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Fracturing of the Crystalline Uppermost Crust Beneath the SVEKA Profile in Central Finland

Marek Grad[1] *and Urmas Luosto*[2]

[1] Institute of Geophysics, University of Warsaw
Pasteura 7, 02-093 Warsaw, Poland

[2] Institute of Seismology, P.O. Box 19
FIN-00014 University of Helsinki, Finland

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Abstract

Seismic measurements along the SVEKA profile located in Central Finland were performed in 1981 as an international co-operation to study the crustal structure of the Fennoscandian shield in the contact zone of the Archaean and Svecokarelian provinces. On the basis of the P- and S-waves and the well developed Rayleigh surface waves (R-waves) the distributions of seismic velocities and quality factors were determined using the dynamic ray tracing method (2-D modelling) and reflectivity method (1-D modelling). The velocity ratio V_P/V_S varies in the upper crust from 1.67 to 1.74, reaching the maximum values of 1.8-2.0 in the uppermost 200-500 m. The quality factors Q_P and Q_S vary in the uppermost 1 km from 20 to 140, and from 200 to 600 down to 4 km depth. The low values of V_S and Q in the uppermost 1 km are interpreted to be due to rock fracturing. The results of P- and S-wave velocity analyses point to an isolated saturation of cracks in the uppermost crustal rocks. The crack density was estimated for the uppermost crust along the profile and the relation to the tectonics, surface geology, and fault and schist belts is discussed.

1. Introduction

In 1981 seismic measurements were carried out along the 325 km long SVEKA profile in Central Finland (Fig. 1). The first results based on interpretation of P-wave recordings were published by *Luosto et al.* (1984) and *Guterch et al.* (1985), and more detailed interpretations of S- and R-waves were published later by *Grad* and *Luosto* (1987 and 1993). According to these investigations the crustal thickness is 55-59 km. The P-wave velocities in the upper crust are 6.0-6.35 km/s, in the middle crust 6.6-7.1 km/s and in the lower crust about 7.3 km/s. The P-wave velocity below the crust in the upper mantle is about 8.0 km/s. The ratio of the P-wave velocity to the 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 there is a low velocity layer between 5 and 15 km and a high velocity body was found in the northern part of profile.

The modelling of R-waves gave the qualitatively new information about rocks below the Earth's surface, especially in a layer with a thickness of only a few kilometers. Interpretation of the low velocities of S-waves made it possible to draw conclusions about the fracturing, saturation of the fractures and the fracture density in the uppermost crust and their relation to the geology and tectonics.

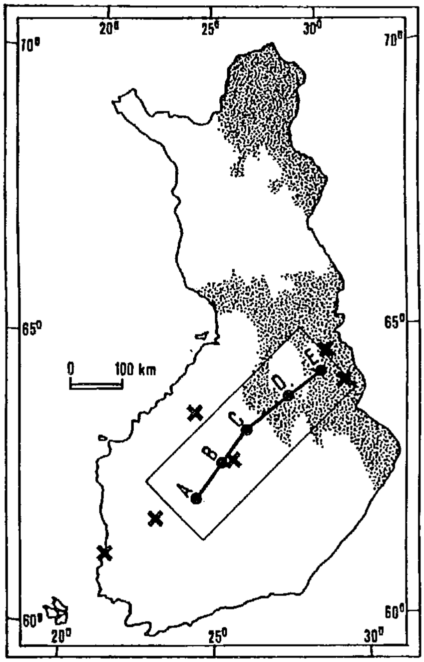

Fig. 1. Location of the deep seismic sounding profile SVEKA on the background of the major tectonic units of Finland (*Simonen*, 1980): Archaean basement (shaded area) and Svecokarelides (white area). The area discussed is bounded by a rectangle. Crosses show the location of boreholes discussed in the text: from north to south - Hyrynsalmi, Kuhmo, Sievi, Konginkangas, Lavia and Eurajoki, respectively.

2. *Body and surface waves in the uppermost crust*

The very good recordings obtained along the whole profile SVEKA make it possible to make detailed studies of the seismic wave field and crustal structure. Apart from the P- and S-waves well developed surface Rayleigh waves (R-waves) were also recorded. An example of the R-waves recorded from SP B is shown in Fig. 2. On all the record sections with bandpass filter of 0.5-2.5 Hz the R-waves can be observed clearly along the whole profile. The wave field of R-waves from the different shot points on the SVEKA profile have some similarities. Two kinds of waves are observed: the "high" frequency R1-wave, with an average period of 0.5 s, and the "low" frequency R2-wave, with an average period of 1.7 s. The R1 wave can be observed up to a distance of 40-100 km from the shot point and the R2 wave up to end of profile. The corresponding average velocities of these waves are about 2.9 and 3.2 km/s, respectively. Similar short-period R-waves with group velocities of 2.8-3.05 km/s had been recorded earlier in Scandinavia at distances up to 200-500 km (e.g. *Båth*, 1971 and 1975; *Wahlström*, 1975). It is interesting to note that the velocities of R1-waves are relatively small very close to the shot point, being only about 2.7 km/s. This fact indicates that the S-wave velocities in the uppermost few hundred metres should be only about 2.8-2.9 km/s, and the corresponding V_P/V_S ratio in the order 1.8-2.0. This situation was not found out by 2-D modelling of body waves, where values for V_P/V_S ratio of 1.67-1.74 were determined. This disparity for the ratio between the two methods can be explained by poor determination of S-wave velocities for the uppermost few hundred metres due to difficulties in correlation of later arrivals at distances of a few kilometres from the shot point. In this distance interval only the correlation of the P-waves is unambiguous, while the S-waves interfere with phases of other waves near the source. So in this unexpected case, the interpretation of surface waves can improve our knowledge of the uppermost 1 km structure.

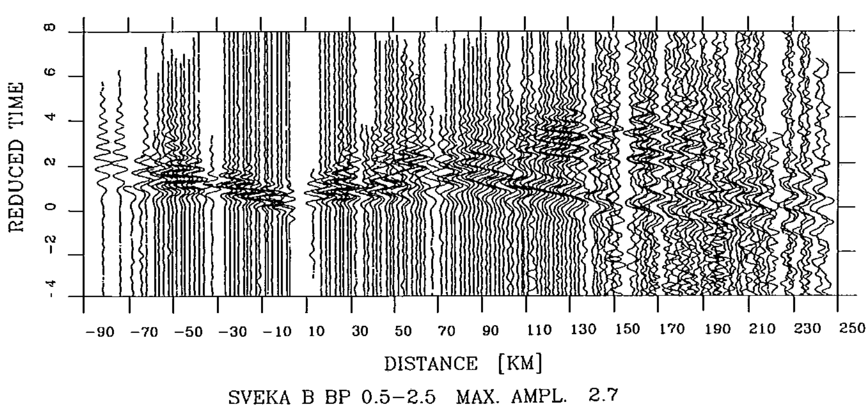

Fig. 2. Amplitude normalized R-wave record sections for the SVEKA profile, SP B. Reduction velocity 3.0 km/s; vertical component; filter band 0.5-2.5 Hz. Note two kinds of R-waves: "high" frequency waves R1 at distances up to about 70 km from the shot point (period about 0.5 s, apparent velocity 2.9-3.0 km/s) and "low" frequency waves R2 at greater distances (period about 2.0 s, apparent velocity 3.2 km/s).

In the analysis of the wave amplitudes only records of the Finnish digital stations PCM1218-80 were used (*Nurminen* and *Hannula*, 1981). The amplitudes were corrected for the charge size using the amplitude - charge size dependence $A(W) = A_0 W^{0.894}$, where W is the weight of TNT charge (*Lanne*, 1982; *Grad* and *Luosto*, 1993). A detailed analysis of the amplitudes of body waves and the quality factors Q_P and Q_S have been presented in our previous paper (*Grad* and *Luosto*, 1993).

The amplitudes of R-waves recorded on the SVEKA profile versus distance from shot point are plotted in Fig. 3. For comparison purposes the theoretical attenuation curves are also plotted. The theoretical curves are,

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

where A_0 is a constant and x the distance from the source; $x^{\frac{1}{2}}$ - assumes a cylindric geometrical spreading of the 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. The theoretical curves were calculated for f_R=1.0 Hz, C_R =3.0 km/s and for successive values of Q_R = 10, 25, 50, 100 and 300. It can be easily seen that the decay of observed amplitudes changes with distance. In the distance range 120-300 km the amplitudes have a slope corresponding to Q_R =300 while at smaller distances the decay of amplitudes is much bigger. For distance up to about 60 km, which corresponds to a depth penetration of R-waves of about 1 km only, the amplitude decay corresponds to Q_R =10-50. So in this case we can expect low values of Q_P and Q_S in the uppermost crust. In modelling of the R-waves synthetic seismograms were calculated using a reflectivity method (*Fuchs*, 1968; *Kind*, 1978). The synthetic seismograms were calculated for each shot point in both directions and compared with the observed ones. Several tests of different velocity and quality factor distributions confirmed the need for the existence of a low S-wave velocity and a low value of quality factors down to a depth of about 1.0 km. The seismograms calculated for the final version of the models show good agreement with the kinematic and dynamic properties of the observed seismograms. An example of the results of R-wave modelling is presented for SP A and SP E in Fig. 4. In the modelling for SP A

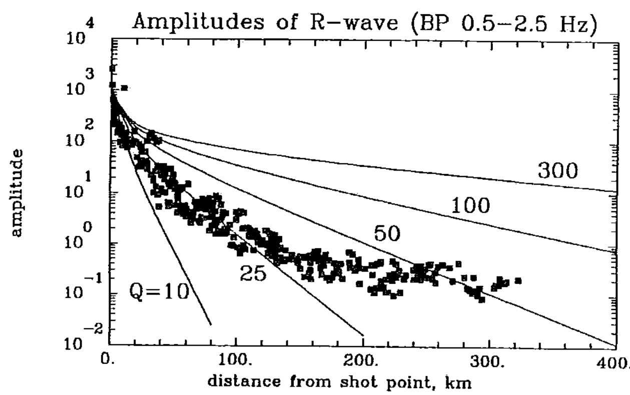

Fig. 3. Observed amplitudes of R-waves on the SVEKA profile (black squares) and theoretical lines for Q = 10, 25, 50 100 and 300 according to formula (1). For further details see the text.

two 1-D models were used to explain the observed wave field because of decreasing velocities at distances of 220- 320 km. This fact indicates that horizontal inhomogeneities also exist along the profile, and 1-D modelling is not sufficient in such case.

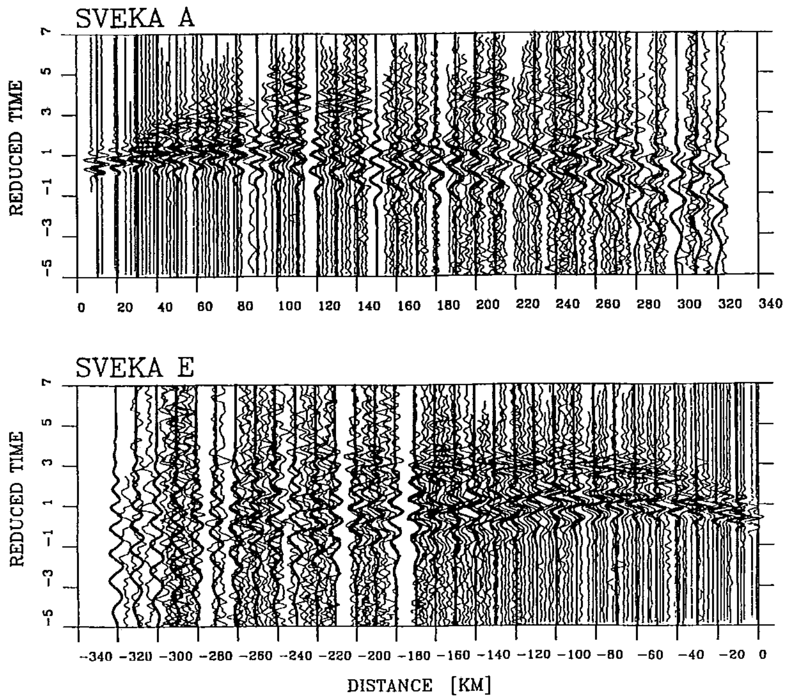

Fig. 4. Examples of 1-D modelling of R-waves on the SVEKA profile for SP A and SP E. Thin lines - selected observed seismograms; solid lines - theoretical (synthetic) seismograms obtained using the reflectivity method (*Kind*, 1978). Note for the SP A a very weak S-waves both in observed and synthetic seismograms in the distance interval 60-100 km and reduced time from about -3 s to about -5 s. It confirms the correctness of P- and S-wave velocities and quality factor distributions used in modelling of the body and surface waves.

3. *Seismic velocities and quality factors in the uppermost crust*

As a result of kinematic and dynamic studies of P-, S- and R-waves the model of the elastic properties of the uppermost crust beneath the SVEKA profile was obtained. The results up to 4 km depth are compiled in Fig. 5, where the velocities, V_P/V_S ratio, Q-factors and crack density are presented.

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 depth 4 km. The S-wave velocities vary in the uppermost 200 m from 2.80 to 2.95 km/s and from 3.10 to 3.45 km/s down to 1 km in depth. In the depth interval of 1-4 km the velocities of the S-waves are 3.44-3.68 km/s. The corresponding V_P/V_S ratios in the depth intervals mentioned above are 1.83-2.0, 1.76-1.88 and 1.65-1.75, respectively.

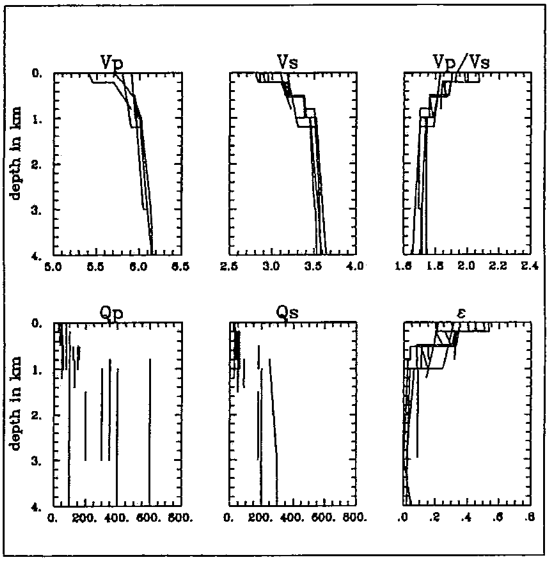

Fig. 5. Uppermost crustal structure representation beneath the SVEKA profile: velocities of P- and S-waves in km/s, V_P/V_S ratio, quality factors Q_P and Q_S and crack density ε.

The low Q_P values in the uppermost 1 km were found to be 40-140. For the depths greater than 2 km higher values of Q_P up to 600 were found. The values of Q_s factor in the uppermost 1 km vary from 20 to 80. For depths deeper than 2 km values of Q_S between 200-300 were determined. The depth interval 1-2 km is a transition zone for Q-values of both P- and S-waves (*Grad* and *Luosto,* 1993). The results of interpretations of the body and surface waves are in good agreement, however, interpretation of the R-waves enriched information about the uppermost few hundred meters, which had a thin zone of low velocities for S-waves.

Similar results concerning the uppermost crust were obtained also in other regions of the Earth. Large values for the V_P/V_S ratio were obtained, for example, in western United States where seismic velocities were studied in fractured crystalline rocks in situ. In the densely fractured uppermost 300 m the V_P/V_S ratio varies from 1.75 to over 2.0 (*Moos* and *Zoback,* 1983). Comparable low values of S-wave velocities in the c.a. 1 km uppermost crust were found for the Precambrian basement in Sweden, Siljan Ring area (*Juhlin,* 1990), in SE Norway, NORSAR (*Lokshtanov et al.,* 1991) and southern Sweden (*Åstrom* and *Lund,* 1992). For the Arabian shield the S-wave velocity increases from 2.6 km/s at the surface to 3.4 km/s at depth of 400 m. The value of Q_S increases from 30 in the uppermost 50 m to 150 at 500 m depth. The underlying material has a Q_S of 400-500 for the outcropping igneous rocks such as granite and may reach values higher than 700 for the metamorphic green schist rocks (*Mokhtar et al.,* 1988). For the French Massif Central *Thouvenot* (1983) obtained Q_P increasing in a rather linear way from about 40 at the surface up to 600 at 7 km depth for waves with frequencies close to 20 Hz. A value of $Q_P = 400$ was found for the

SW England granitic batholith in the depth interval of 0-10 km (*Scheirer* and *Hobbs*, 1990). For the upper crust of the Fennoscandian shield beneath the FENNOLORA profile a value for Q_P of 200-800 for 15 Hz waves was found (*Havskov* and *Medhus*, 1991).

It should be noted that the quality factors above were obtained using waves of different frequencies. Also the quality factor Q_R describing the decay of amplitude of the surface waves doesn't correspond directly to the quality factors of body waves. The Q_R value determined from the amplitude decay is about 300, while the quality factor values of P- and S-waves for the corresponding depth interval are 200-600. Similar differences were observed e.g. in South Africa. 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 (*Shapira*, 1988 and 1989).

4. *Fracturing of the uppermost crust - discussion of results*

Both the low values of V_S velocity and Q-factors in the uppermost 1 km or so of crust beneath the SVEKA profile 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 *Budiansky*, 1977). The crack density parameter ε can be defined by

$$\varepsilon = \frac{1}{V}\Sigma a^3 \equiv N\langle a^3 \rangle \tag{2}$$

where V is a volume, a is a crack size (radius) and N is a number of cracks per unit volume. For all cases, both seismic wave velocities decrease with increasing crack density. V_P decreases more rapidly in dry or nearly dry rocks, while V_S decreases more rapidly in saturated or near saturated rocks. The velocity ratio V_P/V_S decreases for dry cracks and increases for saturated cracks (*O'Connell* and *Budiansky*, 1974; *Hadley*, 1975 and 1976). Assuming that the lowering of seismic velocities is due to fracturing only, the observed velocities V_P and V_S and k= V_P/V_S for SVEKA profile are those of "cracked" rocks. We assumed that the velocities and velocity gradients at a depth of 6 km are for "uncracked" rocks. By interpolation of these values up to the surface we obtained "uncracked" velocities V_{0P} and V_{0S} and $k_0 = V_{0P}/V_{0S}$ for the uppermost layers. The results from the SVEKA profile show clearly a increase of k/k_0 ratio with decreasing V_S/V_{0S}, and imply a saturation of the uppermost crustal rocks. The comparison of our seismic data with theoretical curves for the two limiting cases of dry cracks or fully saturated cracks and results of laboratory measurements for different kind of granites is shown in Fig. 6. For the fully saturated circular cracks the crack density parameter can be expressed by the formula:

$$\varepsilon = \frac{45}{32}\,\frac{(\sigma-\sigma_0)(2-\sigma)}{(1-\sigma_0^2)(1-2\sigma)} \tag{3}$$

where σ and σ_0 are the Poisson's ratio for "cracked" and "uncracked" rock, respectively (*O'Connell* and *Budianski*, 1974). Using formula (3) we found for the SVEKA profile ε values of 0.3-0.5 in the uppermost 200 m, 0.1-0.3 at depths of 0.2-1.0 km and 0.1 for depths 1-4 km (Fig. 5). A comparison of the ε values for successive shot points and depth intervals is presented in Table 1. The observed decrease of the crack density with depth (and with increasing P- and S-wave velocities) correspond to results of laboratory investigations obtained for Westerly granite by *Hadley* (1976). This comparison is shown in Fig. 7. P-wave velocities from the SVEKA profile decrease from about 6.0 km/s for ε=0, to about 5.5 km/s for ε=0.5. For the same values of ε the S-wave velocity decrease is from about 3.6 km/s to about 2.9 km/s. So, we can estimate the decrease as about 8% for V_P and about 20 % for V_S velocities, for ε changing from 0 to 0.5. As has been shown by *O'Connell* and *Budiansky* (1977) for the fluid-saturated cracks which are in communication the shear modulus decreases more rapidly with an increase in crack density than it does for the saturated isolated case. For the crack density ε=0.5 and saturated isolated case a decrease of V_P and V_S velocities is about 10 % and 25 %, respectively, while for fluid-saturated cracks which are in communication, the decrease in velocities is about 25 % for V_P and more than 60 % for V_S. Application of these conclusions to our results clearly show an isolated saturation of cracks in the uppermost crust beneath the SVEKA profile.

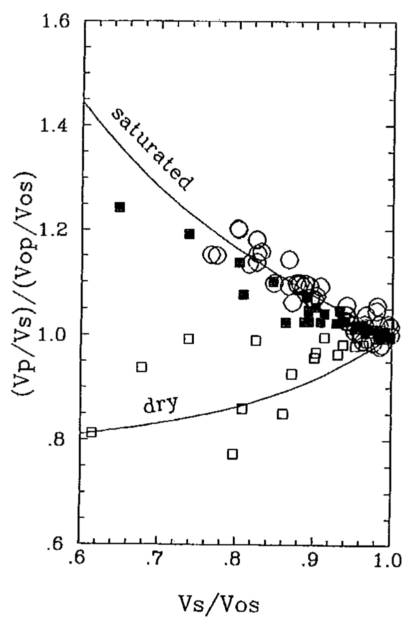

Fig. 6. Characteristics of the seismic wave velocities of the uppermost crustal rocks beneath the SVEKA profile (open circles). The data of laboratory measurements for dry (open squares) and saturated samples (filled squares) of Westerly, Casco and Troy granites (*Nur* and *Simmons*, 1969; *Takeuchi* and *Simmons*, 1973). The theoretical curves for either completely dry or saturated cracks are also shown (*O'Connell* and *Budiansky*, 1974).

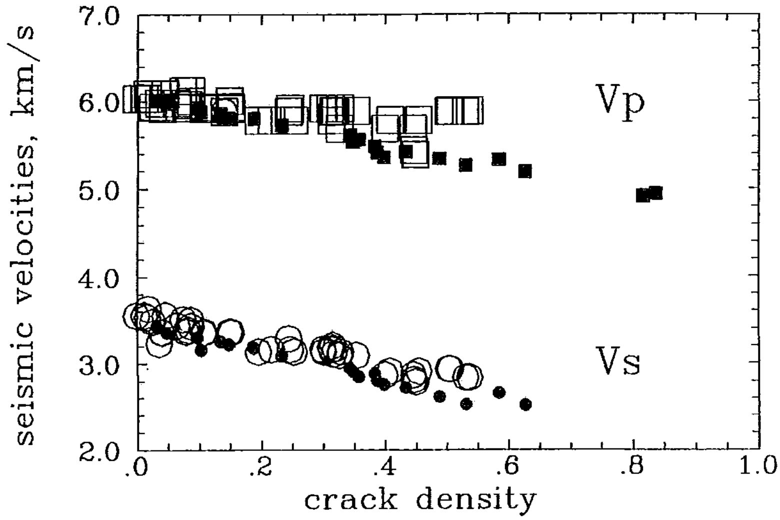

Fig. 7. Dependencies of seismic P- and S-wave velocities on crack density. Open squares and circles are the seismic data from the SVEKA profile, filled squares and circles are laboratory data for Westerly granite (*Hadley*, 1976).

Table 1. Values of the crack density beneath the SVEKA profile.

shot points							
A(N)	B(S)	B(N)	C(S)	C(N)	D(S)	D(N)	E(S)
depth interval 0.0-0.2 km, $\bar{\varepsilon}$=0.427							
0.447	0.354	0.218	0.532	0.401	0.504	0.451	0.314
0.456	-	-	0.538	0.409	0.506	0.448	-
$\bar{\varepsilon}$(A-C)=0.424				$\bar{\varepsilon}$(C-E)=0.430			
depth interval 0.2-1.0 km, $\bar{\varepsilon}$=0.198							
0.255	0.329	0.218	0.319	0.197	0.321	0.328	0.314
0.301	0.109	0.142	0.302	0.248	0.313	0.317	0.245
0.109	0.109	-	0.080	0.042	0.154	-	-
0.150	-	-	0.084	0.042	0.154	-	-
$\bar{\varepsilon}$(A-C)=0.155				$\bar{\varepsilon}$(C-E)=0.242			
depth 1.0 km, $\bar{\varepsilon}$=0.044							
0.088	-	-	0.066	0.026	0.026	-	0.037
0.088	-	-	0.018	0.001	0.014	-	0.020
0.076	-	-	-	0.046	-	-	-
$\bar{\varepsilon}$(A-C)=0.063				$\bar{\varepsilon}$(C-E)=0.024			
surface fault density, $\bar{\varepsilon}$'=0.197							
0.184		0.150		0.203		0.251	
$\bar{\varepsilon}$'(A-C)=0.167				$\bar{\varepsilon}$'(C-E)=0.227			

5. *Discussion of results - implication for tectonics*

The importance of the results from the point of view of their tectonic and geological implications are compiled in Table 1 and Fig. 8. In the wave field of R-waves a number of zones of strong amplitudes as well as the zones of strong attenuation of surface waves are observed. One such zone is easily seen on the record section from SP B (Fig. 2). In the distance range 190-250 km from the shot point and 1-5 s of reduced time, the R-wave phases of the "high" frequency are completely attenuated, while the "low" frequency waves have almost the same shape as at smaller distances. Similar zones are observed on the record section from SP A (Fig. 4.) at distances of 140 and 250 km. The locations of all the zones marked with arrows and their possible correlation with the main tectonic elements of the Precambrian basement are shown in Fig. 8. The interpretation of "reflected" R-waves for the SVEKA profile gives the location of the reflectors which coincide with the Svecofennian volcanic belt SW of SP A and with greenstone belt NE of SP E (Fig. 8c). A full interpretation of the R-waves, however should be made using 2-D or 3-D methods to take into consideration the horizontal inhomogeneities.

The crack density parameter ε determined from the seismic wave velocities can be compared qualitatively with the number of faults in the crystalline basement (*Härme*, 1961). In the vicinity of the SVEKA profile (Fig. 8b) the faults and fractures are mostly in the SE-NW direction. From the map of the most marked fault lines a "surface crack density" parameter ε' was determined as a ratio of summed length of the faults in the 50 km wide rectangle between successive shot points to the area of this rectangle. To obtain easily comparable values, we divided them by a factor of 2. The "normalized" values of ε' are listed in Table 1.

Analysis of values of ε from the Table 1 shows a differentiation of this parameter with depth and place. In the uppermost 200 m the parameter has very big values, but we do not observe a significant differences between the southern part (Proterozoic basement, approximately between SP A and SP C; $\bar{\varepsilon}$(A-C)=0.424) and the northern part (Archaean basement, approximately between SP C and SC E; $\bar{\varepsilon}$(C-E)=0.430). Because there is no correlation with geology, we can conclude that the fracturing of the uppermost about 200 m thick layer is the main reason for the lowering seismic velocities and quality factors. In the depth interval 0.2-1.0 km the mean value of the crack density parameter is $\bar{\varepsilon}$=0.198, but a big difference between the southern ($\bar{\varepsilon}$(A-C)=0.155) and the northern part ($\bar{\varepsilon}$(C-E)=0.242) is observed. The older rocks of the Archaean basement are almost two times more fractured than the Proterozoic ones. At depths greater than 1 km along the whole profile the ε values are considerably lower than 0.1. It is interesting to compare the values of ε with those of the "surface fault density" parameter ε'. Its values correspond to values of ε for depth 0.2-1.0 km, being $\bar{\varepsilon}'$(A-C)=0.167 and $\bar{\varepsilon}'$(C-E)=0.227 for the southern and the northern parts of profile, respectively. On the basis of this coincidence we can speculate that the range of the depth penetration of the majority of faults is of the order of

1 km. The tectonic importance of the results concerning fracturing of the uppermost crust presented above can be discussed together with the results of other geophysical investigations in this area. Differences of Proterozoic and Archaean rocks forming the crystalline basement are reflected also very clearly in the surface density of rocks (Fig. 8a), which are 2670-2700 kg/m^3 and 2650-2670 kg/m^3, respectively (*Puranen et al.*, 1978; *Lähde*, 1985).

Investigations in boreholes give information about the properties of the bedrock to a depth of about 1 km. The location of boreholes discussed is shown in Fig. 1. In the Lavia deep testhole P-wave velocities in granodiorite and granite obtained using acoustic log method are about 6.0-6.5 km/s (*Saksa*, 1985). In the Hyrynsalmi, Kuhmo, Sievi, Konginkangas and Eurajoki boreholes the P-wave velocities obtained using the methods of vertical and horizontal seismic profiling are within the interval 5.45-5.95 m/s (*Keskinen et al.*, 1992). Corresponding values of S-wave velocities are 3.12-3.55 km/s (*Keskinen*, 1992 - personal communication). So, the values of the ratio V_P / V_S =1.68-1.77 are significantly lower than we obtained from the analysis of the data from SVEKA profile. It should be mentioned, however, that boreholes were located in selected rocks which were intact and slightly fractured. For example, the seismic P-wave velocity logging in borehole Kivetty KR1 indicated that V_P of the intact rock is about 5.85-6.05 km/s, which is much higher than the mean velocity determined from the shallow refraction sounding (*Heikkinen et al.*, 1992). Different seismic methods used showed that changes in velocity are mostly due to fracturing, faults, crushed zones and contacts between rock types.

The uppermost rocks are very weak electrical conductors, and their resistivity can reach a value of many thousand Ohm metres. The observed differences in resistivity are mainly caused by differences in water content in pores and crack and water salinity. However, high resistivity generally implies a rather isolated saturation of cracks (*Korja*, 1990; *Korja* and *Koivukoski*, 1990), what coincides with our results obtained from seismic soundings.

Finally we conclude, that an analysis of seismic velocities in the uppermost crust using the R-waves can be a useful tool for the investigation of the physical properties of the crystalline bedrock. The method of interpretation should be developed also for 2-D and 3-D cases and applied to very good quality seismic data from profiles in Finland and other parts of the Fennoscandian shield.

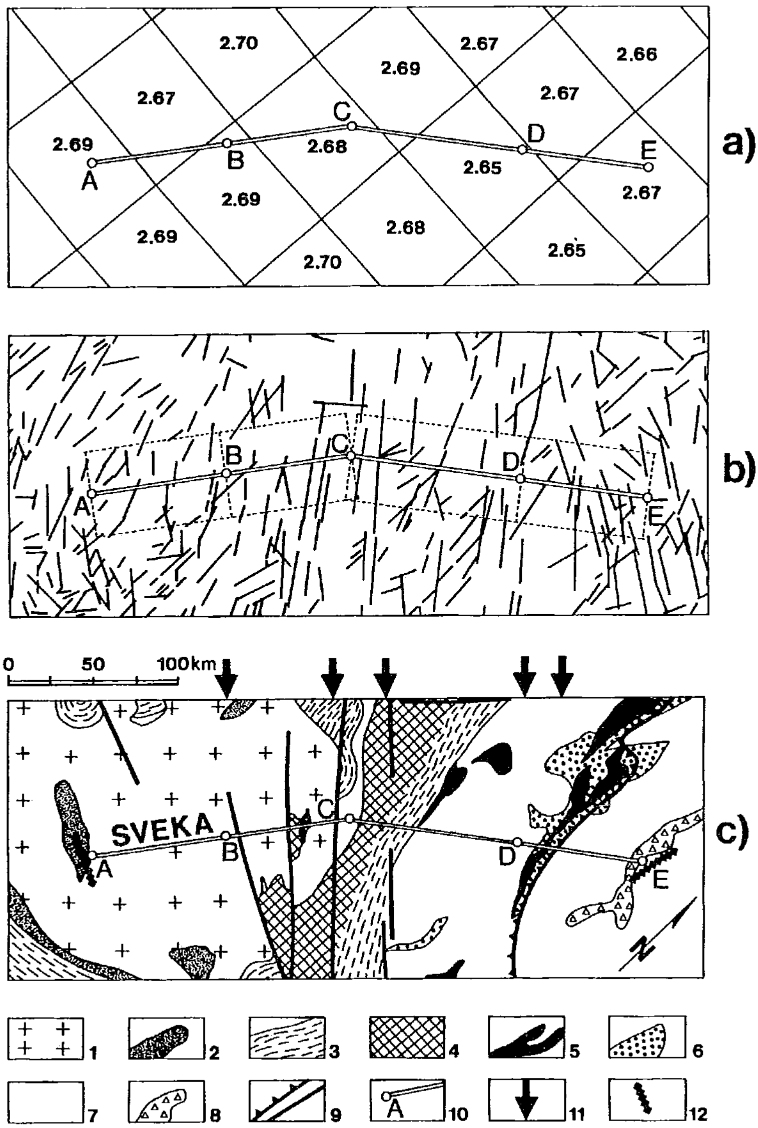

Fig. 8. Properties of the uppermost rocks in the area of the SVEKA profile. a) average densities of the rocks (*Puranen et al.*, 1978); b) fault lines (*Härme*, 1961); c) stratigraphic-tectonic map around the SVEKA profile (*Gaál*, 1982). The discussed area is shown bounded by a rectangle in Fig. 1.

SVECOKARELIAN GEOSYNCLINAL COMPLEX: 1- Proterozoic granitoids; 2- Svecofennian volcanic belts; 3-medium-grade metamorphosed Svecofennian metaturbidites; 4- high-grade metamorphosed Svecofennian metaturbidites; 5- Kalevian group; ARCHAEAN BASEMENT COMPLEX: 6- Jatulian group; 7- Archaean area; 8- greenstone belts; 9- thrust fault and fault in general; 10- location of the SVEKA profile and shot point; 11- location of "R-wave inhomogeneities", which coincide with the main tectonic lines; 12- location of the R-wave reflectors in the vicinity of the shot points A and E.

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