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# The possible reflection of mantle discontinuities in Pacific Geoid and bathymetry

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**Abstract.** Geoid anomalies over the Pacific plate show lineated undulations approximately oriented in the direction of absolute plate motion. Conventional spectral analyses have revealed a broad range of dominant wavelengths, but as filtering is direction-dependent, results are difficult to interpret. Here, we present a new approach designed to quantify the correlation between the geoid undulations and Pacific plate motion. We calculate the spatial correlation between geoid lineations and arbitrarily oriented, axisymmetric sinusoidal undulations of given wavelength. The pole (i.e., the orientation) of the sinusoid which maximizes the correlation is determined. The distance between this pole and the Pacific hotspot pole is calculated and represents a measure of how well a geoid lineation of a given wavelength aligns with Pacific plate motion. This distance varies with undulation wavelength and has discrete minima for several wavebands. These minima, moreover, occur at wavelengths whose values are remarkably close to the depths of seismically inferred mantle discontinuities. A similar analysis of available bathymetry corroborates these findings. If these correlations are significant, they suggest that geoid (and bathymetry) undulations are influenced by mantle structure and thus are likely to reflect mantle dynamics.

## Introduction

The availability of altimeter data from the Seasat and Geosat missions has provided unprecedented coverage of the Earth's gravity field over oceanic regions [*Haxby*, 1987; *Sandwell and McAdoo*, 1990], and facilitated rapid advances in our understanding of lithospheric and sublithospheric processes. One of the major findings during the last decade was the discovery of a lineated pattern of gravity anomalies over the younger portions of the fast-moving Pacific and Indo-Australian plates [*Haxby and Weissel*, 1986]. The wavelengths of the gravity undulations (150–300 km) are short enough to accommodate several possible explanations, most notably small-scale mantle convection [*Buck and Parmentier*, 1986; *Haxby and Weissel*, 1986], tensional cracks and magmatic intrusions [*McAdoo and Sandwell*, 1989; *Winterer and Sandwell*, 1987], and regional variations in the lithospheric cooling process [*Cazenave et al.*, 1992]; their origin thus remains controversial. More recently, intermediate-wavelength (400–600 km) geoid undulations have also been detected after along-track filtering of the Seasat altimeter data [*Baudry and Kroenke*, 1991; *Maia and Diament*, 1991]. These lineations appear to be roughly parallel to the absolute motion of the Pacific plate (Fig. 1) and are continuous across fracture zones; some undulations have linear volcanic seamount chains at their crests. Systematic filtering has revealed geoid anomalies which are preferentially elongated in the east-west direction and have average amplitudes of ~0.3 m and dominant wavelengths of 750 km and 1100 km [*Cazenave et al.*, 1992]. While the longer wavelength geoid undulations make a mantle dynamic origin more probable, a lithospheric mechanism can not be precluded since interpretation of geopotential data is nonunique (i.e., many different mechanisms may give rise to identical geopotential anomalies).

While previous studies [*Baudry and Kroenke*, 1991; *Cazenave et al.*, 1992; *Maia and Diament*, 1991] have clearly demonstrated that the lineated geoid undulations are not artifacts of filtering, they disagree about the dominant wavelengths of the undulations, with estimates ranging from 400 to 1100 km. Some of this scatter may be related to directional bias introduced by examining power spectra of sea-surface heights along satellite ground tracks [*Cazenave et al.*, 1992; *Maia and Diament*, 1991] or along north-south profiles sampled from gridded data sets [*Baudry and Kroenke*, 1991]. Taken together, it appears evident that while the geoid over the Pacific plate exhibits significant power at many wavelengths, the inferred dominant wavelength is dependent on the direction along which one analyzes the data.

Previous studies of Pacific gravity and geoid undulations have noted their apparent alignment with the absolute motion of the Pacific. This alignment is deemed important as it is generally interpreted as a result of upper mantle convection. It has long been known that three-dimensional convection patterns will be aligned into cylindrical rolls by the shearing of an overriding plate [*Richter and Parsons*, 1975; *Sparks and Parmentier*, 1993], although this alignment only occurs above some critical plate velocity [*Rabinowicz et al.*, 1990]. However, the alignment of the geoid/gravity undulations with plate direction has never been rigorously demonstrated, and we seek herein to quantitatively assess this alignment.

## Directional Analysis of Geoid and Bathymetry

First, we determine the actual orientation of the Pacific geoid undulations by calculating their correlation with spherically axisymmetric sinusoidal undulations defined in an arbitrary reference frame (Figure 2). We use a combined Seasat/Geosat altimetric geoid (W. F. Haxby, pers. comm., 1990.) Since the geoid undulations appear at several wavelengths, we carry out this calculation for a full spectrum of sinusoid wavelengths (150–2000 km). To avoid bias due to filtering we use a spherical harmonic geopotential model to remove only the longest wavelengths (> 3200 km) from the data set and cosine-taper the coefficients for the intermediate wavelengths (1600–3200 km). Original features with wavelengths < 1600 km thus remain unaltered. We choose to limit the data area to a polygonal portion of the plate where the lineations are most clearly developed (see Figure 1). Next, we search for the north pole of the sinusoid's reference frame that maximizes the geoid-sinusoid correlation in



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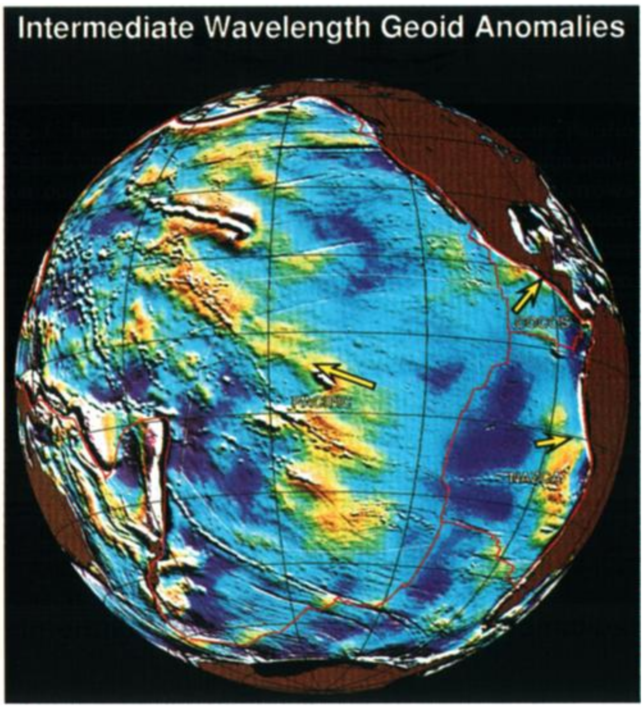


Fig. 1. Intermediate wavelength geoid anomalies over the Pacific ocean from combined Geosat/Seasat altimetry. The white polygon outlines the region studied in this paper. Yellow arrows indicate direction and relative amplitude of absolute plate motion for the Pacific, Nazca, and Cocos plates. The lineated anomalies can best be seen subparallel to the direction of absolute motion for the Pacific plate and obliquely cross major fracture zones in the area. In this geoid image the lineations are most visible north of the yellow arrow indicating Pacific plate motion as subtle undulations superimposed on the background geoid.

a least-squares sense. Figure 3 shows examples of the spatial variations of the correlations for both geoid and bathymetry at two wavelengths. The point of maximum correlation represents the location of the best-fitting sinusoid pole. The pole for the 300-km-wavelength sinusoid (cross-hair) is very close to the Pacific hot spot Euler pole (circle at ~68°W/69°N), while the pole for the 750-km-wavelength sinusoid are far from the hot spot pole. To constrain the calculations we only searched for poles on a grid surrounding the hot spot pole (the longitude-latitude extent of this area is indicated in Figure 3). It is possible that global maxima exist outside this area; however, undulations aligned with poles that far away are certainly not related to Pacific plate motion. Finally, for all sinusoid wavelengths, the spherical distance $\Delta$ between this optimal pole and the Pacific hot spot Euler pole (at ~68°W/69°N) is calculated. The great circle distance $\Delta$ is a measure of how closely the geoid lineations of a given wavelength align with Pacific plate motions. We further accentuate this dependency by plotting the inverse distance ($\Delta^{-1}$) as a function of wavelength. For completeness, we subject the ETOPO5 bathymetry data [*National Geophysical Data Center*, 1988] to the same analysis (after removing the age$^{1/2}$-dependency [*Parsons and Sclater*, 1977]).

## Results

Results indicate that $\Delta^{-1}$ varies strongly with geoid undulation wavelength (Figure 4a) and appears to have maxima within several discrete wave bands, centered on wavelengths equal to 160 km, 225 km, 287 km, 400 km, 560 km, 660 km, 850 km, 1000 km, and 1400 km. For other wavelengths, the best-fitting

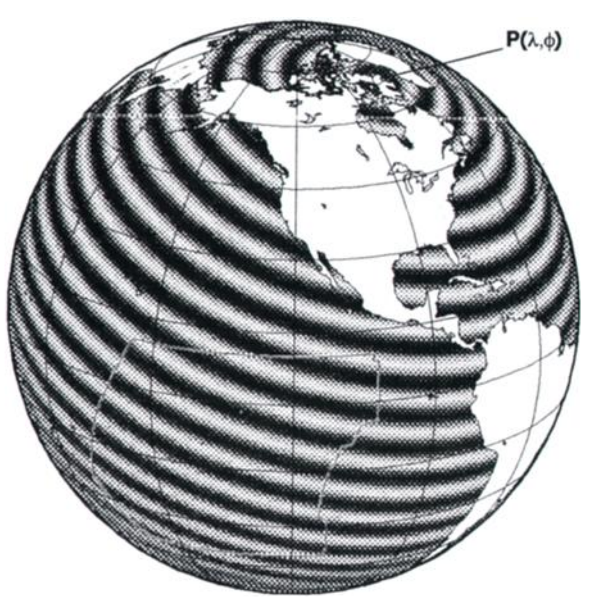


Fig. 2. An example of axisymmetric sinusoidal geoid undulations for a 600 km wavelength. Light and dark areas correspond to positive and negative amplitudes, respectively. We search, using a grid centered on the Pacific hot spot pole, for the pole orientation (P) for this undulation wavelength that gives the maximum correlation with the data shown in Fig. 1. Only data inside the polygon were used in the optimization.

sinusoid poles are frequently more than 25 spherical degrees away from the Pacific hotspot pole (i.e., $\Delta^{-1} < 0.04$). The shortest wavelengths (< 300 km) determined by this method are most likely the so-called "Haxby-lineations" first detected in gravity anomalies derived from Seasat altimetry [*Haxby and Weissel*, 1986]. The remaining dominant wavelengths correspond to the geoid undulations reported a few years later [*Baudry and Kroenke*, 1991; *Cazenave et al.*, 1992; *Maia and Diament*, 1991], including a 1400-km wavelength undulation which appear on power spectra of along-track sea-surface heights [*Cazenave et al.*,

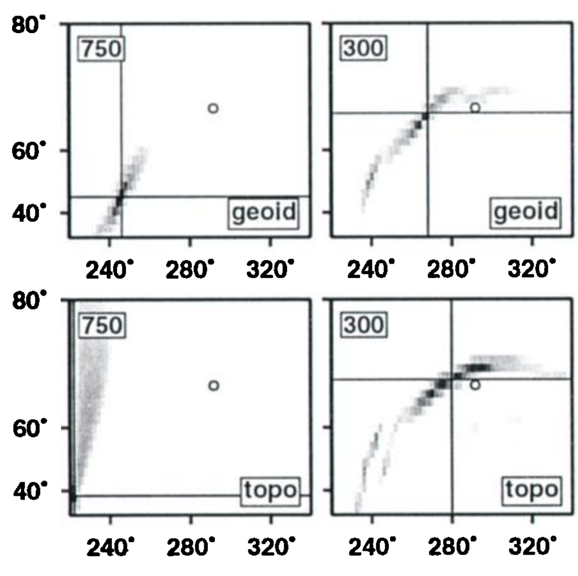


Fig. 3. Example of the correlations between the axisymmetrical sinusoid and the data for a range of sinusoid poles. Black indications the highest correlation; white areas have correlations less than 70% of the maximum. The elongated shape of the correlations reflects the fact that poles away from the crosshair but along a great circle normal to the actual undulations may still correlate well.

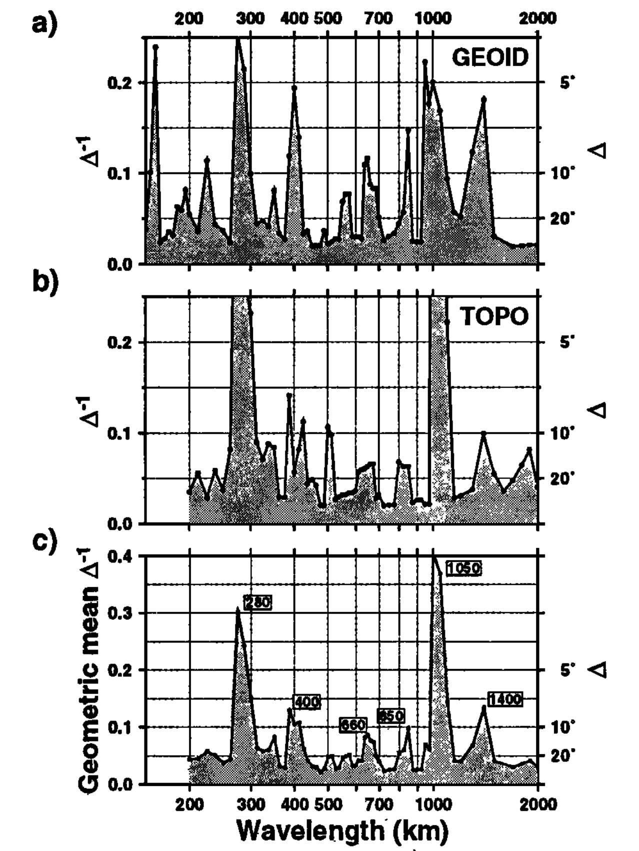


Fig. 4. a) Inverse distance, $\Delta^{-1}$, in spherical degrees between geoid undulation poles and Pacific hotspot pole at 68°W/69°N. Distances range from 4.5° to ~50°. b) The inverse distance ($\Delta^{-1}$) as a function of wavelength for bathymetry in the same region. c) The geometric mean of $\Delta^{-1}$ for the two data sets. This transformation highlights the wavelengths associated with geoid and bathymetry undulations that are approximately copolar with the Pacific plate motion. It should be noted that while the geoid coverage in this area is uniform the bathymetry coverage is much sparser.

1992]. The variation in $\Delta^{-1}$ for bathymetry is displayed in Figure 4b. It is evident that the dominant wavelengths determined from the geoid are to a large extent also present in the bathymetry. This connection is further highlighted in Figure 4c which presents the geometric mean of $\Delta^{-1}$ for the two data sets; this estimate will be large only when both the geoid and bathymetry poles are close to the hot spot pole. We have labeled the most pronounced wavelengths that have copolar expressions in both geoid and seafloor relief. It should be noted that while the bathymetric undulations cannot be seen directly in bathymetry maps, their presence has been previously demonstrated by two-dimensional filtering [*Cazenave et al.*, 1992].

## Significance of Correlations

While the location of maximum correlation for each wavelength is well resolved (Figure 3), the correlations themselves are rather small ($r < 0.1$). This occurs because the correlation coefficient is normalized by the standard deviation of the entire geoid (or bathymetry) data set, while most of the observed data are not due to copolar undulations, e.g., geoid anomalies associated with the "Superswell" [*McNutt and Fischer*, 1987], fracture zones, isolated seamounts, etc. (Unity correlation would mean the entire geoid looked like the synthetic undulation in Figure 2.) Hence, rather small correlations between the synthetic and geoid-bathymetry undulations can be expected and standard tests will render the correlations statistically insignificant. We are therefore primarily concerned with relative values of the correlations. Moreover, we have tested our technique on random Gaussian noise and found correlation maxima two orders of magnitude smaller than those inferred from real data, thus implying that the correlations with the data are not random. However, we feel the strongest support for the significance of the geoid correlations comes from the bathymetry analysis. Although the bathymetry coverage in this region is sparse, it is clear that the bathymetry results corroborate the geoid analysis.

## Discussion: Possible Reflection of Mantle Discontinuities

An intriguing outcome of this study is that the dominant wavelengths are very nearly equivalent to the depths of various seismic discontinuities in the mantle. Several well-documented discontinuities exist in the Earth's mantle, most notably the ones at depths of 410 km (presumed to be the exothermic olivine-spinel phase change [*Ringwood*, 1975]) and 660 km (probably the endothermic spinel-perovskite phase change [*Ito and Takahashi*, 1989]), the latter separating the upper and lower mantles. Recent seismic models of Earth's radial structure have given compelling evidence for a discontinuity at 520 km depth [*Shearer*, 1990], and tenuous suggestions of ones at 220 km [*Anderson*, 1979], 840 km [*Shearer*, 1990], 700 km and 900 km [*Revenaugh and Jordan*, 1991]. Of the eight dominant wavelengths indicated in Figure 4a, six of them are within 5% of the depth of a distinct or suggested discontinuity. The number of dominant wavelengths that are nearly equivalent to discontinuity depths argues against this correlation being a coincidence. It would seem possible, therefore, that the geoid undulations aligned with the Pacific plate motion are reflecting mantle structure.

If the apparent relation between the copolar geoid/bathymetry undulations and mantle discontinuities is significant, it suggests that geoid and bathymetry undulations are influenced by mantle dynamics. In general, the geoid expression of complex mantle dynamics will be difficult to infer from surface observations since lithospheric processes overprint the mantle contribution. Moreover, the bathymetric expression will be subdued by the dampening effect of the elastic lithosphere and sedimentation. However, in the region of the equatorial Pacific, plate motion possibly organizes mantle flow into coherent, axisymmetric structure whose geoid and bathymetry signatures are detectable with the technique presented here.

While mantle convection may be a first obvious candidate for the cause of the undulations, it cannot easily explain the above results. First, it is not clear why so many discontinuities should influence the scale of convection cells. While the 660 km phase change may impose multi-layer flow [*Tackley et al.*, 1993; *Weinstein*, 1992], the 410 km boundary should facilitate cross-boundary flow [*Schubert et al.*, 1975]. Unless the destabilizing effect of an exothermic phase transition imposes a preferred wavelength on convection, the 410 km discontinuity should have little influence on cell size. Secondly, if convection cells between the surface (or base of the lithosphere) and a discontinuity are the cause for the undulations, then they have anomalously small aspect ratios. Convection is, however, not necessarily the only cause for the undulations. Other forms of mantle dynamics are also possible, e.g., multiple, long-lived mantle plumes [*Fleitout and Moriceau*, 1992] and superplastic instabilities associated with phase changes [*Parmentier*, 1981]. Furthermore, the correlation for wavelengths in the 800–1000-range may possibly reflect periodicities in the hot spot distribution [*Yamaji*, 1992].

## Conclusion

We have quantitatively demonstrated an apparent correlation between the direction of absolute plate motion and alignment of geoid and bathymetry anomalies for several discrete wavelengths. Our analysis reconciles the differing results of earlier studies [*Baudry and Kroenke*, 1991; *Cazenave et al.*, 1992; *Maia and Diament*, 1991] by showing that all the previously reported lineations are indeed present in the Pacific geoid and aligned in the direction of absolute plate motion. Interestingly, the wavelengths of these lineations possibly correspond to the depths of seismic discontinuities in the upper and lower mantle. The agreement between the analyses of geoid and bathymetry data lends credence to these results. Our findings possibly vindicate a long held belief that the geoid is diagnostic of internal mantle dynamics [*Richards and Hager*, 1984; *Runcorn*, 1967]. Traditionally, the relation between large scale geoid anomalies and mantle flow is indirectly inferred from the combination of geoid-topography correlations and fluid-dynamic models; this relation is somewhat nonunique. If our findings are significant, they constitute the first direct evidence of a distinct mantle signature in the geoid. Further analyses of the geoid and bathymetry undulations and validation of the correlation technique presented here will be necessary to attach statistical significance to such claims.

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