LETTERS

Seismic reflection images of the Moho underlying melt sills at the East Pacific Rise

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The determination of melt distribution in the crust and the nature of the crust-mantle boundary (the 'Moho') is fundamental to the understanding of crustal accretion processes at oceanic spreading centres. Upper-crustal magma chambers have been imaged beneath fast- and intermediate-spreading centres¹⁻⁴ but it has been difficult to image structures beneath these magma sills. Using three-dimensional seismic reflection images, here we report the presence of Moho reflections beneath a crustal magma chamber at the 9° 03' N overlapping spreading centre, East Pacific Rise. Our observations highlight the formation of the Moho at zero-aged crust. Over a distance of less than 7 km along the ridge crest, a rapid increase in two-way travel time of seismic waves between the magma chamber and Moho reflections is observed, which we suggest is due to a melt anomaly in the lower crust. The amplitude versus offset variation of reflections from the magma chamber shows a coincident region of higher melt fraction overlying this anomalous region, supporting the conclusion of additional melt at depth.

Multichannel seismic (MCS) reflection studies from fast- and intermediate-spreading centres have shown the presence of uppercrustal melt sills, which has led to the suggestion that melt accumulates predominantly within and immediately below these features¹⁻⁴. These melt sills are typically 250–4,000 m wide, <100 m thick^{5,6} and are underlain by a broad, partially molten region characterized by low seismic velocities^{7–10} and high attenuation¹¹. Some seismic and seafloor compliance studies suggest the presence of melt within or beneath the Moho—the transition zone separating lower crust and upper mantle—in the form of a melt sill or a large partially molten region^{12–14}. The detailed nature of upper-crustal magma chambers is now well understood^{4,15}, but the geometry and size of lower-crustal melt bodies and their relationship to subcrustal reservoirs is still poorly known.

In 1997, a three-dimensional (3D) MCS reflection and tomography experiment was carried out over the $9^{\circ}03'$ N overlapping spreading centre (OSC) at the East Pacific Rise (EPR). The 3D MCS data were acquired over a 20 km by 20 km area of sea floor (Fig. 1) covering both limbs of the OSC. The $9^{\circ}03'$ N OSC has an offset of 8 km and the two limbs overlap for about 27 km. The eastern limb of the OSC is propagating southward at a rate of 42 km Myr⁻¹, or about half of the present-day spreading rate, whereas the western limb is receding¹⁶.

The extensive presence of axial magma chamber (AMC) reflections beneath both limbs and portions of the overlap basin⁴ is indicative of a robust supply of magma beneath this feature (Fig. 1 inset). The AMC reflections located at upper-crustal depths between ~1,650 and 2,200 m beneath the sea floor are up to 4.5 km wide in the north, narrowing down to ~250 m in the south. On the eastern limb, the melt sill is asymmetric and lies mainly west of the ridge crest. The geometry of these magma sills is not consistent with large-scale crustal migration of melt away from mantle upwelling at the segment centre, but instead seems to be related to vertical transport from the underlying mantle and subsequent focusing in the mid-crust.

Using 3D MCS reflection data processed in a new manner to





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Figure 2 | Three-dimensional view of reflection images of the Moho and melt sill. A 3D cut through the ARAD seismic reflectivity volume revealing the observed travel-time anomaly (\sim 2.1 s maximum value) between the AMC and the base of the crust (the Moho). Multibeam bathymetry has been included to provide spatial context between seafloor morphology and underlying crustal structure. This 3D cube spans an area extending $15.5 \text{ km} \times 11.5 \text{ km}$ covering most of the eastern limb and overlap basin. Part of the volume has been removed to show the relationship between the sea floor, the AMC and the Moho (highlighted) reflections. See Fig. 3a for the location of the trimmed 3D volume. AMC reflections are imaged along both overlap limbs and beneath the northern half of the overlap basin, whereas Moho reflections are present throughout most of the 3D volume (although absent beneath the western limb). Note a rapid increase in two-way travel time between the AMC and Moho reflections along the displayed 12.6km-long facet of the volume (increasing from 1.3 s to 2.0 s over a distance spanning only <7 km).

highlight deeper structure, we observed Moho reflections beneath the AMC along the entire eastern limb (Figs 2 and 3a). The polarity of the Moho reflections is complex, but it is generally positive, similar to the seabed reflections, requiring a positive velocity contrast. The existence of near-vertical incidence reflections from the Moho means that the crust–mantle boundary is sharp compared to the wavelength (300 m) of the seismic energy at this depth. This critical relationship has never been observed on any two-dimensional (2D) MCS profile; thus, these new 3D data now permit the exploration of changes in lower crustal structure between the magma chamber and Moho boundary.

A part of the 3D volume of reflection data has been removed to focus on crustal structure beneath the eastern limb in Fig. 2 and Supplementary Fig. S2, highlighting the relationship between AMC and Moho reflections. Moho reflections are easily identifiable on the along-axis sections of the 3D seismic volume, although they are also present on the cross-axis sections (Fig. 2 and Supplementary Figs S1 and S2). Moho reflections are observed over 50% of the 3D box; these events are predominantly seen beneath the eastern limb, the northern part of the overlap basin and west of the receding limb (Fig. 3a). There could be significant attenuation¹¹ within the upper-crustal magma chamber ($Q_p \approx 10-20$), so a strong impedance contrast between the uppermost mantle and lower crust would be needed to produce the observed Moho reflections. The compressional-wave (P-wave) velocity of the solid mantle beneath the ridge axis is about 7.6–7.8 km s⁻¹. It is therefore likely that a low P-wave velocity (for example, 5.0-6.0 km s⁻¹) in the lower crust owing to additional melt would be needed to produce a visible reflection; if there exists reduced mantle velocity due to subcrustal melt accumulation, this effect would be offset, requiring even lower velocity above the Moho.

There are two possibilities for the presence of the Moho beneath the AMC: (1) the AMC has propagated over the pre-existing Moho underlying older crust, (2) the Moho was formed at zero age. Because Moho reflections are present beneath a wide AMC (4.5 km) in the north along the propagating limb of the spreading ridge, we prefer the latter explanation for the presence of the Moho. This observation suggests that differentiation of oceanic crust occurs over a very limited spatial region, and hence, a short period of geologic time; although this fundamental boundary may be modified as crust slides away from the rise axis, these new images reveal insights into the dynamics of the lower-crustal formation.

Off-axis, the Moho reflections are observed between 1.9 and 2.3 s below the sea floor (Fig. 3a), which are similar to those observed in ref. 17 using widely spaced 2D seismic lines, whereas these reflections are 2.6-2.9 s below the sea floor beneath the wide AMC on the eastern limb, about 0.6-0.7 s more than the off-axis travel time. If we assume an average crustal velocity of 6.0 km s^{-1} , the crust would be about 6-7 km thick off-axis, which is consistent with the crustal thickness determined from tomographic study outside the 3D box¹⁸. However, the crust would be around 8-9 km thick beneath the AMC on the eastern limb, which is anomalous.

It is intriguing to note that the contribution to this large traveltime anomaly comes from the difference in travel time between the AMC and Moho reflections, that is, from the lower crust. For example, the two-way travel time between the AMC and Moho reflections is about 1.30 s near the rift tip in the south, but then increases dramatically to over 2.0 s along the flank of the eastern ridge abutting the northern overlap basin, within a distance of <7 kmalong the axis and <5 km across the axis; that is, a short wavelength increase in travel-time difference of 35–40% in the lower crust. If the whole anomaly is produced by the presence of melt then over 45% of the lower crust could be molten, assuming horizontally aligned, spheroidal inclusions with an aspect ratio of 1/10 between the semiminor and semi-major axes¹⁹.

This lower-crustal travel-time anomaly could be caused either by a thick lower crust, the presence of a large amount of melt, or a combination of both. If we assume that the average P-wave velocity in the lower crust is 6.8 km s^{-1} at the ridge axis, where the temperature should be around 1,100 °C, then the thickness of the lower crust below the propagating rift tip would be 4.4 km, in contrast to just 7 km further north, where the lower-crustal thickness value would exceed 6.8 km. Under this scenario, an unexpected crustal thickness variation from 6.2 to 8.5 km would occur over a very short distance (5–7 km), which has never been observed before. Canales et al.¹⁸ found a V-shaped wake located about 20 km north of the OSC where the crust is thick (7.3-7.8 km). Therefore, crustal thickening can explain only a part of the total signal observed, and a significant amount of melt in the lower crust would be required to explain the large travel-time anomaly beneath the AMC. Furthermore, to create a thicker crust, extra melt supply would be required, supporting the idea that there must be a large amount of melt in the lower crust.

To gain more insight into the source of this lower-crustal traveltime anomaly, the reflection volume was reprocessed using a novel technique¹⁵ to investigate the internal structure of the overlying AMC. Amplitude variation with offset (AVO) studies can be used¹⁵ to distinguish melt-rich regions with fresh magma supply from areas of only partial melt that have been cooled and crystallized. The 3D AVO results (Fig. 3d) reveal that the northern OSC basin and eastern limb are underlain by a melt-rich sill, while the southern most reaches of the propagator tip are melt-starved or crystal-rich. This geographic association of melt-rich region with lower-crustal anomaly suggests that the melt-rich sill may be replenished by a melt anomaly within the lower crust.

Tomographic studies²⁰ also show a broad low-velocity anomaly at mid-crustal levels (3 km below the sea floor), which is roughly coincident with the overlying melt-rich sill and lower-crustal anomaly. The shallowest mantle is also characterized by lower velocities beneath this site²¹. Similarly, seafloor compliance measurements show very low S-wave velocities in the lower crust near this anomalous site²². Taken together, these various measurements provide evidence for a melt-rich delivery system at all depth levels, where melt is transported across the mantle into the lower crust, stored within the lower crust and the upper-crustal magma sill.



The southern limit of the lower-crustal anomaly is marked by a thin lower crust (1.3 s), with a total crustal thickness of $\sim 6 \text{ km}$ near the southern tip of the eastern limb (Fig. 3b). Beneath the eastern limb, it follows the asymmetric AMC reflections and seafloor morphology, and is elongated in the N15°W direction (Figs 1 and 3b). Kent *et al.*⁵ have observed a wide (4 km) asymmetric melt sill south of the 9° 17′ N ridge-axis discontinuity. The depth and nature of this extended melt sill is similar to the AMC observed along the eastern limb of the OSC. If the presence of the Moho and melt anomaly is associated with the wide melt sill, then this lower-crustal anomaly may continue up to 9° 17′ N. The presence of young basalt²³ (<50 yr) between 9° 12′ N and 9° 14′ N and black smokers²⁴ near 9° 16.8′ N might be associated with the large fresh melt supply in the crust from the mantle⁶.

The 3D data volume can also be used to search for large melt sills within the lower crust. The seismic imaging condition and the continuity of the Moho reflections allow us to test whether similar reflections from melt-sill events exist between the AMC and the crust-mantle boundary to verify whether the lower crust might be formed by a series of sill intrusions within the lower crust^{25,26}. The dominant frequency used in our study is 10-30 Hz, and the dominant wavelength at these depths is about 300-600 m, assuming a P-wave velocity of 6.8 km s⁻¹. Therefore, the resolution in our data is about 500 m laterally, and 50 m in depth; any melt sill with dimensions greater than this volume should be imaged. But no laterally continuous events are observed between the Moho and AMC reflections in this data volume, so we can confidently say that there are no high-amplitude, large seismic events between the AMC and the Moho that are of similar size when compared to the melt sills on top of the low-velocity zone. Melt sills of smaller size could be present, but we cannot resolve them using our present data set. The

Figure 3 | Two-way reflection times of Moho and amplitude versus offset for melt sill. a, b, Twoway reflection travel times (TWTT) of the Moho to the sea floor (**a**) and the Moho to the AMC (**b**). Spatial outline of magma chamber reflections are shown as thin black lines (a and b). The geographical position of the 3D subvolume shown in Fig. 2 is marked by a thick dashed line (a). The maximum Moho to AMC travel time is nearly 2.1 s (**b**), located near the transition where the AMC narrows and plunges down the propagating eastern ridge tip⁴. c, d, AMC reflection amplitude map using all streamer source-receiver offsets (red-orange-green-blue colour palette; **c**) and a composite of the inner half (red-orange) and the outer half (blue-green) of streamer (d). d, The AVO analysis highlights regions within the survey area that are melt-rich. These melt-laden regions lack any significant transmission of S-waves through the magma sill, resulting in a characteristic drop-off of P-wave energy in the 1.6-3.2-km offset band¹⁵. The AVO amplitude map shows a reflection image (blue-green) using the outer half of the streamer, combined on top of the image from the inner half (red-orange); in regions where S-wave transmission through the sill occurs (where the sill is crystal-rich), significant reflected energy in the outer range band (blue-green) masks the red-orange image from more vertically travelling energy. Melt-rich regions (red-orange) are found just to the north and south of the overlap basin centre; the melt-rich region in the northern half of the survey area corresponds with the underlying Moho-AMC travel time anomaly, suggesting that increased melt within the lower crust may be important in the observed traveltime delay.

absence of any observable melt sills in the lower crust suggests that the melt in the lower crust could be distributed in small pores or in very small pockets.

These results are consistent with a model where the lower crust is porous on an intergranular scale, and melt is efficiently transported to the shallower melt sill²⁷. Our results are also consistent with crustal accretion models where crystallization takes place in very small melt pockets at a range of depths within the axial crust²⁸. Using the correlation between the seafloor morphology along the ridge axis and ridge migration relative to a fixed hotspot frame of reference, Carbotte *et al.*²⁹ suggest that the variations in the seafloor morphology may result from melt focusing across discontinuities from an asymmetric zone of mantle upwelling beneath the advancing plate. The large melt anomaly in the crust at the northern end of the OSC might have resulted from such an asymmetric mantle upwelling. These results lead us to suggest that the localized asymmetric large lower-crustal melt anomaly could be responsible for the propagation of the OSC southwards.

METHODS

Navigation, binning and imaging. The 3D seismic reflection data were acquired within a 20 km by 20 km patch of sea floor (Fig. 1) positioned over the OSC at 9°03' N, using the academic research vessel RV *Maurice Ewing.* In this box, over 201 seismic profiles were collected at 100-m intervals using a 3,100-m-long streamer, with an in-line shot spacing of 38 m. The shooting direction was rotated 15° counter-clockwise of north, which was roughly perpendicular to the ridge axis.

In-line 2D profiles were corrected for dip-moveout, using water velocity $(1,500 \text{ m s}^{-1})$ before 3D binning. Subsequently, these data were re-gathered in 12.5 m by 100 m common-midpoint (CMP) 3D bins, with an elastic binning strategy extending out 50 m on either side of the active bin (to even out offset coverage within individual CMP gathers)³⁰. Velocity analysis of CMP gathers was performed every 100 m along every 10th in-line profile (or 1.0 km cross-line

spacing). To enhance deeper events such as Moho reflections, only source–receiver offsets up to 2,300 m were stacked down to 5.0 s two-way travel time, with greater ranges included up to 3,100 m below this time horizon in a tapered fashion. This muting strategy was used to minimize strong reverberations within layer 2A, which can potentially mask weaker, underlying Moho reflections. Seafloor multiples were digitized and muted to avoid artefacts during the migration or imaging sequence.

A two-pass Kirchoff time migration was performed using 95% of the stacking velocity. First, a two-dimensional in-line migration operation was performed, which allowed the focusing of energy in the up-dip in-line direction. To reduce the spatial aliasing effect in the cross-line direction, the data were then interpolated onto a 25 m by 25 m grid. Finally, a two-dimensional cross-line direction. This processing sequence is significantly different in several respects from that of ref. 4, which was focused on enhancing signals for layer 2A and magma-chamber reflections, whereas 2D dip-moveout, far-offset muting and Kirchoff migration, when combined, provided a better low-frequency imaging tool for deeper reflections such as the Moho.

Amplitude variation with offset analysis. The AVO analysis was performed using the same basic processing scheme presented by ref. 4, but modified to select specific source–receiver ranges to produce complementary range-gated images. Following the methodology of ref. 15, energy reflecting from the magma sill was processed in a parallel fashion for source–receiver offsets below and above \sim 1,625 m, which effectively isolates reflections from a mushy sill on the outer half of the streamer. For a melt-rich sill, the inability to transmit shear-wave (S-wave) energy across this body results in a precipitous drop in P-wave reflection amplitude, with minimal values in a range band extending from \sim 2 to 3 km. Conversely, a crystal-rich sill capable of supporting S-wave propagation is characterized by only a slight decrease in reflection amplitudes for ranges extending from \sim 0 to 3 km.

Next, these two AVO images can be combined to highlight areas of the magma sill that can or cannot transmit S-wave energy (or melt-rich or mushy); for example, if the image from the outer half of the streamer is layered on top of the inner half, wherever the magma body is crystal-rich, that particular image (outer half) will essentially mask energy from the inner half of the streamer. Correspondingly, for a melt-rich sill, there will be very little energy in this outer band, so only the inner-half image is visible. With an appropriate use of complementary colour palettes for both images, variations in magma sill properties can easily be shown.

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