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Trench migration and upper plate strain over a convecting mantle

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ABSTRACT

Trench motion and upper plate deformation ultimately respond to mantle flow. Herein I build upon the mantle flow model results of Conrad and Behn (2010) and compute the drag forces underneath all plates, and show that they control the dynamics of plates and plate boundaries. The small misfit angle between between the traction azimuths of mantle traction and absolute plate motion corroborates the idea that convective mantle drag is a prominent driver of plate tectonics. Less intuitive is the fact that the interplay between the drag forces from the upper and lower plates, that amounts to -5 to 8.5×10^{12} N m^{-1} (per unit trench length), dictates both trench migration rates and upper plate deformation. At odds with the classic view that assigns the prime role to the idiosyncrasies of subduction zones (slab age, interplate friction, water content etc), I find that the intrinsic properties of subduction zones in fact only modulate this behavior. More specifically, the mean value of the integrated trenchward mantle drag force from the lower and upper plates (from -2 to 6.5×10^{12} N m^{-1}) controls upper plate deformation. Conversely, it is the difference between the lower and upper plates mantle drag forces (from -3 to 10×10^{12} N m^{-1}) that controls trench migration rates. In addition, I find that a minimum trenchward force of $\sim 2.5 \times 10^{12}$ N m^{-1} must be supplied by mantle drag before trenches can actually advance, and before upper plates undergo compression. This force results from the default tendency of slabs to rollback when solely excited by their own buoyancy, and is thus the effective tensional force that slab pull exerts on the plate interface.

1. Introduction

The deformation of upper plates, as well as the surface migration of the trench (Fig. 1) are the prevailing observables of interplate dynamics, and substantial work has taken advantage of these quantifiable features (e.g. Chase, 1978; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980; Jarrard, 1986; Garfunkel et al., 1986; Heuret and Lallemand, 2005; Lallemand et al., 2005, 2008; Funiciello et al., 2008; Schellart, 2008). On this basis, the usual way to classify plate boundaries is to cross-correlate the kinematical and geometrical properties of plate boundaries, that should ultimately mirror their dynamics. Ruff and Kanamori (1980) suggested that back-arc deformation responds to the coupling between the upper and lower plates, that coupling itself relating to the slab age-buoyancy. Uyeda and Kanamori (1979), or more recently Heuret and Lallemand (2005), instead found that back-arc deformation roughly correlate with upper plate velocity. As to trench migration rates, Lallemand et al. (2008) found that they are chiefly controlled by lower plate velocity, which in turn depends on the slab age buoyancy. But while theory suggests that trenches should retreat faster for old slabs, observations show the opposite tendency (Heuret and Lallemand, 2005). Departure from the intuitive behavior laws were further explored by invoking the many local -or intrinsic- parameters of subduction zones (see e.g. Billen, 2008; Gerya, 2011, for reviews).

Recent case studies (Becker and Faccenna, 2011; Cande and Stegman, 2011; Husson et al., 2012) revealed that mantle drag is a primordial, yet seldom quantified, source of force that may help reconcile observations and theory. In this paper, I explore the possibility that variations of the effective slab pull force – and more generally any intrinsic property of a given subduction zone – does not explain these discrepancies and that instead, global plate tectonics viewed in the framework of convection may explain interplate dynamics. In other words, are the dynamic forces arising from mantle flow controlling trench migration and upper plate deformation? This is already suggested by kinematic studies, but we now have the possibility to explore the question from a dynamic standpoint thanks to models of global mantle circulation. I thus compute mantle traction forces and match the observed dynamics of subduction zones against mantle drag underneath converging plates.

2. Force balance at plate boundaries and interplate kinematics

In order to explore the dynamics of plate boundaries, I take advantage of the existing databases for trench migration and upper

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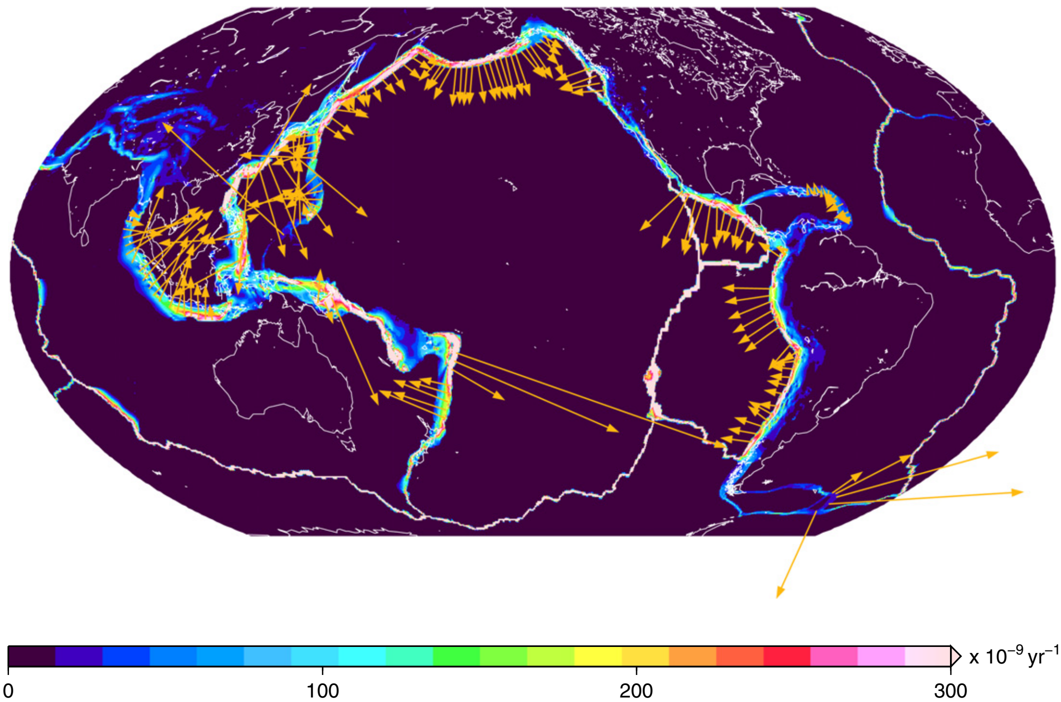

Fig. 1. Normal component of trench migration rates (orange vectors, from Funiciello et al., 2008) in the reference frame *SB04* (Steinberger et al., 2004). World strain map on the background (second invariant of strain rate, Kreemer et al., 2003). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plate deformation (Lallemand et al., 2005; Heuret and Lallemand, 2005; Funiciello et al., 2008); I discarded ten data points from the original databases because they belong to slabs that are too small when compared to the resolution of the current study (Sulawesi, Negros, Luzon and Batan). I consider trench migration rates in the four representative reference frames chosen by Funiciello et al. (2008): *SB*04 (Steinberger et al., 2004, Fig. 1), *HS*3 (Gripp and Gordon, 2002), *GJ*86 (Gordon and Jurdy, 1986) and *NNR* (DeMets et al., 1994). Note that the last one, *NNR* is kinematically defined and by no means rooted on a dynamic ground. For upper plate deformation, I will use the *UPS* (upper plate strain) qualitative parameter of Heuret and Lallemand (2005) that ranges from highly compressive (C3) to highly extensive (E3). In the following, I dropped the prefixes *C* and *E* and simply swapped *E* for a negative sign.

2.1. Kinematics at plate boundaries: trench migration and upper plate deformation

From a dynamic viewpoint, trench migration can be described as the result from the imbalance between the forces exerted by the lower and upper plates at the plate interface, F_{lp} and F_{up}. Of course, forces balance, and the missing force component thus must be taken up elsewhere than in the lithospheres, namely by viscous dissipation in the underlying mantle $VD = |F_{lp} - F_{up}|$. Schematically in two dimensions, it corresponds to the drift of the entire surface system including both the plates and the trench, accompanied by a laminar flow in the underlying mantle (Fig. 2). For a Newtonian rheology, trench velocity should therefore scale with $F_{lp} - F_{up}$ (both F_{lp} and F_{up} being counted positive trenchward). This behavior is exemplified by the Pacific system that possibly drifts to the West as a response to the westward force at the plate boundary (Husson et al., 2008). The force exerted by the South American plate exceeds the resistance of the lower plate, and is accommodated by the viscous shear of the Pacific mantle.

Mountain building, or more generally upper plate deformation, conversely results from the mean force that is exerted at their boundaries, *i.e.* F_{lp} and F_{up}, such that the orogenic load $OL = (F_{lp} + F_{up})/2$, F_{lp} and F_{up} being counted positive trenchward (Fig. 2). Note that the orogenic load equals the sum of the buoyancy and viscous forces in the lithosphere, in the deforming plate boundary (e.g. England and McKenzie, 1982; Husson and Ricard, 2004). If both plates are pushing towards the trench, compression at the plate interface is expected, as well as mountain building, and conversely, back-arc extension will typically arise if the net force is extensive. In a comparable way to trench migration, upper plate deformation should therefore scale with $\Sigma_F = (F_{lp} + F_{up})/2$.

If correct, and as obvious as it may sound, there should be a correlation between the force balance at the plate boundaries and the dynamics of the plate margin. However, and this is less obvious, because trench migration and upper plate deformation depend on the same forces, they may also correlate to one another *via* the quantities F_{lp} and F_{up}. Those forces result from sources that are distributed over the entire plates, and not restricted to the subduction zones *sensu-stricto*. Heuret and Lallemand (2005) concluded that upper plate strain and trench migration are poorly correlated. Indeed, no regression by a monotonic function gives a satisfying fit. However, further exploration yields different conclusions, particularly when considering multiple reference frames, and above all when considering circum-Pacific trenches only (Fig. 3). Interestingly, the relationship is not linear but there rather seems to be a threshold at $UPS \sim -1$: Fig. 3 reveals a bimodal distribution for trench migration rates V_t, particularly for the Pacific domain. Some 70% circum-Pacific trenches are jointly retreating and compressive to moderately extensive, while some 25% are jointly advancing and strongly extensive: together, it indicates that some 95% of the trenches corroborate the existence of a relationship that ties *UPS* to V_t. In the three dynamically-based reference frames (*SB*04 (Steinberger et al., 2004), *HS*3 (Gripp and Gordon, 2002), *GJ*86 (Gordon and Jurdy, 1986)), retreating trenches are