# Response to Comment on "Mantle Flow Drives the Subsidence of Oceanic Plates"

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Croon *et al.* challenge our conclusion that sea-floor depth variations are driven by the underlying mantle convection. We point out that, contrary to their claim, our data analysis is pertinent and that the sea-floor linear trend as the square root of the distance from the ridge is a robust observation. The mechanism responsible for this trend is an asthenospheric flow, faster than the overlying plate, which shapes the lithosphere structure.

Even if it is widely accepted that mantle convection exists, its causes and consequences are still subject to debate. We investigated the subsidence of the oceanic lithosphere and proposed, based on the sea-floor depth analysis, that it is driven by the underlying mantle convection (*1*). This approach, different from previous studies, is strongly criticized by Croon *et al.* (*2*). Here, we provide answers to what they contend are shortcomings of our work.

Croon *et al.* first claim that our flow lines do not match the trajectories of our illustrative profiles. Our computation was based on the velocity grid obtained through the UNAVCO Plate Motion Calculator Site (*1*), for the NUVEL-1A kinematics model, in the No Net Rotation reference frame. We doubled-checked our trajectories estimation by refining the velocity grid step down to 10 km. We confirm that the trajectories shown in (*1*)—very similar to Croon *et al.*'s in the northern part—are correct. We would appreciate a deeper comparison between the methods in order to understand where the discrepancy comes from.

We agree that one of the major problems when studying the sea-floor thermal subsidence is to remove from its topography all data that could be linked to any different process. In other words, "The central problem is in satisfactorily defining normal" (*3*). Many methods have been proposed to remove abnormal sea floor from the data sets, from statistics (*4*) to manual removal of topography (*5*). As pointed out by Kim and Wessel (*6*), robust methods for filtering the bathymetry do exist, but in any case, the use of a median filter alone is inadequate for removing the shallow topographic features. This point has been clearly demonstrated by several authors, including the authors of the comment (*7*). Indeed, the median filter has "a tendency to pass through topography" (*7*). It tends to overestimate the sea-floor main trend, especially at old ages where these features are statistically concentrated (*8*), thus introducing an apparent "flattening." This artifact is enhanced by stacking the profiles [see figure 2A in (*2*)].

In our study (*1*), we did not attempt to remove any "abnormal" sea floor on purpose. Because the wavelength of the intraplate anomalies is much shorter than the subsidence trend, they did not interfere with its visual determination (*1*). In Fig. 1, we show that, by using a method based on an adequate bathymetry filtering, the MiFil method (*9*), the trend can be automatically recovered in a reproducible way. The results from this method are in good agreement with our previous fit.

The discussion of Croon *et al.* (*2*) on the short wavelength features crossed by our profiles may be interesting for the general knowledge of the Pacific geological features but is irrelevant for the present study. Indeed, contrary to their claim, we did not retain these features in our analysis, as explained in (*1*). Our subsidence trend describes accurately the sea-floor basement. Negative departures correspond to fracture zones. The shallow features appear clearly above the main trend (yellow areas in Fig. 1).

The *xx*′ profile is located close to the transition zone, where the length of the mantle convective cell (distance ridge-trench) jumps from 7000 km (south) to more than 14,000 km (north). Strong perturbations in the convection pattern are expected in this area, which could explain the departures from the main subsidence trend. Still, we roughly recover the general trend (*xx*′, Fig. 1). The main difference with Croon *et al.*'s analysis likely originates from the discrepancy in the trajectories computation.

To account for the local variations in ridge height and subsidence rate, it is indispensable to consider single profiles. Stacking the profiles, as Croon *et al.* (*2*) did, impedes any physical interpretation of the regional variations of the subsidence parameters. These variations are generally interpreted in terms of active mantle processes. However, they are ignored by these authors, who precisely claim their importance for understanding the lithosphere/asthenosphere interaction.

Another purported shortcoming pointed out by Croon *et al.* is the lack of a physical mechanism that could support our assertion. Here, we discuss a mechanism through which the large-scale convection—with no additional heat supply at old ages—shapes the lithosphere structure. This requires an asthenospheric flow faster than the overlying lithosphere (Fig. 2). This scenario is realistic if one considers the resistive forces acting at the trenches, already discussed by several authors (*10*–*12*). In particular, Höink and Lenardic demonstrated that a "sluggish" lid mode, where asthenospheric velocities exceed surface velocities, is a robust scenario for plate tectonics (*12*). The presence of a low-viscosity layer at the base of the lithosphere leads to the channelization of the flow in the asthenosphere, which affects the lithospheric thermal structure, all over the plate.

Assuming the existence of an asthenospheric flow faster than the lithosphere, it is possible to develop an analytical model, which quantitatively assesses how this flow shapes the lithosphere structure. If, contrary to Höink and Lenardic's model (*12*), we do not consider a Poiseuille-Couette flow in the asthenosphere, but a velocity profile $v \sim \omega z^{\alpha}$, where $\alpha \rightarrow 0$, then the velocity in the asthenosphere is constant over most of its depth, with a thin upper boundary layer (Fig. 2), and the term $v \cdot \vec{\nabla} T$ is predominant to determine the asthenospheric temperature field. The choice of the asthenospheric flow structure determines the shape of the overlying lithosphere, which, in this case, scales as the square root of the distance from the ridge. This choice is obviously not unique but provides a plausible explanation for the sea-floor depth observations.

Höink and Lenardic (*12*) showed that the asthenospheric flow characteristics depend on the plate geometry and boundaries. If these characteristics allow an asthenospheric flow faster than the lithosphere for the Pacific, this may not be the case for the other tectonic plates.

In conclusion, we agree with Croon *et al.* (*2*) that sea-floor depth yields important information on the thermal structure of the lithosphere and its interaction with the underlying asthenosphere. The data analysis, however, requires a more careful approach. The points developed above show that our data selection and analysis are pertinent. To account for the observed correlations, we propose that the asthenospheric flow, faster than the overlying lithosphere, shapes the structure of the plate. The variation of the sea-floor depth as the square root of the distance from the ridge along the flow lines is a robust observation and may help to discriminate among the many asthenospheric flow structures proposed in the literature.

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### References and Notes

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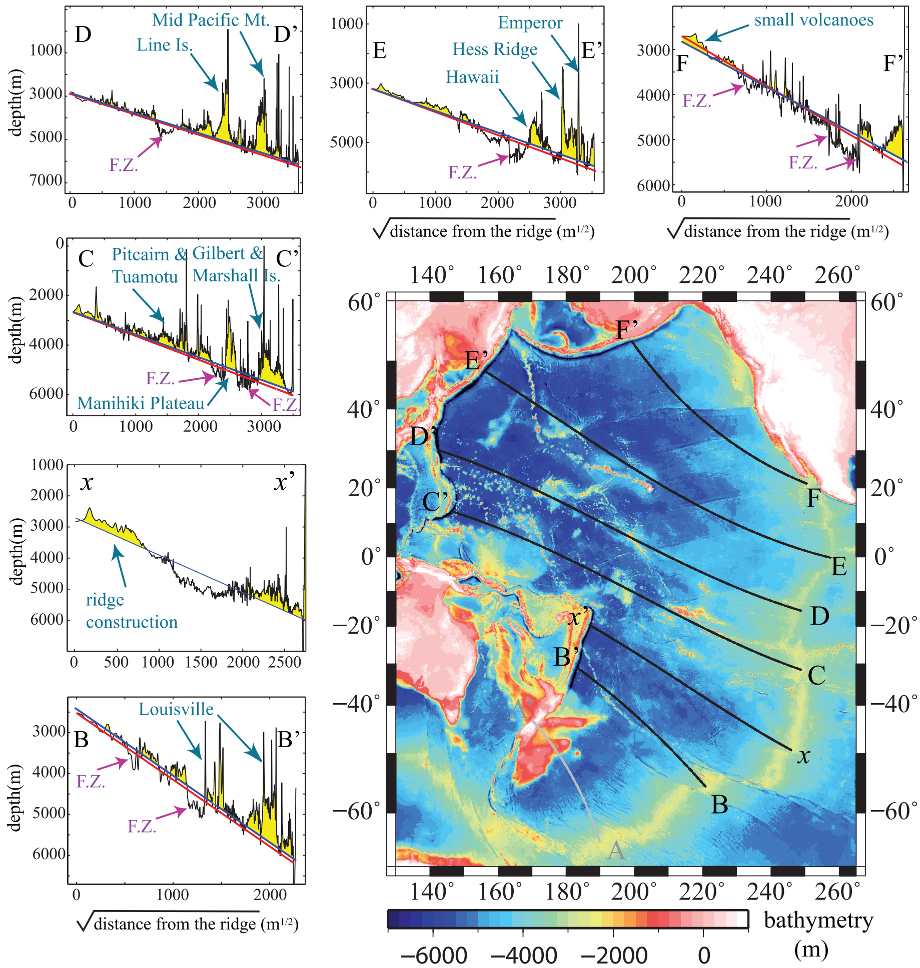


**Fig. 1.** (Large panel) Bathymetry of the Pacific plate corrected for sediment loading and flow lines (*1*). (Small panels) Profiles along the flow lines; in black, sea-floor depth as a function of the square root of the distance from the ridge; in red, linear trend $z \propto x^{1/2}$ visually recovered (*1*), in blue the new reproducible fit. To obtain the automatic fit, we first remove the general trend from the bathymetry profile. Indeed, the median filtering, involved in the second stage of the MiFil method (*9*) used here, is very sensitive to sloping trends. We then filter the depth anomaly (bathymetry, minus first linear fit in $x^{1/2}$) with the MiFil method ($r = 80$, 40, 150, 180, 120, and 40 km for BB′, *xx*′, CC′, DD′, EE′, and FF′, respectively, and $R = 4000$ km; the ridge proximity is filtered with $r = 5$ km and $R = 100$ km in all the profiles). We then add the filtered depth anomaly to the general trend we first determined and perform a second linear fit. This second fit is represented in blue. Arrows indicate the local geological features responsible for the departures from the linear trend (FZ, fracture zone). We highlight in yellow the shallow features (volcanoes, swells, superswell, and oceanic plateaus), which clearly stand upon the main subsidence trend.

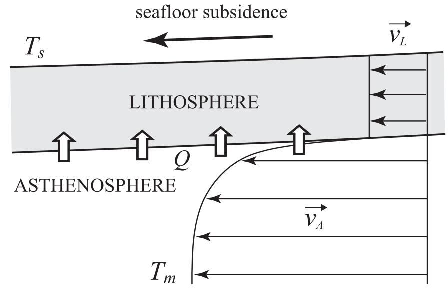


**Fig. 2.** Sketch of the lithosphere-asthenosphere interaction. In our model, the velocity in the asthenosphere is faster than the overlying plate and almost constant over the asthenosphere depth, except for a thin upper boundary layer. $T_s$ and $T_m$ indicate the seawater and mantle temperature, respectively. The heat flux $Q$ at the base of the lithosphere is imposed by the flow within the asthenosphere.

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