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A 2-D velocity model of the Vrancea region in Romania: prediction of teleseismic waveforms

J. Perrot,[1,*] A. Deschamps,[1] V. Farra[2] and J. Virieux[1]

[1] *Institut de Géodynamique, UNSA-CNRS, Rue A. Einstein, 06560 Valbonne, France*

[2] *Institut de Physique du Globe de Paris, Départment de sismologie, tour 14-24 4e étage, 4, place Jussieu, 75252 Paris cedex 5, France*

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SUMMARY

In previous studies, anomalies in arrival time and amplitudes of depth phases *pP* and *sP* recorded at teleseismic distances and produced by large intermediate-depth events of the Vrancea region were pointed out (Perrot *et al.* 1994). The modelling of major recent events has shown that the presence of a dipping interface and thick low-velocity sediment layer in the upper crust above the hypocentral area can explain such anomalies. Simulating broad-band records of the 1990 May 31 earthquake, it is shown that the 2-D crustal velocity model derived by Perrot *et al.* (1994) can also be used to explain observed waveforms in an extended azimuthal range from 105° to 243° and is valid for earthquakes having different hypocentral locations in the deep Vrancea seismic zone. Using records in the azimuthal range where a classical spherical model produces a good fit to the observed waveforms, the source is best modelled by two point sources at 90 and 93 km depth releasing the same amount of seismic moment, and separated by 1.5 s in time. Synthetics calculated for this source time history and the 2-D velocity model above the source give a much improved fit of the observed waveforms over what could be achieved with a 1-D spherical model. The results suggest that teleseismic waveforms could be reasonably well predicted for any event in the region with the 2-D velocity model, which accounts for the main structural features in the upper crust of the Vrancea region.

Key words: broad band, hybrid ray-tracing method, seismic modelling, Vrancea region.

1 INTRODUCTION

The Vrancea region is located in the south-eastern bend of the Carpathian Arc, and is well-known for its frequent large earthquakes at intermediate depths, e.g. 1940 November 10 ($M_s = 7.4$), 1977 March 4 ($M_s = 7.2$), which produced much damage in the surrounding areas, 1986 August 30 ($M_s = 6.9$, $m_b = 6.4$), and 1990 May 30 ($m_b = 6.7$) (Radu 1974; Fuchs *et al.* 1979; Trifu & Oncescu 1987; Monfret, Deschamps & Romanowicz 1990; Trifu *et al.* 1992). The presence of a trench, revealed by a strong negative Bouguer anomaly (Roman 1970), a folded arc, a volcanic arc (Bleahu *et al.* 1973) and a retroarc basin (the Transylvanian basin, part of the Pannonian basin) suggests that the Carpathian Arc formed as a consequence of collision between two oceanic plates. At present, however, the Carpathian Arc appears to mark the convergence of two intra-continental zones within the Eurasian plate, i.e. the Pannonian basin and the Moldavian platform (Radulescu & Sandulescu 1973) (Fig. 1).

Seismic analysis (e.g. Radu 1974; Oncescu 1984; Trifu 1987; Trifu & Oncescu 1987; Trifu *et al.* 1992) carried out in this region revealed a Wadati–Benioff zone along a vertical profile oriented NW–SE. These studies also outlined a significant decrease of seismicity between 40 and 60 km depth, and the recurrence of large-magnitude earthquakes below 60 km depth down to about 200–220 km. Consequently, it has been suggested that the lithosphere has been ruptured between 40 and 60 km depth and a piece of slab is plunging independently from its crustal part. Focal solutions of large earthquakes confirm a slab plunging under the Carpathian Arc with pure-thrust mechanisms in a NE–SW direction and a dip angle of about 60° (Roman 1970; Radu 1974; Fuchs *et al.* 1979; Tavera 1991), in agreement with the downward extent of the aftershock activity (Trifu & Oncescu 1987).

Three earthquakes have occurred in the Vrancea region since 1986: 1986 August 30, 1990 May 30 and the main aftershock, 1990 May 31. For all these events, large discrepancies in both arrival time and amplitude have been noticed

* Now at: Instituto de Ingeniería—UNAM, Coordinación de Sismología, Ap. Postal 70-472, Coyoácan-04510 Mexico D.F., Mexico.

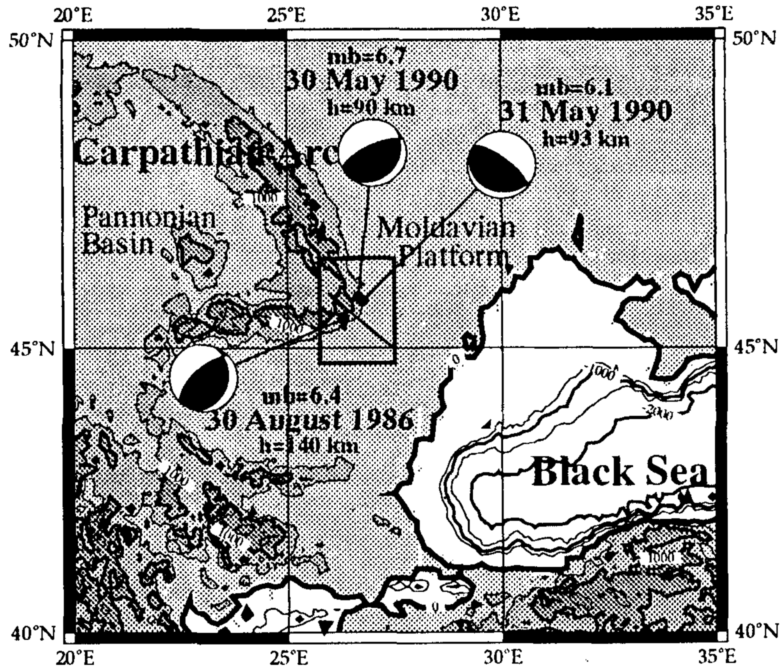


Figure 1. Seismotectonic map of the Vrancea region (after Perrot *et al.* 1994). Focal solutions of the studied earthquakes are also shown. The centre box depicts the frame of Fig. 8. The thin line within this rectangle shows the cross-section profile on which the 2-D velocity model is defined (Fig. 2).

between the observed and the theoritical *pP* and *sP* phases at stations in a specific azimuthal range using a spherically symmetric velocity model of the Earth. These observations underlined the importance of the velocity structure above the source. The synthetic *pP* waveform exhibited a smaller amplitude as compared to that of the observed phase, whereas the amplitude of the synthetic *sP* phase waveform was larger than the observed one.

The analysis of the 1986 August 30 and 1990 May 30 earthquakes made by Perrot *et al.* (1994) pointed out that these anomalies were caused by propagation effects in complex media above the source, not accounted for by the assumed spherically symmetric velocity model. Based on a hybrid ray-tracing technique and the modelling of the depth phases recorded at station RER for the 1986 August 30 event and the modelling at stations AGD, HYB and RER for the 1990 May 30 event, Perrot *et al.* (1994) have determined a 2-D velocity model that explains the anomalous phases observed in the south-eastern azimuthal range of 105° to 153°. The amplitude of the observed *pP* phase has been recovered at three stations, AGD, HYB and RER (Fig. 16b of Perrot *et al.* 1994).

The 2-D model included superficial sedimentary layers. Such is the case for the interface dipping 20° to the south-east (Fig. 2), which separates a sedimentary basin from a granitic layer. The strong velocity contrast associated with the dipping interface significantly distorted the *pP* and *sP* ray paths over the source region (Fig. 2) (Perrot *et al.* 1994). Towards the south-east, where a thick and extended sedimentary basin exists, the reflected *sP* phases propagate through this basin, where they lose part of their energy in reverberations. The thin sedimentary layer (1 km) at the free surface allows us to model the very low amplitude of the *sP* phase at the AGD station (Perrot *et al.* 1994).

This 2-D structure is symmetric to a profile in the median azimuth of 135° (Fig. 1) for a width of 50 km, and allows good waveform simulation for stations in the south-eastern azimuths. For all other stations, the EP86 earth model proposed by Madariaga & Papadimitriou (1985) beneath western Europe was concluded to be sufficient. Since the dipping interface is just above the source, the depth phases at stations to the north-west reach the surface without crossing this interface, as shown by the dashed lines in Fig. 2.

For the 1986 August 30 event the use of the 2-D model led to an improvement of the fit at the only broad-band station present at that time, RER, (Fig. 18 of Perrot *et al.* 1994). The arrival-time delays of the *pP* and *sP* phases were recovered as well as the amplitude of the *pP* phase to some extent. However, this earthquake did not occur in the same area as the 1990 events. Therefore the true dip of the interface could have a 3-D effect on the azimuthal distortion of ray paths, leading to a somewhat lower amplitude than that obtained with the 2-D model. An independent verification of the 2-D model should be carried out for validation.

Through the waveform modelling of the main aftershock (May 31) of the large 1990 earthquake, the validity of the 2-D proposed model has been extended to a wider azimuthal range. Before testing this extension, an improvement of the understanding of the rupture process was necessary, in order to ensure that the remaining anomalies are due to propagation effects in this 2-D velocity model.

2 EVALUATION OF SYNTHETIC WAVEFORMS FOR INTERMEDIATE-DEPTH EARTHQUAKES OF THE VRANCEA REGION: MODELLING OF THE 1990 MAY 31 EARTHQUAKE

Seismic records of the 1990 May 31 earthquake are simulated using the 2-D velocity model previously discussed. The wave-

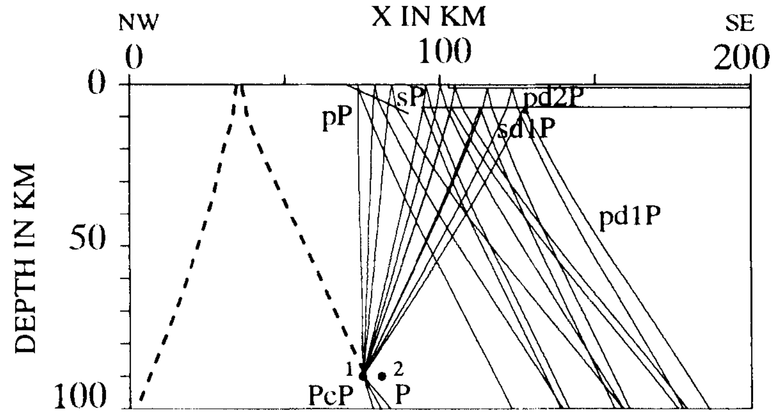


Figure 2. Hybrid ray tracing in the 2-D Cartesian model proposed for the Vrancea region (after Perrot *et al.* 1994). The projection at the free surface of the profile is shown in Fig. 1. The interface dipping at 20° to the south-east separates a sedimentary layer with a *P*-wave velocity of 4.6 km s^{-1} from a granitic layer with a velocity of 6.5 km s^{-1}. The flat interface at 7 km depth delimits the bottom of a sedimentary layer with a velocity of 4.4 km s^{-1}. The thin sedimentary layer (1 km) at the free surface has a velocity of 2.5 km s^{-1}. The ray plotted in solid lines represents the trajectories computed for the stations RER, AGD, HYB from the foci of the 1986 August 8 and the 1990 May 30 events. The ray plotted in a dashed line represents the trajectory of rays that are computed for the stations in the north-western azimuth. We also model multiple reflections at the bottom of each flat sedimentary layer: *pd1P*, *pd2P*, *sd1P*, and also *PcP*, the reflection at the core. The source is located at 90 km depth. Number (1) on the profile indicates the location of the May 30 hypocentre, and number (2), the May 31 hypocentre.

forms confirm that the EP86 model, like any other spherical symmetrical velocity model, is not predictive enough, compared with the 2-D model.

The event (45.81°N, 26.77°E, GMT 00:17:47.8, $H = 88$ km, $Mb = 6.1$) occurred 14 hours after the main shock, about 10 km to the south-east of the principal shock. The focal solution determined by Harvard (Table 1) was a thrust fault with a strike-slip component, and the suggested fault plane had a strike of 309°, a dip of 69° and a slip angle of 106°. The associated seismic moment was 3.2×10^{18} N m. Similar fault parameters were found by Tavera (1991), who inverted broad-band waveforms using the Nabélèk procedure. However, Tavera's solution indicates a deeper hypocentre, of 94 km depth rather than the 87 km depth obtained by Harvard. This difference lies within the errors of the methods, but the deeper depth is confirmed by the aftershock activity determined from local data (Trifu *et al.* 1992).

The strike and dip angles of this mechanism are consistent with a vertical rupture perpendicular to the strike of the Wadati–Benioff zone. Trifu *et al.* (1992) interpreted this event as representing the failure of the subducted plate, which appears to be continuous in the north-eastern part of the Carpathian Arc, but seems to be detached in the south-eastern part. The inversion carried out by Tavera (1991) with low-pass filtered data provided a triangular source time function of 3 s duration, but, however, without a good fit of the double pulse observed in the *P* waves (Fig. 3).

Table 1. Different evaluations of source parameters of the 1990 May 31 earthquake.

Source	depth	Focal Solution			Seismic Moment
	(km)	Azimuth (°)	Dip (°)	Slip (°)	(10^{18}Nm)
NEIC	88	310	70	90	
Harvard	87	309	69	106	3.2
Tavera (1991)	94	308	71	97	3.5
this study					4.8
1st event	93	308	70	97	2.4
2nd event	90	315	70	107	2.4

2.1 Waveform simulation using the spherical earth model EP86

To separate clearly the effects due to the rupture process from those due to wave propagation in a complex medium, the source time function had to be improved using the EP86 model before introducing the 2-D model. The stations used for this modelling are listed in Table 2. In addition to the stations used in previous studies, data from stations MBO, TAM, BNG and AGD were included in the analysis.

A source time function composed of two distinct 1 s pulses separated by 1.5 s provided a good fit to the observed *P*-wave double pulses (Fig. 4). However, the synthetic *pP* phase also shows a double pulse that is not observed on the recorded

Table 2. Azimuth and distance to the Vrancea area of broad-band *P*-wave records used for the 1990 May 31 event. Where a letter is assigned, the record at the station is modelled in this work and the letter should be used to identify the position on the focal sphere (Fig. 3). An asterisk indicates that the station did not record the 1990 May 31 event but was used in the study of Perrot *et al.* (1994) of the 1990 May 30 main shock.

letter	station	azimuth in (°)	distance in (°)
f	HIA	49.8	58.9
g	INU	51.7	77.7
k	WMQ	69.9	42.3
h	LZH	70.5	56.9
*	HYB	105.7	51.4
*	RER	151.5	71.7
a	AGD	153.0	36.8
c	BNG	192.3	41.8
j	TAM	224.1	28.7
i	MBO	243.9	48.2
d	CCM	314.9	79.7
b	ANMO	323.2	89.2
e	COR	339.1	86.2

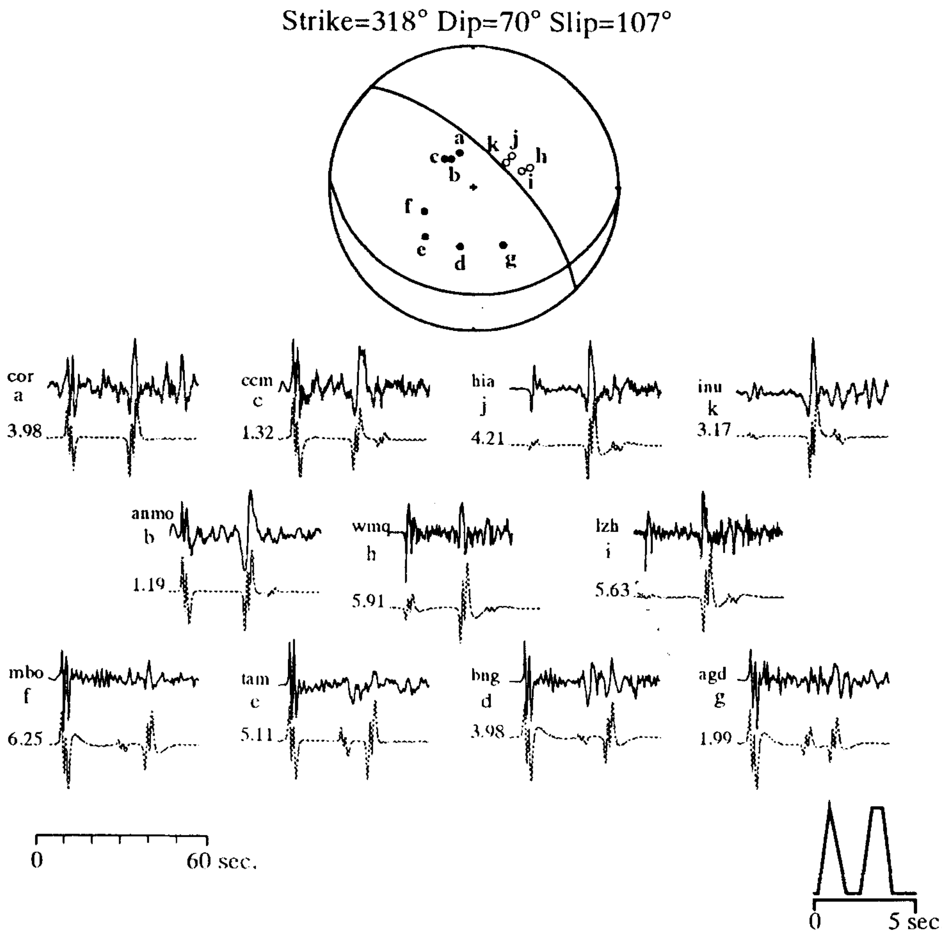


Figure 3. Simulation of velocity records generated by the 1990 May 31 event using the spherical symmetric earth model EP86 with a thrust mechanism (strike = 318°, dip = 70°, slip = 107°) and a source time function that consists of two subevents separated in time by 1.5 s and located at the same depth. Synthetic seismograms are plotted below the observed ones. The number on the left is the seismic moment (in 10^{18} N m). Each station was assigned a letter to allow for identification on the focal sphere. A good fit in shape of the direct *P* phase is obtained, but the *pP* arrival times and amplitudes are not well matched at stations MBO, TAM, BNG and AGD.

seismograms. This may be explained if the two subevents are clearly separated in both time and depth, the second being several kilometres shallower than the first. An additional argument in favour of two separated subevents is the relative amplitude of the synthetic *P* and *pP* phases at stations COR and CCM, as compared with the observed phases. Summation of two *pP* phases will lead to a better fit.

Adjusting the different parameters by eye, the rupture process of the 1990 May 31 earthquake was finally modelled using two point sources. The corresponding Green's functions were calculated independently for locations at 90 and 93 km depth. These Green's functions were then convolved with the source time functions shown in Fig. 5.

The best shape and amplitude fit is obtained for two subevents of the same seismic moment. The seismic moment is calculated for each station, comparing amplitudes of observed and synthetic seismograms. As those are proportional to ground velocities, the individual values are very sensitive to the source model and superficial station conditions. Nevertheless, the average value is a good estimation of the seismic moment. We obtained $M_0 = 3.6 \times 10^{18}$ N m, which is consistent with the value determined by Tavera (1991).

The rupture process is illustrated in Fig. 5. The relative depth of the two subevents is constrained by the traveltimes of the *pP* phase. A first subevent occurred at 93 km depth with a source duration of 1 s, whereas a second subevent occurred at 90 km depth directly above the first subevent and 1.5 s later. This separation was sufficient to reduce the arrival time of the *pP* phase of the second event such that the summation of the *pP* phases from the two events create synthetic *pP* waveforms, similar to the observed ones. A rupture velocity of 0.45 of the *S* wave velocity was assumed. The above result is in agreement with an upward propagating rupture, as previously suggested by Tavera (1991). However, the mechanism proposed herein (Table 1) for the two subevents provides a better fit of the data.

Although this rupture model has significantly improved the overall fit, some problems still remained for the synthetic amplitudes of the *sP* phases at stations MBO, TAM, BNG and AGD, which are currently larger than the corresponding observed amplitudes. This discrepancy has already been reported by Monfret *et al.* (1990) and Perrot *et al.* (1994) for other intermediate-depth events in the Vrancea region. For the event of the May 31, the above behaviour extended in azimuth from 153° to 243°, outside the limits of the previously defined

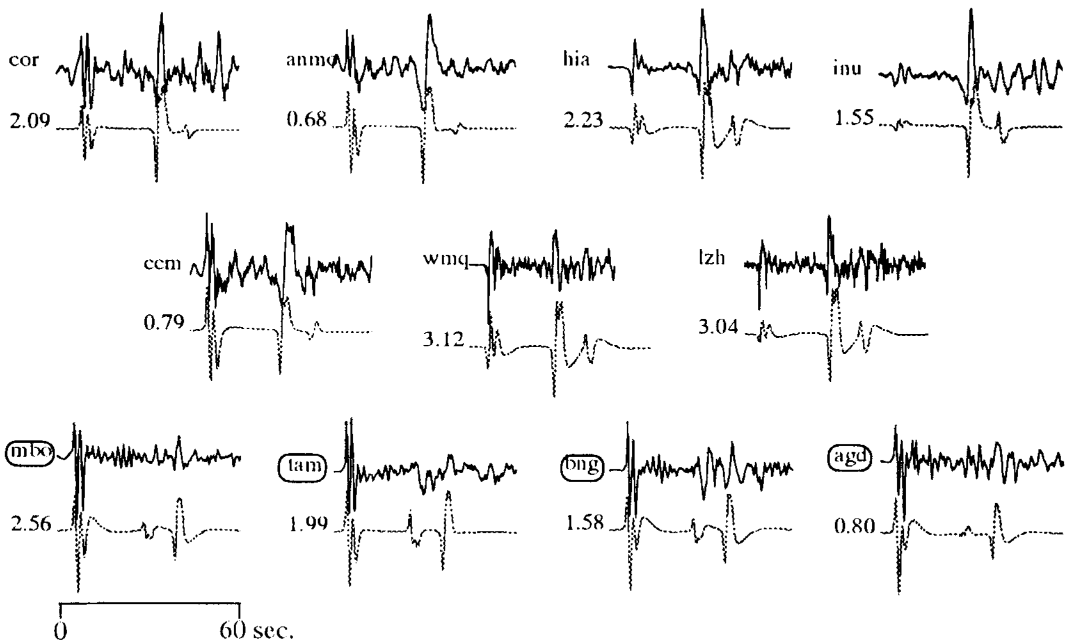


Figure 4. Waveform simulation for the 1990 May 31 earthquake using the EP86 earth model and the source parameters shown in Fig. 5. The synthetics are plotted below the observed seismograms. The number on the left is the seismic moment at each station in 10^{18} N m. Two subevents separated in depth improve the fit, but problems remain in fitting the amplitudes of depth phases at stations MBO, TAM, BNG and AGD; the code names of these stations are surrounded by a border.

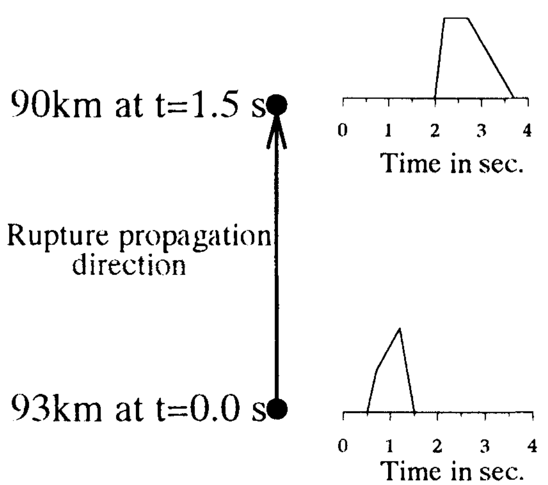


Figure 5. Description of two subevent source parameters used to model the 1990 May 31 earthquake. The model simulates a vertically propagating rupture at a rupture velocity of $2\ \mathrm{km\ s^{-1}}$. The initial depth is 93 km. The two subevents have different focal mechanisms (Table 1) and shapes of the source time function. However, they have the same seismic moment.

range. Note that stations BNG and TAM did not trigger for the principal shock, whereas stations RER and HYB did not trigger for the main aftershock.

2.2 Waveform simulation using the 2-D velocity model for the Vrancea region

Synthetic seismograms calculated with a spherically symmetric earth model for the May 31 event did not exhibit all the anomalies seen for the main shock of 1990 May 30 (Perrot *et al.* 1994). The observed *pP* phases in the south-eastern azimuths had much smaller amplitudes than for the main shock. The tectonic context, however, was different. Thus, the focal mechanism was not the same, and the azimuthal distortion over the focal sphere had a different effect on the amplitudes of the *pP* phases. Moreover, the epicentre was located at 10 km to the south-east of the main shock. Due to this particular geometry, there are no rays reflected or refracted on the dipping interface that arrive at teleseismic distances from 30° to 90° (see Fig. 6).

Fig. 7 shows the synthetic seismograms obtained using the 2-D configuration and the source parameters previously constrained with the EP86 model (Fig. 4). These synthetics suggest that the proposed 2-D velocity model of the Vrancea region allows for the synthetic amplitudes of the *sP* phases to fit the observed pulses at stations MBO, TAM, BNG and AGD. On the other hand, the modelling that incorporated the sedimentary basin was not found appropriate for stations located outside the azimuthal range of 105°–243°, as outlined by a comparison of the corresponding seismograms in Figs 4 and 7.

Predicted reflections at the bottom of the sedimentary layers showed a good fit to the data (*pd1P* and *pd2P*). However, the synthetic arrival times of each of the *sd1P*, *sd2P* and *sP* phases seemed to have been delayed compared to the observed phases at stations MBO, TAM and BNG (Fig. 7). Variations of seismic velocities, Poisson coefficient or thickness of the sedimentary layer may explain such observations. Another phase observed at all stations, but not modelled, arrived just after the direct *P* wave. It could be due to a reflection at a discontinuity located only a few kilometres above the source.

We calculated the seismic moment, i.e. the average of the value obtained for the best fit at each station. For MBO, TAM,

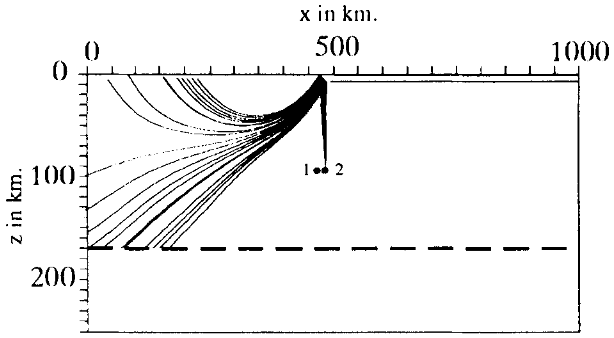


Figure 6. Ray tracing in the 2-D velocity model proposed for the Vrancea region for a point source located at the location of the 1990 May 31 event. This is an attempt to simulate a reflection at the bottom of the dipping interface to be recorded at epicentral distances of 30° to 90° in a north-western and south-eastern azimuth. Due to the spatial extension that we give to the reflector, and to the relative position of the reflector and the source, no reflected ray has a suitable parameter to be observed in this distance range. Number (1) indicates the location of the May 30 hypocentre and number (2), the May 31 hypocentre.

BNG and AGD, this value corresponded to the seismic moment obtained using the 2-D velocity model; for all of the other stations, it corresponded to the seismic moment obtained using the EP86 model. The average seismic moment of all stations was 4.8×10^{18} N m, slightly higher than that previously estimated.

Through the modelling of the May 31 main aftershock, the applicability of the proposed velocity distribution within the Vrancea region was extended to explain teleseismic waveforms recorded in the azimuthal range of 105°–243°.

3 STRUCTURAL SYNTHESIS AND DISCUSSION

To synthesize the main features of the 2-D velocity model of the Vrancea region, as obtained from teleseismic broad-band records, the intersections between the ray paths and the interfaces, for every station and each phase, have been projected to the surface of a topographic map in Fig. 8. The black triangles, representing the structure of the EP86 model, delimit an area to the north of the Vrancea region. The white symbols represent the 2-D sedimentary structure that was found to the south, with white circles corresponding to the *pd1P*, *pd2P* and *sd1P* phases, and white squares to the *pP* phase crossing the dipping interface. The western boundary of this structure is not clear, as there were no stations available in the azimuth range of 243° to 323°. Despite this, the good agreement obtained at station MBO using the EP86 model for the 1990 May 30 earthquake, and the 2-D model for the 1990 May 31 earthquake indicates that the boundary between the EP86 model and the sedimentary structure is located on the free surface next to the Vrancea Mountains. This boundary coincides with the geological boundary between the crystalline basement of the Vrancea Mountains and Quaternary sediments of the Foscani depression.

A dipping interface is shown by using ray paths travelling perpendicular to its strike. Thus, the white squares indicate an interface striking N40°E and dipping to the SE. The presence of white circles corresponding to flat interfaces at various locations along the dipping interface is not surprising, given that the direction of the ray paths is almost parallel to the strike of the dipping interface. In this case, the waves propagate in an equivalent 1-D structure and cross an apparently flat interface.

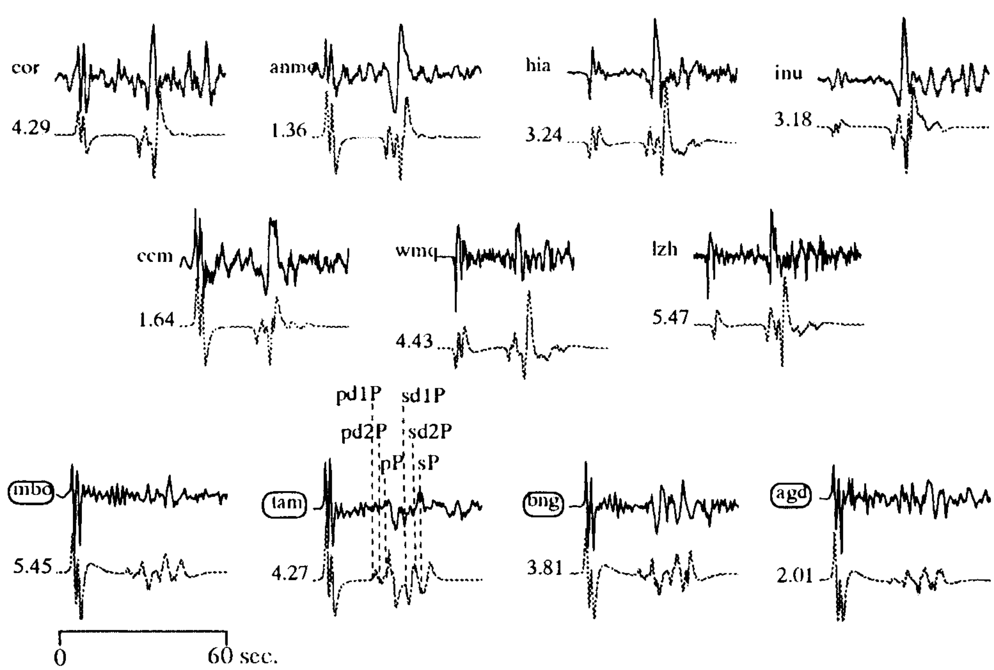
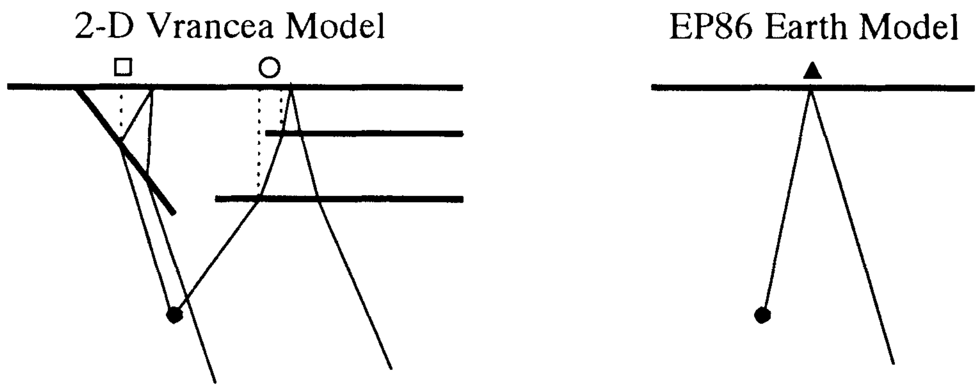


Figure 7. Waveform simulation for the 1990 May 31 earthquake using the 2-D velocity model. The notations are as those for Fig. 4. The source parameters are as those described in Fig. 5. We improve the fit of depth phases at the stations located to the south-east (code names of these stations are surrounded by a border), but the quality of fit of the *pP* phase at the other stations is reduced. The synthetic arrival time of the reflected phases are reported for the TAM station. We noticed a slight delay in time for all the *S* reflected phases, except for the AGD station.



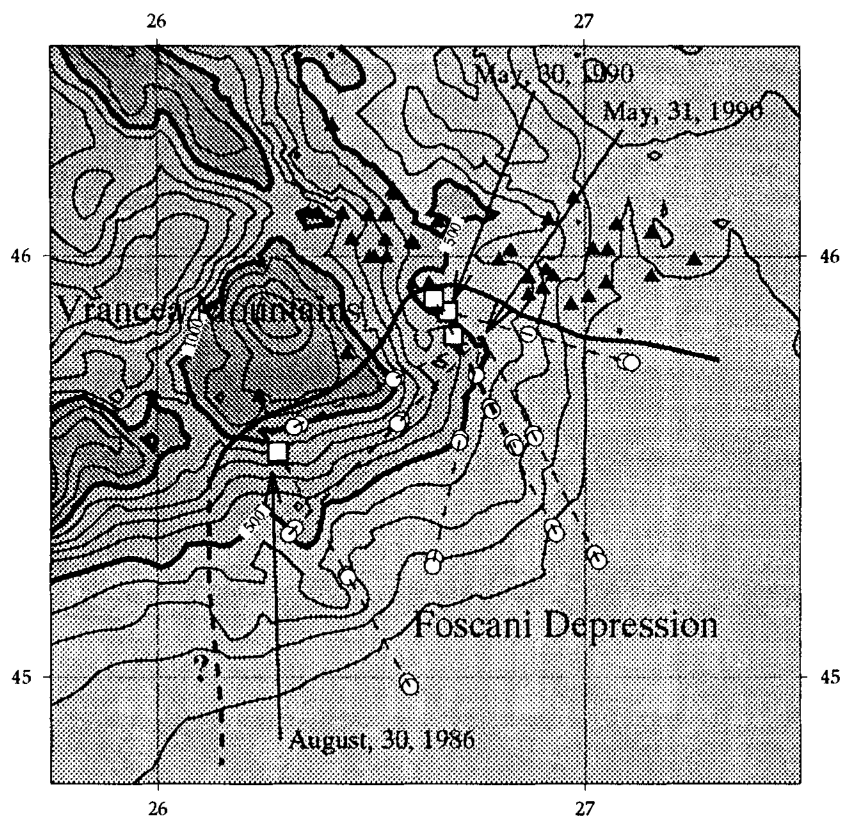


Figure 8. Synthesis of the results of the 1986 August 8 and 1990 May 30 and May 31 events reported on a topographic map of the Vrancea region within the rectangle shown in Fig. 1. Full triangles represent reflection points at the free surface for the *pP* ray calculated in the EP86 velocity model and used in modelling of seismograms at stations in an azimuthal range of 245° to 105°. Circles represent the projection at the surface of the reflection points of the rays contributing to the *pP* phase at the base of the sediments and calculated in the 2-D velocity model. Squares mark intersections with the 20° dipping interface; circles mark intersections with the flat sedimentary layers. The dashed lines indicate the azimuths between the earthquake epicentres and the stations. The boundary between the sediments and the crystalline basement has been traced with a dashed line in the south-western part as there is no data in this area to allow the tracing of a definite boundary. The sedimentary layers correspond to the Foscani depression.

The relatively poor fit of the *pP* phase observed at station RER for the 1986 August 30 event (Fig. 18 of Perrot *et al.* 1994) indicates that the 2-D model cannot sufficiently explain teleseismic waveforms from all intermediate-depth earthquakes in the Vrancea region. However, in order to extend the velocity model to 3-D, more broad-band data over a wider azimuthal range is required to derive a reliable model.

Knowing the velocity structure of the Vrancea region, detailed source-parameter modelling is possible for the deeper earthquakes that occur in this area. For shallower sources, a relocation of earthquake hypocentres could lead to a better understanding of the regional tectonics. An evaluation of the seismic hazard for this region is also possible in the studied frequency range. A good knowledge of the medium properties permits the calculation of the analytical Green's functions, which further allows for the prediction of teleseismic waveforms.

4 CONCLUSION

Anomalies in the arrival times and amplitudes of depth phases (*pP*, *sP* and others) have been observed for intermediate earthquakes in the Vrancea region, as recorded by broad-band sensors located between azimuths 105° and 243°. These records are characterized by smaller amplitudes for the synthetic *pP* phases and much larger amplitudes for the synthetic *pP* phases than the corresponding amplitudes observed within the specified azimuthal range.

In an earlier study, Perrot *et al.* (1994) had attributed these anomalies to propagation effects in a complex 2-D velocity distribution through the modelling of the event of 1990 May 30. The proposed velocity structure includes an extended sedimentary basin 7 km deep. Its boundary with the crystalline basement to the north-west was modelled by an interface dipping 20° to the south-east. The presence of this large sedimentary basin is supported by the Foscani depression to the south-east of the Carpathian Arc, the depth of which has been found to be as great as 17 km. The dip of the sediment–granite interface, and the velocity contrast associated with it, cause variations of the amplitudes of depth phases and distortions of take-off angles on the focal sphere. The 2-D velocity model of the crust in the Vrancea region predicts reflections from the bottom of the sedimentary layer that are in good agreement with the observations.

The main aftershock of the 1990 May 30 Vrancea earthquake occurred on 1990 May 31, and consisted of two separate events about 1.5 s apart in time and separated in depth by 3 km. Accounting for this source time history, phases associated with the 2-D crustal model of Perrot *et al.* (1994) could be clearly identified at the four stations AGD, MBO, TAM and BNG located in an azimuthal sector from 153° to 243°. For these stations, observed broad-band waveforms are well matched by incorporating the 2-D model in the synthetic seismogram calculations. This suggests that the 2-D model for the Vrancea region is applicable to a wider azimuthal range of observations. Comparison with the mapped surface expressions of geological units, the location of the sedimentary structure in the 2-D model corresponds to the Foscani depression to the south-east of the Carpathian Arc.

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