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THE ANALYSIS OF THE SEISMIC SEQUENCE STARTED ON NOVEMBER 22, 2014 BASED ON ETAS MODEL

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Abstract. The purpose of this study consists in the analyses of ETAS (Epidemic-Type Aftershock Sequence) parameters for the sequence recorded on November 22nd, 2014 in Marasesti area. The main shock of the sequence, a moderate-size earthquake with $M_L = 5.7$, at 40.9 km depth, is the largest crustal event instrumentally recorded at the bending of the Eastern Carpathians. The ETAS model parameters for the Marasesti area were estimated using the seismic events from the Romplus catalogue, between January 1, 2010 (00:00:00) and November 17, 2017 (00:00:00), with magnitude between $1.2 < M_w < 5.4$ and depth $0.6 < h < 70$ km. The estimated model is applied further on an independent data set recorded in the same area, for automatic identification of Marasesti sequences using the residual analysis techniques. The studied model encourages research for evaluation of the real-time probability earthquake occurrence and sustains the international initiatives such as the Operational Earthquake Forecast (OEF)

Key words: ETAS model, crustal seismicity.

1. INTRODUCTION

The crustal seismicity in front of the Carpathian Bend is distributed to the East, in a band delimited by the Peceneaga-Camena fault [1, 2], to North and East, and to the South and it is lost to the Intramoesica fault. Seismic activity is usually characterized by groupings in space and time, in Ramnicu Sarat subareas through seismic sequences and seismic swarms in the Vrancioaia area [3, 4]. The crustal seismicity has never exceeded the magnitude $M_w = 5.9$, for a historical earthquake (March 1, 1894) [5] and seems to be independent to the seismic activity in the subducted lithosphere. The major shock of the Marasesti sequence, from November 22, 2014, at 19:14, local time ($M_L = 5.7$, $M_W = 5.4$ and $h = 40.9$ km,) is the largest event recorded in the area, during the instrumental period [6].

The present study is an analysis of the ETAS model applied on the seismic sequence recorded from November 22, 2014 to February 1, 2015 in Marasesti region, between latitude 45.7 N – 46.2 N and longitude 26.8 E – 27.4 E, with local

magnitude 0.1 < M_L < 5.7, and depth range 0< h <52 km. In the Romplus catalog the sequence contains 222 events over a period of 70 days. Besides the main shock, only three aftershocks exceeded M_L 3.0, in November 22, 2014 (M_L 3.1), December 7, 2014 (M_L 4.5) – the largest aftershock and January 19, 2015 (M_L 3.8).

The triggered component of seismicity and the background activity can be separated by using the ETAS model, as the seismic activity of a region is assessed through the driving physical process which is correlated with the parameter's values.

2. COMPLETENESS MAGNITUDE AND *b* VALUE ESTIMATION. ETAS METHODOLOGY

The studies are based on the Romanian National Seismic Network detection capabilities during 2014–2015 period. The completeness magnitude, M_c = 1.5, presented in Fig. 1 was obtained with Goodness-of-fit test, GFT 90%, and could be considered as a reasonable completeness magnitude for most of the Marasesti area starting from November 22, 2014. The computing code was written in Matlab and was used to perform the GFT [7] and MBS (M_c by b-stabilty) methods [8].

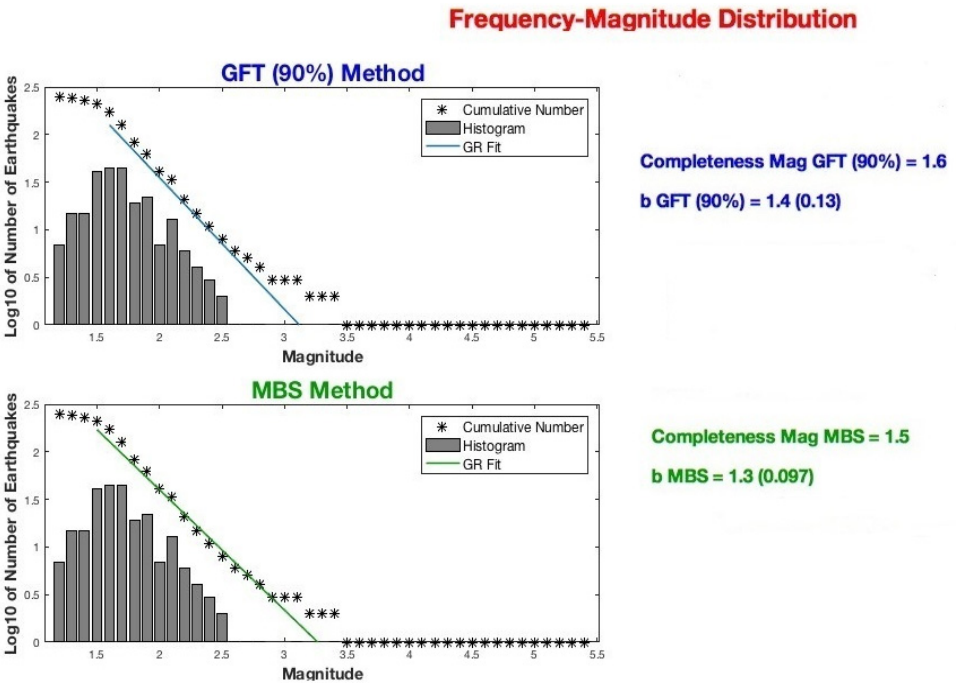

Fig. 1 – The FMD Frequency - Magnitude distribution and the completeness magnitude during the analysed Marasesti sequence (November 2014 – February 2015).

The *b*-value parameter of the Frequency Magnitude Distribution FMD is around 1.2 and indicates the stress concentration of the region during the seismic swarm period [9]. Figure 1 also shows the FMD. There is a sudden increase in the number of events in a short time from the beginning of the studied sequence. Thus, in the first 4 days, 150 events were registered out of a total of 222 events on the entire sequence. Starting with day 5 the sequence evolution was in accordance with Omori law [10], characterised by the *p* parameter. The results from Fig. 1 are synthesized in Table 1.

Table 1

Marasesti sequence recorded on November 22, 2014- estimation values

Estimation values	MBS	GFT (90%)
M_c Completeness Magnitude	1.5000	1.6000
b value	1.2647	1.3842
Standard deviation of the *b* value	0.974E-01	0.134E+00

Many studies revealed significant variation in *p* and *b* value in different tectonic regions, well correlated with regions under high stress or low crustal heterogeneity, as predicted in laboratory studies [11]. The aftershocks decay rate is measured by the Omori *p* parameter, with a variation value from 0.9 to 1.5 that can be related to the structural heterogeneity, the stress and crust temperature [12, 13].

The ETAS Epidemic type aftershock sequences model have been used in analyses of the local and regional catalogue [14, 15, 16]. In general, ETAS TM is a stochastic point process of particular relevance for modelling coseismic stress-triggered aftershock sequences model. The ETAS model is useful for summarizing patterns of seismicity

In the estimation ETAS -TM we used SEDAv.1 program [17, 18, 19]. We chose that the learning period in the coordinate grid Lat (45.45, 46. 20) and Long (26.80, 27.48) (Fig. 2) should contain seismic events recorded from the Romplus catalogue between November 21, 2014 (00:00:00) and 01 February 2016 (00:00:00), with magnitude in the range $1.2 < M_w < 5.4$.

The number of events in the total range of the sequence is 222. The number of rolls is limited to NRUN = 100. The following data are obtained from the rolls:

– The values of the 5 parameters of the TM model (Fig. 3), for each of the 100 runs of the Simulated Annealing (SA) algorithm;

– The value of the Log-Likelihood function (LOG LIK) for each run (Fig. 4);

– The expected number of events (EXP NEV) from the target period for each run (Fig. 4);

– The observed number of events (OBS NEV) in the target period for each run;

– The optimal values of the parameters of the TM model, for which the maximum value of the Log-Likelihood function is obtained.

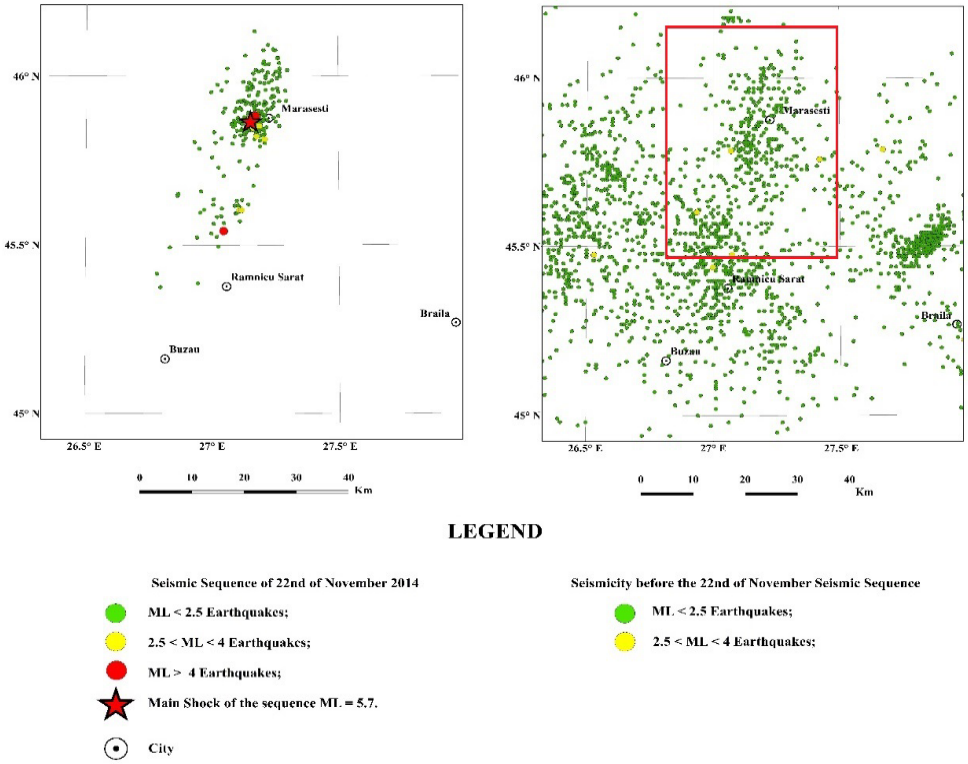

Fig. 2 – On the left side is presented the seismic sequence recorded at Marasesti with $M_L = 5.7$, in the right side it is presented before the sequence recorded at Marasesti, where the ETAS model was applied for the area delimited by the red rectangle [26.80E-27.48E,45.45N-46.20N].

Table 2 shows the results regarding the optimal values of the model parameter ETAS TM – (LOG LIK, EXP NEV, OBS NEV) as well as the value of the median and the confidence interval limits of 95%.

Table 2

TM ETAS parameters for the Marasesti sequences of the parameters resulting from the 100 runs with 95% confidence bounds

Parameter	Optimal value	Median value of runs	Confidence interval limits 95%
μ (event/day/km^2)	1.65e-03	1.56e-03	(1.40e-03, 2.16e-03)
k	2.62e-02	2.92e-02	(2.25e-02, 3.24e-02)
p	1.45e+00	1.47e+00	(1.41e+00, 1.49e+00)
c (days)	7.76e-02	8.36e-02	(6.31e-02, 9.16e-02)
α (1/magnitude)	1.57e+00	1.54e+00	(1.50e+00, 1.61e+00)
LOG LIK	5.21256e+02	5.21138e+02	(5.20698e+02, 5.21250e+02)
EXP NEV	222	224	(223, 224)
OBS NEV	222	222	224

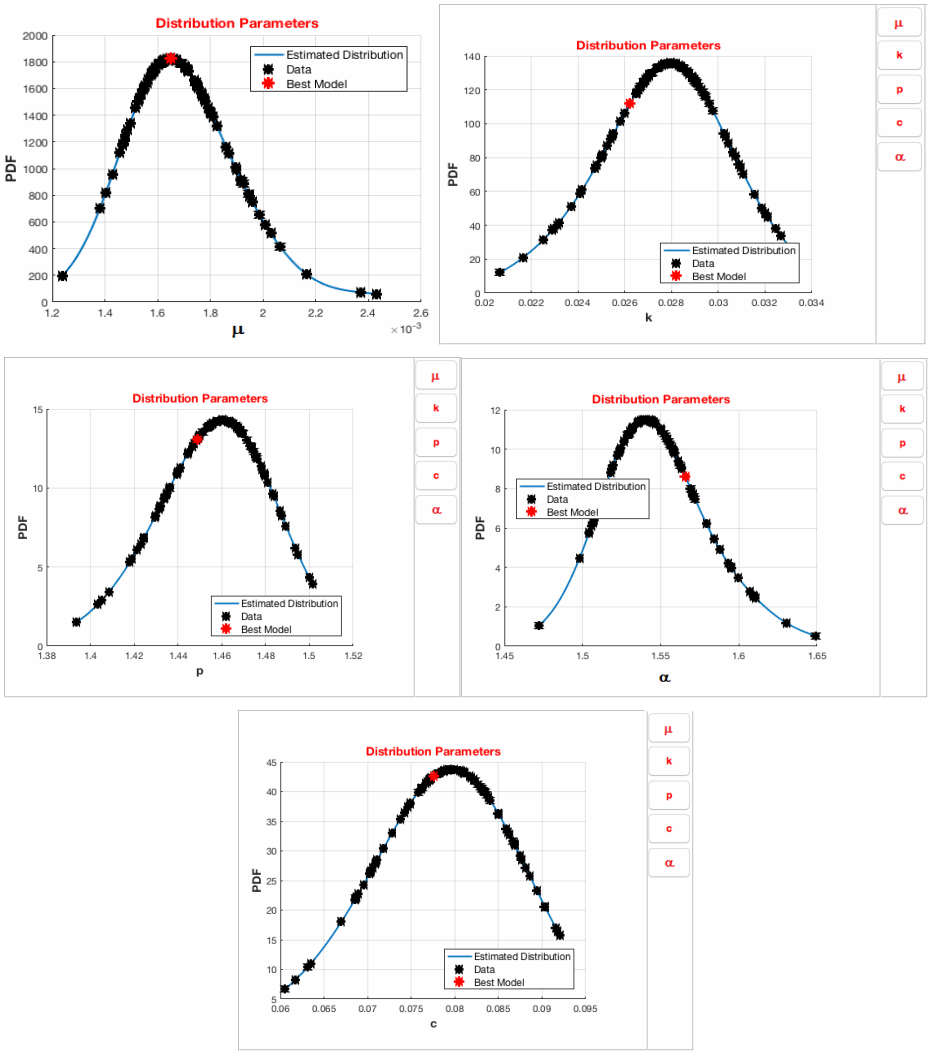

Fig. 3 – Distributions of TM model parameter values after 100 runs.

The parameter μ (shocks / day) is related to the background seismic activity. The parameter k (shocks / day) is part of the parameter K_i

$$K_i = k\mathrm{e}^{\alpha(M_i - M_{co})}, \tag{1}$$

which depends on the shock magnitude M_i and the cut off magnitude, M_{co}.

The parameter α (magnitude^{-1}) indicates the capacity to generate aftershocks of an earthquake with a magnitude higher than the threshold value. A subunit value of α indicates a group of seismic events occurring in a relatively short time

(earthquake swarms). In the case of seismic activity characterized by a main shock followed by aftershocks, the value of α is over 1.5.

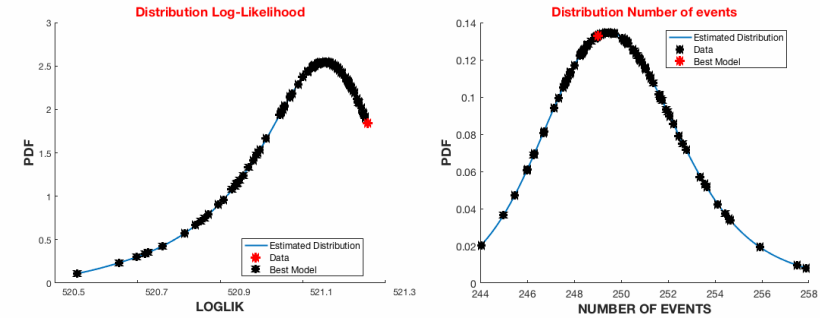

Fig. 4 – LOG LIK and EXP NEV parameter value distributions after 100 runs.

The *p* parameter (dimensionless) represents the rate of decrease of the number of replicas and is considered to reflect geophysical effects specific to the analysed region.

The value of the μ parameter 1.65e-03 indicates a low background seismic activity and the value of the parameter α 1.57 indicates a clear connection between a main event and a series of aftershocks.

Based on the data sets obtained from the 100 runs, the correlation graphs (Fig. 5) can be drawn between all the pairs of parameters $\{\mu, k, p, c, \alpha\}$ of the TM model. There are clearly positive correlations between the sizes in the set $\{k, p, c\}$ and clearly negative between the parameter α and the sizes in the set.

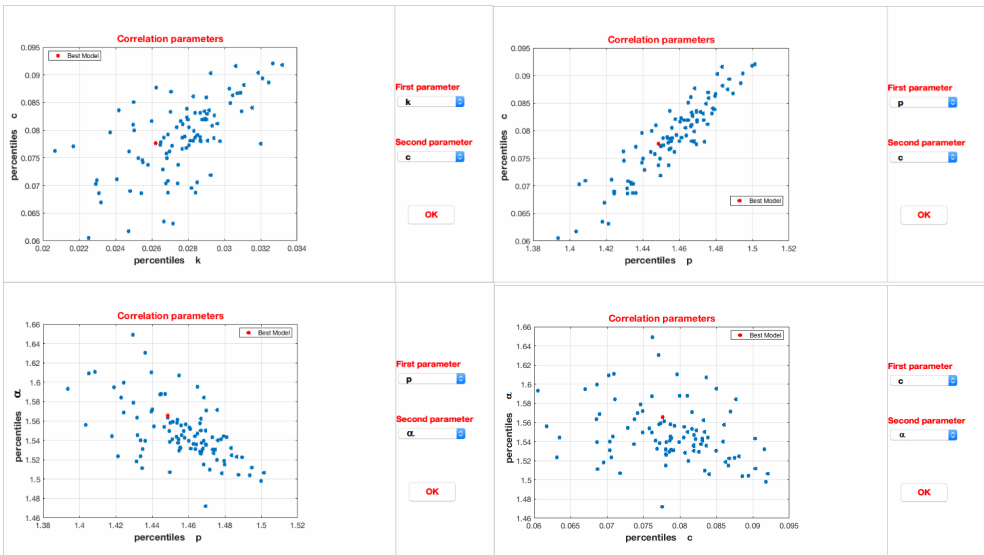

Fig. 5 – Correlation graphs between TM model parameters.

The TM model can be tested by running the residual analysis or testing the number of events.

3. RESIDUAL ANALYSIS

In estimating the ETAS – TM model and the seismic residual, we chose the learning period of the algorithm on the localized seismic events with Lat 45.705N – 46.180N and Long 26.800E – 27.300E coordinates.

Seismic events recorded from the Romplus catalogue are used between January 1, 2010 (00:00:00) – November 17, 2017 (00:00:00), with magnitude between $1.2 < M_w < 5.4$ and depth $0.6 < h < 70$ km.

The analysis of the residual seismic activity, proposed by [14] starts from the epidemic model, which assumes that each shock / seismic event has its own aftershock generated with a stochastic frequency proportional to its magnitude. The general seismic activity model assumes that the seismic data from the initial moment is produced with the rate $\lambda(t)$. The integral of the rate of event production according to time t_i is calculated:

$$\tau_i = \int_0^{t_i} \lambda(s)\ \mathrm{d}s = \mu\ t_i + \int_0^{t_1} \sum_{t_i<t_i} \frac{k \cdot e^{\rho(M_J\ M_c)}}{(s - t_j + c)^p} \mathrm{d}s. \tag{2}$$

The time scale is modified by integrating the event production rate, realizing the biunivocal transformation of time moments $\{t_i\}$ into the sequence $\{\tau_i\}$ and having a distribution according to a standard stationary Poisson process.

If there are differences between the seismic activity and the associated model, estimated by a standard stationary Poisson process, specific characteristics of the data set that are not included in the initial model are detected. By this method [14], there were detected periods of inconsistency with the Poisson model, characterized by rates of production of events below the expected rate, called periods of seismic calm, detected immediately before the production of major shocks or strong replicates of a main shock.

In testing the model by residual analysis, the SEDAv.1 program was used, using the method [17] and verifies the Poisson distribution hypothesis of the residual through two tests:

– the RUNS test verifies that there is a temporal tendency in the periods between events detected in the variables associated with the transformed time moments $\{\tau_i\}$;

– the Kolmogorov-Smirnov (1) test applied to a sample, which determines whether the time variables transformed $\{\tau_i\}$ in the periods between events follow an exponential distribution [20]

The value of the exponent p resulting from the RUNS test is $p = 0.0225$, and that given by the Kolmogorov-Smirnov test is $p = 0.56$ (Table 3).

Table 3

The ETAS parameters – TM-technique was applied for the area delimited by the red rectangle [26.80E-27.48E,45.45N-46.20N] in period January 1, 2010 (00:00:00) – November 17, 2017 (00:00:00), with magnitude between $1.2 < M_w < 5.4$ and depth $0.6 < h < 70$ km

Parameter	Optimal value	Median value of runs	Confidence interval limits 95%
μ	3.61 e-02	3.52e-02	(2.93e-02, 3.85e-02)
k	6.29 e-03	6.88 e-03	(5.94-03, 7.3-02)
p	1.07	1.07+00	(1.06e+00, 1.08e+00)
c	2.42 e-02	2.49e-02	(5.82 e-03, 2.91e-02)
α	1.96 e+00	1.94 e+00	(1.54e-04, 1.98e+00)
LOG LIK	–3.32404 e+02	–3.32597 e+02	(–4.0957e+02, –3.32409+02)
EXP NEV	560	562	562
OBS NEV	559	559	559

Residual analysis for the Marasesti sequence – illustrated in Fig. 6 shows no major inconsistencies regarding the background activity compared to the statistical model, the data is recorded in the period 2010–2018 for the total number of events 559 events.

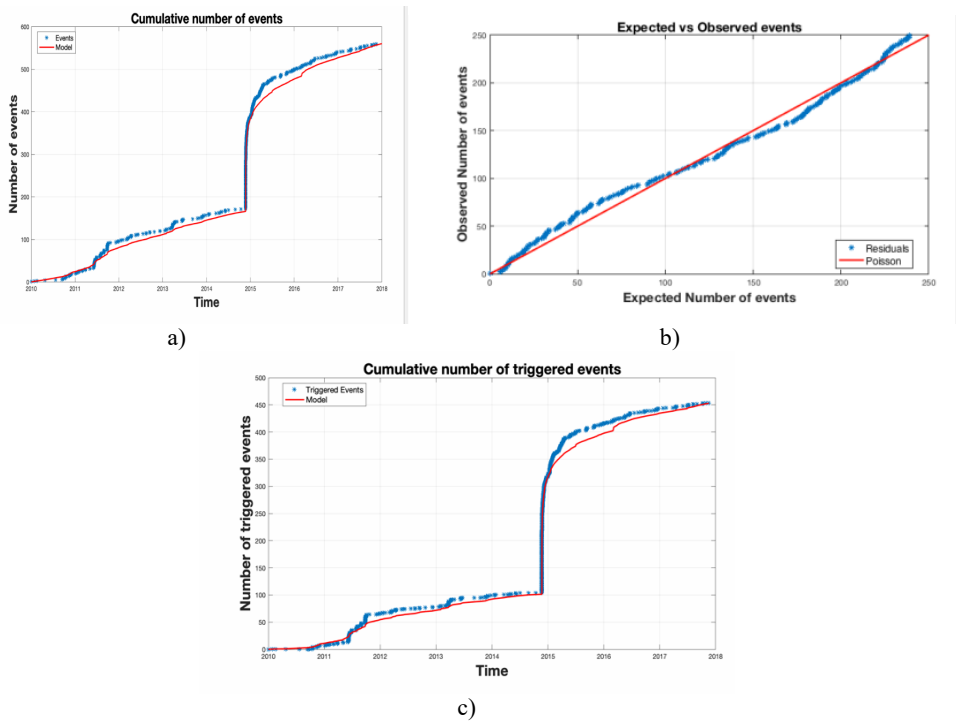

Fig. 6 – (Color online) Residual analysis for the Marasesti sequence: a) cumulative number of events; b) cumulative plot of observed events (blue points) in the Marasesti region, together with the expected cumulative distributions (red line); c) number of triggered events.

The comparative results between the data provided by the model (estimated) and the observed ones are given in Table 4. We observe close values between the total number of expected and estimated events, both for the events belonging to the background seismic activity and for the triggered ones.

Table 4

Residuals Analysis

	Expected number of events	Observed number of events
Total number of the events	559.95	559
Expected number of background events	105.6	105
Observed number of triggered events	248.6111	247.7894

4. IDENTIFICATION OF A SEISMIC SEQUENCE

Seismic sequence identification is one of the main objectives of this paper and is graphically presented in Fig. 7.

For the identification of the seismic sequence from Marasesti from November 22, 2014 were used the test parameters from the ETAS applied on the Romplus catalogue presented in Table 2.

Statistical parameters were calculated for the coordinates Lat (45.705, 46. 180)N and Long (26.800, 27.300)E.

The test was successfully recorded with threshold probability of 0.95% (PL).

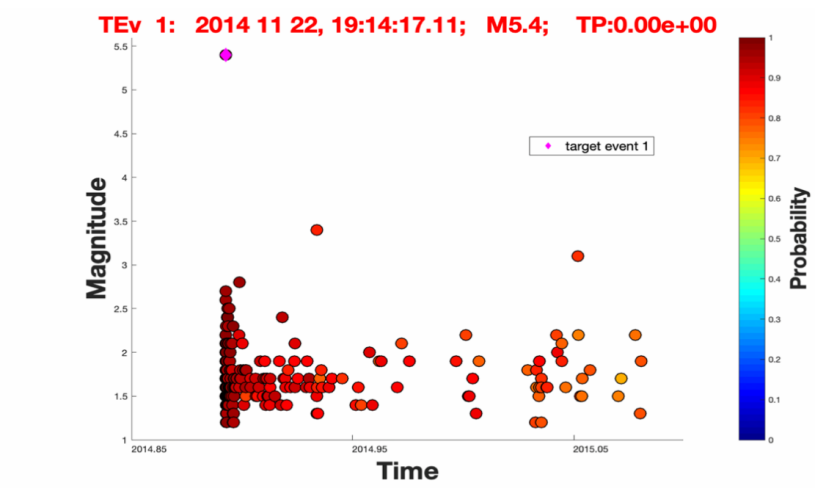

Fig. 7 – Identification of Marasesti sequence on November 22, 2014.
The figure shows the time-magnitude plot of the identified events.

A stochastic model was used after [20] and implemented in SEDAv1.0. The model for the Marasesti crustal area was obtained by using NRUNS-type statistical tests after [21] associated with a threshold probability PL in detecting the occurrence of a running sequence seismic events from the Romplus catalogue.

5. RESULTS AND DISCUSSIONS

To identify Marasesti seismic sequences with a stochastic method we applied the tests on a set of 559 crustal events. These tests were validated with a threshold probability PL > 95% as seen in Fig. 7.

The distribution of b reveals a high concentration of stress, *b* value 1.2 was used to perform the GFT 90% (Goodness-of-fit test), including seismic swarm.

The main objective of this paper was materialized by the creation of an ETAS catalogue with the calculation parameters specific to the location surface of the seismic events related to the Marasesti sequence on November 22, 2014.

The achievement of this objective encourages further research for increasing the sequence ETAS database in Romania by modelling the statistical algorithms that use the background seismicity in order to estimate the main shock of a seismic sequence correlated with precursors in general.

Thus, in a time-dependent forecast, the probabilities $P(t)$ depend on the information $I(t)$ available at time t when the forecast is made.

The most useful information for operational forecasting comes from seismic catalogues and the geological history of surface ruptures.

The application of these modern calculation techniques by stochastic methods is of major importance for estimating regional and local seismic hazard.

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