INPUT PARAMETERS FOR THE PROBABILISTIC SEISMIC HAZARD ASSESSMENT IN THE EASTERN PART OF ROMANIA AND BLACK SEA AREA

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Common borders. Common solutions.

CROSS BORDER COOPERATION

Study content

In this study we have used the most reliable and homogeneous seismic datasets at the European scale, covering historical and modern instrumental seismicity until present days for the Eastern part of Romania and the Black Sea Area. The catalogue was obtained as a compilation of 4 existing catalogues: ANSS-Advanced National Seismic System-USA, NEIC - National Earthquake Information Centre, World Data for Seismology Denver-USA, ISC-International Seismological Centre-UK and INCDFP – Romplus, Romania.

The *seismic zonation* of the Eastern part of Romania and the Black Sea Area was obtained using the *distribution map of earthquakes* and the map of the zones with *active tectonics*. There were established in this way fifteen crustal and one intermediate seismic sources:

Vrancea intermediate (VRI), Vrancea normal (VN),
Barlad Depression (BD),
Predobrogean Depression (PD),
Intramoesian Fault (IMF),
North Dobrogea (BS1),
Central Dobrogea (BS2)
Shabla (BS3),
Istanbul (BS4),
North Anatolian Fault (BS5),
Georgia (BS6),
Novorossjsk (BS7),
Crimeea (BS8),
West Black Sea (BS9)
Black Sea (BS10)

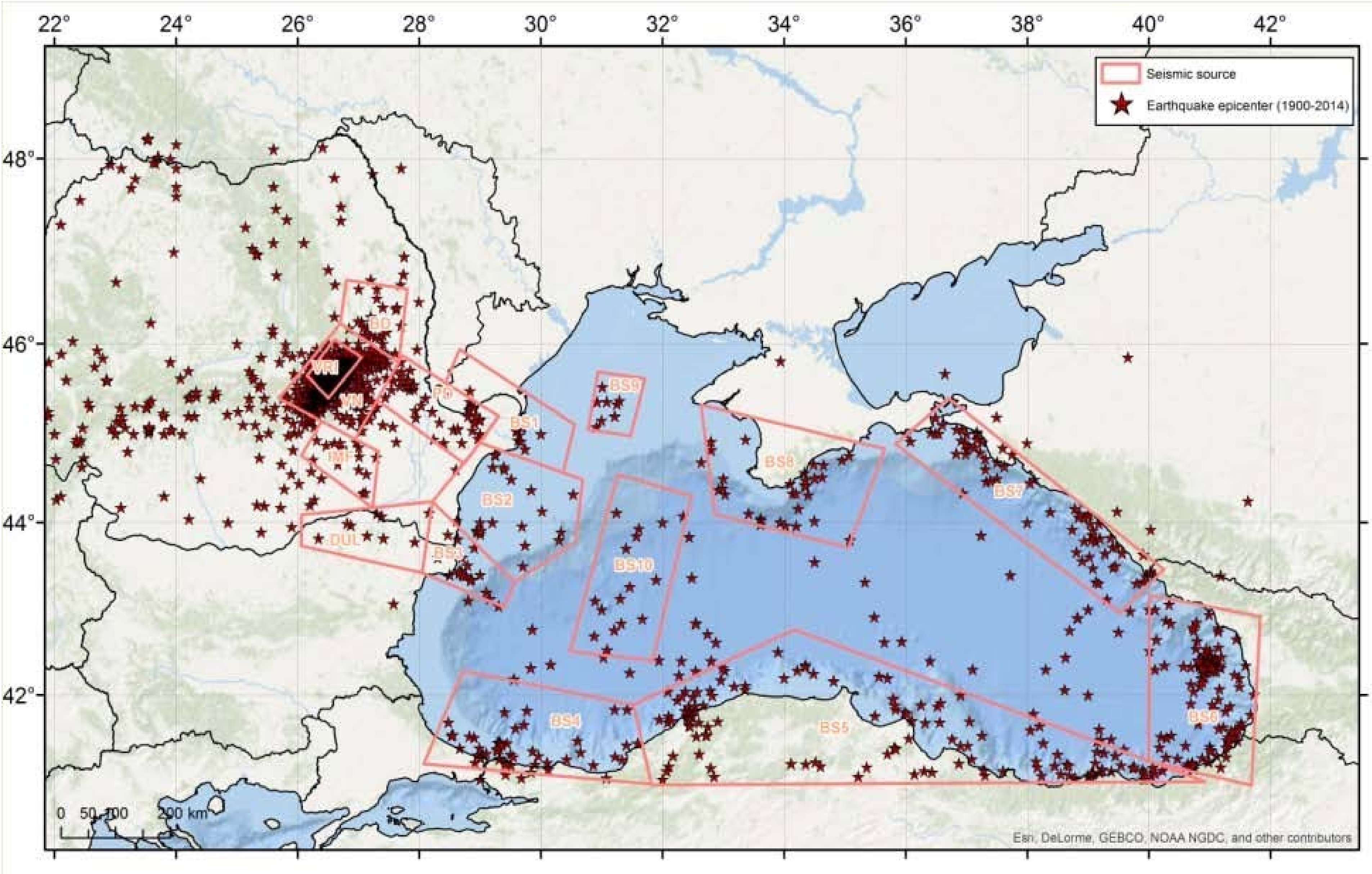


Figure 1. The seismic zonation of the Eastern part of Romania and the Black Sea Area

For each source we have compiled all the requested parameters for **a probabilistic hazard assessment** (Table 1): geographical distribution, average depth, activity rate

and

Gutenberg Richter parameters (Figures 2-17): a, b, maximum possible and most probable magnitudes and intensities and their return periods.

The b values for the sources from Black Sea have been mapped to emphasize the zones with low and high stress, for different periods of time.

Seismic Sources	Average depth (km)	M min (Mw)	M max (Mw)	b	I min	I max	bi	i= =bln10	Seismic activity rate
VRI	**130**	**5.0**	**7.9** **7.7**	**10**	**4.0**	**10**	**0.48**	**1.10524**	**1.762380**
VN	30	3.0	5.9 **5.7**	0.91	2.5	7.0 **6.0**	0.6	1.38155	0.514526
BD	10	3.0	5.5	0.75	2.0	6.5	0.49	1.12826	1.534712
PD	10	3.0	5.5	0.81	3.0	6.5	0.53	1.22037	0.360254
IMF	15	3.0	5.4	0.39	3.0	6.5	0.32	0.25740	0.034600
DUL	15	3.0	7.2	0.39	3.0	9.0	0.32	0.25740	0.028000
BS1	33	3.0	3.5 Mb=4.7	0.65	2.5	3.5	0.43	0.99011	0.386363
BS2	11	3.0	5.0	0.65	2.5	5.5	0.43	0.99011	0.118644
BS3	16.4	3.0	7.2	0.32	2.5	9.0	0.21	0.48354	0.165137
BS4	22.1	3.0	6.7	0.53	2.5	8.0	0.35	0.8059	0.47761
BS5	14.8	3.0	6.1	0.61	2.5	7.5	0.40	0.92103	0.740741
BS6	13.5	3.0	5.5	0.59	2.5	6.5	0.39	0.89800	1.039215
BS7	20.8	3.0	5.2	0.75	2.5	6.0	0.50	1.15129	0.59091
BS8	22.8	3.0	6.5	0.38	2.5	8.0	0.25	0.57564	0.25301
BS9	14.8	3.0	4.9	0.61	2.5	5.5	0.40	0.9163	0.19512
BS10	26.9	3.0	3.9	0.72	2.5	4.0	0.48	1.10524	0.25581

Table 1. Input parameters for probabilistic hazard assessment using intermediate and crustal sources

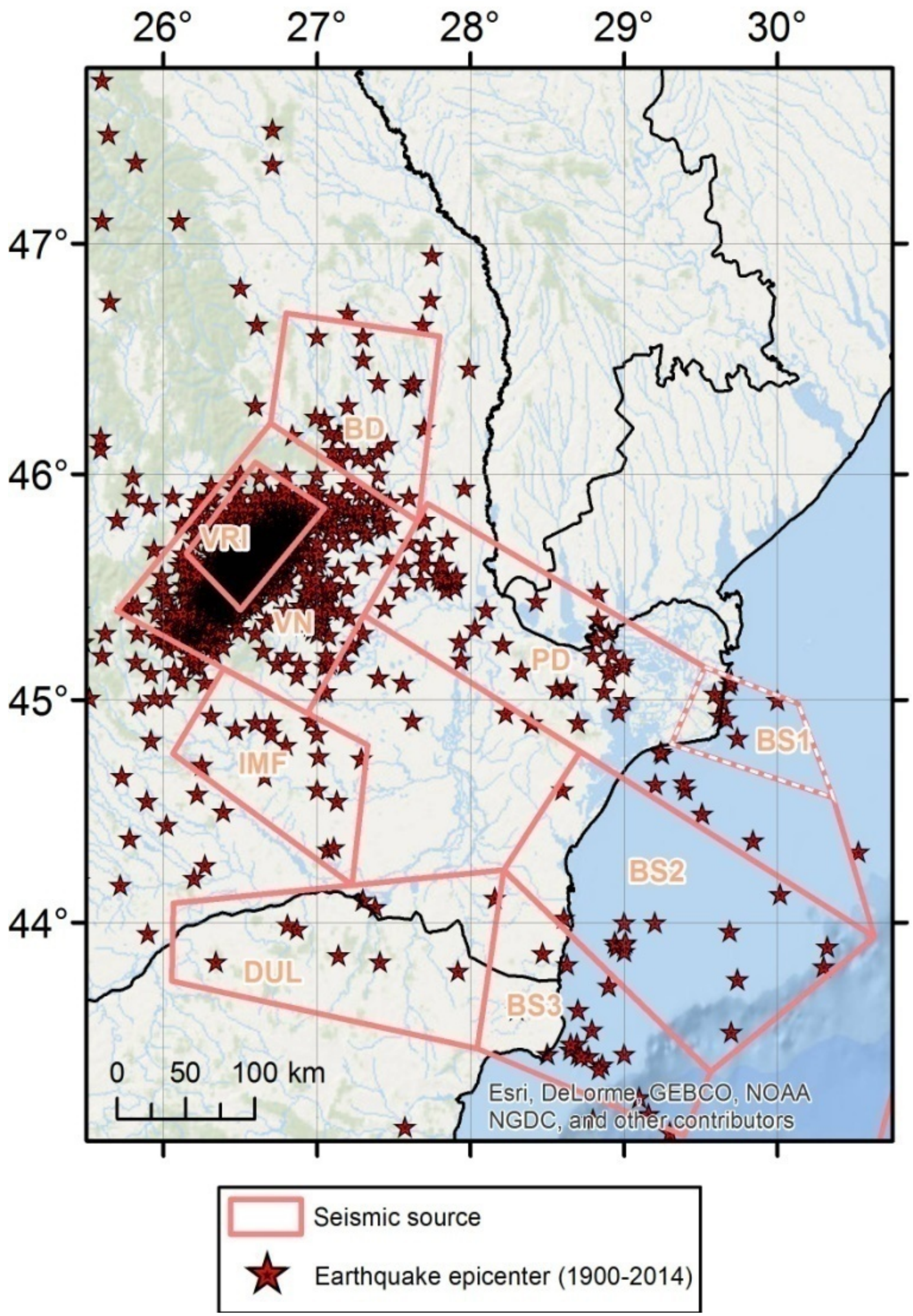


Figure 2. Seismic sources selected for this study together with the associated seismicity. We plotted epicenters for Mw>3.5 for the inland sources and

Mw>3.0 for the marine sources.

VRANCEA INTERMEDIATE SOURCE - VI

The seismic activity rate for earthquakes with 5.0<Mw<7.7 is ν0 = 1.762380 events/year. The frequency-magnitude distribution for VI, determined from the 1900-2014 earthquake catalogue, for different magnitude intervals, is plotted in the Figure 4.

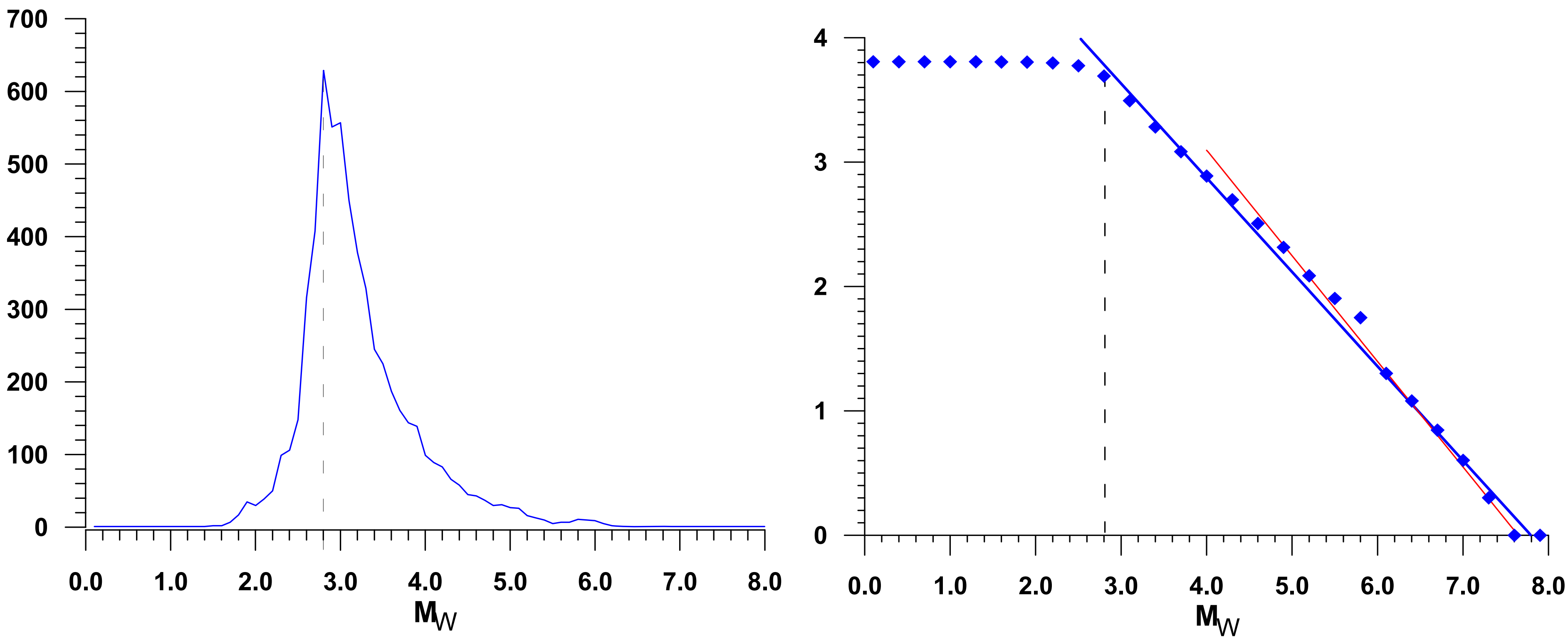


Figure 4. The frequency-magnitude distribution for **VI** zone: a) non-cumulative; b) cumulative; MW≥2.8- blue line, MW≥5.0-red line

VRANCEA CRUSTAL EARTHQUAKES (VN)

The seismic activity in the Vrancea in the crustal domain (VN) is located in front of the South-Eastern Carpathians arc, spread over a stripe area

delimited to the north by the Peceneaga-Camena fault and to the south by the Intramoesian fault. The seismicity is more diffuse than for the subcrustal source and consists only of moderate-magnitude earthquakes (Mw < 6.0) generated frequently in clusters, localized in the eastern part (seismic sequences of **Râmnicu Sarat** area) and in the northern part (seismic swarms in the **Vrincioaia** area and seismic sequences north of **Focşani**). The catalogue contains only two earthquakes with magnitude above 5.0: one occurred on **March 1, 1894** of Mw = 5.9, with magnitude estimated from historical information (possibly overestimated), and the

most recent one, of **November 22, 2014**, with Mw = 5.7.

The rate of the seismic moment release, Mo = 5.3 x 1015 Nm/year, is four orders of magnitude less than the moment rate characteristic for the Vrancea intermediate-depth domain.

The analysis of the fault plane solutions shows a complex stress field in the Vrancea crust, like a transition zone from the compressional regime at subcrustal depths to extensional regime characteristic for the entire Moesian platform. The largest earthquakes, for which the fault plane solutions could be relatively well constrained, are the main shocks of the sequences occurred between 1983 and 2014.
The frequency-magnitude distribution for **VN**, determined from the 1900-2014 earthquake catalogue, for different magnitude intervals, is plotted in the Figure 5 and the equations for the regression lines are given below (equations 5 and 6).

EV- 1900, Mc=2.2-5.5,   log Nc=-(1.02 ±0.04)MW + (5.45 ±0.23),   green line   (5)
R=0.99, σ=0.16

EV- 1900, Mc=3.0-5.5,   log Nc=-(0.95 ±0.05)MW + (5.10 ±0.21),   blue line   **(6)**
R=0.98, σ=0.14

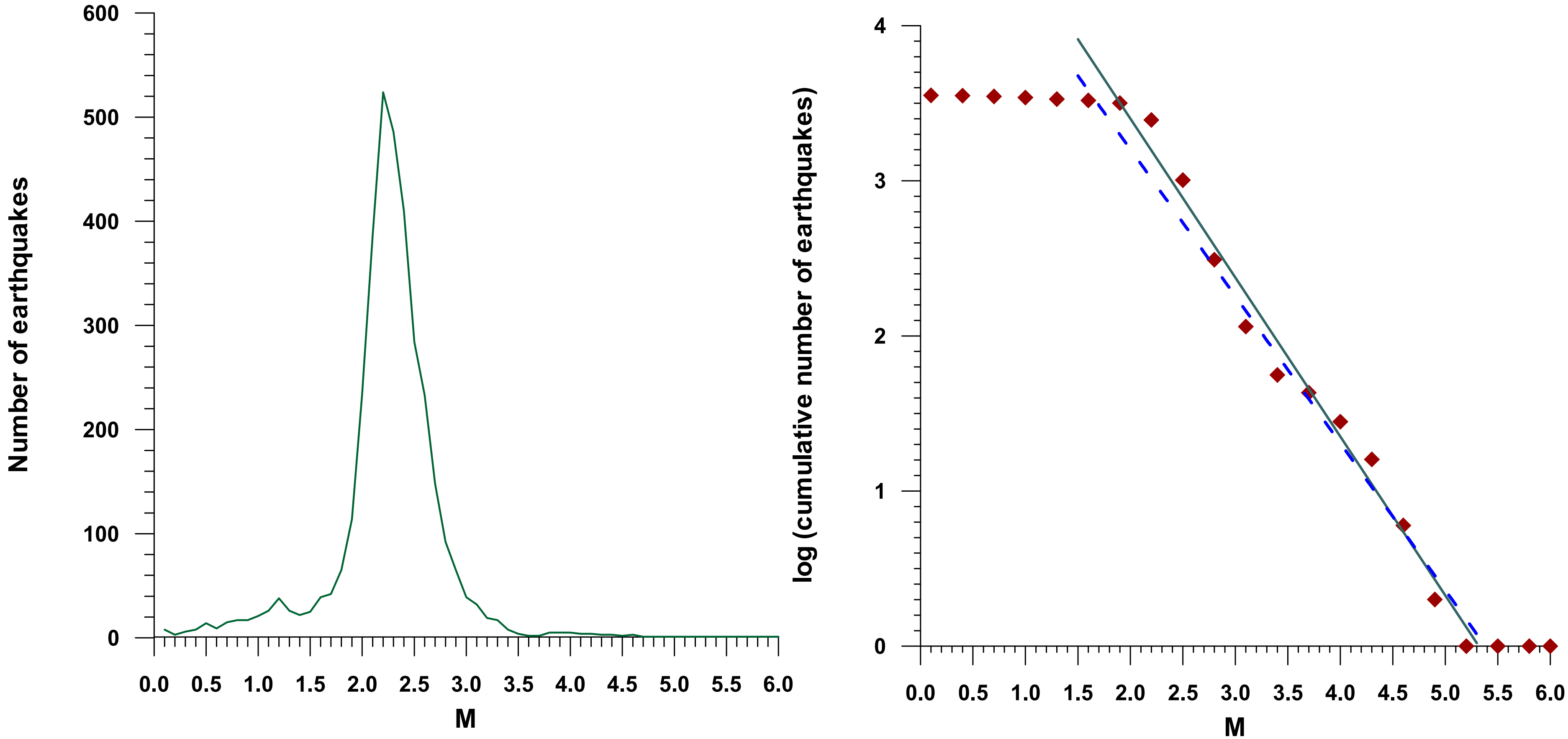


Figure 5. The frequency-magnitude distribution for **VN** zone: a) non-cumulative; b) cumulative

The frequency-epicentral intensity distribution obtained from Eq. 6 and *Mw=0.66 Io+1.23 (Radu, 1979)* is: *lg Ncum = -0.6*Io+3.98.* From the above equations we obtain: ai =3.98 and bi=0.6 and β=1.38155.

BARLAD DEPPRESSION (BD)

Barlad Deppression (BD), situated NE of the Vrancea zone, is characterized only by **moderate size events** (only four shocks with Mw>5.0, but not exceeding Mw=5.6). Having in mind that from seismotectonic point of view the Barlad Depression belongs to the Scythian platform as well as the Predobrogean Depression (Mutihac and Ionesi, 1974), we considered for both zones the same maximum magnitude, respectively the maximum observed one, MW = 5.6.

The frequency-magnitude distribution for **BD**, determined from the 1900-2014 earthquake catalogue, for different magnitude intervals, is plotted in Figure 6, and equations of the

regression lines are given below (relations 7 and 8).

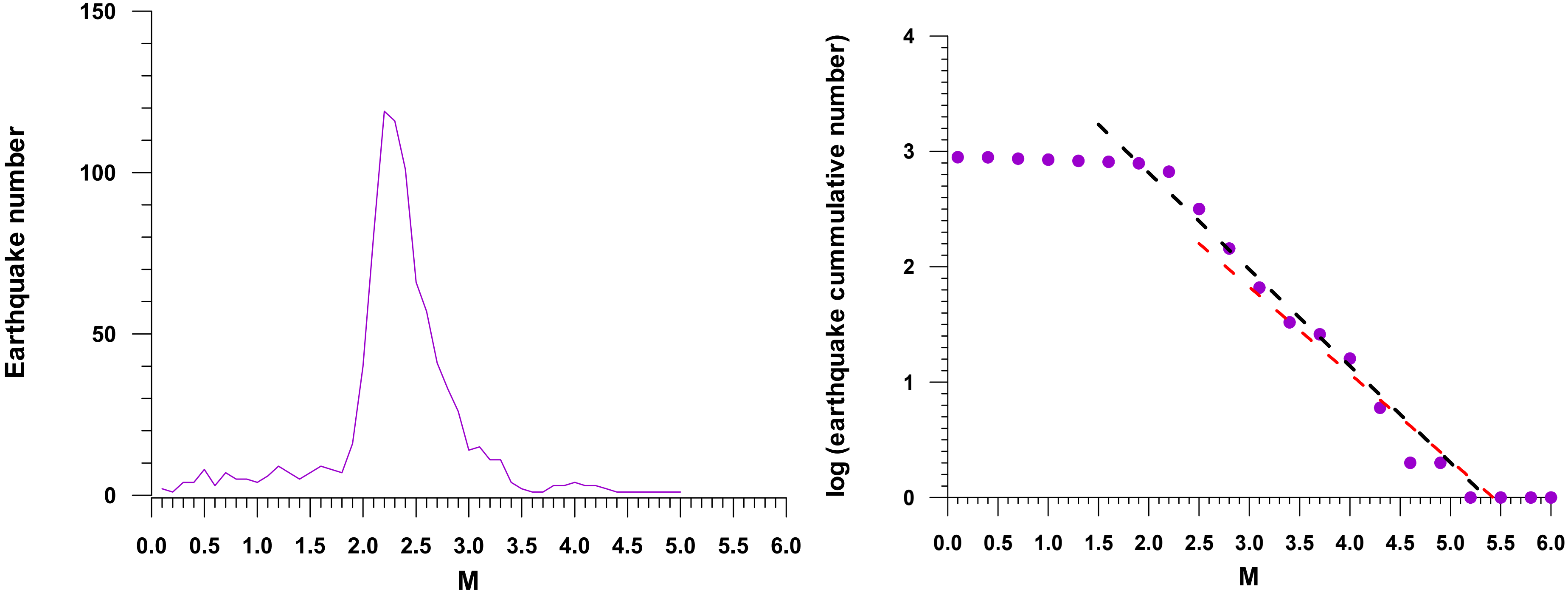


Figure 6. The frequency-magnitude distribution for **BD** zone: (a) non-cumulative; (b) cumulative

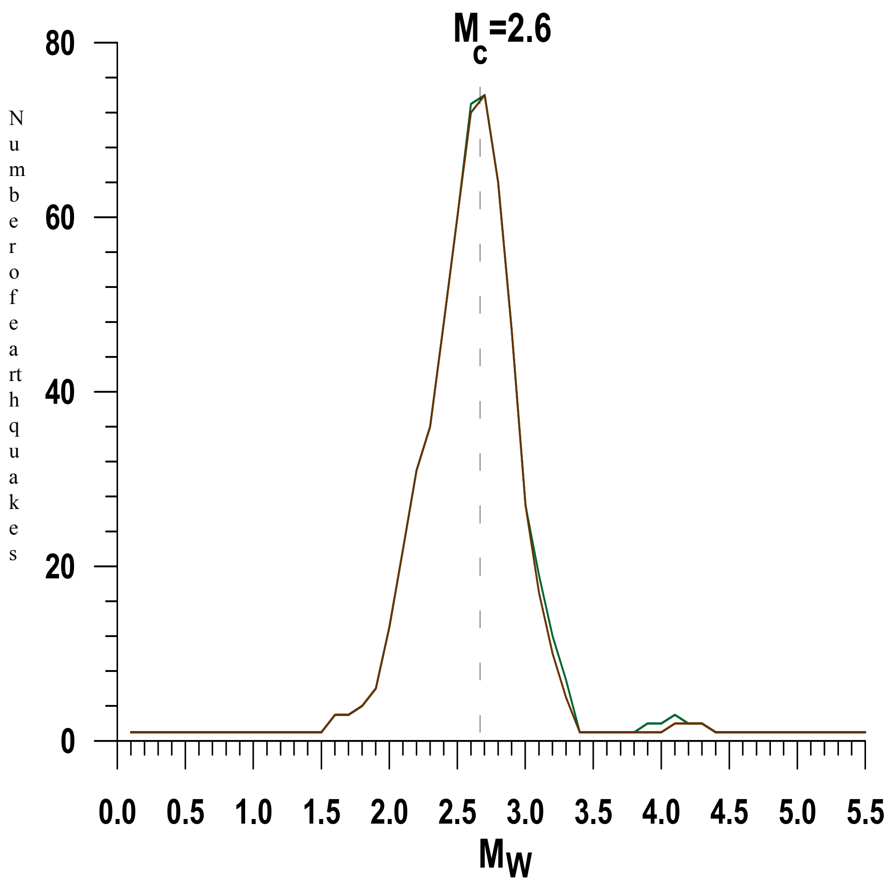
BD-1900 Mc=2.2-5.8, log Nc=-(0.84 ±0.05)MW + (4.49 ±0.19) (black line) (7)
R=0.98, σ=0.18

BD-1900 Mc=3.1-5.8, log Nc=-(0.75 ±0.07)MW + (4.08 ±0.30) (red line) (8)
R=0.97, σ=0.18

The frequency-epicentral intensity distribution obtained from Eq. 8 and *Mw=0.66 Io+1.23 (Radu, 1979)* is: *lg Ncum = -0.495*Io+3.227.* From the above equations we obtain: a =3.227 and b=0.495 and β=1.12826.

PREDOBROGEAN DEPRESSION – PD

Predobrogean Depression (PD) zone belongs to the southern margin of Predobrogean Depression. It follows the alignment of the Sfantul Gheorghe fault. Only moderate-size events are observed (Mw < 5.3) clustered especially along Sfantul Gheorghe fault. The fault plane solutions reflect the existence of the extensional regime of the deformation field. In our opinion this consistently reflects the affiliation of the Predobrogean Depression to the Scythian platform tectonic unit. The rate of the seismic moment release is Mo = 1.8 * 1015 Nm/year. The maximum observed magnitude for the Predobrogean Depression crustal zone is ***Mw = 5.3***, assigned to the event occurred on *February 11, 1871.*
The seismic activity for events with Mw>3.0 is v0 **=** no. of seismic events/T(years) = **0.36** seismic events/year. Considering that from seismotectonic point of view the Predobrogean Depression belongs to the Scythian platform as well as Barlad Depression we considered the **observed maximum magnitude for both zones, Mw= 5.5**



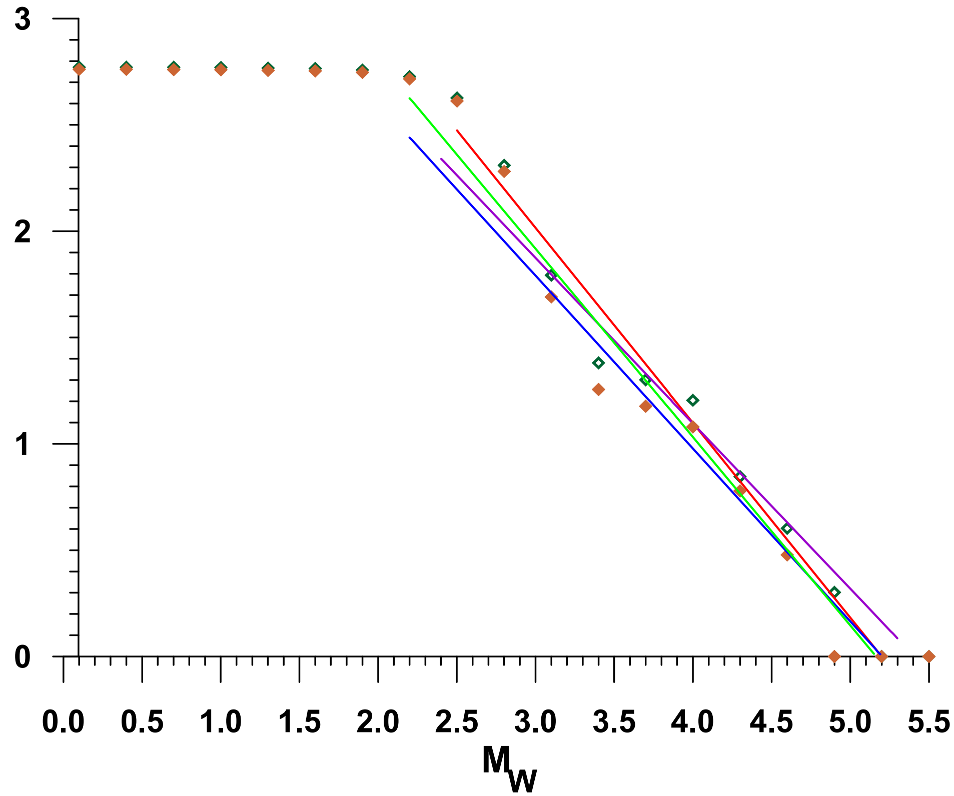


Figure 7. The frequency-magnitude distribution for **PD** zone: (a) non-cumulative; (b) cumulative

***PD**-all catalogue Mc=2.5, log Nc=-(0.92 ±0.05)MW + (4.76 ±0.20) red line* (10)
R=0.98, σ=0.13

***PD**-all catalogue Mc=2.9, log Nc=-(0.78 ±0.05)MW + (4.21 ±0.19) purple line* (11)
R=0.98, σ=0.12

***PD**-1900 Mc=2.5, log Nc=-(0.89 ±0.06)MW + (4.57 ±0.27) green line* (12)
R=0.97, σ=0.2

PD-1900 Mc=2.9, log Nc=-(0.81 ±0.05)MW + (4.23 ±0.25) blue line **(13)**
R=0.97, σ=0.16

The frequency-epicentral intensity distribution obtained from equation (13) and *Mw=0.66 Io+1.23 (Radu, 1979)* is: ***lg Ncum = -0.5346*Io+3.234.*** The resulted Gutenberg-Richter parameters are: a =3.234 and b=0.5346 and β=1.22405 (Table 1).

THE INTRAMOESIAN FAULT and **DULOVO zone- IMF-DUL**

The Intramoesian fault (IMF) crosses the Moesian platform in a SE-NW direction, separating two distinct sectors with different constitution and structure of the basement. Although it is a well-defined deep fault, reaching

the base of the lithosphere (Enescu and Enescu, 1993), and extends southeast to the Anatolian fault region (Sandulescu, 1984), the associated seismic activity is scarce and weak. Geological and geotectonic data indicate only a relatively small active sector in the Romanian Plain, situated to the NE from Bucharest.

The geometry of the Intramoesian fault source and the distribution of the earthquakes with MW $\geq$ 3.0 occurred between 1892 and 2001 (30 events) are presented in Fig. 1.

The magnitude domain of earthquakes is **Mw$\in$[3.0, 5.4].**

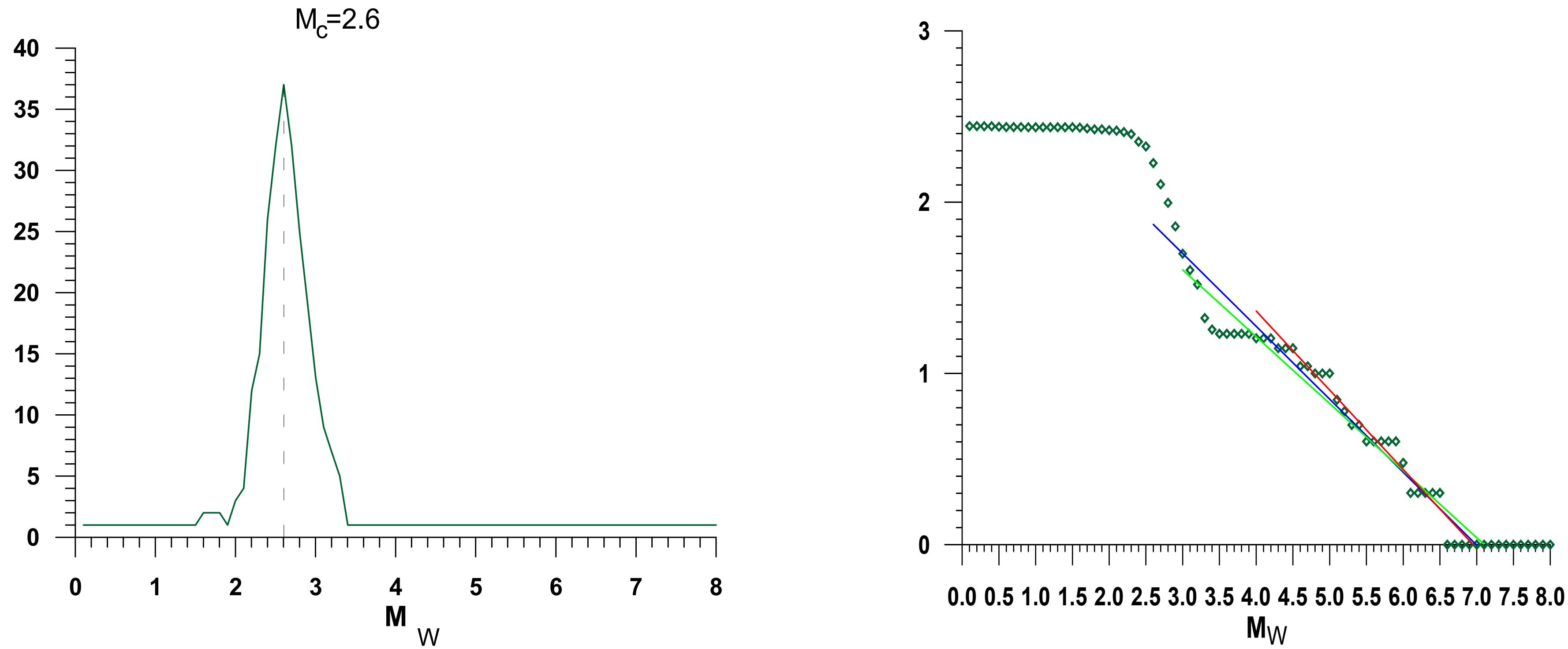
The maximum magnitude was recorded in *January 4, 1960* (***Mw* = *5.4***) in the central part of the Romanian Plain.

The seismic activity for events with Mw>3.0 is v0 **=** no. of seismic events/T(years) **= 0.034600** seismic events/year.

The frequency-magnitude distribution for **Intramoesian fault - Dulovo crustal sources**, determined for the magnitude interval [4.5, 7.2], is presented in relation (14) and plotted in Figures 8, with red line. The green and blue lines are for smaller threshold magnitudes (2.6 and 3.0).

DULIMF-1900 Mc=4.5, log Nc=-(0.46 ±0.02)MW + (3.21 ±0.10) red line (14)
R=0.98, σ=0.07

The frequency-epicentral intensity distribution obtained from Eq. 14 and *Mw=0.66 Io+1.23 (Radu, 1979)* is: ***lg Ncum = -0.3*Io+2.6442.*** From the above equations we obtain: ai =2.6442 and bi=0.3 and β=0.69078 (Table 1).



Figures 8. The frequency-magnitude distribution for **IMF** and **DUL** zone:
(a) non-cumulative; (b) cumulative.

BLACK SEA SEISMIC SOURCE NO.1. NORTH DOBROGEA – BS1

The earthquakes in the North Dobrogea are associated to the prolongation of **Peceneaga-Camena, Sf. Gheorghe and Sulina Faults**. Some of the earthquakes belong to the **Lacu Rosu fault** as well.
The maximum observed magnitude for 1967-2007 period in North Dobrogea was mb=4.7 (7 July 2005).

Applying the practice of increment on the maximum observed magnitude we obtain the expected value of the maximum possible magnitude to be **mb=5.2/Mw=4.0** with an error value of ±0.1.

The average depth is **33 km**.

*For seismic hazard purposes the minimum magnitude was considered **m0= 3.0** (Mw).*

The seismic activity v0 **=** no. of seismic events/T(years) = **0.425** seismic events/year.

The Gutenberg-Richter values are assumed to be the same as the values of **PD** zone, because **BS1** is included in **PD**.

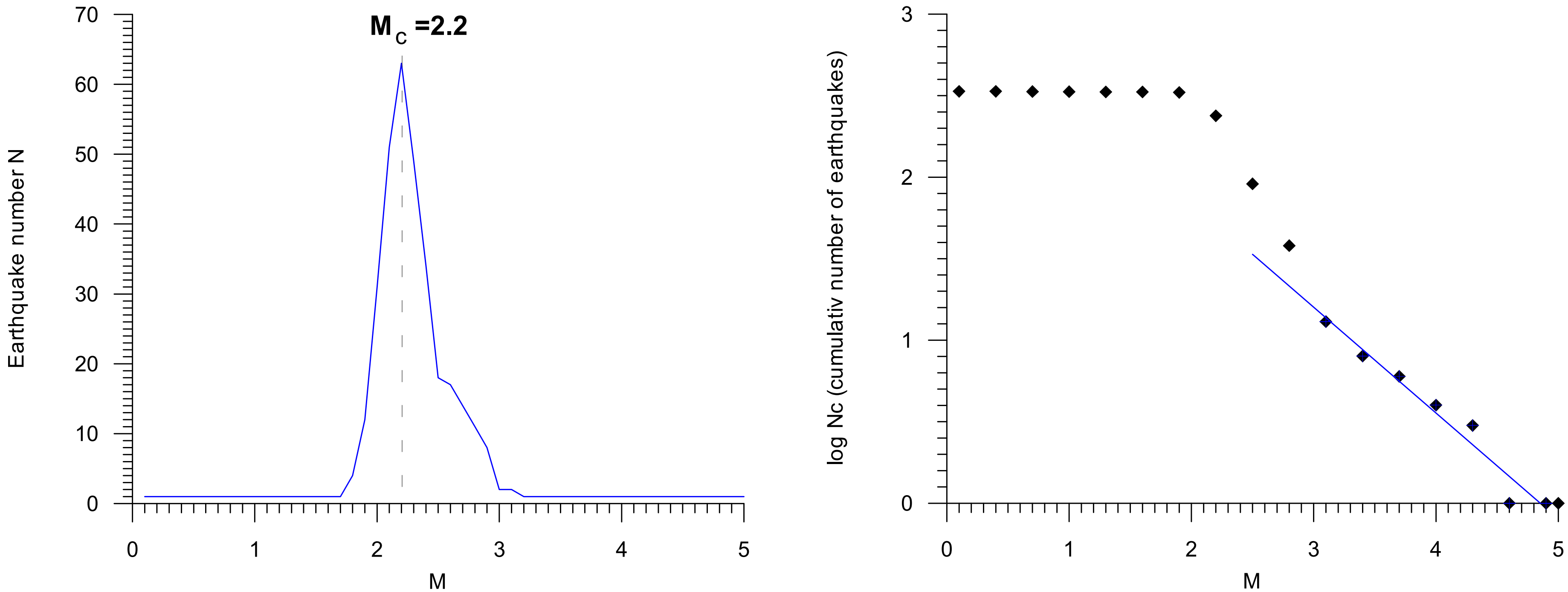
BLACK SEA SEISMIC SOURCE NO. 2. CENTRAL DOBROGEA– BS2

Seismic source cover all the seismic events occurred within 1843-2014 time interval. The earthquakes in this area are associated to the prolongations of ***Capidava – Ovidiu fault and Horia – Pantelimonul de Sus fault in the Black sea shelf***. The 118 years catalogue (1892-2010), contains 336 earthquakes with Mw>0.5, but only 14 events with Mw≥3. In this area there are numerous active quarries which disturb in a way the local seismicity caused by tectonic events in the low magnitude range (Mw be1low 2). ***The maximum observed magnitude in Central Dobrogea was Mw = 5 (12.12.1986).***
Applying the practice of increment on the maximum observed magnitude, ***the expected value of the maximum possible magnitude is considered to be Mw.max= 5.2*** with an error value of ± 0.1. For Central Dobrogea, the minimum magnitude was considered
m0=3.0 (Mw).
The seismic activity v0 **=** no. of seismic events/T(years) = 14 seismic events/118 years= **0.118644** seismic events/year. The average depth is **11km.**

The Gutenberg-Richter frequency-magnitude distribution for **S2**, determined for magnitudes Mw between 3.0 and 5.0 intervals, is presented in relation 15 and plotted in Figures 9.

$$\log Nc = -(\mathbf{0.65} \pm 0.06)M + (3.15 \pm 0.25), \qquad 3.0 < M < 5.0 \qquad (15)$$

$R=0.98$, $\sigma=0.10$



Figures 9. The frequency-magnitude relations for BS2 with MW≥3.0; a) non-cumulative; b) cumulative

The frequency-epicentral intensity distribution obtained from Eq. 2 and *Mw=0.66 Io+1.23 (Radu, 1979)* is: ***lg Ncum = -0.5346*Io+3.234.***

From the above equations we obtain: ai =2.3505 and bi=0.429 and β=0.99011 (Table 1).

BLACK SEA SEISMIC SOURCE NO.3. – SHABLA – BS3

The Shabla seismic area, located in Bulgaria, belongs from tectonic point of view to the south edge of **Moesian Platform**.

The earthquakes recorded in the Shabla – Cap Kaliakra area have the focai located along a NE-SW alignment. This active tectonic area is the north-east border of major crustal foci which is developed collateral by Black Sea, with NE-SW direction and which sinks in Burgas area. The foci of Shabla source have limited development, the active sector having 20-25 km length with 15 earthquakes of Mw≥4. ***The distribution of epicenters marks the coupling between existent structural lines in the Shabla area, where the powerful earthquake of magnitude 7.2 occurred on 31.03.1901.***

For seismic hazard assessment we used from a 113-year catalogue (1901-2014), containing 37 earthquakes with Mw > 1.1, only 19 events with Mw > 3.0 (Table 4).

The average depth is **16.4 km.** The minimum magnitude was considered **m0= 3.0** (Mw). Seismic activity v0 **=** no. of seismic events/T (years) = 0.**165137** seismic events/year.

The Gutenberg-Richter frequency-magnitude distribution for **S3**, determined for magnitudes Mw between 3.0 and 7.2, is presented in relation 16 and plotted in Figures 10.

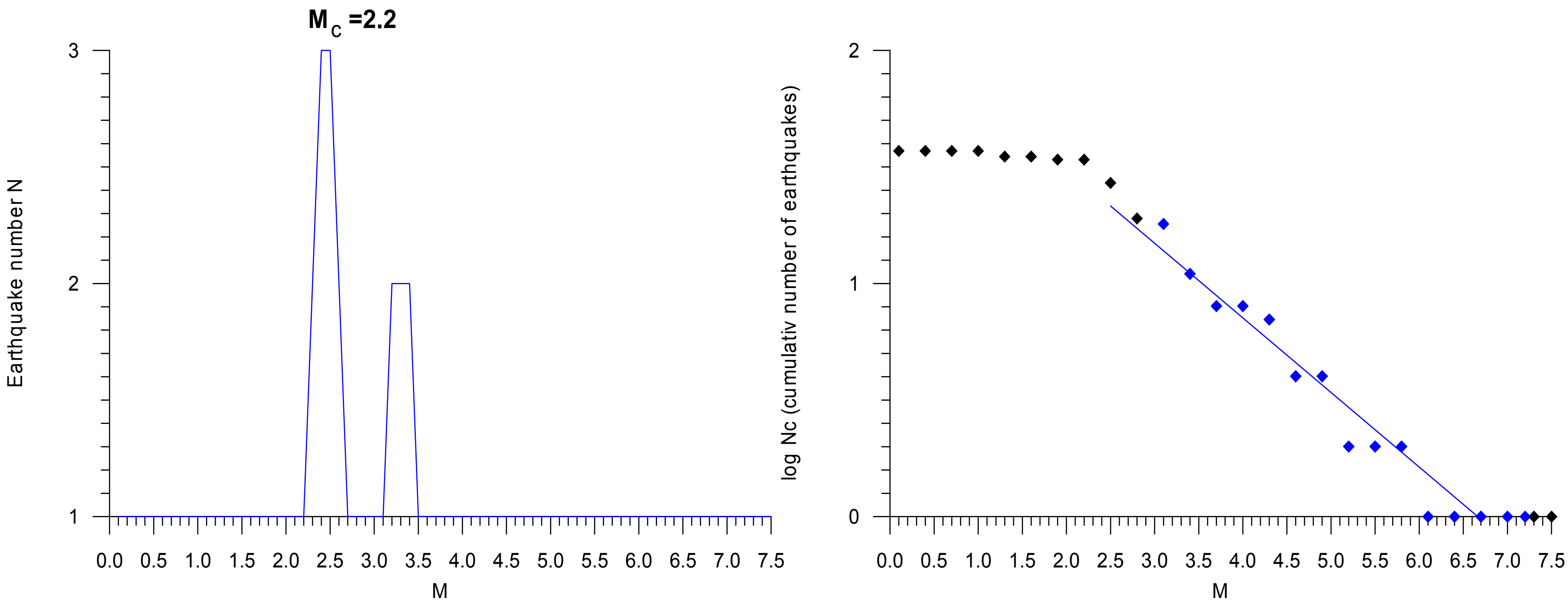


Figure 10. The frequency-magnitude distribution for BS3 zone The frequency-magnitude relations for with MW≥3.0; a) non-cumulative; b) cumulative

$\log Nc=-(\mathbf{0.32}\pm0.02)M + (2.13 \pm 0.11)$, $3.0 < M < 7.2$ (16)

$R=0.97$, $\sigma=0.11$

The frequency-epicentral intensity distribution obtained from Eq. 16 and *Mw=0.66 Io+1.23 (Radu, 1979)* is: ***lg Ncum = -0.2112*Io+1.7364.***

From the above equations we obtain: ai =1.7364 and bi=0.2112 and $\beta=0.48631$ (Table 1).

2. The assessment of seismic hazard using the probabilistic approach

The theoretical fundamentals of the deductive procedure for probabilistic seismic hazard analyses were formulated in the reference paper of Cornell (1968). The paper develops a method which produces **relationships between the parameters describing the ground motion – macroseismic intensity, peak ground acceleration, peak ground velocity – and their average return period for a given site**. The input data needed are the estimates of the average activity levels of the various potential seismic sources. The technique integrates the individual influences of potential earthquake sources, near and far, more active or less, into the probability distribution of maximum annual values of the ground motion parameters (intensity, peak ground acceleration, etc.).

Ground motion probability

The assumption widely used in the probability model for hazard analysis is that earthquakes occur as a **Poisson process** in time. The probabilistic methodology quantifies the hazard at a site from all earthquakes of all possible magnitudes, at all significant distances from the site as probability of exceeding some amplitude of shaking at a site in periods of interest (Thenhaus and Campbell, 2003).

Mathematical formulation

The formal procedure for probabilistic calculations taking account of spatial and temporal uncertainty in the future seismicity was presented by Esteva (1967, 1968) and Cornell (1968). The probabilistic method of seismic hazard analysis, as it is currently understood, was presented by Cornell (1971), and by Merz and Cornell (1973).

It is commonly assumed that the occurrence of individual event can be represented as a Poisson process. The probability that at a given site a ground motion parameter, Z, will exceed a specified level, z, during a given time period, t, is given by the expression:

where v(z) is the average frequency during time period t at which the level of ground motion parameter Z exceeds z at the site resulting from earthquakes in all sources in the region.

The "return period" of z is defined as:

$$R_z(z) = \frac{1}{\nu(Z \geq z)} = \frac{-t}{\ln(1 - P(Z \geq z))}$$

The frequency of exceedance, v(z), is a function of the uncertainty in the occurrence time, size and location of future earthquakes and uncertainty in the level of ground motions they may produce at the site. It is computed by expression

$$\nu(z) = \sum_n \alpha_n(m^0) \int_{m^0}^{m^u} \int_0^{\infty} f(m) f(r \mid m) P(Z \geq z \mid m, r) dr dm$$

PSHA software

A key milestone in the development of PSHA was the computer **program EQRISK**, written by McGuire (1976). Nowadays there are a number of PSHA computer codes available to the analyst, but the most widely used in practice are those developed by McGuire (1976, 1978) and Bender and Perkins (1982, 1987). A version of machine code EQRISK (McGuire, 1976) improved by Leideker et al (2001) was formerly used in practice for probabilistic hazard assessment in Romania (Moldovan, 2007 and Moldovan et al, 2008). The code is widely distributed, and today is still the most frequently used hazard software. The PSHA output is often referred to as Cornell- McGuire method (Bommer and Abrahamson, 2006).

Work across boundaries

Seismic hazard is traditionally assessed at national scale and within national boundaries, to serve as input for various regulatory applications, making it impossible to achieve regional harmonization, for lack of data or limited geographical extent. In this project national experts have participated with their knowledge in building regional consensus models, transcending the traditional administrative and disciplinary boundaries.

Probabilistic hazard assessment (PSHA) for the south-eastern part of Romania using crustal inland and marine sources

With the input parameters as defined in Table 1 for the nine selected sources which likely affect the eligible area ***we computed seismic hazard values for three return periods (100, 475 and 1000 years) and for two hazard parameters, PGA (g) and Modified Mercalli Intensity (IMM)***. The computations were performed on a grid of 0.250 x 0.250 cell, covering the whole eligible area.

The hazard maps obtained when considering only the seismic sources in the crust, in terms of PGA/IMM are presented in the Figure 11 for 100 years return period, Figure 12 for 475 years return period and Figure 13 for 1000 years return period. In Figures 14 and 15 are highlighted the hazard values for the Romanian eligible area.

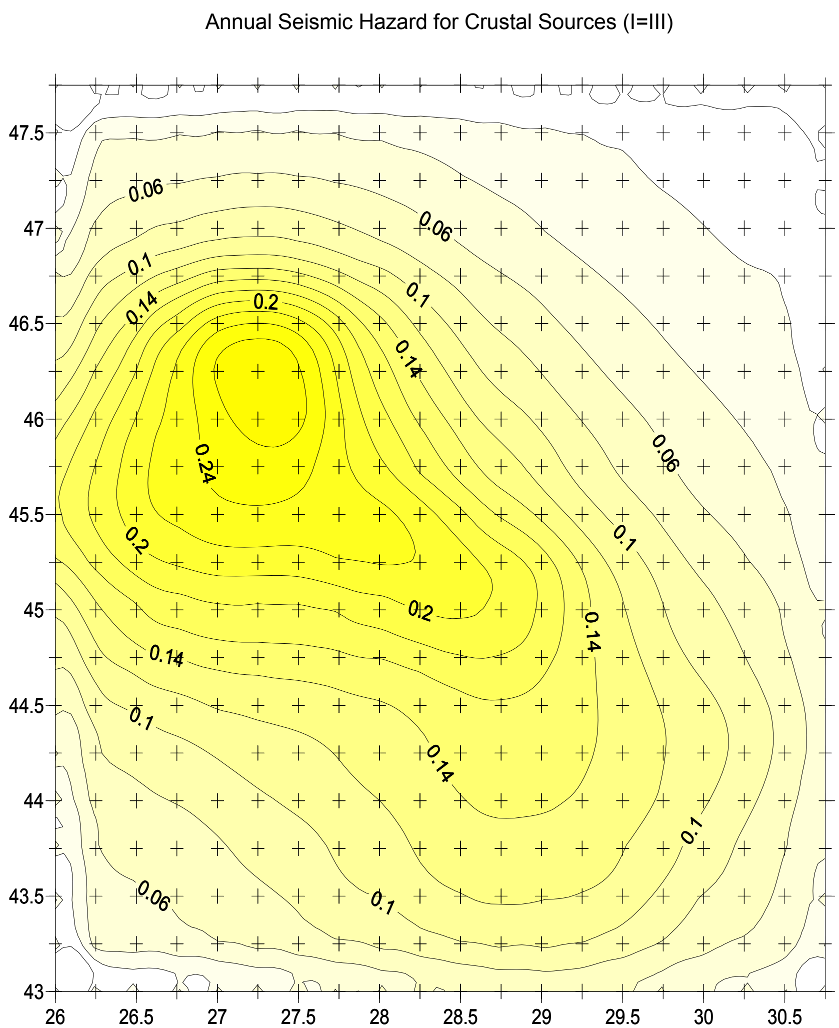
The conversion between macroseismic intensities and peak ground motion is given by STAS 3684-71 in Table 2

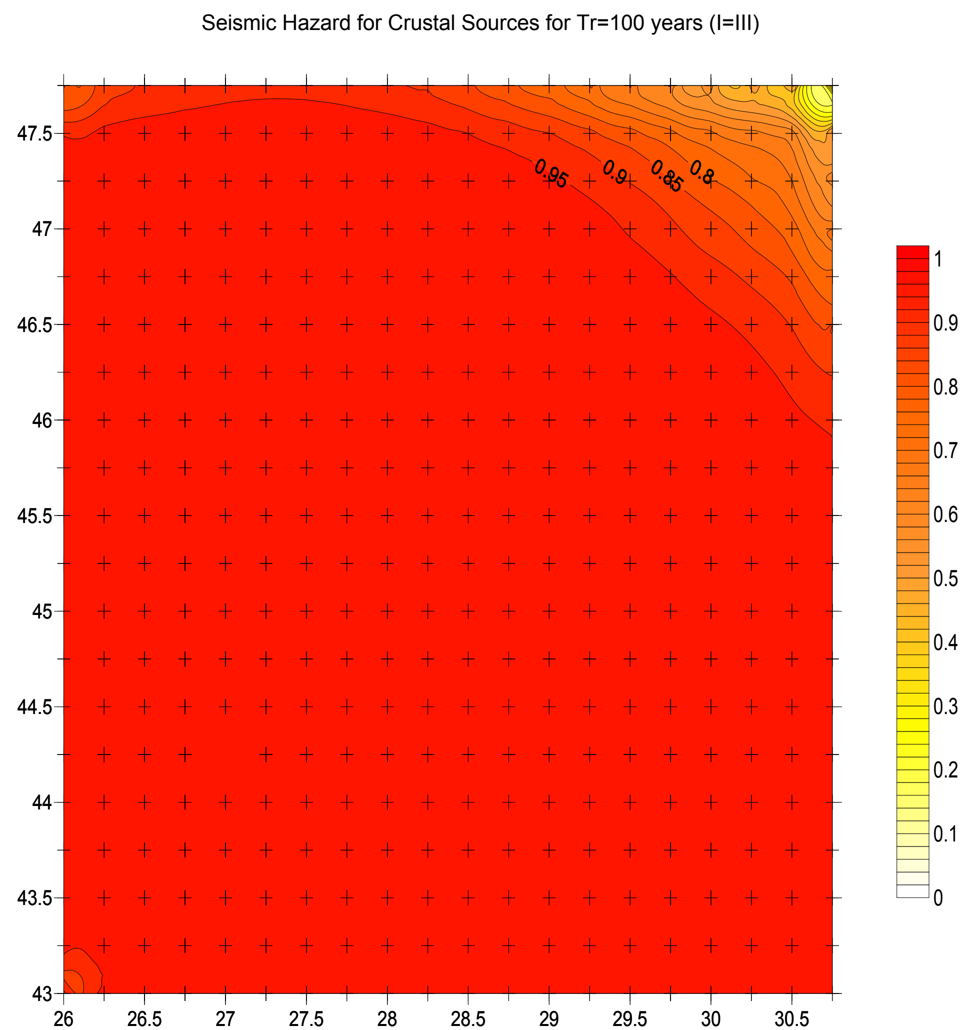
Table 2. Macroseismic intensity based on instrumental recordings (STAS 3684-71)

IMM (degrees)	**a ($cm.s^{-2}$)**	**v ($cm.s^{-1}$)**	**x_0 (mm)**
V	12….25	1,0…2,0	0,5….1,0
VI	26…50	2,1…4,0	1,1….2,0
VII	51…100	4,1…8,0	2,1…4,0
VIII	101…200	8,1…16	4,1…8,0
IX	201…400	16,1...32,0	8,1…16,0
X	401…800	32,1…64,0	16,1…32,0

a – peak ground motion for periods of 0,1…0,5 s;.
v – peak ground velocity for periods of 0,5….2,0 s;
x_0 - amplitude of the relative displacement of a pendulum with natural period of 0,25 s and damping of 0,5.

In Figures 16 - 20 are presented the macroseismic intensity curves for different exposure/return periods: 50, 100, 475, 1000 and 2000 years using only crustal sources.





A comparison between the annual hazard and the seismic hazard for 100 years for I=III

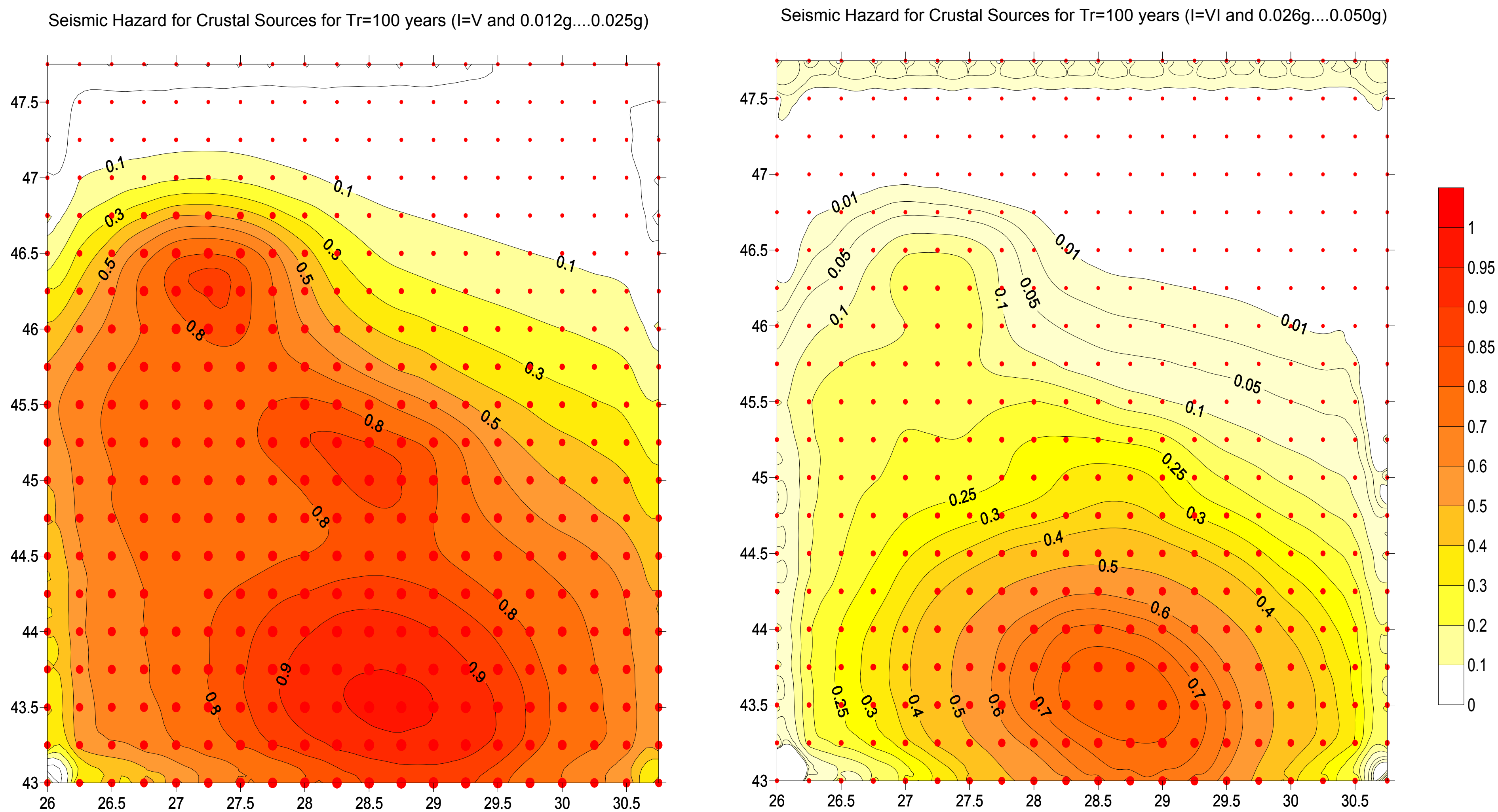


Figure 11. Seismic hazard for Tr=100 years for I=V and I=VI (using only crustal sources)

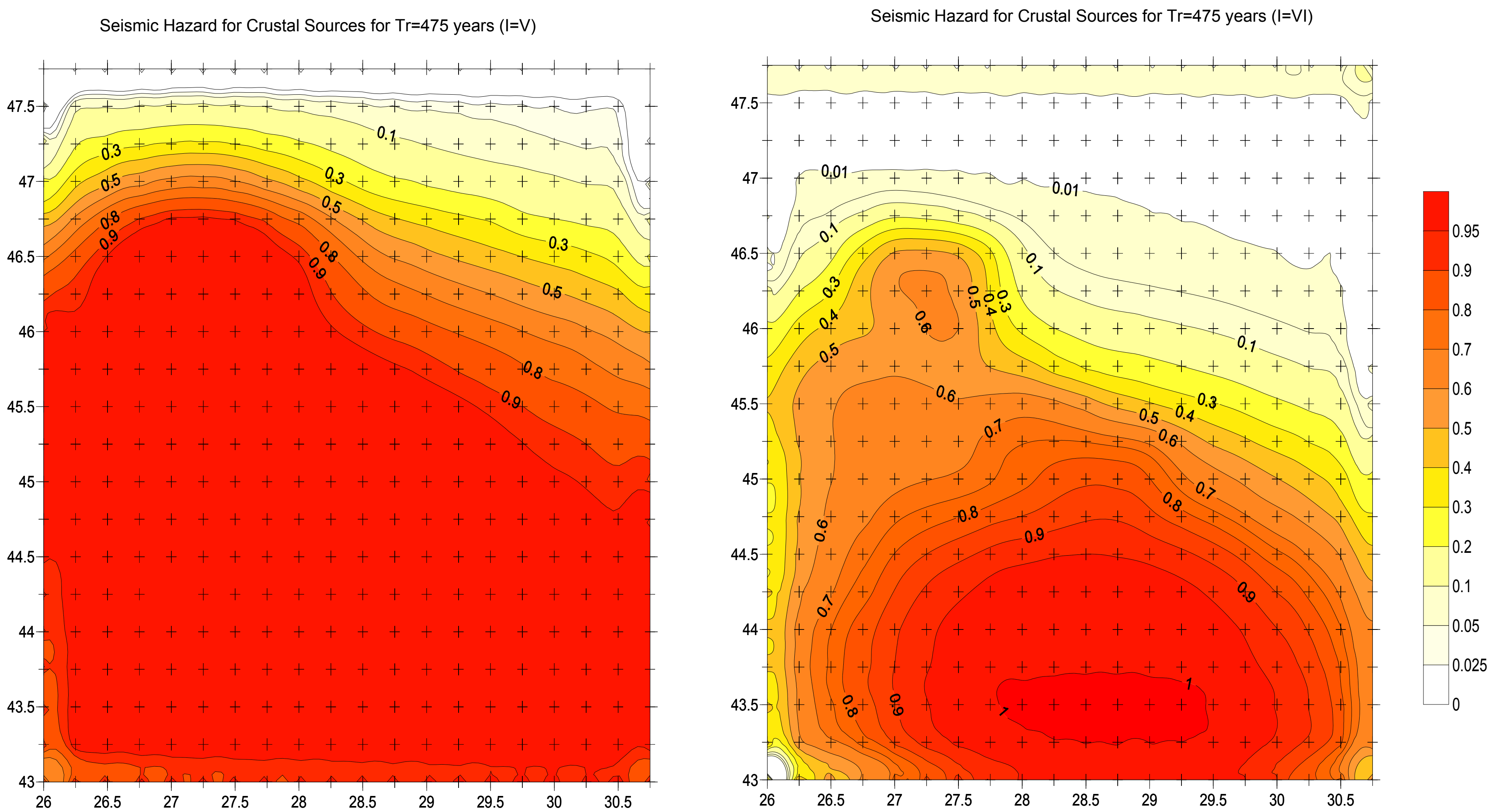


Figure 12a. Seismic hazard for Tr=475 years for I=V/ a=0.012g....0.025g and I=VI/ a=0.026g....0.050g

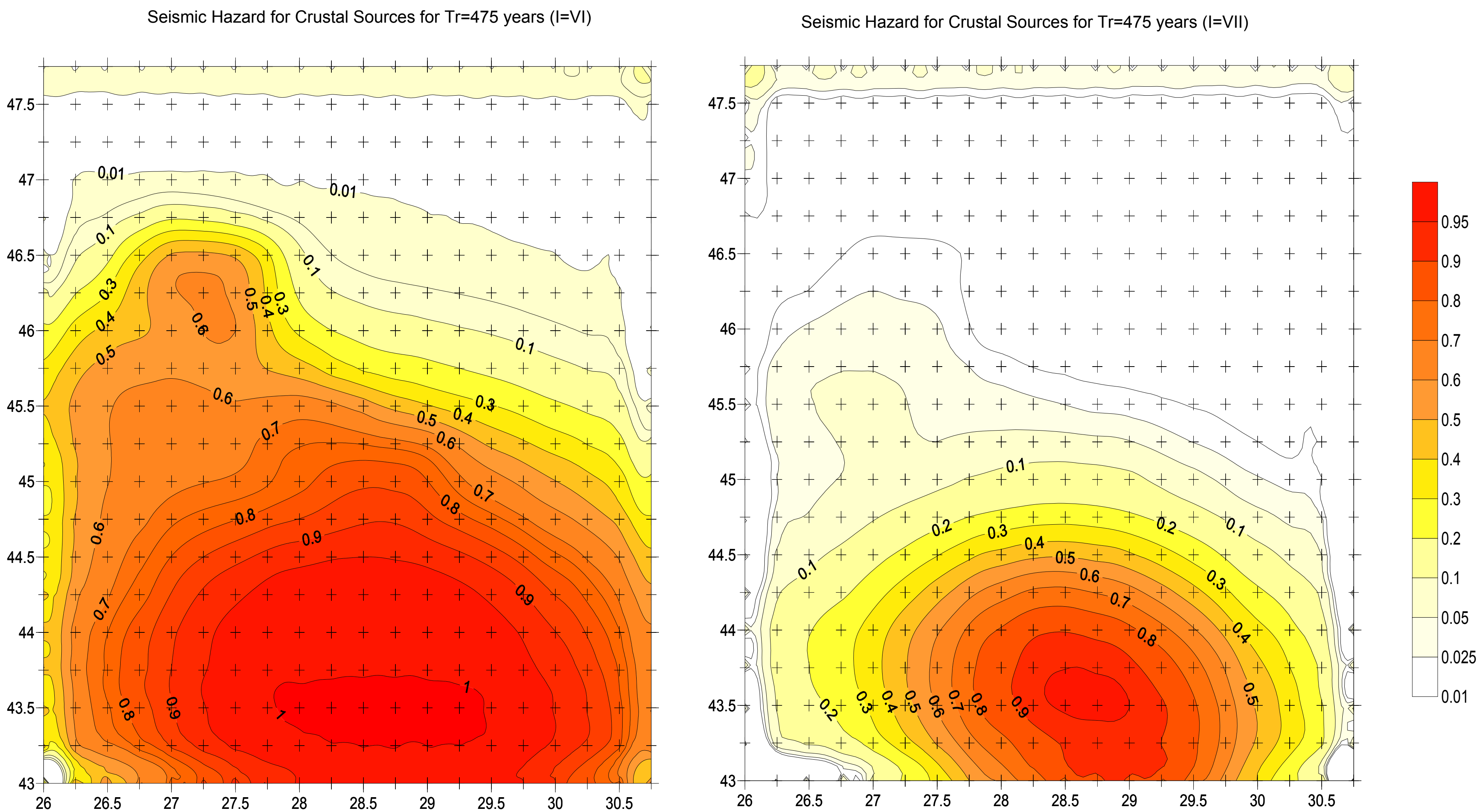


Figure 12b. Seismic hazard for Tr=475 years for I=VI/ a=0.026g....0.050g and I=VII / a=0.051g...0.100g

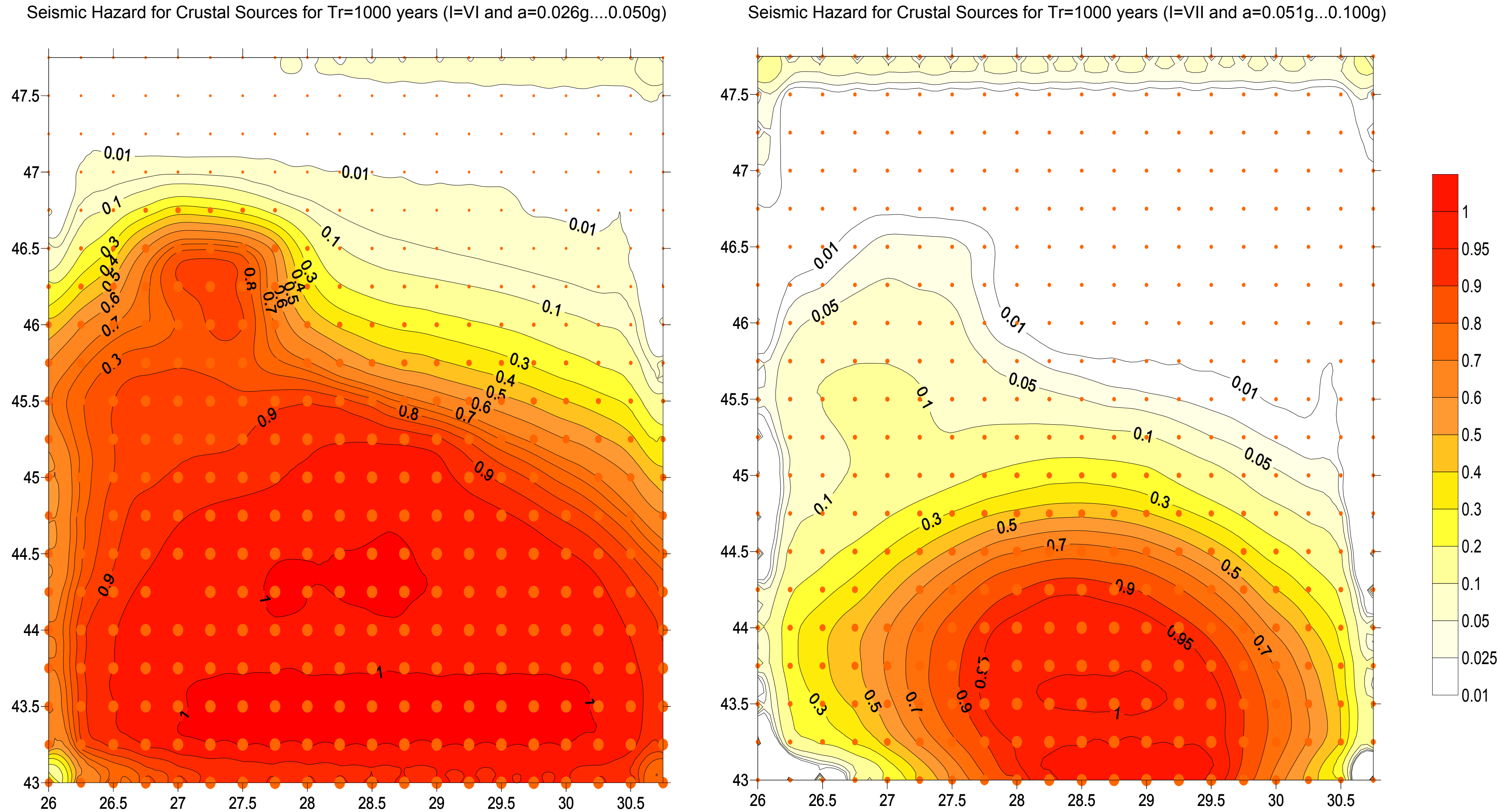


Figure 13. Seismic hazard for Tr=1000 years for I=VI/ a=0.026g....0.050g and I=VII / a=0.051g...0.100g

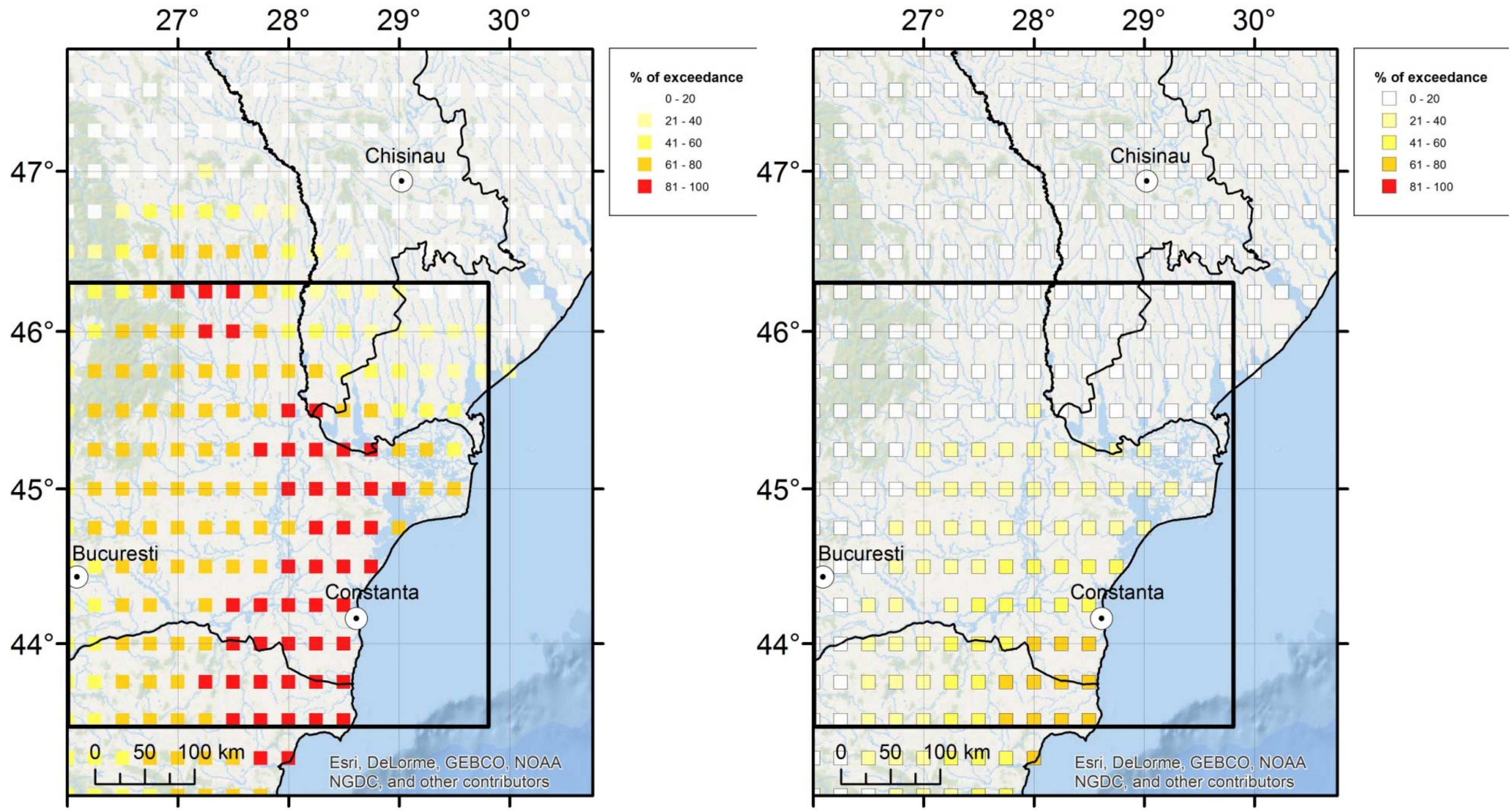


Figure 14. Exceedance probability (%) of I=V and I=VI in an 100 years return period

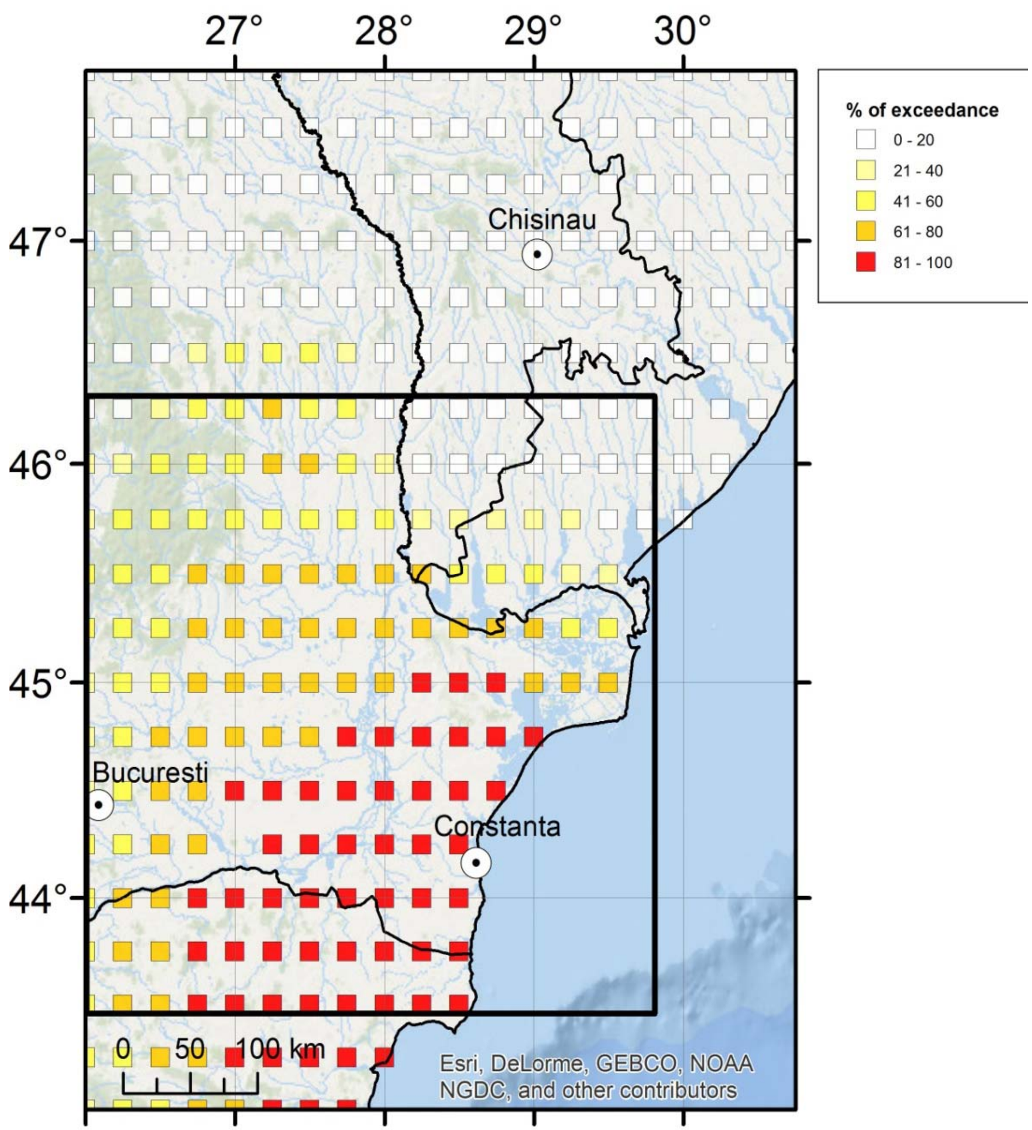


Figure 15. Exceedance probability (%) of I=VI in 475 years return period

- The hazard values are also given in the attached xls tables, consisting in a grid of examined points every 0.25 of degree covering the whole eligible area, presenting the geographical coordinates of each examined point and the results of seismic hazard assessment for different return periods (1 year, 50 years, 100 years, 475 years and 1000 years) and for the macroseismic intensity. The studies have been made in two different cases: (i) using only crustal sources and (ii) using both crustal and intermediate depth seismic sources.

- This splitting of our studies was necessary because when using intermediate depth Vrancea earthquakes, the local influences of crustal sources are completely covered. Only BS3 - Shabla zone is an exception. It's effects might be seen (together with those due to VI) on the maps from Figures 21-24 and 25-27.

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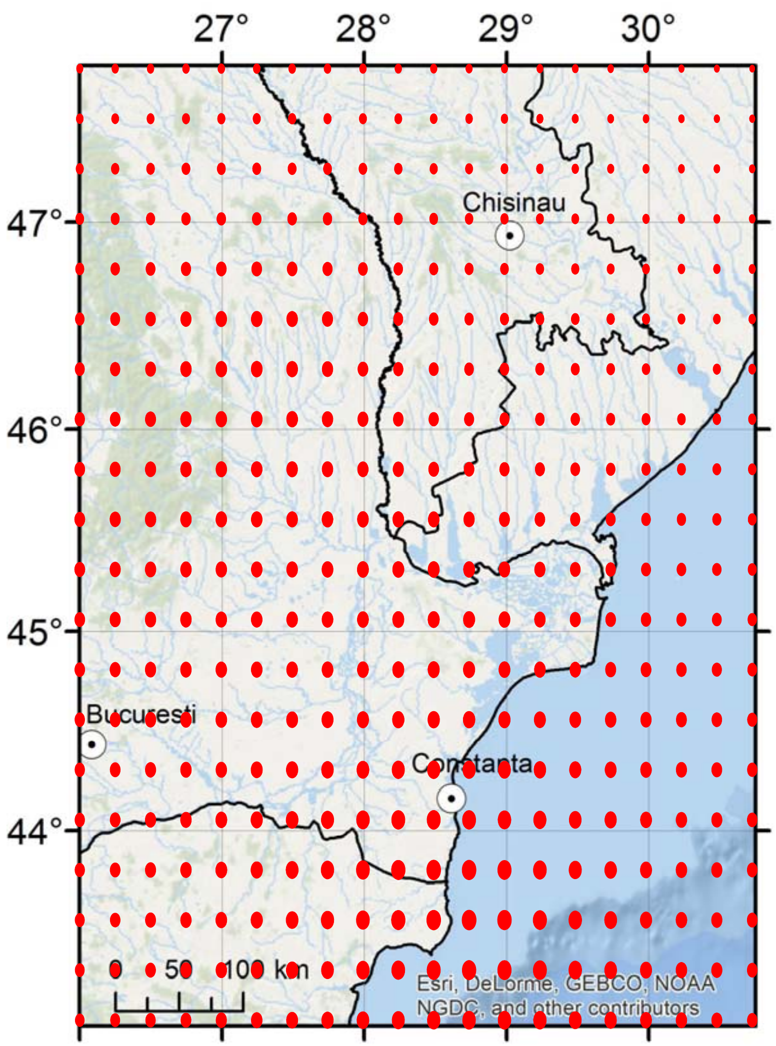
Macroseismic intensity curves for a return period of Tr=100 years



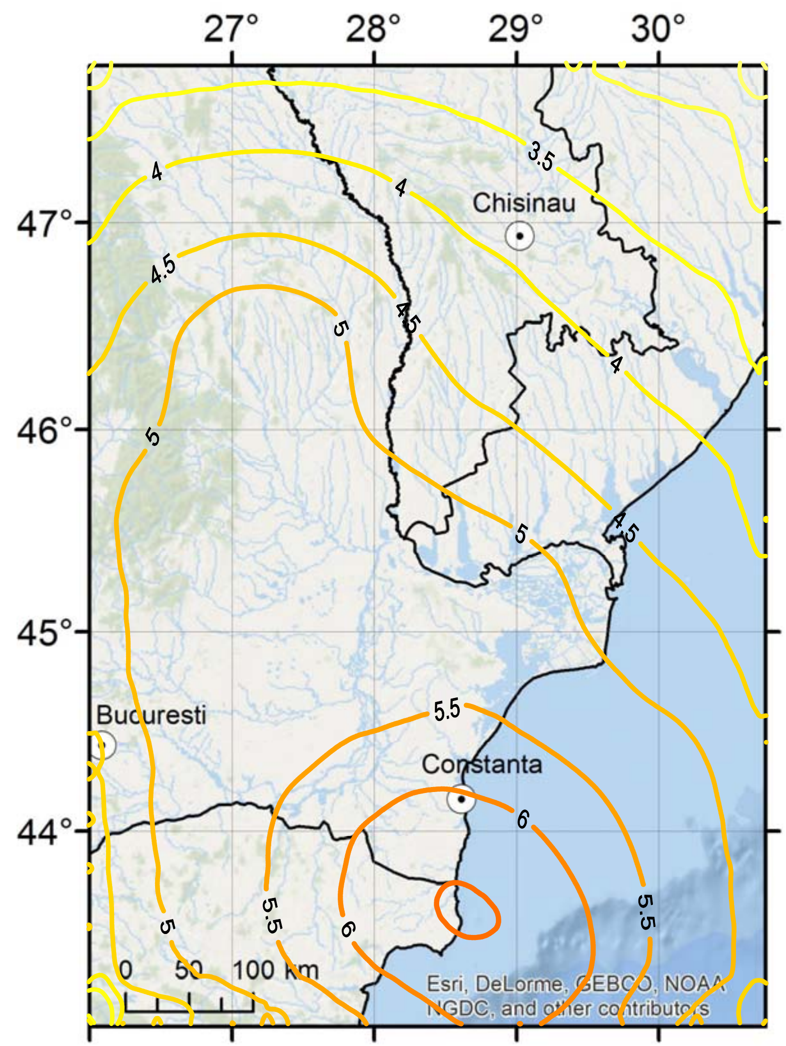


Figure 19. Macroseismic intensity values and curves for Tr=100 years

Macroseismic intensity curves for a return period of Tr=475 years

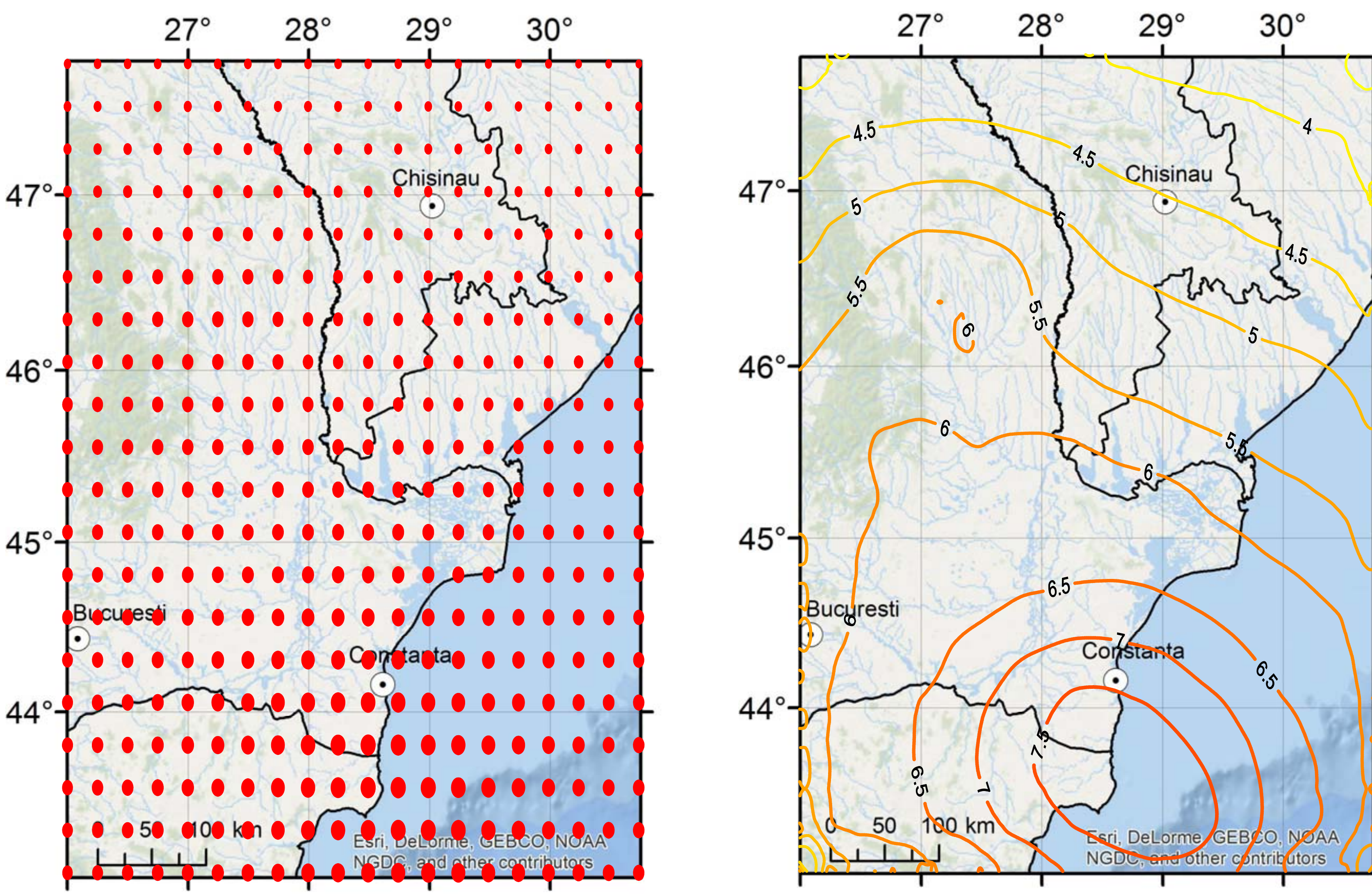


Figure 20. Macroseismic intensity values and curves for Tr=475 years

Macroseismic intensity curves for a return period of Tr=100 years

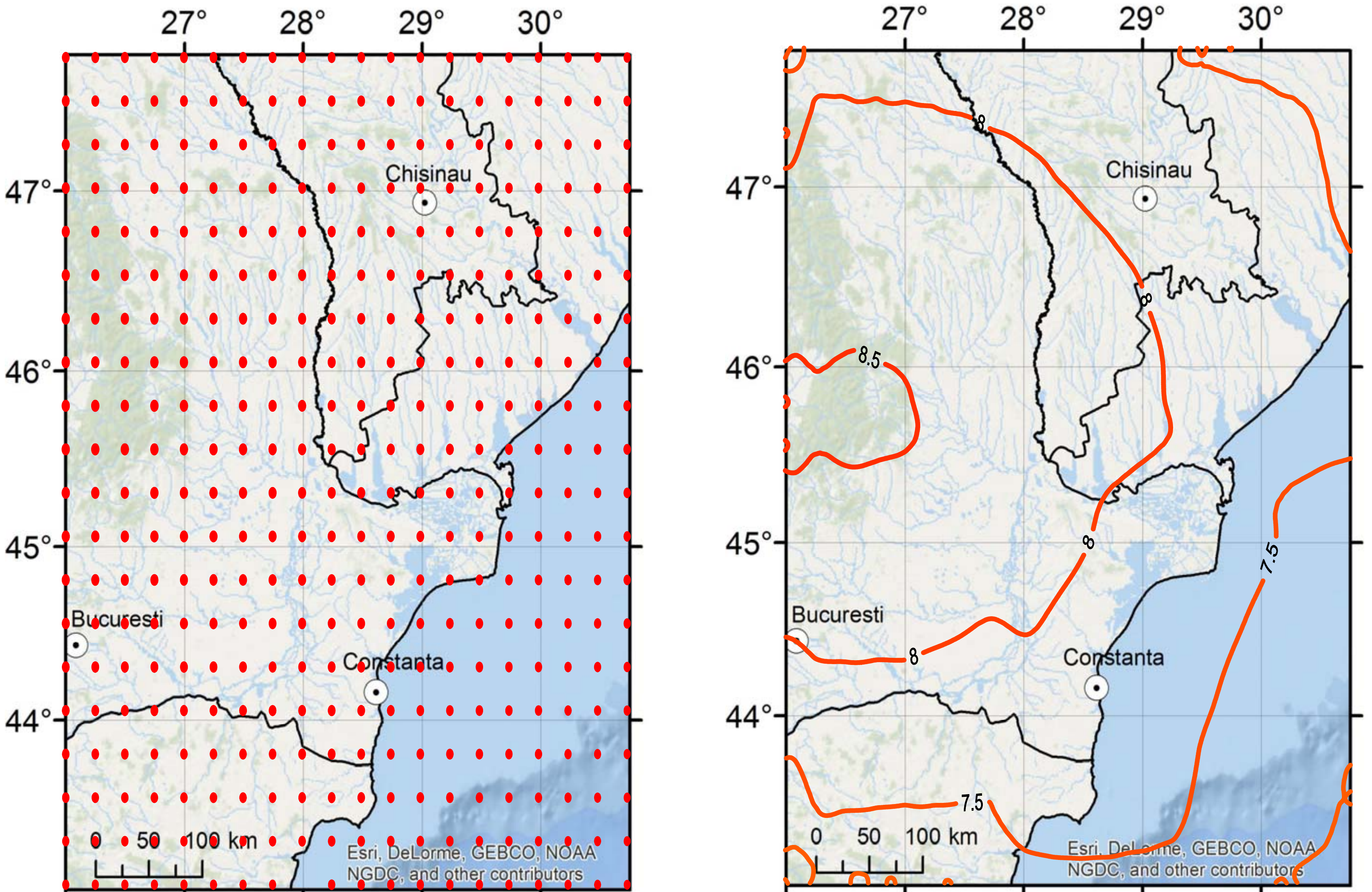


Figure 27. Macroseismic intensity curves for Tr= 100 years

Acknowledgements:

This work was partially supported by the Partnership in Priority Areas Program – PNII (under MEN-UEFISCDI), DARING Project no. 69/2014,

FP7 FP7-ENV2013 6.4-3 Project number: 603839/2013,

ASTARTE/PNII, Capacity Module III

and

SciNetNatHaz (Project nr. 268/2014)

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Thank you !