                  | C    | C+   | HC   | HBC-9 | HBC-7 | HBC-4 |
|------------------|------|------|------|-------|-------|-------|
| **Heating cycle**| 0-1511 | 0-1404 | -    | 1397-1472 | 1383-1482 | 1304-1465 |
| **Cooling cycle**| 1511-1120 | -    | 1410-650 | 1472-850 | 1482-1070 | 1465-1338 |
| **Heating cycle 2** | - | - | - | - | - | 1338-1470 |

|                  | $\text{E}_a \, (\text{J.mol}^{-1})$ | error ($\text{J.mol}^{-1}$) | In $\sigma_0 \, (\text{S.m}^{-1})$ | error ($\text{S.m}^{-1}$) |
|------------------|-----------------|-----------------|-----------------|-----------------|
| C                | 42150           | 700             | 8.26            | 0.05            |
| C+               | 41950           | 1330            | 8.2             | 0.12            |
| HC               | 43460           | 670             | 8.47            | 0.05            |
| HBC-9            | 46360           | 2300            | 8.58            | 0.17            |
| HBC-7            | 54900           | 3400            | 8.84            | 0.32            |
| HBC-4            | 126500          | 2700            | 13.02           | 0.2             |

**a**, Heating and cooling cycles. Cycles of the different experimental runs with corresponding temperature ranges (°C). Runs HC and HCB-9, -7 and -4 were heated from room temperature to 700 °C. A step of 10 min was performed at 700 °C before a rapid increase to the measurement temperature. **b**, Arrhenius parameters and their errors determined for each melt studied.
Extended Data Table 3 | Parameters used for equations (3) and (4)

| Parameters | H₂O  | CO₂   |
|------------|------|-------|
| a          | 88,774 | 789,166 |
| b          | 0.3880 | 0.1808  |
| c          | 73,029  | 32,820  |
| d          | 4.54E-05 | 5.50E-05 |
| e          | 5.5607  | 5.7956  |