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THE UPPER MANTLE DEGREE TWO PATTERN: CONSTRAINTS FROM GEOSCOPE FUNDAMENTAL SPHEROIDAL MODE EIGENFREQUENCY AND ATTENUATION MEASUREMENTS.

Barbara Romanowicz, Genevieve Roult, and Thomas Kohl

Laboratoire de Sismologie
Institut de Physique du Globe de Paris

Abstract. We have analyzed fundamental spheroidal mode spectra obtained from very long period Geoscope records, in terms of global distribution of eigenfrequencies and attenuation. With a new data set and a different data processing approach, involving time variable filtering and the removal of higher order effects in the spectra, we confirm the strong upper mantle degree two signature in the eigenfrequency data. The higher frequency content of the Geoscope spectra allows us to put better constraints on the depth range at which this pattern originates, which appears to be somewhat shallower than was proposed before. While some effect may persist down to the bottom of the transition zone, the frequency signature of the strongest degree two pattern requires an S velocity heterogeneity concentrated in the depth range 300-500 km and this signature is also apparent in the distribution of Q, which is indicative of a probable thermal origin. The data also resolve a shallow degree 2 pattern, well explained by heterogeneity spanning from the surface to depths of about 300 km, and associated with the distribution of tectonic provinces. It is shifted by about 45° with respect to the deep degree 2 pattern, and its expression in the Q data is not clear.

Introduction

Analysis of global long period digital data made available during the past ten years has revealed a very strong degree 2 signature originating in the earth's upper mantle. This was first discovered by Masters et al.(1982) as a result of frequency shift measurements for fundamental spheroidal modes, made on vertical records from the IDA network. It was later confirmed in studies of global long period surface wave data (Souriau and Souriau, 1983; Woodhouse and Dziewonski, 1984; Nataf et al., 1986) which have led in particular to the now well known first generation 3D models of the upper mantle. The degree 2 pattern was attributed by Masters et al.(1982) to heterogeneity in the transition zone (420-670 km) and no corresponding signature has so far been found in normal mode attenuation data (Masters and Gilbert, 1983; Davis, 1985). However, the IDA network data used in these studies did not permit measurements beyond angular orders 40 to 43.

We present here first results of an analysis of spheroidal mode observations from very long period records at globally distributed GEOSCOPE stations, as these have gradually come into operation in the past 4 years. The advantage of these modal data is the wider frequency range over which measurements are possible, leading to better depth resolution for the inferred lateral heterogeneity. We show here how the extension of the available band to higher frequencies, combined with our data analysis approach, brings additional constraints on earlier findings concerning the upper mantle degree 2 pattern, both from eigenfrequency and modal attenuation measurements.

Data analysis

We have used all available high quality vertical component records of length greater than 20 hours, observed since 1983 on Geoscope stations for earthquakes greater than Ms≃7, plus a number of additionnal records obtained in the interval 1977-81 on French long period stations (Blum and Gaulon, 1971) as well as a few IDA records (Agnew et al., 1976) to fill holes in the global distribution. This yields a total of 120 records, which provide a reasonably good coverage of the earth in terms of great circle paths.

In order to extract the fundamental spheroidal mode, variable filtering is applied to the data (Cara, 1973) according to group velocity dispersion determined separately for R_1, R_2 and R_3 trains. The resulting time series are tapered and Fourier transformed and periods of peak maxima are measured as described in Roult and Romanowicz (1984). The eigenfrequency shifts with respect to PREM exhibit the characteristic fluctuations as a function of angular order, well described by higher order asymptotics (Romanowicz and Roult, 1986). In order to remove the higher order effects, low pass filtering with respect to angular order ℓ is applied to the frequency shift series, and the resulting smoothed values are kept. Zeroth order correction for ellipticity is then applied according to the formulation of Dahlen(1975) and Dziewonski and Sailor(1976). Figure 1 gives two examples of relative frequency shift plots thus obtained, before and after smoothing. Several points are worth noting here: measurements are generally possible from Geoscope records in the angular order range ℓ=10 to ℓ=65-70 (periods down to T≃135 sec). Also, the frequency shift curves associated with the largest positive shifts (Figure 1a) have a distinctly different shape from those associated with the largest negative shifts (Figure 1b) indicating a different depth distribution for the corresponding heterogeneity of structure. When plotted as a function of pole position at given angular orders, the smoothed frequency shifts display the characteristic pattern dominated by degree two. This is illustrated in Figure 2 for angular order ℓ=30. Maps at other angular orders look similar.

The Q measurements are obtained from the filtered spectra using an amplitude decay method as described in Roult (1975). No direct correction for higher order effects is possible in the manner applied to eigenfrequency data, although such effects on Q have been previously predicted (Davis, 1985) and observed (Roult and Romanowicz, 1984), since only rarely did we have Q measurements on the same record for a sufficient number of consecutive angular orders. Instead, averaging over 5 consecutive angular orders is performed for each record, yielding a total of 80 globally distributed measurements at angular orders ℓ=20,25,30...As already noted in previous studies, the degree two pattern, if it exists, is not as obvious in the Q plots as a function of pole position. Figure 3 gives an example, for ℓ=45, in which we do note, however, broad alternating regions of positive and negative anomalies.

The available frequency shift and Q measurements can further be analyzed in terms of local functionals of the earth's structure and their depth dependence, and will be the subject of a forthcoming paper (Roult et al., in preparation). We wish to concentrate here on the question of the degree two pattern, its depth extent and nature.

Degree 2 pattern in the eigenfrequency measurements.

Using the dataset obtained after smoothing, and then following an approach similar to that of Masters et al. (1982) we

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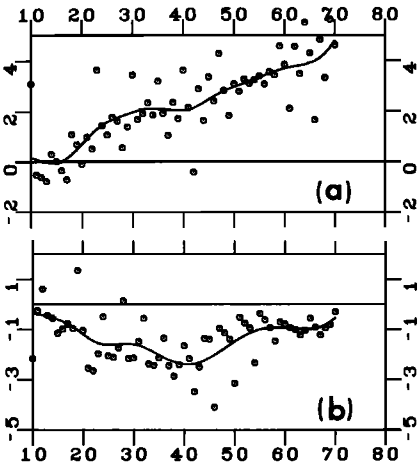

Fig. 1. Examples of relative frequency shift plots (with respect to PREM) as a function of angular order ℓ (in abscissa), before (circles)and after (continuous line) smoothing.a) A typical "fast" path: the Kurile event of 03/24/84 observed at TAM, Algeria. The pole of the corresponding great circle is at latitude =24.5° S and longitude = 84.54°E. b) A typical "slow" path: the Chagos event of 10/30/83 observed at PAF, Kerguelen. The pole is at latitude 1.8°S and longitude 162.3°E. This path goes right along the Mid Indian Ridge and the East Pacific Rise. A conservative estimate of error on the smoothed frequency shifts is on the order of 0.3°/$_{00}$ over the frequency band considered.

have obtained the spherical harmonics expansions of the relative frequency shift distributions up to degree and order 2, between angular orders ℓ=10,65. The degree two pattern accounts for 65-75% of the data variance between degrees ℓ= 16 and 50, extending beyond ℓ=40 results found in previous studies, while the variance reduction is only slightly improved when including terms up to order 4 or 6, the degree and order 4 terms being particularly small. In Figure 4, we have plotted the power in degree 2 as a function of angular order. The striking feature in Figure 4 is the clear maximum in degree two power at around ℓ=45. This maximum occurs in a range where more than 100 out of the maximum 120 measurements were available and is stable with respect to spatial averaging of the data. Masters et al.(1982) had measurements only up to ℓ=40-43 and inferred, from the shape of their power curve(which seemed to level off beyond ℓ=35), an S velocity heterogeneity located in the mantle transition zone. Our results seem to indicate that the primary source of the degree 2 pattern should in fact be located at somewhat shallower depth,

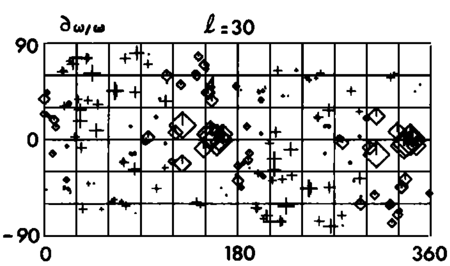

Fig. 2. Relative frequency shifts with respect to PREM as a function of pole position for angular order ℓ=30. Diamonds are negative shifts, crosses positive shifts. Symbols are proportionnal to the amplitude of the shifts. Largest symbols correspond to frequency shifts on the order of 0.35% in absolute value. The pole is that of the great circle containing epicenter and station and the patterns as plotted do not correspond to the geographical distribution of lateral heterogeneity.

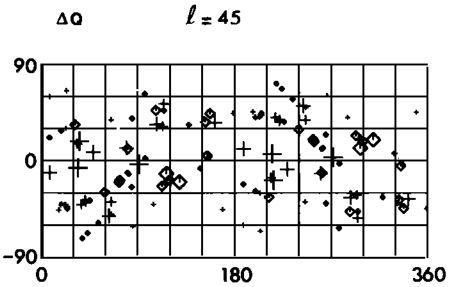

Fig. 3. Attenuation measurements as a function of pole position for angular order ℓ=45, expressed as shifts with respect to PREM.There are four sizes of symbols. The smallest corresponds to ΔQ=0-25, the largest to ΔQ=75-100, in absolute value. Crosses indicate positive shifts, diamonds negative shifts.

since the depth of maximum sensitivity for angular orders 40-45 is on the order of 300-400 km. We find it even more instructive to examine the amplitude of each degree 2 coefficient individually, as shown in Figure 5. The degree 2 expansion of the relative frequency shift is here expressed in the form:

$$\frac{\delta\hat{\omega}(\Theta,\Phi)}{\omega} = \frac{\delta\omega_0}{\omega} - \frac{1}{2}\sum_{m=0}^{m=2} X_2^m(\Theta)\,(C_{2m}\cos m\Phi + S_{2m}\sin m\Phi)$$

where X_2^m are normalized Legendre functions according to:

$$X_\ell^m(\Theta)=\sqrt{\frac{2\ell+1}{4\pi}\,\frac{(\ell+m)!}{(\ell-m)!}}\;P_\ell^m(\Theta)$$

$\delta\omega_0$ is the degenerate frequency shift at angular order ℓ and (Θ,Φ) are the coordinates of the great circle pole. The C's and S's are then the degree 2 coefficients of the corresponding local frequency distribution (Backus, 1964).

Figure 5 indicates that, not only does the degree 2 effect come mainly from the ℓ=2, m=2 terms, as known previously, but that the signature present in Figure 4 comes mainly from

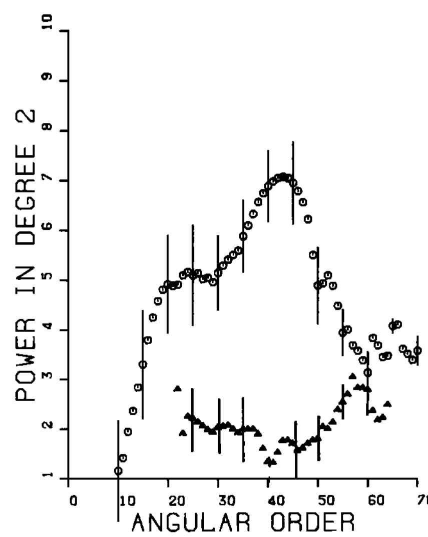

Fig. 4. Power in degree 2 for the relative eigenfrequency shift measurements, as a function of angular order.(O), our data; (Δ) Okal's regionalized model. Error bars reflect the scatter in the data.

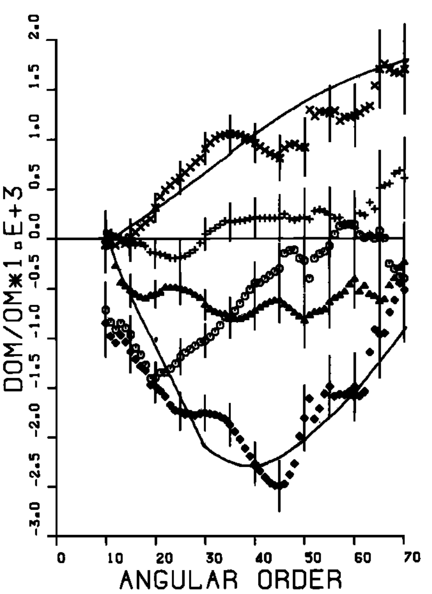

Fig. 5. Individual degree 2 coefficients as a function of angular order, with 1σ error bars: C_{20}○ ;C_{21}△ ;S_{21}+ ;C_{22}× ;S_{22}◇ . Modelling of the ℓ=2,m=2 terms with heterogeneity localized in radius is shown by continuous lines: anomaly concentrated between 300 and 500 km for S_{22}, between 80 and 300 km for C_{22}. Error bars reflect the scatter in the data. A formal error analysis leads to error estimates at most one third of those displayed here.

the S_{22} term. There are then 2 significant upper mantle degree two components. One, associated with the $S_{22}\sin 2\lambda$ term is best modelled with heterogeneities localized in radius between 300 and 500 km, as shown in Figure 5. For this component, slow velocities are centered in the Pacific and Central Indian Ocean. It is noteworthy that slow anomalies in this depth range have been detected in regional dispersion studies in the Pacific ocean (Cara, 1979; Wielandt and Knopoff, 1982). The slower fall off at low angular orders, with a plateau around ℓ=20-30, indicates however that some heterogeneity persists at least down to the bottom of the transition zone. This may permit to reconcile previous results on the depth extent of the degree 2 pattern, some favoring anomalies in the 400-670 km depth range (Masters et al., 1982; Woodhouse and Dziewonski, 1984), others, in the depth range 250-450 km (Nataf et al., 1986).

The next most significant degree 2 component, coming from the $C_{22}\cos 2\lambda$ term, is well modelled by heterogeneity distributed in a layer starting at shallow depth and reaching about 300 km. This component is well correlated with the distribution of ridges and subduction zones, and is present in the degree 2 expansion of Okal's(1977) regionalized model. We believe it represents the degree 2 pattern associated with shallow tectonic heterogeneity (Kawakatsu, 1983). On the other hand, the degree 2 term associated with S_{22} is not present in the regionalized model, as can be seen for instance in Figure 4, where we have plotted, for comparison, the power in degree 2 contained in the model of Okal(1977), taking the same sampling of the sphere as with our dataset. It is a fortunate coincidence that the position of the Greenwich meridian permits such a separation of the two components of upper mantle degree 2. The optimal reference longitude, which maximizes the peak in S_{22} is on the order of 11° W. The deeper degree 2 pattern, represented by S_{22} sin2λ, is rotated by 45° with respect to the shallow one. These numbers are only approximate, since they assume that each degree two pattern can be modelled by heterogeneity localized in a single layer. They are compatible with inferences made by Woodhouse and Dziewonski (1984) on the basis of their M84 model. We also note in Figure 5 the large ℓ=2, m=0 term at low angular orders, opposite in sign to the ellipticity of figure correction, as reported previously (Silver and Jordan, 1981; Masters et al, 1982). This term peaks around ℓ=20 and our broad frequency range allows it to be modelled rather easily by heterogeneity localized between 550 and 800 km. The rapid fall-off at lower ℓ precludes concentration in the lower mantle. This indicates that it could be associated with the 670 km discontinuity whose ellipticity of shape could be larger than accounted for by the classical ellipticity corrections. This feature, as all other reported here, is very stable with respect to our data averaging procedure, so it is unlikely that it could be due to spatial aliasing. We will present elsewhere the degenerate eigenfrequencies $\delta\omega_0$ obtained, which are in good agreement with those obtained by Masters et al. (1982) for the lower angular order range.

Degree two pattern in Q measurements.

Evidence for regional variations in global Q measurements has been reported previously (Nakanishi, 1979; Roult, 1982). In particular, a distinct correlation of low Q values with the fraction of great circle path contained in young oceans has been observed (Roult, 1982). Although the degree two pattern in our data is not as striking to the naked eye in the ΔQ distributions, pole locations corresponding to the largest negative shifts in eigenfrequencies do agree with those corresponding to lowest Q values (Figure 3). We have therefore analyzed our data, after averaging over several consecutive angular orders as described above, in terms of degree 2 expansion, in the same way as was done for eigenfrequencies. As expected, the variance reduction obtained is very poor especially at low angular orders. However, it reaches 20% between angular orders 40 and 50, the range in which the peak in degree 2 power is observed for eigenfrequencies. If we now plot the amplitude of the individual ℓ=2,m=2 coefficients as a function of angular order, as shown in Figure 6, we observe a distinct peak in the amplitude of the S_{22} term between ℓ=40,50 reaching about 20%. C_{22} has no such trend but there is some indication of higher Q values at high angular orders (shallow depths). The S_{22} term also has the correct sign, as would be expected from a correlation of effects in S velocity and attenuation. These results are moreover stable with respect to the way our data are averaged over several consecutive angular orders. The error bars given in Figure 6 correspond to a formal error analysis obtained using the inversion method of Tarantola and Valette (1982), assuming a conservative error of 10% on the Q measurements. All these elements tend to indicate that we are indeed observing an uppermantle degree two in Q, correlated with that expressed in the eigenfrequency shifts and originating at depths around 300 km. We infer that there must be some strong thermal hetero-

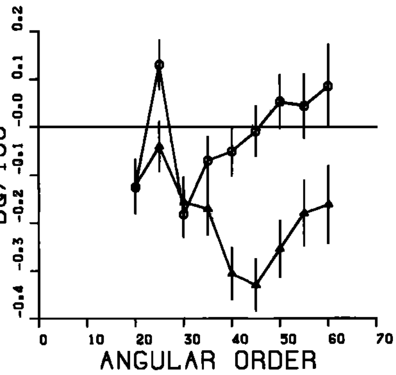

Fig. 6. Degree 2 expansion of Q measurements with 1σ error bars, expressed as departures from PREM: ○ C_{22}; △ S_{22}. Error bars obtained by formal error analysis.

geneity in this depth range, with warm regions somewhat offset with respect to the fast spreading ridges.

Conclusions

On the basis of accumulating data available at the now 15 globally distributed GEOSCOPE stations, it is now possible to put more constraints on the depth extent and nature of the upper mantle degree 2 pattern, observed until now with data spanning a narrower band of frequencies. From the analysis of fundamental spheroidal mode eigenfrequency shifts, it appears that the degree 2 pattern in S velocities has two components. The deeper one, associated with the S_{22} term, originates in the depth range 300-500 km, somewhat shallower than was previously thought. The low velocities in this depth range are correlated with low Q values, as obtained from a degree 2 expansion of attenuation measurements, indicative of a thermal origin for this component. The shallow one, expressed in the C_{22} term, is well modelled by a layer extending from near the surface to about 300 km depth and represents the degree 2 content of the tectonic regionalization. We confirm the observation of a negative C_{20} term which could perhaps be related to excess ellipticity at the 670 km discontinuity.

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