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Q_R - Factors in the Crystalline Uppermost Crust in Finland from Rayleigh Surface Waves

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Abstract

During the period 1981-1993 five deep seismic sounding profiles were performed in Finland as an international co-operation to study the crustal structure of the Fennoscandian Shield. Apart from P- and S-waves, well developed Rayleigh surface waves (R-waves) with periods of 0.5-1.0 s were recorded from all the shot points on profiles SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA. In the seismic record sections, filtered in the frequency band 0.5-2.5 Hz, the R-waves were clearly observed up to distances of about 300 km. Short-period recordings from permanent seismograph stations on Finnish territory were used to study the relationship between the amplitude and charge size of the shot points. Amplitudes of R-waves corrected for charge size were used to study Q_R *quality factor of the rocks below the Earth's surface, especially in the uppermost 4 or 5 kilometres. The quality factor* Q_R *varies in the uppermost 1 km on average from 30 for Archean basement in the northern and eastern Finland to 60 for the Proterozoic Svecokarelides in Central and Southern Finland. For depths of 1 to 4 km quality factor* Q_R *has larger value for both tectonic units being about 130 and 250, respectively.*

Key words: Q, Rayleigh waves, Upper Crust, Finland

1. Introduction

During the last 15 years five modern deep seismic sounding profiles (Fig. 1) were made on Finnish territory to study the crustal structure of the Fennoscandian Shield in the contact zone of the Archaean and Svecokarelian provinces (*Simonen* 1980). The main result which was obtained was an anomalous big crustal thickness in the Central Finland reaching 60 km. The results based on interpretation of P- and S-wave recordings were published in a number of papers (*Luosto et al.,* 1984, 1989, 1990, 1996; FENNIA Working Group, 1996; *Guterch et al.,* 1985; *Grad and Luosto,* 1987, 1992 and 1993; *Luosto,* 1991). According to these investigations the crustal thickness in Finland is in the range of 42-60 km. The P-wave velocities in the upper crust are 6.0-6.4 km/s, in the middle crust 6.6-6.9 km/s and in the lower crust > 7.0 km/s. The thickness of the upper and middle crust is in the range of 32-42 km. The thickness of the lowermost high-velocity crustal layer is in the range of 4-24 km. The P_n- velocity in the uppermost mantle is 8.0-8.2 km/s. The ratio of P-wave velocity to S-wave velocity varies from about 1.70 in the upper crust to 1.77 in the lower crust. In the upper mantle the ratio is about 1.73. In the upper crust (between 5 and 15 km deep) low velocity layers and high velocity bodies were found in some parts of profiles.

Particularly, the uppermost crust along the SVEKA'81 profile was investigated in detail using P-, S- and R-waves (*Grad and Luosto*, 1987, 1992 and 1994). The P-wave velocity increases from about 5.7-5.9 km/s at the surface to about 6.0 km/s at a depth of 1 km, and about 6.15 at a depth of 4 km. The S-wave velocities vary from 2.80 to 2.95 km/s in the uppermost 200m and from 3.10 to 3.45 km/s down to 1 km deep. In the depth interval of 1-4 km the velocities of S-waves are 3.44-3.68 km/s. The corresponding V_P /V_S ratio in the depth intervals mentioned above are 1.83-2.0, 1.76-1.88 and 1.65-1.75, respectively. Amplitude study of the body and surface waves shows low values for the quality factor of the uppermost 1 km. Corresponding values of Q_P , Q_S and Q_R are 50-80, 70-120 and 20-60, while in the depth interval of 1-5 km they are 100-800, 150-300 and 80-280, respectively.

Because the properties of the short period R-waves, such as velocities, amplitudes and quality factors $Q_{R,}$ are strongly involved with the structure of the uppermost one or two kilometers they give useful additional tools for studying structural properties of the rocks in those depths. The main aim of the present study is to investigate amplitudes and quality factors Q_R of surface waves for the uppermost 5 km of the basement along the refraction profiles SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA.

2. *Surface waves in the uppermost crust*

Very good quality recordings of R-waves obtained along all the profiles make it possible to make a detailed study of amplitudes and quality factors Q_R. Examples of the R-waves recorded along the SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA profiles are shown in Fig. 2. On the all record sections made with band pass filter of 0.5-2.5 Hz the R-waves are observed along the whole profile. The wave field of R-waves from the different profiles and from different shot points have some similarities. Two kinds of waves are observed: the R_1 -wave, of "high" frequency, with an average period T ≅0.5 s, and the R_2 -wave, of "low" frequency, with average period of T ≅0.8 s. The wave R_1 is observed up to a distance of 40-100 km from the shot point and wave R_2 up to the end of profile. The corresponding average velocities of waves are $c_1 \cong 2.9$ km/s for the R_1 -wave and $c_2 \cong 3.1$ km/s for the R_2 -wave, respectively. According to our earlier investigations the R_1 -wave is connected with the uppermost 0.2-1 km crystalline basement, while the R_2 -wave propagates in the depth range of 1-4 km (*Grad and Luosto*, 1987, 1992 and 1993). The average values of the periods and velocities for the SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA profiles are listed in Table 1.

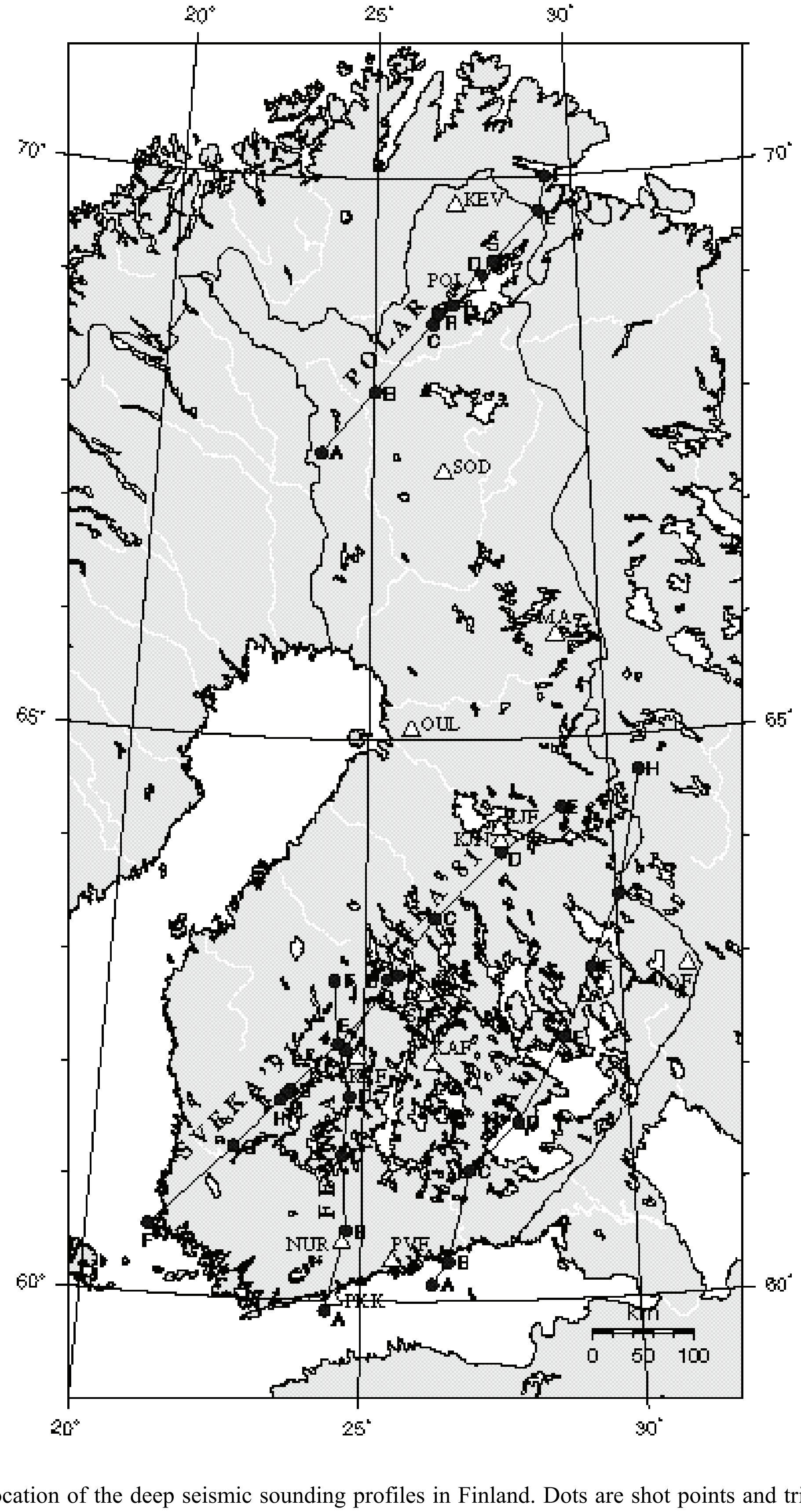

Fig. 1. Location of the deep seismic sounding profiles in Finland. Dots are shot points and triangles are permanent seismograph stations (with the exception of station POL), records of which were used in the analysis of amplitude - charge size dependencies.

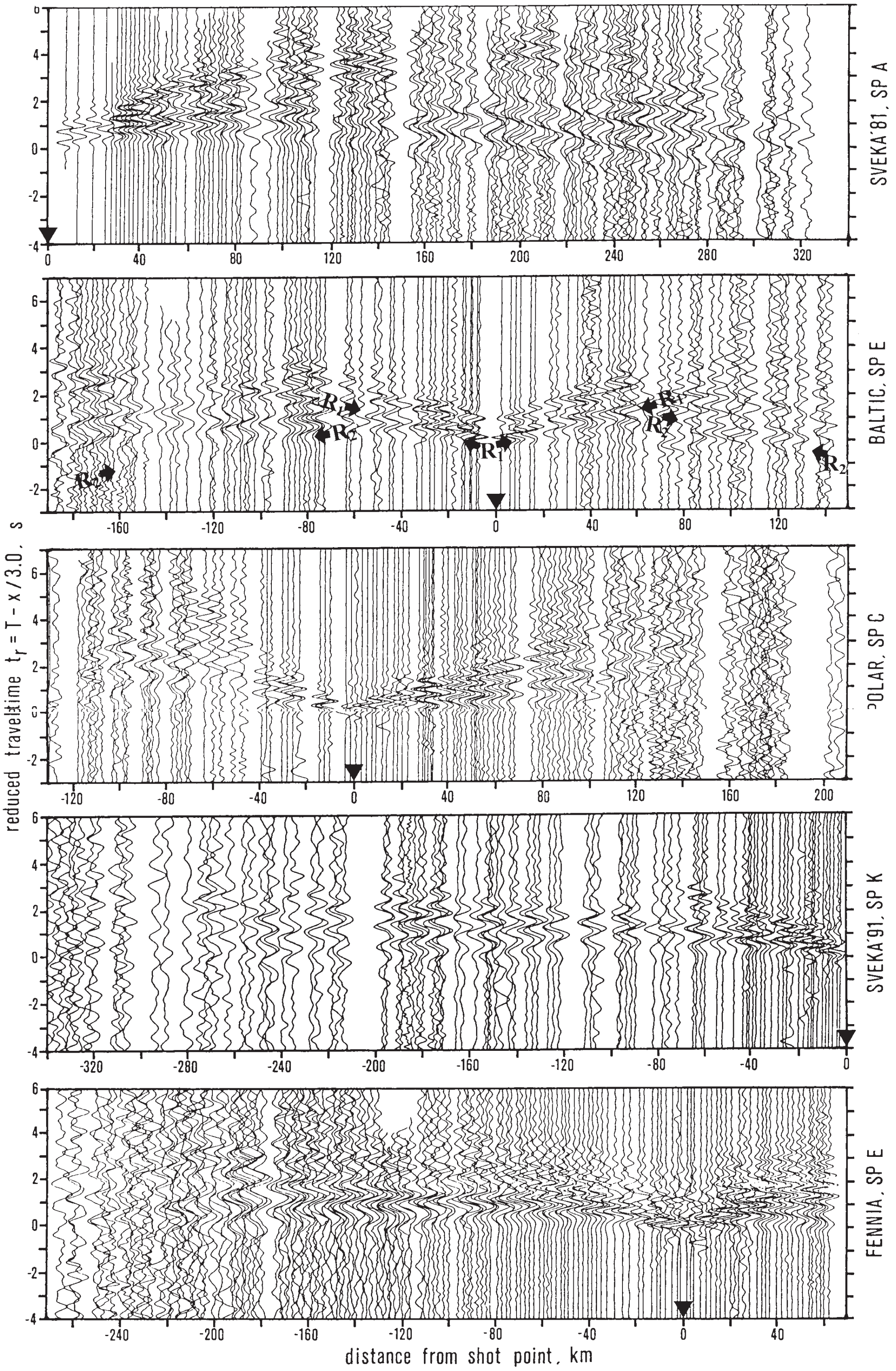

Fig. 2. Examples of amplitude normalized R-wave record sections for deep seismic sounding profiles SVEKA'81 (SP A), BALTIC (SP E), POLAR (SP C), SVEKA'91 (SP K) and FENNIA (SP E); vertical component; filter band 0.5-2.5 Hz; reduction velocity 3 km/s. Note two kinds of R-waves: "high" frequency waves R1 at distances up to about 50-70 km from the shot point and "low" frequency waves R2 at greater distances.

Table 1. Average periods T and velocities c of surface R_1 - and R_2 - waves

Profile	T_1 [s]	T_2 [s]	c_1 [km/s]	c_2 [km/s]
SVEKA '81	0.50	0.94	2.90	3.20
BALTIC	0.59	0.72	3.01	3.08
POLAR	0.46	0.64	2.88	3.02
SVEKA '91	0.55	0.82	3.01	3.09
FENNIA	0.53	0.92	2.97	3.08
all together	0.53	0.79	2.95	3.10

Similar short-period R-waves with group velocities of 2.8-3.05 km/s have been recorded earlier in Scandinavia at distances up to 200-500 km (*e.g. Båth*, 1971 and 1975; *Wahlström*, 1975; *Lokshtanov et al*., 1991; *Åström and Lund,* 1992).

3. Amplitude - charge size dependence

Altogether more than 180 shots of 80-1800 kg TNT were fired along five profiles the SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA. The shots were fired mostly in small lakes with depths of 2-10 m. In order to ensure better energy transmission, small charges of 10-50 kg were distributed in the lake bottom in a grid with distance of about 8 m between the charges. Some shots were fired in the sea at depths of 20-50 m (BALTIC – SP A and SP B; SVEKA'91 – SP F; FENNIA – SP A).

The fact that records were made from different shot charges has been taken into account in the R-wave amplitude analysis. For this purpose, short-period recordings from thirteen permanent seismograph stations on Finnish territory were studied. Readings from the standard heat pen, ink pen or photographic records have been made according to general observatory practice. One exception to this was the portable station POL which recorded all shots at the same position only during the POLAR experiment. Altogether more than 100 records from shot points to seismograph stations were analyzed; the configurations of the shot points and seismograph stations are shown in Fig. 3.

Amplitude measurements were made from the maximal amplitudes of the P-, S- and R-wave trains (see examples in Figs. 4 and 5). To study the relationship between the amplitude and charge size, the power function (e.g. O'Brien, 1960):

$$A(W) = A_0\, W^n \qquad (1)$$

was fitted to the data, where A_0 is amplitude in mm, W the weight of TNT charge in kg, and A and n are unknown constants. Analysis gave more than 200 values of n in the range of 0.2-1.3. The amplitude - charge size relationships for the SVEKA'91 profile are presented in Fig. 6. It is interesting to note that n values for shot point F fired in the sea at a depth of about 20 m are in the range 1.04-1.29, while n values for shots fired in lakes at a depth of an average of 5.5 m are only 0.26-0.59. Similar effect is observed

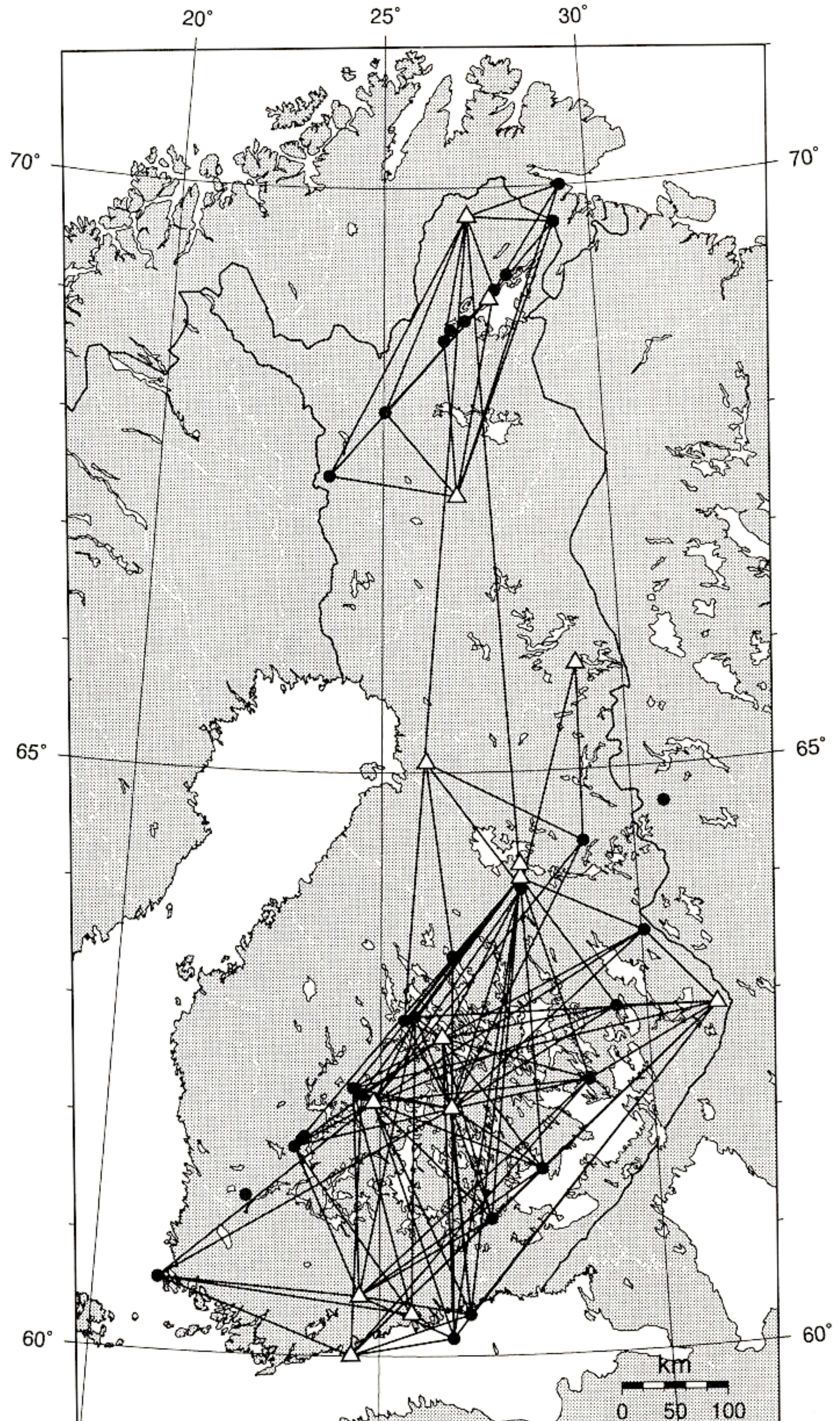

Fig. 3. Configuration of shot points and permanent seismograph station (marked by lines) for which amplitude - charge size dependencies were analyzed. Other explanations as in Fig. 1.

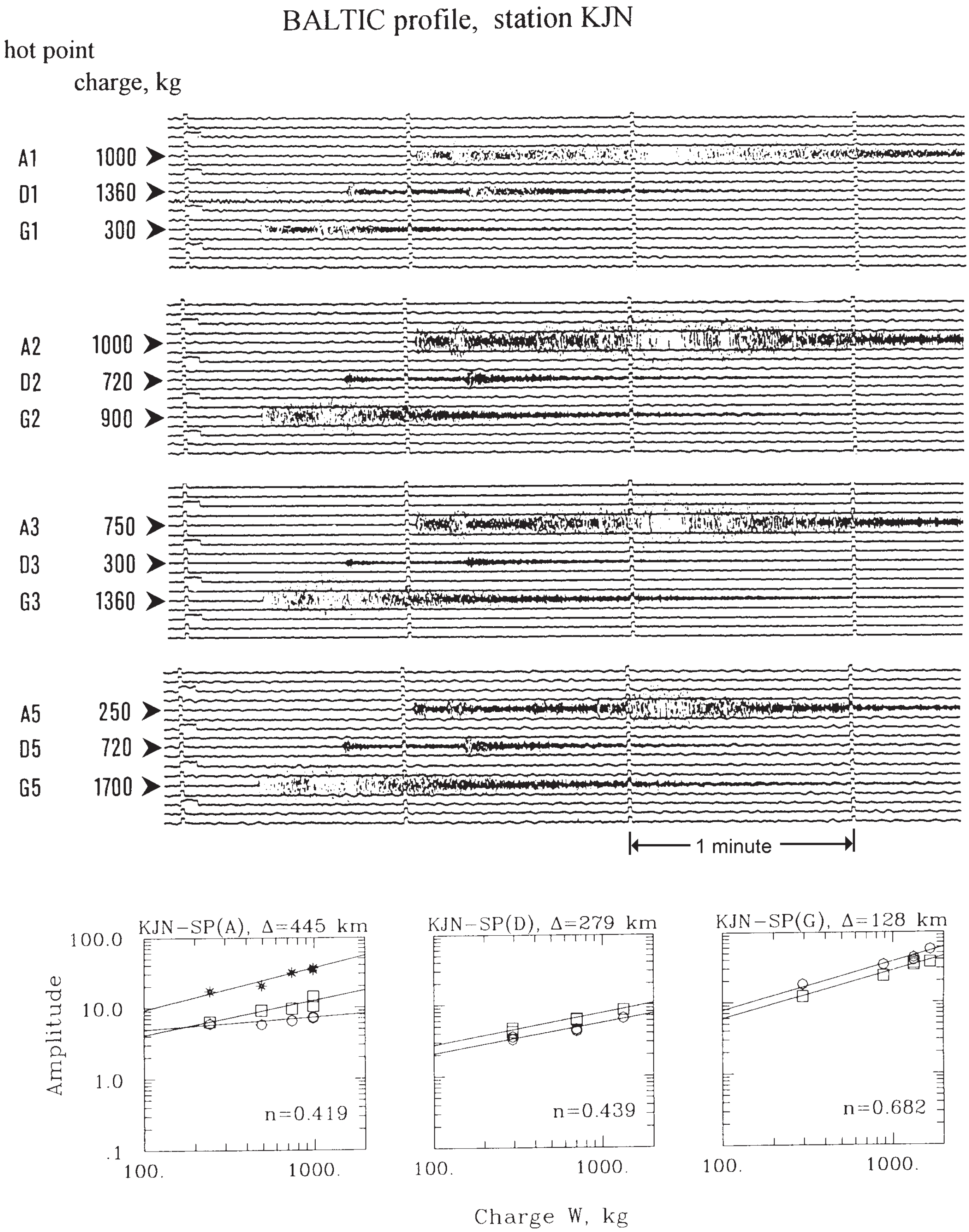

Fig. 4. Examples of seismograms from permanent seismograph station KJN and amplitude - charge size dependencies. Each seismogram shows records of three shot points from the BALTIC profile (SP A, SP D, SP G) for different charge size, from 300 kg to 1700 kg. In the bottom observed amplitudes (open circles for P-waves, squares for S-waves, stars for R-waves) are shown; the straight lines represent least square fit of function (1); n - average value of exponent; Δ = distance from shot point to the station.

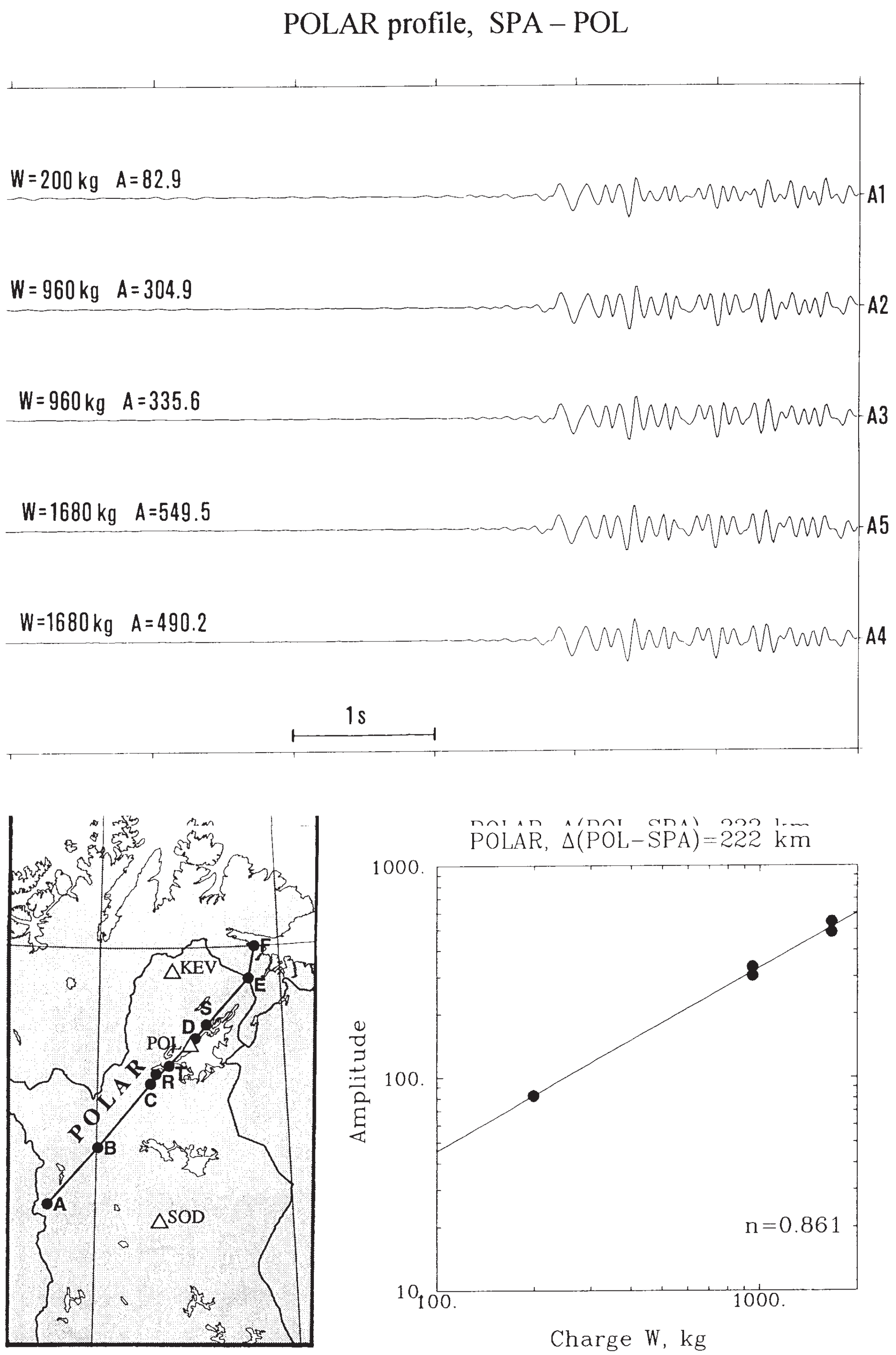

Fig. 5. Examples of seismograms from station POL, which recorded all the shots of the POLAR experiment at the same position, and amplitude - charge size dependencies for shot point A. Each seismogram shows records for different charge size, from 200 kg to 1680 kg, at shot point A. Note the identical shape of amplitude - normalized seismograms. A is the scaling factor. The figures at the bottom shown the observed amplitudes for P-waves (dots); the straight line represents the least square fit of function (1); n - value of exponent; D = distance from shot point to the station.

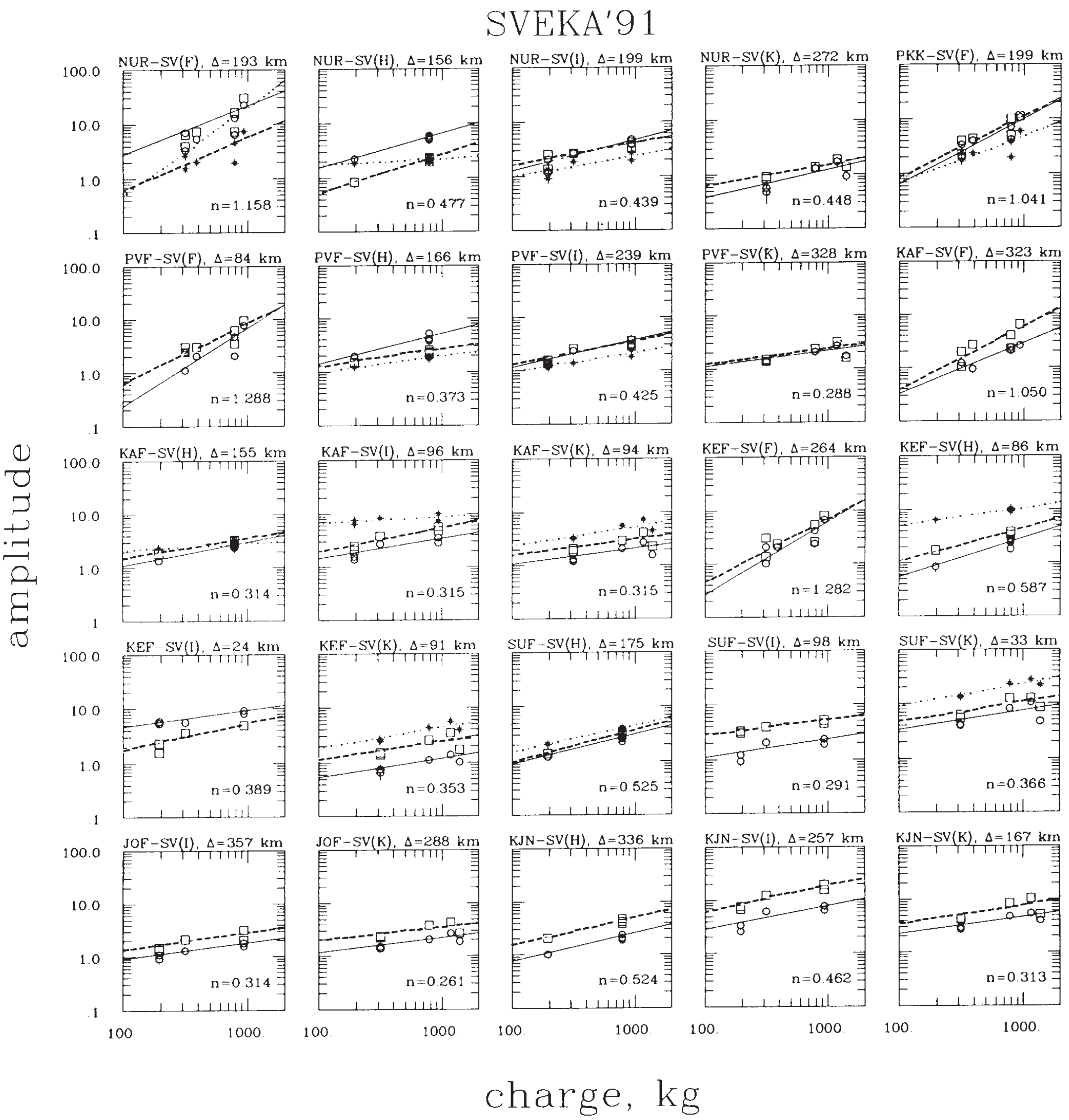

Fig. 6. Amplitude - charge size dependencies for the SVEKA'91 shots based on records at permanent seismograph stations NUR, PKK, PVF, KAF, KEF, SUF, JOF and KJN. The function (1) is fitted to the observed amplitudes; open circles and solid lines refer to P-waves, squares and dashed lines to S-waves, stars and dotted lines to R-waves); n = average value of exponent; Δ= distance from the station to shot point. Note the much bigger values of n for shot point F fired in the sea.

also for other profiles. The results are compiled in Table 2. The average value of n for sea shots is $\langle n \rangle = 0.865$, while for shots fired in lakes $\langle n \rangle = 0.607$. For each profile an average value of n for shots in lakes is given together with an average lake depth $\langle h \rangle$. The coincidence of $\langle n \rangle$ and $\langle h \rangle$ is visible: shots fired in deeper lakes are more effective (the value of $\langle n \rangle$ is bigger).

Many other authors have also investigated the amplitude-charge size relationship for explosive sources using formula (1). *Gurvich* (1965) obtained a value of n = 0.78 for charges W between 25 and 300 kg and frequencies ranging from 2.5 to 10 Hz. For charges between 100 and 2200 kg exploded in a 3-4 m deep reservoir, *Ryaboy* (1965) obtained a value of n = 0.85 for frequencies close to 16 Hz. Similar values for underwater explosions were obtained by *O'Brien* (1960), *Luecke* (1960) and *Müller et al.* (1962), who found n-values of 0.67, 0.55 and 0.65, respectively. Analysis of the data from 21 pairs of shot point - seismograph station for SVEKA'81 profile gave values of n in the range 0.59-1.10, with an average value of n = 0.74 (*Lanne*, 1982). The data from seismograph stations KEF, SUF and KJN located very close to the SVEKA'81 line gave an average value of n = 0.89 (*Grad and Luosto*, 1994).

Table 2. Average n-values: shots in the sea <n> = 0.865, shots in the lakes <n> = 0.607.

Profile	$< n >$	$< h >$ in m
SVEKA '81	0.787	7.0
BALTIC	0.703	7.0
POLAR	0.675	6.5
SVEKA '91	0.392	5.5

where
$< n >$ - average *n*-value, $< h >$ - average shot depth in lakes

4. *Amplitudes of surface waves and quality factors Q_R in the uppermost crust*

Recordings along the SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA profiles were performed in the framework of international co-operation by different stations in digital or analog form. All the data were used to construct normalized seismic record sections. However, in the amplitude analysis only records from the Finnish PCM1218-80 stations (*Nurminen and Hannula*, 1981) and Polish MK-4/P stations (during FENNIA experiment) were used. All these stations have the same amplitude - frequency characteristics, digital system of recording and geophones; so they are "homogeneous" from the point of view of amplitude analysis.

In the analysis of the R-wave data the amplitudes were corrected for the charge size using the amplitude - charge size dependence (1) and average n values for each profile listed in Table 2. Using these values the amplitudes have been scaled to a charge size of 100 kg TNT. The examples of R-wave amplitude decays with distance from shot point are plotted in Fig. 7 for the same examples of seismic sections as shown in Fig. 2. The Q_R values were found by fitting the function,

$$A_R(x) = A_0\, x^{-1/2} \exp(-\gamma x), \qquad \text{where } \gamma = \pi f_R / Q_R C_R \tag{2}$$

to the observed amplitudes $A_R(x)$. A_0 is a constant and x the distance from the source; $x^{-1/2}$ is the cylindrical geometrical spreading attributed to surface waves; γ is the attenuation coefficient of R-waves; f_R, Q_R and C_R are frequency, quality factor and velocity of R-wave, respectively. It can be easily seen that the decay of observed amplitudes changes with distance. In the distance range 100-300 km the amplitudes have a slope corresponding to Q_R =250 on average while at smaller distances the decay of amplitudes is much bigger. For distances up to about 70 km, which correspond to the depth penetration of R-waves of about 1 km only, the amplitude decays correspond to Q_R =20-90. Similar features are observed for all 33 diagrams and the results are summarized in Fig. 8 and in Table 3, showing Q_R distribution along the SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA profiles.

Table 3. Quality factors Q_1 and Q_2 in the uppermost crust of the Fennoscandian shield in Finland.

Profile	**Q_1**	**(range)**	**Q_2**	**(range)**
SVEKA '81	50	(30 - 75)	~ 250	(90 - 230)
BALTIC	65	(40 - 90)	> 250	(120 - 590)
POLAR	30	(20 - 40)	> 130	(60 - 290)
SVEKA '91	85	(50 - 110)	> 250	(180 - 260)
FENNIA	75	(50 - 100)	~ 200	(160 - 220)

5. *Discussion of results*

Short-period recordings from permanent seismograph stations on Finnish territory were used to study the relationship between the amplitude of seismic waves and charge size of the shot points. Analysis using power function (1) gave more than 200 values of n in the range of 0.2-1.3. The average value of n for sea shots is <n>=0.865, while for shots fired in lakes it changes to the range <n>=0.39-0.79. The coincidence of average value of <n> with average depth of lake <h> is observed: shots fired in deeper lakes are more effective.

Amplitudes of R-waves corrected for charge size were used to study Q_R quality factor of the rocks below the Earth's surface, especially in the uppermost few kilometres. The quality factor Q_R varies in the uppermost 1 km on average from 30 for the Archean basement in the northern and eastern Finland to 60 for the Proterozoic Svecokarelides in the Central and Southern Finland. For depths of 1 to 4 km the quality factor Q_R has a larger value for both tectonic units being about 130 and 250, respectively.

It should be noted that the quality factor Q_R which describes the decay of amplitude of surface waves does not correspond precisely to the quality factors of body waves. According to our previously results for the SVEKA profile (*Grad and Luosto*, 1992 and 1994) the Q_R value determined from the amplitude decay was about 300, while the quality factor values of P-waves for the corresponding depth interval were about 600 on average but on the other hand quality factors of 200-300 of the S-waves are not very far from those found for the R-waves. *Shapira (*1988 and 1989) has also observed differences in the quality factors determined from different wave types in South Africa. Namely, studies of the amplitude decay of R-waves yield a specific quality factor Q_R =195, which is much lower than the value of 495 obtained using coda waves.

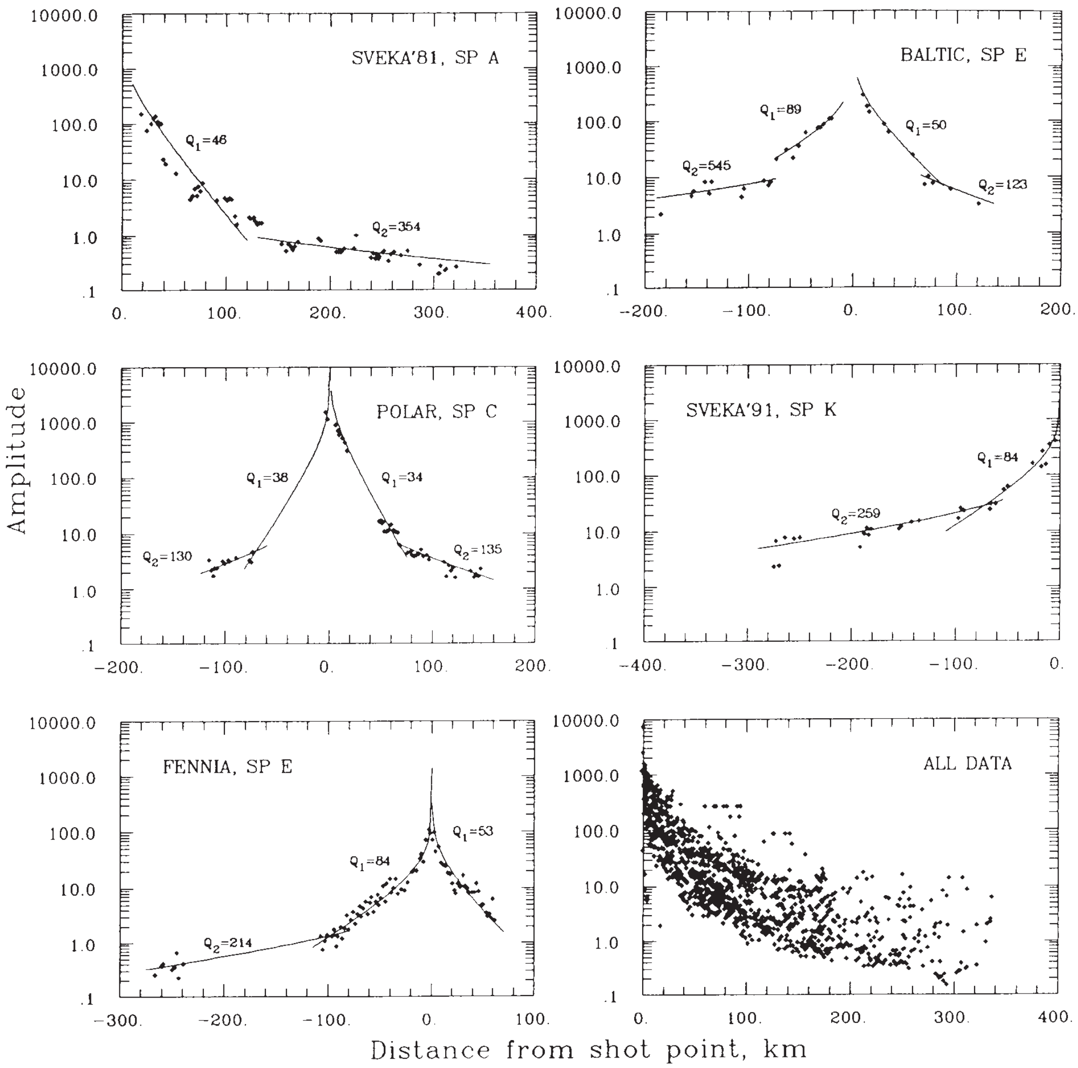

Fig. 7. Examples of observed amplitudes of R-waves for the SVEKA'81 (SP A), BALTIC (SP E), POLAR (SP C), SVEKA'91 (SP K), FENNIA (SP E) profiles and all the data. Q_1 and Q_2 values of quality factors according to formula (2).

The low values of the Q_R -factors for R_1 in the 1 km or so uppermost crust of the Fennoscandian Shield in Finland can be due to fracturing of the basement. The presence of the fractures, cracks and pores in a rock lower its P- and S-wave velocities, as well as values of the quality factors (*O'Connell and Budianski,* 1977). The extremely low Q values of the reworked Archean basement in northern Finland (even value of 20) are evidently connected to the large amount of fractures formed during the long life time of the basement. Havskog and Medhus (1991) also found that along the FENNOLORA profile there is a general tendency of increasing Q_p values when moving from north to south. They suggested that small values might correlate with more complex structures and low velocity layers in the northern Fennoscandian Shield. The rocks in the uppermost 2 kilometers in the POLAR profile are also much better electrical conductors, resistance of about 1000 ohmmeters, than in the Archean basement and in the Central Finland Granitoid Complex along the SVEKA profile where the resistivity can reach a value of many thousand ohmmeters. Observed differences in the resistivity are mainly caused by differences in water content in pores and crack and water salinity (*Korja*, 1990; *Korja and Koivukoski*, 1990).

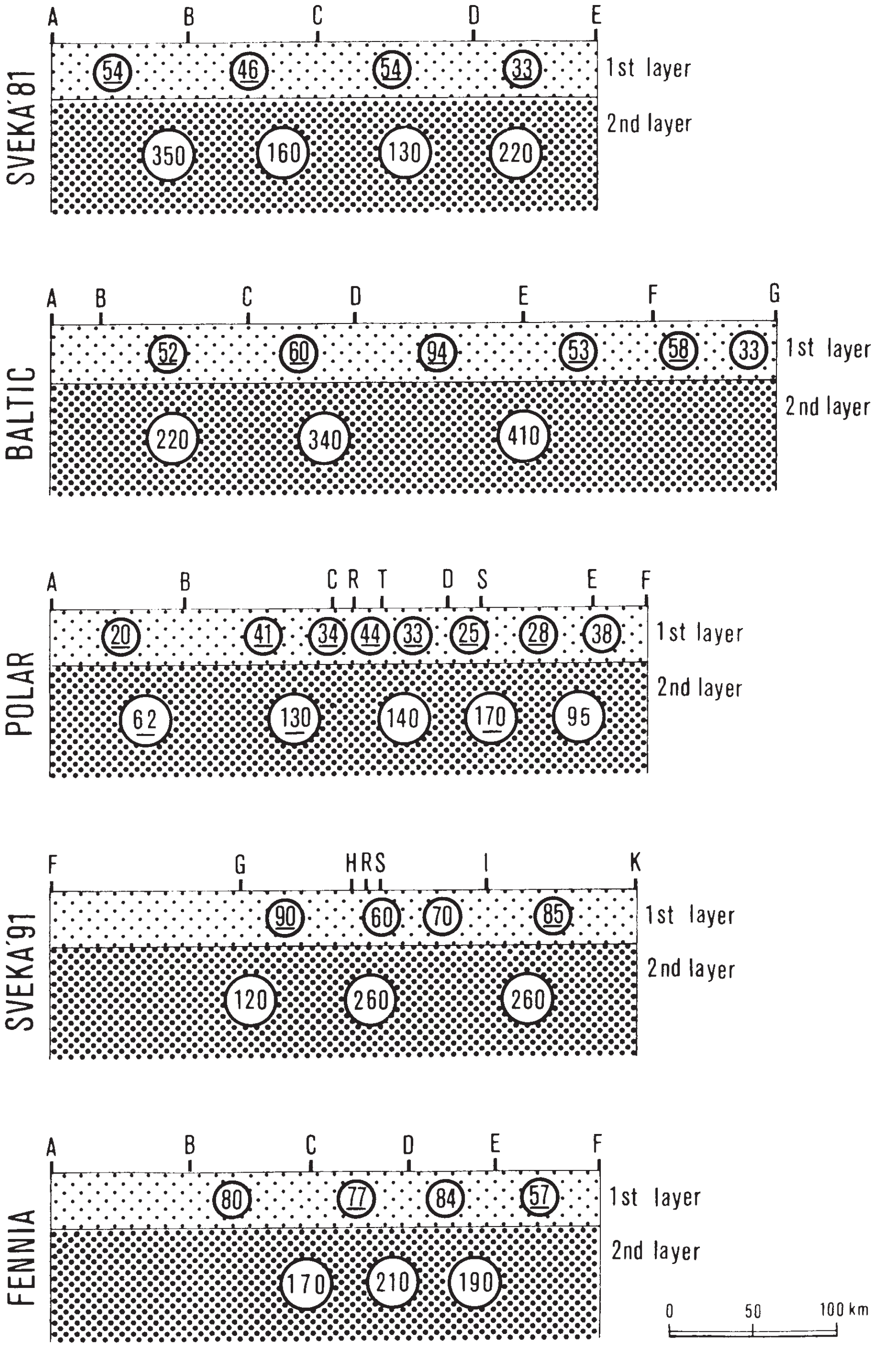

Fig. 8. Uppermost crustal structure along the deep seismic sounding profiles: SVEKA'81, BALTIC, POLAR, SVEKA'91 and FENNIA from Q_R values of R-waves. Underlined values are average Q_R factors obtained from neighboring shot points (as an example the value Q_R=54 for profile SVEKA is an average from Q_R=46 for SP A and Q_R=62 for SP B); the 1st layer is an uppermost basement, thickness of about 1 km and the 2nd layer reaches a depth of about 4 km.

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