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TOROIDAL-POLOIDAL PARTITIONING OF PLATE MOTIONS SINCE 120 MA

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Abstract. Changes in plate motions and plate configurations during the Cenozoic and Mesozoic have been investigated extensively, but most geodynamical models have concentrated on present-day plate motions. We have investigated the recent evolution of plate tectonics by examining the history of toroidal-poloidal partitioning of plate motions. Taking into account estimated errors, our results suggest a significant increase in the ratio of toroidal to poloidal motions postdating the Hawaiian-Emperor (H-E) bend at 43 Ma, corresponding to an overall decrease in global plate motions. These changes may reflect greater mantle plume activity in the Mesozoic, but a causal mechanism is not obvious. In general, observed Cenozoic and Mesozoic plate motions do not appear to be random, which implies that they are correlated. We also find perhaps three significant changes in net rotation of the lithosphere with respect to hotspots since 120 Ma.

Introduction

Plate motions at the Earth's surface can be separated into trench-ridge (surface divergence or poloidal field) and transform components (radial vorticity or toroidal field) [*Chandrasekhar*, 1961; *Hager and O'Connell*, 1978; *Kaula and Williams*, 1983; *Forte and Peltier*, 1987] Recently much attention has centered on the fact that there is a significant toroidal component in the Earth's plate motions [*Hager and O'Connell*, 1978; *Forte and Peltier*, 1987; *O'Connell et al.*, 1991, *Olson and Bercovici*, 1991; *Čadek and Ricard*, 1992]. Toroidal motion is not generated by a homogeneous convecting system and results mainly from the presence of Earth's rigid plates [*Ricard and Vigny*, 1989; *Gable et al.*, 1991; *O'Connell et al.*, 1991; *Vigny et al.*, 1991]. Nonetheless, recent analyses [*O'Connell et al.*, 1991, *Olson and Bercovici*, 1991; *Čadek and Ricard*, 1992] suggest that plate motions tend to minimize the toroidal-poloidal ratio for a given plate geometry. This ratio is a function of both the plate boundary geometry and the degree of correlation (non-randomness) among plate motions. Therefore, temporal changes in the toroidal-poloidal partitioning ratio which do not result from changes in plate boundaries alone may indicate changes in the way plate motions are coupled to mantle driving forces or, perhaps, changes in the driving forces themselves.

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Thus the time-dependence of the partitioning ratio, which has only recently been examined [*Čadek and Ricard*, 1992], may provide important clues to understanding the dynamics and history of plate motions.

Theory and Error Analysis

We have calculated the toroidal and poloidal components of plate motions, the toroidal/poloidal ratio and the degree to which it is minimized, and the net lithospheric rotation since 120 Ma using global plate reconstructions [*Larson and Chase*, 1972; *Larson and Pitman*, 1972; *Minster and Jordan*, 1978; *Engebretson et al.*, 1985; *Gordon and Jurdy*, 1986; *Scotese*, 1990; *Engebretson et al.*, 1992] in the hotspot reference frame. For the present we used three absolute motion models [*Minster and Jordan*, 1978 (AM1-2); *Gordon and Jurdy*, 1986; *Gripp and Gordon*, 1990 (HS2-NUVEL1)] to compare different models of the hotspot reference frame. For each reconstruction stage (six Cenozoic and five Mesozoic) we calculated by direct expansion the spherical harmonic coefficients -- to degree and order 50 -- of the surface divergence and radial vorticity given respectively by

$$\vec{\nabla}_h \cdot \vec{v}(\theta,\varphi) = \sum_{\ell=0}^{50}\sum_{m=0}^{\ell} D_\ell^m Y_\ell^m(\theta,\varphi) \qquad (1)$$

$$\left(\vec{\nabla} \times \vec{v}(\theta,\varphi)\right)\cdot \hat{r} = \sum_{\ell=0}^{50}\sum_{m=0}^{\ell} V_\ell^m Y_\ell^m(\theta,\varphi) \qquad (2)$$

where $\vec{v}$ is the surface velocity, a function of colatitude θ, and longitude φ, and $\hat{r}$ is the radial unit normal. The coefficients of the divergence and vorticity expansions are easily converted to a poloidal-toroidal representation of the velocity field. The poloidal and toroidal coefficients are given respectively by $S_\ell^m = \frac{D_\ell^m a}{\ell(\ell+1)}$ and by $T_\ell^m = \frac{V_\ell^m a}{\ell(\ell+1)}$ where a is the radius of the Earth and ℓ the harmonic degree. The velocity spectra for both components decay approximately as ℓ^{-2}. The total toroidal and poloidal velocity components, shown in Figure 1, are given by $\sum_{\ell=0}^{20}\sigma_i^2(\ell)$, where $\sigma_i^2(\ell)$ is the degree variance of either the poloidal or toroidal fields. (We exclude toroidal degree 1 from the calculations in Figure 1 to obtain results less dependent upon the particular plate motion model chosen. This term corresponds to the rotation of the lithosphere with respect to the mantle in the hotspot reference frame. Its value is therefore dependent on the reference frame and plate motion model used. We consider its effect in Figure 3 below.) For the stages since 84 Ma we compute 2σ confidence intervals for all quantities, calculated from formal uncertainties in the relative plate motion pairs [*Gary Acton*, personal comm.]. To these we add the error associated with the plate-Hs rotation vectors estimated from *Molnar and Stock*

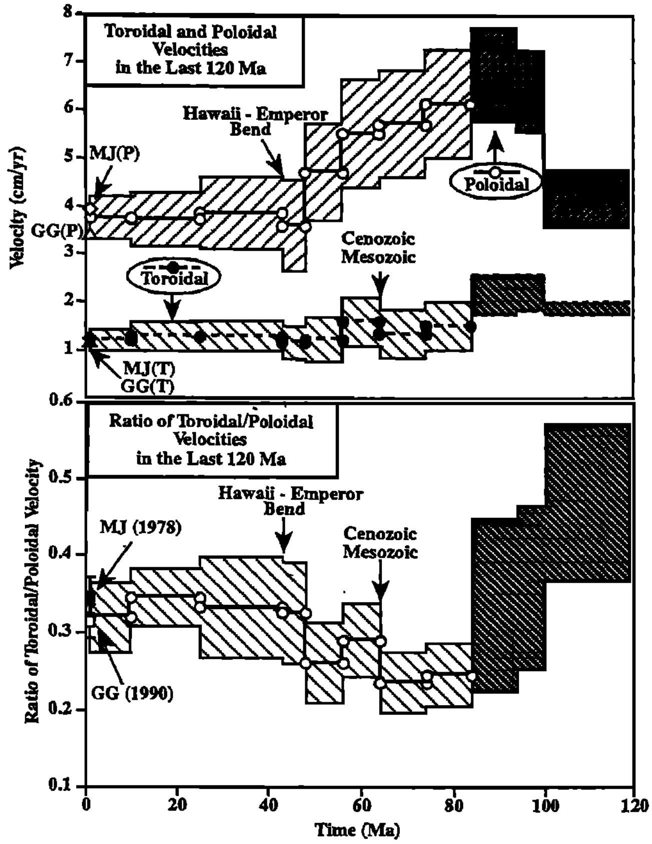

Fig. 1 -- (Top) Toroidal (solid circles (●), dashed line (— —)) and poloidal (open circles (o), solid line (——)) velocities, net rotation not included. The Cenozoic is based on Gordon and Jurdy [1986], and the Mesozoic on Engebretson et al. (1985) and Engebretson et al. (1992). The circles mark the beginning and end of each stage. The light hatched areas (slanted to the right for poloidal and to the left for toroidal) around the solid and dashed lines represent the 2σ confidence contour on the velocities. The dark hatched areas represent the range (not formal uncertainties) of velocities from 84-119 Ma, given two choices of poles [*Engebretson et al.*, 1985; *Engebretson et al.*, 1992]. The open (◇ MJ) and solid rhombohedra (◆ MJ) are the poloidal and toroidal velocity, respectively, for AM1-2, the open (△ GG) and solid triangles (▲ GG) for HS2-NUVEL1, 2σ error bars are smaller than the symbols; (Bottom) Ratio of toroidal/poloidal velocities; net rotation not included. Hatching as in (a). Solid (■) and open (□)squares are the ratios from AM1-2 and HS2-NUVEL1.

[1987]. To take into account the paucity of error information on plates that have since been completely subducted we use the largest error estimates for all times for all plates. The magnitude of the velocity and its uncertainty, shown in Figure 1, is dominated by the Pacific plate, for which we have chosen similar (and probably overestimated) error bounds for all times. This results in 2σ bands of comparable magnitude for all times prior to 10 Ma, while in fact those after 64 Ma should be smaller. For the earlier Mesozoic formal uncertainties are unavailable, so we show the range of results obtained with two alternative sets of poles [*Engebretson et al.*, 1985; *Engebretson et al.*, 1992]. Uncertainties in the positions of the plate boundaries are difficult to quantify and are not included in our error analysis.

Toroidal-Poloidal Partitioning

Figure 1 shows that there is a marked decrease in the overall rate of plate motion from 84 Ma to 48 Ma (late Mesozoic to early Cenozoic). The toroidal/poloidal partitioning ratio (Figure 1) has increased about 30% from ~0.25 at 84 Ma to ~0.35 at present. This increase appears significant given the estimated errors and corresponds with the overall decrease in plate motions. The partitioning ratio appears to also increase with the overall decrease in plate motion in the early Mesozoic, but these older reconstructions are more uncertain. Remarkably, these changes in partitioning (and overall plate motion) are due almost entirely to changes in the poloidal component, while the toroidal component has remained relatively constant.

From a dynamical standpoint it would be most useful to know whether these changes result from changes in the plate boundaries alone, or whether they indicate more fundamental changes in the dynamics of plate motions. One way to elucidate this issue is to test the hypothesis that observed partitioning ratios are the result of random, or uncorrelated, plate motions [*Olson and Bercovici*, 1991], which would imply that statistically significant changes in the partitioning ratio are merely the result of evolving plate boundary configurations. We have calculated partitioning ratios for past plate geometries using random angular velocity vectors for each plate at each stage, similar to the analyses of O'Connell et al. [1991] and Čadek and Ricard [1992]. Figure 2 shows the distribution of 1000 randomizations of the toroidal/poloidal

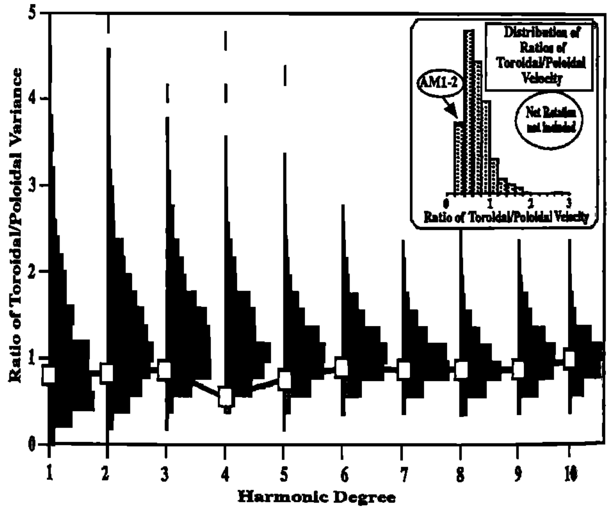

Fig.2 -- Distribution of the toroidal/poloidal ratios of each harmonic degree for a thousand randomizations of pole positions and rotation rates, starting from the plate configuration and poles of AM1-2. The open (□) squares and solid line (——) are the ratios of AM1-2. (Inset) Distribution of the mean toroidal/poloidal velocity ratios for the same initial configuration. The present day ratio given by AM1-2 is represented by the black bar (——). The toroidal velocity does not include net rotation.

ratio for each spherical harmonic degree using the present-day plates, along with the observed present-day (model AM1-2) values. For all degrees shown except degree 1 (which is reference frame dependent), the observed ratio falls toward the lower end of the random distribution. The inset of Figure 2 shows a histogram of total toroidal/poloidal velocity ratios for these randomizations, and the observed value occurs at the lower end of the distribution.

Figure 3 compares the observed toroidal/poloidal ratios since 120 Ma with the means and minima of randomizations computed using past plate configurations. All observed ratios since ~84 Ma fall closer to the minima than to the means. Absolute minima are approached only during the time of the lowest observed ratios. If the percentage of randomizations which fall between the observed and the minimum of a randomization set is less than 1% we say that the observed ratio is a 'minimum'. This criterion is only satisfied for the four consecutive stages from 48-84 Ma. The present is not minimized for any of the three plate motion models, particularly AM1-2 and HS2-NUVEL1, with 20-50% of the randomizations falling below the observed partitioning ratio.

If the observed variations in the partitioning ratio are caused by variations in plate geometry alone, the randomizations should cluster around the observed values, with shifts in the minima tracking changes in the observed ratios. The results in Figure 3 show quite the opposite, i.e., that the observed partitioning ratios are much more nearly minimized (with respect to random plate motions) when the observed ratio itself is small and plate motions are most vigorous. This suggests that the observed change in partitioning at ~48 Ma may not have resulted from changes in plate geometry alone, and that plate motions from ~48-84 Ma were more highly correlated (less 'random') than for more recent times. These results do not support Olson and Bercovici's [1991] suggestion, based on Cartesian kinematic models, that the Earth exhibits uncorrelated plate motions that result in toroidal-poloidal 'equipartitioning'. Observed plate motions are not equipartitioned and do not appear to be random for any of the plate motion models considered.

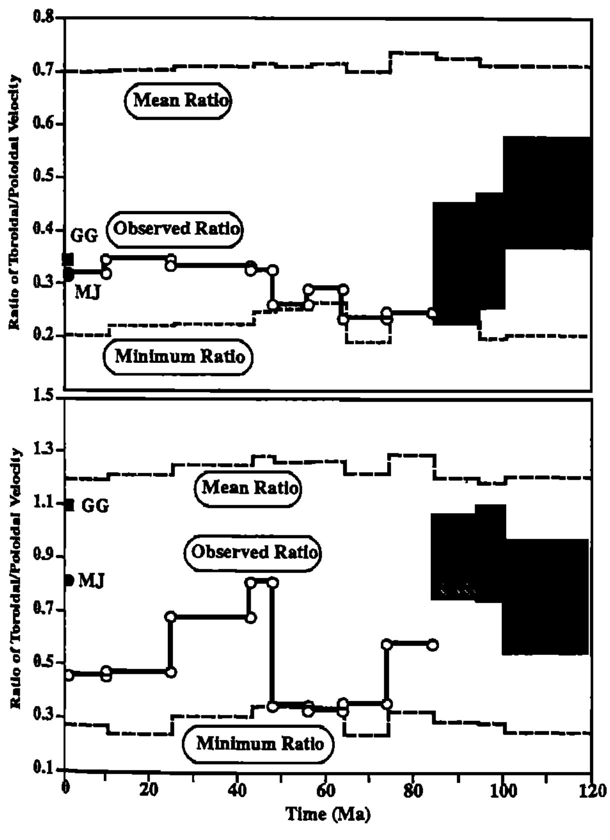

Fig. 3 -- (Top) Mean and minimum (dashed lines (— —) toroidal-poloidal ratios from 1000 randomizations, net rotation not included. The solid line and open circles represent the observed ratios. The two solid symbols (● MJ, ■ GG) are the ratios from AM1-2 and HS2-NUVEL1. Range of values for the Mesozoic as in Fig.1(b); (Bottom) Mean and minimum toroidal/poloidal ratios from 1000 randomizations including net rotation.

Net Lithospheric Rotation

We now consider the effect of including the net rotation of the lithosphere with respect to the hotspot reference frame (toroidal degree 1) in our calculations. Figure 4 shows that there are at least two and possibly three significant changes in net rotation since 84 Ma. The present value is 1.0-1.8 cm/yr [*Gordon and Jurdy*, 1986; *Ricard et al.*, 1991] when absolute motions are referred to all the hotspots. However, other models for present plate motions referred only to Pacific hotspots, marked MJ for AM1-2 and GG for HS2-NUVEL1, give net rotations a factor of 2-3 higher. This ambiguity follows from the fact that Pacific hotspots seem to move with respect to the Atlantic and Indian Ocean hotspots [*Molnar and Stock*, 1987]. The stages preceding (43-48) and postdating (25-43) the H-E bend show the highest net rotation (with respect to all hotspots) in the Cenozoic, as shown by Gordon and Jurdy [1986], and are bounded by periods with low values similar to the present. The high values prior to 84 Ma

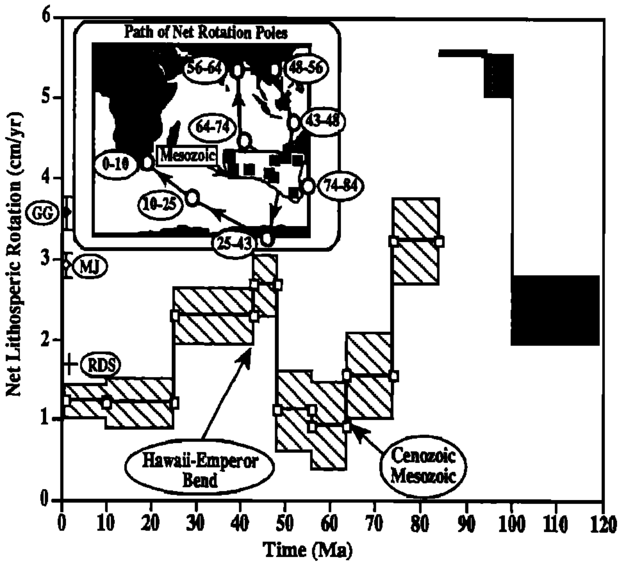

Fig. 4 -- Net rotation of the lithosphere with respect to the mantle. Velocity models and confidence regions as in Fig. 1. The dark hatches slanting to the right from 84-119 Ma is a range of solutions, not formal uncertainties as in Fig. 1. The solid rhombohedron (♦ GG) is the net rotation in HS2-NUVEL1 ; the open rhombohedron (◇ MJ) is from AM1-2 and the cross (+) is the value of Ricard et al. [1991].
(Inset) Path followed by the net rotation axis for the last 84 Ma. The pole location for each stage is identified by an open circle (O) and the time interval of the stage. A range of solutions for the period between 84-119 is indicated by the white area with the solid squares (■) labeled Mesozoic.

are suspect because they result from the large spin of the Farallon plate in these models. In the Cenozoic the axis of net rotation (Figure 4, inset) migrates continuously from the Northern to the Southern Indian Ocean [*Gordon and Jurdy*, 1986; *Čadek and Ricard*, 1992], with the largest change encompassed by the stages preceding and postdating the H-E bend. Mesozoic variations in the axis location are not discernible, except for a migration toward Northern India entering the Cenozoic. Including the net rotation term in the toroidal/poloidal ratio amplifies the temporal changes previously discussed (Figure 3). Moreover, including net rotation in the randomization analyses reinforces the previous conclusion regarding minimization of the toroidal/poloidal ratio, i.e., that absolute minima are only achieved prior to 48 Ma.

Discussion

The most intriguing of our results is the difference between the nature of plate motions in the periods 0-48 Ma and 48-84 Ma: During periods of high spreading/subduction rates (early Cenozoic and late Mesozoic), poloidal motions are more dominant, and the toroidal/poloidal ratio is more nearly minimized with respect to the existing plate geometries. At this point it is difficult to speculate as to the cause of these temporal changes. Nonetheless, it is interesting to note that the changes we observe are preceded by an apparently intense period of mantle plume activity [*Larson*, 1991; *Richards et al.*, 1991]. Mantle plumes may cause more dominantly divergent plate motions, since they tend to create new spreading centers and triple junctions. Speculations aside, our results suggest that recent plate motions, which appear to be driven largely by subduction and oceanic plate thickening [*Hager and O'Connell*, 1981] may not be a reliable guide to more vigorous regimes of plate tectonics in the past.

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