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INTENSITY AND MACROSEISMIC MAPS OF THE LATEST MODERATE SIZED VRANCEA EARTHQUAKES

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Abstract. Vrancea is the major region with the highest seismic hazard in Romania. We investigate macroseismic data and analyze also the influence of local geological structure on earthquake intensities in many areas affected by these earthquakes. It's known that the soft sediments existing in many areas of the territory have also a strong influence on seismic ground motion. The topographic effects can be also responsible for this apparent amplification of the ground motion. In this paper we determined intensities according to MSK Macroseismic Scale for seven small to moderate earthquakes (M_w > 4.5) occurred between 2013 and 2020 in Vrancea seismogenic region. Following the shaking, many people submitted reports to NIEP *via* the online questionnaire in which recorded their experience, while others reported macroseismic observations in the classic questionnaires requested by NIEP experts to the local authorities. The intensity data points resulted after analysis of the collected macroseismic data showed that a maximum intensity of V–VI was experienced for many localities for four of the seven earthquakes, also isolated/sporadic a few IDPs of degree VI were assigned. The shaking with intensity of V was experienced with a majority in the case of all the earthquakes studied here. Surprisingly, strong shaking of this intensity (V) was also experienced at great distances, about hundreds of km from the epicenter.

Key words: macroseismic intensity, Vrancea seismogenic region, subcrustal earthquake, macroseismic questionnaire

1. INTRODUCTION

The occurrence of each perceptible earthquake provides unique and fundamental data regarding its actual manifestation on the earth's surface. Observations about manifestation of any earthquake, even a weak one, are important for assessment of the macroseismic intensity and Shake map of the felt area. In other words the macroseismic intensity quantifies the effects produced by earthquakes being also a measure of the severity of ground motion.

Analyzing the earthquakes impact on humans, objects, buildings and natural environment is the goal of macroseismology [1]. Although the extent of seismic networks is considerable and instrumental data are very numerous and qualitative, it does not completely substitute macroseismic investigations, the latter providing a large amount of data from all the areas affected by earthquakes. Macroseismic observations in Romania date back 1000 years, and give valuable contribution to earthquake research even today, especially being the era of the internet.

The intensity data and instrumental records are very important for engineering applications (*e.g.* ground motion parameters attenuation and correlation and site effects), for seismic hazard assessment and risk analysis, which emphasizes the particularities of the active or potentially active seismo-tectonic sources from Romania [2–6]. Reliable macroseismic information can be used to increase the seismic resilience and help to estimate earthquakes impact. Macroseismology provides essential and unique data for recent earthquakes for which seismic records are also available, being deeply complementary and not an alternative to instrumental seismology [7–10].

In the last years several small to medium size earthquakes ($4.6 \leq M_w \leq 5.7$) have occurred in Romania. They could be felt on the extended area of the country, *i.e.* extra-Carpathian zone, including the capital, Bucharest, thus many people have felt the shocks and observed their effects. The events caused general panic, the intensity of panic depending on the event magnitude and observer location. The purpose of this paper is to describe the macroseismic effects and the process of assigning intensity and to analyze the influence of local geological structure on intensity values in many areas affected by seven of these earthquakes that occurred in Vrancea zone between 2013–2020 and to evaluate the observed intensity distribution.

2. QUESTIONNAIRE SURVEY

The macroseismic questionnaire survey based on MSK scale [11] was used for the most significant earthquakes in Romania including the 1977 earthquake (with the most forms collected) and then intensity values used for macrozoning of the territory and microzoning of urban areas [12–15]. The current version of questionnaires was modified and contains 45 questions about effects on people, objects and natural environment, also building type and damage degrees and was constructed based on the same seismic scale. This type was designed to cover every intensity degree for the seismic scale in use. The modified questionnaire was used for two moderate earthquakes studied here ($M_w = 5.2$ 2013 and $M_w = 5.5$ 2018 earthquakes). For the other earthquakes only the online form contained 87 questions, constructed on the base of MM scale was used [16]. The online macroseismic questionnaire, like the classic one, consists of questions about the same type of effects. In this questionnaire most of the questions have a set of answers from which the respondent can choose the one most appropriate to his experience (www.infp.ro). Both forms inquire how objects around humans and infrastructure have been shaking and how people feel and observe during the earthquake occurrence. All online questionnaires were manually reviewed and assigned intensities.

3. EARTHQUAKES ANALYSIS AND INTENSITY EVALUATION

A selected number of small to medium size earthquakes occurred in Romania during the last years were studied through questionnaire surveys (Table 1). As I said before the observations collected and used in this analysis were obtained as follows: questionnaires completed online on the NIEP website by people who felt the earthquakes and distribution of classic questionnaires by NIEP scientists to IGSU (Romanian General Inspectorate for Emergency Situations) whose employees redirected them to citizens' homes, workplaces and schools from all the felt areas. Nowadays, it is known that the social media has a great effect on the collection of macroseismic questionnaires by increasing the amount of the data received. The information existing on detailed questionnaires filled in by the affected people are used for macroseismic intensity evaluation. Although given by non-expert observers, the over 30970 questionnaires filled in were statistically analyzed and was estimated the macroseismic intensity field of these earthquakes. Rigorous evaluation of online data and detailed presentation of the process were necessary because of the subjective nature and the ambiguity of the collected macroseismic information.

Table 1

Source parameters of the studied earthquakes (source: Romplus catalogue [17])

No	Date (DD.MM.YYYY)	Time (UTC)	Lat. N	Long. E	h (km)	Mw	Imax	No. MQ
1	06.10.2013	01:37:21	45.67	26.58	135.1	5.2	V	730
2	23.09.2016	23:11:20	45.71	26.62	92	5.7	VI	1000
3	27.12.2016	23:20:55	45.71	26.59	96.9	5.6	V–VI	350
4	08.02.2017	15:08:20	45.48	26.28	123.2	4.8	V	1160
5	28.10.2018	00:38:11	45.61	26.40	147.8	5.5	V–VI	23600
6	31.01.2020	01:26:47	45.69	26.69	118.2	4.8	V–VI	2300
7	24.04.2020	22:04:18	45.89	27.46	22.6	4.6	V	1830

Brief description of the effects produced by these earthquakes with reference to various characteristics of the macroseismic investigation is presented below.

3.1. VRANCEA EARTHQUAKE OF OCTOBER 6, 2013

A moderate earthquake of moment magnitude 5.2 with epicentre about 39 km west of Focsani town, rocked Vrancea zone and the surrounding area, at 1:37 GMT on October 6, 2013. The earthquake generated an intensity of V MSK and the felt area was extended in all the extracarpathian part and the depth of focus was about 135 km. Despite of the frequent experience of tremors in the most active seismic area since the Romania or so, the present earthquake caused considerable panic amongst the inhabitants of the felt area. A total of 730 observations were collected only from classic questionaires and are distributed in 100 IDP as is shown in Figure 1a. Unfortunately, the online questionnaires did not produce good and complete observations and were lost for various reasons. Despite the generally good response received by the scientists from the field from many respondents and the major impact and tremendous panic created by the earthquake, quite a few people were sent feedback and were interested in participating at the survey. The maximum effects observed in locations with intensity V MSK are described below: Sleeping people are awaken. Observers felt a strong shaking of the whole building. Furniture shook, especially the light one. Hanging objects such as lights swung considerably, also pictures have moved on the walls. Animals became uneasy, frightened and left the shelters. Only fine fissures in the walls of a few poorly constructed buildings (type A) were reported.

3.2. 23 SEPTEMBER AND 27 DECEMBER 2016 EARTHQUAKES OBSERVATIONS

A pair of moderate earthquakes of similar magnitude (M_w = 5.6) occurred in the Vrancea seismogenic zone in the last quarter of 2016. The two events are separated in time by two months and are located very close to each other (same epicentral coordinates and volume of rocks/depths, respectively) and could be considered as being an earthquake doublet [18]. Both earthquakes were felt over an extended area covering most of the part of Romania, north of Bulgaria, Republic of Moldova and south of Ukraine. An observed maximum intensity of VI MSK was assigned for the first shock and V–VI MSK for the second one. No damage was caused to any of the structures in the epicentral area and in the locations with maximum intensity observed. The distribution of the effects of these two earthquakes is specific to the Vrancea seismogenic zone, toward the NE–SW.

In summary, 963 questionnaires were filled in (298 from Bucharest) for shock from September and 343 answers were received for the one from December and intensities were assigned to 200 settlements for first shock and 95 locations to second, respectively.

For September 23 the maximum intensity value (VI) was assigned to Rediu, Neamt county and for December 27 the maximum intensity value (V–VI) was assigned to two localities: Afumati (Ilfov county) and Tecuci (Galati county) (Figs. 1b and 2a). In these settlements the earthquakes were accompanied by strong sound. Most of the people were awakened, frightened and many run outdoors, few of them said that was difficult to remain steady. Animals became nervous and scared before the shocks, especially dogs barked, howled, whined or ran. Hanging pictures swung. The buildings were shaking, many small objects overturned, many light furniture shaken, heavy furniture often were shaken. Small fissures in a few walls were reported.

3.3. 8 FEBRUARY 2017 EARTHQUAKE OBSERVATIONS

The Vrancea earthquake of February 8, 2017, was widely felt in all the extra-Carpathian area, and some responds come from distances up to about 250 km. This event was located 52 km N–W of Buzau, Buzau County, and originated at Vrancea Seismogenic zone. Figure 2b shows the macroseismic map obtained for this earthquake. We received more than one thousand questionnaires in the time after the occurrence. The observed effects corresponding to V MSK degree were the highest at about 90 km N–E of the epicenter, at the village of Vulturu, Vrancea county. There was a general feeling of shaking, many people felt the earthquake, furniture moved and small objects moved a bit from shelves and made noise, pictures from walls also moved. No damages to property were reported. As in the case of the other earthquakes, this one also recorded many responses for Bucharest, a total of 710 MQ.

3.4. THE VRANCEA EARTHQUAKE OF OCTOBER 28, 2018 AND ITS EFFECTS

The October 28 earthquake was one of the moderate seismic events generated in the same seismogenic area in recent years, occurred around 03:38:11 (local time) at a depth of 147.8 km, with a magnitude of $M_w = 5.5$ and $I_0 =$ V–VI MSK. Questionnaire survey was taken up immediately after the occurrence of the quake which was well responded by the authorities and the public in general, especially by the internet users, given us a good feedback regarding the effects observed. Also, immediately it was possible to communicate with some affected people, and in this way we found out how extended the felt area was and decided how large to be the investigated area. A total of 23600 questionnaires were collected (Table 1), with 3600 questionnaires completed online, resulting in 1158 IDP. Despite the reluctance of many people to participate at the survey, the greatest amount of questionnaires were obtained from the field distribution, with the help and involvement of IGSU. Because of that the macroseismic analysis was very reliable. Figure 3a shows the final macroseismic map for this Vrancea earthquake, the intensity values vary from II to V–VI. The field intensity of V could be assigned to very large area, extended most in the southern part of Romania (see Fig. 3a). People as far as 439 km SW of the epicenter in Serbia, also reported feeling the shaking from the earthquake as well as in Odessa (Ukraine) at 350 km E from epicenter. In the locations with maximum observed and reported effects we had the following descriptions: sleeping people were awakened by the shock and they heard a strong noise. The specific noise was not heard only in these locations.

Strong shaking was felt in houses, the furniture was shaken, glass and crockery rattled, small light objects fell, hanging objects swayed (lights and pictures). In some houses the old small cracks and fissures in the plaster became wider and new ones formed. No loss or significant damages to property were reported.

3.5. 31 JANUARY 2020 EARTHQUAKE OBSERVATIONS

On 31 January 2020 an earthquake of magnitude moment 4.8 occurred near the village of Nereju, Vrancea (Romania), which was the first moderate Vrancea earthquake at the beginning of year 2020. This event was recorded by 138 Romanian strong motion stations, with higher values on the NE direction and in the eastern part of the epicenter, reaching 34.4 cm/s^2 at Vaslui station, thus it is very good documented. Nevertheless, the complementary and complex set of data obtained through macroseismic survey it is very useful for achievement of the shake map and the spatial distribution of felt locations *via* received answers. This earthquake was felt in the entire eastern half of Romania. The number of incoming macroseismic questionnaires was over two thousand and effects descriptions for the epicentral area reached almost one hundred and fifty. Intensity values were assigned to 304 locations (Fig. 3b). During data collecting the uneven spatial distribution of the questionnaires received was evident, there were many more questionnaires from big cities (especially from Bucharest – 870 forms) than from the epicentral area.

The earthquake caused non building damages, the maximum intensity was estimated as V–VI on the MSK-64 scale [19] and was assigned to Corbita locality (Vrancea county) situated at 70 km distance from the epicenter. The shock was accompanied by strong noise. Most of the people were awakened, pretty much of them were slightly frightened and agitated and few wanted to run outside, but no injuries were reported. Animals became anxious and scared. Hanging pictures swung, glass objects overturned and in a few cases fell. The buildings were shaking, many small objects on shelves overturned, light furniture moved, heavy furniture often were shaken. In the following we present some quotes extracted from macroseismic questionnaires that present what the respondents felt at that moment: *"It felt great, everything was moving in the house. The earthquake woke me up in the middle of the night. The bed was shaking together with the rest of the room. Not too violent, but enough to feel in the sleep. Dogs barking outside."*

3.6. MACROSEISMIC MANIFESTATIONS OF THE APRIL 24, 2020 EARTHQUAKE

Macroseismic effects of $M = 5.0$ crustal seismic event occurred on the evening of April 24, 2020 were felt over a wide area. The macroseismic information used in this study are coming from individuals spontaneously reporting to the NIEP web site (www.infp.ro) and they are provided in two ways. First type of information coming from online macroseismic questionnaires. A second kind of information consist in macroseismic intensity values assessed directly by the individuals (rapid feedback). A total number of 600 positive macroseismic questionnaires forms were received. The maximum effects observed appeared in several localities situated at various distances from the epicenter (the farthest being at 130 km). From the macroseismic observations collected through online questionnaires from areas where the quake was felt, it appears that the maximum effects refer to: sleeping people awoken by the shock, unfixed things on shelves moved and made noise and some of them dropped, movement of the pictures on the walls, small cracks in the plaster of building walls, the abnormal animal behavior (dogs, birds, cats agitated and left the shelters) shortly before and during the earthquake. In addition to the seismic shaking felt, the population reported the appearance of more or less intense noises during the earthquake. These maximum effects were felt at highest seismic intensity as large as 5 degrees MSK in 24 settlements (Fig. 4).

For example, macroseismic effects corresponding to intensity I = V MSK were observed in Tecuci at 5.5 km distance from the epicenter. In this town the earthquake was felt by all people inside, the movement being described as strong, also they reported: swinging of hanging objects, tremors and swaying of furniture, the paintings moved on the walls, objects on the shelves moved a little and made noise, some overturned and fell, fine cracks were reported in the plaster of building walls. Another location assessed with intensity V was the settlement of Marasesti, located 18 km from the epicenter, in which the following effects were observed: fine/small cracks in the houses walls, the movement of furniture, hanging objects swung, the chandeliers were swaying, hanging pictures moved, shaking of unfixed objects on shelves, animals became uneasy and scared. In Braila (80 km far from epicenter) were reported very small fractures on the walls of buildings of types A and B (very few), swinging of hanging objects, pictures hanging on the walls were displaced, the furniture was swaying, unfixed objects on shelves were being moved, unusual animal behavior was reported. Taking into account these effects, the intensity in Braila was also estimated at V MSK.

4. INTENSITY DATA POINTS MAPS

The seismic shaking due to an earthquake depends on several factors such as size and depth of the earthquake, the epicentral distance, and the rock type [20]. The intensity distribution maps have been and still are an effective tool in estimating the ground motion characteristics of each shaken region, and for the past time the only ones used to determinate the earthquake magnitude and focal depth [21]. The estimated seismic intensity maps of the analyzed seismic events are shown in Figs. 1, 2, 3 and 4.

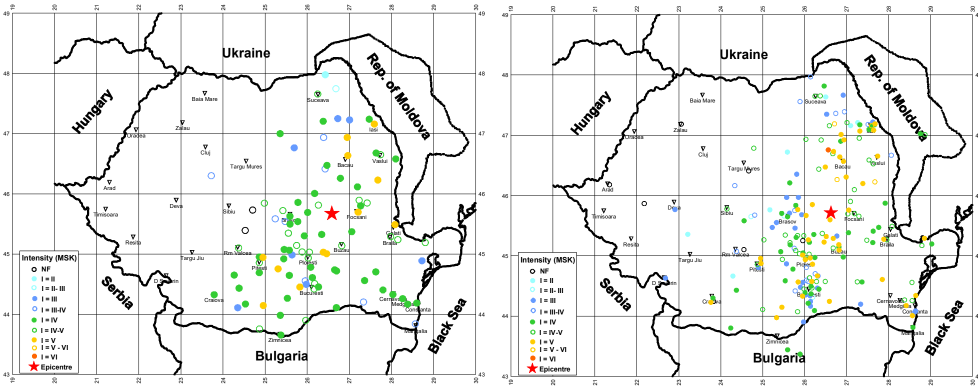

Fig. 1 – Macroseismic intensity maps for the: a) 06.10.2013; b) 23.09.2016 earthquakes.

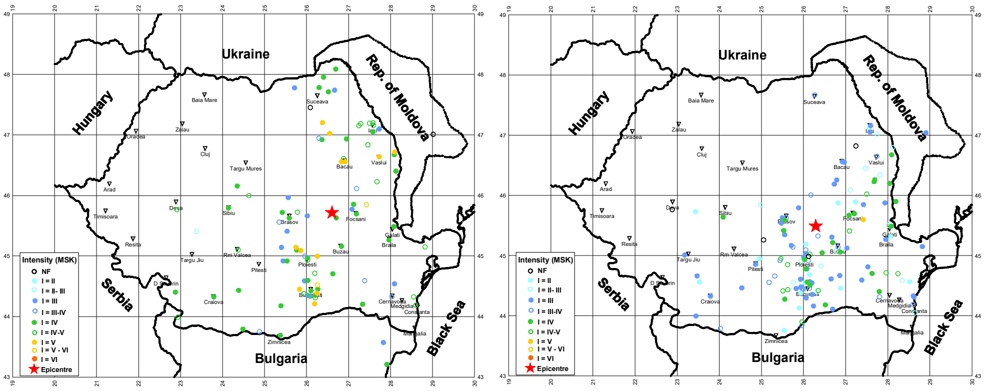

Fig. 2 – Macroseismic intensity maps for the: a) 27.12.2016; b) 8.02.2017 earthquakes.

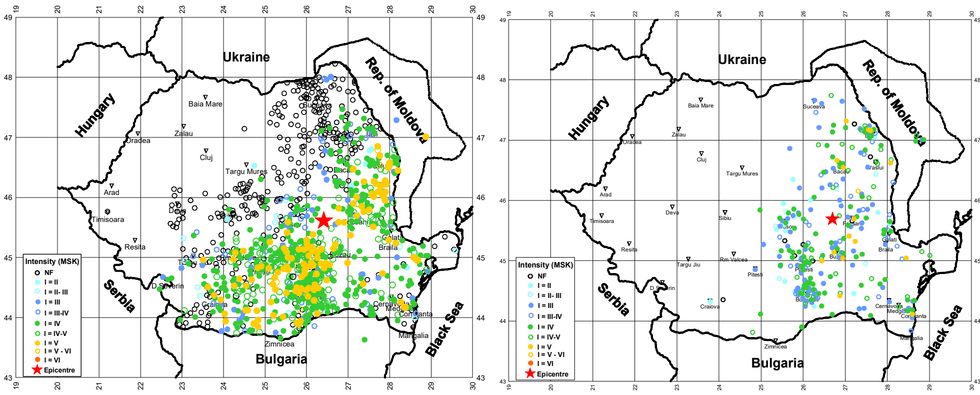

Fig. 3 – Macroseismic intensity maps for the: a) 28.10.2018; b) 31.01.2020 earthquakes.

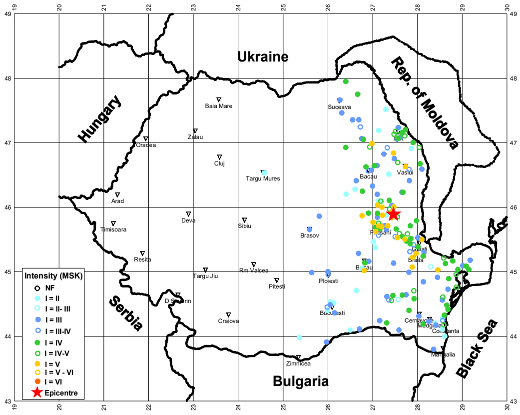

Fig. 4 – Macroseismic intensity map for the 24.04.2020 crustal earthquake.

As can be seen in figures, the evaluation of macroseismic effects shows an extremely uneven distribution of the shaking intensity over the felt area and epicentral distance. One of main causes of the high intensity values recorded in some locations situated at long distances appears to have been site amplification due to local geology and/or topography, a possible explanation being offered below.

5. GEOMORPHOLOGICAL AND GEOLOGICAL CHARACTERISTICS: INFLUENCE ON POSSIBLE LOCAL EFFECTS

As it is known and can be seen in the macroseismic maps of earthquakes, the intensity is greatly influenced by the geological environment, such as the properties of the deposits through which the seismic waves propagate, the existing tectonics structures, the geological features of each area, topographic characteristics etc. [22–23]. In this context, below we try to reveal the causes of the amplification that appeared in one of such specific regions. The region discussed here includes Bucharest and its adjacent areas.

The majority of sites with anomalous intensities are located on soft sediments typically along river valleys or alluvial plains of the Arges, Ciorogarla, Dambovita, Colentina, Pasarea, Mostistea, Ialomita, Prahova, Teleajan and Cricov rivers, where the geotechnical properties of terrains are poor. Their local geology consists, without exception, of gravels, sands and boulders accidentally interspersed with sandy clays. In this area the amplification of the seismic motion is increased by the structure of the local geology, the presence of unconsolidated sediments being the main factor. Geomorphologically, the presence of unconsolidated sedimentary deposits in the geological constitution of the valleys favors the amplification of the local effects of earthquakes as well as the presence of two large interfluves, one in the south Arges-Dambovita-Mostistea [24] and another in the north of the area, Prahova-Teleajan-

Cricov, with a similar geological structure. Thus, in the Arges Valley there are unconsolidated sedimentary deposits (belonging to the lower Holocene) of the type of gravel, sand and boulders with a thickness varying between 7 and 12 meters. A similar situation can be found in Dambovita valley [25]. At the base of these deposits, the Mostistea sands support intermediate deposits (Bucharest area) made up of clays and sandy clays with a thickness of 5–10 meters [26]. Over these intermediate deposits there is a 4–8 meter thick horizon of gravels and sands called Colentina gravels. The Upper Holocene also consists of gravels, sands and boulders whose thickness is 5–10 meters [27]. In the NW part the structure is continuing with the Candesti strata (Lower Pleistocene) which consists in sands and gravels with intercalations of conglomerates. Overlapped on these strata we found 10–15 m thick loessoidal deposits (middle Pleistocene) with alternating intercalations of sandy and clayey dusts.

6. CONCLUSIONS

The assessment and the collection of observed macroseismic effects have always been of very important in the field of seismology. In pre-instrumental era and/or in the one of limited instrumentation, the annotated and field observations were particularly useful and sometimes the only ones. Despite the continuous progress in instrumental monitoring and computation in the field of seismology, the importance, implications and contributions of macroseismology cannot be denied and/or excluded. Nowadays, through a combination of all the possible approaches (*i.e.* traditional and online questionnaires, all kind of testimonies, fast interactive feedback, field surveys, dense seismic networks, and high-resolution mapping tools), the macroseismic investigations have achieved a level of high accuracy.

In this study we have constructed intensity maps based on macroseismic surveys and other available information (testimonies, fast feedback) of effects due to Vrancea earthquakes with $4.6 \leq M_w \leq 5.7$ occurred between 2013 and 2020 and interpreted them to obtain MSK intensities at over 1822 locations. Based on the questionnaires which is commonly used in macroseismic investigation and manual evaluation, intensities were assigned at all the locations mentioned above, for two of them the evaluation was based on both classical and online questionnaires. A maximum intensity of VI was assigned to the seismic event from September 23, 2016, from the entire set of events. Intensity distribution of V degree is very large in the case of majority of the events analyzed here. The intensity maps reveal several interesting particularities, characteristic for this region. The elongated shape of the intensity distribution (macroseismic field) on each map shows that most of the affected areas are concentrated toward the NE–SW side of the epicenter, especially the intensity of V, which may be due to directivity and/or site effects. Also, the evaluation of macroseismic effects in the felt area shows an extremely uneven distribution of the shaking intensity over the area and epicentral distance. The study of macroseismic field after these moderate Vrancea earthquakes provide a valuable dataset of intensities which are also additional information for earthquake source parameters and will be useful for future studies regarding the relation between macroseismic intensity and other earthquake parameters. Bottom line, the observations of the macroseismic field of each felt earthquake are necessary and available for seismological studies, civil emergency, Governmental institutions and insurance companies.

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