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Recent tectonic plate decelerations driven by mantle convection

A. M. Forte,[1] R. Moucha,[1] D. B. Rowley,[2] S. Quéré,[3] J. X. Mitrovica,[4] N. A. Simmons,[5] and S. P. Grand,[6]

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[1] We explore recent changes in tectonic plate velocities using a model of mantle flow that is based on a new high-resolution global tomography model derived from simultaneous inversions of global seismic, geodynamic and mineral physical data sets. This plate-coupled mantle convection model incorporates a viscosity structure that reconciles both glacial isostatic adjustment and global convection-related data sets. The convection model successfully reproduces present-day plate velocities and global surface gravity and topography constraints. We predict time-dependent changes in mantle buoyancy that give rise to present-day decelerations of several major plates, in particular the fast-moving Pacific and Nazca plates. We verify the plausibility of these predicted plate decelerations using space geodetic and oceanic magnetic anomaly constraints on tectonic plate motions. These plate kinematic constraints are employed to determine a new global map of present-day plate decelerations that agree well with the mantle flow predictions. **Citation:** Forte, A. M., R. Moucha, D. B. Rowley, S. Quéré, J. X. Mitrovica, N. A. Simmons, and S. P. Grand (2009), Recent tectonic plate decelerations driven by mantle convection, *Geophys. Res. Lett.*, *36*, L23301, doi:10.1029/2009GL040224.

1. Introduction

[2] A number of recent studies of tomography-based mantle convection have revealed the crucial role of convection-driven changes in mantle buoyancy for understanding the temporal variations of fundamental geological observables that include oceanic bathymetry, continental elevation, geoid undulations and sea level [*Iaffaldano et al.*, 2006; *Moucha et al.*, 2008a, 2008b; *Spasojević et al.*, 2008]. An outstanding issue raised by these calculations is whether we have robust, global tests of the plausibility of the temporal changes in mantle buoyancy predicted by the convection models. We will therefore consider a new global surface observable that constrains the rate of change of the buoyancy distribution in the mantle.

[3] We begin with a recently constructed model of time-dependent mantle convection that incorporates density anomalies provided by seismic tomography models derived from simultaneous inversions of global seismic, geodynamic and mineral physical data sets [*Simmons et al.*, 2007, 2009]. This mantle convection model has been previously used to predict the convection-driven uplift of the Colorado Plateau [*Moucha et al.*, 2008b] and the late-Cenozoic history of relative sea level variations on the eastern margin of North America and the west coast of Africa [*Moucha et al.*, 2008a]. The convection model is global in scale and it provides excellent fits to global data sets related to present-day mantle convection, including free-air gravity anomalies, tectonic plate motions and dynamic surface topography [*Simmons et al.*, 2009]. These observables only provide constraints on the current instantaneous distribution of mantle density anomalies. Are there, then, globally defined surface observables that can be used to directly constrain the time-rate of change of the mantle density structure?

[4] To address this issue, we first note that convection-driven changes of mantle density anomalies must produce corresponding temporal changes in all the convection-related surface observables that we employed in deriving the global tomography model [*Simmons et al.*, 2009]. We focus here on the most direct manifestation of convection, namely the surface tectonic plate motions. We employ our convection model to predict the rate of change of plate velocities and we assess their plausibility by comparing space-geodetic constraints on present-day global plate motions with plate motions in the geological past reconstructed from analyses of marine magnetic anomalies. We find that the combined geodetic-geologic estimates of current plate decelerations are indeed compatible with those independently predicted by the mantle convection model.

2. Tomography-Based Mantle Convection Model

[5] To explore the implications of time-dependent convection for the rate of change of plate motions, we employ a (Newtonian) viscous flow model of the mantle [*Richards and Hager*, 1984] that incorporates internal buoyancy forces derived from the joint inversion of seismic and geodynamic data sets that also include constraints from mineral physics [*Simmons et al.*, 2007, 2009]. The mantle flow at any instant is calculated from a solution of the gravitationally-consistent equations of mass and momentum conservation in a compressible spherical shell [*Forte and Peltier*, 1991]. The surface motions of the tectonic plates are viscously coupled to the internal buoyancy-driven mantle flow and they are predicted rather than imposed [*Forte*, 2007]. The time-dependent evolution of the mantle flow is determined using a pseudo-spectral solution of the conservation of energy

[1]GEOTOP, Université du Québec à Montréal, Montreal, Quebec, Canada.
[2]Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois, USA.
[3]Department of Earth Sciences, Utrecht University, Utrecht, Netherlands.
[4]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA.
[5]Atmospheric, Earth and Energy Division, Lawrence Livermore National Laboratory, Livermore, California, USA.
[6]Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.

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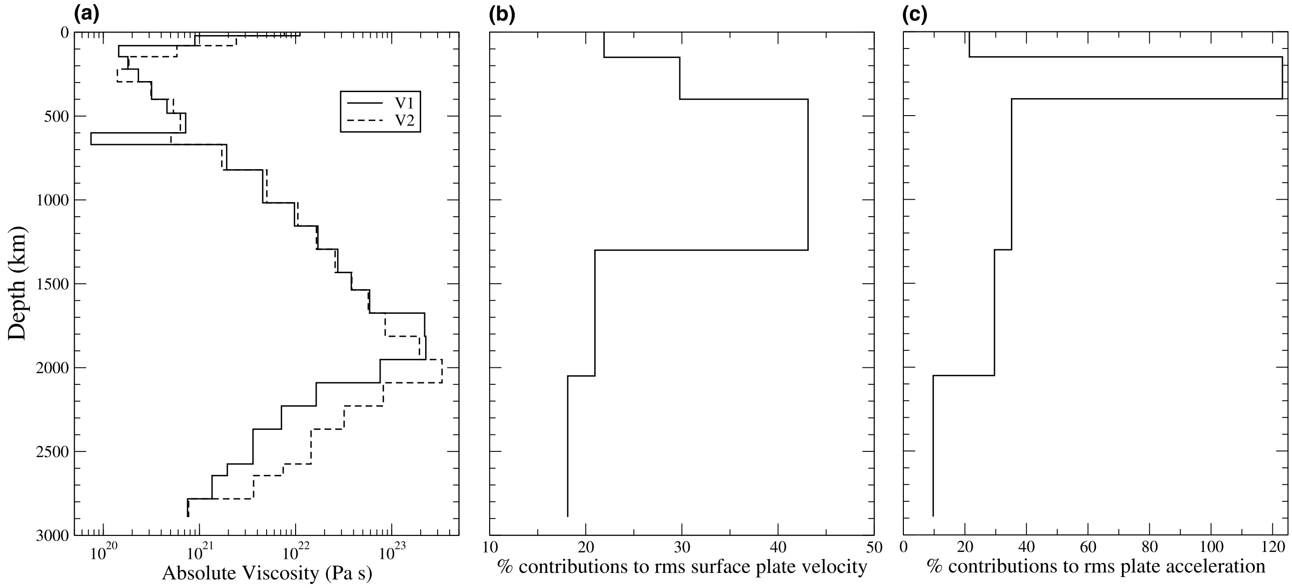

Figure 1. (a) Radial variation of horizontally averaged effective viscosity derived from joint inversions of glacial isostatic adjustment data and global convection data [*Mitrovica and Forte*, 2004]. (b) The fractional contribution to the predicted rms plate velocities due to density anomalies in different depth intervals in the mantle. The mantle-flow response functions for the V1 viscosity model and the density anomalies from the joint seismic-geodynamic tomography model [*Simmons et al.*, 2007] are used in the calculation. The relative contributions from each depth interval have been normalised by the total rms surface value of the predicted plate velocities. (c) The fractional depth-dependent contribution to the rms amplitude of the predicted acceleration of the surface plates. A value of over 1.0 (i.e., greater than 100% contribution) in any depth interval indicates that other layers in the mantle provide contributions that partially cancel. The viscosity model and mantle density anomalies are the same as in Figure 1b.

equation for a compressible mantle [*Glatzmaier*, 1984; *Espesset*, 2001; *Forte and Espesset*, 2001; *Moucha et al.*, 2008a, 2008b].

[6] An important convection model input is the mantle rheology, here modelled in terms of a depth-dependent viscosity. The viscosity profile is derived from a global joint inversion of present-day convection-related surface observables and glacial isostatic adjustment data associated with the rebound of the Earth's surface in Laurentia and Fennoscandia [*Mitrovica and Forte*, 2004]. This profile (model 'V1' in Figure 1a) is characterised by a relatively weak ($\sim 2 \times 10^{20}$ Pa s) viscosity in the asthenospheric mantle and a nearly three order of magnitude increase down to the mid lower mantle. Despite these large radial variations in viscosity, the average viscosity in the top $\sim$1000 km of the mantle is close to 10^{21} Pa s, in accord with the Haskell constraint [*Mitrovica*, 1996].

[7] Confidence in the predicted rate of change of the geodynamic observables depends to a large extent on the degree to which the convection model can match the present-day convection data sets. The mantle buoyancy distribution derived from the joint seismic-geodynamic tomography model [*Simmons et al.*, 2007], in conjunction with the viscous response of the mantle determined by the V1 viscosity profile (Figure 1a), yields flow predictions that fit the observed free-air gravity, plate divergence, and dynamic topography data (up to spherical harmonic degree 16) with variance reductions of 90%, 94%, and 76%, respectively. An important factor in obtaining these good geodynamic fits is the explicit inclusion of large-amplitude positive chemical buoyancy in the lithospheric roots below continents (the 'tectosphere') and the negative chemical buoyancy in large-scale upwellings in the lower mantle [*Simmons et al.*, 2007, 2009].

[8] The predicted plate velocities and their time-rate of change are sensitive to the choice of mantle viscosity. We therefore consider a second viscosity profile, referred to as 'V2' (Figure 1a). V2 also yields good fits to the convection-related surface data, though the low-viscosity notch at the base of the upper mantle is almost absent and it has a higher deep-mantle viscosity than V1. In addition, to estimate the sensitivity of the rate of change of the predicted plate velocities to the distribution of mantle buoyancy we will also consider the most recent joint seismic-geodynamic tomography model [*Simmons et al.*, 2009] derived by employing stronger smoothing constraints in the inversions relative to the preceding model [*Simmons et al.*, 2007].

3. Changing Mantle Buoyancy and Predicted Plate Decelerations

[9] The mantle flow predicted by the tomography-based convection model and the corresponding predictions of surface plate motions are all carried out in a reference frame in which there is no net rotation at any depth, including the lithosphere. This no-net-rotation (NNR) reference frame, corresponding to zero degree-1 toroidal flow motions, is a natural reference frame for mantle dynamics in which the plates are uniformly coupled to the underlying flow and hence the global torque on the lithosphere is zero [*Solomon and Sleep*, 1974; *Ricard et al.*, 1991; *Forte and Peltier*, 1994]. In this 'mantle dynamic' NNR-reference frame, our

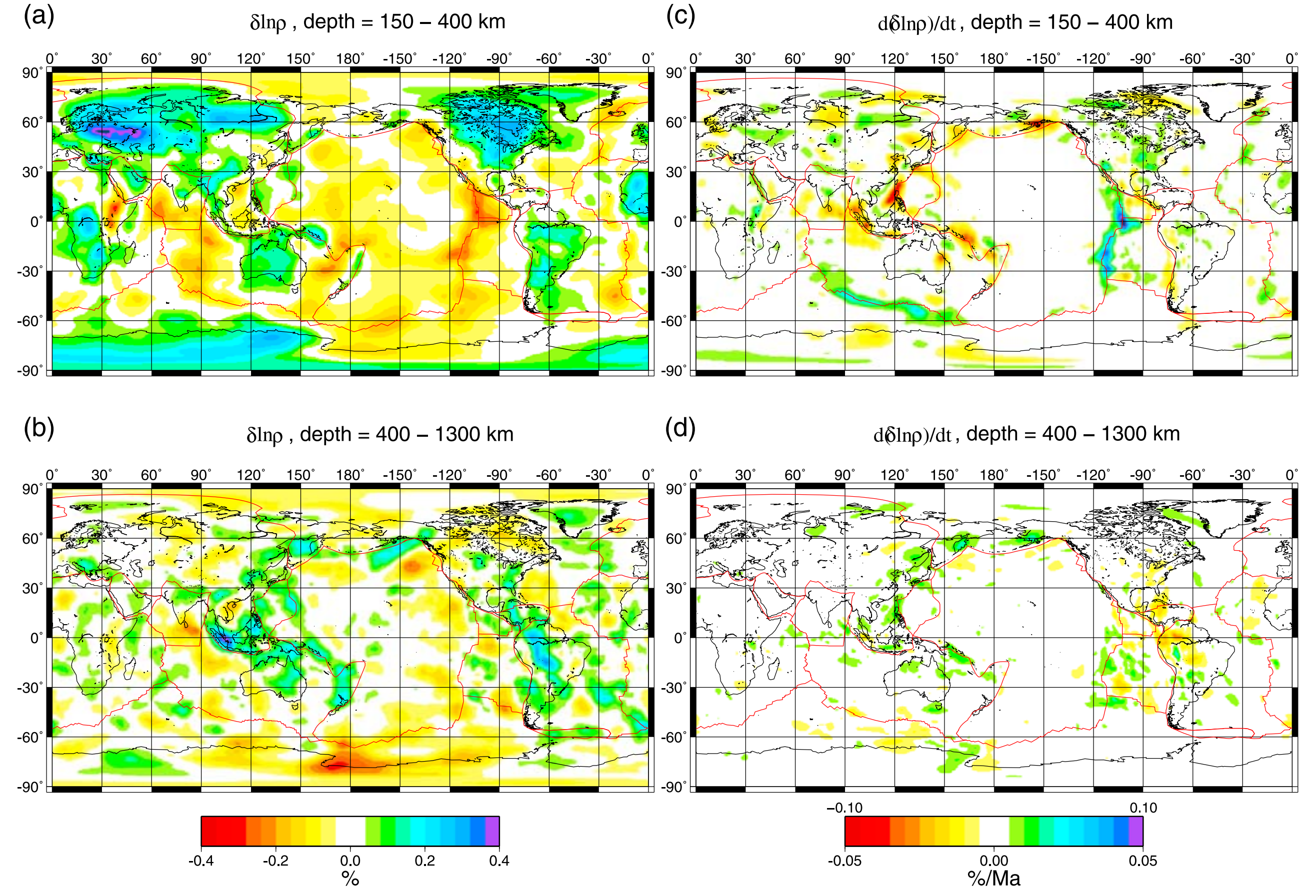

Figure 2. Upper-mantle buoyancy and its present-day rate of change. Maps of the depth-averaged value of the mantle density anomalies in two depth intervals, (a) 150–400 km and (b) 400–1300 km, respectively. The amplitudes, expressed as relative (%) perturbations in density, are defined by the bottom (left) scale bar. (c and d) Maps of the depth-averaged values of the time-derivative of the relative density perturbations for the same two depth intervals as Figures 2a and 2b. The amplitudes are defined by the bottom (right) scale bar. Note that scale of variations for Figure 2c ranges from −0.1 to +0.1, whereas for Figure 2d it varies from −0.05 to +0.05. In all cases the density anomalies are derived from tomography model of *Simmons et al.* [2007].

convection model yields a 90% fit to the present-day plate velocities (see Figure S1 of the auxiliary material).[1]

[10] The dependence of the predicted plate velocities on the driving buoyancy sources in different depth intervals is summarised in Figure 1b. We note that buoyancy forces in the top half of the mantle are the most efficient drivers of plate motions. The corresponding spatial distribution of upper-mantle buoyancy is mapped out in Figures 2a and 2b, for depth ranges 150–400 km and 400–1300 km respectively. The circum-Pacific pattern of subducted slab heterogeneity is evident in the shallow layer (150–400 km), especially under the western Pacific margin, and it becomes substantially broader in spatial extent in the deeper layer (400–1300 km), likely due to the dynamical effect of a rapid increase in viscosity across the upper mantle (Figure 1a). In addition to the important negative buoyancy from subducted slabs, we also note a significant source of positive plate-driving buoyancy that resides under the northern half of the East Pacific Rise (Figure 2a).

[11] The predicted time-dependent changes in mantle buoyancy have been mapped (Figures 2c and 2d) in the same two upper-mantle layers discussed above. We now note, as a consequence of the lower average viscosity in the top layer (150–400 km), the rate of change of buoyancy is at least a factor of two greater than in the deep layer (400–1300 km). The buoyancy changes in this upper layer (Figure 2c) are such that there is a progressive temporal reduction in the amplitude of the negative buoyancy of subducted slabs under the western Pacific margin. This reduction of slab heterogeneity in the upper layer is associated with a corresponding increase in the amplitude of slab buoyancy in the deeper layer, but at a substantially lower rate owing to the higher viscosity in the deeper mantle. This is, in effect, a non-steady-state change in the depth distribution of slab buoyancy due to the ongoing descent of previously subducted slabs across the upper mantle. In addition, the time-rate of change of positive buoyancy under the East Pacific Rise (Figure 2c) varies inversely with respect to that of the slabs: as the upwelling continues its rapid ascent across the upper layer it, in effect, leaves behind it a region of decreased buoyancy. When this upwelling enters the upper thermal boundary layer at the top

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040224.

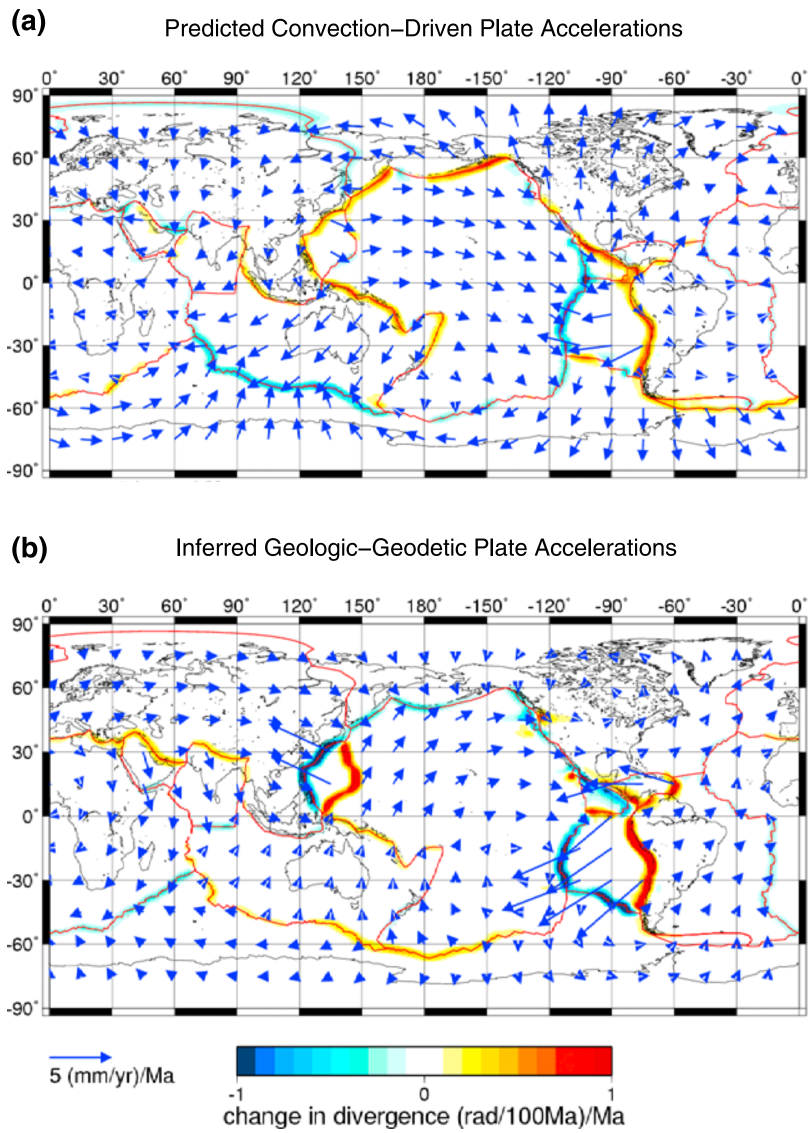

Figure 3. Present-day tectonic plate accelerations in the global NNR reference frame. (a) Predicted, convection-driven plate accelerations and rate of change of horizontal divergence rate. The horizontal divergence rate is an angular measure of the rate of spreading and convergence of plates at ridges and trenches, respectively [*Forte and Peltier*, 1994; *Forte*, 2007]. The predicted accelerations are calculated on the basis of a time-dependent convection model that uses the V1 viscosity profile (Figure 1a) and the mantle density anomalies from the joint seismic-geodynamic tomography model [*Simmons et al.*, 2007]. (b) Tectonic plate acceleration obtained by subtracting the geologic inference of plate velocities at 5 Ma [*Rowley*, 2006] from the geodetic measurements of present-day velocities [*Sella et al.*, 2002]. The blue arrows represent the direction and magnitude (arrow scale on bottom of Figure 3b) of the local plate acceleration field. The colour contours represent the rate of change of horizontal divergence of the plate velocities.

(upper 150 km) of the mantle its buoyancy will generate significant topography, but will be a less efficient driver of plate motion.

[12] The predicted plate accelerations driven by these changes in mantle buoyancy (Figure 3a) show the deceleration of the Pacific plate, as a clockwise counter-rotation relative to its current velocity (Figure S1a), and the strong deceleration of the Nazca plate. The Indian, Arabian and African plates also show predicted decelerations relative to their current plate velocities (Figure S1a). We trace the cause of the plate decelerations in the Pacific to the time-dependent shift of slab buoyancy to greater depths under the western Pacific and especially to the non-steady-state decrease of positive buoyancy under the East Pacific Rise (Figure 2c).

[13] In Table S1 we quantify the predicted plate acceleration that include uncertainties arising from different mantle viscosity and buoyancy distributions. The plates with the largest predicted decelerations are in the Pacific Ocean basin (Figure 3). The predicted deceleration of the Nazca plate due to changing mantle buoyancy is compatible with the inferred slowing down of the convergence between the South American and Nazca plates over the past 10 Myrs [*Norabuena et al.*, 1999; *Sella et al.*, 2002], but we note that this relative deceleration has been previously attributed to Andean crustal shortening and mountain uplift [*Iaffaldano*

et al., 2006; *Garzione et al.*, 2008]. The predicted deceleration of the Pacific plate, however, has not been previously recognised in past studies and its magnitude is comparable to the global rms average of the predicted plate decelerations (Table S1).

4. Geologic and Space-Geodetic Verification of Predicted Decelerations

[14] To test our model, we employ a geological reconstruction [*Rowley*, 2002, 2006] of Cenozoic plate configurations and velocities based on fitting marine magnetic anomalies and evaluate the rates of change relative to present-day velocities for comparison to our model predictions. Here we consider the present-day plate velocities inferred from space geodetic data, specifically the REVEL model [*Sella et al.*, 2002] derived entirely from GPS measurements. To be consistent with the mantle dynamic reference frame we employed, the geological inference of the plate velocities will be represented in the same global NNR frame. (In practise this is done by removing the spherical harmonic degree-1 toroidal component of the plate velocity fields.)

[15] We estimate plate decelerations averaged over the past 5 Myr by subtracting the geological inference of plate velocities [*Rowley*, 2006] at 5 Ma from the REVEL description of present-day velocities and dividing by the 5 Myr time interval.

[16] The resulting map of inferred plate accelerations (Figure 3b) shows the Pacific plate is decelerating with a counter-clockwise rotation relative to its current motion (Figure S1b).

[17] The amplitude and direction of this inferred Pacific deceleration is compatible with that predicted by the mantle convection model (Figure 3a). We also note that the azimuth of the inferred Nazca plate deceleration is very similar to, but about two times greater, than the convection prediction (Figure 3a). The Indian, Arabian and African plates are also inferred to be decelerating (Figure 3b) relative to their current plate velocities and this is also true of the decelerations predicted by the time-dependent convection model (Figure 3a). In the auxiliary material, we have explored the uncertainties in the geologic-geodetic inferences of plate decelerations (see maps in Figure S2) by examining a number of different plate history reconstructions (Table S2).

[18] The joint geologic-geodetic inferences of the plate decelerations, along with their estimated uncertainties, are quantified in Table S1. Here we note that the global rms average of the inferred decelerations is of the order $\sim$2 (mm/yr)/Myr and this is approximately the same magnitude as the deceleration of the largest plate, namely the Pacific. Despite the uncertainties in the geologic-geodetic inferences and the convection predictions, the heretofore unrecognised recent deceleration of the Pacific plate is a robust result.

5. Conclusions

[19] Table S1 and Figure 3 suggest that current efforts to develop seismically and geodynamically constrained models of the time-dependent evolution of mantle convection can provide good fits to the rate of change of horizontal surface motions. This is an important new test of the validity of convection models that have been recently employed to model the rate of change of vertical surface motions [*Moucha et al.*, 2008a, 2008b]. The predicted deceleration of the Pacific plate is particularly noteworthy given its dynamical significance as Earth's fastest and largest tectonic plate surrounded by our planet's most active subduction zones and spreading ridges.

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A. M. Forte and R. Moucha, GEOTOP, Université du Quebec à Montréal, CP 8888, Succ. Centre-ville, Montréal, QC H3C 3P8, Canada. (forte.alessandro@uqam.ca)
S. P. Grand, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78712, USA.
J. X. Mitrovica, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.
S. Quéré, Department of Earth Sciences, Utrecht University, NL-3508 TA Utrecht, Netherlands.
D. B. Rowley, Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637, USA.
N. A. Simmons, Atmospheric, Earth and Energy Division, Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94551, USA.