



Declustering of Iran earthquake catalog (1983–2017) using the epidemic-type aftershock sequence (ETAS) model

Nader Davoudi¹ · Hamid Reza Tavakoli¹ · Mehdi Zare² · Abdollah Jalilian³

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Abstract

The main goal of this article is to decluster Iranian plateau seismic catalog by the epidemic-type aftershock sequence (ETAS) model and compare the results with some older methods. For this purpose, Iranian plateau bounded in 24°–42°N and 43°–66°E is subdivided into three major tectonic zones: (1) North of Iran (2) Zagros (3) East of Iran. The extracted earthquake catalog had a total of 6034 earthquakes ($M_w > 4$) in the time span 1983–2017. The ETAS model is an accepted stochastic approach for seismic evaluation and declustering earthquake catalogs. However, this model has not yet been used to decluster the seismic catalog of Iran. Until now, traditional methods like the Gardner and Knopoff space–time window method and the Reasenber link-based method have been used in most studies for declustering Iran earthquake catalog. Finally, the results of declustering by the ETAS model are compared with result of Gardner and Knopoff (Bull Seismol Soc Am 64(5):1363–1367, 1974), Uhrhammer (Earthq Notes 57(1):21, 1986), Gruenthal (pers. comm.) and Reasenber (Geophys Res 90:5479–5495, 1985) declustering methods. The overall conclusion is difficult, but the results confirm the high ability of the ETAS model for declustering Iranian earthquake catalog. Use of the ETAS model is still in its early steps in Iranian seismological researches, and more parametric studies are needed.

Keywords Declustering · Earthquake catalog · Seismotectonic provinces of Iran · Windowing methods · ETAS model

Abbreviations

| | |
|------|---|
| Re | Reasenberg |
| Uh | Uhrhammer |
| G-K | Gardner and Knopoff |
| Gr | Gruenthal method |
| ETAS | Epidemic-type aftershock sequence model |

Introduction

Declustering an earthquake catalog or, similarly, separating it into independent earthquakes (mainshocks) and dependent earthquakes (foreshocks and aftershocks) is very important in seismological studies. There are several declustering approaches that have been proposed over the years (Van Stiphout et al. 2012) which include deterministic approaches such as window-based method (Gardner and Knopoff 1974; Uhrhammer 1986; Gruenthal pers. comm.), single-link cluster method (Frohlich and Davis 1990; Davis and Frohlich 1991), linking to spatial interaction zones (Reasenber 1985; Savage 1972) and probabilistic approaches such as stochastic model (Kagan and Jackson 1991; Zhuang et al. 2002, 2004, 2006), independent stochastic declustering model (Marsan and Longline 2010), model-based inter-event time distribution (Hainzel et al. 2006), coefficient of variant inter-event times (Bottiglieri et al. 2009). (See Van Stiphout et al. 2012 for more information about the Gruenthal method.)

The epidemic-type aftershock sequence (ETAS) model is a statistical approach based on a space–time branching process model that explains how each earthquake epidemically can generate its aftershocks (Van Stiphout et al. 2012).

✉ Hamid Reza Tavakoli
tavakoli@nit.ac.ir
Nader Davoudi
naderdawoodi@gmail.com
Mehdi Zare
mzare@iiees.ac.ir
Abdollah Jalilian
jalilian@razi.ac.ir

¹ Department of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran
² Department of Seismology, International Institute of Earthquake Engineering and Seismology, Tehran, Iran
³ Department of Statistics, Razi University, Kermanshah, Iran

Despite the great potential of the ETAS model, mainly due to the simplicity of traditional methods, generally, researchers have used traditional deterministic approaches to decluster Iran earthquake catalog. The Iranian plateau is part of the Alpine-Himalayan seismotectonic belt. The vast seismic zone in the earthquake-prone Iranian plateau has various seismotectonic provinces with different seismicity pattern. In this paper, based on the zoning proposed by Shahvar et al. (2013), a new zoning is presented. The Iranian plateau is divided into three major seismotectonic zones, and a central region without recorded seismic sequences is neglected. Researchers have proposed different major seismotectonic provinces for Iran. Mirzaei et al. (1997) provide a uniform seismic catalog of Iran (22°–42°N and 42°–66°E) in time span 4th century B.C.—1994. They subdivide Iranian plateau into five main seismotectonic areas: (1) Alborz-Azerbaijan, (2) Kopeh-Dagh, (3) Zagros, (4) Central-East of Iran, (5) Makran. Following this research, this zoning has been documented in many studies (Zafarani and Soghrat 2012; Karimiparidari et al. 2013; Zare et al. 2014; Mousavi-Bafrouei et al. 2015). Shahvar et al. (2013) present an integrated catalog for Iranian plateau (1900–2011, $M_w > 4$). They subdivide Iran's plateau into two major areas: (1) Zagros and (2) Alborz-Central Iran and decluster the extracted catalog by Uhrhammer (1986) procedure. Karimiparidari et al. (2013) present a uniform catalog for the Iranian earthquakes (3rd century B.C.—2010). They use Gardner and Knopoff (1974) window method to decluster the compiled catalog. Mousavi-Bafrouei et al. (2015) prepared an integrated catalog for the Iranian plateau from the 4th century B.C. to 2012. They used Gardner and Knopoff (1974), Uhrhammer (1986) and Reasenber (1985) methods to decluster Iran earthquake catalog. Amini (2014) compared Reasenber (1985) and Gruenthal (pers. comm.) declustering methods for Alborz-Azerbaijan and Kopeh-Dagh seismotectonic regions in the north of Iranian plateau in time span 550 B.C.—2006. She concluded that Reasenber's (1985) declustering method estimates the number of mainshocks three times more than the Gruenthal's (pers. comm.) method. Ommi et al. (2016) have studied aftershock decay rate for 15 selected earthquakes occurred in Iranian plateau during the period 2002–2013. They used Gardner and Knopoff (1974), Wells and Copper-smith (1994) and Burkhard and Grünthal (2009) methods to decluster the earthquake catalog of Iran.

In this study, Iranian plateau is subdivided into three major seismotectonic zones: (1) North of Iran, (2) Zagros and (3) East of Iran. An earthquake catalog including 6034 earthquakes ($M_w > 4$) in the time span 1983–2017 is extracted for these three zones. Finally, the extracted catalog has been declustered using the window-based method (Gardner and Knopoff 1974; Uhrhammer 1986; Gruenthal pers. comm.), single-link cluster method (Reasenber 1985) and ETAS model. The results are compared, and discussions and conclusions are made.

Methods

Window-based methods

So far, in most studies conducted to decluster earthquake catalogs, the Reasenber's (1985) linked-window method or the variant of Gardner and Knopoff (1974) windowing technique has been used. In Gardner and Knopoff's windowing method, a specified distance interval $L(M)$ and a specified time interval $T(M)$ have been defined for each earthquake with a magnitude of M . Subsequent earthquakes will be identified as an aftershock if they occur within this time-space window. Foreshocks will be identified the same as aftershocks. The largest shock in a sequence has the largest time-space window and is a mainshock (Van Stiphout et al. 2012). The size of time-space windows in Gardner and Knopoff (1974), Uhrhammer (1986) and Gruenthal (pers. comm.) methods is shown in Table 1.

In the linked-window method (Cluster Method) presented by Reasenber (1985), earthquakes are associated with clusters by defining spatial and temporal interaction zone around the earthquakes. The temporal property of the interaction zone is defined by Omori's law. The spatial extension of the interaction zone is chosen according to stress distribution near the mainshocks. (For more details, see Reasenber 1985; Molchan and Dmitrieva 1992; Van Stiphout et al. 2012.) The input parameters for the Cluster Method are presented in Table 2. In this study, the standard parameters of Reasenber (1985) method are used.

Table 1 Windows sizes in Gardner and Knopoff (1974), Uhrhammer (1986) and Gruenthal (pers. comm.) declustering methods

| Method | Distance (km) | Time (day) |
|----------------------------|---------------------------------|--|
| Gardner and Knopoff (1974) | $10^{0.1238M + 0.983}$ | $\begin{cases} 10^{0.032M+2.7389} & \text{if } M \geq 6.5 \\ 10^{0.5409M-0.547} & \text{else} \end{cases}$ |
| Uhrhammer (1986) | $10^{1.77 + (0.037 + 1.02M)^2}$ | $\begin{cases} e^{-3.95 + (0.62 + 17.32M)^2} & \text{if } M \geq 6.5 \\ 10^{2.8 + 0.024M} & \text{else} \end{cases}$ |
| Gruenthal (pers. comm.) | $e^{-1.024 + 0.804M}$ | $e^{-2.87 + 1.235M}$ |

Table 2 Input parameters for the Cluster Method presented by Reasenber (1985)

| Parameter | Standard | Min | Max |
|-------------------|----------|-----|------|
| τ_{\min} | 1 | 0.5 | 2.5 |
| τ_{\max} | 10 | 3 | 15 |
| p_1 | 0.95 | 0.9 | 0.99 |
| x_{meff} | 4.0 | 0 | 1 |
| x_k | 0.5 | 1.6 | 1.8 |
| r_{fact} | 10 | 5 | 20 |

τ_{\min} and τ_{\max} are the minimum and maximum look-ahead time of observing the next earthquake at a certain probability, p_1 . x_k is the increase of the lower cutoff magnitude during clusters: $x_{\text{meff}} = x_{\text{meff}} + x_k M$, where M is the magnitude of the largest event in the cluster, x_{meff} is the effective lower magnitude cutoff for catalog, r_{fact} is the number of crack radii surrounding each earthquake within new events considered to be part of the cluster (Van Stiphout et al. 2012)

ETAS model

An earthquake catalog typically includes date, time (t), magnitude (m) and epicenter coordination [longitude (x), latitude (y)] of earthquakes. The earthquake catalog can be expressed by a point pattern in time-space (Vere-Jones 1970; Ogata 1998; Zhuang et al. 2002). As many scholars explained (Molchan and Dmitrieva 1992; Ogata 1998; Zhuang et al. 2002; Van Stiphout et al. 2012) that such point process can be described by conditional intensity function as follows:

$$\lambda(t, x, y | \mathcal{H}_t) = \mu(x, y) + \sum_{\{i: t_i < t\}} \kappa(m_i) g(t - t_i) f(x - x_i, y - y_i; m_i) \quad (1)$$

where $\lambda(t, x, y | \mathcal{H}_t)$ is the space-time conditional intensity function. $\mathcal{H}_t = \{(t_i, x_i, y_i, m_i); t_i < t\}$ is the history of earthquakes occurrence up to time t (Ogata 1998; Zhuang et al. 2002). $\mu(x, y)$ is the background seismicity rate and $\kappa(m_i) g(t - t_i) f(x - x_i, y - y_i; m_i)$ is the seismicity rate induced by the i_{th} event that has already occurred (Zhuang 2011).

$\kappa(m_i)$ is the expected number of triggered earthquakes from an earthquake of magnitude m_i . $g(t - t_i)$ and $f(x - x_i, y - y_i; m_i)$ respectively are the probability density function of the occurrence time and occurrence location of triggered earthquakes.

The background seismicity rate function is assumed to be stationary in time and is defined by a Poisson process.

Occurrence time function is based on modified Omori law and occurrence location function is a radially symmetric function dependent on the location and magnitude of earthquakes (Ogata 1998; Zhuang et al. 2002). The second part in Eq. 1 shows how a mainshock with the magnitude of m_i trigger its aftershocks. In the ETAS model, any triggered earthquake (aftershock) can also have its aftershocks. The aftershocks sequence can be continued epidemically. As proposed by Zhuang et al. (2002), the probability that the j_{th} earthquake is triggered by the i_{th} earthquake can be estimated by Eq. 2 (Van Stiphout et al. 2012):

$$p_{ij} = \frac{k(M_i) g(t_j - t_i) f(x_j - x_i, y_j - y_i | M_i)}{\lambda(t_j, x_j, y_j, M | \mathcal{H}_{ij})} \quad (2)$$

Consequently, the probability that the j_{th} earthquake is a triggered (dependent) earthquake is

$$p_j = \sum_{i=1}^{j-1} p_{ij} \quad (3)$$

The value of p_j can range from 0 to 1. An earthquake catalog can be declustered by calculating this probability for all events in the catalog and considering a threshold value of p_j .

Results and discussion

In a statistical approach such as the ETAS model, the data quality and quantity have a great impact on the final results. The earthquake catalog that is used in this study is extracted from the data center of the International Institute of Engineering and Seismology (<http://www.iiees.ac.ir/fa/eqcatalog/>). The study area is bounded at 24°–42°N and 43°–66°E, and the study time period is 1983–2017. We subdivide the Iranian plateau into three major tectonic zones: (1) North of Iran, (2) Zagros and (3) East of Iran (Fig. 1). Our analysis showed that these three seismic zones have different seismicity regimes in stochastic approach and should not be combined together. Finally, our extracted catalog had a total of 6034 earthquakes ($M_w > 4$) in the time span 1983–2017. As shown in Fig. 1, the number of earthquakes occurring in the center of Iranian plateau is very small. Modeling this region is not possible due to lack of required data. Adding this area to the eastern region will reduce the seismicity rate incorrectly. Thus, this region is neglected in this study.

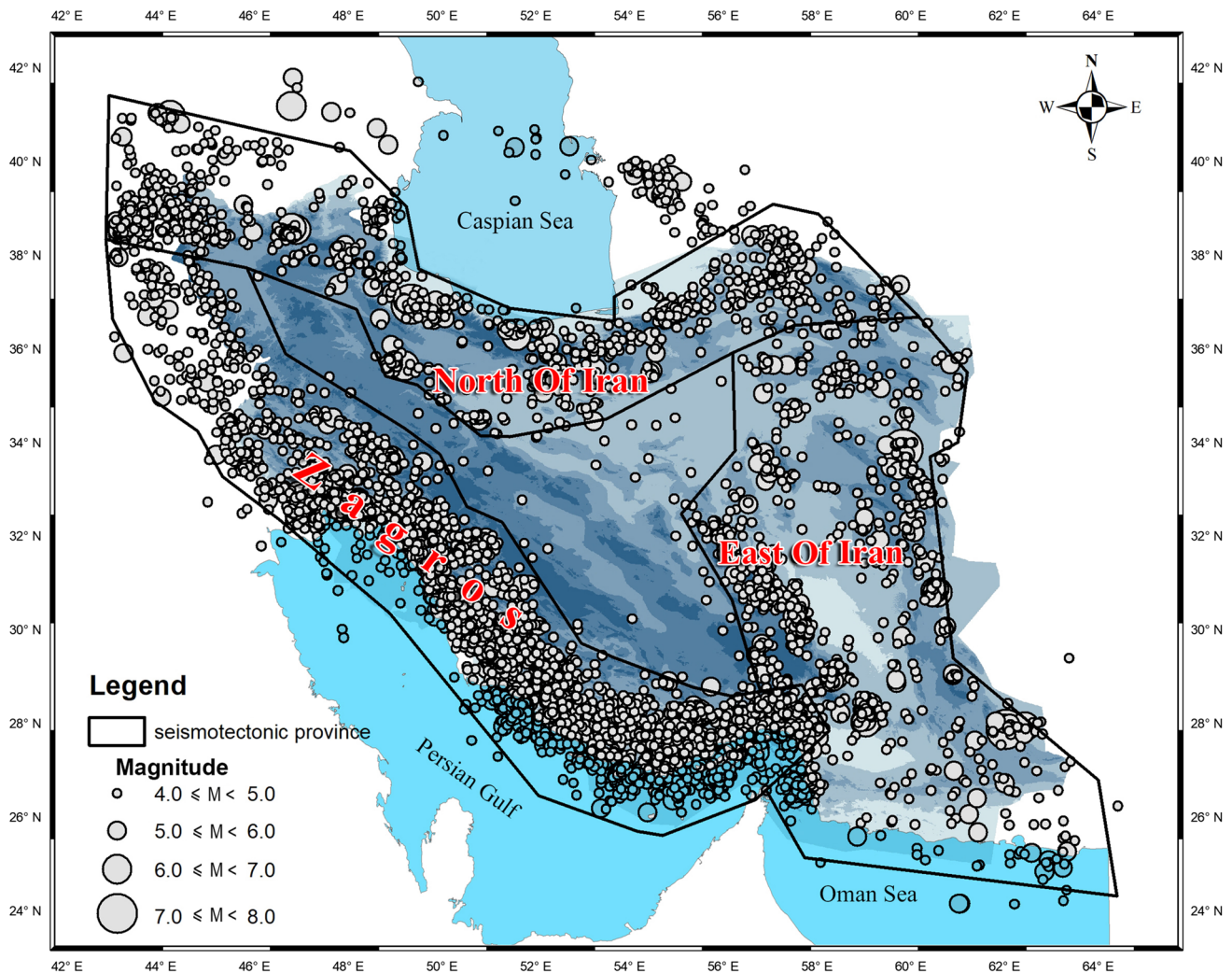


Fig. 1 Major seismotectonic provinces of Iran. Zoning that is used in this study. Circles show epicenters of earthquakes ($M_w > 4$) that occurred from 1983 to 2017

The moment magnitude scale (M_w) is the most appropriate scale for earthquakes. This scale has not been saturated; it has physical meaning and is a more adequate magnitude scale for great earthquakes (Kanamori 1977). For preparing a unified catalog, all other magnitudes scales are converted to the moment magnitude scale using the regression method and statistical analysis proposed by Shahvar et al. (2013). As Huang and LiWX (1994) pointed out, “the completeness and reliability of data are the basis of earthquake research”. In particular, data reliability will be more important when using the stochastic ETAS model. Actually, we need a large

number of recorded earthquake sequences in the catalog to fit the ETAS model. The date January 1, 1983 is the starting point of analysis by investigating the Iranian instrumental earthquake catalog considering the Iranian seismic network development. The magnitude of completeness (M_c) is variable in different seismotectonic zones. The study results (Zare et al. 2014; Mousavi-Bafrouei et al. 2015) show that the threshold of M_c optimistically is above 4 ($M_w > 4$) for a recent modern instrumental catalog of the Iranian plateau.

According to Eq. 3, the probability that the j_{th} earthquake is a mainshock or a dependent earthquake (aftershock and

foreshock) can be estimated with the intensity function values and background seismicity rate. The catalog can be declustered with this specified probability for each event available in the catalog. In fact, a probability threshold must be chosen. If the value of $1 - p_j$ from Eq. 3 be greater than the selected threshold of probability, the event will be considered as a mainshock. Selecting the threshold value is optional and based on engineering judgment. Obviously, assuming different thresholds will result in different catalogs. In fact, this user-defined optional property of the ETAS approach is one of the advantages of this probabilistic model compared to the traditional deterministic declustering methods. The three listed seismotectonic zones of Iran have different seismic parameters. By fitting a separated ETAS model on any of the three zones, the background seismicity rate and the declustered catalog are extracted. In this study, we use the R (Jalilian and Zhuang 2016) package ETAS from the Comprehensive R Archive Network (CRAN) available at <http://CRAN.R-project.org/package=ETAS> and GitHub at <https://github.com/jalilian/ETAS> (under GPL 2 license). Also in this study, the ZMAP software package (Weimer 2001) is used to decluster the Iran earthquake catalog, using the mentioned windowing methods. The results of declustering the earthquake catalog in the three major seismotectonic regions of Iran are presented in Table 3 by different methods in ZMAP software.

The final maximum likelihood estimates values of the ETAS model parameters for the three different major seismotectonic zones of Iran are presented in Table 4. In Fig. 2 are shown the background seismicity rate and the clustering coefficient for the three zones.

Table 3 Results of declustering the earthquake catalog of Iran (1983–2017, $M_w > 4$) using ZMAP software

| Zone name | Total number of earthquakes | Method | Number of clusters | Number of mainshocks | Mainshock ratio to total events |
|---------------|-----------------------------|--------|--------------------|----------------------|---------------------------------|
| North of Iran | 1196 | a | 39 | 974 | 0.81 |
| | | b | 83 | 764 | 0.63 |
| | | c | 151 | 638 | 0.53 |
| | | d | 184 | 521 | 0.43 |
| Zagros | 3741 | a | 149 | 3251 | 0.86 |
| | | b | 332 | 2531 | 0.67 |
| | | c | 509 | 1684 | 0.45 |
| | | d | 547 | 1094 | 0.29 |
| East of Iran | 1097 | a | 48 | 905 | 0.82 |
| | | b | 78 | 686 | 0.62 |
| | | c | 124 | 544 | 0.49 |
| | | d | 151 | 433 | 0.39 |

(a) Reasenber (1985), (b) Uhrhammer (1986), (c) Gardner and Knopoff (1974) and (d) Gruenthal (pers. comm.)

Table 4 Maximum likelihood estimates values of ETAS model in the three seismotectonic provinces of Iran

| Parameter | North of Iran | Zagros | East of Iran |
|-----------|---------------|----------|--------------|
| μ | 0.802126 | 0.767781 | 0.827309 |
| A | 0.280538 | 0.418631 | 0.396799 |
| c | 0.024071 | 0.012243 | 0.020602 |
| α | 1.018709 | 1.278380 | 0.949921 |
| P | 1.10199 | 1.074867 | 1.120693 |
| D | 0.002009 | 0.009581 | 0.002298 |
| q | 1.832303 | 2.091095 | 1.532486 |
| γ | 0.887649 | 0.181203 | 0.558234 |

The frequency of each magnitude in the declustered earthquake catalogs is presented in Figs. 3, 4 and 5. The total number of earthquakes in the catalogs after declustering by different methods is shown and compared in Fig. 6. For a better comparison in Fig. 6, the ETAS model results are presented with respect to different threshold values. As expected, we have a catalog with a maximum number of independent earthquakes considering the least threshold (0.5). Uhrhammer and Reasenber's methods compared to ETAS model estimate more mainshocks in the declustered catalog. This is the case in all seismotectonic zones in this study. There is a great difference that roughly we can say that the Uhrhammer and Reasenber's methods overestimate the mainshocks number. The maximum number of clusters and therefore a maximum number of dependent earthquakes are estimated using the Gruenthal windowing

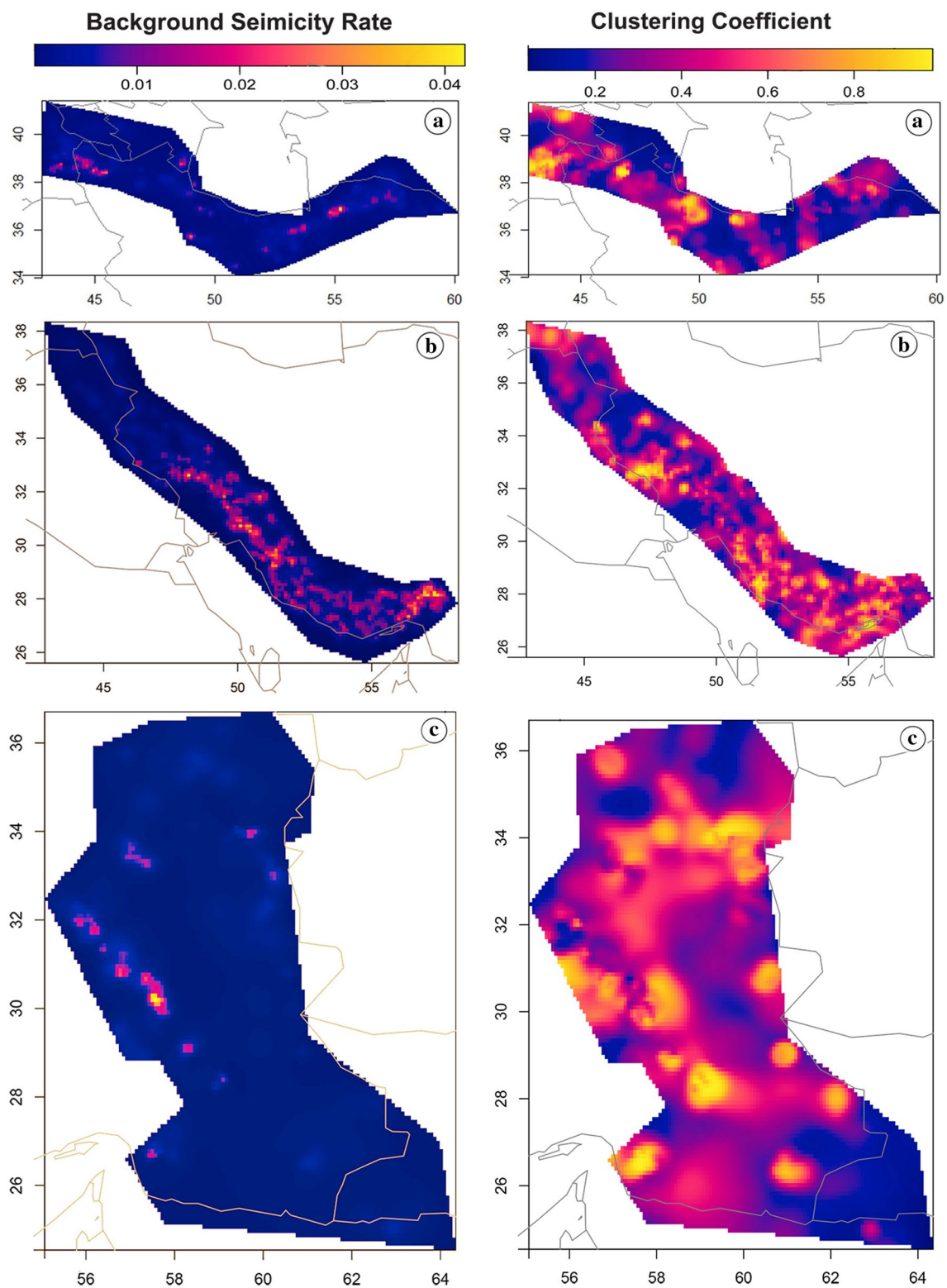


Fig. 2 Background seismicity rate and clustering coefficient for the three major seismotectonic zones of Iran using ETAS model. **a** North of Iran. **b** Zagros region. **c** East of Iran

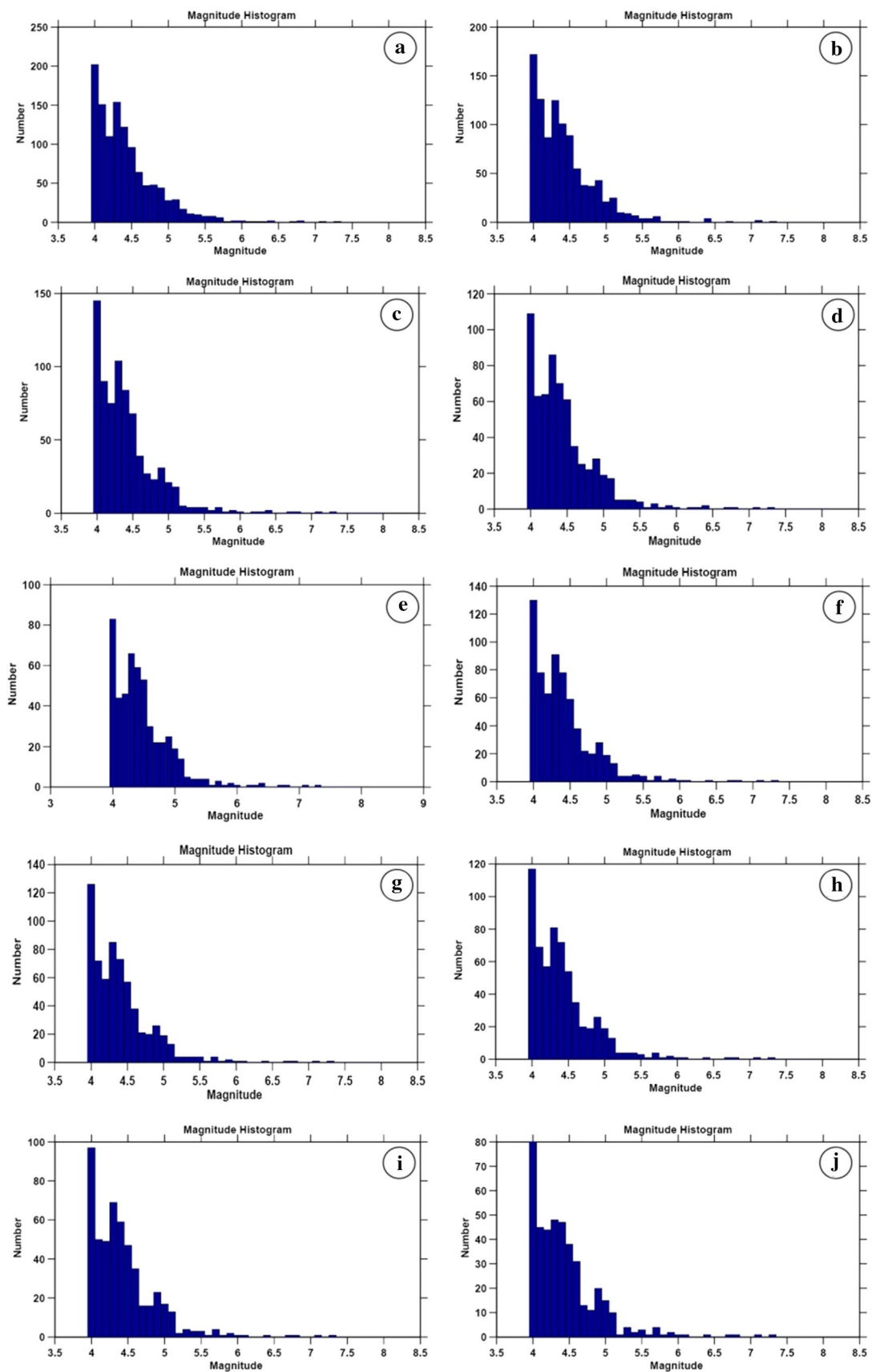


Fig. 3 Frequency of each magnitude in earthquake catalog of North of Iran that is declustered using different methods. **a** not declustered. **b** Reasenberg. **c** Uhrhammer. **d** Gardner and Knopoff. **e** Gruenthal method. **f, g, h, i, j** ETAS model with probability thresholds 0.5, 0.6, 0.7, 0.8, 0.9, respectively

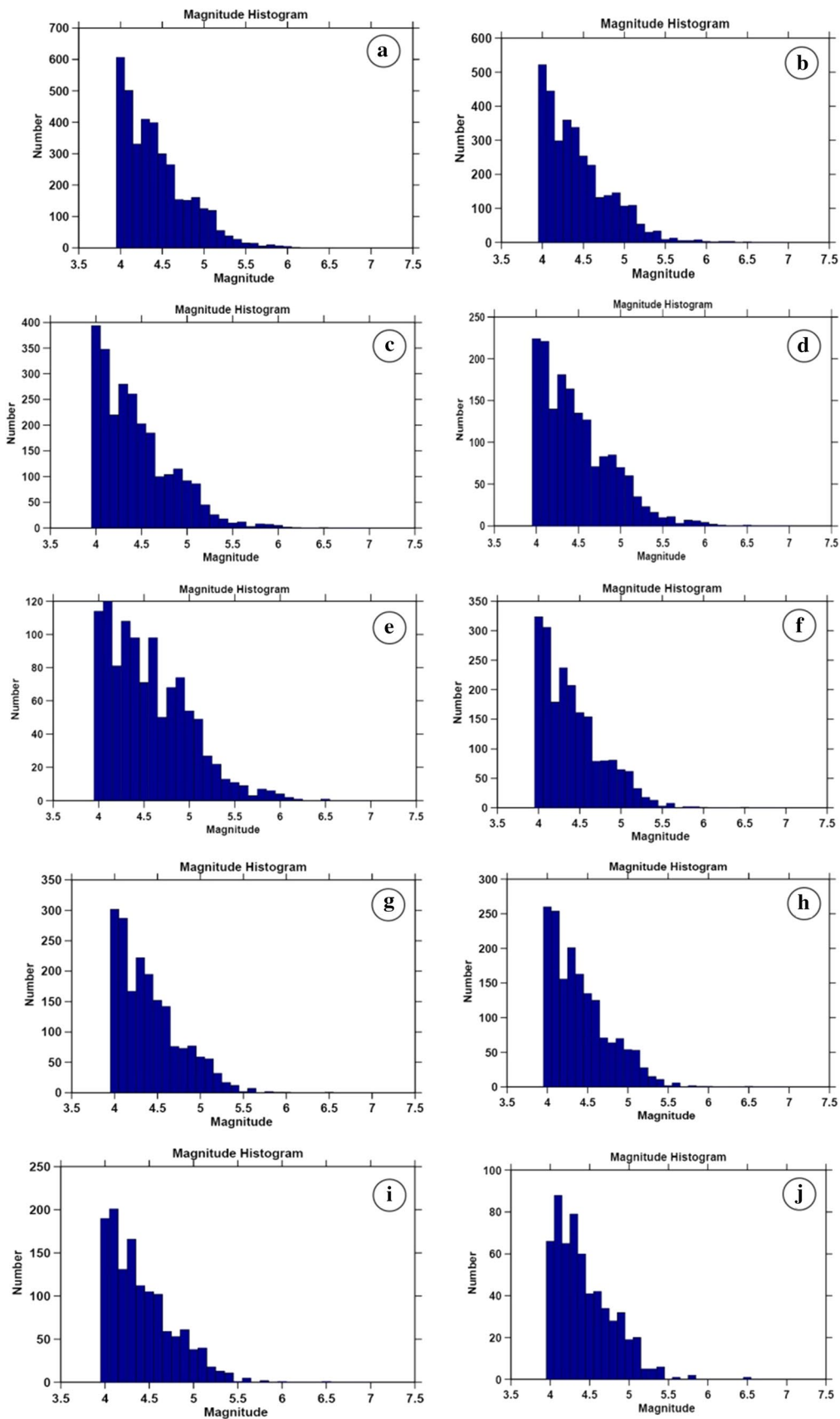


Fig. 4 As in Fig. 3 for Zagros region of Iran

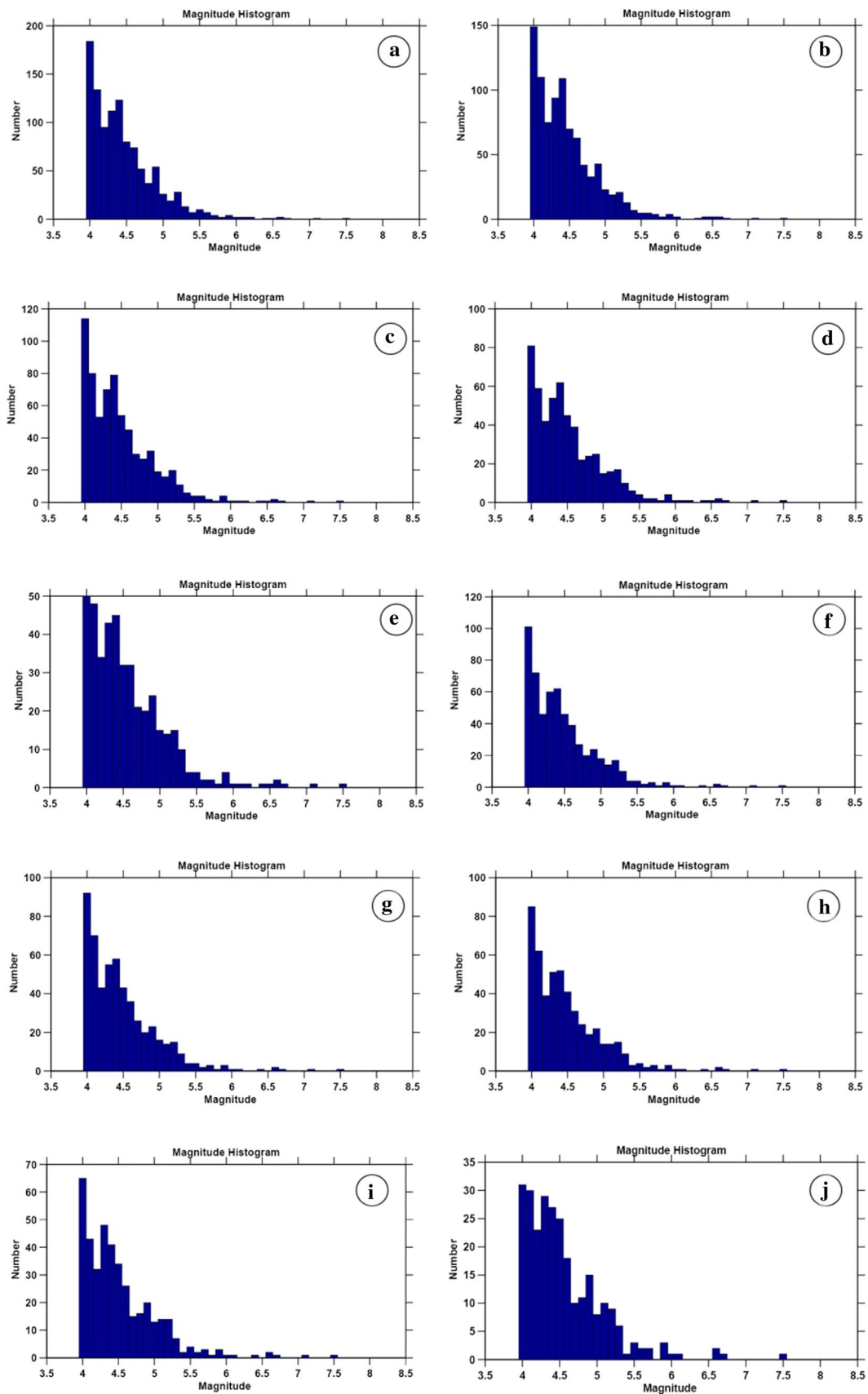


Fig. 5 As in Fig. 3 for East of Iran

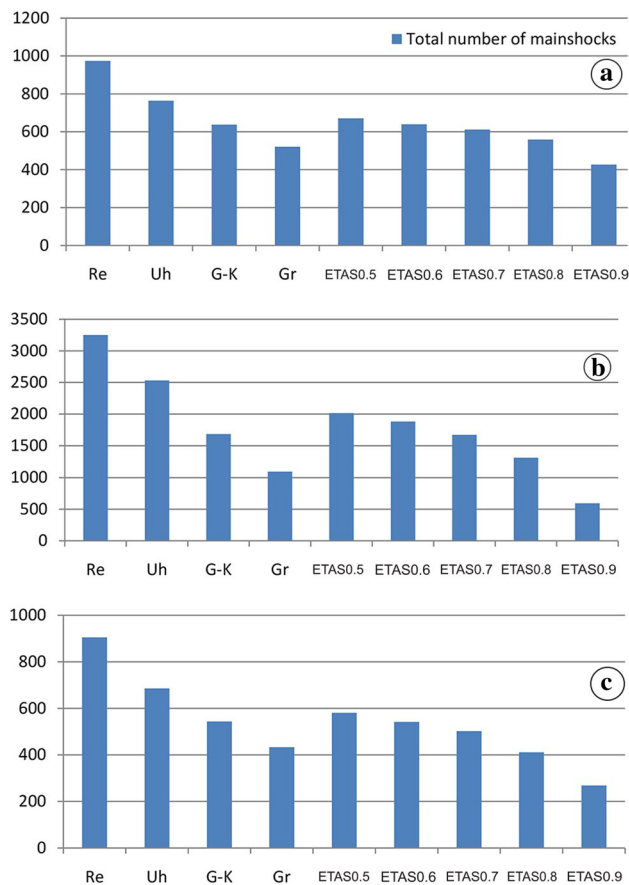


Fig. 6 A chart for comparing the results of different declustering methods. Re: Reasenber method, Uh: Uhrhammer method, G-K: Gardner and Knopoff method, Gr: Gruenthal method, ETAS: ETAS model with different thresholds. **a** North of Iran. **b** Zagros. **c** East of Iran

method. On the other hand, the Reasenber's method estimates a catalog with the least number of clusters.

As previously stated, according to different thresholds in the ETAS model, different catalogs will be obtained. In this study, for North and East of Iran, the number of mainshocks in the declustered catalog by the Gardner and Knopoff method was equal to that of the ETAS model with a threshold of 0.6. In the Zagros region, the threshold values in the ETAS model increased to 0.7 to match the results of the two methods. The number of mainshocks in the declustered catalog by the Gruenthal method and the ETAS model will be matched considering the threshold in the ETAS model equal to 0.79 in East and North of Iran and equal to 0.84 in Zagros region. In Table 5, the ratio of the number of dependent earthquakes to the total number of earthquakes is calculated for Iran seismotectonic zones using the discussed methods. The results presented in Table 5 confirm that there is the highest number of dependent earthquakes in the

Table 5 Dependent earthquakes–total number of earthquakes ratio in the Iranian earthquake catalog

| Seismotectonic province | Total number of earthquakes | Percent of dependent earthquakes (%) |
|-------------------------|-----------------------------|--------------------------------------|
| North of Iran | 1196 | 52 |
| Zagros | 3741 | 64 |
| East of Iran | 1097 | 57 |

Time interval 1983–2017, $M_w > 4$. This catalog is declustered using the ETAS model with a threshold of probability equal to 0.8

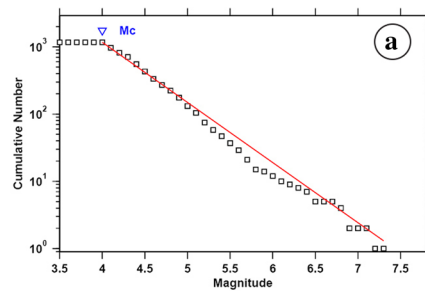
Zagros region. In other words (and neglecting foreshocks), the earthquakes in this region can trigger more aftershocks.

In Figs. 7, 8 and 9, the cumulative number–magnitude distribution plot in the three tectonic zones of Iran is calculated using ZMAP software (Weimer 2001). The summary of calculated plots in Figs. 7, 8 and 9 is presented in Table 6 including a value and b value in the Gutenberg and Richter (1944) relation. The Chi-square test is used to check the null hypothesis that the declustered catalogs follow the Poissonian distribution. The results of the Chi-square test showed that all the declustered catalogs in the three seismotectonic areas follow the Poisson process. It should be noted that in most of the commonly used techniques for Poisson test the declustered catalogs such as Chi-square test and Kolmogorov–Smirnov test, the spatial location of earthquakes has been ignored (Luen and Stark 2012). It can change the results, especially when the study area is large like the current study.

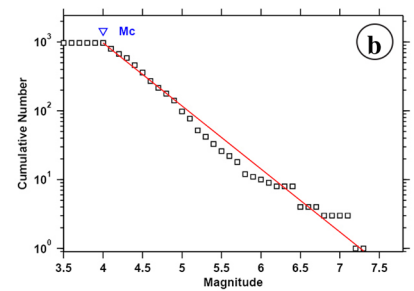
Conclusions

In this article, the Iran earthquake catalog during the period 1983–2017 is declustered by different methods. Windowing methods include Gardner and Knopoff, Gruenthal, Uhrhammer, the linking Reasenber's method and epidemic-type aftershock sequence (ETAS) model. We believe that due to the uncertainties and unknown nature of earthquake sequences, it is impossible to do a precise comparison between results of various declustering methods. This is the first article that uses the ETAS model for declustering the Iranian seismic catalog. This case and the other mentioned issues make comparisons difficult. However, the results show the good ability of the ETAS model for declustering of the earthquake catalog and evaluating aftershock probabilities. The authors emphasize that the use of the ETAS model is still in its early steps in Iranian seismological research and more parametric studies are needed. Some of the initial challenges in future studies are the use of Poisson test techniques that take into account the effect of the earthquake location,

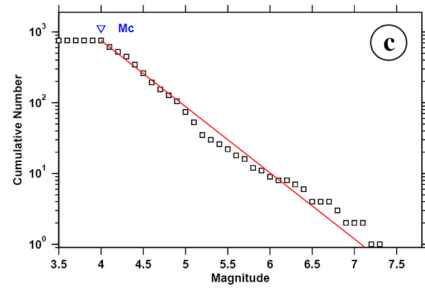
Fig. 7 Cumulative number–magnitude plot in North of Iran. **a** not declustered. **b** Reasenberg. **c** Uhrhammer. **d** Gardner and Knopoff. **e** Gruenthal method. **f, g, h, i, j** ETAS model with probability thresholds 0.5, 0.6, 0.7, 0.8, 0.9, respectively. The magnitude of completeness (M_c) considered equal to the minimum magnitude ($M_w = 4.0$)



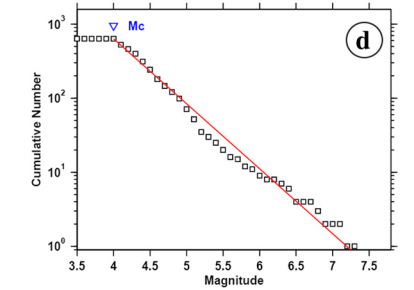
b-value = 0.89 +/- 0.02, a value = 6.65, a value (annual) = 5.13



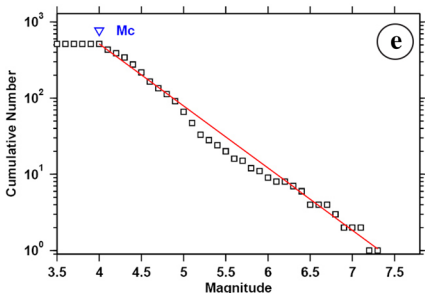
b-value = 0.92 +/- 0.03, a value = 6.65, a value (annual) = 5.13



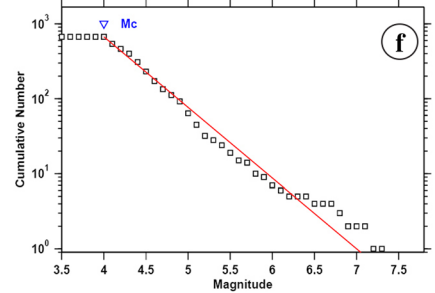
b-value = 0.94 +/- 0.03, a value = 6.62, a value (annual) = 5.1



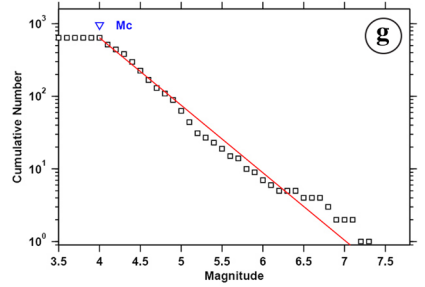
b-value = 0.88 +/- 0.03, a value = 6.31, a value (annual) = 4.79



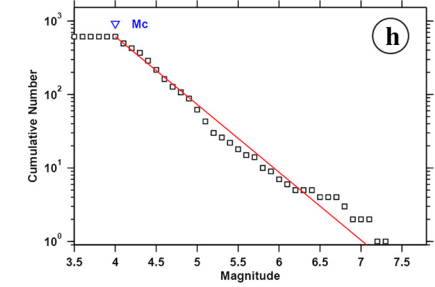
b-value = 0.82 +/- 0.03, a value = 5.97, a value (annual) = 4.46



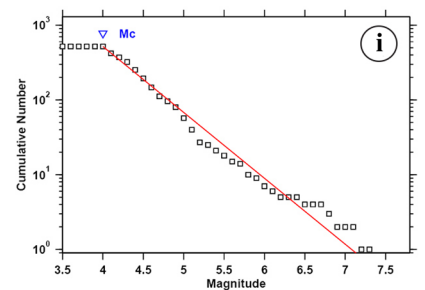
b-value = 0.94 +/- 0.04, a value = 6.6, a value (annual) = 5.08



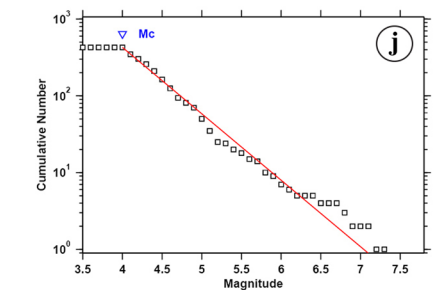
b-value = 0.93 +/- 0.03, a value = 6.52, a value (annual) = 5.01



b-value = 0.92 +/- 0.04, a value = 6.48, a value (annual) = 4.96



b-value = 0.88 +/- 0.04, a value = 6.24, a value (annual) = 4.72



b-value = 0.86 +/- 0.04, a value = 6.09, a value (annual) = 4.57

Fig. 8 As in Fig. 7 for Zagros region of Iran

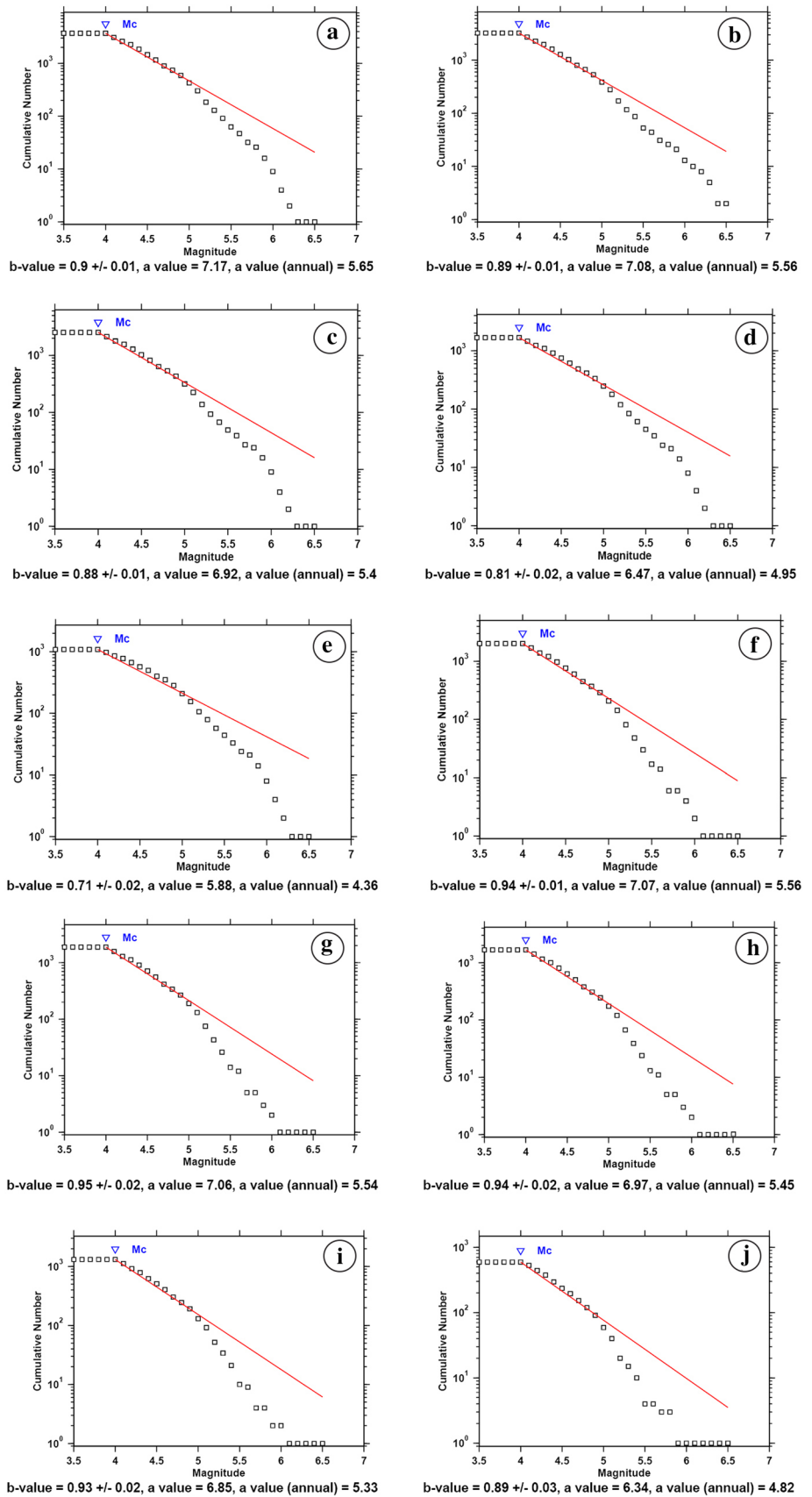


Fig. 9 As in Fig. 7 for East of Iran

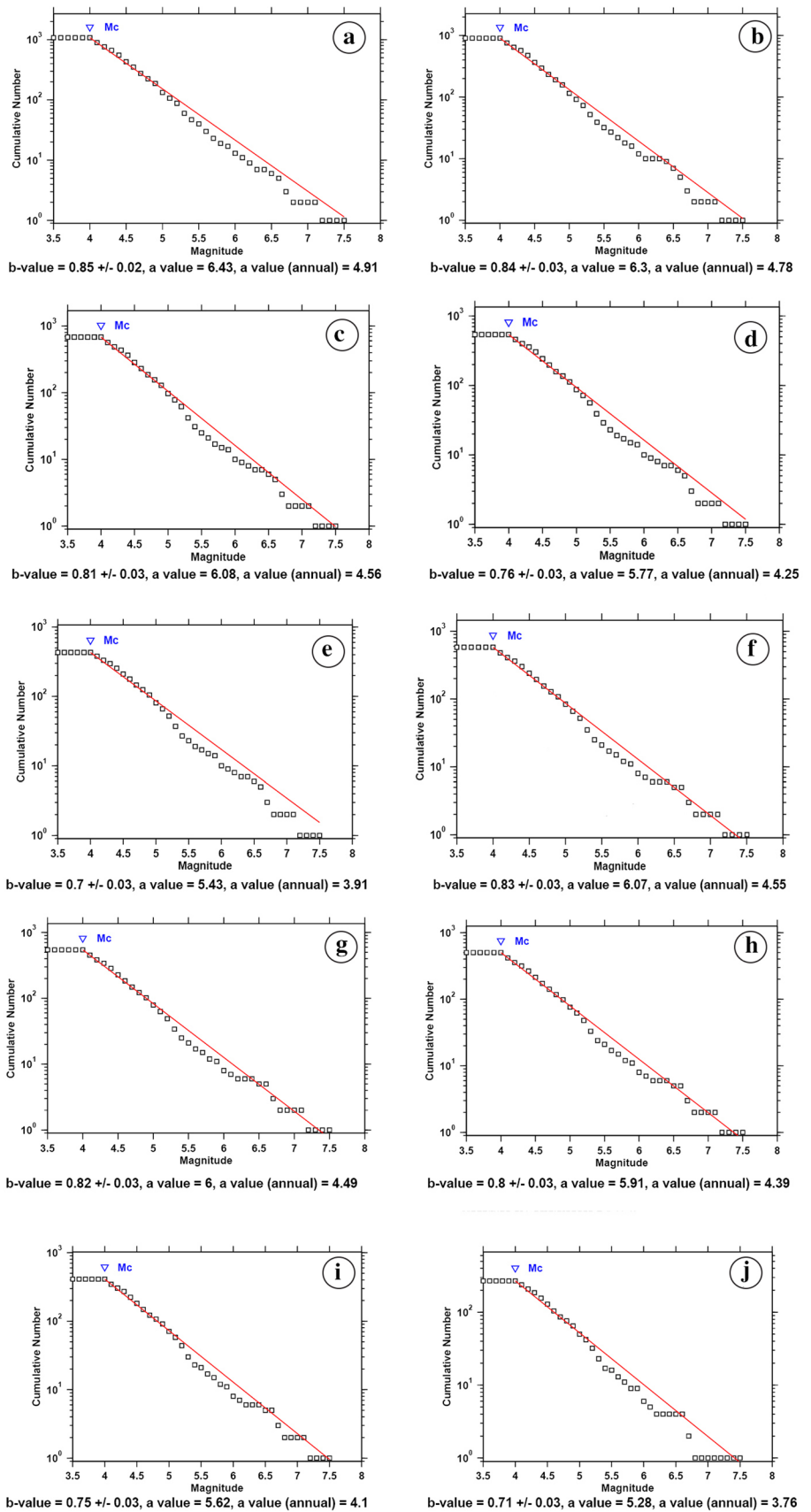


Table 6 *a* value and *b* value in the declustered catalog of Iran's major tectonic zones using different methods

| Zone | Declustering method | | | | | | | | | | | | | | | | | |
|---------------|---------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| | Re | | Uh | | G-K | | Gr | | ETAS-0.5 | | ETAS-0.6 | | ETAS-0.7 | | ETAS-0.8 | | ETAS-0.9 | |
| | <i>a</i> | <i>B</i> | <i>a</i> | <i>b</i> | <i>A</i> | <i>b</i> | <i>a</i> | <i>b</i> | <i>a</i> | <i>b</i> | <i>a</i> | <i>b</i> | <i>a</i> | <i>b</i> | <i>a</i> | <i>b</i> | <i>a</i> | <i>b</i> |
| North of Iran | 5.13 | 0.92 | 5.10 | 0.94 | 4.79 | 0.88 | 4.46 | 0.82 | 5.08 | 0.94 | 5.01 | 0.93 | 4.96 | 0.92 | 4.72 | 0.88 | 4.57 | 0.86 |
| East of Iran | 4.78 | 0.84 | 4.56 | 0.81 | 4.25 | 0.76 | 3.91 | 0.70 | 4.55 | 0.83 | 4.49 | 0.82 | 4.39 | 0.80 | 4.10 | 0.75 | 3.76 | 0.71 |
| Zagros | 5.56 | 0.89 | 5.40 | 0.88 | 4.95 | 0.81 | 4.36 | 0.71 | 5.56 | 0.94 | 5.54 | 0.95 | 5.45 | 0.94 | 5.33 | 0.93 | 4.82 | 0.89 |

Time interval 1983–2017. (Re) Reasenberg, (Uh) Uhrhammer, (G-K) Gardner and Knopoff, (Gr) Gruenthal method. ETAS model with probability thresholds 0.5, 0.6, 0.7, 0.8 and 0.9, respectively

choosing different catalogs at different time intervals, evaluating the impact of the threshold magnitude and zoning of seismotectonic regions.

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Authors' contributions HRT proposed the initial idea and guided us in the analysis. ND analyzed the data completed all experiments and wrote the manuscript. MZ directed us to create a seismic catalog and seismic zoning. AJ developed the ETAS model code. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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