Geophysica (1991), 27, 1-2, 1-11

Travel Time Residuals of a JVE Explosion Recorded in Finland and Differences in Crustal Structure

Marek Grad[1] *and Jukka Yliniemi*[2]

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

[2] Geophysical Observatory, University of Oulu
SF-90570 Oulu, Finland

Abstract

A Soviet nuclear explosion conducted at the Semipalatinsk Test Site on 14 September 1988 as an outcome of the Joint Verification Experiment (JVE) Agreement was recorded very well along the Kemi - Kostamus deep seismic sounding profile and at all permanent seismic stations in Finland. The seismic waves recorded in Finland in the distance interval 3180 - 3550 km on the Baltic (Fennoscandian) Shield penetrated through the upper mantle of the southern part of the west Siberian platform, Ural Mountains and East European platform. The maximum deviations of the observed travel times of the P-waves are of the order of 0.5 s. These result from major differences in the crustal structure in Finland, and are fully explained by Moho depth and mean crustal velocity differentiation.

1. *Introduction*

A nuclear explosion was conducted at the Semipalatinsk Test Site on 14 September 1988 as a direct outcome of the Joint Verification Experiment (JVE) Agreement (*SIPRI Yearbook*, 1989). The times of origin as published in the USSR (*Operational Seismological Catalogue*), the USA (*Earthquake Data Report*) and Sweden (*Seismology 1988*, 1989) are the same:

$$t_0 = 03^h\ 59^m 57.4^s\ UT$$

The geographical coordinates given by these sources differ slightly but for a distance of the order of 3400 km, corresponding to Finland, the differences in epicentral distances are insignificant, being around 2 km. The following analysis is based on the coordinates in the Soviet bulletin.

Published by the Finnish Geophysical Society, Helsinki (1992)

$\lambda = 78.91°E, \quad \phi = 49.87°N, \quad h = 0$

The JVE explosion was recorded very well along the Kemi - Kostamus deep seismic sounding profile and at all permanent seismic stations in Finland. Characteristic of all the records are very strong first arrivals of P-waves without any distinct later arrivals. A recording similar in character to this was obtained at the Hagfors observatory in Sweden (*Seismology 1988*, 1989). An absence of distinct S-waves from nuclear explosions at the Semipalatinsk Test Site is also typical of records in Finland.

2. *Records of the Soviet JVE explosion along the profile Kemi - Kostamus*

The Soviet JVE explosion was recorded along the Kemi - Kostamus (KE) deep seismic sounding profile in central Finland. Six three- component mobile field stations SN-PCM-80 (*Nurminen* and *Hannula*, 1981) were spaced about 40 km apart along the profile in the epicentral distance interval 3286 - 3481 km. Their locations are shown in Fig. 1. The explosion was recorded very well at all these stations, and a section from the Kemi - Kostamus profile is shown in Fig. 2. The geographical coordinates of the stations, times of first arrivals of P-waves, epicentral distances and travel times are listed in Table 1.

Table 1. Locations (λ,ϕ) of seismic stations on the Kemi - Kostamus profile at the time of the JVE, recorded times i_p of the first P-wave arrivals and travel times t_p.

Station	λ°, E	ϕ°, N	i_p, hms UT	Δ ,*)km	t_p, *)s	t_p -Δ/10,s
1	29.579	64.873	04:06:04.32	3287.5	366.91	38.16
2	28.808	65.047	04:06:07.05	3325.8	369.65	37.07
3	28.008	65.211	04:06:10.64	3365.0	373.24	36.74
4	27.178	65.356	04:06:14.06	3405.1	376.60	36.09
5	26.392	65.497	04:06:16.70	3442.7	379.21	34.94
6	25.555	65.644	04:06:19.81	3482.5	382.39	34.14

*) distances Δ and time t_p calculated according to source location and time of origin data from the Operational Seismological Catalogue.

The apparent velocity of the first arrivals of P-waves is about 12.5 km/s, and the travel times of the explosion for the whole epicentral distance range from 3286 to 3481 km are very close to those calculated for the East European platform models KCA (*King* and *Calcagnile*, 1976) and MUMEP (*Grad*, 1987, 1988). The JVE travel times are about 1-2 s shorter than the times to the Baltic Shield and Western Russia determined from earthquakes and nuclear explosions (*Enayatollah*, 1972; *England* and *Worthington*, 1977)

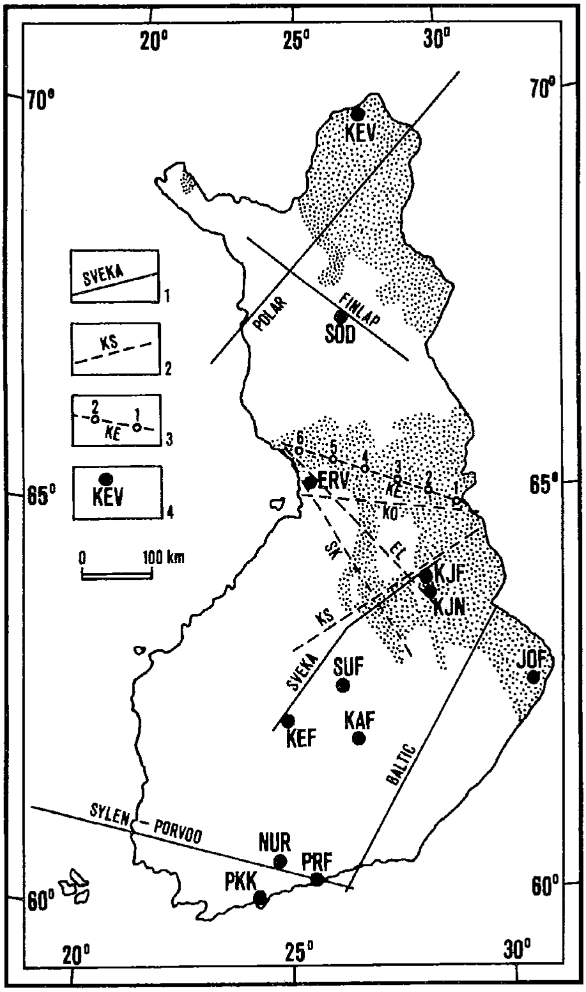

Fig. 1. Location of seismic stations and profiles against the background of the major tectonic units of Finland: Archaean basement (shaded area) and Svecokarelides (white area). 1- deep seismic sounding profiles; 2- quarry blast profiles; 3- seismic field stations on the Kemi - Kostamus (KE) profile; 4- permanent seismic stations.

and about 2-3 s shorter than those of *Jeffreys* and *Bullen* (1940). The scatter in the times of P-waves is of the order of 0.4 s, and since the locations of the stations along the Kemi - Kostamus profile and the arrival times were determined with a very high degree of accuracy, the deviations from a smoothed line must result from inhomogeneities in the structure. Several deep seismic sounding profiles have been produced for this part of Finland, and the crustal structure is known fairly well (*Yliniemi*, 1989). In general, the P-wave velocity beneath the Kemi - Kostamus profile changes from about 5.8 km/s at the

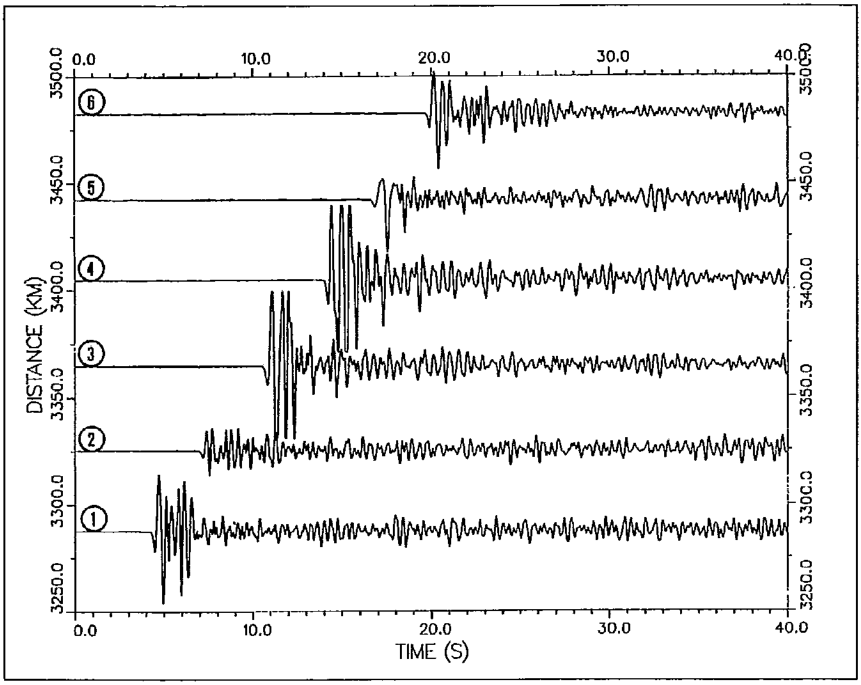

Fig. 2. Seismic records (vertical component) along the Kemi - Kostamus profile in central Finland of the JVE explosion in the USSR. Distance from the source computed according to source data from the Operational Seismological Catalogue. Time t=0 corresponds to $04^h06^m00^s$ UT.

near surface to about 6.5 km/s at depths of about 12-15 km and to about 7.2-7.3 km/s in the lower crust. The largest variations are observed in the Moho depth, which changes along the profile from about 40 km to greater than 55 km, while the velocity in the upper mantle, determined from refracted P_n waves, also changes from 7.9 to 8.1 km/s between blocks along the profile. Detailed interpretations of the deep seismic soundings and 2-D modelling along the Kemi - Kostamus profile will be the subject of a later paper. Such large variations in structure could produce relative differences of the order of 0.4 s in the time of arrival. Fig. 3 shows a comparison of the observed travel times and those calculated using the ray tracing method (*Červený* and *Pšenčik*, 1983), in order to obtain a generalized lithospheric model along the Kemi - Kostamus profile. Inhomogeneities in the structure explain the deviations in the observed travel times very well. This example shows that even for shield regions without any low-velocity sedimentary cover, time correction connected with the crustal structure could be observed and have significant values. Thus knowledge of the Moho depth and mean crustal velocities are of great importance in seismic investigations.

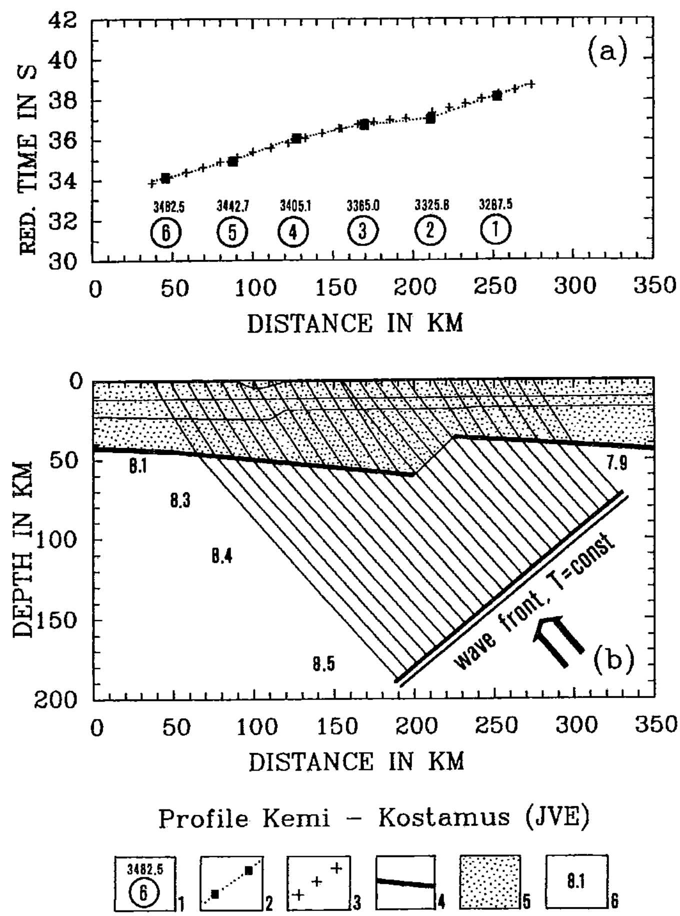

Fig. 3. Comparison of observed and calculated travel times (a) and the ray diagram for the model of the lithosphere beneath the Kemi - Kostamus profile (b). Distance in km from the beginning of the profile, reduction velocity v_{red} = 10.0 km/s.
1- location of a seismic station on the profile and epicentral distance from the JVE nuclear explosion in km; 2- observed times of the JVE explosion; 3- calculated travel times; 4- Moho boundary; 5- Earth's crust; 6- P-wave velocities in km/s in the upper mantle.

3. *Crustal thickness and mean velocities in the crust*

Several deep seismic sounding profiles have been obtained in Finland in the last ten years, all of them situated on the Fennoscandian Shield, in the Archaean and Svekokarelide provinces (Fig. 1). Results concerning the Sylen - Porvoo, Finlap, Sveka, Baltic and Polar profiles have been published earlier in many papers (e.g. *Luosto*, 1986; *Luosto et al.*, 1983, 1984, 1985, 1989; *Grad* and *Luosto*, 1987). A number of profiles have also been run in the central part of Finland using quarry blasts as sources of seismic waves (*Yliniemi* and *Luosto*, 1983; *Yliniemi*, 1990), and all the resulting data are gathered together in the map of Moho depth in Fennoscandia (*Luosto*, 1990). The variations in crustal thickness are of the order of 20 km, the maximum depth of the Moho discontinuity being observed in the middle Finland.

It is obvious that the mean crustal velocity also depends on the thickness of the crust. The values for the mean crustal velocities, collected from 1-D and 2-D models for all the profiles shown in Fig. 1, are presented in Fig. 4a. The linear dependence between mean crustal velocity and crustal thickness was calculated for all the data using the least-square method:

$$\bar{\upsilon}(h_M) = 6.10 + 0.0114 \ h_M \qquad (1)$$

where $\bar{\upsilon}$ is the mean velocity in km/s, and h_M the crustal thickness in km. The mean crustal velocity versus crustal thickness increases from about 6.55 km/s for a 40 km thick crust to about 6.80 km/s for a 60 km thick crust. The scatter in the data is small, and all the points are in the band between -0.1 and +0.1 km/s of the average line (1).

The mean velocities could also depend on the age of the crust. When all the data were divided into two files corresponding to the Archaean and Svecokarelide provinces the formulae were:

$$\bar{\upsilon}(h_M) = 6.05 + 0.0126 \ h_M \qquad \text{for Archaean} \qquad (2)$$

$$\bar{\upsilon}(h_M) = 6.17 + 0.0100 \ h_M \qquad \text{for Svecokarelides} \qquad (3)$$

A relatively small difference in mean velocity is observed, and for crustal thickness from 40 to 60 km, corresponding to the Fennoscandian Shield in Finland, the differences are insignificant (Fig. 4b).

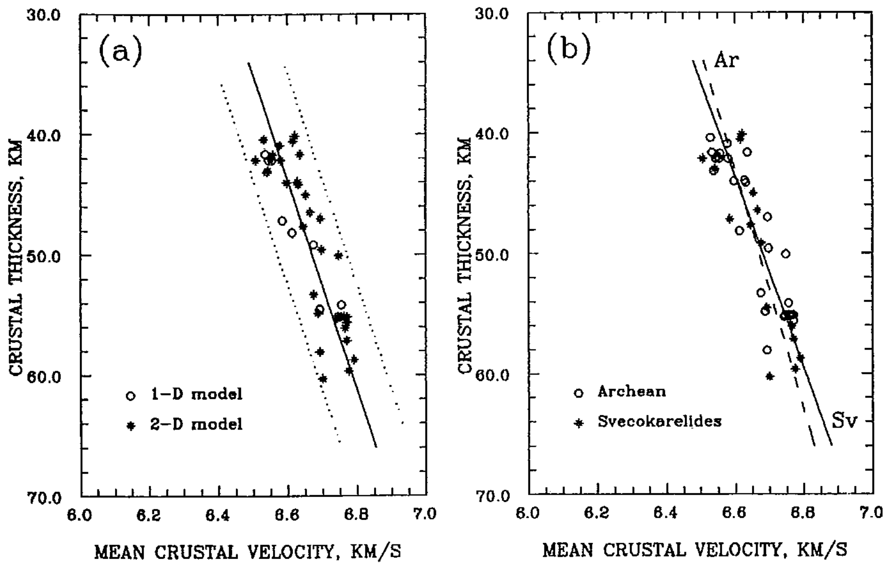

Fig. 4. Mean crustal velocities versus crustal thickness for the Fennoscandian shield in Finland. (a)- all data: solid line derived from formula (1) and dotted lines corresponding to values -0.1 and +0.1 km/s; (b)- data divided into Archaean and Svecokarelide provinces: Ar - dashed line derived from formula (2) and Sv - solid line from formula (3).

4. *JVE records from permanent seismological stations in Finland*

The JVE explosion was recorded very well at all the Finnish seismological stations, data from all of which were used in the present analysis, both the stations with digital recording systems and those with paper recording systems of speed 60 mm per min. Thus the accuracies of the time readings for the first arrivals are of the order of 0.01 and 0.1 s respectively. The locations of the permanent Finnish stations and times of the first arrivals of P-waves from the JVE explosion are listed in Table 2, and reduced travel times are shown in Fig. 5a. The scatter of the order of 0.5 s observed in the arrival times can be explained by crustal structure differentiation.

The time correction Δt connected with differentation of the crustal structure beneath the seismological station can be expressed in the form:

$$\Delta t = \frac{h_M - H_M}{\sin e}\left(\frac{\bar{v}_c - v_m}{\bar{v}_c\, v_m}\right) \qquad (4)$$

where h_M - Moho depth under the station, H_M - reference depth, e - emergence angle, $\bar{\upsilon}_c$ - mean velocity in a crust of thickness h_M, υ_m - velocity in the upper mantle. The time corrections for the JVE records were calculated for the reference depth of the Moho H_M = 40 km. Depths of the Moho boundary h_M were taken from the map of crustal thickness for the Fennoscandian Shield (*Luosto*, 1990). Mean crustal velocities $\bar{\upsilon}_c$ were calculated from formula (1) and the average velocity in the uppermost mantle υ_m was taken to be 8.2 km/s. The value of the emergence angle e was calculated for the average model MUMEP of the East European platform (*Grad*, 1987, 1988). All the results are gathered together in Table 2. The minimum value of the time correction is -0.04 s and the maximum -0.53 s. Corrected values for the reduced times of the first arrivals are shown in Fig. 5b.

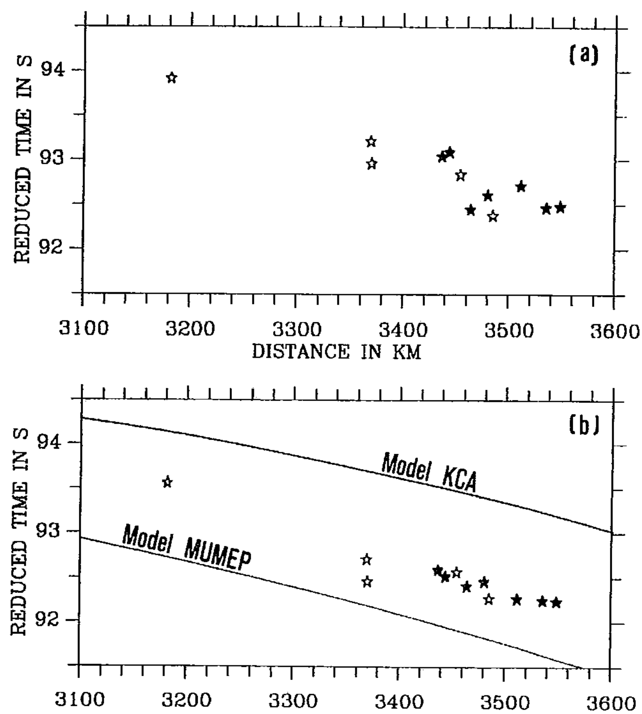

Fig. 5. Reduced travel times for the JVE explosion recorded at the permanent seismological stations in Finland. Black stars correspond to data from digital stations and open stars to those with a paper recording system. Reduction velocity 12.0 km/s.
(a)- uncorrected data; (b)- corrected data and comparison with reduced travel times for KCA and MUMEP models (*King* and *Calcagnile*, 1976; *Grad*, 1987, 1988).

Table 2. Locations (λ, ϕ) of permanent seismological stations in Finland, recorded times i_p, Moho depths h_M and time corrections Δt for the JVE explosion.

Station	λ,°E	ϕ, °N	h_M, km	Δ, *)km	i_p, hms UT	Δt,s	t_c *),s
PKK	24.517	60.005	46.5	3548.7	04:06:25.60	-0.22	387.98
PRF	25.681	60.386	44.0	3480.4	04:06:20.04	-0.14	382.50
NUR	24.651	60.509	46.0	3535.4	04:06:24.48	-0.21	386.87
KAF	26.306	62.113	53.0	3436.7	04:06:16.83	-0.42	379.01
KEF	24.871	62.166	53.0	3511.3	04:06:22.72	-0.42	384.90
SUF	26.151	62.719	57.0	3443.7	04:06:17:46	-0.53	379.53
JOF p)	31.312	62.918	50.0	3181.6	04:05:56.45	-0.33	358.72
KJN p)	27.713	64.085	53.0	3369.5	04:06:11.35	-0.42	373.52
KJF p)	27.715	64.199	53.0	3370.1	04:06:11.15	-0.42	373.33
ERV	25.842	65.085	41.0	3464.3	04:06:18.52	-0.04	381.08
SOD p)	26.629	67.371	47.5	3454.4	04:06:18.10	-0.25	380.45
KEV p)	27.007	69.755	43.0	3485.1	04:06:20.20	-0.11	382.69

*) - distance Δ and corrected times t_c calculated according to source location and time of origin data from the Operational Seismological Catalogue.

p) - stations with paper recording system.

5. *Summary and discussion*

The recordings of the JVE explosion provided a good opportunity to examine of the effect of differences in crustal thickness on the travel times of seismic waves under well known conditions. The results of seismic refraction measurements along profiles in Finland have shown that the Moho depth changes considerably in this part of the Baltic Shield, and an increase in mean crustal velocity versus crustal thickness has also been observed. The scatter in mean velocities is less than ± 0.1 km/s. The difference in mean velocity dependences between the Archaean basement and the Svecokarelides is insignificant, and one can use the general formula (1) for the whole territory of Finland.

The maximum difference in the arrival times recorded at the Finnish permanent seismic stations resulting from differences in crustal structure is 0.5 s. Using a simple formula (4), all the differences can be fully explained by Moho depth and mean crustal velocity differentiation. It should be noted that the time corrections increase for small epicentral distances (i.e. small values of the emergence angle e) and these could reach values of the order of 0.8 and 0.3 s respectively for crustal thickness of 60 and 45 km at distances of 500 km. This could produce a significant systematic error, especially for the location of near by earthquake.

Acknowledgements

We thank Dr. Urmas Luosto for providing crustal models along the deep seismic sounding profiles in Finland. Dr. Seppo Pirhonen provided the records of the JVE explosion at the Finnish seismological stations. The work was carried out within the framework of an exchange between the Polish Academy of Sciences and the Academy of Finland.

References

Červený, V. and Pšenčík, I., 1983: Program RAY83, Charles University, Prague.

Earthquake Data Report, 1988: U.S. Department of the Interior, Geological Survey, No. 9-88, Part 1 of 2, p. 1-118.

Enayatollah, M.A., 1972: Travel times of P-waves for the Swedish - Finnish Seismograph Network. Pageoph., **94**, 101-135.

England, P.C. and Worthington, M.H., 1977: Travel time of P seismic waves in Europe and Western Russia. *Geophys. J.R. Astr. Soc.*, **48**, 63-70.

Grad, M., 1987: Seismic model of the Earth's crust and upper mantle of the East European Platform. *Acta Geophys.* Pol., **35**, 2, 121-155.

Grad, M., 1988: Seismic model of the Earth's crust and upper mantle for the East European platform. *Phys. Earth Planet. Int.*, **51**, 182-184.

Grad, M. and Luosto, U., 1987: Seismic models of the crust of Baltic Shield along the SVEKA profile in Finland. *Annales Geophysicae*, **5B**, 639-649.

Jeffreys, H. and Bullen, K.E., 1940: Seismological tables. *British Assoc. Adv. Sci.*, London, 48 pp.

King, D.W. and Calcagnile, G., 1976: P-wave velocities in the upper mantle beneath Fennoscandia and Western Russia, *Geoph. J.R. Astron. Soc.,* **46**, 407-432.

Luosto, U., 1986: Reinterpretation of Sylen - Porvoo refraction data. Inst. Seismology, Univ. of Helsinki, Rep. S-13, 19 pp.

Luosto, U., 1990: Seismic data from the Northern Segment of the EGT and from the nearby profiles. In: R. Freeman and St. Mueller (eds.), Proc. Sixth Workshop EGT Project, 53-63.

Luosto, U., Zverev, S.M., Kosminskaya, I.P. and Korhonen, H., 1983: Observations of Fennolora shots on additional lines in Finnish Lapland. In: E. Bisztricsany, Gy. Szeidovitz (eds.), Proc. 17th Ass. ESC, Budapest 24-29 August 1980, Elsevier, Amsterdam, 517-521.

Luosto, U., Lanne, E., Korhonen, H., Guterch, A., Grad, M., Materzok, R. and Perchuć, E., 1984: Deep structure of the Earths crust on the SVEKA profile in central Finland. *Annales Geophysicae*, **2**, 559-570.

Luosto, U., Korhonen, H., Kosminskaya, I.P., Zverev, S.M., Lund, C.-E., Sharov, N.V., Lanne, E., Tuppurainen, A., Ilmola, V.-M. and Foursov, A.N., 1985: First results from the DSS study on the Baltic profile in SE Finland. Inst. Seismology, Univ. of Helsinki, Rep. S-11, 22 pp.

Luosto, U., Flüh, E.R., Lund, C.-E. and Working Group, 1989: The crustal structure along the Polar profile from seismic refraction investigations. In: R. Freeman, M. von Knoring, H. Korhonen, C.-E. Lund, St. Mueller (eds.), The European Geotraverse, Part 5: The Polar Profile. *Tectonophysics*, **162**, 51-85.

Nurminen, S. and Hannula, A., 1981: Deep seismic sounding equipment model PCM 1218-80, Service guide. Inst. Seismology, Univ. Helsinki, Rep. T-7, 33 pp (in Finnish).

Operational Seismological Catalogue, 1988: 11-20 Sept. 1988, Inst. Phys. Earth Ac. Sci. USSR, Obninsk (in Russian).

SIPRI Yearbook 1989 - World Armaments and Disarmaments, 1989: Nuclear explosion, p. 49-63, Stockholm International Peace Research Institute, Oxford Univ. Press.

Seismology 1988, 1989: FOA Rapport, C 20754-9.1 (2.2), Stockholm.

Yliniemi, J., 1990: Seismic model of deep crust beneath Kemi - Kajaani profile. XIV Geofysiikan päivät, Helsinki 3-4 May 1989, 11-18 (in Finnish with English abstract).

Yliniemi, J. and Luosto, U. , 1983: Deep seismic sounding studies on the line Kemi - Kajaani. In: H. Kananen, J. Yliniemi (eds.), XIth Geofysiikan päivät, Oulu 10-11 May 1983, 49-53 (in Finnish with English abstract).