6.6 Eurobridge — ground truth observations at the Fennoscandian arrays

Introduction

In order to meet the requirements for event location accuracy of the International Monitoring System (IMS), it has been realized that regionalized travel-time models are needed. Events whose exact origin times and coordinates are known are very important for deriving such models. E.g., NORSAR (NOA) observations of shots used for refraction profiling have previously been investigated by several authors to derive information on travel-time anomalies and the corresponding velocity structure in Fennoscandia (Cassell et al., 1983; Mereu et al., 1983).

A 1130 km seismic refraction profile crossing the Baltic Shield in the northwest and the Ukrainian Shield in the southeast was part of an experiment (Eurobridge) described in the doctoral dissertation of Giese (1998). There were three series of shots, one in 1995 and two in 1996. Observations of these explosions at the Fennoscandian arrays (ARCESS, FINESS, HAGFORS, and NORESS) provide an opportunity to check the accuracy of the travel-time tables in use at NORSAR for Fennoscandia. Figs. 6.6.1 and 6.6.2 show maps of the shot points and the arrays used in this investigation.

Details on origin times, locations and yields of the Eurobridge shots are given in Table 6.6.1, together with information on the SNR of the automatically detected P-arrivals at each array. The term "*visual*" in Table 6.6.1 indicates cases when no automatic P-detections are found, but where a signal was found by manual analysis. The shots along the main profile had yields varying between 150 and 1100 kg, whereas the largest shot, located off the coast of Gotland, had a yield of 3500 kg.

For each station, 900 seconds of data beginning approximately 60 seconds before the origin time of each shot were retrieved and stored on disk. The main part of the data was requested via AutoDRM from the prototype International Data Center (pIDC) in Arlington, Virginia. In several cases where data were unavailable from the pIDC; we were able to retrieve them from our archive tapes at NORSAR. For some events, data from FINESS and NORESS are missing (see Table 6.6.1).

In the case of Hagfors data requested from the pIDC, it was necessary to correct for a 0.493 second delay introduced by a FIR filter used in the Nanometric data acquisition system. This correction had already been made for data read from the tapes stored at NORSAR.

Automatic event locations provided by the GBF system

Results from NORSARs automatic signal detection system DP/EP, as operated at the time of the Eurobridge experiment in 1995 and 1996, were reprocessed with the Generalized Beamforming (GBF) method (Kværna et al., 1999) to provide automatic network-based event locations. As described by Kværna et al. (1999), some improvements were recently made to the GBF software. Among others this included an enlarged grid system where the events were located on a grid with a density of 0.2 degrees. Our first experiment was to compare the event locations provided by the GBF method to the ground-truth locations of the Eurobridge shots.

Fig. 6.6.3 shows the locations of the GBF events associated with the Eurobridge experiment (filled squares), where the number of arrays used to locate the events are given together with the shot labels. Table 6.6.2 provides origin times and coordinates of the GBF locations, local magnitudes, the number of P- and S-phases associated with each event, and the absolute location error.

Except for one case, we find that events located with all four stations had small absolute location errors, 17.8, 14.9, 27.1, 19.9, and 9.1 km, respectively. For shot I1, the location difference is as large as 322.6 km. From analyzing the list of associated phases for shot I1, we find that the Sn arrival at FINES is misinterpreted as Lg by the GBF procedure, resulting in a location too close to the FINES array.

Seven of the shots had no S-phase detections and were located using P-phases only. These shots had location errors varying between 134.6 and 1026.7 km. This relatively poor performance can be explained by configuration of the array network as seen in relation to the Eurobridge profile (see Fig. 6.6.1). With only P detections available, this network will have a relatively low resolution for locating events outside of the network. The GERES array is also included in the network processed by GBF, but due to the blockage of regional seismic waves by the Teisseyre-Tornquist zone (Schweitzer, 1995), none of the Eurobridge shots are observed at GERES.

From Table 6.6.2 we also see that all events located with two or more S-phases had location errors less than 27.1 km. The importance of having S-phase detections available for the GBF processing were taken into account in a recent upgrade of the processing recipes for the signal detection system (Schweitzer, 1994; Kværna et al. 1999). New beams with S-type velocities, combined with rotations of the horizontal components into both radial and transverse directions were introduced for all arrays. However, in 1995 and 1996, when the original data were processed by the DP/EP system, these features were not yet implemented.

Array observations of P-phases from the Eurobridge shots

One task in this study is to analyze the travel-times of the ground-truth Eurobridge events, and compare these to the travel-times calculated from the Fennoscandian crustal and upper mantle velocity model. This model, illustrated in Fig. 6.6.4 (Mykkeltveit and Ringdal, 1981), is currently used at NORSAR for locating events in Fennoscandia and adjacent areas. At the pIDC, a similar travel-time model is used for locating events in the same region.

As seen from Table 6.6.1, P-phases from most of the Eurobridge shots are observed at FINESS, HAGFORS and NORESS arrays. At the more distant ARCESS array, located between 1400 and 2000 km from the profile line, 12 out of 29 events are seen. For each array, seismic sections were plotted with a reduction velocity of 8 km/s (13.9 s/deg), see Figs. 6.6.5 - 6.6.8. The travel-time curves of the Fennoscandian model are also shown on each section. For each shot, the array data were beamformed using the estimated slowness and azimuth of the arriving P-phase. The traces shown on the seismic sections are the beams filtered in the passband providing the highest SNR.

On the seismic sections (Figs. 6.6.5 - 6.6.8) we observe significant differences between the model predictions and the P-onsets, and it is our plan to investigate these in more detail. A striking feature is the difference between the Hagfors and NORESS sections shown in Figs. 6.6.5 and 6.6.6. At Hagfors, the P-onsets are consistently late as compared to the model predictions, whereas the consistency at NORES is much better. Details on the time differences between the manual time picks and the model predictions are given in Table 6.6.3. In view of the fact that Hagfors and NORES are located only 135 km apart along the direction of the

Eurobridge profile line (see Fig. 6.6.1), it is difficult to interpret these differences in terms of anomalous velocity structures below these two arrays. This means that we also have to look into alternative explanations like timing problems at the two arrays.

In the extension of this study we plan to include data form the large-aperture NORSAR array (NOA), and also to analyze the S-arrivals. Our ultimate goal will be to derive station-specific travel-time corrections (SSSCs) for the region of the Eurobridge shots such that we can obtain more accurate event locations in the Lithuania-Belarus region.

L. Taylor
J. Schweitzer
T. Kværna

References

Cassell, B.R., S. Mykkeltveit, R. Kanestrøm and E.S. Husebye (1983): A North Sea-Southern Norway seismic crustal profile. *Geophys. J. R. Astron. Soc.* **72**, 733-753.

Giese, Rüdiger (1998). Eine zweidimensionale Interpretation der Geschwindigkeitsstruktur der Erdkruste des südwestlichen Teils der Osteuropäischen Plattform (Projekt EUROBRIDGE). PhD thesis Freie Universität Berlin. GeoForschungsZentrum Potsdam, Scientific Technical Report STR98/16, 190 pp.

Kværna, T., J. Schweitzer, L. Taylor and F. Ringdal (1999): Monitoring of the European Arctic Using Regional Generalized Beamforming. In: NORSAR Semiannual Tech. Summ. 1 October 1998 - 31 March 1999, *NORSAR Sci. Rep. 2-98/99*, Kjeller, Norway, 78-94.

Mereu, R.F., S. Mykkeltveit and E.S. Husebye (1983): FENNOLORA Recordings at NORSAR (NORSAR Contribution No. 322). *J. Geophys.* **52**, 119-130.

Mykkeltveit, S. and F. Ringdal (1981): Phase identification and event location at regional distance using small-aperture array data. In: Husebye, E.S. and S. Mykkeltveit (eds.), 1981: *Identification of seismic sources - earthquake or underground explosion.* D. Reidel Publishing Company, 467-481.

Schweitzer, J. (1994): Some improvements of the detector / SigPro - system at NORSAR. In: NORSAR Semiannual Tech. Summ. 1 October 1993 - 31 March 1994, *NORSAR Sci. Rep. 2-93-94*, Kjeller, Norway, 128-139.

Schweitzer (1995): Blockage of regional seismic waves by the Teisseyre-Tornquist zone. *Geophys. J. Int.* **123**, 260-276.

Table 6.6.1: EUROBRIDGE Shots

Origin Time (GMT)	Lat (deg)	Lon (deg)	Yield (kg)	Shot Point	Shot Label	SNR of automatic P_n detection			
						ARC	FIN	HFS	NRS
1995-147:21.00.02.400	55.1792	22.9417	600.00	6	G0	visual	39.5	11.0	13.0
1995-147:21.20.01.290	54.4321	24.4526	1000.00	10	K0	12.8	61.9	23.7	15.0
1995-147:21.40.01.187	55.5133	22.2094	800.00	4	E0	visual	42.8	10.5	10.5
1995-147:22.00.01.375[a]	54.8254	23.6588	800.00	8	I0	visual	33.4	6.2	12.2
1995-147:22.19.59.616	55.8599	21.4519	1000.00	2	C0	6.1	81.8	44.5	26.2
1995-148:21.00.05.230	55.3447	22.5173	200.00	5	F0	no det.	12.2	visual	no det.
1995-148:21.20.01.960	54.6089	24.0969	200.00	9	J0	no det.	no det.	6.6	visual
1995-148:21.40.00.807	55.7066	21.8052	200.00	3	D0	no det.	21.6	15.7	6.1
1995-148:22.00.01.255	55.0024	23.3008	200.00	7	H0	no det.	visual	visual	visual
1995-148:22.20.01.187	56.0105	21.1390	200.00	1	B0	4.2	37.7	17.9	16.4
1995-150:02.00.00.000[b]	57.1710	18.0760	3500.00	0	A0	88.7	103.9	187.9	77.3
1996-189:21.00.01.172	54.6089	24.0972	300.00	10	J1	visual	no data	11.7	5.6
1996-189:21.30.01.944	54.0644	25.1653	679.20	12	M1	no det.	no data	23.3	10.8
1996-189:22.30.00.339	53.7111	25.8383	508.80	14	O1	no det.	no data	13.4	5.7
1996-189:23.00.04.146	52.9389	27.0944	339.20	18	S1	no det.	no data	visual	visual
1996-190:00.00.03.025	54.2528	24.8258	150.00	11	L1	no det.	no data	8.7	5.2
1996-190:21.00.03.630	54.8258	23.6617	800.00	8	I1	visual	17.6	12.2	13.1
1996-190:22.00.01.012	53.5244	26.1500	212.40	15	P1	no det.	no det.	no det.	no det.
1996-190:22.30.00.726	53.3322	26.4944	679.20	16	Q1	no det.	no det.	visual	no det.
1996-190:23.00.00.701	52.5600	27.6425	1102.40	20	U1	no det.	6.3	5.7	6.3
1996-191:00.00.00.214	53.8922	25.4983	212.00	13	N1	no det.	5.0	visual	visual
1996-194:21.00.00.591	53.7111	25.8383	848.00	14	O2	visual	9.4	27.5	9.8
1996-194:22.30.03.260	52.1436	28.2553	848.00	22	W2	no det.	visual	8.1	no data
1996-194:22.59.59.982	51.7170	28.8300	1102.40	24	Y2	no det.	4.8	no det.	no data
1996-195:01.00.01.066	53.1311	26.8344	848.00	17	R2	6.3	visual	7.6	no data
1996-195:21.00.00.775	52.5600	27.6425	460.80	20	U2	no det.	no det.	no det.	no data
1996-195:22.00.00.249	51.9233	28.5569	212.00	23	X2	no det.	no det.	no det.	no data
1996-195:22.30.02.695	52.3164	27.9810	212.00	21	V2	visual	5.4	7.8	no data
1996-195:23.00.00.361	52.7439	27.3810	212.00	19	T2	no det.	4.8	visual	no data

a. Shot time originally listed as 1995-147:21.20.01.375 by Giese (1998)
b. Shot time originally listed as 1995-149:22.20.01.187 by Giese (1998)

Table 6.6.2: GBF events associated with the Eurobridge experiment

Shot Label	GBF Origin Time (GMT)	Lat (deg)	Lon (deg)	Mag	Number of defining Arrays	P	S[a]	Error (deg)	Error (km)
G0	1995-147:21.00.37.0	57.48	25.02	1.38	1	1	1	2.8782	320.4067
K0	1995-147:21.20.00.0	54.48	24.64	2.56	4	4	3	0.1598	17.7920
E0	1995-147:21.40.02.0	55.49	22.05	2.39	4	4	4	0.1334	14.8522
I0	1995-147:22.00.01.0	54.67	23.43	2.22	4	4	2	0.2430	27.0532
C0	1995-147:22.19.57.0	55.69	21.52	2.34	4	4	3	0.1790	19.9250
F0	1995-148:20.59.57.0	54.57	23.10	1.93	1	1	1	0.9098	101.2797
J0	1995-148:21.19.41.0	52.93	24.82	-	2	2	0	1.7773	197.8511
D0	1995-148:21.39.52.0	54.97	22.09	2.02	3	3	1	0.7729	86.0448
H0	1995-148:21.59.54.0	54.28	25.16	1.93	1	1	1	1.6795	186.9633
B0	1995-148:22.20.02.0	56.09	21.16	1.56	4	4	1	0.0814	9.0599
A0	1995-150:02.00.03.0	57.37	17.95	2.33	4	3	7	0.2255	25.0990
J1	1996-189:21.00.33.0	56.42	22.39	-	3	3	0	2.2934	255.3047
M1	1996-189:21.28.05.0	46.56	32.15	-	2	2	0	9.2231	1026.7120
O1	1996-189:22.30.42.0	54.94	20.00	-	2	2	0	4.8984	545.2934
I1	1996-190:21.00.35.0	57.45	22.18	1.38	4	4	1	2.8982	322.6284
O2	1996-194:20.58.57.0	49.07	28.35	-	3	3	0	5.0384	560.8758
R2	1996-195:01.00.18.0	54.34	26.79	-	2	2	0	1.2094	134.6338
V2	1996-195:22.29.45.0	51.16	28.78	-	2	2	0	1.3156	146.4529

a. Includes S, Lg, and Rg

Table 6.6.3: Observed - predicted arrival times for Pn (seconds)

Shot	ARC	FIN	HFS	NRS
G0	-	0.976	0.831	-0.759
K0	-1.799	0.037	0.753	-0.743
E0	1.827	2.000	-0.866	0.342
I0	-1.145	0.724	0.486	-0.594
C0	-0.737	0.954	1.582	0.283
F0	-	1.551	2.916	-
J0	-	-0.115	1.062	0.093
D0	-	1.269	1.357	-0.180
H0	-	0.832	1.525	1.655
B0	-0.957	1.362	2.338	0.536
A0	-2.893	1.592	1.757	0.116
J1	1.270	-	4.689	3.554
M1	-	-	0.727	-0.226
O1	-	-	1.559	0.079
S1	-	-	1.135	0.458
L1	-	-	1.087	0.135
I1	-4.852	0.509	0.376	-0.587
P1	-	-	-	-
Q1	-	-	1.527	-
U1	-0.093	-0.525	-0.584	-0.649
N1	-	-0.324	1.127	-0.570
O2	-1.233	0.303	0.670	-0.302
W2	-	-0.682	1.156	-
Y2	-	-	-	-
R2	2.292	1.122	1.056	-
U2	-	-	-	-
X2	-	-	-	-
V2	0.605	-1.420	-0.017	-
T2	-	-0.878	0.707	-

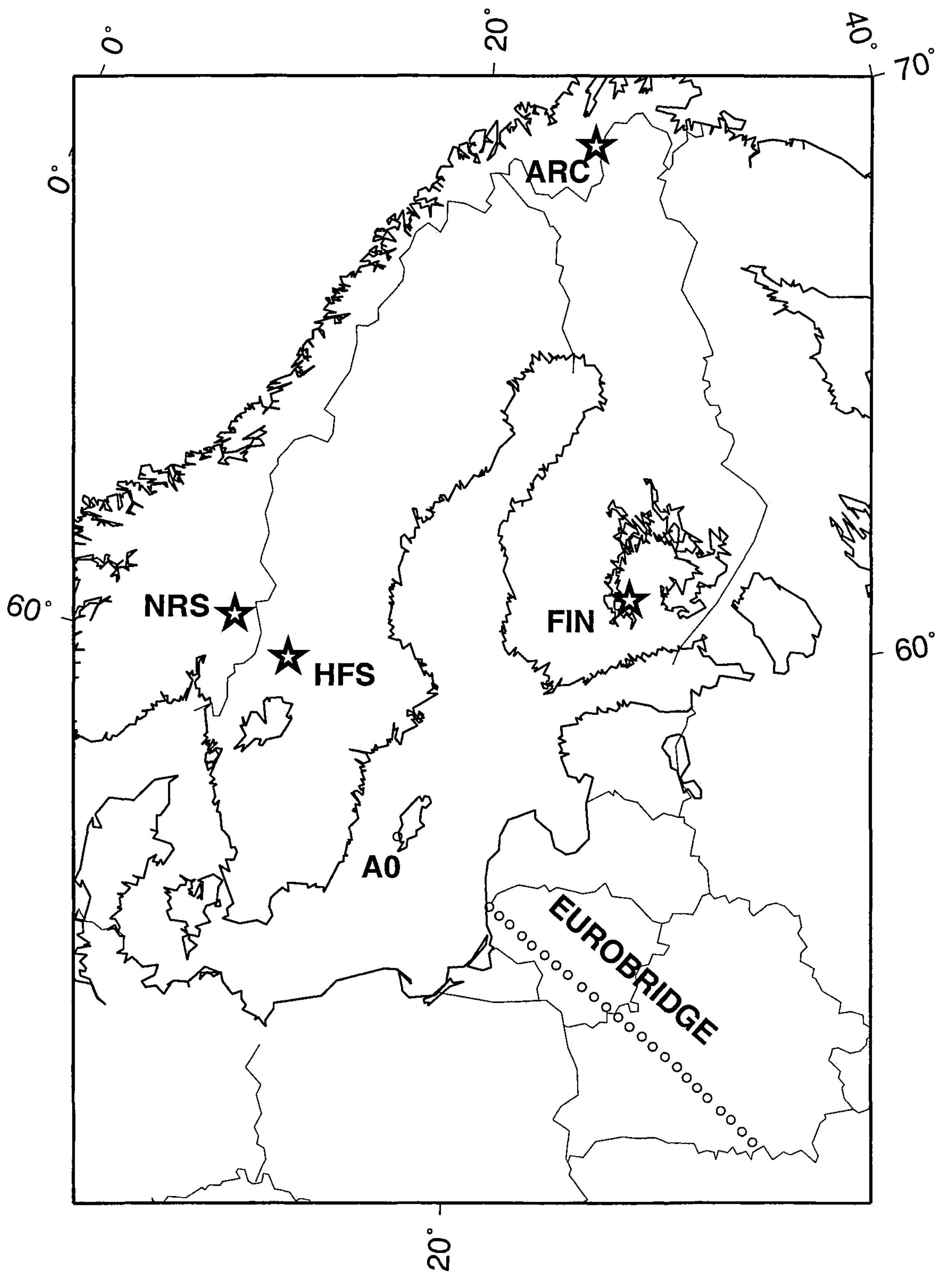

Fig. 6.6.1. *Map showing the locations of the Eurobridge shots and the four arrays included in this study (ARCESS, FINESS, HAGFORS, and NORESS). A0, located off the southern coast of Gotland, was part of the Eurobridge experiment. See Fig. 6.6.2 for a more detailed map of the remaining shot points.*

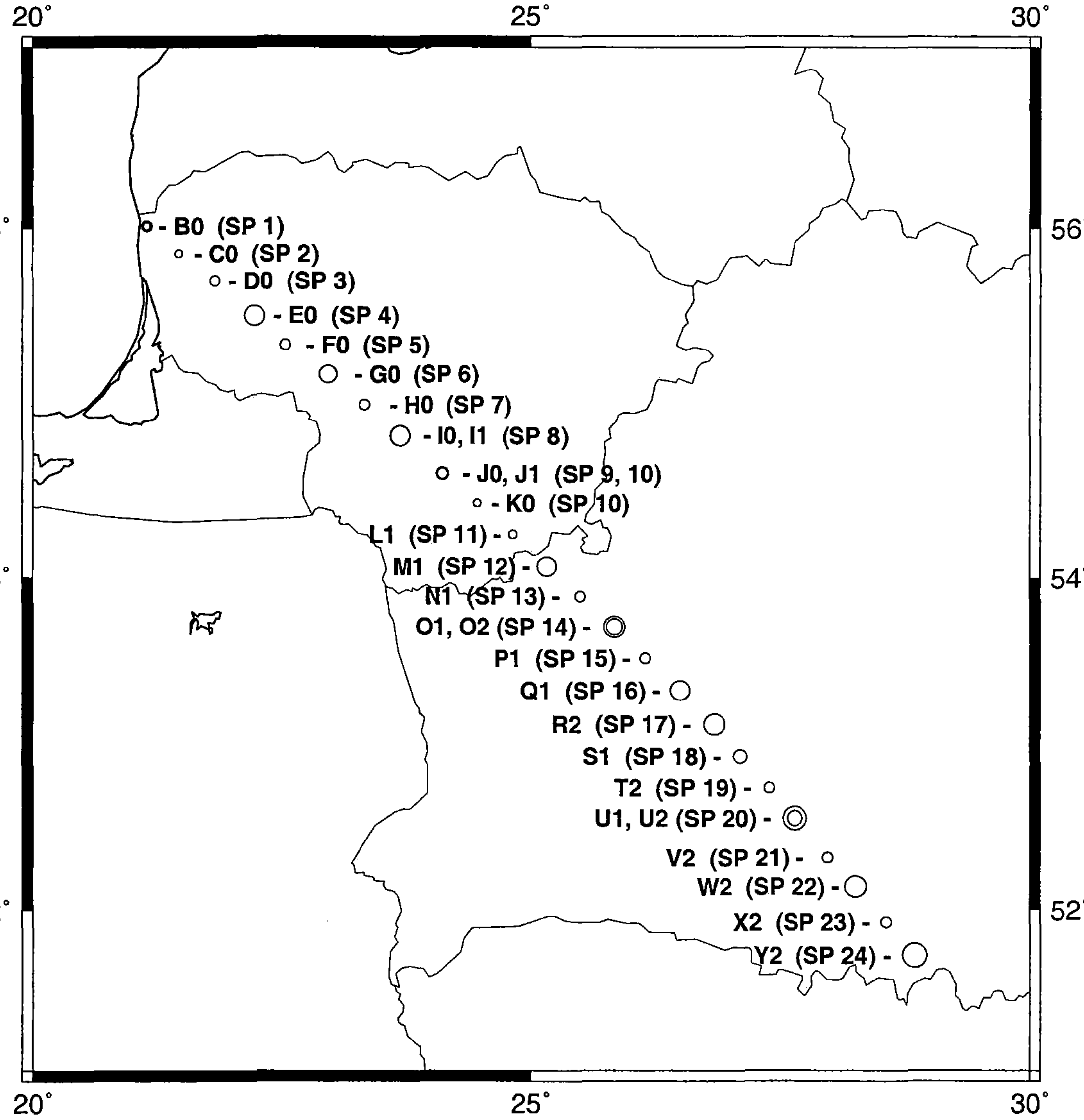

Fig. 6.6.2. *Map showing the Eurobridge shot points represented by circles with areas proportional to the yields. The labels that we have adopted are shown along with the original shot point numbers. See Fig. 6.6.1 for shot A0, which was located off the southern coast of Gotland. Detailed information on each shot is given in Table 6.6.1.*

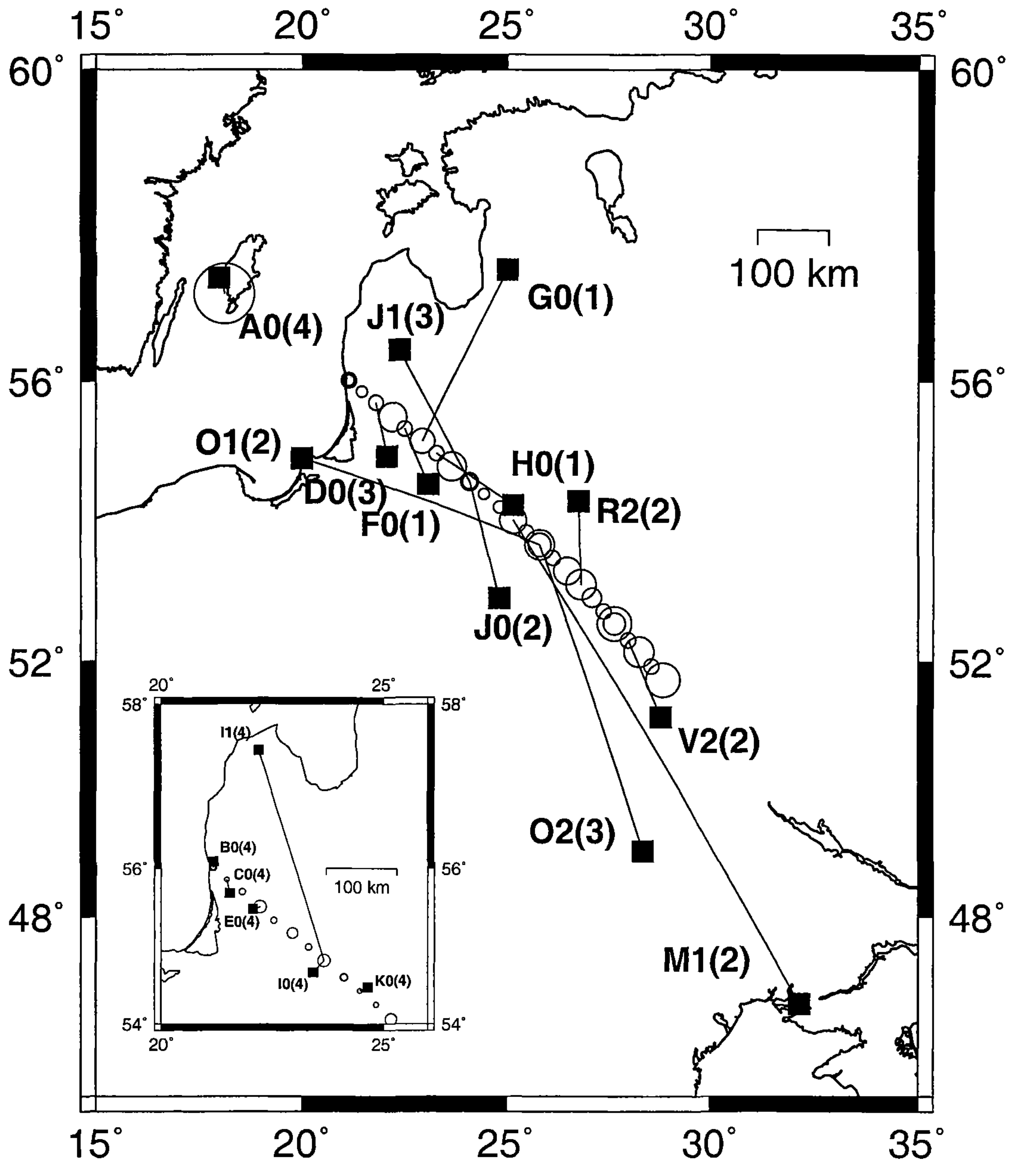

Fig. 6.6.3. *GBF events associated with Eurobridge experiment. A line is drawn between each GBF location (black squares) and the corresponding Eurobridge shot (circles). The shot label is given with the number of arrays used to locate the event. All mainland locations, where four arrays were used, are shown in the inset; the remaining locations are shown on the main map.*

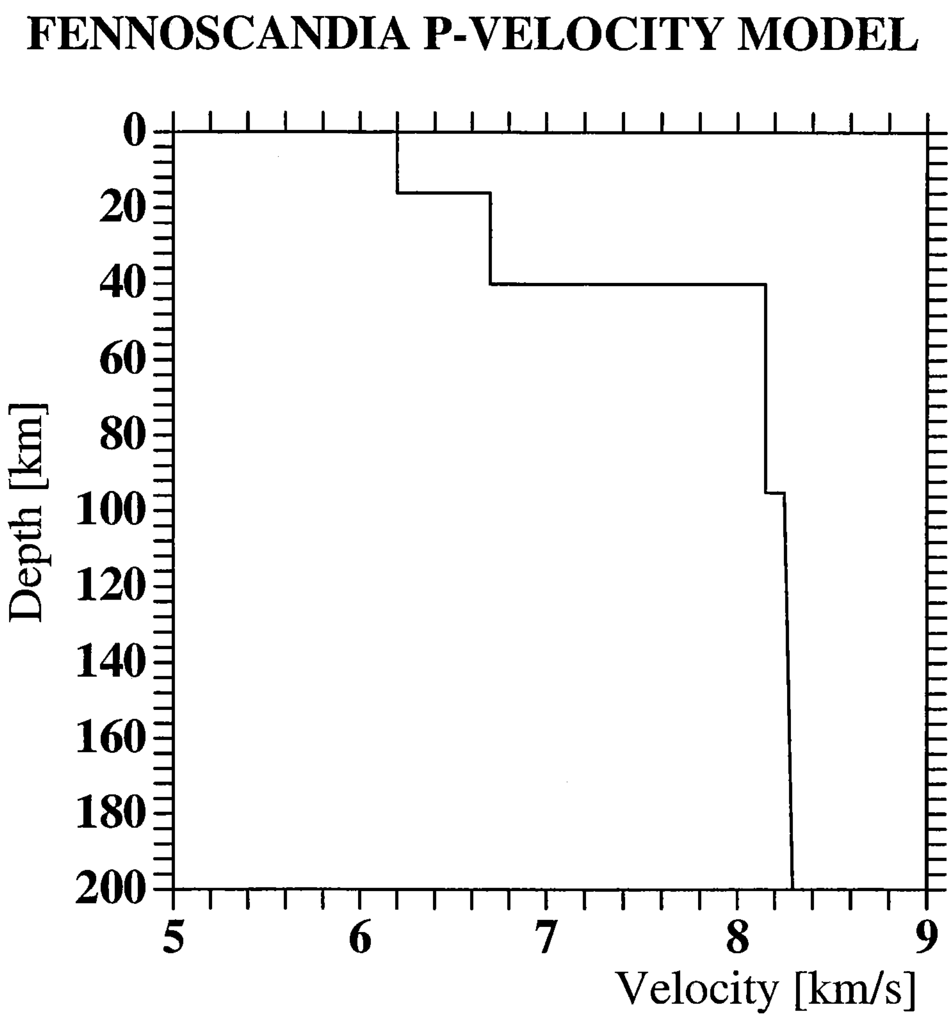

Fig. 6.6.4. *One-dimensional P-velocity model used for locating events in the Fennoscandian region and for calculating the theoretical travel-time curves shown in Figs. 6.6.5 - 6.6.8.*

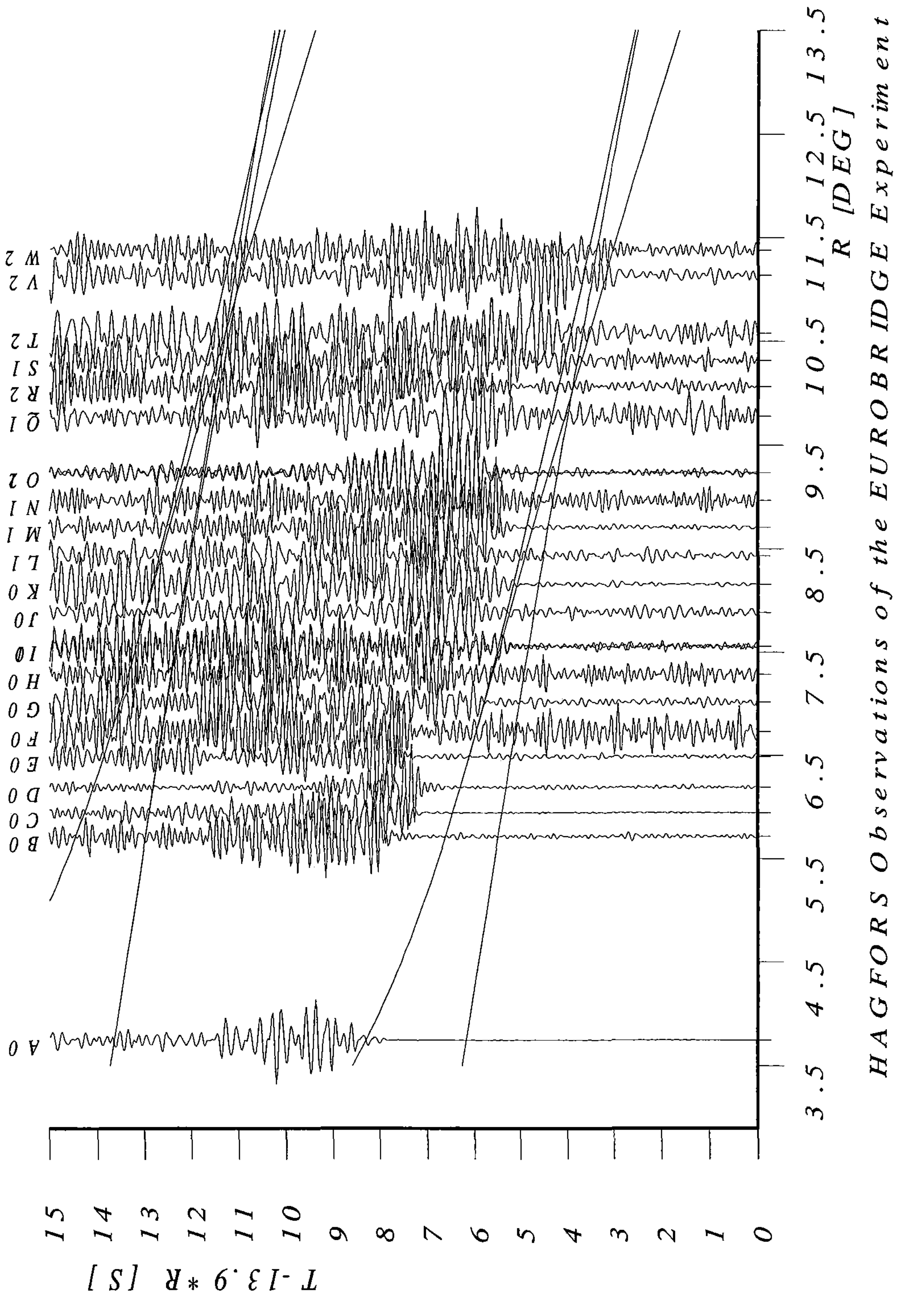

Fig. 6.6.5. *Section of Eurobridge shots recorded at Hagfors with travel-time curves of the Fennoscandian model superimposed. The shot labels (see Table 6.6.1) are shown above each trace.*

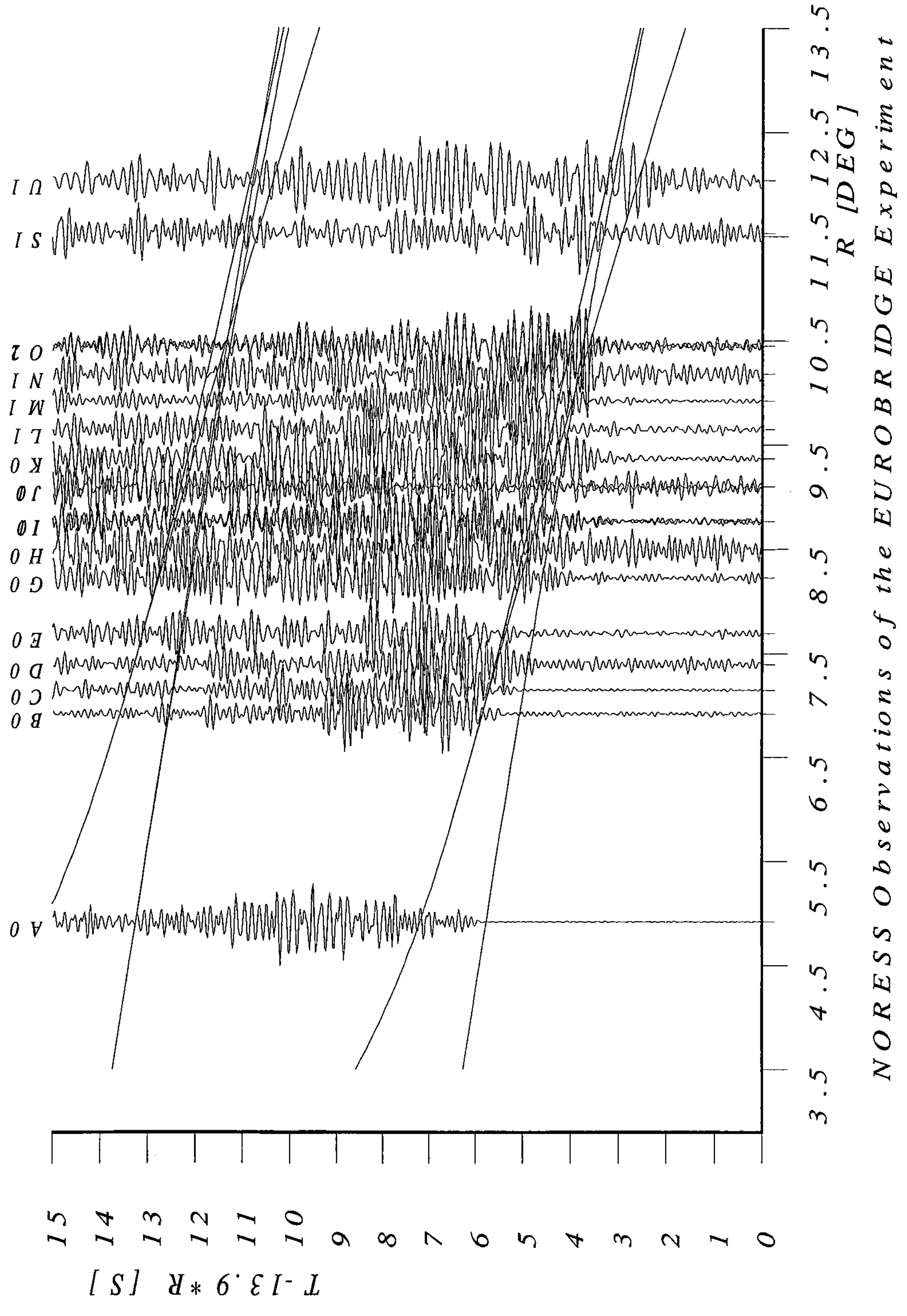

Fig. 6.6.6. *Section of Eurobridge shots recorded at NORESS with travel-time curves of the Fennoscandian model superimposed. The shot labels (see Table 6.6.1) are shown above each trace.*

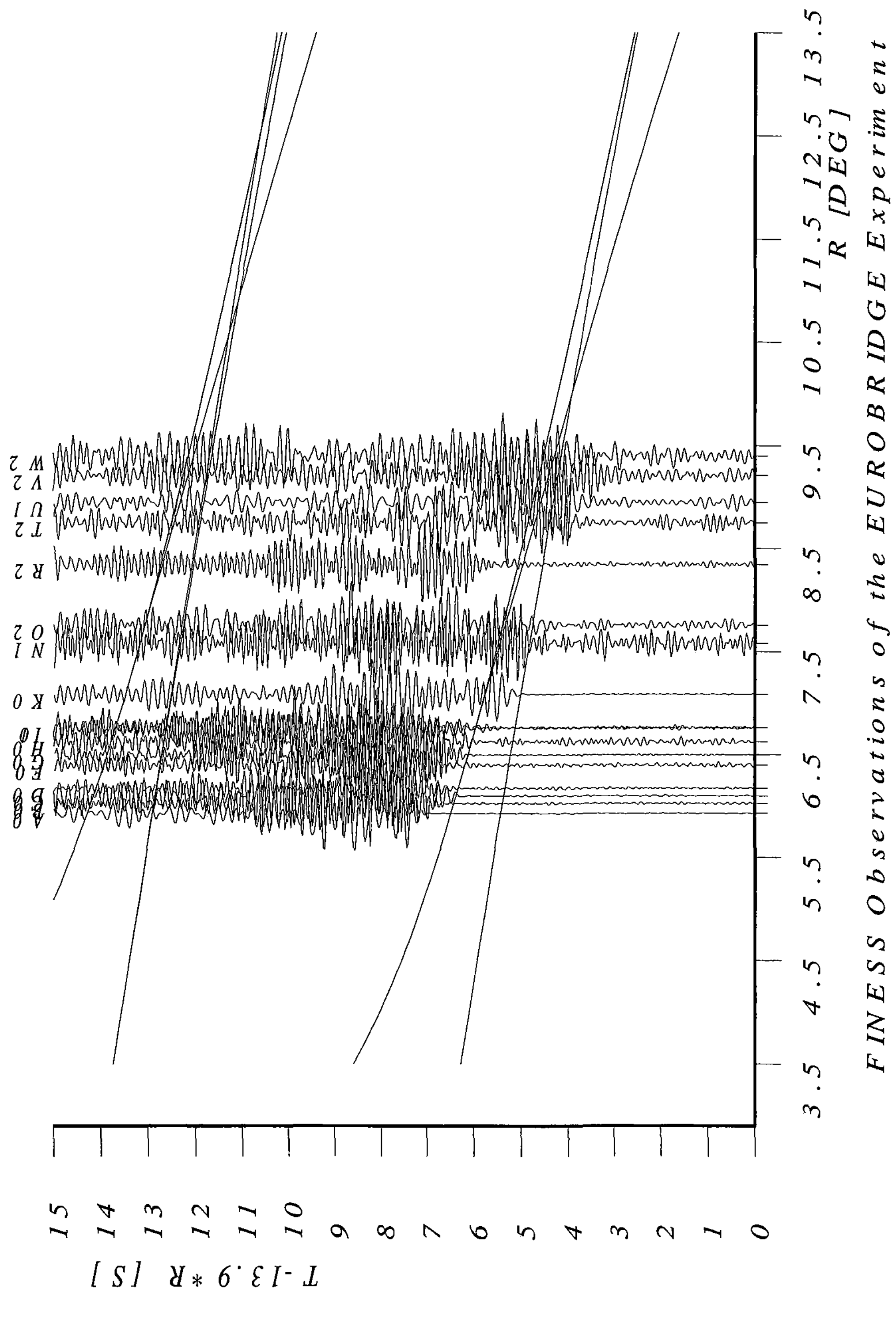

Fig. 6.6.7. *Section of Eurobridge shots recorded at FINESS with travel-time curves of the Fennoscandian model superimposed. The shot labels (see Table 6.6.1) are shown above each trace.*

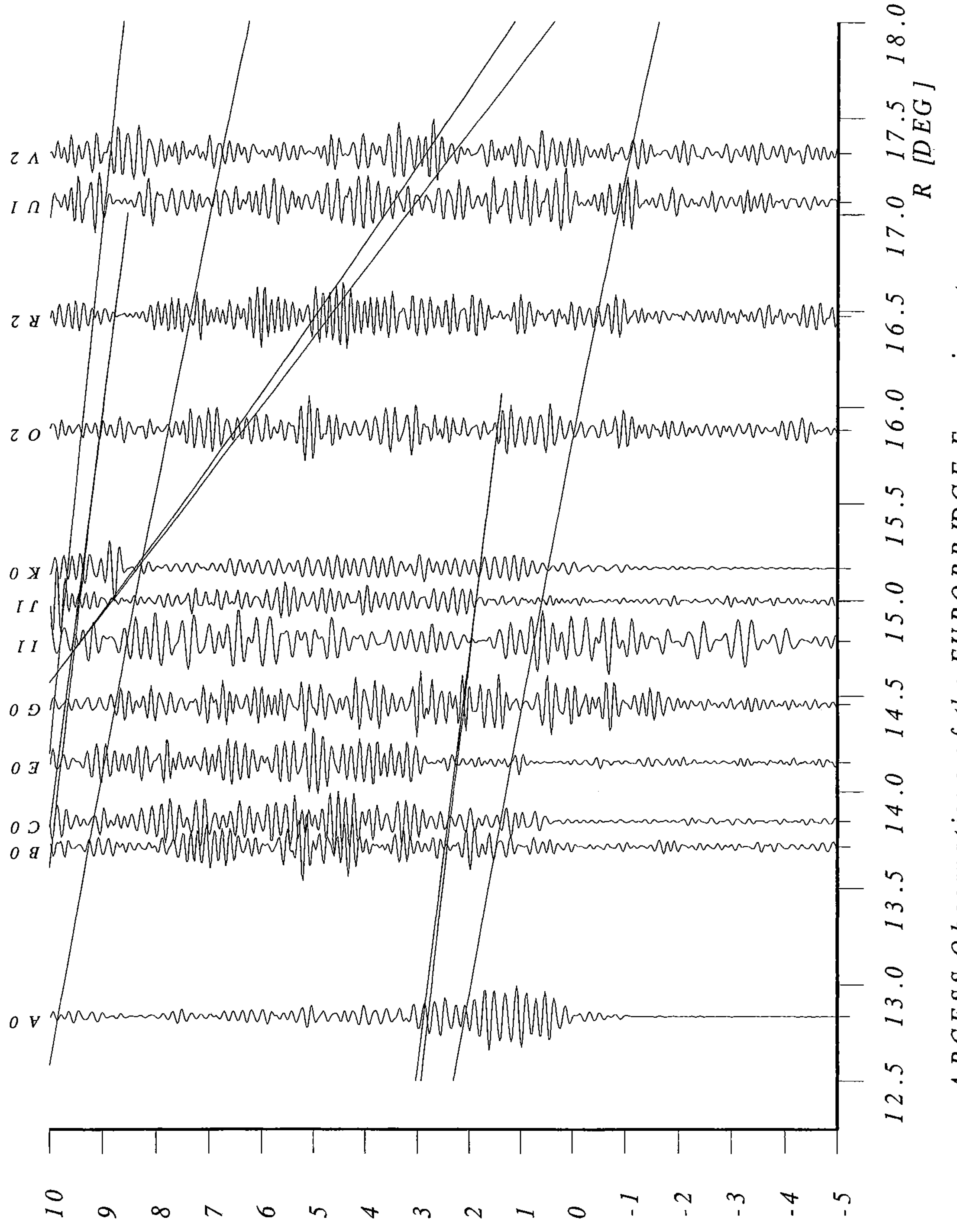

Fig. 6.6.8. *Section of Eurobridge shots recorded at ARCESS with travel-time curves of the Fennoscandian model superimposed. The shot labels (see Table 6.6.1) are shown above each trace.*