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RESEARCH NOTE

Westward drift of the lithosphere: not a result of rotational drag

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SUMMARY

It is shown that any non-zero torque resulting from differences in angular velocity between individual shells in the Earth would be an extremely short transient phenomenon as a consequence of the viscosity of the asthenosphere. Consequently, it cannot be a factor in the origin of the toroidal velocity field of degree one ('westward drift') of the lithosphere.

Key words: lithosphere.

INTRODUCTION

It has long been known that plate motion has a roughly westward component (Bostrom 1971; Knopoff & Leeds 1972; Nelson & Temple 1972; Moore 1973; Uyeda & Kanamori 1979; Doglioni 1990; Ricard *et al.* 1991; Gordon 1995), both with respect to the Earth's rotational axis (i.e. regarding the Antarctic plate as fixed; Knopoff & Leeds 1972), and in the hot spot reference frame (Ricard *et al.* 1991; Gordon 1995 and references therein). According to Ricard *et al.* (1991), the toroidal field of degree one describing the global rotation of the lithosphere has magnitude 0.15° Myr^{-1} (corresponding to a maximum linear velocity of 1.7 cm yr^{-1}) about a pole situated at 84°E, 56°S. This differs little from other estimates: for instance, Gordon (1995) gives the values of these parameters as 0.33° Myr^{-1} (3.7 cm yr^{-1}), 65°E, and 49°S, respectively.

An idea associated with 'westward drift' has been that it has something to do with the rotation of the Earth. Tidal drag has been proposed as a mechanism (Bostrom 1971; Moore 1973). This is energetically feasible: the energy lost in tidal dissipation is about 5×10^{12} W (Munk & MacDonald 1960; Rochester 1973) and, even if up to 50 per cent of it is dissipated in shallow seas and by internal friction of the solid Earth, the remaining energy ($\sim10^{20}$ J yr^{-1}) is about two orders of magnitude higher than the total seismic energy release, estimated at about 10^{18} J yr^{-1} (Bott 1982). However, it can be proved that the torque necessary to maintain the motion is of the order of 10^{27} N m; that is, about 10 orders of magnitude higher than the tidal torque (Jordan 1974). Since the torque is linearly proportional to the viscosity of the asthenosphere, this result implies that the viscosity of the asthenosphere is 10 orders of magnitude too large for tidal drag to result in a differential rotation of the lithosphere with respect to the underlying mantle.

In this note, an argument is presented showing that no mechanism originating in the Earth's rotation can be a factor in the westward drift of the lithosphere. It is proved that any non-zero torque, generating differential rotation of the Earth's outer shell, would have an extremely short relaxation time due to the viscosity of the asthenosphere. While the conclusion is not new, the argument is more general than the one about tidal drag (Jordan 1974), and may be useful in clarifying the relative role of individual plate tectonic forces.

Relaxation time of rotational drag

In a spherically symmetric Earth, differential rotation of the lithosphere cannot represent an equilibrium state, because viscosity tends to equalize the angular velocity of individual shells (and at the same time adjust the rotation rate of the planet). Here, an argument proposed by Scheidegger (1963) in a discussion of zonal rotation (the increase in angular velocity towards the equator, observed in the Sun and the larger outer planets) is adapted to the rotational drag between spherical shells in the Earth.

With reference to Fig. 1, assume that a difference in angular velocity between the mantle below the asthenosphere (ω_m) and the lithosphere (ω_l) is taken up by a linearly viscous asthenosphere with density ρ, viscosity η, and thickness r_2-r_1. Applying the equation of motion to any thin layer of thickness dr within the asthenosphere, we have

$$rF'(r)dr=-\dot{\omega}dI\,, \qquad (1)$$

where $F(r)$ is the viscous drag force, whose variation in the r-direction is given by $F'(r)$, dI is the moment of inertia of the layer of thickness dr, and $\dot{\omega}$ the angular deceleration.

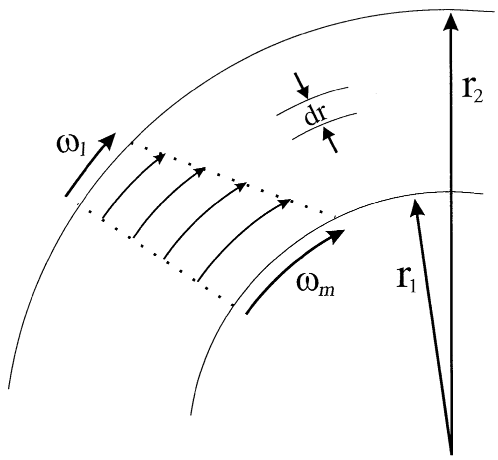

Figure 1. Differential rotation between mantle and lithosphere, taken up by the asthenosphere. See discussion in the text.

The viscous drag force is obtained by integration over the spherical surface of radius r of the stress acting on it; that is,

$$F(r) = \int_S \eta \frac{dv}{dr} ds = -2\pi^2 a r^3 \eta \,, \tag{2}$$

where use has been made of the relations $v = \omega r \cos\theta$ (θ is latitude) and $\omega = -ar$, representing the decrease of angular velocity within the asthenosphere. It should be noted that η has been assumed constant, but that dv/dr is a function of latitude.

The moment of inertia of a thin spherical shell of radius r and mass dm is $dI = (2/3)dmr^2$. Therefore, the change in angular momentum is

$$-\dot{\omega} dI = \frac{8}{3}\pi \dot{a} \rho r^5 dr \,. \tag{3}$$

Using eqs (2) and (3) in eq. (1) and integrating, we have

$$a = a_0 \exp\left[-\left(\frac{9\pi\eta}{4\rho r^2}\right) t\right], \tag{4}$$

where a_0 is the initial value and $\tau = (4\rho r^2/9\pi\eta)$ is the relaxation time of the differential rotation. Taking the reasonable values $\rho = 3300\ \mathrm{kg\ m^{-3}}$, $r = 6250$ km, and $\eta = 10^{20}$ Pa s (see, for example, Ranalli 1995), we obtain $\tau = 1.8 \times 10^{-4}$ s

Any rotational drag decays exponentially with a very short viscosity-dependent relaxation time. This decay would result in unrealistic changes in the Earth's rotation rate, as pointed out also by Ricard *et al.* (1991). The viscosity would have to be of the order of 10^{11} Pa s to result in a relaxation time of about one day (i.e. compatible with tidal drag), a value similar to that inferred by Jordan (1974) using a different argument. In a different context, Hager & O'Connell (1981) have also shown that the toroidal velocity field of degree one is uniform in a mantle with only radial variations in viscosity.

The above estimate of relaxation time is very simplified, but a difference of 10 orders of magnitude between the observed and the required viscosity cannot be attributed to model approximations alone. Any basal drag on the lithosphere exerted by Earth rotation cannot be an equilibrium state, contrary to what is assumed in some models (e.g. Smith & Lewis 1999), but would decay very rapidly. In this sense, the lithosphere and the underlying mantle are not 'decoupled' to any significant extent.

DISCUSSION

The above argument does not imply that the mantle exerts no drag on the overlying plates, nor that the lithosphere shows no 'westward drift', in the sense of non-zero toroidal field of degree one, as inferred for instance by Ricard *et al.* (1991) and Gordon (1995). It implies, however, that mantle drag cannot result from differences in angular velocity between individual shells. Although the magnitude of the drag resulting from the net westward rotation of the lithosphere is of the right order (about 10^{20} N for a net rotation of $0.15^\circ\ \mathrm{Myr^{-1}}$, and consequently about an order of magnitude less for individual plates; see also Smith & Lewis 1999), any differential rotation caused by it would quickly disappear due to the viscosity of the asthenosphere.

Ricard *et al.* (1991) have shown that a differential rotation of the lithosphere can arise if the degree of coupling between plates and underlying mantle shows lateral variations. A laterally varying degree of coupling reconciles the mechanical requirement of zero net torque on the lithosphere (Lliboutry 1974) and observed net rotation. Analysis of creep parameters for asthenosphere material shows that lateral variations in viscosity of one to two orders of magnitude are to be expected (see, for example, Ranalli 1995).

Torque balance analysis of plates (see, for example, Forsyth & Uyeda 1975) shows that mantle drag is an important tectonic force, which in general tends to resist plate motion. However, analyses of mantle convection (see, for example, Yuen & Malevsky 1992; Davies 1998) concur in the conclusion that the velocity pattern is complex, and consequently the planform of mantle movement below the plates cannot be envisaged as a simple 'eastward counterflow', exerting an eastward drag on the plates. This result stands out quite clearly when one observes the movement of individual plates, several of which move in directions different from the overall lithosphere rotation; indeed, in one case (i.e. Nazca), almost exactly opposite. This in itself is a geological argument against any simple flow pattern which casts some doubt on interpretations of large-scale tectonic features based on the idea of 'mantle counterflow' (see, for example, Doglioni 1990; Smith & Lewis 1999). The net rotation of the lithosphere detected in various 'absolute' reference frames requires nothing more than the well-known plate tectonic forces (including laterally varying mantle drag as a part of the convective process), but cannot arise from global differences in angular velocity of individual shells related to the Earth's rotation.

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