WAVEFORM MODELING TO ESTIMATE THE SEISMIC WAVE ATTENUATION IN THE CRUST, IN THE VRANCEA REGION

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The modeling of the high frequency waveforms from low magnitude shallow earthquakes located in the Vrancea region and surroundings is used to evaluate depth-dependent models for the quality factor in the crust, optimal for ray paths crossing the area from the bending of the Eastern Carpathians. The study points out lateral variations of the attenuation of the seismic waves with frequencies up to 5 Hz, indicating high values of the Q factor in the extra-Carpathian region, in the East European, Scythian, and eastern Moesian Platforms, and higher attenuation in the orogen from the major bend of the Carpathians, and in the Carpathian foredeep area.

Key words: Vrancea seismic region, low magnitude crustal earthquakes, high frequency waveforms, attenuation of seismic waves, Q-factor, 1D structural models.

1. INTRODUCTION

The territory of Romania is exposed to a high seismic risk, due mainly to the seismogenic source of strong earthquakes located at the bending of the Eastern Carpathians.

The seismic hazard assessment, the first step towards the mitigation of human loss and economical damages, is traditionally performed by two distinctive methodologies.

(i) The probabilistic approach is based on the analysis of the regional earthquake catalogue, by considering a seismotectonic model of the seismic sources, and ground motion attenuation laws empirically determined.

(ii) The deterministic approach is based on the numerical reconstruction of the ground motion by calculating theoretical seismograms.

The major destructive earthquakes of the Vrancea region are phenomena with low occurrence rate, and the number of available strong motion records is relatively small at present. Therefore the deterministic methods are particularly important for the evaluation of the seismic hazard on the territory of Romania.

In the deterministic approach the availability of appropriate models for both seismic source and Earth structure represents a key element.

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The large collection of high quality seismological data accumulated during the last years, consisting in digital records of the permanent networks as well as of the temporarily installed instruments (the tomographic experiment CALIXTO'99 and the refraction experiments VRANCEA'99 and VRANCEA 2001), allowed the increase of the accuracy of the velocity models for the crust and Upper Mantle beneath the Vrancea region and the adjacent zones (*e.g.* [1] – [9]).

The less known structural parameter in the area is the quality factor of the medium Q.

Recent studies on the asymmetric ground motion distribution in the Southeastern Carpathian region [10–13] point out peculiarities of the seismic wave attenuation beneath the intra-Carpathian and extra-Carpathian zones; however they do not provide specific values for Q.

The estimates of the quality factor obtained by Russo *et al.* [14] for the Carpathian bend region and surroundings from local intermediate depth earthquake data are Q-values characterizing the hypocenter – station path as a whole (including both crust and subcrustal zone).

In the present paper we use the modeling of the high frequency waveforms from low magnitude shallow events to evaluate optimal depth-dependent models for the Q factor in the crust, for a series of ray paths crossing the area from the bending of the Eastern Carpathians; we aim to provide more accurate structures for the deterministic seismic hazard studies and to point out lateral variations of the seismic wave attenuation in the crust in the study region.

2. METHOD

The modeling of the wave attenuation in the Vrancea region and the adjacent zones is approached in relation with the study of the seismic source by local seismogram inversion.

The focal mechanism of crustal earthquakes with local magnitudes around 3.0 was analysed using the INPAR algorithm developed by Šílený *et al.* [15] (*e.g.* [16–18]).

INPAR is a 2 steps algorithm which implements the indirect parameterization of the point source. The first step is a linear inversion (very rapid) which determines 6 independent time functions – representing the time derivatives of the 6 components of the seismic moment tensor –, by taking advantage of the linear relation between them and the ground displacement. The second step is a non-linear inversion, which reduces the 6 independent functions (involving a mechanism varying in time – unreasonable assumption for the weak events) to a common time function (the source time function) and a constant mechanism.

The INPAR algorithm is designed to perform also a dynamic relocation of the hypocentre and an optimization of the structural model simultaneously with the determination of the mechanism.

The dynamic relocation is carried out by constructing the Green's functions in a grid around the kinematically localized hypocentre, and by allowing the source to move inside this grid during the inversion.

To optimize the structural model along the source-station path two extreme structures, representing reasonable approximations of the propagating medium, are a priori proposed. The best-fitting model is then selected on the continuous scale between the two extremes, during an iterative search; the data are inverted using Green's functions generated as a weighted sum of the "extreme" functions, the weighting factor is allowed to vary between 0 (Green's function corresponding to the first model) and 1 (Green's function corresponding to the second model).

The method applied for the synthesis of the Green's functions is the summation of the modes of oscillation for vertically heterogeneous flat Earth models, with the body wave dispersion and the phase attenuation included ([19, 20]); the method allows to solve in an exact and complete way the full wave equation in a preassigned interval of frequencies and phase velocities. Since the modal summation synthesizes the complete wavefield, the method is particularly advantageous for the study of the weak earthquakes of Vrancea which frequently display complex waveforms.

3. DATA AND STRUCTURAL MODELS

The data set investigated by the inversion procedure of Šílený *et al.* [15] is presented in Table 1. The earthquakes have local magnitudes between 2.4 and 3.7, and depths in the range from 5 to 39 km.

Table 1

List of the earthquakes

Event #	*Date*	*Origin time*	*Lat.* [°N]	*Lon.* [°E]	*Depth* [km]	*Local magnitude*
1	30 June 1982	21: 38: 47	45.42	26.43	13	3.5
2	4 September 1982	23: 39: 45	45.43	27.75	5	3.4
3	21 February 1983	18: 21: 05	45.33	26.97	16	3.6
4	21 February 1983	18: 33: 37	45.37	27.02	17	3.0
5	21 February 1983	20: 27: 16	45.28	26.93	19	3.3
6	22 February 1983	11: 42: 25	45.37	27.01	17	2.9
7	22 February 1983	18: 04: 16	45.31	26.91	24	3.5
8	10 August 1984	16: 36: 12	45.84	27.29	15	3.6
9	8 July 1985	9: 36: 33	46.06	27.35	11	3.4
10	1 September 1991	13: 39: 12	45.55	26.95	32	3.1
11	1 September 1991	18: 37: 19	45.54	26.95	31	3.7

(continues)

Table 1 (continued)

Event #	*Date*	*Origin time*	*Lat.* [°N]	*Lon.* [°E]	*Depth* [km]	*Local magnitude*
12	28 January 1992	14: 35: 14	45.62	26.82	33	3.4
13	29 January 1993	16: 55: 56	45.5	26.81	17	3.2
14	31 January 1995	21: 48: 55	45.44	27.16	13	2.7
15	12 May 1996	18: 46: 36	45.76	27.46	10	3.5
16	1 June 1996	3: 07: 06	45.82	26.55	22	3.3
17	3 August 1996	2: 10: 25	45.07	25.99	14	3.5
18	27 August 1997	20: 17: 13	45.73	27.33	7	3.8
19	6 December 1997	12: 34: 35	45.67	27.04	14	2.9
20	27 May 1998	19: 17: 07	45.7	27.44	33	3.1
21	28 May 1998	6: 26: 16	45.69	27.45	32	2.9
22	29 May 1998	0: 52: 05	45.82	27.39	31	2.7
23	30 May 1998	14: 09: 06	45.69	27.36	7	2.4
24	30 July 1999	20: 44: 29	45.58	26.64	26	2.5
25	9 August 1999	23: 24: 30	44.96	27.04	25	3.2
26	23 August 1999	20: 57: 41	45.55	27.09	24	2.9
27	26 August 1999	13: 06: 52	44.9	27.08	23	2.9
28	30 August 1999	0: 52: 05	45.97	27.09	39	2.9
29	14 September 1999	9: 15: 15	45.36	25.12	11	3.1

The observed waveforms are short period velocity records (1 s free period and damping 0.7), vertical component, with the sampling rate of 50 samples/s, collected by 9 stations of the Romanian telemetered network: Bordeşti (BRD), Carcaliu (CFR), Coloneşti (CLI), Covasna (CVO), Istriţa (ISR), Muntele Roşu (MLR), Popeni (PPE), Topalu (TLB), Vrâncioaia (VRI).

For each source-to-station path an 1-D structural model for the elastic parameters was adopted; it approximates the local structure for an area of a few km^2 around the seismic station. The velocity and density models were available from Răileanu *et al.* [21] and are presented in Ardeleanu *et al.* [18]

The pairs of extreme structures were constructed by varying only the Q-factor (Fig. 1); the values are adopted from literature, in correlation with the rock type and seismic wave velocity in each layer.

4. RESULTS

Both the synthetics generated by multimodal summation up to 10 Hz, and the original records were low-pass filtered with the cut-off frequency at 5 Hz. The time windows selected for the inversion, generally around 10 seconds, contain the most energetic part of the signals, including the S-wave and surface-wave trains.

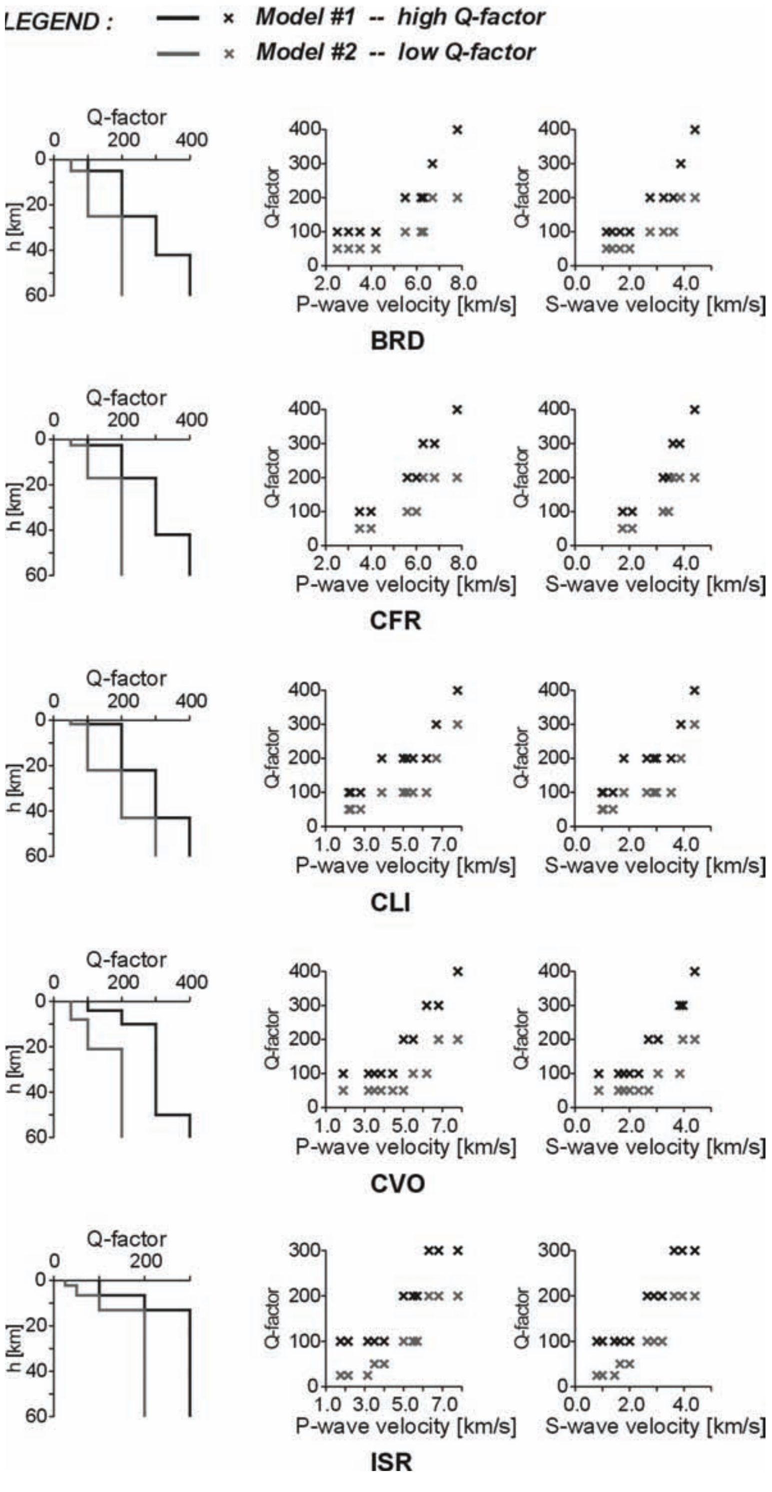

Fig. 1 – Extreme Q models considered for the seismic stations. Velocity models from [21].

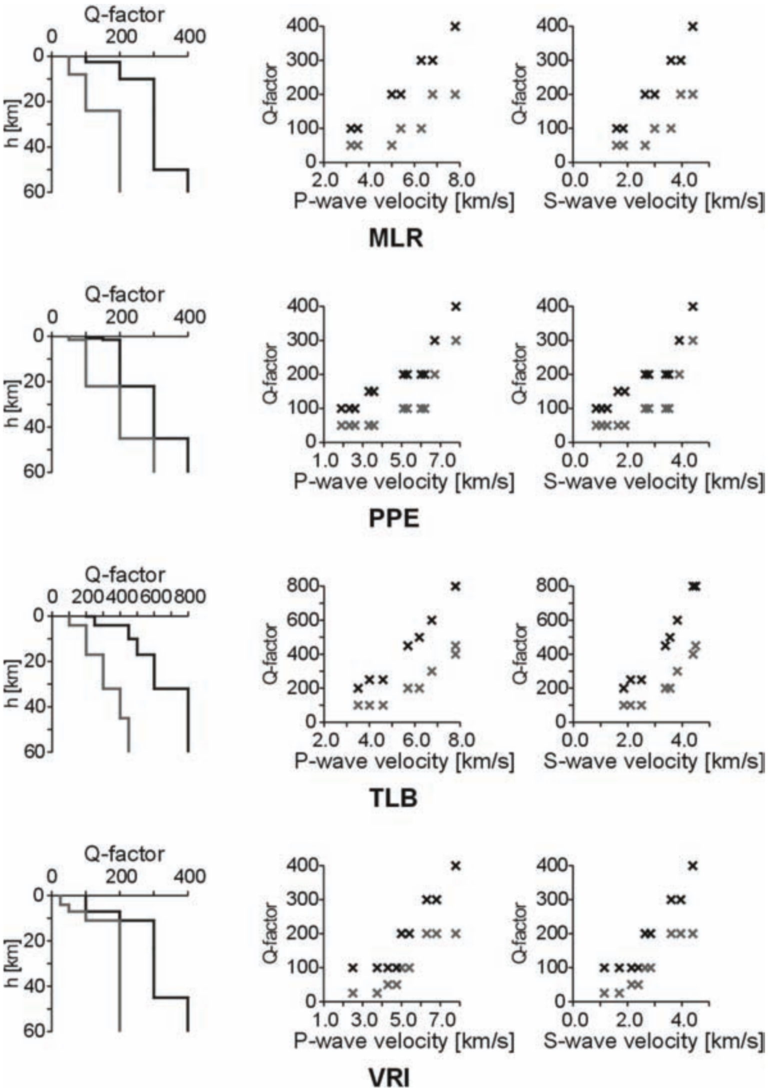

Fig. 1 (continued) – Extreme Q models considered for the seismic stations.
Velocity models from [21].

The best-fitting Q-models retrieved for each hypocenter – receiver path by the INPAR algorithm are classified according to the value of the weighting parameter (Table 2).

Several examples are presented in Figs. 2–6. The observed data (velocity records, [m/s]) are displayed together with the theoretical seismograms [m/s] generated for sources located in several levels around the hypocenter depth, and for the extreme structural models. The synthetics correspond to an instantaneous

Table 2

Estimation of the optimum structural model

Weighting factor	*Optimal model*
0–0.15	Model #1
0.15–0.35	Intermediate model – closer to model #1
0.35–0.65	Intermediate model
0.65–0.85	Intermediate model – closer to model #2
0.85–1	Model #2

point source with the scalar moment $M_0 = 10^{15}$ Nm, and based on a moment tensor with M_{11} the only nonzero component. Observed and computed seismograms are aligned relative to the origin time.

The optimal estimated Q-models are summarized in Fig. 7.

It comes out that for several stations the best fitting model points to one of the extreme structures, for all the investigated azimuths: the models with high Q-values are appropriate for the stations CFR, CLI, and PPE, while the model with low values of the quality factor appears as suitable for the station CVO. On the contrary, the stations BRD, ISR, MLR, TLB, VRI exhibit a notable azimuthal dependence of the models which reproduce better the observed data.

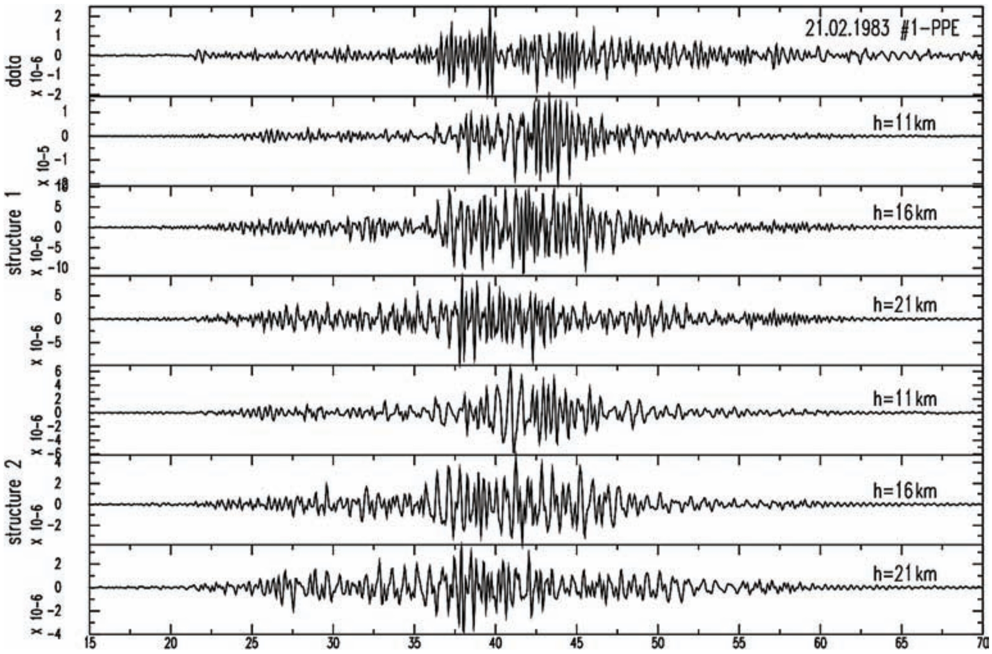

Fig. 2 – Optimal estimated model: model #1.

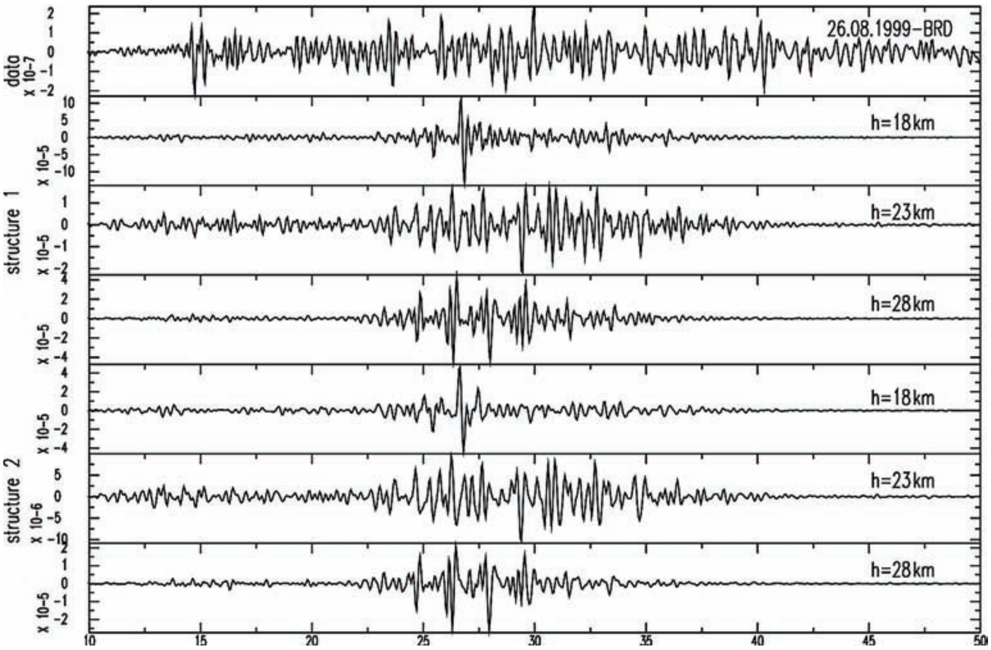

Fig. 3 – Optimal estimated model: intermediate model – closer to model #1.

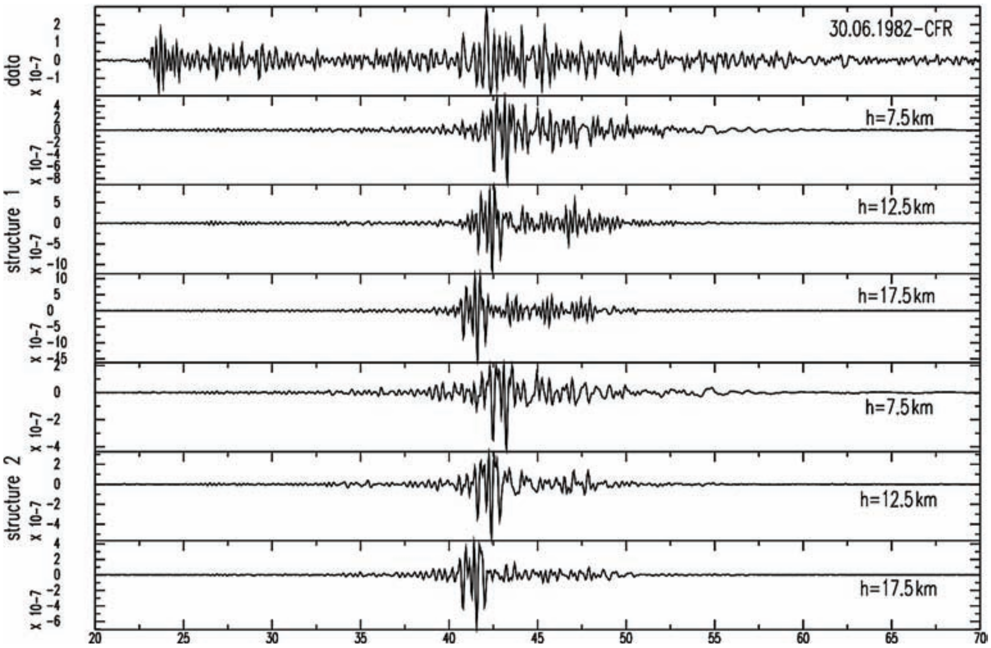

Fig. 4 – Optimal estimated model: intermediate model.

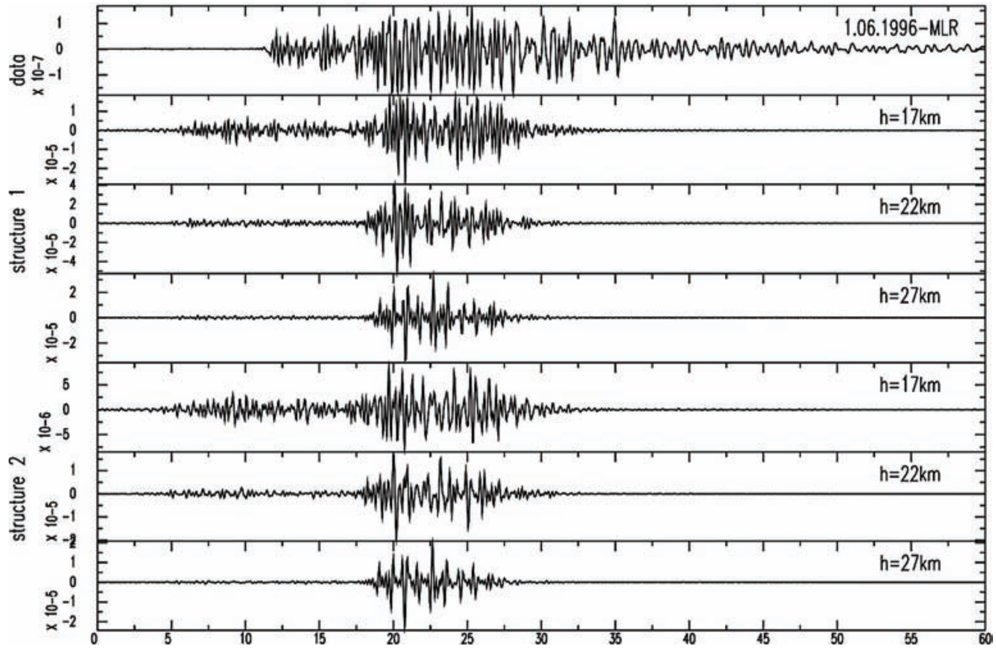

Fig. 5 – Optimal estimated model: intermediate model – closer to model #2.

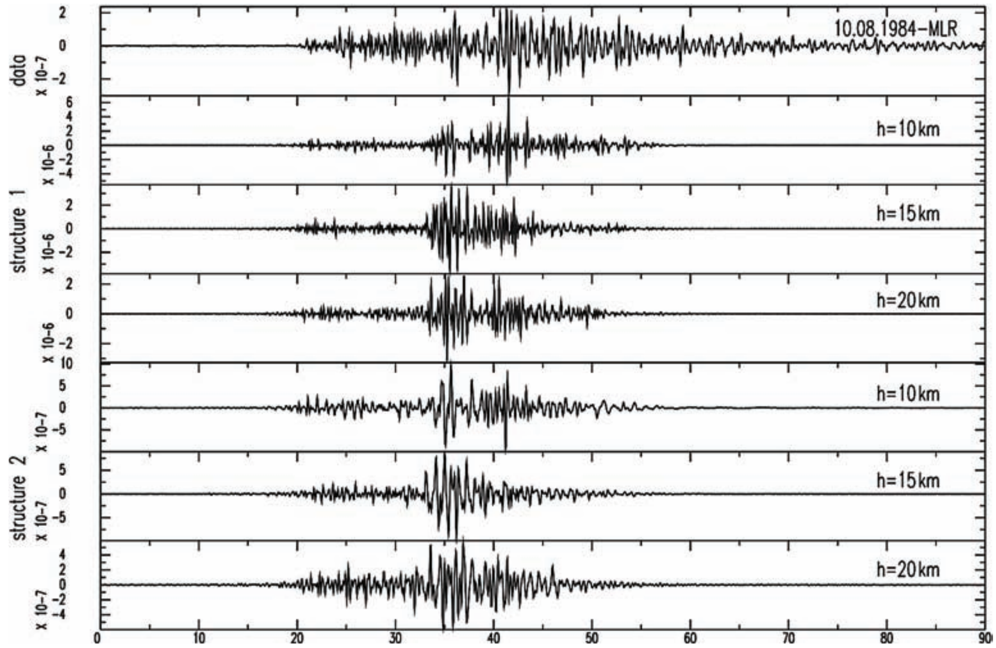

Fig. 6 – Optimal estimated model: model #2.

5. DISCUSSION

The modeling of short period waveforms (maximum frequency 5 Hz) evidences the effect of the adopted Q-values on the amplitudes and the frequencies of the synthetic signals, and points out the importance of using adequate models for this parameter to obtain reliable solutions in the source studies, or for confident deterministic hazard analyses.

Our study proposes depth dependent models for the quality factor in the crustal range, adequate for a series of ray paths crossing the Vrancea seismic region and the adjacent areas.

The optimum 1-D structures retrieved during the waveform inversion reveal lateral variations of the attenuation parameter in the study region. The best-fitting models indicate high values of Q for the paths located in the extra-Carpathian region, in the East European, Scythian, and eastern Moesian Platforms. For the rays situated within the orogen from the bending of the Eastern Carpathians and the Carpathian foredeep zone the optimal values of the quality factor are lower; the results emphasize a higher attenuation of the seismic waves with frequencies up to 5 Hz for the paths crossing this area, which might be related to a significant scattering process during the wave propagation through the rather fractured crust beneath the sedimentary Focşani Basin and orogen structures, and the thrust and faulted nappes of the Vrancea region orogen.

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Fig. 7 – The best-fitting Q-models for the investigated ray paths.