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DEPTH DEPENDANCE OF Q BENEATH THE BALTIC SHIELD INFERRED FROM MODELING OF SHORT PERIOD SEISMOGRAMS

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Abstract. We use Rg waves (fundamental Rayleigh wave) to measure shear wave velocity and attenuation in the crust in central Finland. We used seismograms from quarry blasts in USSR recorded during the LITHOSCOPE - SVEKA 89 experiment. We deduced from dispersion curves a shear wave velocity model for the upper crust. From the attenuation of Rg waves as a function of frequency, we found the quality factor Qs in the uppermost crust as a function of depth. The quality factor appears to be low (about 100) in the shallow crust and to increase rapidly at depth (to about 1000). In order to test this result we calculated complete synthetic seismograms for this velocity-attenuation model. We were able to simulate accurately the arrival times and the relative amplitudes of all the major phases present in the actual seismograms (including Pg and Lg waves). This comparison supports the presence of a very attenuative surface layer with a thickness of about 1 km beneath the Baltic shield while the deep crust presents a very weak attenuation. This relatively thick attenuative superficial layer plays an important part in the overall attenuation observed in shield areas.

Introduction

The estimation of seismic hazard requires knowledge of both source mechanisms and the properties of the transmitting medium. The knowledge of the attenuation of seismic waves in the crust is important for the correct modeling of the wave propagation and the amplitude of the different wave phases.

This study is an attempt to estimate the depth distribution of shear wave quality factor Q in the upper crust of a shield area. We first analyse Rg waves (fundamental Raylegh mode) measured by a portable network during the SVEKA-LITHOSCOPE experiment in Finland (Mantyniemi et al. 1991). We next compare synthetic seismograms for different earth models with the seismic records in order to find a simple model of the attenuation in the crust which allows to match correctly all the major phases of the seismograms. Our ultimate goal is to give the thickness and the quality factor of an equivalent surficial attenuative layer that can be used in further applications.

Mokhtar et al. (1988) studied Rg waves in the Arabian Shield and found by a stochastic inversion of the apparent attenuation that Q increases rapidly with depth. In their study the depth distribution of Q was quite different for different parts of the profile under consideration. In Maine, USA, Toksöz et al. (1988) found a depth dependent Q in the crust by the analysis of Rg waves. Considering the quality factor in the upper crust, a general problem for the inversion of Rg wave attenuation is that the resolution of the inversion at depth is poor because of the limited penetration of high frequency Rg waves (about 1-2 Hz).

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Moreover the measured Q value is a combination of anelastic attenuation and attenuation due to scattering and fluid flow possibly resulting in a frequency dependent apparent Q (Toksöz et al. 1988). It is therefore difficult to eliminate the bias between frequency and depth dependance when studying Rayleigh wave attenuation.

The average shear wave quality factor in the crust is known from the analysis of Lg waves (shear waves trapped in the crust). Q seems to depend on the tectonic activity in the region under consideration. High values of Q were reported in shield areas. Singh and Herrmann (1983) mapped Q in the United States and found that Q_0, the quality factor at 1 Hz, varied between 800 and 1350 in the tectonically stable north Eastern and Central U.S. Dwyer et al. (1983) found a value of about 1500 in central U.S. and Hasegawa estimated a Q_0 of 900 in the Canadian shield.

In the Baltic Shield only little information about the attenuation is available. Kvamme and Havskov (1989) analysed coda waves in southern Norway and found quite a low coda Q_0 (about 120). The higher value (560) found by Sereno et al. (1988) in the same area from the analysis of Lg waves is more consistent with the results obtained in similar areas.

The profile used in this study offers an opportunity to investigate the influence of weathering of an archean basement on the attenuation of short period seismic waves. It was recorded on the Archaean Basement Complex which is a central part of the tectonically stable Baltic Shield. The waves do not cross major structural boundaries and we therefore assume a flat layered earth, an assumption which is necessary for our calculations.

Data

Twenty five digital seismic stations of the LITHOSCOPE portable network (Poupinet et al. 1989) were installed along the SVEKA profile in Finland (Grad and Luosto 1987). The seismometers have a natural period of 1 sec.The main purpose of the experiment was the study, from teleseismic time delays, of the lithosphere in Finland, and especially the deep structures beneath the frontier between the Archaean basement complex and the Svekokarelides (Mantyniemi et al. 1991).

On the 28th of June 1989 10 of the stations situated on the Archaean Basement Complex recorded a quarry blast fired in the Soviet Union near the Finnish border (figure 1). The distance between the source and the stations ranged from 60 to 240 km. The records (figure 2) are dominated by the Rg wave (fundamental mode Rayleigh wave), which shows a clear amplitude decrease as the distance to the source increases. The Pg wave (multiply reflected P waves in the crust) shows quite a small amplitude decrease in the distance interval under consideration. We see a gradual build up of the Lg phase (S waves guided in the upper crust). The energy of the signal is dominated by Rg which has frequencies mainly between 0.5 and 2.0 Hz. The first step of our study is the analysis of the Rg phase that we isolate by time windowing of the seismograms. The limits of the window corresponding to Rg are defined by the group velocities 2.4 km/s and 3.4 km/s.

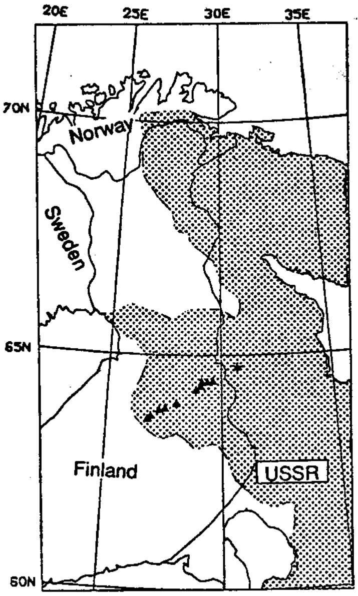

Fig. 1. Locations of the LITHOSCOPE stations (triangles) and the recorded quarry blast (✳). Both the stations and the source are located on the Archaean Basement Complex (shaded area).

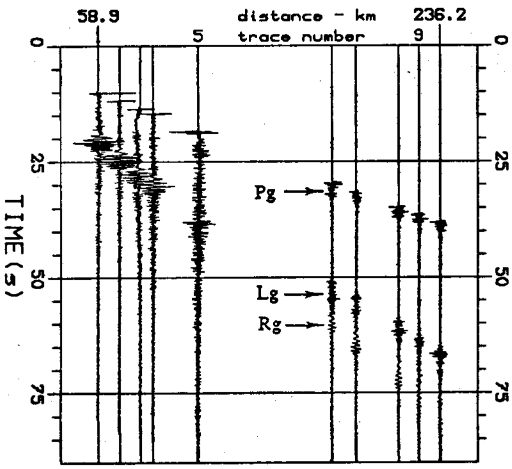

Fig. 2. The unfiltered records of the quarry blast.

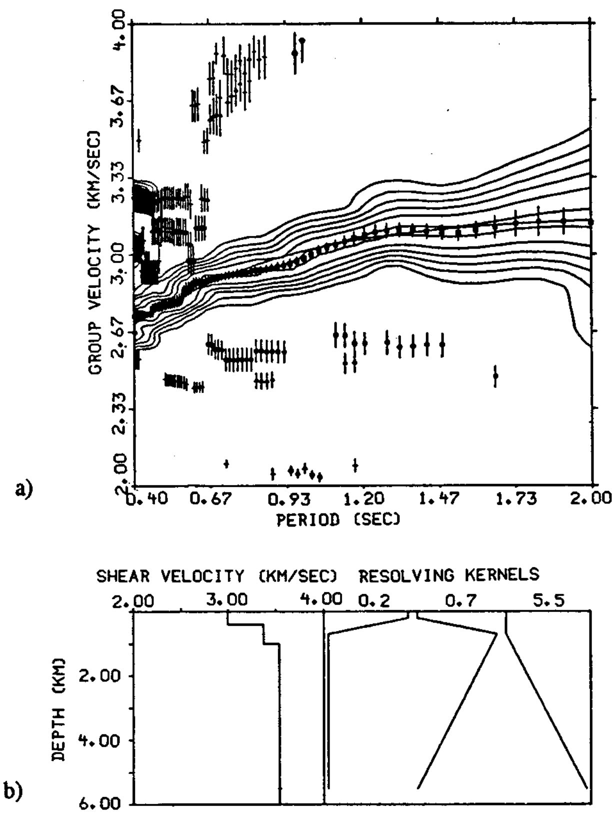

Fig. 3. a) Measured dispersion curve. Vertical bars indicate the standard deviation of the measure. The curve which corresponds to the earth model found by inversion of the dispersion curve is superimposed.

b) The S - wave structure found by inversion of the dispersion curve and the resolution of the inversion.

Velocity model

In order to calculate the group velocity dispersion curves we used the multiple filter analysis as presented by Dziewonski et al. (1969) with the extension proposed by Barker (1988). We used the set of programs of surface wave analysis developed at St Louis University (Herrmann 1985).

We obtained a well defined dispersion curve (figure 3a). The group velocities were calculated with very small standard deviations in the period range between 0.4 and 1.4 sec. The group velocities increased from 2.6 km/s to 3.2 km/s in this interval. There was no evidence of contamination by higher modes in this velocity range.

We used the generalized (stochastic) inversion scheme described by Mokhtar et al. (1988) to infer the shear wave velocity depth distribution, assuming a flat layered earth. We tried to build up a simple velocity model, with a small number of layers, that will be used to study the attenuation. A preliminary study of this method applied on dispersion curves for synthetic seismograms had shown that the results of the inversion are very sensitive to the a-priori thicknesses of the layers. A shear wave velocity inversion for an earth model composed of many horizontal layers and a calculation of the resolution matrix permits one to define a simple earth model: layers with the same depth resolution cannot be individually separated by the inversion, and should therefore be combined into one unit.

We were able to explain the measured dispersion curve by a 3 layer model with shear wave velocities of 3.0 km/s near the surface (0-400 m) and about 3.5 - 3.6 km/s in layers deeper than 1 km (figure 3b). As shown in the figure the observed dispersion curve is well fitted by the model. This implies small standard errors on the velocities of each layer. The simple model allows us to obtain a good resolution of the shear wave velocity in the layers. Due to the limited period band used, we have no information about layers deeper than about 4 km.

Seismic wave attenuation

Rg waves contain information about the shear wave attenuation in the depth interval through which they propagate. We therefore studied their apparent attenuation as a function of frequency.

We assumed an attenuation of the form $\exp(-\gamma r_i)$, where r_i is the distance between the source and the i'th receiver. We corrected the data for geometrical spreading ($1/\sqrt{r_i}$) and calculated the apparent attenuation γ for a number of frequencies by linear regression of the amplitudes measured at the ten stations. This calculation assumes that the attenuation does not change in the area under consideration.

The apparent quality factor Q_a can be calculated because it is a simple function of the attenuation $\gamma(\omega)$ and of the group velocity $u(\omega)$. $Q_a(\omega)$ seemed to have a constant value of about 100 in the frequency interval 0.5 - 2.0 Hz (figure 4).

The depth distribution of the actual shear wave quality factor Q_s in the crust is generally unknown, as is its frequency dependance. It is therefore not possible to separate these two effects with the Rg wave as the only source of information. Due to the narrow frequency content of our data we supposed Q_s to be independent of the frequency in the range of our study and we tried to find its variation with depth.

A stochastic inversion of the Rg wave attenuation did not constrain very well the distribution of Qs with depth. The resolution of the inversion was poor regarding the values of Qs, particularly in deep layers. In order to get quantitative constraints on Qs at depth we therefore compared the observations with

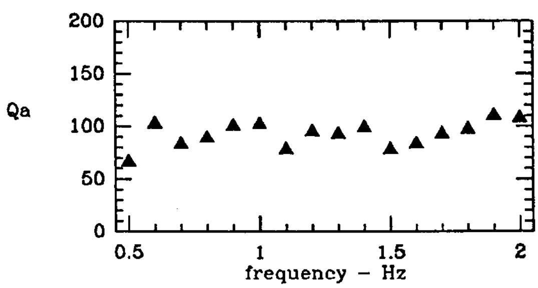

Fig. 4. The apparent quality factor Q_a as a function of frequency, found by linear regression as described in the text.

synthetic seismograms for different Earth models. The synthetic seismograms were computed by the discrete wavenumber method of Bouchon (1981). This method permits the inclusion of all the seismic phases of a flat layered homogeneous earth.

Based on the seismic studies of Grad and Luosto (1987) we added information about the velocity structure of the deeper crust

Table 1. Earth model used to compute the synthetic seismograms.

Z - km	Vp - km/s	Vs - km/s
0.0 - 0.4	5.23	2.99
0.4 - 1.0	5.90	3.37
1.0 - 10.0	6.10	3.54
10.0 - 17.0	6.30	3.66
17.0 - 26.0	6.54	3.73
26.0 - 40.0	7.10	4.03
40.0 - 55.0	7.30	4.12
55.0 -	8.00	4.62

to our velocity model. The Moho is about 55 km beneath the profile. The crustal model used for the synthetics is given in table 1.We assumed an almost elastic crust (Qs = Qp = 1000) overlain by an attenuative surface layer, and we calculated synthetic seismograms for earth models which were identical except for the thickness of the attenuative layer. We chose a shear wave Q of 100 in the attenuative surface layer, which is equal to the apparent Q of Rg waves at 2.0 Hz.

Figure 5 shows an example of a comparison between data and synthetics. In this case we assumed a shallow (1 km) attenuating layer. The prominant phases (Pg and Rg) are correctly simulated at most stations. One may note the absence of Rg at station 5. This is due to a local effect since Rg is visible at further locations. The case of Lg is more difficult. We do not here address the problem of radiation of S waves during a real explosive experiment.

Figure 6 shows the Rg wave attenuation parameter as a function of frequency both for the data and for several synthetic seismograms. In order to calculate the attenuation we used the method described previously: the Rg wave was separated using a time window defined by the group velocities 2.4 km/s and 3.6 km/s. The signal was corrected for geometrical spreading and the attenuation was measured by linear regression as described above. The attenuation measurement may therefore be contaminated by seismic phases (body waves, Lg waves) other than Rg, which may explain that the curves are not perfectly smooth especially for the high frequencies. The only parameter which changes for the different synthetics is the thickness of the attenuative surface layer. On the figure the bold line corresponds

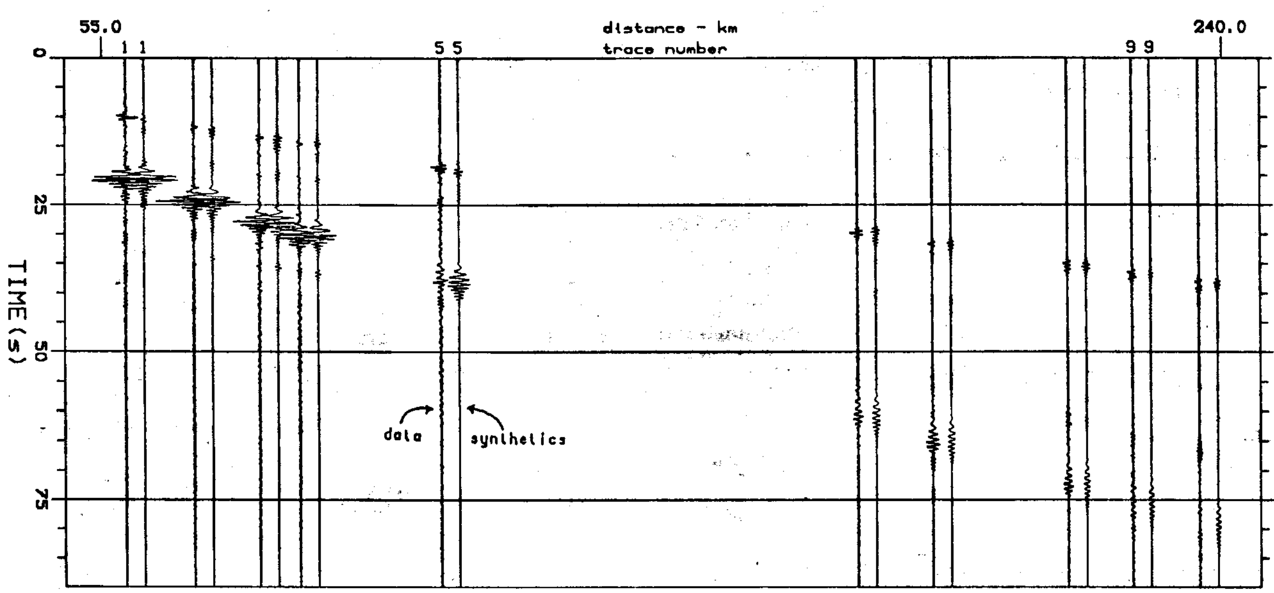

Fig. 5. Data (bold) and synthetic seismograms calculated for a crust with a 1 km thick attenuative surface layer. Both data and synthetic seismograms are bandpass filtered 0.5 - 2.0 Hz.

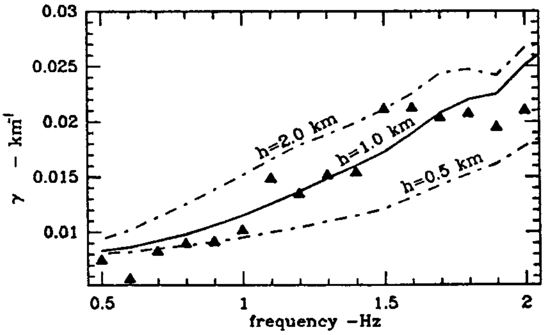

Fig. 6 Rg wave attenuation as a function of frequency for the data (triangles) and for three synthetic seismograms: model as described in table 1 (bold), models as described in table 1 but with a attenuative layer 0-2000 m (upper dashed - dotted) and 0-500 m (lower dashed - dotted).

to a thickness of the attenuative layer of 1 km, while the dashed - dotted lines correspond to thicknesses of 0.5 and 2 km respectively. In order to fit the data over the entire frequency interval the thickness of this layer must be bounded in a quite narrow range. We emphasize that our results are obtained under the assumption of a frequency independent Q_S in the frequency interval 0.5 - 2.0 Hz.

Conclusion

The short period seismological data of this study show evidence of a highly attenuative layer at the surface of the Archaean part of the Baltic shield. We calculated complete synthetic seismograms to constrain the dependance of Q with depth. The thickness of the attenuative layer is found to be about 1 km. This is in good agreement with the velocity structure which indicates a weathered zone of about 1 km thick. The presence of a very strongly attenuative layer above the quasi-elastic shield is an important feature for the quantitative interpretation of the amplitude of seismic waves on shields.

Q_S deduced from regional phases represents a mean attenuation in the crust (Campillo et al. 1985). The clear variation of Q_S with depth shows that it is dangerous to use Lg attenuation measurements to predict ground motion at short distances from the source.

In the narrow frequency window of our data we did not observe evidence of the frequency dependence of the quality factor suggested for shallow layers by Toksöz et al. (1988). We do not, though, deny that a slight frequency dependance may be present.

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