Sub-Lithospheric Small-Scale Convection Tomographically Imaged Beneath the Pacific Plate

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Key Points:

- A broadband OBS array in the equatorial Pacific allows P-wave imaging of the uppermost mantle in a region of elongated gravity anomalies
- We observe elongated P-wave velocity anomalies of order ±2% beneath the oceanic lithosphere, striking parallel to gravity lineations
- These anomalies are inferred to arise from small scale convective cells beneath the plate with planform parallel to absolute plate motion

Key words:
Oceanic lithosphere
Asthenosphere
Mantle convection
Body wave tomography
Ocean Bottom Seismometer

Abstract

Small-scale convection beneath the oceanic plates has been invoked to explain off-axis non-plume volcanism, departure from simple seafloor depth-age relationships, and intraplate gravity lineations. We deployed thirty broadband OBS stations on ~40 Ma seafloor in the equatorial Pacific, in a region notable for gravity anomalies measured by satellite altimetry elongated in the direction of plate motion. P-wave teleseismic tomography reveals alternating upper mantle velocity anomalies on the order of ±2%, oriented parallel to the gravity lineations. These features, which correspond to ~300-500 ˚K lateral temperature contrast, and possible hydrous or carbonatitic partial melt, are strongest between 150 and 260 km depth, indicating rapid vertical motions through a low-viscosity asthenospheric channel. Coherence and admittance analysis using new multibeam bathymetry soundings substantiates the presence of asthenospheric density variation, and forward modelling predicts gravity anomalies that qualitatively match observed lineations. This study provides observational support for small-scale convective rolls beneath the oceanic plates.

Plain Language Summary

Covered by kilometers of water, and therefore hard to access, Earth's oceanic tectonic plates have several features we cannot explain. Among these are linear undulations ("rolls") in the strength of gravity at the sea surface. Using data from a rare underwater seismic experiment, we have produced 3-D maps of seismic properties of Earth's sub-surface in a location of clear gravity rolls. We find linear blobs of fast and slow material in the mantle beneath the oceanic plate, parallel to the gravity features. These represent cold sinking and warmer rising material, revealing a highly dynamic convective system underneath the plate which has long been theorized but not previously directly observed at this scale.

1. Introduction

Traditional plate tectonic models fail to explain several aspects of the oceanic lithosphere. For instance, widespread off-axis, non-plume volcanism within the Pacific plate has unknown origin (Ballmer et al., 2009; D. T. Sandwell et al., 1995), while the depth-age relationship predicted by lithospheric conductive cooling models breaks down in old (>70 Ma) ocean plates with anomalously shallow seafloor topography and high heat flow (Crosby et al., 2006; Parsons & Sclater, 1977; Parsons & McKenzie, 1978; Stein & Stein, 1992). Sub-lithospheric small scale convection (SSC) (Ballmer et al., 2007; Buck, 1985; Haxby & Weissel, 1986) has been proposed to explain these phenomena. This dynamic process, which is favored by a thicker, lower-viscosity asthenospheric layer, would increase the heat flow at the base of the lithospheric thermal boundary layer, and could concentrate upwellings and consequent melting. SSC spontaneously develops in the upper mantle due to the instabilities at the base of lithosphere whenever its thickness exceeds a critical value (Ballmer et al., 2007; Buck & Parmentier, 1986). It is expected to take the form of convective rolls aligned with absolute plate motion (APM) (Buck & Parmentier, 1986; Richter & Parsons, 1975) (Fig. 1b) due to shear between the plate and the deeper mantle. Despite the geodynamic significance of SSC beneath the oceanic plates, it has never previously been directly imaged at length scales <~2000 km (French et al., 2013) with seismic tomography beneath mature oceanic plate.

To date, the most powerful argument for widespread SSC beneath the plates are free air gravity lineations observed in the oceans, aligned parallel to APM and with wavelength of ~150-400 km, comparable to SSC predictions (Haxby & Weissel, 1986). Others have proposed alternative explanations for these gravity anomalies, including mechanical modification of the lithosphere and viscous fingering (Bull et al., 1992; Cormier et al., 2011; Gans et al., 2003; Sandwell & Fialko, 2004; Sandwell et al., 1995). Lithospheric boudinage (non-linear lithospheric extension) or thermal contraction bending (Fig. 1b) can produce elongated topographic and gravity undulations. Associated cracking might provide conduits for upward percolation of preexisting asthenospheric melt to form volcanic ridges; in this case the drainage of melt might lead to shallow high-velocity anomalies beneath the ridges (Karato & Jung, 1998). Viscous fingering, caused by lateral intrusion of low-viscosity material within a thin asthenospheric channel (Fig. 1b) has also been proposed to explain spreading-aligned ridge-adjacent seamounts, gravity variation, and long-wavelength velocity anomalies beneath young seafloor (Holmes et al., 2007; Weeraratne et al., 2007). Our study area is in older seafloor in a region with no volcanic ridges or major seamounts. Notably, gravity lineations here obliquely cross fracture zones (that record fossilized relative plate motion), suggesting they are not inherited from the mid-ocean ridges.

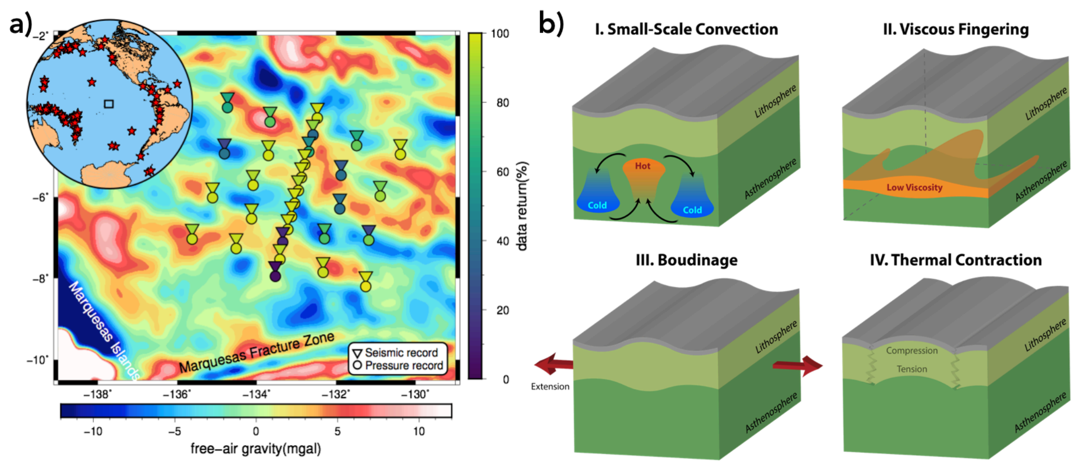

Fig. 1 | Map of the research area (a) and schematics of candidate processes causing gravity lineations (b). a*, Broadband OBS array comprising three-component seismometers (triangles) with differential pressure gauge (circles). Symbol colors indicate fractional data return, and the underlying map shows filtered free air gravity anomalies (Figure S9). Inset shows location of the array, with stars representing earthquakes from which differential travel times were measured.* ***b****, Block diagrams showing exaggerated lithospheric and asthenospheric structures proposed to explain free air gravity undulations (adapted after Weeraratne et al., 2007). Any bathymetric anomalies, exaggerated here, are highly contingent on elastic thickness of the lithosphere.*

Discriminating the above hypotheses requires tomographic resolution of features with <200 km lateral wavelength in the upper mantle, together with high-precision local constraints on bathymetry. Sparse island stations and ocean basin-traversing seismic rays offer only coarse imaging of the oceanic upper mantle. A previous study, the GLIMPSE Ocean Bottom Seismometer (OBS) experiment (Forsyth et al., 2006) aimed to probe gravity lineations in ~2-10 Ma Pacific plate just west of the East Pacific Rise (EPR). Body (Harmon et al., 2007) and Rayleigh wave (Weeraratne et al., 2007) imaging revealed elongate low velocity lineaments beneath volcanic ridges with lateral wavelength of order ~250 km. Substantial data loss precluded fine depth resolution with body waves, but velocity variation was estimated using surface waves to reside at <70 km depth. No other OBS experiments before or since have imaged uppermost mantle 3-D isotropic wave speed variations suggestive of small scale convection in regions unperturbed by plume or other intra- or inter-plate volcanic activity.

2. Data

The Pacific OBS Research into Convecting Asthenosphere (ORCA) experiment (Eilon et al., 2022) deployed 30 OBS instruments across a 500x500 km^2 footprint on ~40 Ma lithosphere northeast of Marquesas Islands. These instruments, deployed for 13 months, included three-component broadband seismometers and differential pressure gauges. The array was oriented approximately orthogonal to ±15 mGal free air gravity lineations observed from Seasat altimetry (Haxby & Weissel, 1986), with aperture spanning 2-3 wavelengths (~500 km) of the gravity rolls (Fig. 1a). This experiment also collected new high-resolution multibeam swath data which has been integrated into the global seafloor database (Smith & Sandwell, 1997) to provide substantially better constrained bathymetry in this region.

We extracted the vertical seismic and pressure waveforms for P-wave arrivals recorded on the ORCA array from teleseismic events (>30° distance; Fig. 1) in the GCMT catalogue between April 2018 and May 2019 with moment magnitudes ≥5.5. For each event, we measured relative arrival times of direct *P*-waves using multi-channel cross-correlation (MCCC; Fig. S1) (VanDecar & Crosson, 1990) on vertical and pressure records independently, yielding 1096 and 598 differential travel times respectively. We combined these data (see *Supporting Information*) to yield 1196 high-quality P-wave travel times (Supp. Fig. 2a).

3. Methods

We inverted these differential travel times for 3-D upper mantle *P*-wave velocity perturbations (δV_p) using a finite frequency tomography approach. To regularize the inverse problem we applied both model norm damping and first derivative damping (*i.e.*, “flattening”) with a horizontal-to-vertical smoothing ratio of 2. We weighted observations by estimating travel time errors *a* *posteriori* during the MCCC process. To avoid unrealistically low estimated errors, we set a minimum standard deviation of 0.625s, equal to 1/20 of the central filter period. We solved for station and event static terms. Optimal regularization parameter values were determined by L-test. For a much more comprehensive description of the inverse problem, see the *Supporting Information*.

To explore apparent lineations in observed velocity structure, we conducted a series of "2.5-D" inversions by enforcing flattening (*i.e.*, no model variation) along a single horizontal direction, seeking a lineation direction that minimized data misfit. We also evaluated the resolution and reliability of our inversion through input-output tests that included checkerboard structures (Fig. S5) and velocity lineations that mimic features of dynamical interest (Fig. S4). For checkerboard tests, we quantify feature recovery using semblance (Zelt, 1998) computed at each point over a 3-D volume with radius equal to checker length scale. Finally, we performed a suite of inversions for which the model nodes below and above various "squeezing depths" were heavily damped. By evaluating the fractional reduction in overall data fit for each squeezed case, and observing whether or not the inversion re-injects structure once the damping is relaxed (see *Supporting Information*), we determined the depth range over which the data require major velocity anomalies.

4. Results

4.1 Tomographic inversion

Simple thermal cooling models predict essentially no upper mantle velocity heterogeneity on the length scale of this array. Nonetheless, we measured differential arrival times of up to ±0.5s (with an RMS of 0.27 s). This travel time variance substantially exceeds signal that can be produced in the crust, and systematic back azimuthal variations seen at several stations confirm this signal to have an upper mantle origin (Figure S2).

Our tomographic model shows substantial upper-mantle velocity structure. The most prominent pattern in the 3D model (Fig. 2) is alternating velocity anomaly bands parallel to local gravity lineations, with lateral wavelength ~250-300 km. The amplitude of these anomalies is on the order of ±2% (±2.3% for the 1-99 percentiles, or ±1.8% for the 2.5-97.5 percentiles, in the best resolved regions; Fig. S8). For our preferred model, the final RMS data error was 0.23s, the RMS of event static values was 0.10 s and the RMS of station static values was 0.01 s. The weighted variance reduction was 85.29%, indicating good data fit.

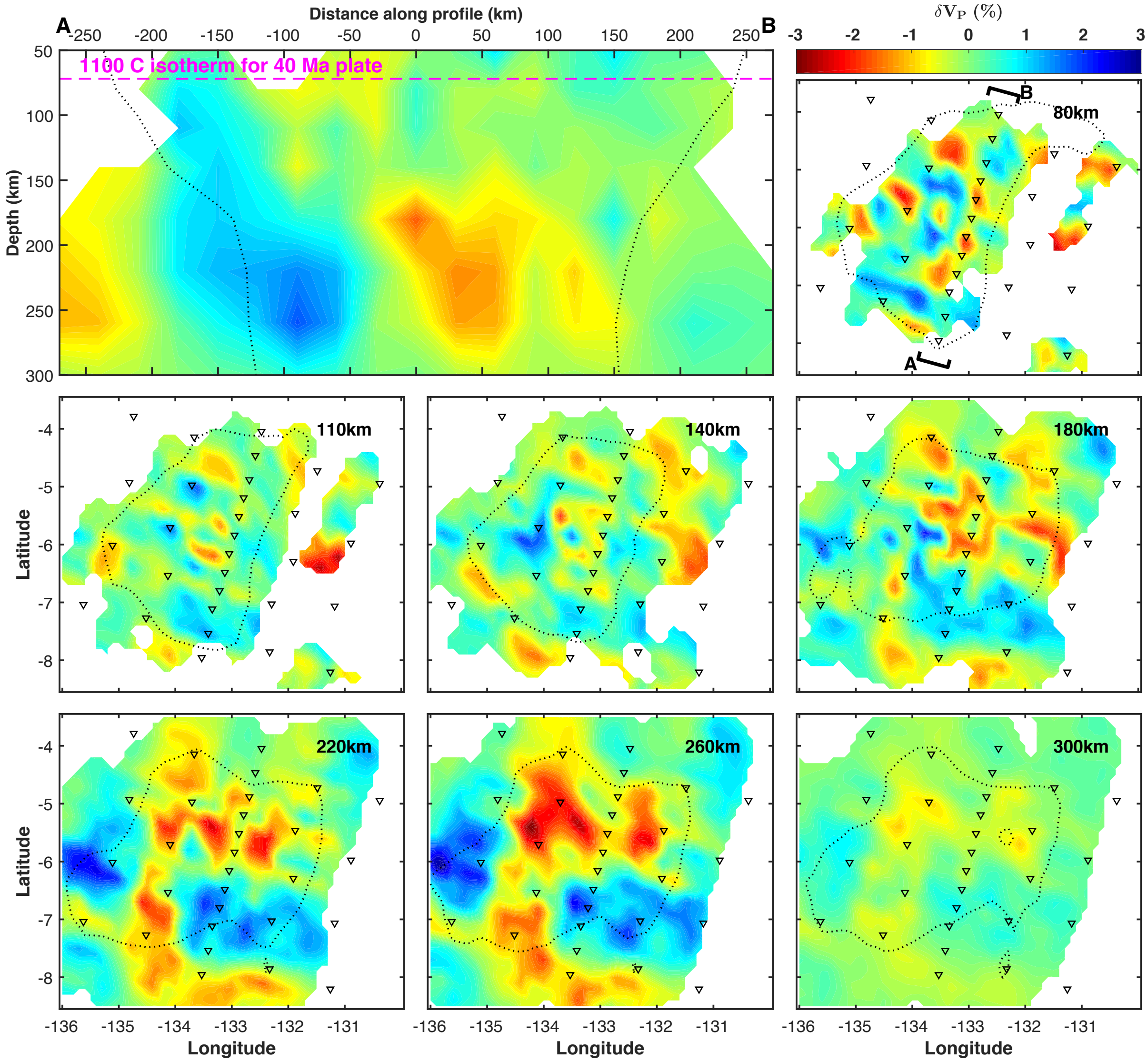

Fig. 2 | The tomographic model. *A vertical slice (top left) and several horizontal slices through our preferred 3-D δV_p model, where structure is shown only for model nodes with 'hit quality'* (Eilon et al., 2015) *above 0.3. Black dotted line shows region with semblance (a measure of checkerboard recovery* (Zelt, 1998)*) greater than 0.7. The vertical section depicts values averaged ±30 km in the direction perpendicular to the line of the section (indicated by black brackets in the 80 km depth cross-section), to avoid overly emphasizing any particular plane.*

4.2 Testing the model

2.5-D inversions to test for preferred lineation (Figs. 3, S7) showed that best fit to data (78% as good as the full 3-D model) involves structure elongated in the 115° direction (Fig. 3b). We infer that this direction reflects the dominant structural elongation. This orientation is subparallel to (independently constrained) gravity lineations and local absolute plate motion. Note, this minimum-misfit 2.5-D model (Fig. 3b) was used to compute 1-D gravity variations (Fig. 4).

Synthetic tests indicated that our data coverage can indeed recover the geometry and position of the observed features (Fig. 3, S4, S5). These tests – especially at the model edges – suffer from as much as 40% amplitude loss due to sparse seismic ray coverage. This observation, typical for these sorts of regularized inversions, theoretically implies that observed velocity, and hence inferred temperature, contrasts are in fact lower bounds.

We individually tested shallow squeezing and deep squeezing, finding that the data require relatively deep anomalies: at least 140km, and as much as 300 km in depth (Figs. S4, S6). We attempted to quantitatively determine the optimal depth range for the most prominent mantle velocity anomalies by squeezing structure into a moving window of three model layers (Fig. 3). These tests showed that the data require the most prominent anomalies to be fit by structure within the 180-260km depth range. This finding is not particular to a three-layer test; similar two- and four-layer tests confirmed that the 140-260 km depths are most important to fitting the data. This finding does not preclude structure at other depths in the model, rather it indicates that velocity anomalies in this depth range have the greatest influence on measured travel times. Lastly, we explored the depth extent of imaged features by increasing the model base to 480 km (Fig. S6). We found that although some structure is smeared to depths >300 km, the pattern of the anomalies is extremely similar to the preferred model, and the strongest anomalies are still present in the 150-300 km depth range.

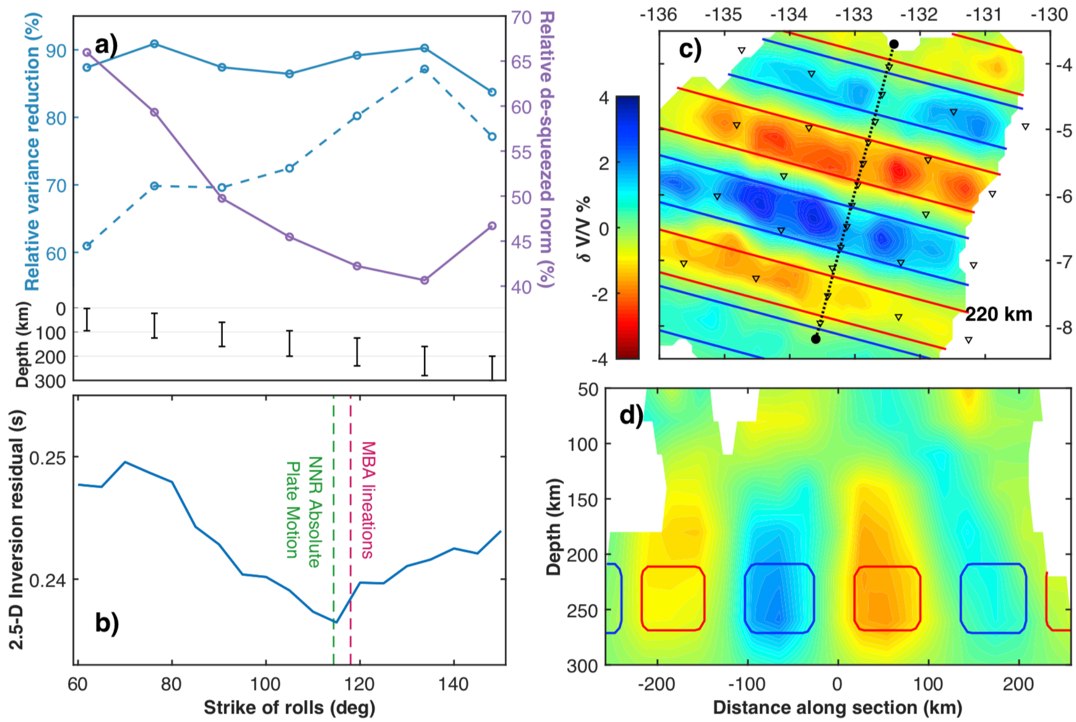

Fig. 3 | Tests of the tomographic model. a) *Squeezing tests of anomaly depth. Lower subplot shows depth extent over which structure was allowed to enter into the model space, while upper subplot shows data fit (measured by variance reduction – high values indicate better data fit) and explanatory power of the un-squeezed region of model space (purple line; low values indicate the squeezed model does a better job of explaining the data) for the associated models. Variance reduction is plotted relative to the un-damped, preferred, model. De-squeezed model norm is plotted relative to the norm of the squeezed model in each iteration and can thus be thought of as fractional model addition once squeezing is relaxed.* ***b)*** *Tests of feature elongation direction, showing data misfit (residual) when grid searching through possible orientations of 2.5-D models.* ***c)*** *Horizontal slice and* ***d)*** *vertical section through models yielded by synthetic recovery tests with input rectangular velocity anomalies (dashed lines) of ±4%.*

4.3 Gravity signals

The ORCA experiment measured high-resolution multibeam topography throughout the OBS array footprint, allowing for detailed comparison with gravity (Fig. S9). To identify subsurface density heterogeneity, we computed free air coherence and admittance, and the theoretical mantle Bouguer anomaly (MBA; see *Supporting Information*). At wavelengths greater than 20 km, observed free air admittance in this region is approximately 0.025 mGal/m. This value is substantially less than the theoretical admittance for uncompensated topography, but also significantly greater than the prediction for topography compensated at the Moho (Fig. S10).

5. Discussion and conclusions

5.1 Thermal anomalies

The tomographic models show alternating slow and fast δV_p features within the oceanic asthenosphere. We infer that these features result from hot upwellings and cold downwellings, respectively. These cells take the approximate form of cylindrical rolls, with horizontal length scale ~250-300 km and aspect ratio approximately unity. These features are not consistent with lithospheric warping (boudinage or cracking), which predict negligible, and certainly not >200 km deep, upper-mantle velocity variations. They are also not consistent with viscous fingering, which would require velocity variations confined to a shallow (<100 km deep) and thin (<30 km thick) channel (Weeraratne & Parmentier, pers. comm.) Rather, these observations provide the first tomographic evidence for small-length-scale thermal convection beneath the oceanic plates, aligned by shear between the plate and underlying deeper mantle.

Differential travel time tomography provides constraints only on lateral velocity gradients, not absolute velocity. The ~4% peak-to-peak amplitude of the observed velocity anomalies is relatively high. Absent melt, this implies up to ~ 500˚C lateral temperature variations (see *Supporting Information*; Fig. S8). Our default expectation is that SSC is driven here by positive density anomalies that drip or sink from the base of the lithospheric thermal boundary layer. In this framework, the fast *dVp* anomalies correspond to material that is cold in an absolute sense, while the slow *dVp* anomalies represent relatively warm ambient mantle.

However, upwelling parcels displaced by the downwellings must undergo adiabatic decompression. If the mantle contains dissolved volatiles, this upwelling material could produce small-fraction hydrous and/or carbonatitic melt fraction even at depths up to 200 km (Dasgupta et al., 2013; Hirschmann, 2010). Melting could introduce a small active component to upwellings by reducing density and viscosity. Melt would also lower the absolute P-wave velocity in the upwelling cells. Accounting for both elastic and anelastic effects (see *Supporting Information*), the observed peak-to-peak *dVp* variation can also be explained by a 0.5% melt fraction, together with a *dT* of ~ 300˚C (Fig. S8). We prefer this latter (temperature plus melt) scenario for explaining observed anomalies, since the implied temperature gradient is more consistent with (although still greater than) the temperature contrast invoked in numerical models of sub-lithospheric SSC (Ballmer et al., 2009; Manjón-Cabeza Córdoba & Ballmer, 2021). This same analysis predicts a Q_{μ} of 100-180 in the oceanic asthenosphere, consistent with previous observations (Ma et al., 2020).

5.2 Gravity analysis and modelling

A closer examination of observed gravity anomalies provides further insight. Free air admittance indicates some degree of isostatic compensation here. Remaining support for bathymetry must come from plate strength, in line with previous >15 km estimates of effective elastic thickness here (Fischer et al., 1986).

The observed compensation must result from some combination of crustal thickness variations and upper mantle density anomalies. Three primary observations suggest a substantial influence from the upper mantle. Firstly, MBA anomalies here (striking ~120˚) are oriented sub-parallel to plate motion (~115˚), rather than the paleo-spreading direction inferred from abyssal hill fabric and nearby fracture zones (~75˚, although we do note a due E-W swath of seafloor in this region with ~105˚ apparent spreading direction indicated by the trend of the abyssal hill topography (Eilon et al., 2022), perhaps due to oblique spreading, a ridge jump or large overlapping spreading center). Secondly, if the observed gravity and bathymetry anomalies were created from a single mechanism then the coherence should be unity. We observe coherence lower than 0.7 associated with the longest-wavelengths (Fig. S10). Finally, the predicted free air anomaly for compensation at Moho depths under-predicts the admittance, requiring either deeper compensation or density anomalies beneath an elastic plate with flexural rigidity that dampens the topographic expression. Our inference is that multiple mechanisms are at play here, pointing to the loading of a finite-rigidity plate from below as a result of density variations in the mantle, in addition to “frozen-in” partial compensation of the topographic relief by variations in crustal thickness.

As a proof-of-concept, we explored the correspondence between the MBA and our velocity model. For simplicity, and given the strongly linear features in both models, we collapsed the MBA to 1.5 dimensions (*i.e.*, varying in the roll-perpendicular-direction but homogenous in the roll-parallel-direction), using a log-spaced sinusoidal basis. The best fit 1.5-D gravity field (explaining 28% of the full 2-D signal) comprises lineations aligned 118˚ from North. We compare this gravity anomaly to the 2.5-D velocity model smoothed in the same direction, considering dV_P variations only in the plane defined by the vertical and the direction perpendicular to the gravity rolls (Fig. 4). There is no direct association between the pattern of deep (200-300 km) dV_P anomalies and the residual gravity, other than similarity in their wavelength (225-300 km) of variation and orientation of the lineations. This is not surprising: periodic density anomalies at depth approximately equal to their wavelength should negligibly affect surface gravity due to upward continuation. However, using our 2.5-D tomography model to forward calculate 1.5-D gravity variations (see *Supporting Information*, and note this calculation used the more modest temperature variation outlined above, adding support to that scenario), we found good qualitative match between observed and predicted signal, where the predicted signal is dominated by the shallowest features in the velocity model (Fig. 4). Although this portion of the model is not as well resolved, the agreement is striking and demonstrates that mantle temperature heterogeneity alone can theoretically explain the MBA gravity anomaly.

5.3 Asthenospheric rheology

The depth, vertical extent, and wavelength of putative convective features imaged in this study connect to the rheology of the asthenosphere. The presumed source of convective instability, is near the base of the plate. For 40 Ma oceans (assuming mantle potential temperature, T_m, of 1350˚C and thermal diffusivity of 10^{-6} m^2/s), the depth to the 1150˚C isotherm (the 0.85 $T_m$value often used to approximate the thermal lithosphere-asthenosphere boundary) is 73 km. The agreement between the strike of the rolls and local APM in a no-net rotation reference frame (DeMets et al., 2010), together with the lack of another obvious alternative source for small-scale lateral thermal gradients, argues that these features are not deep-rooted but derive from convective processes near the bottom of the plate. Station spacing limits our resolution shallower than ~50 km, but synthetic recovery tests indicate that we should have imaged large-scale velocity anomalies in the 100-200 km depth range, if they were present (Figs. S4, S5). It is surprising, then, that the strongest velocity features in the model are as deep as 250 km and that squeezing tests suggest that the strongest anomalies are deeper than 200 km (Fig. 3).

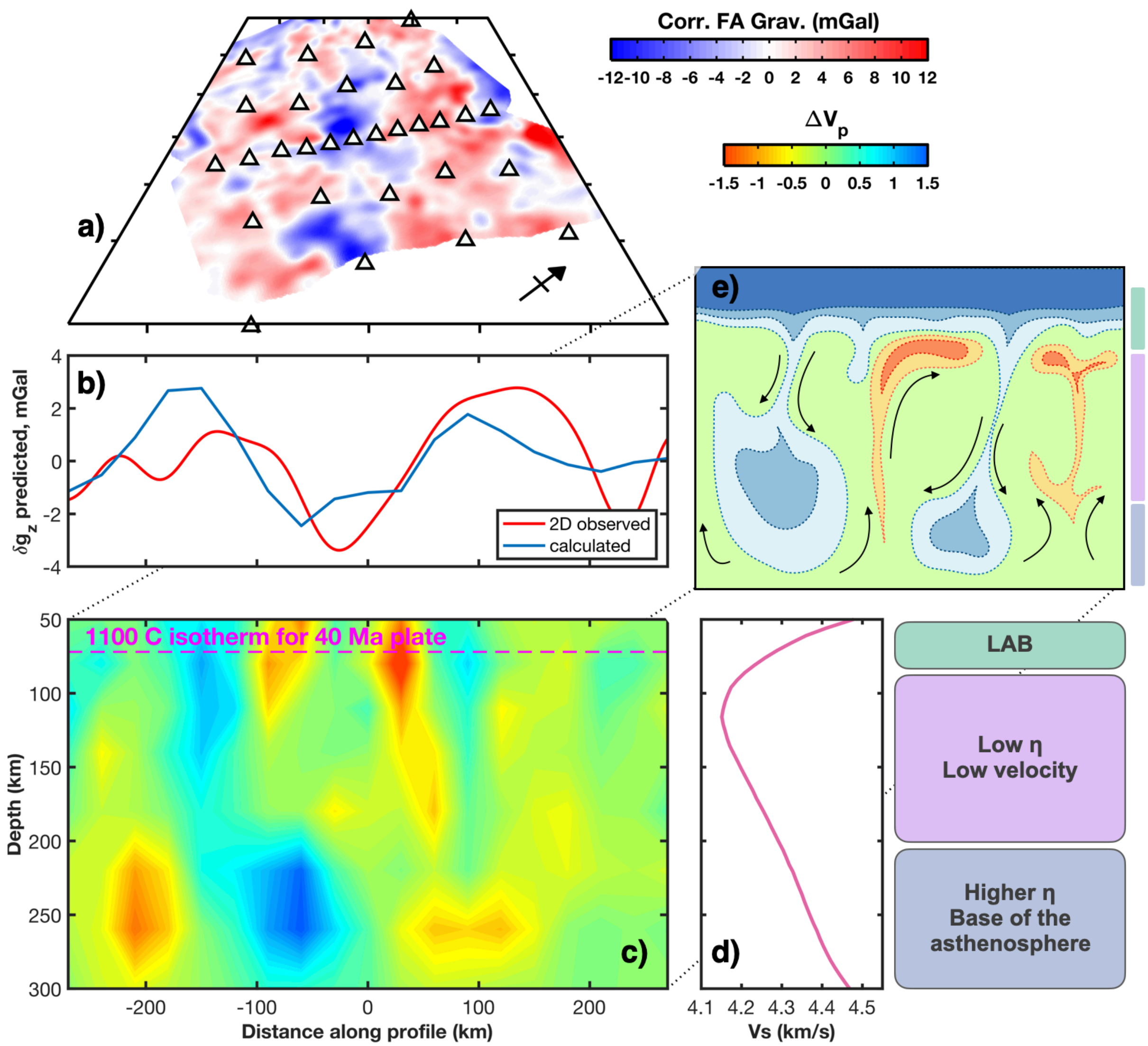

Fig. 4 | Dynamic summary and comparison between gravity and tomography. a) *Mantle Bouguer gravity anomaly corrected for effects of bathymetry and filtered as in Fig. S9.* ***b)*** *One-dimensional variation in gravity anomaly obtained from sinusoidal fitting of observed field (red) and velocity-temperature-density forward modelling (blue) of the model depicted in panel (c). The orientation of the section is ~30˚ east of North.* ***c)*** *Cross section through the 2.5-D velocity model,* *perpendicular to enforced smoothing direction.* ***d)*** *1-D shear velocity profile obtained from inversion of Rayleigh wave phase velocities averaged across ORCA array* (Russell, 2021). ***e)*** *Cartoon cross-section of small scale convection beneath the plate, where bluer colors correspond to colder and more dense material and redder colors correspond to hotter and less dense material.*

A comparison between Rayleigh wave imaging at young ORCA and NoMelt (70 Ma crust) indicates that the young ORCA region exhibits anomalously slow absolute shear velocity beneath the plate (Fig. 4), with a broad velocity minimum from 75-200 km depth (Russell et al., 2021). Small scale convection is favored by a wider low viscosity layer, and the middle of this layer is expected to be roughly isothermal. Our observed anomalies appear deeper than the slowest (and presumably weakest) part of the asthenosphere. It is possible that density anomalies are preserved at lithospheric levels (<100 km depth) and deeper than 200 km due to higher viscosity, while the lowest-viscosity portion of the asthenosphere is roughly isothermal and contains convective structures too fine to resolve. A similar mechanism has been suggested to explain a minimum in the strength of azimuthal anisotropy in the center of the oceanic asthenosphere observed by other focused OBS arrays (Lin et al., 2016; Russell et al., 2019).

This suite of observations suggests a sub-lithospheric SSC system wherein the gravity and velocity anomalies correspond to the upper and lower thermal boundary layers of an asthenosphere-scale convective system, respectively. We posit three depth regimes (Fig 4): 1) The base of the plate (50-100 km), the source of the density instabilities and part of the Bouguer gravity anomalies. The elastic lithosphere partially damps the effect on bathymetry. 2) The low-viscosity center of the asthenosphere (100-200 km), coinciding with the lowest velocities in a surface-wave-derived 1-D shear velocity model (Fig. 4). Imaged anomalies in this regime are minimal, despite good resolving power. We infer that once an instability develops, it sinks rapidly through the low viscosity asthenosphere (Ballmer et al., 2009), perhaps leaving behind thin convective sheets or spokes connecting regimes (1) and (3) that are too narrow to be imaged tomographically. 3) A higher viscosity base of the asthenosphere (200-300 km), where high-density anomalies encounter resistance to sinking and pile up, making for clearly imaged velocity anomalies. Ambient mantle displaced upwards at this depth begins to melt (requiring volatiles to reduce the solidus (Dasgupta et al., 2013; Hirschmann, 2010)), reducing seismic velocities in the upwelling volumes between the downwelling limbs.

This work provides evidence for a highly dynamic asthenospheric system beneath the central oceanic plates, involving small scale lithospheric delamination, and small-fraction hydrous and/or carbonatite melt. Since intraplate volcanism is not ubiquitous in the oceans, upward pathways for melt transport through the lithosphere must be rare. Rather, this melt may pond or freeze in laminae at the base of the plate, contributing to a sharp and possibly radially anisotropic LAB structure observed widely in the Pacific (Beghein et al., 2014; Kawakatsu et al., 2009; Stern et al., 2015). In addition, SSC might introduce uneven topography on the LAB that is not a simple function of age. Together, these phenomena help explain the variability in seismic discontinuities in the uppermost (<100 km depth) oceanic mantle (Schmerr, 2012; Tharimena et al., 2017).

Acknowledgments

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Open Research: Data and code availability

The seismic data from this experiment are available through the Incorporated Research Institutions for Seismology's Data Management Center, under the network code XE (2018-2019). Metadata information is catalogued within Eilon et al. (2022) (DOI 10.1785/0220210173). Multibeam swath bathymetry data is available via the Rolling Deck to Repository portal (DOIs 10.7284/907958 and 10.7284/908257). Free air gravity data is available at https://topex.ucsd.edu/pub/global_grav_1min/ and bathymetry at https://topex.ucsd.edu/pub/global_topo_1min. Codes for all the analysis and figures above are provided via a Dryad repository [#DOI insert available after submission#].

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