



Supporting Online Material for

Mantle Flow Drives the Subsidence of Oceanic Plates

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SUPPLEMENTARY ONLINE MATERIAL

1. Introduction

The manuscript presents six depth profiles, extracted from our analysis (Fig.1). We chose these profiles as the most representative of the different regions of the Pacific plate. However, our analysis has been made over more than 770 profiles, leading to a complete coverage of the Pacific plate. We use this coverage to estimate the profiles predicted by our model along age trajectories (Fig.2).

This supplementary online material presents the methods used to model the Pacific plate thermal subsidence along flow lines trajectories. We remind here that by ‘flow lines’, we intend the trajectories which are representative of the underlying mantle convection. This concept has to be opposed to the ‘age trajectories’, corresponding to the trajectories following an age gradient – traditionally used in previous subsidence models.

2. Hypothesis & Time scale

The lithosphere is defined as the thermal boundary layer of mantle convection. Its structure will thus evolve in order to adapt to any change in the underlying mantle convection – i.e., any change in the thermal conditions imposed at its base, along the entire plate. It will either thicken (respectively thin) if the temperature at its base, defined by the new convective system, is cooler (respectively hotter) than previously. Finally, after a time long enough, the lithosphere will tend toward the structure of the thermal boundary layer for the new underlying mantle flow (Fig.S1), independently of its initial state.

Changes in the lithosphere structure are driven by thermal conduction. A thickness variation d of the lithosphere requires a time dt given by the conduction equation: $dt=d^2/\kappa$. As an example, the time required to thicken (or thin) a lithospheric plate by 20 km would be about 12 Myr, with a thermal diffusivity $\kappa=1\text{ mm}^2\text{ s}^{-1}$.

The Pacific plate has undergone a drastic change in its motion, due to a large-scale rearrangement of the mantle convection 47-50 Myr ago. Its velocity has remained constant over the last 47-50 Myr, providing sufficient time for the lithosphere to adapt to the new thermal conditions. Since the Pacific plate has been in steady state for the last 50 Myr, the lithosphere thickness may have been modified by an amount of 40 km. It is therefore the best candidate to test our hypothesis.

3. Flow lines computation

Several kinematics models have been tested to compute the flow lines, representative of the present-day mantle convection: NUVEL-1A, GSRM, CGPS, ITRF, APKIM2000, and REVEL, recovered from the UNAVCO Plate Motion Site (*S1*). We chose the NNR (No Net Rotation) reference frame (*S2*), which we prefer to the hotspot frame. Indeed, the latter introduces too much uncertainty in plate velocity estimation (*S3*). Trajectories computed with the different models are very similar over the Pacific plate, especially near the ridge. As the results do not differ significantly from one model to the other, we present the results obtained with the NUVEL-1A model (*S4*) in the NNR reference frame. For each point of the EPR, we compute the trajectory along the corresponding flow line. Because ship soundings data do not provide continuous coverage over the Pacific plate, we use the predicted bathymetry of Smith & Sandwell 1997, version 8.2 (*S5*), corrected from sediment loading (compiled by the National Geophysical Data Center (NGDC)). The method for this correction is described in Adam et al. (2005) (*S6*).

We obtained and analyzed more than 770 profiles, representing the seafloor depth vs. the distance from the ridge, along flow lines. The high density of profiles leads to a complete coverage of the Pacific plate.

4. Subsidence parameters

The subsidence trend along each depth-distance profile (flow lines) is found by the following method. First, we choose the 'zero age' point as close as possible to the East Pacific Rise (EPR), avoiding any near-ridge bathymetric feature, which would strongly overestimate the ridge depth. In order to do so, we relied on both the bathymetric profile, and the age profile extracted from the age grid of Müller et al. (1997), version 1.3 (*S7*).

We then chose the westernmost point as close as possible to the subduction zone, just before the region where the lithospheric plate exhibits a sharp slope and dives into the mantle. We voluntarily avoid any fit of the bathymetric data along this profile. Indeed, fitting the depth profile would take into account intraplate features (volcanoes, swells, etc.) which are not linked to the subsidence process. Although apparently arbitrary, the trend deduced from the 'zero age' and westernmost point is determined with a good accuracy. Indeed, the error in the depth estimation of both extreme points does not exceed a cumulative 200m, while the distance over which the trend is considered is of about 5000 km (up to about 10000 km in the north Pacific), giving a ~4% error (~2% in the north Pacific) on the slope determination.

The linear trend deduced from this analysis ignores all intraplate features (volcanoes, hotspot swells, etc.) and holds true along the entire plate. For each profile, the subsidence parameters given by our model are the ridge height and the subsidence rate.

4. Grid interpolation

From the trend obtained along the flow lines, we generated a continuous grid, representing the general trend of subsidence deduced from our model, over the entire Pacific plate. To obtain the continuous grid, we interpolated the profiles through the ‘blockmedian’ and ‘surface’ GMT functions (*S8*).

We extrapolate from this grid depth profiles along the age trajectories, calculated from the age grid of Müller et al. (1997), version 1.3 (*S7*), in order to compare with previous models.

5. Comparison with other models

The comparison of our model with previous subsidence models, along the age trajectories, show that our analysis predicts well the general bathymetric trend (see article, Figs. 1 & 2). However, the models we used for comparison are global models (*S9*, *S10*), which compiled the depth vs. age data over all plates to get an average subsidence rate and ridge height. In order to compare our ‘local’ half-space model to a plate model, a local best-fitting plate model should be considered.

In the plate model, the seafloor can be described by two trends. At young ages, the seafloor depth varies like the square root of the age of the lithosphere (similar to the half-space model). At older ages, the seafloor depth scales as a decreasing exponential function of the lithosphere age, as a consequence of an additional heat supply at the base of the lithosphere. We can then write the theoretical seafloor depth z as a function of its age t :

$$\begin{aligned} z(t) &= z_0 + a\sqrt{t} && \text{for } t < t_c \\ z(t) &= b - c \exp(-\alpha t) && \text{for } t > t_c \end{aligned}$$

where a is the subsidence rate, (b,c) two parameters and α is directly linked to the amount of heat supplied at the base of the lithosphere.

To our knowledge, no local plate model is available over the Pacific plate. In the literature, several local models of seafloor subsidence exist, but only two of them provide a satisfying coverage of the Pacific plate: Calcagno & Cazenave [1994] (*S11*), which covers the North and Central Pacific, and Kane & Hayes [1994] (*S12*) which covers the South Pacific. We did not consider, for example, the study of Marty & Cazenave [1989] (*S13*), who divided roughly the Pacific plate into 6 regions. These local models, however, are simple half-space models: they estimate the depth-age^{1/2} relationship in narrow tectonic corridors, along the ‘age trajectories’, from the ridge up to a maximum age t_c , provided by these authors.

In an attempt to get a local plate model to which we could compare our model, we extended to older ages the profiles of Calcagno & Cazenave [1994] (*S11*) and Kane & Hayes [1994] (*S12*), along the ‘age trajectories’. For each age trajectory, we determined the best-fitting plate model. We based our determination on their calculation of the subsidence rate, valid up to the maximum age t_c , and estimated, by a root mean square error minimization method, the best-fitting parameters for the plate model (exponential seafloor subsidence) above t_c , up to the oldest available age. This classical method to determine the exponential parameters can be found in Stein & Stein [1992] (*S10*) or, more recently, in Hillier & Watts [2005] (*S14*).

For many profiles, the bathymetry at old ages ($t > t_c$) is too high to provide relevant plate model parameters, and no realistic fit is possible for the exponential trend. We nonetheless made an attempt to get a local plate model over the Pacific by compiling the local plate model available trajectories into a grid (‘blockmedian’ and ‘surface’ GMT functions (*S8*)). This makes it possible to get a ‘best-fitting profile’ even for trajectories for which directly fitting the exponential parameters was impossible. Hereafter, we refer to this model as the ‘CK model’.

Profiles extracted from the ‘CK model’ fail to provide an accurate description of the thermal subsidence of the Pacific plate. For short profiles (e.g. in the South Pacific), the linear relationship between depth and the square root of the age holds true all along the profile (see white profiles in Fig.S2, central panel and side panel b)). The CK model provides a reasonable fit of the bathymetry data, but a local plate model is not necessary. Indeed, because the profiles do not extend to old ages ($t < t_c$), a half-space model is enough to provide a good description of the seafloor subsidence. For long profiles extending to $t > t_c$, we find physically unrealistic results [Fig.S2, side panels a), c), e), f)]. Indeed, the solutions would require an irrelevant additional heat supply at the base of the lithosphere. In total, a realistic local plate model has been obtained for only 19 profiles out of the 83 initial extended trajectories, providing a poor coverage of the Pacific plate at old ages.

We conclude this attempt by the statement that determining a local plate model for the Pacific is unrealistic. It is therefore impossible, at this stage, to compare our model to a local plate model. The difficulties found in estimating a local plate model might explain the fact that, to our knowledge, no local plate model is available over the Pacific plate.

In addition to the impossibility, as explained above, to estimate a local plate model, we wish to remind, as already stated in the literature and pointed out in our manuscript, that the plate model itself is still under debate. Indeed, there is no physical reason why the strong hypothesis upon which a plate model (local or global) is based (constant basal temperature) should be true for the entire plate. The physical process which would be responsible for such a boundary condition is still an open issue. Our model is based on the hypothesis that mantle convection, and not cooling from an initial state, drives the subsidence of the oceanic floor. It thus corresponds to a simple half-space model, along the ‘flow lines’, and does not require such assumption.

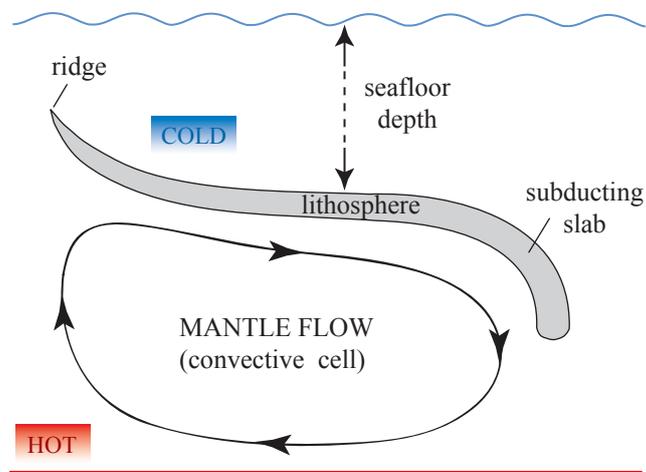


Figure S1. Geodynamic view of the lithosphere as the upper, cold thermal boundary layer of mantle convection.

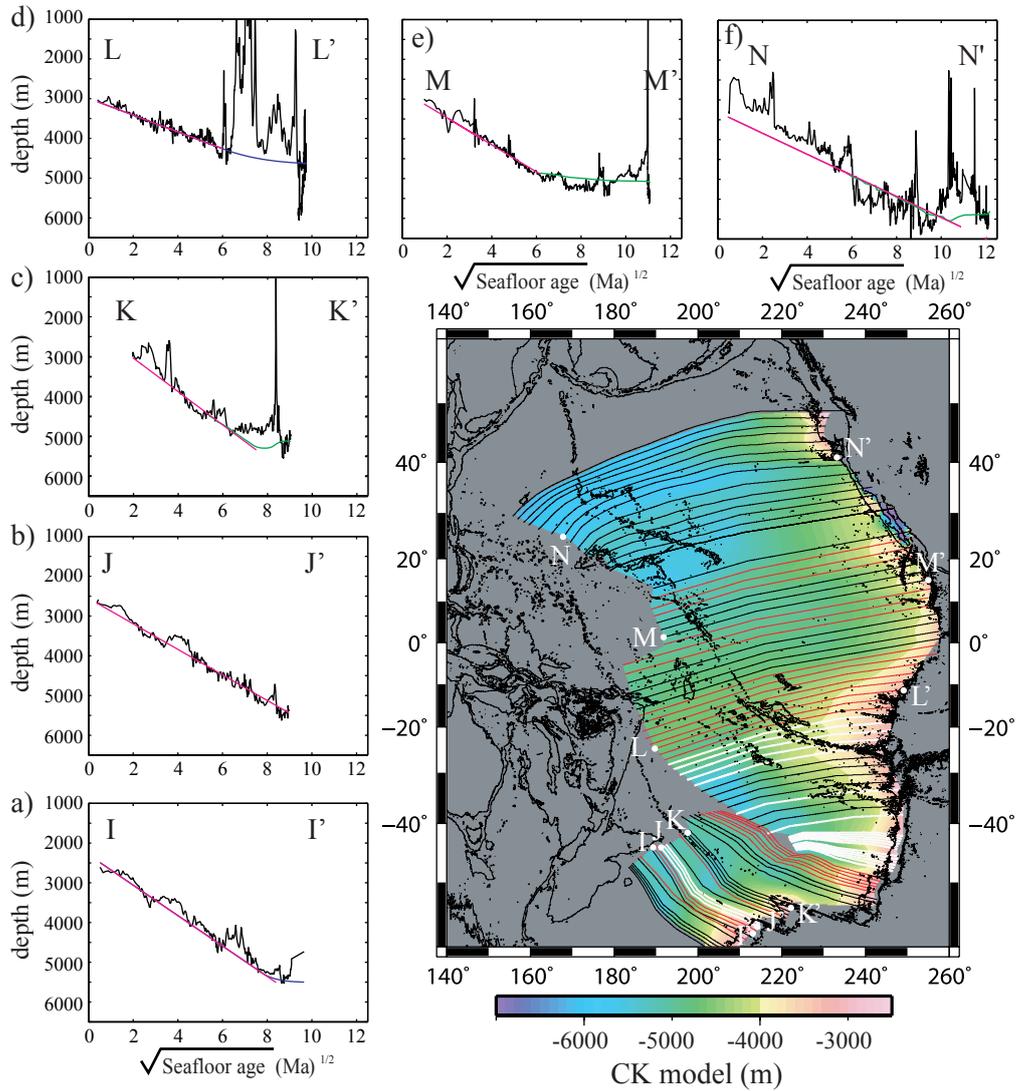


Figure S2. *Main panel:* general trend of the bathymetry according to the CK model. We reported the age trajectories determined by Calcagno & Cazenave [1994] (S11) and Kane & Hayes [1994] (S12). We represented in white the trajectories for which the linear relation between depth and the square root of the age holds true all along the profile; in black, the profiles for which it was mathematically impossible to determine the local plate model; and in red, the trajectories for which we determined the local plate model. *Side panels:* profiles along the age trajectories; in black, seafloor depth as a function of the square root of the seafloor age; in magenta, linear trend $z \sim age^{1/2}$ determined by these authors; in blue, the plate model we determined along the age trajectories and in green, the CK model obtained from the interpolated grid.

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