Geophys. J. Int. (2000) **142,** 279–281

Reply to comment by W. Fjeldskaar 'What about the asthenosphere viscosity? Sea-level change, glacial rebound and mantle viscosity for northern Europe'

Kurt Lambeck and Paul Johnston

Research School of Earth Sciences, the Australian National University, Canberra, ACT 0200, *Australia. E-mail: kurt.lambeck@anu.edu.au*

Accepted 2000 January 31. Received in original form 2000 January 21

We thank Dr Fjeldskaar for the opportunity to comment further on our paper dealing with the Fennoscandian rebound and sea-level question (Lambeck *et al.* 1998a; referred to as LSJ hereafter). The essential criticism he levels at our work is that we have not considered mantle-response models that include a low-viscosity channel in the upper mantle (Fjeldskaar 2000). In our paper we clearly noted that we examined only a part of the possible earth-model space and that we restricted ourselves to a three-mantle-layer model comprising a lithosphere, an upper mantle extending from the base of the lithosphere down to the 670 km seismic discontinuity, and a lower mantle. A broad range of parameters defining these three layers was explored and no *a priori* values were attached to any one layer. This is important in that considerable trade-off between parameters can result. We were careful to note that the analysis yielded only first-order results and that the resulting earth-model parameters are effective values that, while they appear to give an adequate description of the rebound evidence (the relative sea-level change and shoreline migration), may not be a true reflection of the actual physical layering within the Earth. We also noted that further work is required to examine whether a higher degree of mantle layering is appropriate (e.g. p. 135).

The reason we did not conduct a more exhaustive search of the model space was two-fold. The first was that our earlier experience with the British rebound modelling (Lambeck *et al.* 1996) led to the conclusion that five-layer mantle models, including the low-viscosity asthenosphere option, yielded only a marginal improvement in the overall comparison of predictions of sea-level change with observations. Fig. 1 illustrates the two sets of effective earth-model parameters that were found to be optimal for the three- and five-layer models. The five-layer model is physically more intuitive but, in the British Isles case, it does not lead to a significant improvement in the ability to predict Late- and postglacial sea levels and shoreline locations compared to the three-layer model. In this particular case the observational database has only limited resolving power for isolating the higher-resolution structure in the mantle, and for 'all predictive purposes of sea-level change and shoreline evolution, three-layer or five-layer models are essentially equivalent' (p. 135). We noted, however, that 'whether or not this is also the case for the larger areal extent of the Scandinavian ice sheet remains to be tested'.

In some follow-up, and independent, work (Kaufmann & Lambeck 1999) more rigorous inversion methods were used to estimate rebound parameters for multilayered earth models, using a combination of sea-level, geoid and seismic tomography data. These results, illustrated in Fig. 2, indicate the two viscosity profiles that best match the observational database. Neither point to a well-developed low-viscosity channel in the upper mantle, and the second model compares well with the results from the sea-level analysis only.

The second reason for not pursuing the more detailed solutions for the Scandinavian region is that a major limitation in the modelling is the inadequate knowledge of the temporal and spatial distribution of the ice cover over the region, and, based on tests with different ice models, we concluded that this was more important than differences in predictions between three- and five-layer mantle models: unless some modification of the ice sheet was permitted in the inversion, this would result in a very considerable dependence of earth-model results on the adopted ice model (for example, compare Figs 16(a) and (b) and Fig. 33(b) in LSJ). We concluded that further improvements in the knowledge of the spatial and temporal distribution of the ice are required before it becomes worthwhile to explore the earth structure in greater detail. Subsequent inversions in LSJ therefore placed greater emphasis on the ice model than on the detailed earth structure, although care was taken at all times to ensure that an adequate separation of the earth- and ice-model parameters occurred.

Three inversions of independent sea-level data for ice-sheet parameters and (three-layered) mantle parameters led to consistent conclusions about likely ice thicknesses during Lateglacial times. These data sets are the Late- and postglacial geological evidence for sea-level change across the region (LSJ), the tide-gauge data for the region (Lambeck *et al.* 1998b), and the timing and elevation data of various Baltic lake stages (Lambeck 1999). In all cases, thick, quasi-parabolic ice models, in which ice thickness increases rapidly with distance from the ice margin, yield predictions that are inconsistent with the sea-level and shoreline observations for the southern and southeastern Scandinavia and Baltic regions (see also Tushingham & Peltier 1991 and Lambeck *et al.* 1990). With the exception of some of the Norwegian coastal zones, the combined earth–ice-model parameters resulting from these three analyses provide a good description of the observed rebound phenomena. We recognize that earth models of greater

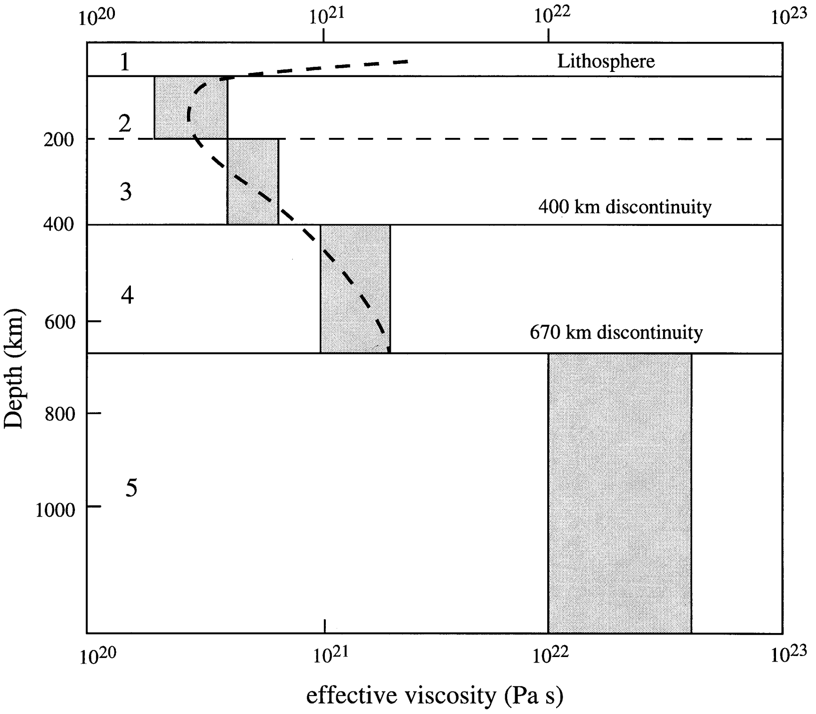

Figure 1. The effective viscosity estimates for a five-layered mantle inferred from sea-level change data for the British Isles (Lambeck *et al.* 1996). The shaded bands indicate the range of values. The thick dashed line gives a hypothetical continuous depth-dependent viscosity function for the upper mantle.

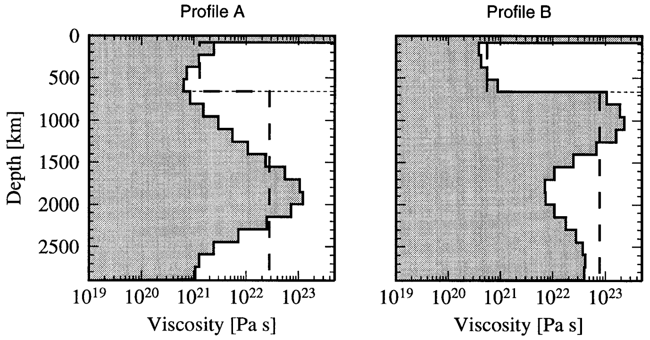

Figure 2. Preferred mantle viscosity profiles derived from an inversion of sea-level observations, geoid data and seismic tomographic information. The thick dashed line indicates the volume-averaged upper- and lower-mantle values of effective viscosity. The thin dashed line indicates the upper–lower mantle separation. (From Kaufmann & Lambeck 1999.)

complexity may lead to different dimensions for the past ice sheet but we anticipate that the principal conclusions about the spatial variation in ice thickness during the Late-glacial are robust and independent of the detail in the layering of the mantle models. This does need to be substantiated, but we prefer to direct our immediate effort at improving our understanding of the ice history rather than at introducing greater complexity into the earth models.

Areas where improvements in the ice models are desirable include those for which the sea-level predictions are also sensitive to detailed mantle structure. Along parts of the Norwegian coast (e.g. the Trondheimfjorden region, Fig. 29 of LSJ) the three-layer models were found to be less appropriate but here the major uncertainty in the modelling arises from inadequate knowledge of the extent, thickness and retreat history of the offshore ice. The ice-retreat models used in LSJ are based on relatively old compilations and interpretations of the offshore ice limits (mainly from Andersen 1981 and Pedersen 1995) and, with new information available, are in need of revision. For example, there is inconsistency between the ice model and the sea-level data for several localities along the Norwegian coast, with offshore ice margins at the same time that there are records of nearby coastal sea-level change. In inverting the sea-level data from such localities, considerable correlation occurs between earth- and ice-model parameters (e.g. Fig. 26 of LSJ). With the known uncertainties in the latter we are therefore reluctant to overinterpret the data, particularly because for other Norwegian sites the agreements between observations and predictions are much more satisfactory (e.g. Figs 28 and 30 of LSJ).

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