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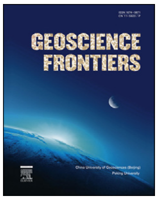

Focus Paper

The westward drift of the lithosphere: A tidal ratchet?

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ABSTRACT

Is the westerly rotation of the lithosphere an ephemeral accidental recent phenomenon or is it a stable process of Earth's geodynamics? The reason why the tidal drag has been questioned as the mechanism determining the lithospheric shift relative to the underlying mantle is the apparent too high viscosity of the asthenosphere. However, plate boundaries asymmetries are a robust indication of the 'westerly' decoupling of the entire Earth's outer lithospheric shell and new studies support lower viscosities in the low-velocity layer (LVZ) atop the asthenosphere. Since the solid Earth tide oscillation is longer in one side relative to the other due to the contemporaneous Moon's revolution, we demonstrate that a non-linear rheological behavior is expected in the lithosphere mantle interplay. This may provide a sort of ratchet favoring lowering of the LVZ viscosity under shear, allowing decoupling in the LVZ and triggering the westerly motion of the lithosphere relative to the mantle.

1. Introduction

The lithosphere is broken in a number of plates (Bird, 2003) that move along a coherent mainstream, best defined by a sort of tectonic equator (Doglioni, 1993; Crespi et al., 2007). Moreover, the lithosphere has a "westerly" rotation relative to the underlying mantle (Le Pichon, 1968; Doglioni, 1993; Gripp and Gordon, 2002); however, its origin is still debated (Bostrom, 1971; Moore, 1973; Jordan, 1974; Ranalli, 2000; Scoppola et al., 2006; Riguzzi et al., 2010). As a function of the reference model, the rotation has been estimated either as a slow accidental residual (0.1°–0.2°/Ma) due to the faster "westerly"-directed motion of the Pacific plate (e.g., Ricard et al., 1991; Torsvik et al., 2010), or a much faster rotation (>1.1°–1.2°/Ma) affecting the entire external lithospheric shell, although segmented in plates having different velocities (Crespi et al., 2007; Cuffaro and Doglioni, 2007, 2017). Regardless of the rate, Pacific hotspots tracks like Hawaii demonstrate that the lithosphere shifts relative to the source of the hotspot, being the decoupling inferred within the low-velocity zone (LVZ), atop the asthenosphere (Fig. 1), which is in average between 100 and 200 km depth or even thinner (Rychert et al., 2005; Panza et al., 2010; Schmerr, 2012). Anderson (2011) and Rychert et al. (2013) have demonstrated that the last residence of the magma chamber beneath Hawaii is located at the top of the asthenosphere, within the LVZ, the inferred decoupling. Moreover, whatever are the origins of the hotspots and the rate of the net rotation (Doglioni et al., 2005), plate boundaries such as subduction and rift zones are asymmetric, supporting a global rotation of the lithosphere with respect to the mantle (e.g., Doglioni et al., 2007, 2015; Doglioni and Panza, 2015; Ficini et al., 2017), which is more consistent with the faster kinematic models and the global asymmetries along plate boundaries moving along the tectonic equator (Fig. 2). Moreover, the computation of the lithospheric volumes recycled in the mantle by subduction zones is about three times larger (about 230 km^3) along W-directed subduction zones with respect to the opposite E- or NE-directed slabs (about 70 km^3) as computed by Doglioni and Anderson (2015). This implies an 'easterly' directed mantle flow to compensate the volume unbalance. The tectonic equator represents the mainstream of plate motions and it is inclined 28°–30° relative to the geographic equator. This angle can be explained by the Earth's precession and the Maxwell time of the lithosphere. In fact the ratio between viscosity and rigidity is about 10^{12} s, i.e., the

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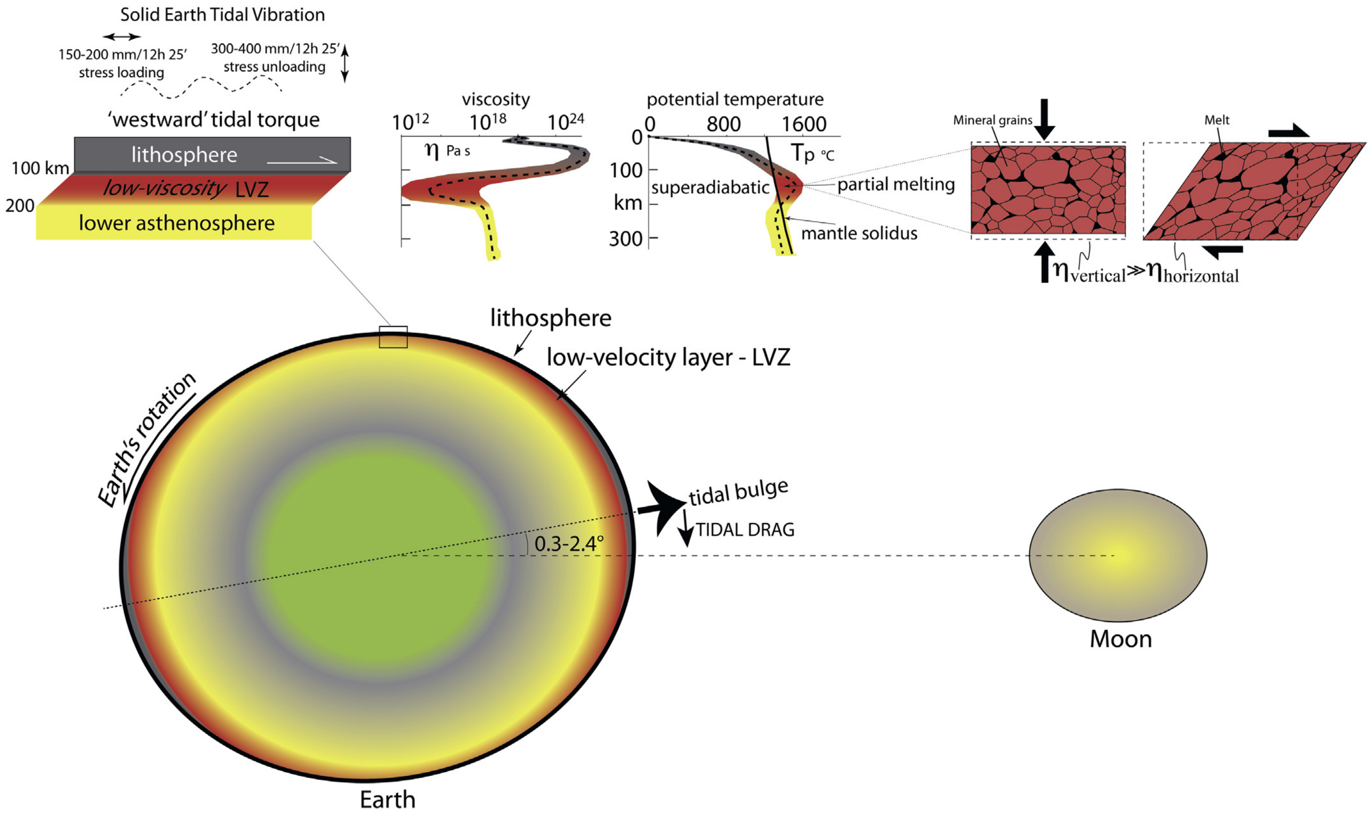

Figure 1. Simplified section of the Earth viewed from above the North Pole. The Earth is not perfectly elastic and it reacts with a few minutes delay to the Moon gravitation. Therefore the tidal bulge, exaggerated in the figure, is slightly misaligned relative to the Earth-Moon gravitational line. This generates a permanent torque toward the "west", opposite to the Earth's rotation, responsible for the tidal drag and the secular deceleration of the Earth's spin and the Moon's receding. The torque may also activate the "westward" drift of the lithosphere, relative to the underlying mantle, which is allowed by the presence of the low-velocity layer (LVZ). This layer has low viscosity due to the presence of partial melting. The effective viscosity in a granular layer with intervening melt in the pores is much smaller when measured for a shear parallel to the bedding (e.g. induced by horizontal plate motion) with respect to a vertical load (e.g., induced by ice formation or melting). The viscosity under shear is also assumed at least two orders of magnitude lower with respect to the vertical loading that is the usual way it is computed. The tidal torque occurs contemporaneously to the semidiurnal and diurnal tidal oscillations. This mechanical setting enhances a non-linear rheology of the mantle.

tectonic equator is the bisector of the angle generated by the oscillating Earth's axis that lasts 20,000–26,000 years (Doglioni and Panza, 2015; Cuffaro and Doglioni, 2017). The tectonic equator best represents also the net rotation or the westward drift of the lithosphere; moving toward the poles of the tectonic equator, plate velocities and seismicity at plate boundaries decrease, as well as ocean spreading rates and size of the orogens rates (Cuffaro and Doglioni, 2017). In their rotation along the mainstream, plates may also have a second sub-rotation that may apparently complicate or hinder the main flow (Cuffaro et al., 2008). It is important to note that the angle between the tectonic and the geographic equators is close to the sum of the inclination of the Earth's axis relative to the ecliptic plane (23°), plus the angle of the Moon's revolution around the Earth (5°).

The key question is: what causes the net rotation? Is it simply due to the fast motion of the Pacific plate toward the west-northwest due to the slab pull, or is it related to astronomical mechanisms such as the Earth's rotation and the consequent body tides generated on the solid Earth by the Moon and the Sun? An astronomical tuning of plate tectonics is suggested by seismicity decreasing toward polar areas (Riguzzi et al., 2010).

The slab pull is often invoked to explain the net rotation of the lithosphere (Ricard et al., 1991). However, the slab pull model is based on far too high values of negative buoyancy (e.g., 40–100 kg/m^3) with respect to the real Earth, where only the middle lithosphere can be inferred heavier than the underlying mantle of about 30–40 kg/m^3 maximum, but only in lenses within the lithospheric mantle (Afonso et al., 2008). Therefore, in average, the lithosphere ab-initio should have a bulk density in average lower than the underlying mantle. Subduction contributes to weigh the slab due to phase changes (van Keken et al., 2011). However, no relation among slab dip and age and temperature of the downgoing lithosphere can be observed (Cruciani et al., 2005). A long list of counterarguments on the slab pull efficiency is in Doglioni and Panza (2015). On the other hand, the tidal drag computed by Bostrom (1971) is energetically feasible for driving plate tectonics (e.g., Riguzzi et al., 2010). The main reason for discarding tidal drag as an effective mechanism to drift the lithosphere to the west has been so far the viscosity of the asthenosphere (Jordan, 1974; Ranalli, 2000). Values inferred from different techniques report variations from ultra-low viscosity (10^{12} Pa s, Jin et al., 1994) to much higher values (10^{19} Pa s, e.g., Cathles, 1975). Pollitz et al. (1998) and Hu et al. (2016) suggested values of 5×10^{17} Pa s. However, present techniques (e.g., glacial isostatic adjustment) are below the detection threshold capability to resolve such a thin layer due to the channel flow model of Cathles (1975). Therefore, a thin low-viscosity layer at the top of the asthenosphere cannot be detected with present techniques and seismological resolution (Scoppola et al., 2006) and the values presented in the literature represent the bulk viscosity of the whole upper mantle or possibly

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