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VII.5 High-frequency P wave attenuation from Central Asia to Norway

It has long been known that the P waves recorded in northern Europe from earthquakes and explosions in Eurasia are often quite rich in high-frequency energy. A detailed quantification of signal transmission characteristics is then possible by studying the spectral characteristics over a broad frequency band. In this study the spectra of NORSAR recordings of some E. Kazakh events are used to develop a model for the average Q along this path. Since the epicentral distance is about 4200 km, this average Q is for paths that penetrate the earth to a depth of about 900 km. The data were processed with the technique applied by Bache et al (1984). For each seismogram energy density spectra are computed for very short (typically 2.2 to 2.5 seconds) time windows isolating the first arriving compressional wave, and the power spectrum of a noise window just before the signal is subtracted. Event spectra are then obtained by averaging over several elements of the array as well as similar events in a small source region, and the spectra obtained this way are quite smooth and are almost entirely shaped by the average source spectrum and the effect of attenuation along the path. Accurate attenuation estimates depend on accurate corrections for the source, assuming that the source spectrum for the direct P wave should be roughly constant up to some corner frequency, above which it is proportional to f^{-n}. For explosions, most of the evidence supports $n = 2$, and the NORSAR results appear to confirm that value.

The spectra computed from five 8 Hz seismometers for two large Degelen events are shown in Fig. VII.5.1. Also shown is the noise spectrum computed from the average noise power (based on a 3.8 second sample of noise before the signal on each element). The signal spectrum is essentially flat from 3 to beyond 7 Hz when plotted with the f^2 source correction, and the spectra for the other events look much the same.

This is an extraordinary result, as the attenuation has almost no frequency-dependent effect between 3 and 7 Hz. Since attenuation cannot be negative, spectra like this confirm the assumption that the source is proportional to f^{-2} above the corner frequency.

In Fig. VII.V.2 we show the spectra for 6 other events. Four are smaller than the Degelen explosions and two are explosions in other paths of the E. Kazakh test site. The spectra for the Degelen events are all similar to those in Fig. VII.V.2, except that they have the different low-frequency behavior expected for smaller (i.e., higher corner frequency) events. The maximum signal/noise occurs around 7 Hz and decreases at higher frequencies. The events in the other two areas seem to depart from the pattern in that the signal spectrum does not decay so obviously above 7-8 Hz.

Three major features of these spectra determine the attenuation model for the E. Kazakh-NORSAR path. First, at low frequencies they are influenced by source corner frequency effects and a correction for them must be introduced. Second, the source-corrected spectra are essentially flat in the band between 3 and 7 Hz. Finally, the spectra decrease above 7-8 Hz, and we see in Fig. VII.5.3 that the line representing $t^* = 0.14$ is a reasonable approximation for the rate of decay.

For frequencies up to 7 Hz, the attenuation effects can be represented by an absorption band model. This is best done with a "path average" spectrum obtained by averaging several spectra (here six), as shown in Fig. VII.5.4, obtaining a spectrum which essentially is a smoothed version of the single event spectra in Fig. VII.5.1. In Fig. VII.5.4 we also show an estimate for the spectrum after correcting for source corner frequency effects and the spectra for several attenuation models. The corner frequency correction is based on spectra computed by Bache et al (1984), utilizing the spectral difference between Degelen and low corner frequency Shagan events to approximately correct the Degelen spectra. A roughly "corrected" spectrum (Fig. VII.5.4) shows that the slope changes below 3 Hz, even though this "corrected" spectrum still underestimates attenuation effects at low frequency.

In Fig. VII.5.4 the "corrected" NORSAR spectrum is plotted with the spectral effect of several absorption band models (Minster, 1978). For this application the model has two parameters, t_o*, which is the ratio of travel time to average path Q at long periods, and τ_m, which specifies where the Q^{-1} begins to decrease with frequency. The key spectral features are the frequency dependence below 3 Hz and the nearly horizontal slope up to 7 Hz. The best fit seems to be with models having $t_o* \simeq 0.6$ seconds (not much constrained by these data) and τ_m slightly greater than 0.05 seconds. For such models the effect of attenuation above 3 Hz reduces to multiplication of the spectrum by a constant, which is about 0.04 for $t_o* = 0.6$, $\tau_m = 0.06$; and 0.07 for $t_o* = 0.5$, $\tau_m = 0.06$. Obviously, the value of this constant depends on the choice of t_o*, characterized by the attenuation at long periods.

An absorption band model with $0.05 < \tau_m < 0.1$ and $t_o* \simeq 0.6$ was found by Bache et al (1984) to represent the low frequency attenuation on the paths from eastern Kazakhstan to four UKAEA arrays, with frequencies above 3 Hz, requiring a second Q^{-1} to explain the constant rate of spectral decay seen at those frequencies. In view of Figs. VII.5.2 VII.5.3, the NORSAR path data also require a second Q superimposed on the absorption band model, but its effect is not felt until 7 Hz and beyond. Thus, similar two-part Q models seem to fit the data for all five paths (with minor adjustments in the t_o* and τ_m), with the major difference being that the effect of the second Q is not felt until higher frequencies at NORSAR.

A key feature of the NORSAR spectra is thus that the effect of attenuation is little more than multiplication by a constant for frequencies between 3 and 7 Hz. Physical mechanisms for absorption must be characterized by $Q \approx f$ above some high-frequency limit on the relaxation spectrum, so absorption band models (e.g., Anderson and Given, 1982) anticipate that attenuation must reduce to a constant multiplier above some limiting frequency. These NORSAR spectra provide an unambiguous observation that such behavior does indeed exist. For most paths it is difficult to observe apparently because attenuation by scattering masks it.

It is not known whether or not the E. Kazakh-NORSAR path is typical of the Eurasian continent. If it is, the detection capability of systems to monitor nuclear explosion testing in this region could be much improved by greater emphasis on high-frequency data. An estimate of the anticipated improvement was recently made by Evernden et al (1984), but it should be noted that these authors made much more optimistic assumptions about the signal/noise at high frequencies than can be supported by the NORSAR data presented here. Some improvement of the NORSAR signal/noise at high frequencies may be possible by using arrays designed specifically for this purpose (e.g., Mykkeltveit et al, 1983), but the scattering attenuation may be impossible to overcome since it is probably due to inhomogeneous structure throughout the lithosphere. Regional phases like P_n also seem likely to be attenuated by scattering at high frequencies. While better use of high-frequency data may improve detection, this is far easier than identifying an event, and more work remains to be done until one knows how much the capability for improving event identification can be improved by exploiting these high-frequency data.

More details about the research reported on here are given in Bache and Bungum (1984).

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Mykkeltveit, S., K. Åstebøl, D.J. Doornbos and E.S. Husebye (1983). Seismic array configuration optimization, Bull. Seism. Soc. Am. 73, 173-186.

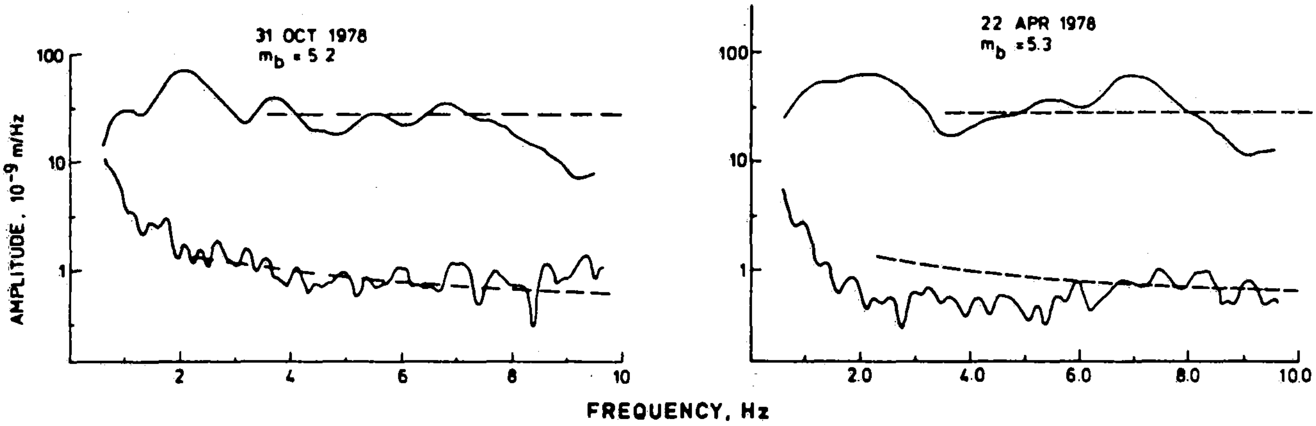


Fig. VII.5.1 The spectra for two of the events of (Table 2 ?) are shown together with the average noise window just before the P signal. A horizontal dashed line is sketched through each signal spectrum and the NORSAR noise model of Bungum (1983) is sketched through the noise.

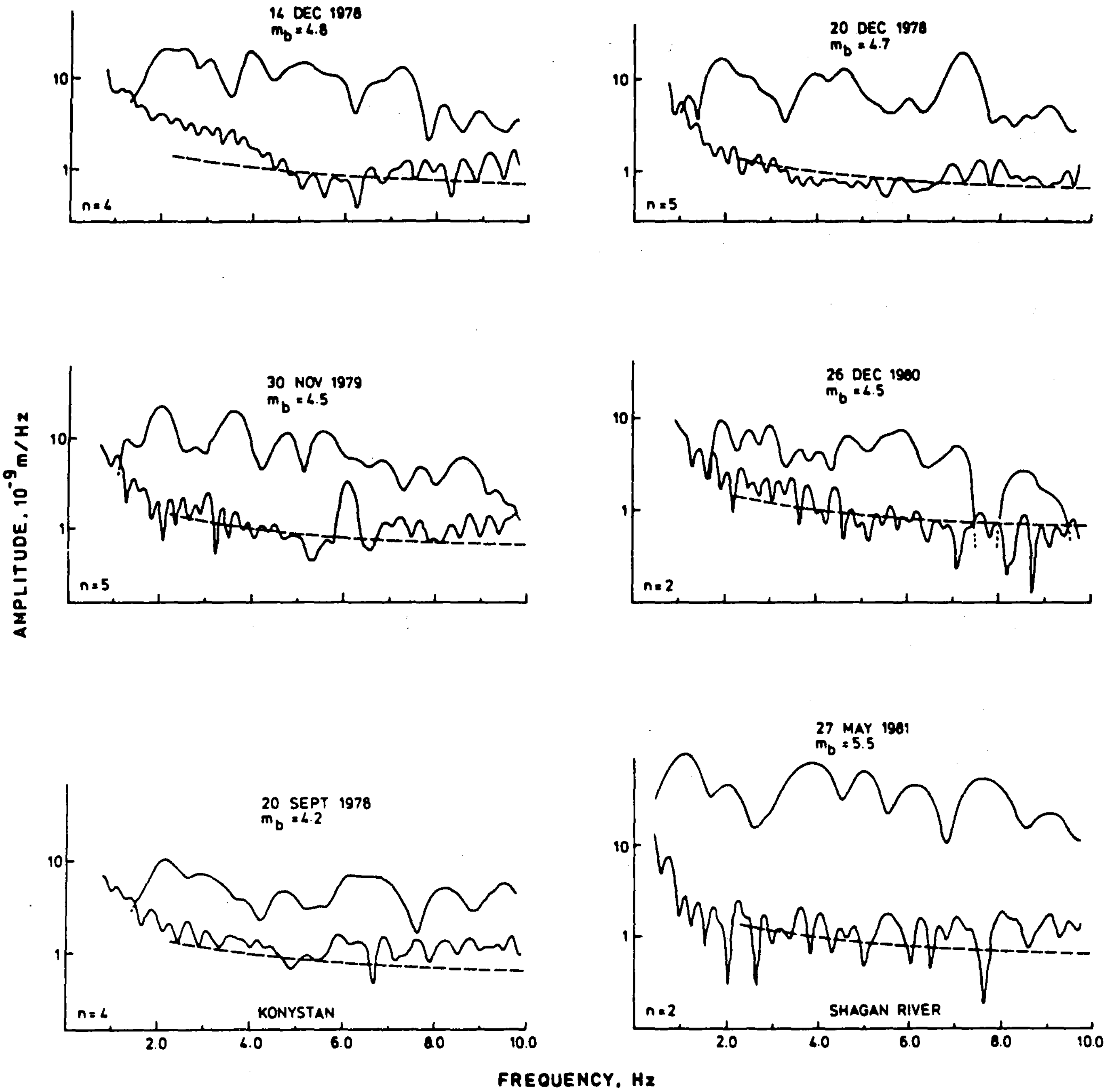
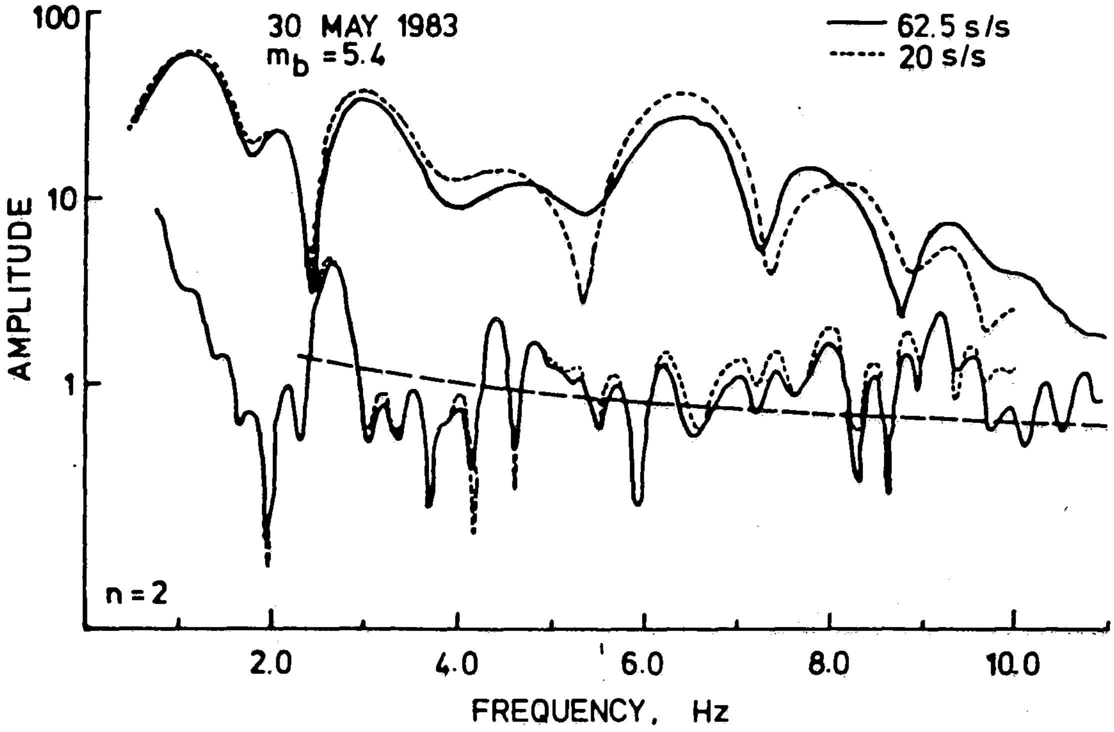


Fig. VII.5.2 Spectra are plotted for six events in the same format as Fig. VII.5.1. The number of elements included in the spectrum is indicated by n.



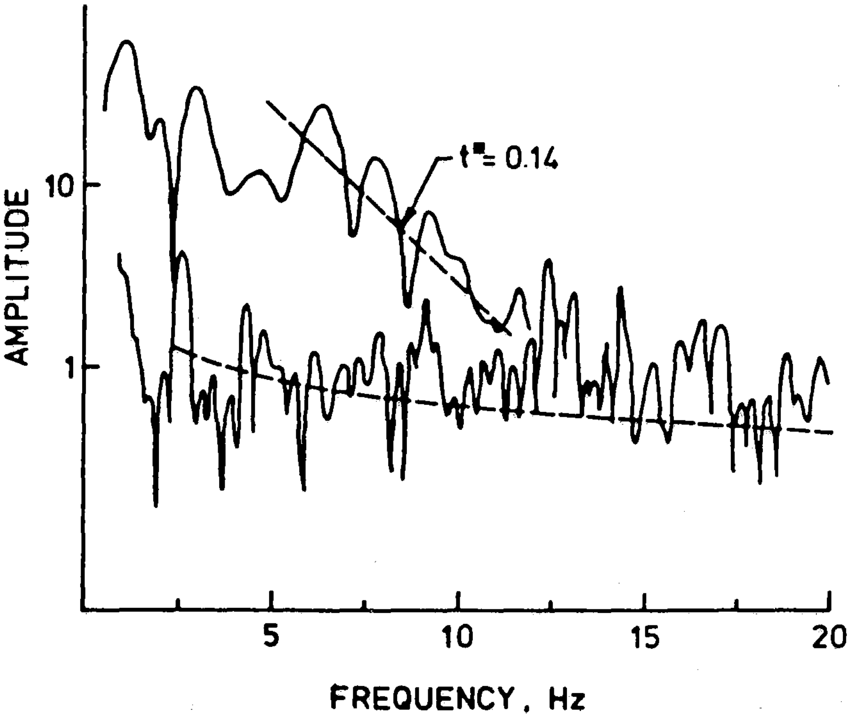


Fig. VII.5.3 Signal and noise spectra are plotted for an event digitized at two different sampling rates. The higher sampling rate spectra are then replotted on a different frequency scale (bottom). On the latter a line with a slope corresponding to t* = 0.14 is drawn through the high-frequency portion of the signal spectrum.

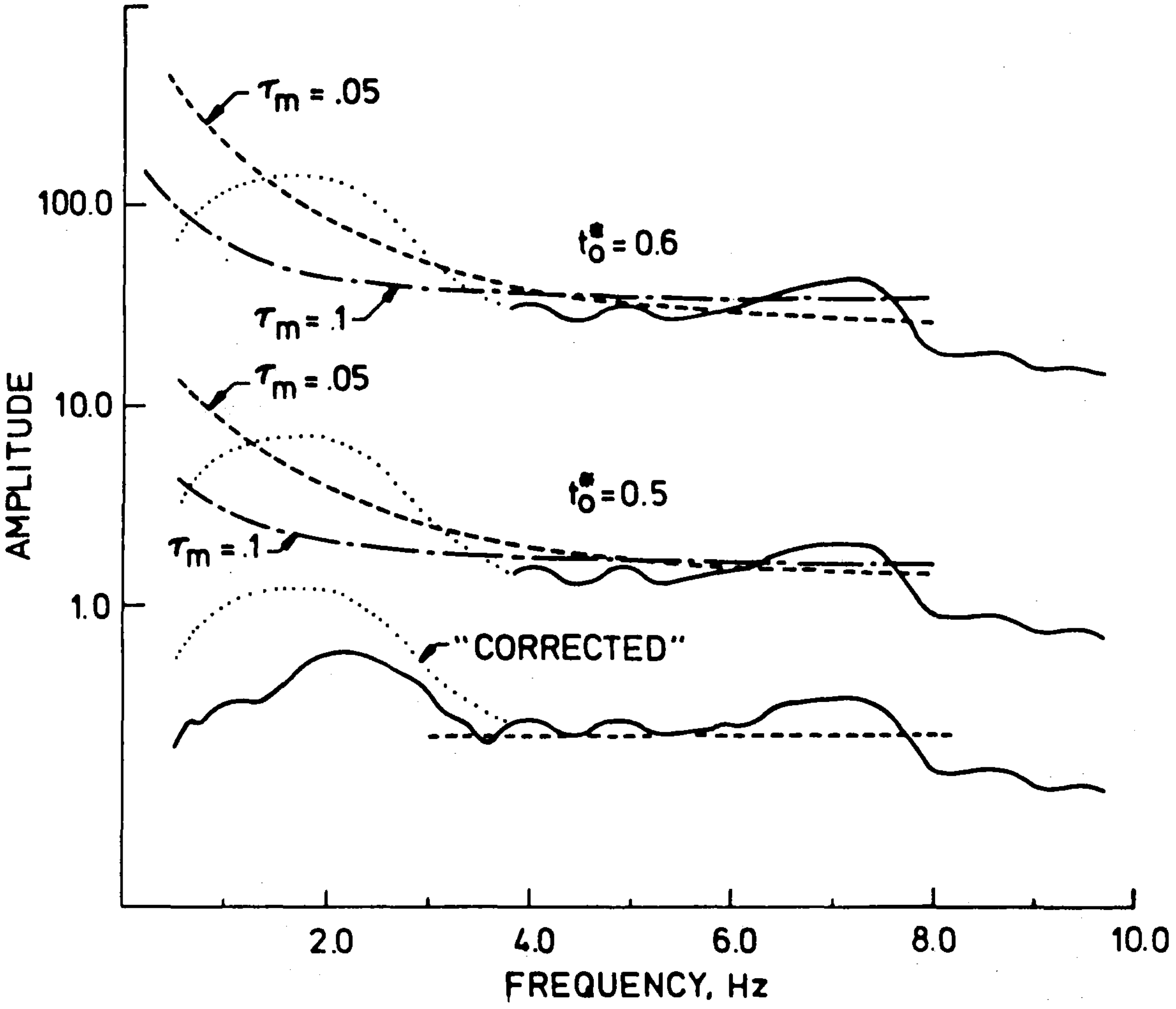


Fig. VII.5.4 The bottom sketch shows the path average spectrum together with a horizontal line and a dotted line showing this spectrum corrected for corner frequency effects. The top two sketches show this corrected spectrum with the spectral effect of several absorption band models for attenuation.