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Reply to comment by L. Cathles and W. Fjeldskaar on 'The inference of mantle viscosity from an inversion of the Fennoscandian relaxation spectrum'

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The analysis of Mitrovica & Peltier (1993; henceforth 'MP') involved inferences of mantle viscosity based on Bayesian inversions of the Fennoscandian relaxation spectrum (henceforth 'FRS'). The inversions yielded constraints on the average viscosity within a set of radial regions resolved by the data, and quantified various trade-offs associated with the inference. The MP study also used forward calculations to predict the relaxation spectrum for a set of nine viscosity models. The inversion-derived constraints were then used to determine the cause of any misfit between these predictions and the observational constraints on the FRS. One of the models chosen in this exercise, labelled LVZ, was characterized by the elastic structure of the seismic model PREM (Dziewonski & Anderson 1981), an elastic lithosphere of thickness 70 km, and a 90 km thick sublithospheric region of low (2×10^{19} Pa s) viscosity overlying an isoviscous, 10^{21} Pa s, mantle. The χ^2 misfit between the observed FRS and the spectrum computed using the LVZ model (~ 295) was significantly in excess of the 99 per cent confidence limit (~ 74).

The comment by Cathles & Fjeldskaar (1996; henceforth 'CF') is directed toward results associated with the LVZ model only. In particular, CF argue that: (1) the LVZ model is a 'miscalculation' of their preferred model for the region, which they label 'FC'; and (2) their own calculation of the relaxation spectrum using the LVZ model differs from the MP prediction—they are able to reproduce the MP results only by altering the thickness of the low-viscosity zone to 55 km. We consider both of these points in turn.

(1) The CF comment defines the FC model as 'the best-fit model (1.3×10^{19} Pa s asthenosphere overlying a 10^{21} Pa s mantle) found by previous workers (Fjeldskaar & Cathles 1991a, b; Cathles 1975, 1980)', and associates 'FC's "best-fit" published model with an asthenosphere 75 km thick and a 70 km thick lithosphere (corresponding to a flexural rigidity of 40×10^{23} N m)'. To suggest the model LVZ appearing in MP is intended to be identical to this model, and thus to categorize the LVZ model as a 'miscalculation', is misleading in two respects. First, the comment implies that the FC model is preferred in each of the references Fjeldskaar & Cathles (1991a, b) and Cathles (1975, 1980). This is not correct; in fact, Cathles (1975) argued for a '10^{21} Pa s mantle overlain by a 75 km low-viscosity channel of 4×10^{19} Pa s and a lithosphere with flexural rigidity 50×10^{23} N m' (p. 182; units of viscosity have been, and will continue to be, converted to Pa s from the original poise). In subsequent work, Cathles (1980) preferred a weaker asthenosphere (2×10^{19} Pa s) with a thickness in the range 75–100 km. More recently, Fjeldskaar & Cathles have argued for a '10^{24} N m lithosphere overlying a 75 km thick 2.0×10^{19} Pa s asthenosphere and a 1.2×10^{21} Pa s mantle' (Fjeldskaar & Cathles 1991b, p. 393) or that 'the lithosphere is less than 50 km thick, the mantle viscosity is 1.0×10^{21} Pa s, and the asthenosphere is 75 km with viscosity 1.3×10^{19} Pa s' (Fjeldskaar & Cathles 1991a, p. 1). These preferred models are all different and none is identical to the FC model. Accordingly, on what basis could any reader of these articles choose the FC model as being the preferred model? Indeed, the lack of any representative low-viscosity-zone model led MP to adopt the generic model LVZ, which was plainly introduced as being the 'type of model, in slightly altered forms, (which) has been proposed' (MP, p. 60) by Cathles & Fjeldskaar. The performance of the specific model FC (now being advocated by CF) in fitting the Fennoscandian relaxation spectrum is, in this case, irrelevant; however, we return to this issue once we have examined, in detail, discrepancies (discussed by CF) in predictions based on the LVZ model.

(2) CF present results based on a viscosity model identical to the LVZ model with the exception that the thickness of the low-viscosity asthenosphere is reduced to 55 km. They find that their calculations based on a half-space model agree, at high degrees, with their spherical earth-model calculations, and that the latter calculations match the relaxation spectrum presented by MP for the LVZ model. They conclude that their own calculations are accurate and that the discrepancy between their predictions and those of MP are attributable, with 'little doubt', to a numerical error in the MP calculation using the LVZ model. This conclusion does not logically follow, since the CF calculations do not rule out more fundamental differences in the CF and MP methodologies for computing the deformation of viscoelastic earth models. In fact, we show below that simplifications in the theoretical formulation adopted by CF likely account for a significant fraction of the observed discrepancy in the predicted relaxation spectra.

We begin, however, by considering the accuracy of the MP calculation of the relaxation spectrum using the LVZ model. In the MP construction of the LVZ model the elastic lithosphere was discretized using a set of nodes of very high viscosity extending from the surface to 70 km depth. The sublithospheric region was discretized using an interval of

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25 km, beginning with a second node at the base of the lithosphere. The low-viscosity asthenosphere was constructed using four nodes (of viscosity 2×10^{19} Pa s) at depths of 70 km, 95 km, 120 km and 145 km. The next node, at 170 km, was characterized by a viscosity of 10^{21} Pa s. This scheme leads to some ambiguity in the asthenospheric thickness, since the base of the asthenosphere (but not its top) is characterized by a viscosity increase across two nodes of different depths (145 and 170 km). The 'effective' thickness of the low-viscosity zone therefore lies somewhere between 75 and 100 km. (In the MP study the asthenosphere thickness was listed as the rough average of these two—90 km).

To determine the effective thickness for the LVZ model we have performed a suite of calculations in which the viscosity jump at the base of the asthenosphere is modelled in the same way as the viscosity change at the base of the lithosphere; that is, with two nodes of different viscosities at the same depth. In particular, the viscosity across the double node increases abruptly with depth from 2×10^{19} Pa s to the bulk mantle value of 10^{21} Pa s, and the free parameter in the calculations is the thickness of the asthenosphere. All other aspects of the original MP calculation using the LVZ model are retained. Results, for various asthenospheric thicknesses (as labelled), are shown by the dotted lines in Figs 1 and 2. (Within the text we refer to this new set of models as LVZ*n*, where *n* represents the exact thickness of the low-viscosity asthenosphere.)

The solid line in Fig. 1 represents the relaxation spectrum for the LVZ model presented by MP. A comparison of this spectrum with the new results indicates that the effective thickness of the asthenosphere for the LVZ model is close to 80 km—not 90 km as was suggested by MP. The difference between the spectra for models LVZ80 and LVZ90 is, however, small, and this is reflected in the fit to the observed FRS. In particular, the models LVZ and LVZ80 yield χ^2 misfits ~ 300, while the misfit associated with the LVZ90 spectrum is ~ 270. The latter value, like the former, is significantly in excess of the 99 per cent confidence limit, thus the main conclusion by MP in regard to this set of models holds.

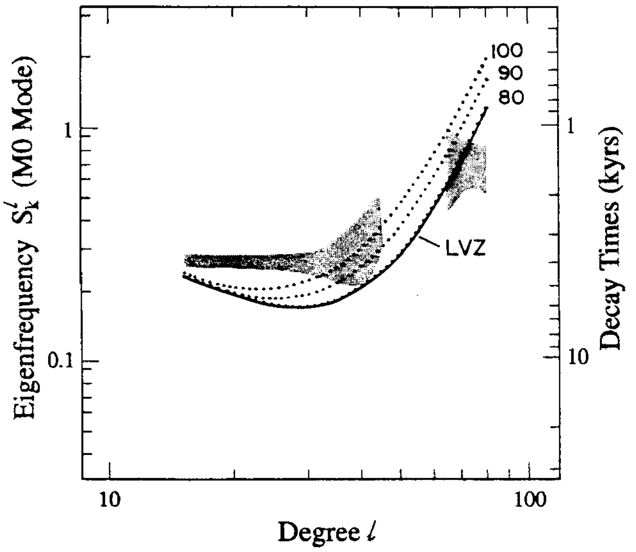

Figure 1. Relaxation spectra for the fundamental ($M0$) mode computed using four spherically symmetric, self-gravitating, Maxwell viscoelastic earth models. The models have the elastic structure of the seismic model PREM, an elastic lithosphere of thickness 70 km, and a thin sublithospheric low-viscosity zone overlying an isoviscous, 10^{21} Pa s, mantle. The results are distinguished on the basis of the model for the low-viscosity zone. The dotted lines represent the cases of 100 km, 90 km and 80 km zones (as labelled) of viscosity 2×10^{19} Pa s. The solid line (LVZ) is the relaxation spectrum for the LVZ model presented by Mitrovica & Peltier (1993).

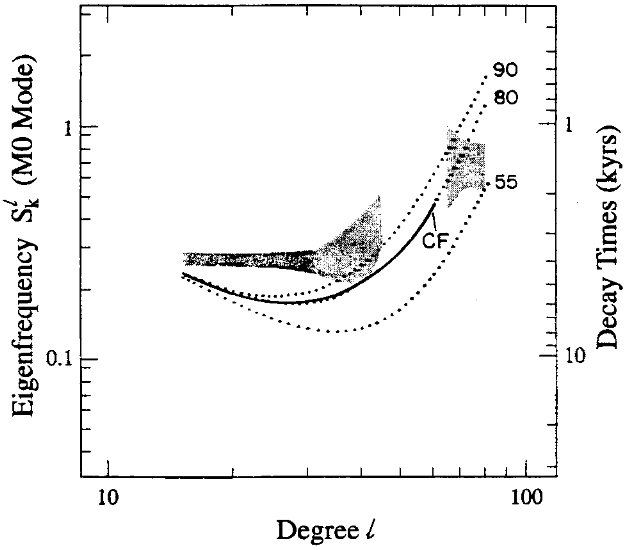

Figure 2. The dotted lines represent relaxation spectra for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 and a low-viscosity (2×10^{19} Pa s) zone of thickness 90 km, 80 km or 55 km (as labelled). The solid line, labelled CF, is the spectrum presented in the comment by Cathles & Fjeldskaar (1996) for the case of a 55 km sublithospheric low-viscosity zone.

Associating model LVZ with model LVZ80 explains only a small fraction of the discrepancy discussed by CF. Fig. 2 provides results for the new set of models LVZ55, LVZ80 and LVZ90. The solid line on the figure (labeled CF) represents the relaxation spectrum for the LVZ55 model as presented in the CF comment. The discrepancy between the CF predictions and our own, for model LVZ55, is three times larger than the discrepancy between models LVZ90 and LVZ80. To consider whether this discrepancy is associated with some other aspect of the MP analysis we have performed several further tests.

Our first test was to compare results for the LVZ80 model with those generated from an independent numerical solution, based on the same theoretical formalism, provided by Dazhong Han. The results, shown in Fig. 3, indicate a remarkable agreement. Indeed, the eigenfrequencies output from the two codes agree, to within 1 per cent, at all degrees considered. Accordingly, Fig. 3 may serve as a useful benchmark for other codes that compute viscoelastic normal modes.

The MP analysis assumed that the response, at each spherical harmonic degree, was characterized by a single decay time, which they associated entirely with the fundamental mode of viscoelastic gravitational relaxation (the so-called $M0$ mode). This assumption was justified by the observation that the $M0$ mode carries appreciably greater than 90 per cent of the total modal strength in the spherical harmonic degree range considered ($\ell \geq 15$). Our understanding of the CF methodology is that decay times are computed from the total time-domain response, and it is therefore possible that normal modes neglected by MP may contribute to the discrepancy in the CF and MP calculations. To consider this issue we have performed

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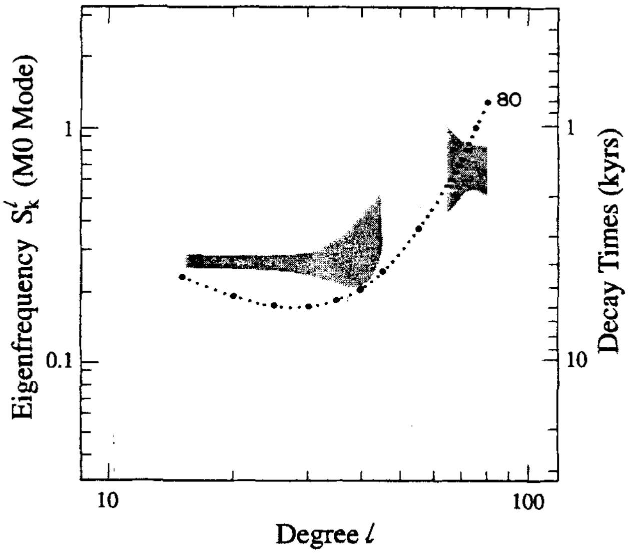

Figure 3. The dotted line represents the relaxation spectrum for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 with an 80 km thick sublithospheric low-viscosity (2×10^{19} Pa s) zone. The large solid dots superimposed on the figure are $M0$ decay times/eigenfrequencies generated at specific degrees using an independent calculation (Dazhong Han, personal communication).

a calculation in which the full multinormal-mode nature of the impulse response is used to compute uplift curves associated with the melting (from 18 to 9 Kyr BP) of a simple disc-load model of the Fennoscandian ice complex. The relaxation spectrum is then determined by applying a Legendre transform through the synthetic beaches and then finding the decay time of the best-fitting single exponential form through the harmonic amplitudes for each degree. Fig. 4 compares results obtained using this approach with the decay spectrum of the $M0$ modal branch for the specific earth model LVZ80. The high level of agreement confirms the validity of the single-mode approach used by MP.

From the above analyses we conclude that the LVZ model has an effective asthenospheric thickness of 80 km and that there were no numerical errors in the MP calculations or inaccurate simplifications in the methodology used to compute the relaxation spectrum. The CF conclusion that the LVZ results appearing in MP are based on a model having an effective asthenospheric thickness of 55 km is, we surmise, a consequence of more fundamental differences in the two methodologies. In the following we consider several potentially relevant issues. These are the elastic structure of the earth model and the theoretical treatment of both the coupling between viscous and elastic deformations and the influence of an elastic lithosphere.

The CF comment does not specify the elastic structure of the earth model adopted in the calculations. The same is true of other recent analyses by the authors (Fjeldskaar & Cathles 1991a, b). We assume that the CF calculations have, following Cathles (1975), used the Haddon & Bullen (1969) model. If this is the case, then the results in Fig. 5, based on the viscosity model LVZ55, indicate that the discrepancy cited by CF is not likely due to this aspect of the calculation. Other calculations (not shown here) indicate that coarse discretizations of the elastic structure can produce large errors in the computed relaxation spectra; however, there is no reason to believe that the CF calculations were based on such models.

The calculations performed by CF and Fjeldskaar & Cathles (1991a, b) are based on the general time-domain formalism outlined by Cathles (1975). This formalism assumes that the deformation of a viscoelastic earth can be decoupled into the sum of elastic and viscous deformations. In contrast to this approach, the correspondence-principle (i.e. frequency-domain)

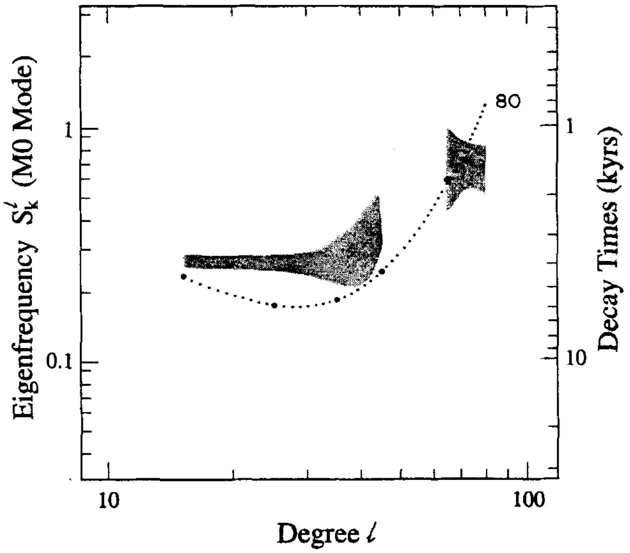

Figure 4. The dotted line represents the relaxation spectrum for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 with an 80 km thick sublithospheric low-viscosity (2×10^{19} Pa s) zone. The large solid dots superimposed on the figure are determined from the (degree-dependent) best-fitting exponential forms through a spherical harmonic decomposition of a synthetic postglacial deformation field for Fennoscandia (see text).

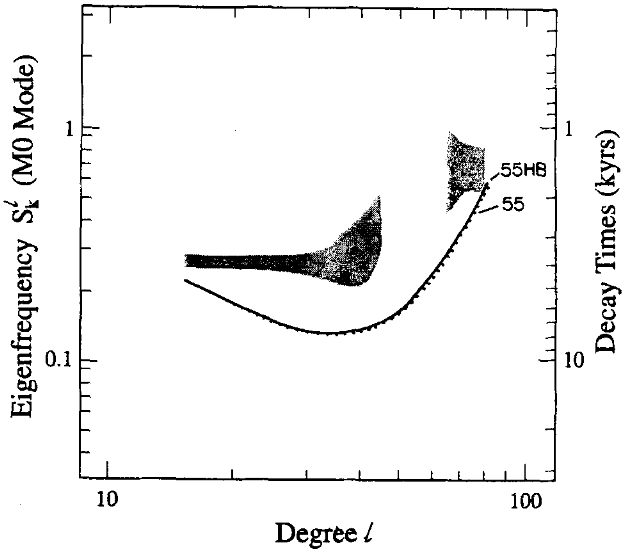

Figure 5. The dotted line represents the relaxation spectrum for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 with a 55 km thick sublithospheric low-viscosity (2×10^{19} Pa s) zone. The solid line on the figure is generated using the same model, with the exception that the Haddon & Bullen (1969) model HB_1 elastic structure is adopted in place of PREM.

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method outlined by Peltier (1974), and adopted by MP, makes no such assumption. Wu (1992) has recently argued that the neglect of coupling in the Cathles (1975) formalism introduces more error in the computed response than had previously been believed. Accordingly, it is logical to consider whether the assumption has a strong influence on the CF predictions of relaxation times.

Analytic expressions exist for the deformation of uniform half-space models. In the case of an incompressible rheology, the inverse decay times (or eigenfrequencies) for viscous (α_{vis}) and viscoelastic (α_{ve}) half-spaces are given by:

$$\alpha_{\text{vis}} = \frac{\rho g}{2\eta k}, \tag{1}$$

and

$$\alpha_{\text{ve}} = \frac{\rho g}{2\eta k} \frac{1}{1 + (\rho g/2k\mu)}, \tag{2}$$

(Turcotte & Schubert 1982; Wu 1992), where ρ is the density, μ is the shear modulus, η is the viscosity, g is the gravitational acceleration and k is the wavenumber. We use these expressions to estimate the influence, on the predicted decay times, of neglecting coupling between viscous and elastic deformations.

Following Wu (1992), we adopt, for a Fennoscandian-scale deformation, a characteristic density of $3800\,\text{kg m}^{-3}$ and a shear modulus of 1.0×10^{11} Pa for the half-space. We also use a viscosity of 10^{21} Pa s. Fig. 6(b) shows the relaxation spectrum, in the degree range 15 to 25, computed by using these values in eqs (1) and (2). The decay times predicted for the viscous half-space are consistently shorter than those computed using the viscoelastic model. Therefore, the decay-time predictions by CF systematically underestimate the decay times of a fully viscoelastic model. This error has the correct sign and also sufficient amplitude to explain the discrepancy between our predictions for the LVZ55 model and those appearing in CF within this degree range (compare Figs 6a and b).

The difference in the predicted decay times for the uniform viscous and viscoelastic half-spaces diminishes as the wavelength of the deformation decreases (Fig. 6b). It is unlikely, therefore, that the neglect, by CF, of coupling between viscous and elastic deformations introduces sufficient error to explain the discrepancy in the LVZ55 and CF predictions at higher degrees. We have, nevertheless, identified a second simplification used in the CF methodology, associated with the treatment of the elastic lithosphere, which introduces errors in precisely this degree range ($\ell \geq 25$).

The MP methodology incorporates an elastic lithosphere by including nodes of very high viscosity extending from the surface of the numerical model to any specified depth (see the discussion above). In contrast, the predictions appearing in Cathles (1975), Fjeldskaar & Cathles (1991a, b) and CF are based on a fundamentally different approach. In particular, the methodology adopted by these authors begins by considering the deformation of an earth model with no elastic plate. The effect of the lithosphere is incorporated, *a posteriori*, by applying a low-pass filter to the no-lithosphere results.

Let us assume that the deformation associated with a specific earth model having no lithosphere has been computed and that the relaxation time is given by $\varepsilon(k)$, where k is, as in eq. (1), the wavenumber. According to Fjeldskaar & Cathles (1991a, b), the inclusion of an elastic plate will act to reduce the decay times to $\varepsilon(k)/\alpha(k)$, where

$$\alpha(k) = \frac{(2\mu k/\rho g)[(S^2 - k^2H^2) + (CS + kH)]}{S + kHC}. \tag{3}$$

H is the mechanical thickness of the lithosphere (which is related to the flexural rigidity), $S = \sinh kH$ and $C = \cosh kH$. This expression is, in fact, in error. The correct equation is:

$$\alpha(k) = \frac{(2\mu k/\rho g)(S^2 - k^2H^2) + (CS + kH)}{S + kHC}. \tag{4}$$

Since eq. (3) would not give reasonable results, we assume that

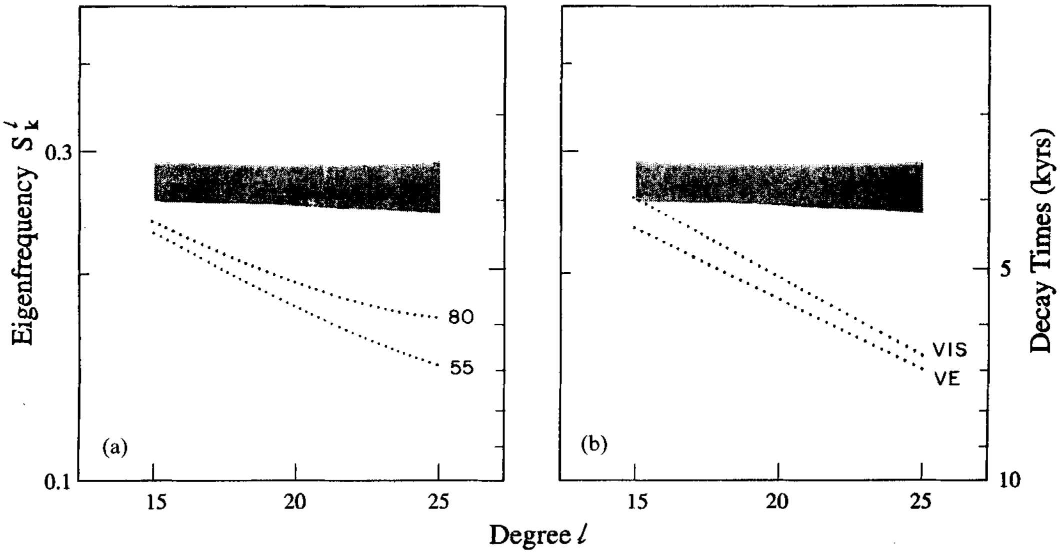

Figure 6. (a) The dotted lines represent relaxation spectra for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 and a 80 km or 55 km thick sublithospheric low-viscosity (2×10^{19} Pa s) zone. (b) Relaxation spectra for viscoelastic (VE) or viscous (VIS) incompressible uniform half-spaces. The density, viscosity, and shear modulus for the half-spaces are, respectively, $3800\,\text{kg m}^{-3}$, 10^{21} Pa s and 1.0×10^{11} Pa. In the compressible case the Lamé parameter is 1.4×10^{11} Pa.

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Fjeldskaar & Cathles (1991a, b) and CF actually used the correct form (4).

A close examination of (4) indicates that the expression is valid only for the case of an incompressible elastic plate. The assumption of incompressibility, which is not made in the MP analysis, seems to have been motivated by a single calculation appearing in Cathles (1975), which led the author to conclude that 'compressibility ... has little effect' (p. 52). The calculation was, however, based on an elastic plate of relatively low flexural rigidity (6×10^{23} N m). In contrast to this, the LVZ55 model has a flexural rigidity nearly an order of magnitude higher ($\sim 40 \times 10^{23}$ N m) and, accordingly, the influence of lithospheric compressibility will be greater.

In analogy with eq. (4), the expression for $\alpha(k)$ valid for a compressible lithosphere is

$$\alpha(k) = \frac{(2\mu k/\rho g)[(\lambda+\mu)/(\lambda+2\mu)](S^2 - k^2H^2) + (CS + kH)}{S + kHC}, \tag{5}$$

(Cathles 1975), where λ is Lamé's parameter.

The CF treatment of an elastic plate differs on an even more fundamental level from the approach adopted by MP. In a complete viscoelastic calculation, in which the elastic plate is included as part of the earth model, coupling processes occur between the plate and the underlying mantle; in fact, a certain branch of normal modes (i.e. $L0$) have been argued to be a consequence of the rheological interface at the base of the lithosphere (Peltier, Drummond & Tushingham 1986). A detailed discussion of these modes may be found in Wolf (1985).

To focus on the issue of a compressible versus an incompressible lithosphere, we have performed the following calculation. First, we begin by computing the relaxation spectrum for a model identical to the LVZ55 model, with the exception that the lithosphere is essentially removed (in fact, the calculation reduced the lithospheric thickness to just 2 km from 70 km). That is, the radius of this revised earth model is $\sim$6300 km. Next, we used eqs (4) and (5) to filter the response for the influence of, respectively, an incompressible and compressible lithospheric plate of thickness 70 km. (All required lithospheric parameters were determined by computing the appropriate mean values of the PREM model.) The flexural rigidity of the plate associated with the LVZ55 model was found to be $\sim 4 \times 10^{24}$ N m. The results of this exercise are shown in Fig. 7. The CF assumption of an incompressible lithospheric plate introduces progressively larger errors as higher spherical harmonic degrees are considered. Furthermore, these errors have the correct sign necessary to reconcile the discrepancy in the MP and CF predictions based on the LVZ55 model. (That is, the assumption of incompressibility leads to an underestimate of the decay times.) At degree 80 the error accounts for approximately 60 per cent of the discrepancy between the two calculations (Fig. 7).

We conclude that two simplifications adopted by CF have introduced errors into their calculated relaxation spectra, and that these errors may account for a significant fraction of the discrepancy reported by CF. These conclusions have implications which extend beyond the CF comment. Our determination that the LVZ model adopted by MP has an effective asthenospheric thickness of 80 km is relevant only for this single calculation in the MP analysis. In contrast, the limitations of the CF methodology extend to all the analyses reported in Cathles (1975, 1980) and Fjeldskaar & Cathles (1991a, b). As an example, consider the FC model defined above. CF argue that this model provides an acceptable fit to the observed relaxation spectrum. However, our calculation using this model (Fig. 8) indicates the opposite. Indeed, the χ^2 misfit for the model ($\sim$280) is comparable to the misfit associated with

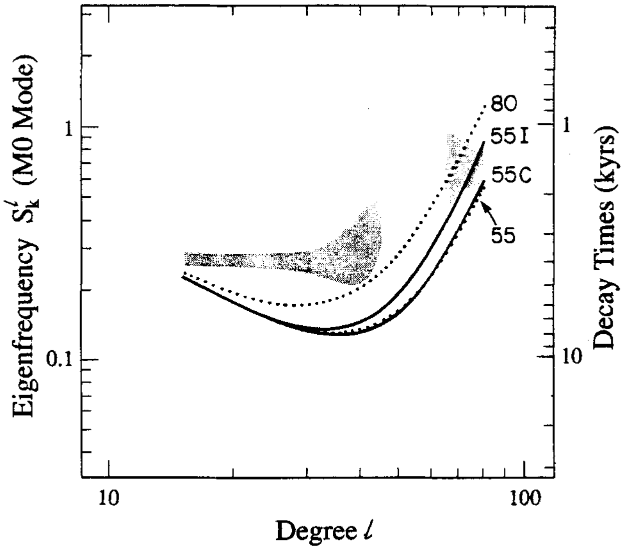

Figure 7. The dotted lines represent relaxation spectra for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 and an 80 or 55 km thick sublithospheric low-viscosity (2×10^{19} Pa s) zone. The solid lines are spectra computed by first determining the spectrum for a model in which the lithosphere overlying the 55 km low-viscosity zone is essentially absent, and then applying an *a posteriori* filter to mimic the effects of an elastic plate (see text). The solid lines labeled 55C and 55I represent results based on filters which assume, respectively, compressible and incompressible lithospheric plates of flexural rigidity 4×10^{24} N m.

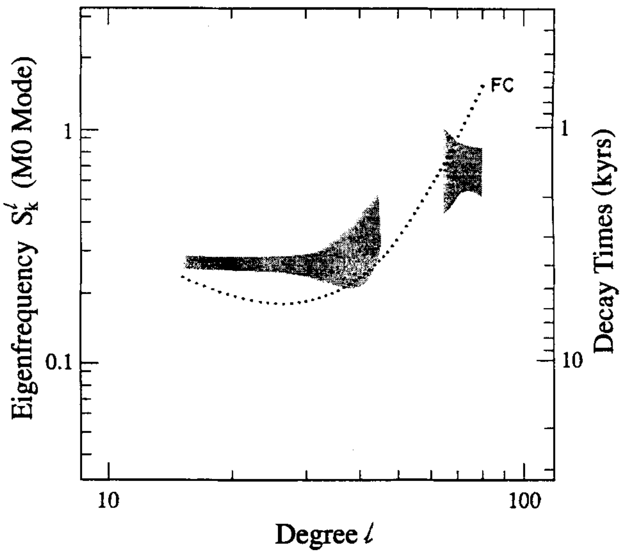

Figure 8. The dotted line (labelled FC) represents the relaxation spectrum for the fundamental ($M0$) mode computed using the earth model described in Fig. 1 with a 75 km thick sublithospheric zone of viscosity 1.3×10^{19} Pa s. The earth model is, according to the comment by Cathles & Fjeldskaar (1996), their 'best-fit' model in previously published work.

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the LVZ and LVZ80 models cited above (~ 300), and it significantly exceeds the 99 per cent confidence limit.

As a final point we take exception to one of the concluding remarks made by CF. The authors write that 'the important point we wish to make here is that despite claims to the contrary there is a simple trade-off between lithospheric thickness and asthenospheric viscosity'. The motivation for the comment is unclear. The MP analysis did not deny this trade-off; quite to the contrary, the MP abstract clearly states that the study 'quantifies the previously described trade-off between a decrease in the viscosity of (the asthenosphere) and a decrease in the lithospheric thickness (Cathles 1975)' (MP; p. 45). The relevant results are found on Table 2 and page 57 of the MP study.

We thank the authors for the opportunity to examine in more detail some of the issues associated with the computation of a viscoelastic relaxation spectrum. Further progress will require a more careful collaboration between interested members of the community. The calculations presented herein, which include a successful benchmark comparison (Fig. 3), may serve as the starting point for these efforts. Future work specifically associated with the Fennoscandian relaxation spectrum will also need to address a potentially problematic issue. A recent analysis by Wolf (1996) indicates that strandline data published by Sauramo (1958) may be inaccurate, and hence the relaxation spectra based upon the Sauramo data set may require revision. A reanalysis of more recent constraints on Fennoscandian strandline patterns for this specific purpose is, in fact, ongoing (Wieczerkowski, Mitrovica & Wolf, in preparation).

ACKNOWLEDGMENTS

Dazhong Han provided me with independent calculations of the impulse response of a number of Maxwell viscoelastic earth models. I gratefully acknowledge his generous assistance. Several of the analyses reported here were derived from work to be described in Wieczerkowski *et al.* (in preparation). I am indebted to Karin Wieczerkowski for her efforts and insight.

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