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VII.7 Attenuation of seismic energy from local events in southern Norway

Seismic wave attenuation characteristics at local and regional distances in Norway and surrounding areas are known to be very dependent on the local geology, with rapid regional variations. Still, very few (if any) more extensive studies on this problem have been carried out in this region, and we therefore now report on a work aimed at analyzing how the quality factor Q appears in the southern Norway region.

Two different methods, the coda decay method and the method of spectral ratio, were tested out and applied to local events recorded within the region studied. In all cases the event-station distances were less than 300 km, and the depth of the events were in the range 0-35 km. Because observed Q in most other studies is found to depend strongly on frequency it is commonly expressed in the form $Q=Q_o*f^m$, where Q_o is Q at a reference frequency (usually 1.0 hz), and m is a constant.

The use of the coda decay method to determine Q was first applied by Aki & Chouet (1975) and is in principle used to investigate how the coda energy from a local earthquake recording decays with time. The coda energy is thought to consist primarily of energy back-scattered from randomly distributed inhomogeneities and boundaries in crust, and a medium which generates coda well will then be less efficient as a wave transmitter. Theoretically, the coda is assumed to be described as a homogeneous pool of scattered energy covered in an ellipsoid with foci at the event's hypocenter and the station, and the measured decay of this energy with time will reflect Q within the ellipsoid. For different scattering models it has been shown that the following simple relation describes the decay of coda energy with time:

$$A(f,t)=S(f)\cdot t^{-u}\cdot \exp(-\pi ft/Q(f))$$

Here A(f,t) is the present coda amplitude, S(f) the coda source factor, t the time measured from origin, and f is the frequency. The dispersion parameter u describes the type of spreading that occur, and is mostly given the value 1.0 which reflects scattered body-waves. Under the assumption that u is a constant and Q is a constant in each frequency band, Q can be found by linear least squares analysis for each fixed frequency f (see Fig. VII.7.1).

Another way to find Q directly from observations is to use the method of spectral ratio. This method is perhaps more known, and the way it is applied in this work is to see how the energy of direct body-waves decays between two stations with approximately equal azimuth relative to the source. By comparing the spectral contents of the direct waves recorded at the two stations , an estimate of the decay of energy as a function of frequency is obtained by linear least squares analysis (see Fig. VII.7.2). The estimated Q found using this method will describe the energy loss along the refracted wave-path of the primary waves and will therefore generally not describe the same volume as Q found from coda-waves.

The data used in this analysis are a selection of 19 local events recorded during 1982-83 by the temporary digital network of southern Norway (SNN) operated by NORSAR. Additionally, a selection of 14 local events recorded between January and March 1985 at the new Western Norway Network (WNN), which is operated by the Seismological Observatory in Bergen, were used. All stations were short period vertical instruments, and the events used were relatively widely distributed south of 62 degrees north.

The coda decay method were applied to recordings from both networks, but the spectral ratio method could only be used for recordings from the SNN-network because the stations in the WNN-network were not calibrated at the time this work was carried out.

To ensure that only high-quality data were used in this analysis, only events with acceptable signal-to-noise ratio were included. Tests showed that the method of coda decay was very sensitive due to the noise level, but a noise level less than about 20% of the signal amplitude was not critical when calculating Q. This observation was then used as a criterion under selection of data. Fig. VII.7.1 shows some examples of chosen coda signals.

In most studies on this problem it is found that the quality factor Q increases with depth. This result was also found in this work in the way that coda Q seems to increase with increasing length of the investigated time window of data used. The increase in Q with window length is tied to the fact that the later parts of coda consists of energy back-scattered from deeper parts of the lithosphere (with higher Q). The observed coda Q did not turn out to differ significantly for subareas within the southern Norway region, and the averaged Q-values for the entire region were

Q-value	Corr. coeff.	No of obs.	Window (secs)
$55*f^{1.15}$	0.93	50	20
$75*f^{1.15}$	0.94	46	30
$120*f^{1.09}$	0.92	46	40

The time window dependence for the spectral ratio method was not as critical as in the coda decay method. The chosen window length was 5 secs and was based on the experience that this length gave the most stable results. The spectral ratio method was applied to P- and S-waves separately and gave the following results:

Q-value	Waves	No of obs.	Q_o	m
$121*f^{0.89}$	P	17	121 ± 90	0.89 ± 0.3
$127*f^{1.08}$	S	11	127 ± 70	1.08 ± 0.2

Some examples of the spectral ratio estimation of Q are shown in Fig. VII.7.2. It must be emphasized, however, that the results were rather scattered, and much more data would be needed to reduce the rather wide error limits.

The results indicate that Q for P-waves generally is lower than Q for S-waves within the region studied (see Fig. VII.7.3). Another interesting observation is that the Q-values for S-waves are quite similar to those obtained for coda-waves. This is shown explicitely for coda Q over a 40 secs time window. The fact that Q for coda waves in this window are almost identical to spectral ratio Q values for S-waves probably means that the coda primarily consists of S-waves, which also is observed in other regions, and that coda in this window samples approximately the same part of crust as the direct S-waves.

The rate of frequency dependence of Q can be thought to give an indication of the amount and size of the scatterers that occur. A scattering model described by Dainty (1981) to explain the frequency dependence of Q showed that observed Q can be divided into two different mechanisms, intrinsic Q caused by the medium's deviation from complete elasticity, and scattering dependent Q caused by inhomogeneities the waves encounter during propagation. Intrinsic Q is in most works assumed to be relatively frequency independent, in which case the frequency dependence of observed Q must be mainly caused by scatterers or inhomogeneities in the crust. The apparent energy loss due to scattering will then be most critical for wave lengths comparable with the typical size of these scatterers, which in turn means that the attenuation of energy at low frequencies must be stronger than expected from intrinsic attenuation only. This is clearly shown if we compare the result found in this work with the result from Hasegawa (1985) for the Canadian Shield area (Fig VII.7.4). These two regions both represent old shield areas and should therefore not be too dissimilar geologically. It is seen from Fig. VII.7.4 that the frequency dependence of Q in southern Norway is much higher, but that Q for both areas seems to coincide for higher frequencies. This can be interpreted in terms of similar intrinsic Q in the two regions, but with more and stronger inhomogeneities in southern Norway.

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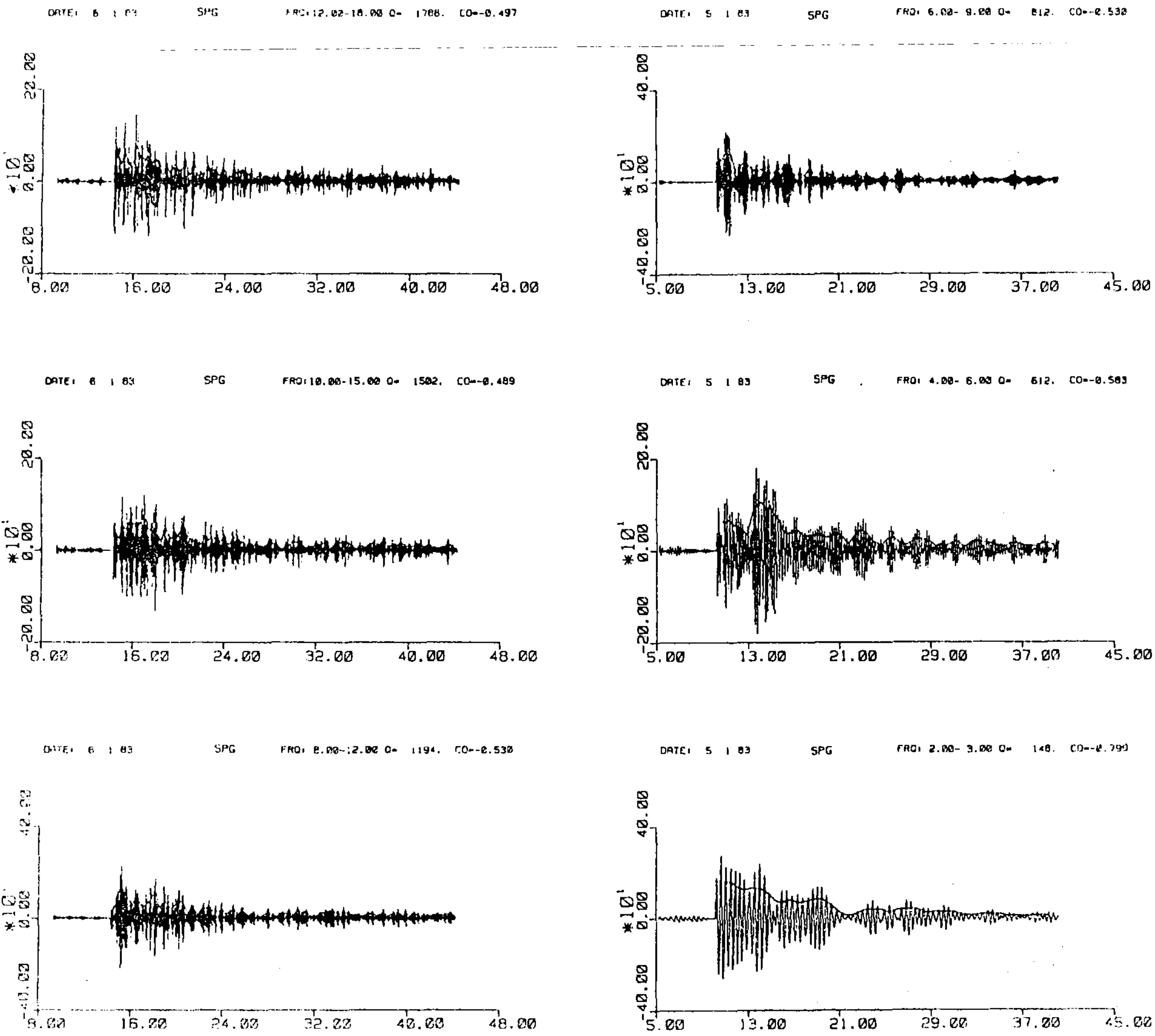

Fig VII.7.1 Examples of coda-recordings for one specific station band-pass filtered at different frequencies. The first part of the recordings indicate the noise level before P-wave arrival, and on top of the signals the RMS-envelope is drawn as an approximation to A(f,t). Axes are time after origin versus amplitude.

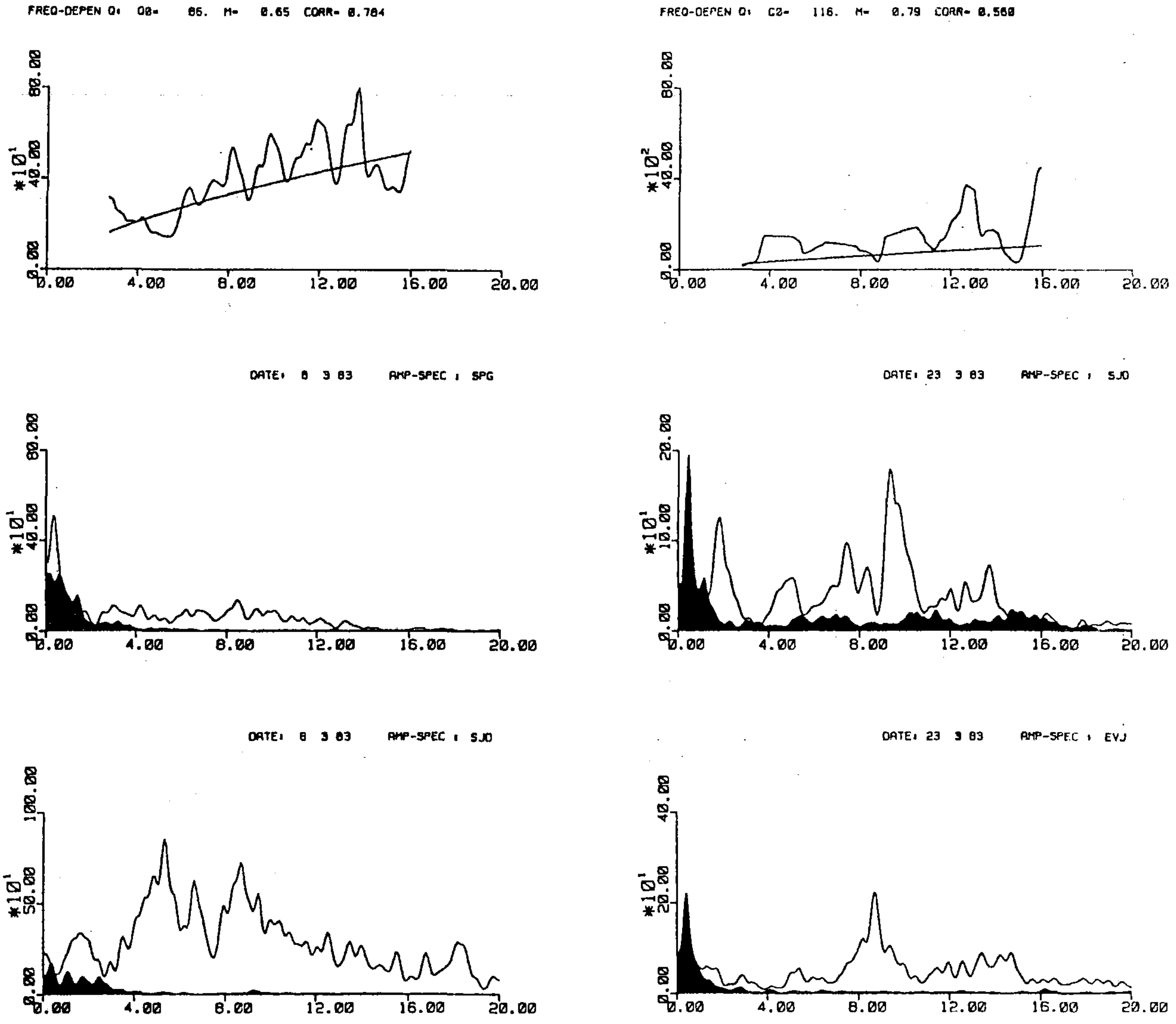

Fig. VII.7.2 Examples of spectral ratio estimation of Q for P-waves. On top the Q(f)-functions of frequency obtained from spectral ratio analysis of the two below recorded amplitude spectra. The least squares lines show the curve of the best fit frequency dependent Q. The black zones on the amplitude spectra indicate the noise before P-wave arrival.

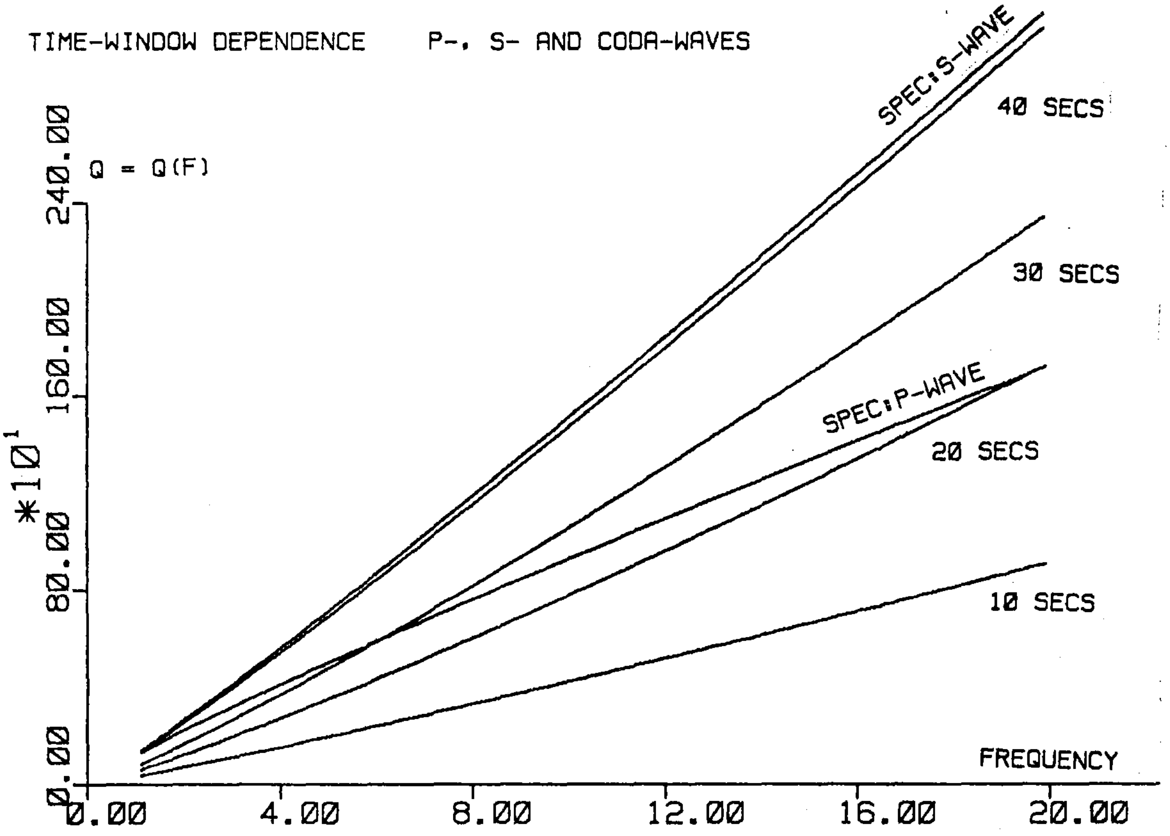

Fig. VII.7.3 Q as a function of frequency for both spectral ratio and coda-decay method. The figure shows coda Q for different time window lengths and Q for P- and S-waves using spectral ratio for a 5-second time window. Dispersion parameter u is fixed at u = 1.0, and data from both SNN- and WNN-networks are used.

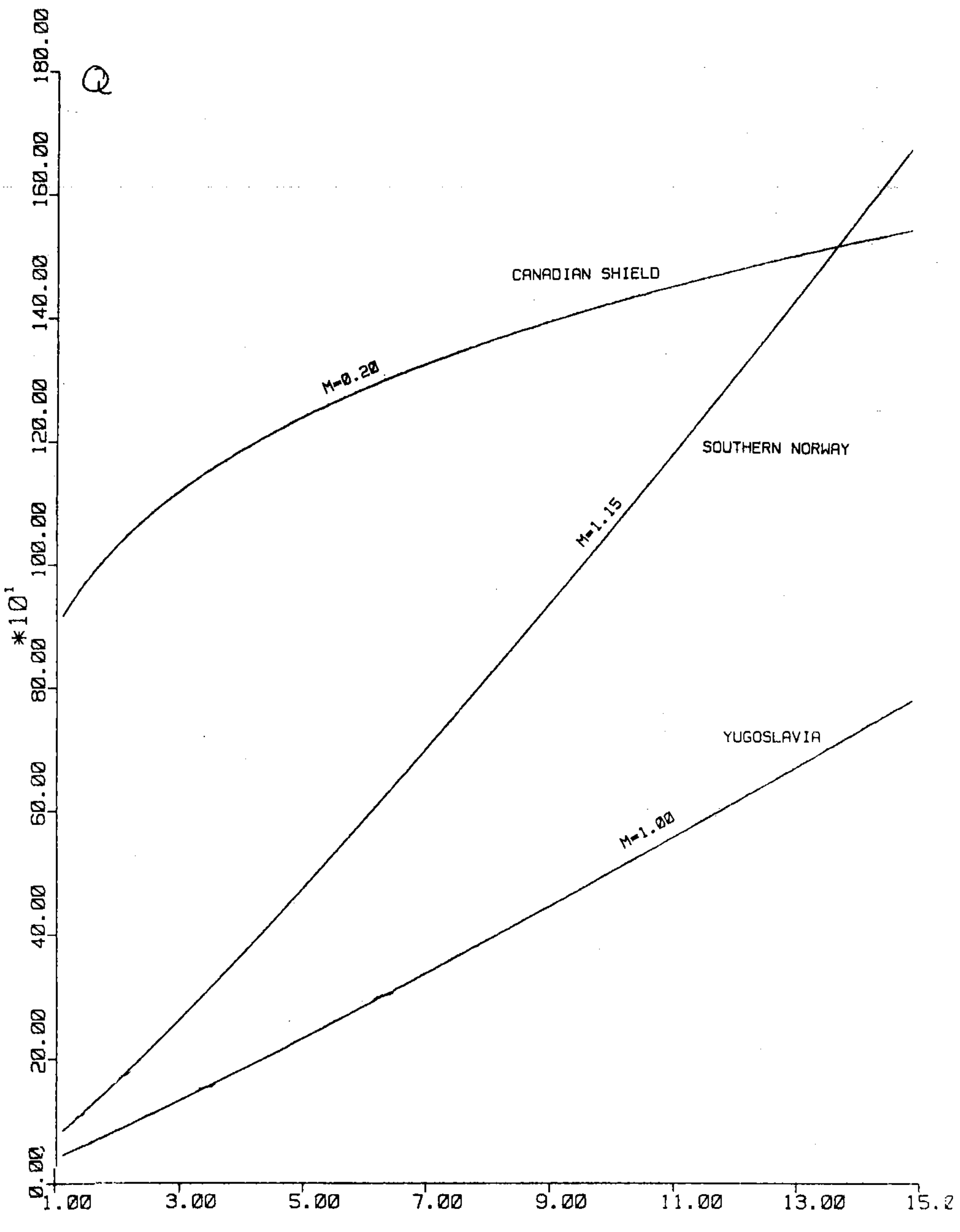

Fig. VII.7.4 Q as a function of frequency for different regions. The value of the scattering index m is shown on the figure. The curves intersect the vertical axis for 1 Hz at the value of the proportionality factor Q_o.