ANNALI DI GEOFISICA, VOL. XXXVII, N. 3, June 1994

Lithospheric structure models applied for locating the Romanian seismic events

Mihaela Rizescu, Emilia Popescu, Victoria Oancea and Dumitru Enescu
Center of Earth Physics, Bucharest, Romania

Abstract
The paper presents our attempts made for improving the locations obtained for local seismic events, using refined lithospheric structure models. The location program (based on Geiger method) supposes a known model. The program is run for some seismic sequences which occurred in different regions, on the Romanian territory, using for each of the sequences three velocity models: 1) 7 layers of constant velocity of seismic waves, as an average structure of the lithosphere for the whole territory; 2) site dependent structure (below each station), based on geophysical and geological information on the crust; 3) curves describing the dependence of propagation velocities with depth in the lithosphere, characterizing the 7 structural units delineated on the Romanian territory. The results obtained using the different velocity models are compared. Station corrections are computed for each data set. Finally, the locations determined for some quarry blasts are compared with the real ones.

Key words *location – velocity models – seismic sequences – quarry blasts – Romania*

1. Introduction

The aim of this paper is to improve the location of the earthquakes which occur on the Romanian territory, using the data recorded by the stations of the national telemetered network. Our attempts are based on the use of refined lithospheric structure models in the location program.

The national telemetered network consists of 14 stations equipped with short-period S-13 instruments. The continuous digital data recording is performed in Bucharest. The data acquisition and processing are operated on a PC system, based on the IASPEI volume 1 software (Tottingham *et al.*, 1989). The telemetered network generally covers the eastern part of the country, being primarily designed to survey the most active seismic region in our territory, the Vrancea region, located at the Carpathian arc-bend and characterized by important seismic activity in the depth range 60-150 km, as well as by crustal activity.

Other seismic regions, located in the western, central and southern part of the territory are characterized by crustal activity. For the location of the earthquakes in these zones, the data recorded by the telemetered network are completed with those obtained at the standalone stations in the country. For the rapid (or automatic) epicenter determination, the data from the standalone stations cannot be used. So, the necessity to improve all the locations using only the telemetered network data, appears.

For locating the local events, a program based on Geiger method (Geiger, 1910) is used (Oncescu, 1983). Its algorithm solves the problem of the determination of the 4 hypocentral parameters, by minimizing the sum of the squared residuals (differences between the observed and theoretical arrival times), supposing a known velocity model.

This program allows to refine the hypocenter determination, due to its characteristics:

– up to 20 different velocity models with any number of layers (with specific constant P and S wave velocity and constant v_P/v_S ratio) can be used, associated with different local structures below the stations. The program uses the velocity structure attributed to a station for the whole path; troubles appear for events which occur out of the network;

– a weightening procedure (phase, epicentral distance and azimuth dependent) is applied;

– locations with fixed depth or fixed epicenter can be performed;

– the values of the adjustments of hypocentral parameters made during the iterative procedure (in order to achieve convergence criterion) are defined by the user and allow high precision in the location determination (Δx, y, $z \leq 0.01$ km, $\Delta t \leq 0.01$ s);

– station corrections for P and S arrival times can be computed for large data sets of events which occurred in the same zone. These corrections can be subsequently used for improving the location of the earthquakes in that region.

2. Velocity models used for location determination

In order to obtain better locations (smaller errors, higher precision) the program is run three times for each data set, supposing different velocity models, as follows:

1) model 1 is the one used in practice in our Institute. It represents an average model for the whole territory, with 7 layers of constant P wave velocity and v_P/v_S = 1.77 (Oncescu, 1984; Oncescu *et al.*, 1984). It is presented in fig. 1a;

2) model 2 is a site dependent one. For each station, a specific velocity model is assumed, based on the geophysical and geological information on the crust at each site (Răileanu *et al.*, 1993). Below the crust, the structure is considered as in model 1. The number of layers differs from station to station, ranging between 11 and 16. The v_P/v_S ratio is constant in each layer, but varies from layer to layer.

Figure 1b presents, as an example, model 2 characteristic for Cheia – Muntele Roşu (MLR) station (45°29.5'N, 25°56.62'E, 1360 m);

3) model 3 is also a site dependent one. It is based on the curves describing the dependence of the P and S wave velocity with depth, in 7 structural units delineated on the Romanian territory (Enescu, 1992; Enescu *et al.*, 1992). In the crust $v(z)$ is described by a second order dependence of depth and in the subcrustal lithosphere by a first order dependence of depth. To each station, the velocity model characteristic for the structural unit the site is located in, is attributed. This velocity structure is completed, for each site, with the corresponding sedimentary layers used in model 2.

Figure 1c presents the model 3 for MLR station, located in the structural compartment including the Southern and Eastern Carpathians and Subcarpathians.

Figure 2 presents the local travel-time curves obtained for station MLR, using model 2. They are appropriate for near events (MLR is located in the neighbourhood of the Vrancea seismic region).

3. Observational data and their analysis

The location program using the three velocity models is run on the following seismic sequences which occurred in different zones, on the Romanian territory:

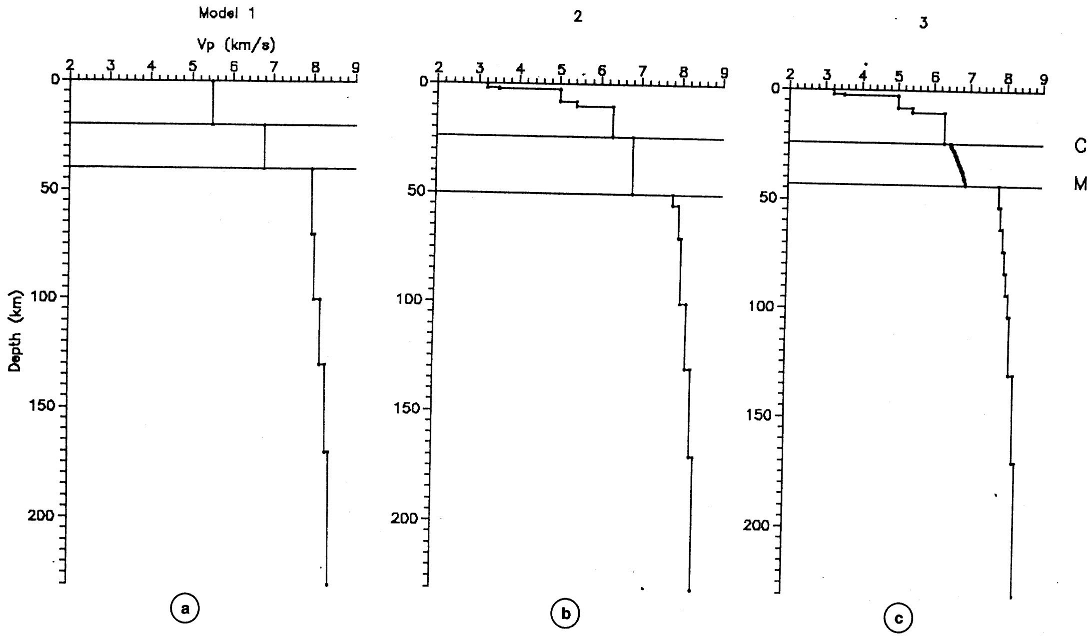

Fig. 1a-c. a) Velocity structure for model 1; b) model 2, for station MLR; c) model 3 for station MLR.

a) 151 intermediate depth earthquakes in the Vrancea region, occurred during 1990, May 30 - July 8, in the depth domain 70-90 km, aftershocks of the May 30 and 31 large events (M_W = 6.9 and M_W = 6.3); the local magnitude ranges between 2.0 and 4.6 (Trifu and Radulian, 1991);

b) 29 crustal earthquakes in the Râmnicu Sărat area belonging to a seismic sequence which occurred during 1991, August 31-September 2, in the depth domain 25-35 km, with local magnitude 2.0-4.8 (Popescu *et al.*, 1993);

c) 55 crustal earthquakes in the Sinaia area, belonging to a seismic sequence which occurred during 1993, May 4-June 10, with depth around 5 km and local magnitude ranging between 2.0 and 5.0 (Enescu *et al.*, 1993). Fixed depth (5 km) is used in locating these events.

Figure 3 presents a map with the seismic sequences mentioned above and the stations used for determining the locations.

For each seismic sequence, three sets of locations are determined, using the different velocity models. On each set of locations, a statistical analysis is performed on the values obtained for the standard deviation of the location estimation – SD, and for the errors in latitude, longitude, depth and origin time. The statistical parameters characterizing the normal distribution of the different sets of error estimators are computed: the average, the parameters characterizing the scattering of the values (variance, standard deviation, average deviation), the symmetry of the distribution (skewness) and its shape (kurtosis).

The three distributions of error estimators are compared, for each seismic sequence which was located with the different velocity models.

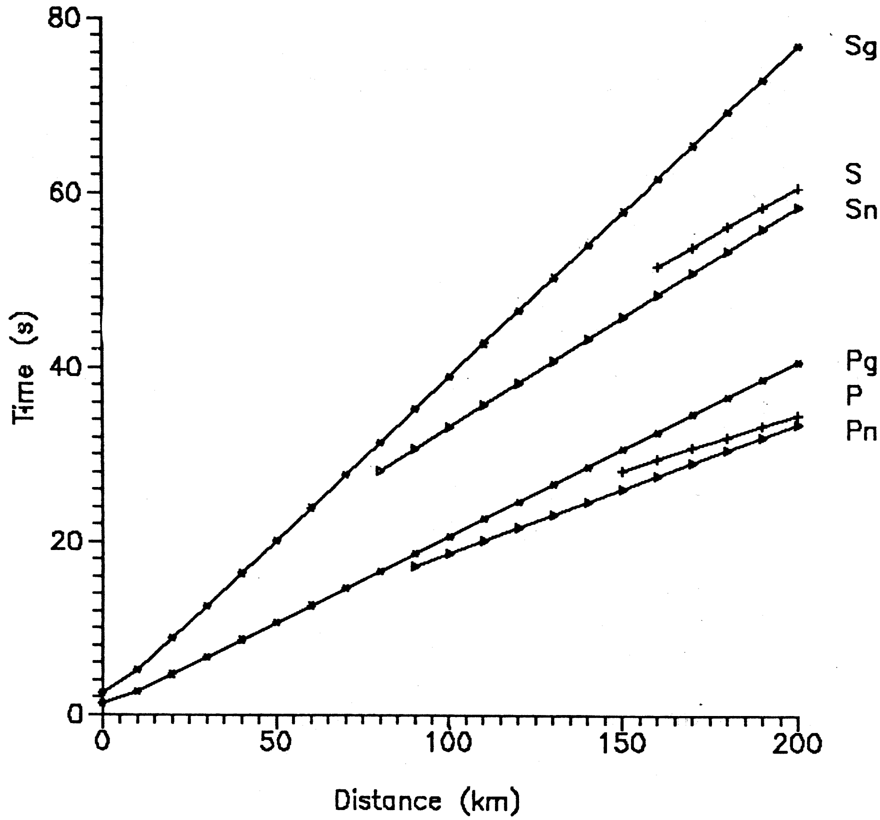

Fig. 2. Travel time curves for station MLR, based on model 2.

4. Results

The comparison of the SD distributions is presented, considering that this parameter offers the most complete information on the location error related with the used velocity structure. Some of the statistical parameters (minimum and maximum value, average, variance) characterizing the distribution of SD values, and of the errors in estimating latitude, longitude, depth and origin time are presented in table I.

a) The best statistics belongs to the sequence of intermediate depth earthquakes in the Vrancea region, due to the largest number of events.

Figure 4 presents the distribution of the SD values determined for this sequence, for the three velocity models. Most of the SD values are concentrated in «the normal distribution» (values up to 0.5), but the «tail of distribution» continues to 1.3. The mean values of SD listed in table I suggest that the best (most accurate) locations are obtained using model 3 and the worst using model 1. Similar results are obtained for latitude and longitude errors (table I).

All these results lead to the conclusion that model 3 gives the least errors in the determination of the Vrancea intermediate depth event locations.

Discussing the SD distributions, all the parameters describing the scattering have

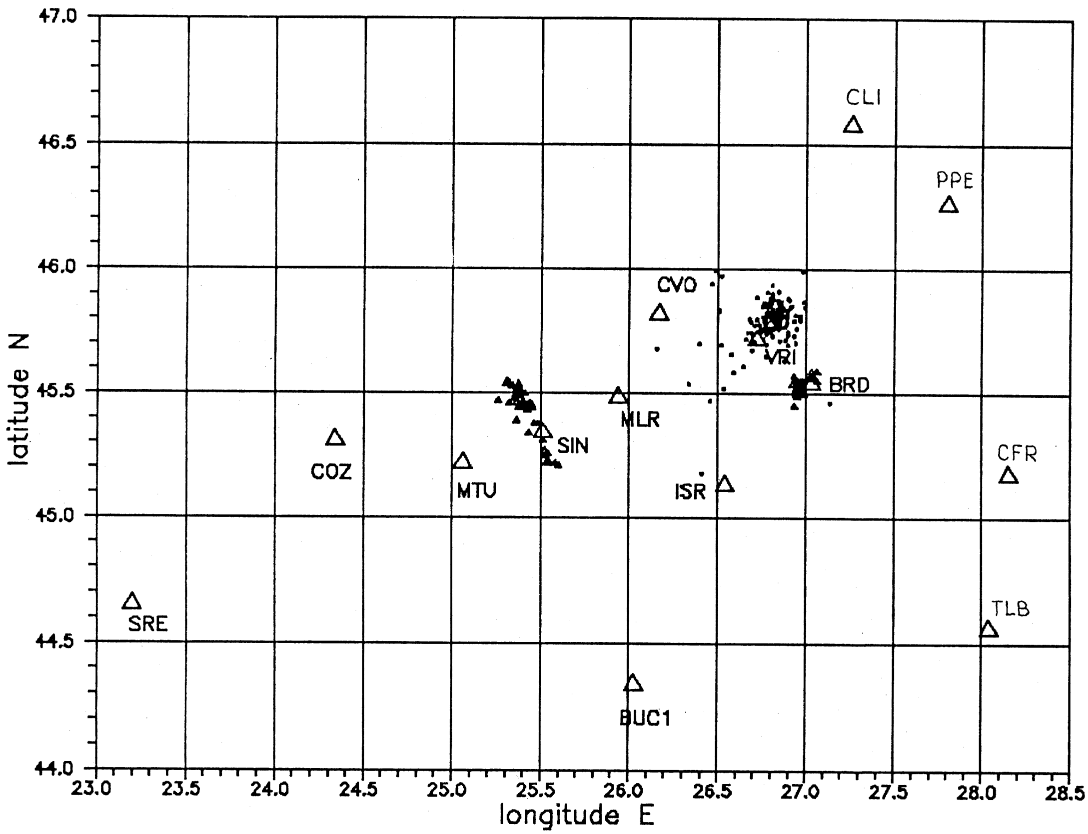

Fig. 3. Analysed seismic sequences (intermediate depth earthquakes are plotted with dots and the crustal ones with triangles).

similar values for the three models (see variance values in table I), proving that the analysed sets of errors in location have the same concentration of values. The positive skewness values prove the rather large degree of asymmetry of the distribution towards the large SD values. The positive kurtosis values show that the curve is more peaked than the normal one (leptokurtic curve).

The Fisher test is applied for pairs of SD distributions and proves the hypothesis that the variance does not differ significantly for the three sets.

In this hypothesis, Student's t test is applied to find the significance degree of the difference between pairs of data sets. The conclusions are: the mean SD values obtained with one of the models 3 and 2 (site dependent ones) differ significantly from the one obtained using model 1 (average structure) at confidence levels of 99% and 95%, respectively; the mean SD values obtained with models 2 and 3 do not differ significantly.

The conclusion of this analysis is that for intermediate depth earthquakes, the use of site dependent velocity models leads to an improvement in the location estimation, compared with the average model.

b) For the 1991 Râmnicu Sărat and 1993

Table I. Statistical parameters characterizing the distributions of SD values and of errors in latitude, longitude, depth and origin time estimations.

Seismic sequence		1990			1991			1993		
Velocity model		1	2	3	1	2	3	1	2	3
SD	MIN	0.07	0.06	0.06	0.15	0.15	0.19	0.04	0.06	0.15
	MAX	1.25	1.31	1.28	0.62	0.62	1.02	0.69	1.16	0.89
	AVE	0.35	0.30	0.27	0.34	0.38	0.54	0.21	0.29	0.37
	VAR	0.024	0.031	0.029	0.016	0.017	0.057	0.018	0.031	0.025
Latitude error (km)	MIN	0.8	1.0	0.7	1.1	1.0	1.2	0.5	1.1	1.5
	MAX	19.9	15.0	23.2	5.4	5.0	7.8	8.8	13.6	49.0
	AVE	3.2	2.8	2.6	2.4	2.3	3.3	3.6	3.2	5.0
	VAR	3.99	3.74	5.13	0.93	0.94	2.94	3.26	3.66	42.6
Longitude error (km)	MIN	0.9	0.9	0.8	1.0	0.8	1.2	0.3	0.4	0.7
	MAX	8.6	10.0	10.4	4.6	3.8	7.0	5.4	10.5	21.1
	AVE	3.3	2.7	2.6	2.0	2.1	3.0	2.3	1.6	2.5
	VAR	1.99	2.20	2.40	0.76	0.62	2.36	1.50	2.16	12.9
Depth error (km)	MIN	0.	0.	0.	0.	0.	0.	–	–	–
	MAX	16.7	19.3	25.1	8.1	10.1	8.8	–	–	–
	AVE	5.3	4.7	4.1	3.1	3.1	4.0	–	–	–
	VAR	8.32	10.9	12.5	3.71	5.54	9.19	–	–	–
Origin time error (s)	MIN	0.15	0.10	0.06	0.13	0.09	0.12	0.06	0.05	0.16
	MAX	2.01	1.88	1.72	0.58	0.68	0.75	0.98	2.63	3.48
	AVE	0.57	0.47	0.42	0.31	0.30	0.38	0.33	0.27	0.38
	VAR	0.068	0.089	0.070	0.013	0.022	0.040	0.034	0.114	0.222

MIN: minimum value; MAX: maximum value; AVE: average value; VAR: variance.

Sinaia crustal seismic sequences, the statistics is not so good, because of the smaller number of studied events. The same analysis is performed, as in the case of the Vrancea intermediate depth events, presented above.

The distributions of SD values obtained with the three different velocity models are presented in fig. 5 for the 1991 sequence. The analysis proves that the best locations are obtained using model 1 (the average one), not the site dependent ones.

For the 1991 Râmnicu Sărat seismic sequence, the mean SD and also the dispersion of the SD values are lower for models 1 and 2 than for model 3 (table I). The low

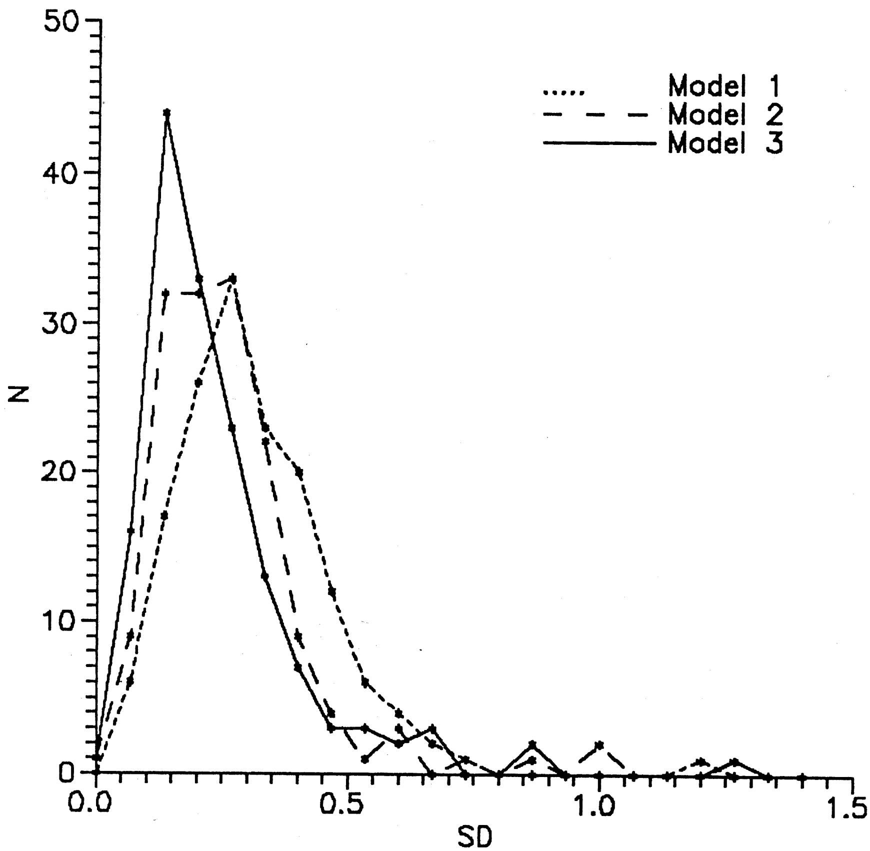

Fig. 4. Distribution of the location estimation of SD values for the 1990 Vrancea intermediate depth seismic sequence.

skewness value indicates an almost symmetrical distribution.

The Fisher test proves that the variances of the SD distributions obtained with model 1 and 2 do not differ significantly, but they are significantly different from the one characterizing model 3.

Starting from these hypotheses, Student's t test is applied and it proves that also the mean SD values do not differ significantly for models 1 and 2; the mean SD values differ significantly for model 3 and both models 1 and 2, at a confidence level of 99%.

c) The statistical analysis performed for the 1993 crustal seismic sequence leads to similar conclusions as presented above, for the 1991 sequence.

Figure 6 presents the SD value distributions for the locations determined using the three velocity models. The lowest mean SD value corresponds to model 1 and the highest to model 3 (table I). The scattering of values is low; the «tail of distribution» is continuing up to SD = 1.2.

Fisher test proves the hypothesis that the variances of the three SD distributions do not differ significantly.

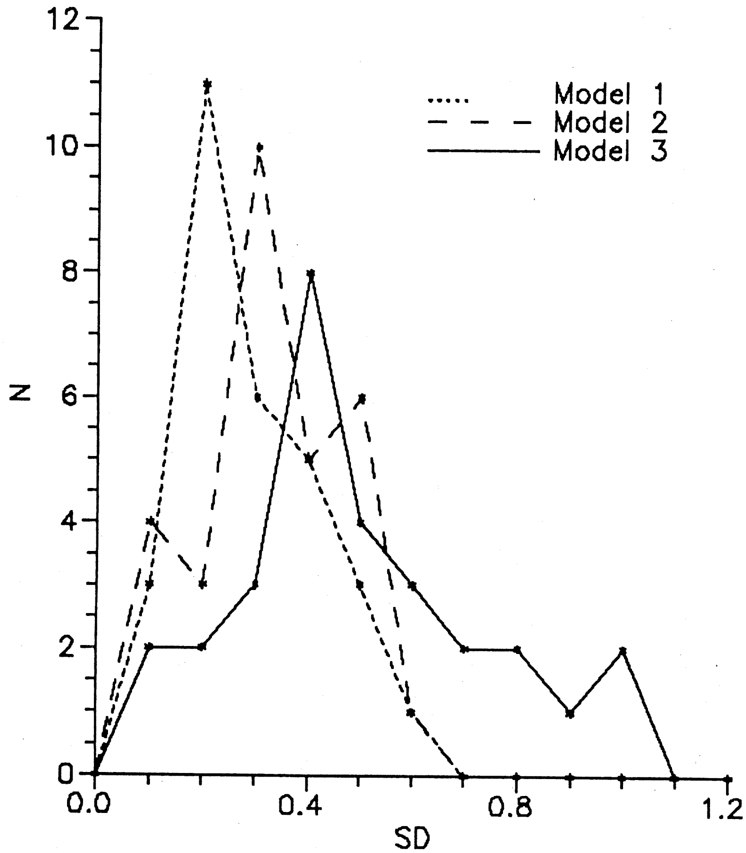

Fig. 5. Distribution of SD values for the 1991 Râmnicu Sărat crustal seismic sequence.

In this hypothesis, using Student's t test to compare the mean SD values of the distributions, significant differences are found between models 1-3, and 2-3, at a confidence level of 99%. Models 1 and 2 do not differ significantly, from this point of view.

The results obtained for the two analysed crustal seismic sequences show that better locations were obtained using model 1, the average one for the whole territory.

Station corrections for each seismic sequence and locations for some quarry blasts are determined in order to check the results presented above.

For each sequence, the station corrections for *P* and *S* waves are computed using all the velocity models. For the Vrancea sequence, containing the largest number of observations, the comparison among the sets of station corrections generally shows agreement with the results of the statistical analysis of the SD values: lower *P* and *S* delays for model 3.

The use of the three velocity models in the location program is tested by comparing the hypocentral parameters obtained for some quarry blasts with the exact ones. The blasts were detonated in two sites located in the south-eastern part of the country. The sites are outside of the telemetered

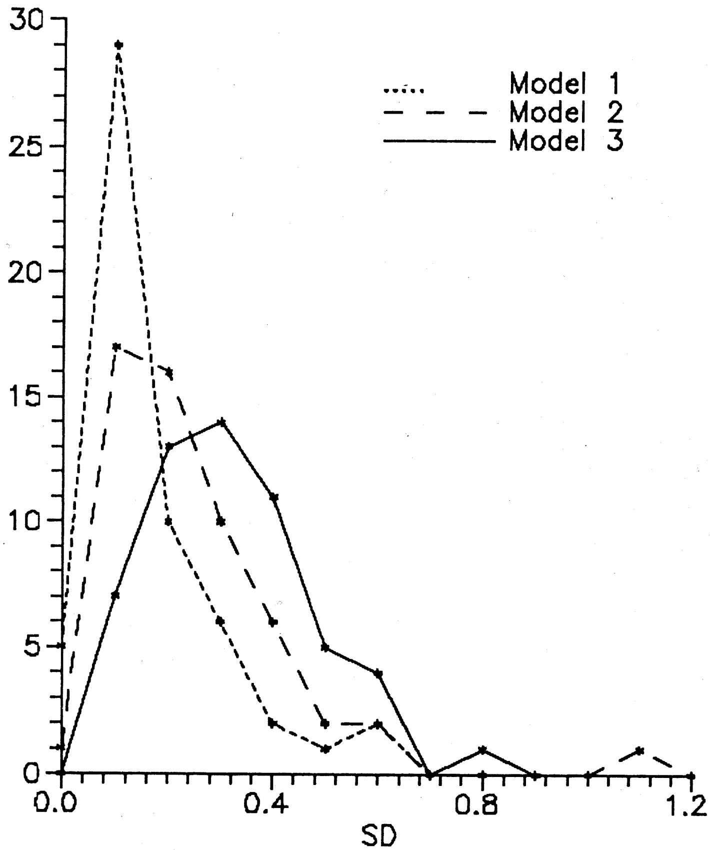

Fig. 6. Distribution of SD values for the 1993 Sinaia crustal seismic sequence.

network; consequently the locations are not very well constrained by the observations (azimuthal gap > 265°) and the errors in the hypocentral parameters are higher than for the seismic sequences presented above. The errors in latitude and longitude range between 4 and 14 km, in origin time between 0.8 and 1.9 s and SD values between 0.4 and 0.9. The locations are performed with fixed depth, using automatic phase identification; 7-11 crustal phases are used.

These results generally agree with the above conclusions on the crustal seismic sequences: the most precise locations are obtained using model 2 (as regards the SD and location parameter errors and also the closeness from the site); model 1 provides slightly larger errors; the errors are larger for model 3.

5. Conclusions

The statistical analysis of the location errors for the studied seismic sequences leads to two apparently different conclusions:

– for the intermediate depth earthquakes in the Vrancea region, the use of site dependent velocity models improves the location estimation, compared with the average model;

– for the studied crustal seismic sequences, better locations are obtained using the average model than the site dependent ones.

These results can be explained by the way the program considers the structural models.

The epicentral area of the intermediate depth events has a good azimuthal coverage of stations, so that the wave path in the crust (where the models differ significantly from station to station) can be characterized by the velocity model below the station and the influence of the local conditions is correctly introduced by models 3 and 2.

For the two crustal seismic sequences, by introducing more refined models (site dependent, many layers) and by considering the model below the station for the whole wave path (as assumed by our program), the errors in location increase. They are correlated with an unreal image of the velocity structure along a larger wave path in a crust with different characteristics than those considered in the computation.

REFERENCES

ENESCU, D. (1992): Lithosphere structure in Romania. I. Lithosphere thickness and average velocities of seismic waves *P* and *S*. Comparison with other geophysical data, *Rev. Roum. Phys.*, **37** (6), 623-639.

ENESCU, D., D. DANCHIV and A. BALA (1992): Lithosphere structure in Romania. II. Thickness of Earth's crust. Depth-dependent propagation velocity curves for *P* and *S* waves, *Stud. Cercet. Geofizică*, **30**, 3-19.

ENESCU, D., E. POPESCU and M. RADULIAN (1993): The preliminary study of the earthquake sequence occurred in the Sinaia zone during May-June 1993, *Internal Report 30.92.1.*

GEIGER, L. (1910): Hedbestimmung bie erdbeben aus den ankunftzeiten, *K. Gessel. Wiss. Goett.*, **4**, 331-349.

ONCESCU, M.C. (1983): HYPO – program for locating local and regional seismic events, *Internal Report 30.81.8.*

ONCESCU, M.C. (1984): Deep structure of Vrancea region, Romania, inferred from simultaneous inversion for hypocenters and 3-D velocity structure, *Ann. Geophysicae*, **2**, 23-28.

ONCESCU, M.C., V., BURLACU, M. ANGHEL and V. SMALBERGHER (1984): Three dimensional *P*-wave velocity image under the Carpathian Arc, *Tectonophysics*, **106**, 305-319.

POPESCU, E., O. BAZACLIU and M. RADULIAN (1993): The earthquake sequence of Râmnicu Sărat (Romania) 31 August-1 September 1991, in *Proceedings of the XXIII General Assembly of ESC, Prague, Czechoslovakia, 7-12 September 1992*, 86-89.

RĂILEANU, V., C., DIACONESCU, D. MATECIUC and M. DIACONESCU (1993): Velocity crustal models under the Romanian telemetered seismological network, in *Proceedings of the «National Conference in Physics», 13-15 October 1993, Constanta.*

TOTTINGHAM, D.M., W.H.K. LEE and J.A. ROGERS (1989): User Manual for MDETECT, in *Toolbox for Seismic Data Acquisition, Processing and Analysis* edited by W.H.K. LEE, IASPEI Software Library (IASPEI and SSA), vol. 1, 49-88.

TRIFU, C. I., M. RADULIAN (1991): A depth-magnitude catalogue of Vrancea intermediate depth microearthquakes, *Rev. Roum. Geol. Geophys. Geogr. Geophys.*, **35**, 31-45.