Some Comments on Tidal Drag as a Mechanism for Driving Plate Motions

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A simple calculation suggests that tidal torques are far too small to drag the lithosphere at any appreciable velocity. Recent models of plate motions with respect to the hot spots support this conclusion.

Recently, Bostrom [1971] and Moore [1973] have advocated that tidal drag is the dominant force responsible for lithospheric plate motions on the surface of the earth. To support this hypothesis, these authors cite a number of observations such as the latitude dependence of seismicity, the asymmetrical distribution of marginal basins in the Pacific, and the curious preference for transform faults to be oriented east-west and ridge segments to be oriented north-south. According to these authors, all plates are moving westward with respect to the lower mantle and 'differences in the rate of westward drift of the various plates are believed to cause most of the observed relative motion between plates' [Moore, 1973, p. 001].

The notion that tidal torques might act to displace the lithosphere westward is an old one and predates the modern theory of plate tectonics by at least 50 years. Wegener [1924], attempting to explain the component of continental displacement he called Westwardung, held the view that 'tides give the impulse to a slight progressive displacement of the crust, due to the viscosity of the sima, which . . . leads to considerable displacements in the course of millions of years.' The enthusiasm for this mechanism was dampened considerably by Jeffreys' calculation that 'the mean secular tidal friction producing the slowing down of the earth's rotation corresponds to a westward stress of the order of only $10^{-4}$ dyn/cm² over the earth's surface' [Jeffreys, 1929], a stress that is inadequate to account for orogenesis or drift.

Undoubtedly, the idea that tidal drag is a driving mechanism for plate motions remains intriguing primarily because it is energetically feasible. Munk and MacDonald [1960] calculated the energy lost in tidal dissipation to be $2.7 \times 10^{19}$ ergs/s, based on Spencer-Jones' old estimate of the lunar orbital acceleration (-22'/century⁸). More recent studies have doubled this value [Rochester, 1973], so that the total energy lost in this process, which is linearly related to the orbital acceleration, likely exceeds $5 \times 10^{19}$ ergs/s. Dissipation in the shallow seas (1.4-1.7 × 10¹⁹ ergs/s ± 50% [Miller, 1966]) and by internal friction in the solid earth (<10¹⁶ ergs/s [Munk, 1968]) can account for only a fraction of this total. Thus about $3 \times 10^{19}$ ergs/s or 10¹⁸ ergs/yr might be available for driving plate motions, a value that exceeds by 2 orders of magnitude the lower bound set by seismic energy release [Gutenberg, 1956]. A simple calculation suggests, however, that tidal torques are far too small to drag the lithosphere over the mesosphere at any appreciable velocity.

Consider a simplified model for the earth consisting of a rigid inner sphere (mesosphere) of radius $r$ and a rigid spherical shell (lithosphere) of inner radius $r_s$ separated by a Newtonian fluid layer (asthenosphere) of density $\rho$ and viscosity $\eta$. Suppose the outer shell rotates at a constant angular velocity $\omega$ with respect to the inner sphere. Steady state flow at very low Reynolds number $Re = \omega(r_s - r)\rho/\eta$ can be approximated by the velocity field

\[
\begin{align*}
\mathbf{u} &= (u_r, u_\theta, u_\phi) \\
n &= \left(0, 0, \frac{\alpha \sin \theta}{r} \right)
\end{align*}
\]

where the function $\alpha$ satisfies the equation [Pearson, 1967]

\[
\frac{d^2 \alpha}{dr^2} + \frac{1}{r} \frac{d \alpha}{dr} - \frac{1}{r^2} \sin \theta \frac{d \alpha}{d\theta} = 0
\]

The solution to this equation has the form

\[
\alpha(r, \theta) = \frac{A}{r^2} + \frac{B}{r^2} \sin \theta
\]

The coefficients $A$ and $B$ are determined by the boundary conditions

\[
\begin{align*}
\alpha(r, \theta) &= 0 \\
\alpha(r_s, \theta) &= \frac{\alpha}{r_s^2} \sin \theta
\end{align*}
\]

which yield

\[
A = \omega(1 - \frac{r_s^3}{r^3}) \\
B = \omega(\frac{r_s^3}{r^3} - \frac{1}{r^3})
\]

For the $\phi$ component of the velocity field we obtain

\[
\varepsilon_{\phi\phi} = \frac{\omega}{2} \frac{\partial}{\partial r} \left( \frac{u_r}{r} \right) = \frac{3\omega r^3}{2(r_s^3 - r^3)} \sin \theta
\]

Stress is related to strain rate by the usual constitutive relation

\[
\sigma_{\phi\phi} = \frac{2}{\eta} \varepsilon_{\phi\phi}
\]

Thus the energy dissipated per unit time is

\[
E = 2\pi \int_{r_s}^r \int_0^\pi \sigma_{\phi\phi} \varepsilon_{\phi\phi} r^2 \sin \theta \, d\theta \, dr = \frac{12\pi \rho \omega}{5(r_s^3 - r^3)} (1)
\]

and the total torque necessary to maintain the flow is

\[
\tau = 2\pi r^3 \int_0^\pi \sigma_{\phi\phi}(r_s, \theta) \sin^2 \theta \, d\theta = \frac{8\pi \rho \omega}{(r_s^3 - r^3)} (2)
\]

Now, the asthenosphere is probably confined between 50-km depth and the seismic discontinuity near 400-km depth, so that we may take $r_s = 6000$ km and $r = 6300$ km. Although
its viscosity is not precisely known, the value is not likely to be much less than $10^{20}$ P [Cathles, 1971]. A typical velocity for plate motions is 5 cm/yr, which corresponds to an angular velocity of $2.5 \times 10^{-18}$ rad/s.

Substituting these values into (1), we find that the energy dissipated is only $0.8 \times 10^{20}$ ergs/s, less than 1% of the energy released by tidal friction. However, from (2) we obtain a value of $1.0 \times 10^{24}$ dyn cm for the torque necessary to maintain this motion. The largest estimate of orbital acceleration of the moon is $-52 \pm 16''/century^2$ [Van Flandern, 1970], so that the total couple exerted on the earth by the moon is probably less than $10^{24}$ dyn cm. This is 9 orders of magnitude smaller than the torque required to drive the lithosphere at 5 cm/yr. Stated another way, the viscosity of the asthenosphere would have to be less than $10^{11}$ P (the viscosity of glucose on a warm summer day) for tidal torques to be important. We conclude that although tidal drag as the tectonic mechanism is energetically feasible, tidal forces are insignificant in lithospheric dynamics.

Some of the speculation concerning the importance of tidal drag has been sparked by Knopoff and Leeds's [1972] calculation that there is a net westward displacement of the lithosphere with respect to Antarctica, which they assumed to be fixed with respect to the mesosphere. Recent models of plate motions with respect to the mesosphere derived from the fixed hot spot hypothesis by Minster et al. [1974] and by Jordan and Minster [1973] indicate that the net westward displacement of the lithosphere is small in comparison with the relative velocities of the fast-moving oceanic plates. The net rotation for their preferred model (AM1) is 0.11º/m.y. about a pole located at 129ºE, 74ºS, which corresponds to a net westward motion of only 1.2 cm/yr at the equator. Minster et al. [1974] state that a model with no net rotation also fits the hot spot data acceptably well. Jordan and Minster [1973] have shown that absolute motion models with net rotations greater than 3 cm/yr are incompatible with the hot spot data. In model AM1 the African, Arabian, Eurasian, and Indian plates all have appreciable (>1 cm/yr) eastward components of velocity, and the Cocos and Nazca plates have eastward velocities exceeding 7 cm/yr. These results can hardly be reconciled with a hypothesis that requires the westward displacement of all lithospheric plates.

The above arguments indicate that tidal forces are not significant in present-day global tectonics and the hypothesis that tidal drag is a driving mechanism should be abandoned. For the moment there remains a discrepancy between the total energy that is known to be dissipated by the tides and the energy that can be accounted for. Integration of the lunar and solar work rates over Hendershott's [1972] recent solution for the global tides yields a dissipation rate of $3.0 \times 10^{20}$ ergs/s, which is about twice Miller's [1966] value of dissipation in the shallow seas but only half the rate necessary to explain the lunar acceleration. More sophisticated calculations will undoubtedly revise upward these estimates of energy dissipation in the oceans. As W. H. Munk has pointed out, significant contributions may come from the internal tides. In any case the eventual explanation will contribute very little toward solving the puzzle of plate dynamics.

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