Melt-rich channel observed at the lithosphere–asthenosphere boundary

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The lithosphere–asthenosphere boundary (LAB) separates rigid oceanic plates from the underlying warm ductile asthenosphere. Although a viscosity decrease beneath this boundary is essential for plate tectonics, a consensus on its origin remains elusive. Seismic studies identify a prominent velocity discontinuity at depths thought to coincide with the LAB but disagree on its cause1–3, generally invoking either partial melting or a mantle dehydration boundary8 as explanations. Here we use sea-floor magnetotelluric data to image the electrical conductivity of the LAB beneath the edge of the Cocos plate at the Middle America trench offshore of Nicaragua. Underneath the resistive oceanic lithosphere, the magnetotelluric data reveal a high-conductivity layer confined to depths of 45 to 70 kilometres. Because partial melts are stable at these depths in a warm damp mantle6, we interpret the conductor to be a partially molten layer capped by an impermeable frozen lid that is the base of the lithosphere. A conductivity anisotropy parallel to plate motion indicates that this melt has been sheared into flow-aligned tube-like structures9. We infer that the LAB beneath young plates consists of a thin, partially molten, channel of low viscosity that acts to decouple the overlying brittle lithosphere from the deeper convecting mantle. Because this boundary layer has the potential to behave as a lubricant to plate motion, its proximity to the trench may have implications for subduction dynamics.

The passive magnetotelluric method uses naturally occurring magnetic fields and induced electric fields to probe mantle electrical conductivity structure. Because pure melts are at least two orders of magnitude more conductive than a typical peridotite, mantle conductivity can be greatly increased by small amounts of partial melt10, whereas conductivity depends to a much lesser extent on mantle temperature and hydration state11. This large conductivity contrast makes magnetotelluric soundings highly sensitive to the presence of mantle partial melts.

We deployed 50 broadband electromagnetic stations across a single 280-km-long profile that extended from the Cocos plate abyssal plain, across the trench, and onto the continental shelf, amounting to the largest subduction zone electromagnetic deployment to date (Fig. 1). Data from high-frequency controlled-source electromagnetic profiling revealed that the pervasive extensional bending faults on the trench outer rise are porous channels that allow for deep crustal hydration and serpentinization of the uppermost mantle12. The lower-frequency magnetotelluric data considered here target deeper conductivity structure in the lithosphere and asthenosphere. We extended the instrument array far onto the abyssal plain to image what we expected to be unremarkable conductivity beneath the oceanic plate, which would provide a baseline for comparisons with conductivity features found beneath the trench axis and continental margin.

We converted the observed magnetotelluric responses into a two-dimensional conductivity model using a nonlinear regularized inversion that solved for the triaxially anisotropic conductivity tensor of 10,000 mesh cells13,14. Figure 2a shows the horizontal resistivity (reciprocal of conductivity) component aligned in the direction of plate motion. All three tensor components are shown in Supplementary Fig. 3.

Landward of the trench, the magnetotelluric data reveal a resistive subducting slab and mantle, with a notable correlation between the location of earthquakes and high resistivity (Fig. 2a). The widespread distribution of earthquakes indicates that the brittle slab is rupturing over a wide depth range (rather than the rupturing being concentrated along the plate interface), consistent with high resistivity indicating a relatively cold, fluid-free mantle.

The conductivity becomes laterally uniform westward of the trench. A veneer of low-resistivity sediments and extrusive volcanics overlies a highly resistive lithosphere, typical of oceanic plate structure17. Below this, we find an anomalously conductive, horizontally extensive layer of 4–6 S m at 45–70 km depth. This conductor extends at least to the western edge of the profile where our magnetotelluric array ends, while its eastern edge lies beneath the trench outer rise wall. The anomalous layer is 1.5–2 times more conductive in the direction parallel to plate motion than parallel to the trench axis (Fig. 2b).
Deeper asthenosphere is isotropic, with resistivity 10–20 Ω m. Model sensitivity studies indicate that the conductance (the product of conductivity and thickness) of the anisotropic conductive layer and the conductivity of the underlying isotropic asthenosphere are well constrained by the data (Supplementary Fig. 4). Because the magnetotelluric data are primarily sensitive to the layer conductance, the response of the observed anomalous layer, which is 25 km thick, is nearly equivalent to that from a 12.5 km layer with a conductivity twice as large; however, we favour the thicker layer found by the inversion because its conductivity and anisotropy are similar to observations beneath our profile (Fig. 3b). The deeper mantle beneath the conductive layer is isotropic, suggesting it is not being sheared.

The anomalous layer is too conductive to be consistent with localized partial melt or a small degree of partial melt beneath our profile (Fig. 3b). That portion of the ridge generates the deepest part of the oceanic plate (Fig. 3c) and inverted triangles denote seafloor magnetotelluric station locations. a. The electrical resistivity in the direction parallel to plate motion (\(\rho_r\)). The colour scale gives log(\(\rho_r\), Ω m), with blue and red colours corresponding to resistive and conductive (less resistive) features, respectively. The dark red line is a model of the top of the subducting slab\(^9\). Earthquake hypocentres from up to 50 km off-axis are shown as black circles (from the USGS/NEIC catalogue). The region enclosed by the dashed black line is where the model is at least 1.5 times more conductive in the direction parallel to plate motion. b. Resistivity ratio for the plate-motion–parallel (\(\rho_r\)) to trench-axis–parallel (\(\rho_y\)) model components. The colour scale gives log(\(\rho_r/\rho_y\)), and the plot shows the strong anisotropy of the conductive layer at 45–70 km depth (red regions >150 km offshore). Although the lithosphere above shows a strong anisotropy, we warn that this is not well constrained, because the magnetotelluric method is primarily sensitive to conductive rather than resistive features\(^9\). The deeper mantle beneath the conductive layer is isotropic, suggesting it is not being sheared.

Deep off-axis melt emplacement can occur during lithosphere formation at the ridge or result from accumulation of a small degree of intraplate melting\(^9\). An earlier magnetotelluric experiment at the southern East Pacific Rise spreading ridge observed an off-axis conductive asthenosphere at 60–120 km depth beneath a resistive lithosphere\(^10,20\). We interpret that conductive layer as requiring partial melt, because its conductivity and anisotropy are similar to observations beneath our profile (Fig. 3b). That portion of the ridge generates the Nazca plate; if we assume equivalent ridge processes are occurring for the Cocos plate, where our profile was measured, then most of the hydrous melt has been emplaced at or near the ridge axis. Additional melt may accumulate through deeper intraplate melting—for example, from small-scale convection\(^22\). Grain boundary migration of deeper partial melt\(^22\) carries with it increased water content as a result of the preferential partitioning of water into silicate melts. As enriched hydrated melt rises, it collects beneath the colder, less permeable lithosphere\(^23\) and shears into a network of interconnected horizontally aligned melt bands\(^25\), possibly driven by large-scale asthenospheric flow\(^26\). Stress gradients perpendicular to the shear direction have been shown to reduce the melt connectivity in the direction along the gradient\(^9\), offering a possible mechanism for our observed anisotropy. The depth extent over which the asthenosphere is being sheared can be inferred from the anisotropy of the melt layer along with its increased conductivity, which the magnetotelluric data constrain to a maximum thickness of 30 km.

The existence of a horizontally extensive melt layer that is being sheared over a confined depth interval indicates the LAB is a thin, low-viscosity channel. Theoretical studies suggest that even small melt fractions (<1%) can lower viscosity by up to two orders of magnitude, effectively decoupling the lithosphere from the asthenosphere\(^27\). The depth extent over which this decoupling occurs as well as its proximity

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**Figure 2 | Resistivity model obtained from anisotropic inversion of the seafloor magnetotelluric data.** At the top is the surface view; arrows show the direction of north and \(\rho_r\) (see below), and inverted triangles denote seafloor magnetotelluric station locations. a. The electrical resistivity in the direction parallel to plate motion (\(\rho_r\)). The colour scale gives log(\(\rho_r\), Ω m), with blue and red colours corresponding to resistive and conductive (less resistive) features, respectively. The dark red line is a model of the top of the subducting slab\(^9\). Earthquake hypocentres from up to 50 km off-axis are shown as black circles (from the USGS/NEIC catalogue). The region enclosed by the dashed black line is where the model is at least 1.5 times more conductive in the direction parallel to plate motion. b. Resistivity ratio for the plate-motion–parallel (\(\rho_r\)) to trench-axis–parallel (\(\rho_y\)) model components. The colour scale gives log(\(\rho_r/\rho_y\)), and the plot shows the strong anisotropy of the conductive layer at 45–70 km depth (red regions >150 km offshore). Although the lithosphere above shows a strong anisotropy, we warn that this is not well constrained, because the magnetotelluric method is primarily sensitive to conductive rather than resistive features\(^9\). The deeper mantle beneath the conductive layer is isotropic, suggesting it is not being sheared.
to the trench axis have potentially new implications for plate dynamics, as previous studies have focused on the effects of melt at the ridge axis and mantle wedge. A pervasive feature that exists beneath oceanic plates at large distances from spreading centres requires the stability of a partially molten layer, as dictated by the solidus of wet peridotite and a warm mantle geotherm. A previous magnetotelluric study of 140–150-Myr-old lithosphere in the Pacific Ocean basin did not find a conductive melt layer. This is consistent with a thicker cold plate containing too little water to sustain hydrous melts at the greater LAB depth.

In our profile, the conductive layer ends near the trench, whereas the layer anisotropy persists in a trajectory that follows the subducting slab, albeit with a decreasing anisotropic factor. This signifies that as the plate subducts, some melt is likely to remain in place beneath the shallower LAB at the trench outer rise owing to its buoyancy. This offers an explanation in which the observed melt-rich LAB is caused by the concentration of low-fraction melts at the trench over time as the plate continues to be subducted; if this mechanism is responsible for locally enriching the asthenosphere with melt, we predict that melt would be most concentrated near the trench and decrease towards younger regions of the plate.

**METHODS SUMMARY**

We processed the magnetotelluric data using a standard robust multi-station impedance estimation approach at periods of 22–32,000 s (ref. 29). Supplementary Fig. 1 presents the data and two-dimensional inversion model fits. The data subset suitable for two-dimensional modelling was evaluated by inspecting impedance polarization diagrams (Supplementary Fig. 2). Sites S31–S34, located on the margin slope near the base of the trench, display strong three-dimensional dance polarization diagrams (Supplementary Fig. 2). Sites S31–S34, located on the margin slope near the base of the trench, display strong three-dimensional dance polarization diagrams (Supplementary Fig. 2). The rest of the data exhibit a profile-wide layer observed off-axis at the southern EPR.

**Figure 3** High asthenosphere conductivity explained by a thin partially molten layer. Evidence for the stability of melt. a, Hydrous olivine resistivity is estimated as a function of H₂O content for different temperatures. The dark grey region represents the observed resistivity (4–6 Ω·m) of the anomalous conductive layer, while the lighter grey region represents a 10 Ω·m conductive layer observed off-axis at the southern EPR. Olivine would be required to contain at least 800 p.p.m. H₂O to account for the observed resistivity if no melt is present. b, Bulk resistivity of partial melt shown as a function of melt fraction for different temperatures and bulk mantle water contents with an assumed mineral/melt partition coefficient of 0.006. c, Solid lines depict the solidus of dry and wet peridotite for various mantle H₂O contents. The dashed lines show the solidus derived from a plate cooling model of 23-Myr-old oceanic lithosphere. Melt is stable at depths greater than 45 km for peridotite with 275 ± 85 p.p.m. H₂O and a 1,420 °C mantle potential temperature. A geotherm with a reduced mantle potential temperature of 1,315 °C requires 505 ± 150 p.p.m. H₂O. The solidus of wet peridotite is calculated with the cryoscopic approximation assuming an oxide molar mass.


Supplementary Information is available in the online version of the paper.

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