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On the validity of the regional time and magnitude predictable model in China

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Abstract
A simplified form of the «regional time and magnitude predictable model» gives the time interval, T, between two successive mainshocks in a region and the magnitude, M_f, of the following mainshock by the relations: $\log T = cM_p + a$; $M_f = CM_p + A$, where M_p is the magnitude of the preceding mainshock, a, A are constants which depend on the minimum considered mainshock and on the region's tectonic loading (moment rate). The physical meaning of the model is that the larger the magnitude of the preceding main shock, M_p, the longer the time, T, will be till the occurrence of the next one and the smaller its magnitude, M_f. This means that parameters c and C are positive and negative, respectively, when the model has been found valid for a certain area. In order to examine if the above model is appropriate to describe the seismicity behavior in the area of China, a detailed inspection was carried out aiming to show if the estimated values of parameters c and C favor the model. The results show that c tends to the global value 0.33, obtained by Papazachos and Papadimitriou (1997), and that C tends to be within the range [-0.30, -0.23]. The results, which favored the model, greatly outnumber those that do not follow it, the latter being concentrated around the boundaries of the seismically active regions. It is concluded that the results, which favor the model, obviously dominate the whole territory of China.

Key words *time dependent seismicity – validation test – China*

1. Introduction

Considerable research work has been conducted on the estimation of earthquakes return period in a specific area, as well as on the size of the impending main event, because both parameters are fundamental factors for seismic hazard assessment. As early as the beginning of this century, Gilbert (1909) had found that there exists a so-called «rhythmic recurrence» of earthquakes. Fedotov (1965) had introduced the seismic gap hypothesis which implies that earthquake hazard is reduced immediately following a large earthquake and increases with the time elapsed since the last main event on a certain active fault segment or plate boundary. On the basis of this hypothesis, Kelleher *et al.* (1973) and McCann *et al.* (1979) carried out early long-term earthquake prediction studies.

Many seismologists have also found that the time dependent occurrence is the basic characteristic of seismic activity (Shimazaki and Nakata, 1980; Sykes and Quittmeyer, 1981, Papazachos, 1989). It was generally accepted that long quiescent time period is often followed by

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the occurrence of large events, and that large earthquakes were followed by comparatively smaller ones. Simply, the active rhythmic pattern behaves in the time domain as concentration/scarcity of seismicity (Mogi, 1985; Papazachos, 1989; Li *et al.*, 1994), and in the size domain as strong/weak (Mogi, 1985; Papazachos, 1989). In respect to the above, Papazachos and Papaioannou (1993) proposed the *regional time and magnitude predictable model* expressed by the following empirical formulae:

$$\begin{aligned} \log T &= bM_{\min} + cM_p + d\log m_0 + q \\ M_f &= BM_{\min} + CM_p + D\log m_0 + m \end{aligned} \tag{1.1}$$

where $M_{\min}$ is the minimum magnitude of the mainshocks considered in the data sample, M_p, the magnitude of the preceding main shock, m_0 the yearly moment rate, q and m are parameters that differ in different tectonic areas. These two constants are considered to be a calibrating factor of the time and size of the future event, which are related to the regional seismicity. This model has been tested in many places in the world (Karakaisis, 1993; Papadimitriou, 1993; Papadimitriou and Papazachos, 1994; Panagiotopoulos, 1995; Papazachos *et al.*, 1997). From the above formulae it is derived that the occurrence time, T, of the following main shock as well as its magnitude, M_f, depend not only on the magnitude of the preceding mainshock, M_p, but also on the magnitude, $M_{\min}$, of the smallest mainshock considered in the data sample, which reflects the general seismic activity level, as well as to the yearly moment rate, m_0, in the examined region, which expresses the tectonic loading exerted in each seismogenic region (Papazachos *et al.*, 1997).

The parameters b, c, d, B, C, and D of the above formulae were determined by Papazachos *et al.* (1997) who used a data sample of mainshocks of the continental fracture system, that is, the circum-Pacific and Alpine-Himalayan belts. This sample consisted of 1811 sets (T, $M_{\min}$, M_p, M_f) coming from 274 seismogenic regions in sixteen areas of this system. In this way, the estimation of the parameters was based not only on the few observations usually available for a seismogenic region, but on a very large sample of data. Thus, relation (1.1) took the form

$$\begin{aligned} \log T &= 0.19M_{\min} + 0.33M_p - 0.39\log m_0 + q \\ M_f &= 0.73M_{\min} - 0.28M_p + 0.40\log m_0 + m. \end{aligned} \tag{1.2}$$

The above authors also discussed the properties of the model and showed, through statistical tests, its superiority in comparison with the classical time independent model, showing that the strong earthquakes occurrence, on a global scale, follows the *time and magnitude predictable model* rather than the slip predictable model or random behavior.

In order to prove that this model is the most appropriate one to describe seismic behavior, Papazachos and Papadimitriou (1997) performed considerable statistical treatment and found that the parameters c and C (the coefficients of M_p in both relations), which globally take a value equal to 0.33 and – 0.28, respectively, are always positive and negative at a high significance level. These results support the validity of the above-described model.

The aim of the present paper was to test if the *regional time and magnitude predictable model* is also valid in the territory of China. As it is known, China is a large country and its tectonic background is fairly complicated. This is due to the northeastward motion of the India plate under the Eurasian plate in its southwest, the westward subduction of the Pacific into the Eurasian plate and the interaction of the Philippine and the Eurasian plates (Wesnousky *et al.*, 1984; Albert *et al.*, 1995; Xu and Deng, 1996), leading to the differentiation of the earthquake activity from region to region. It is of great interest to examine if this model holds in this region with such a complicated tectonic regime and seismic distribution. By the use of a reliable earthquake catalogue of the past two centuries, a detailed examination of the model was made by statistical tests.

2. Data and method

The data set used in the present study is taken from the catalogue that was published and distributed by the China Seismological Bureau (CSB) of P.R. China. This catalog was further checked and corrected accordingly with: a) the catalogue of Pacheco and Sykes (1992) which gives information on all large earthquakes ($M \geq 7.0$) which occurred during the present century; b) the catalogue of Abe (1981) which covers the same time period but gives information on smaller events ($M \geq 6.5$) as well since 1930; c) the ISC bulletins for the time period 1966-1992 for smaller magnitude events. The data of the corrected catalogue, which are depicted in fig. 1, have been found to be complete for the following time periods and magnitude cutoffs (Qin *et al.*, 1999):

Period	*Magnitude cutoff*
1950-1995	$M \geq 5.0$
1900-1995	$M \geq 6.0$
1800-1995	$M \geq 8.0$

The basic idea of the present interpretation is to examine if parameter c of relation (1.1) is always or mostly positive. It implies that longer quiescent periods will follow larger magnitude mainshocks, which expresses the concept of the time predictable model. The same examination will be performed for parameter C, which is expected to be found always or mostly negative, expressing in that way the concept of the mag-

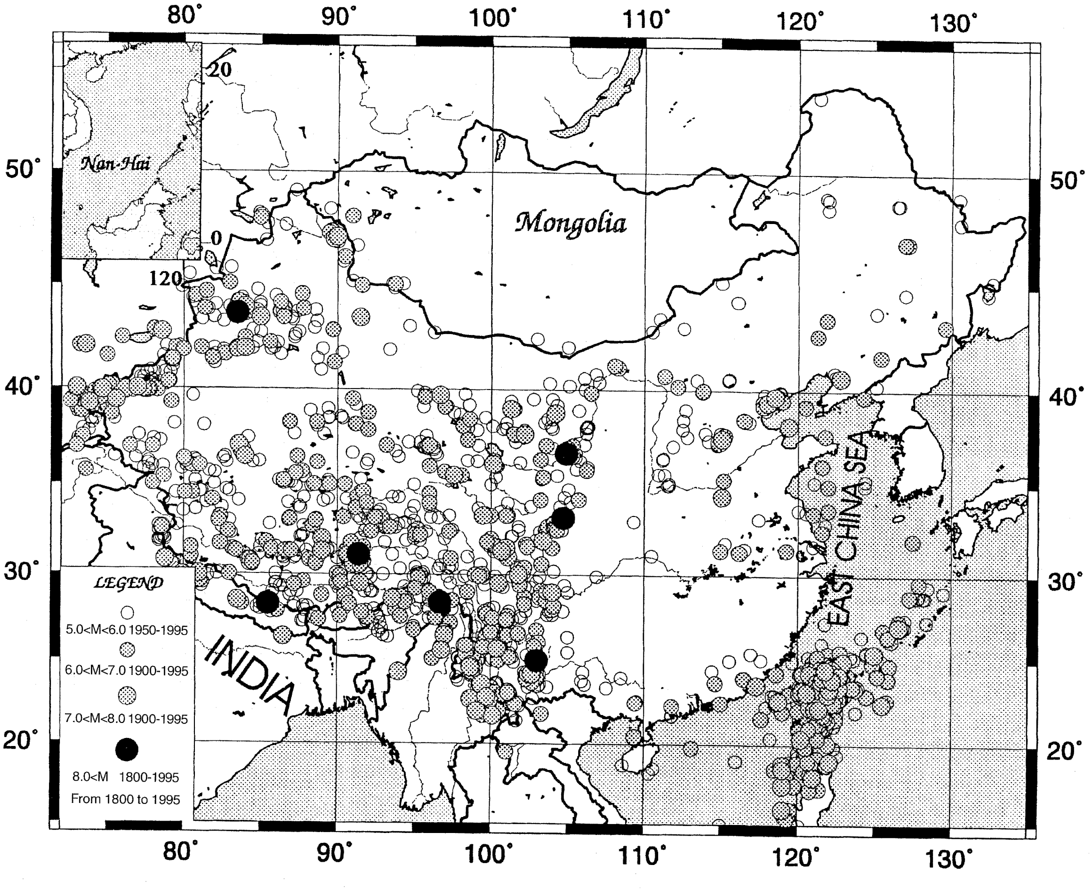


Fig. 1. The epicenter distribution of the complete data sample used in the present study.

nitude predictable model. In order to avoid any «contamination» by the regression that includes other parameters too in this estimation, relation (1.1) can be written in the simple form

$$\log T = cM_p + a$$
$$M_f = CM_p + A \tag{2.1}$$

where a and A are parameters to be determined for each seismogenic region. This relation is obtained by assuming that the each zone is a seismotectonically homogeneous region where the term which includes m_0 can be eliminated since the tectonic loading is unique and that all the observations are based on the same magnitude cut-off ($M_{\min}$) so that the influence of $M_{\min}$ term can be constant as well (Papazachos and Papadimitriou, 1997).

For the application of relation (2.1), only the mainshocks, that is, the largest earthquake during the seismic cycle, and their occurrence time are needed. It is then necessary to define them, as well as their «preshocks» and «postshocks» in the broad sense, as suggested by Papazachos *et al.* (1997). These investigators, based on a large sample of observations, proposed the following two relations for the calculation of the total duration of preshock, t_p, and postshock, t_a, activity

$$t_p = 3 \text{ years}$$
$$\log t_a = 0.06 + 0.13\, M_p \tag{2.2}$$

where M_p is the magnitude of the preceding mainshock. The constant duration of the preshock activity and the increase in the duration of the aftershock activity with the size of the mainshock is in accordance with the results of previous investigators (Mogi, 1985; Karakaisis *et al.*, 1991).

Since we are also interested in proving that zonation under certain criteria does not introduce bias in the results of the model application, the following technique was followed: the whole territory was divided into small areas (cells) of certain dimensions (such as 3° × 3°) without taking into account any zonation based on any other information. In that way no bias has been inserted in our estimations by subjective definition of the tectonic units considered. This inherently assumes that the seismicity is randomly distributed within each cell. This cell is then moved, by a step of 1°, on the nodes of a normal grid superposed on the whole territory. The earthquakes having their epicenters inside each cell were considered as one data set and the parameters of relation (2.1) were determined. In this way an overlapping grid of point values of the parameter can be developed. Thus, the results can be presented as grid-point cell values or prepared for contouring. Furthermore, in order to see if there is any dependence of the c value on the cell dimension (under the assumption of same tectonic background), various cell dimensions (*i.e.*, 4° × 4°, 5° × 5°...) were also tested.

3. Validation test for the time predictable model

In order to examine if the regional time predictable model is followed by the strong earthquake occurrences in China, the parameters of equation (2.1) were estimated in each one of the «moving cells» throughout the whole area under study. For the sake of regression robustness, the number of the observation pairs (M_p, $\log T$), taken from a data sample with a certain minimum magnitude $M_{\min}$, was chosen to be not less than 3. Let us consider the data of table I, for example, which are the complete data for a region with cell dimension 3° × 3° in Southwest China.

First, the declustering of the data was performed as explained in the following. The largest magnitude earthquake was selected (1951, M8.0 event in the present case) and its preshocks (marked as ‘f’ in table I) and postshocks (marked as ‘a’ in table I) were defined according to relation (2.2). Then the second largest event (1915, $M = 7.0$ in the present case) was considered. Applying relation (2.2) again its preshocks and postshocks were found. The procedure was repeated till the minimum magnitude mainshock possible in the data set (1964, $M = 5.0$ in the present case). It should be noted here that each mainshock was expressed by the cumulative magnitude, M_{cum}, derived by summing the seis-

Table I. Information on the earthquakes of a region in Central China used as an example to show how the data were treated in the present study. The symbols ‘f’ and ‘a’ are used to indicate foreshocks and aftershocks in the broad sense, respectively, and M_{cum} is the magnitude which corresponds to the total seismic moment released by the corresponding seismic sequence.

Date			Epicenter		M_s	M_{cum}
			Lat. (N°)	Long. (E°)		
21	4	1901	29.50	90.10	6.7	6.7
3	12	1915	29.50	91.50	7.0	7.1
15	10	1921	30.50	91.00	6.2	a
14	8	1924	29.50	90.00	6.0	a
9	10	1924	30.00	90.00	6.5	a
12	1	1925	30.50	91.50	6.5	a
3	9	1940	30.70	91.70	6.2	6.3
4	10	1940	30.50	91.50	6.0	a
6	9	1950	29.30	92.00	5.0	f
17	11	1951	31.00	91.60	6.2	f
18	11	1951	30.90	91.50	6.7	f
18	11	1951	30.50	91.50	5.7	f
18	11	1951	30.50	91.50	5.5	f
18	11	1951	31.10	91.40	8.0	8.1
19	11	1951	30.50	91.50	5.5	a
19	11	1951	30.50	91.50	5.5	a
19	11	1951	31.00	91.60	5.0	a
23	11	1951	30.50	91.50	5.0	a
25	11	1951	31.00	91.60	5.5	a
3	12	1951	30.00	92.00	5.7	a
8	12	1951	31.00	90.50	5.7	a
26	12	1951	31.30	90.60	6.5	a
15	3	1952	30.50	91.60	5.0	a
2	6	1952	30.50	91.50	5.2	a
2	6	1952	30.50	91.50	5.0	a
15	6	1952	31.50	90.80	5.2	a
18	8	1952	31.00	91.50	7.6	a
18	8	1952	30.00	93.00	5.2	a
16	9	1952	30.00	92.00	5.0	a
27	3	1955	29.80	90.20	5.7	a
27	3	1955	29.90	90.20	6.2	a
4	8	1955	32.00	91.50	5.0	a
19	12	1955	30.00	90.00	5.2	a
29	12	1955	30.10	90.30	5.5	a
23	3	1956	29.90	90.10	5.2	a
18	11	1959	30.30	94.10	5.2	a

Table I (*continued*).

Date			Epicenter		M_s	M_{cum}
			Lat. (N°)	Long. (E°)		
19	12	1959	31.50	91.00	5.0	a
7	2	1960	31.50	91.00	5.0	a
4	11	1961	32.50	92.20	5.5	a
11	6	1964	31.80	93.10	5.0	5.0
15	8	1967	31.10	93.60	5.5	5.6
31	1	1968	29.80	92.20	5.2	a
23	5	1971	32.40	92.20	6.1	6.3
21	9	1971	32.40	91.80	5.1	a
23	7	1972	31.50	91.70	6.0	a
28	5	1977	31.80	90.90	6.3	6.3
22	1	1982	30.90	90.00	5.7	a
26	9	1987	29.90	90.80	5.6	f
7	10	1987	29.90	90.80	5.3	f
25	1	1988	30.40	95.10	5.6	f
4	2	1989	30.00	90.10	5.9	6.1
30	7	1992	29.58	90.25	6.7	6.8
17	8	1992	30.00	91.90	5.5	a
18	1	1993	31.10	90.60	6.3	a

mic moments of preshocks, mainshock and aftershocks.

The minimum magnitude mainshock was then considered and the inter-event times of all mainshocks during a period of completeness were determined. Since in the present case $M_{min} = 5.0$ only the mainshocks which occurred during 1950-1993 were taken into account. Thus, six observations were found for $M_{min} = 5.0$ (first part of table II). The next minimum magnitude mainshock of table I is the 1967, M 5.6 event, which belongs to the same completeness period. For $M_{min} = 5.6$ the number of observations found is equal to 5 (second part of table II). For M_{min} equal to 6.1, 6.3, 6.7, 6.8 and 7.1, the number of observations is 7, 6, 3, 2 and 1, respectively. In the procedure followed, the minimum observation number for the same minimum magnitude, M_{min}, is set to be 3. Thus, the observations with M_{min} equal to 6.8 and 7.1 will not be used for any c value calculation. In the present case, five c values were estimated. If the minimum observation number were set to be 7, only one c value could be obtained. In order to statistically obtain a reliable c value distribution, the whole number of observations should be as large as possible.

The parameters of the simplified form were first estimated in areas with 3° × 3° dimension. This cell dimension was chosen because after a first inspection it was found that it was the minimum area containing enough data to apply the above-described procedure. In each cell the c value was estimated as described above. From the total number of these values 323 were found positive and shown as gray diamonds in each cell center in fig. 2a, whereas 43 of them were negative, shown as black diamonds in fig. 2a. The ratio of the number of the positive c values to that of the negative ones is about 8:1. This means that the positive values dominate the results.

Table II. The final set of data used in the present study for the seismogenic region for which the original data are given in table I.

$M_{\min}$	M_p	M_f	T (years)	t_p	t_f
5.0	8.1	5.0	12.56	1951	1964
	5.0	5.6	3.18	1964	1967
	5.6	6.3	3.77	1967	1971
	6.3	6.3	6.01	1971	1977
	6.3	6.1	11.68	1977	1989
	6.1	6.8	3.49	1989	1992
5.6	8.1	5.6	15.74	1951	1967
	5.6	6.3	3.77	1967	1971
	6.3	6.3	6.01	1971	1977
	6.3	6.1	11.68	1977	1989
	6.1	6.8	3.49	1989	1992
6.1	6.7	7.1	14.62	1901	1915
	7.1	6.3	24.75	1915	1940
	6.3	8.1	11.21	1940	1951
	8.1	6.3	19.51	1951	1971
	6.3	6.3	6.01	1971	1977
	6.3	6.1	11.68	1977	1989
	6.1	6.8	3.49	1989	1992
6.3	6.7	7.1	14.62	1901	1915
	7.1	6.3	24.75	1915	1940
	6.3	8.1	11.21	1940	1951
	8.1	6.3	19.51	1951	1971
	6.3	6.3	6.01	1971	1977
	6.3	6.8	15.17	1977	1992
6.7	6.7	7.1	14.62	1901	1915
	7.1	8.1	35.96	1915	1951
	8.1	6.8	40.70	1951	1992
6.8	7.1	8.1	35.96	1915	1951
	8.1	6.8	40.70	1951	1992
7.1	7.1	8.1	35.96	1915	1951

It must be mentioned that the simplified model applies assuming uniform tectonic loading (constant moment rate) inside each cell. Since the tectonics of China territory are very complicated from a seismotectonic point of view (Tapponnier and Molnar, 1977; Ding, 1982; Ma, 1987; Deng, 1995a,b; Xu and Deng, 1996), the continuously shifting cells will contain different tectonic regime when superposed on transition belts. In this case, the simplified model

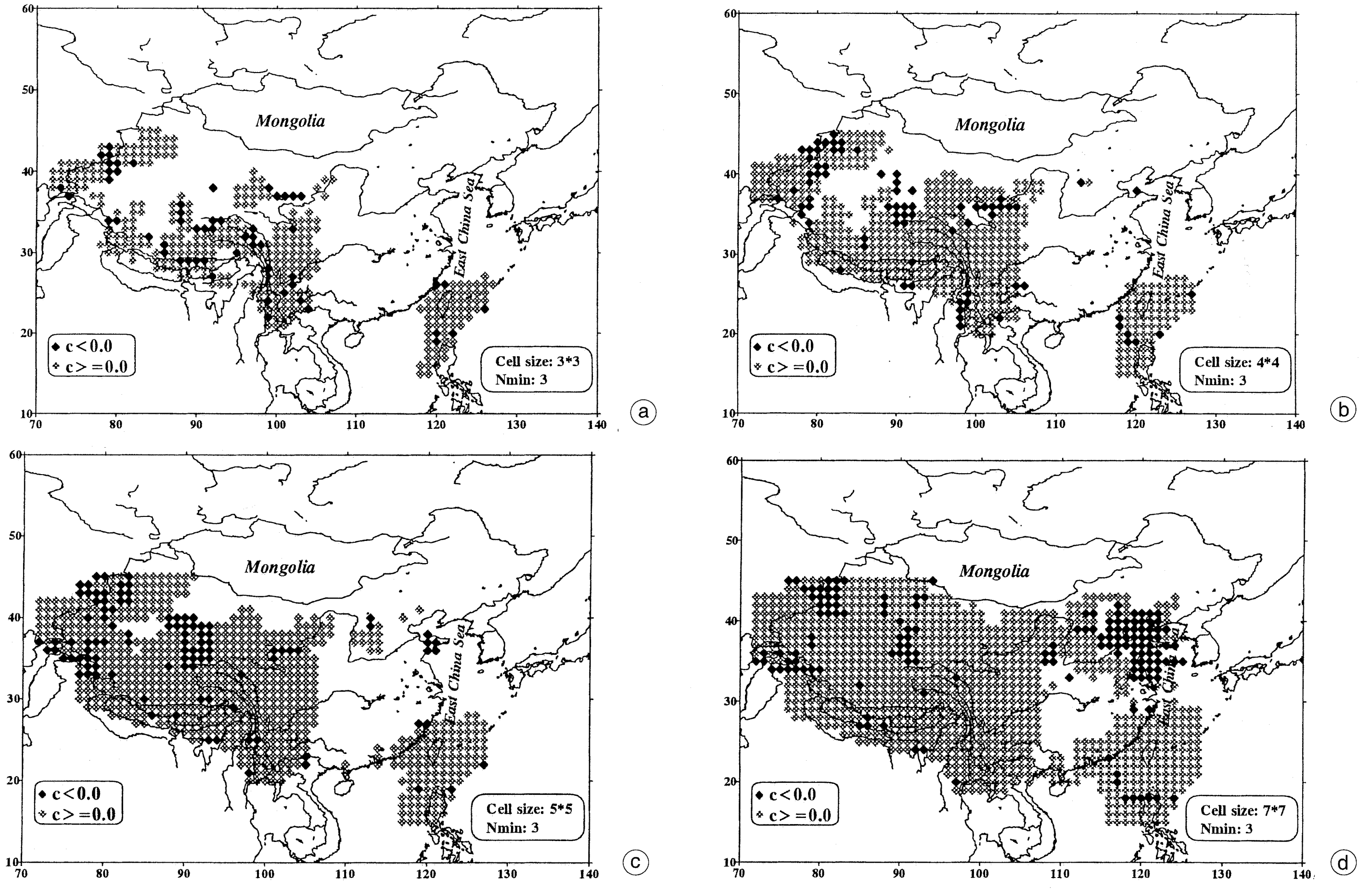


Fig. 2a-d. The c value distribution for four different cell sizes. The minimum number of observations is 3. The gray and black diamonds plotted at the center of each cell denote positive and negative *c* values, respectively. Cell area is equal to: a) 3° × 3°; b) 4° × 4°; c) 5° × 5°, and d) 7° × 7°, respectively.

cannot describe the seismic activity faithfully, resulting in unstable c values. If we further study the distribution of the negative c values, we can also see from fig. 2a that most of the negative values are situated around transition zones where both tectonics and seismic activity are differentiated.

As already pointed out the minimum number of observations required to fit the model adequately should not be less than 3. This requirement resulted in leaving some regions without consideration due to the scarcity of data, although some of them are known to have experienced strong earthquakes in the long run. For example, historically, many catastrophic earthquakes occurred around the Ordos block in Northern China. However, only one c value was estimated around its boundary and found to be negative. In order to obtain c values in these regions, more data are required, which means that larger sampling areas should be considered. We must bear in mind that the increase in size of the area is based on the assumption that the data within the area considered are still homogeneous. It must also be pointed out that, with the increase in size of the cell, only the general feature of c value distribution in some regions will be shown. This means that some individual c values will be smoothed with the increase of the cell area.

In fig. 2b-d the results for the cell size $4° \times 4°$, $5° \times 5°$ and $7° \times 7°$, respectively, are shown. The ratios of the numbers of the positive c values to the negative ones are about 12:1, 10:1 and 11:1, respectively. Although the number of the negative c values also increases when the area is enlarged, it does not increase at the same rate as the number of positive ones. As mentioned above, the negative ones are often concentrated on the transition zones. In most cases, these negative values are located at the place where the seismicity is low. By increasing the cell size, parts of high seismicity regions are included in the cell, which finally leads to an increase in observation number compared to that in the smaller size. However, with the increase in cell size, events from high seismicity regions nearby might be counted, which eventually leads to the new negative c value. Thus, although the number of negative c values also increases, the new negative c values concentrate on the low seismicity regions, whereas in some places with high seismicity, the negative values completely disappeared.

In order to better understand the c value distribution, its variation with the range of M_p magnitudes considered in each data sample, the cell size and the observation number was examined (fig. 3a-d). It can be seen that if either the range of the magnitude or the observation number increases, the c values tend to a steady value which is close to the global one obtained by Papazachos and Papadimitriou (1997), *i.e.* $c_{\mathrm{global}} = 0.33$. We also note that the size of the area does not influence so much the results as the magnitude range or the observation number do. Obviously, the larger the magnitude range as well as the observation number, the closer the c value is to the global one. The histogram (fig. 4a-d) of the c values also show a tendency of Gauss distribution centered on the $c_{\mathrm{global}} = 0.33$ for different cell sizes.

4. Validation test for the magnitude predictable model

The same procedure was also followed for the second of relation (2.1), where C parameter obtained a global value equal to -0.28 according to Papazachos and Papadimitriou (1997). This relation implies that the larger the magnitude, M_p, of the preceding mainshock, the smaller the magnitude, M_f, will be of the following one. It is the concern of this study to prove if this pattern is generally valid all over China and how strong this correlation is.

The same data set and the same procedure used for the time predictable model was also used to testing the magnitude predictable model. The estimated C values were classified into negative and positive ones. In order to qualitatively show the spatial distribution of the estimated C values, negative and positive values are shown as gray and black diamonds, respectively, put in the cell center in fig. 5a-d. From an inspection of this figure, it is obvious that negative C values dominate, evidencing that the magnitude predictable model prevails.

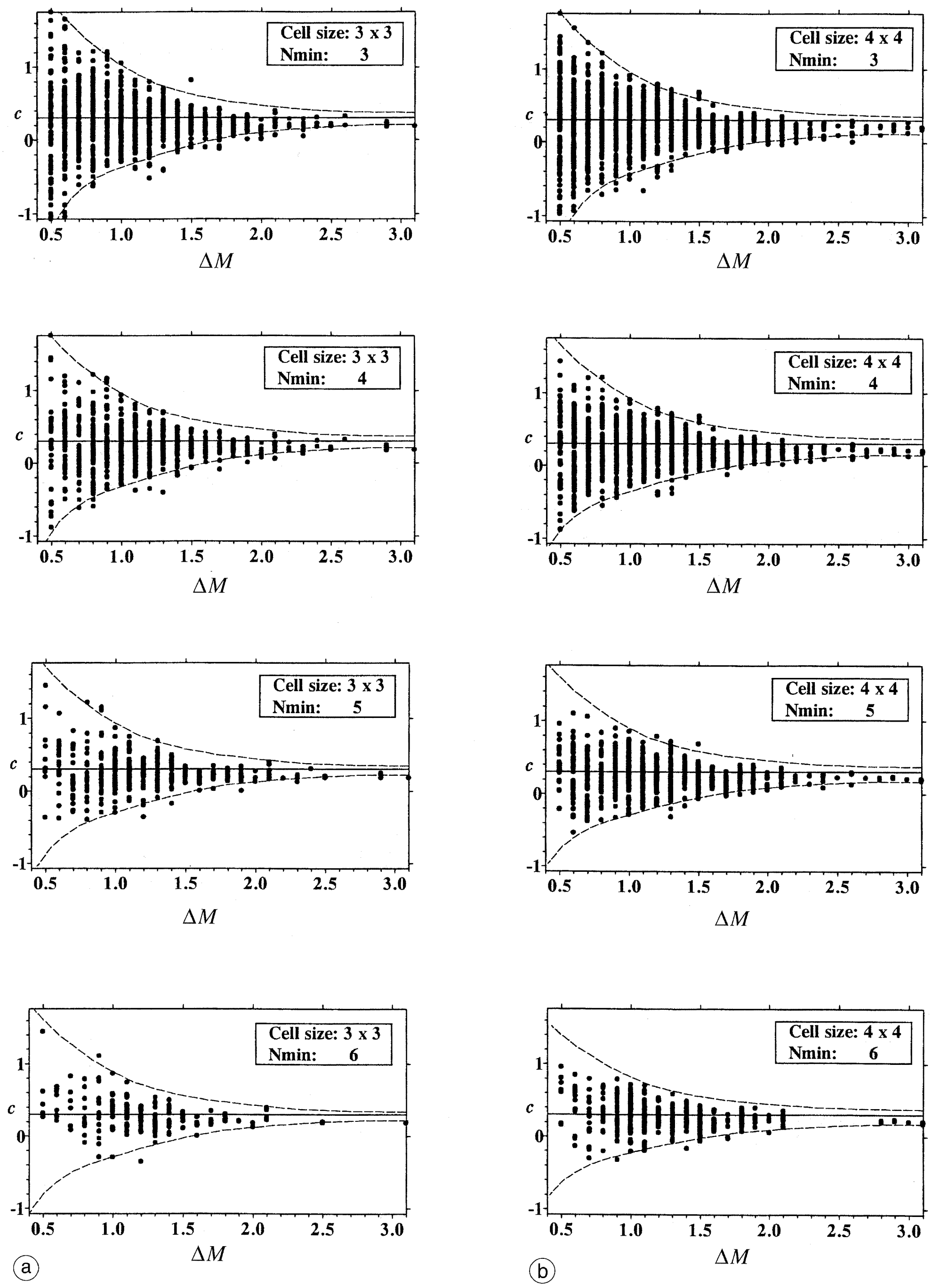
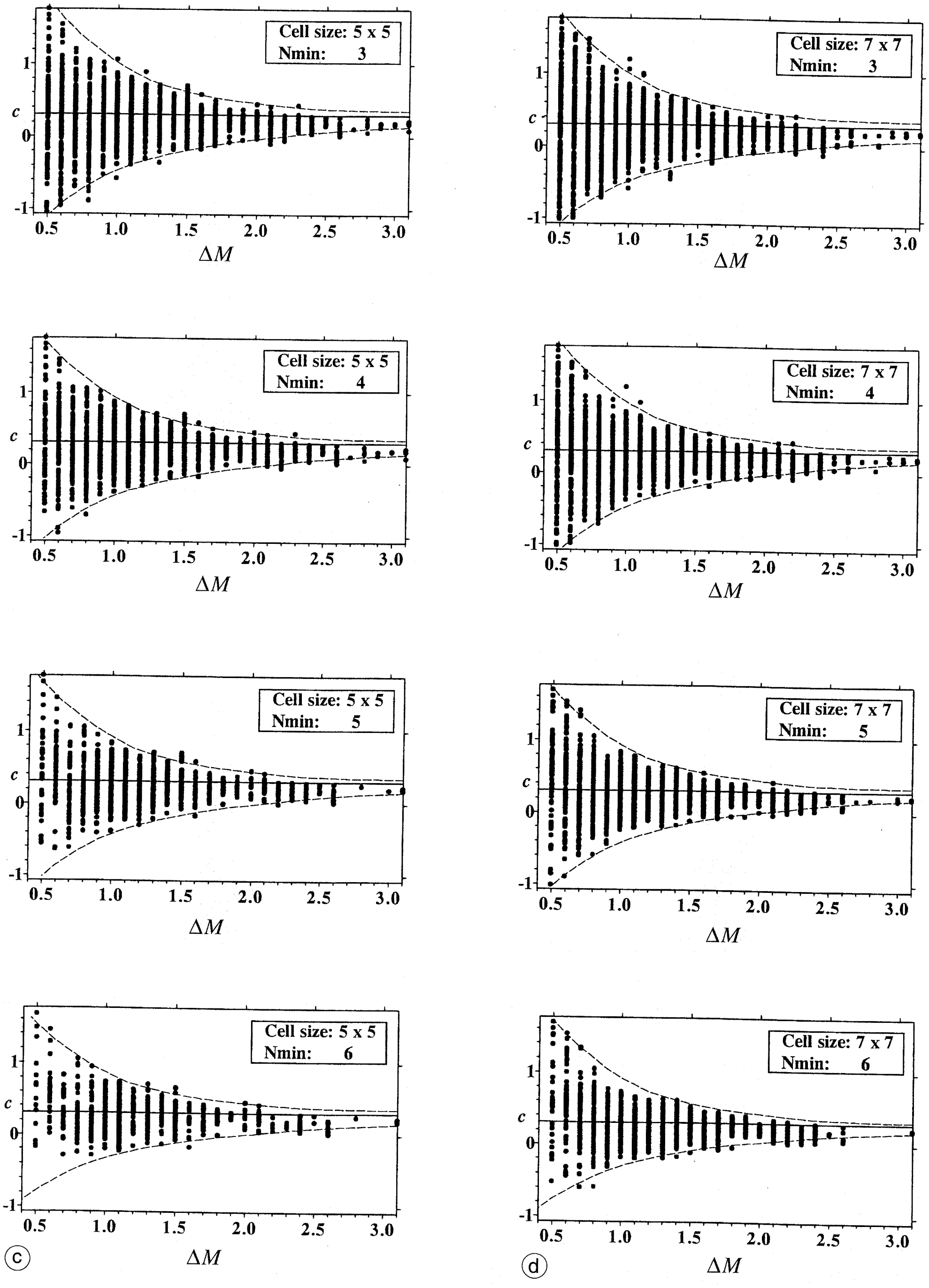


Fig. 3a-d. The *c* value *versus* magnitude range for four different minimum observation numbers



and four different cell sizes. Straight line was put a $c = 0.33$.

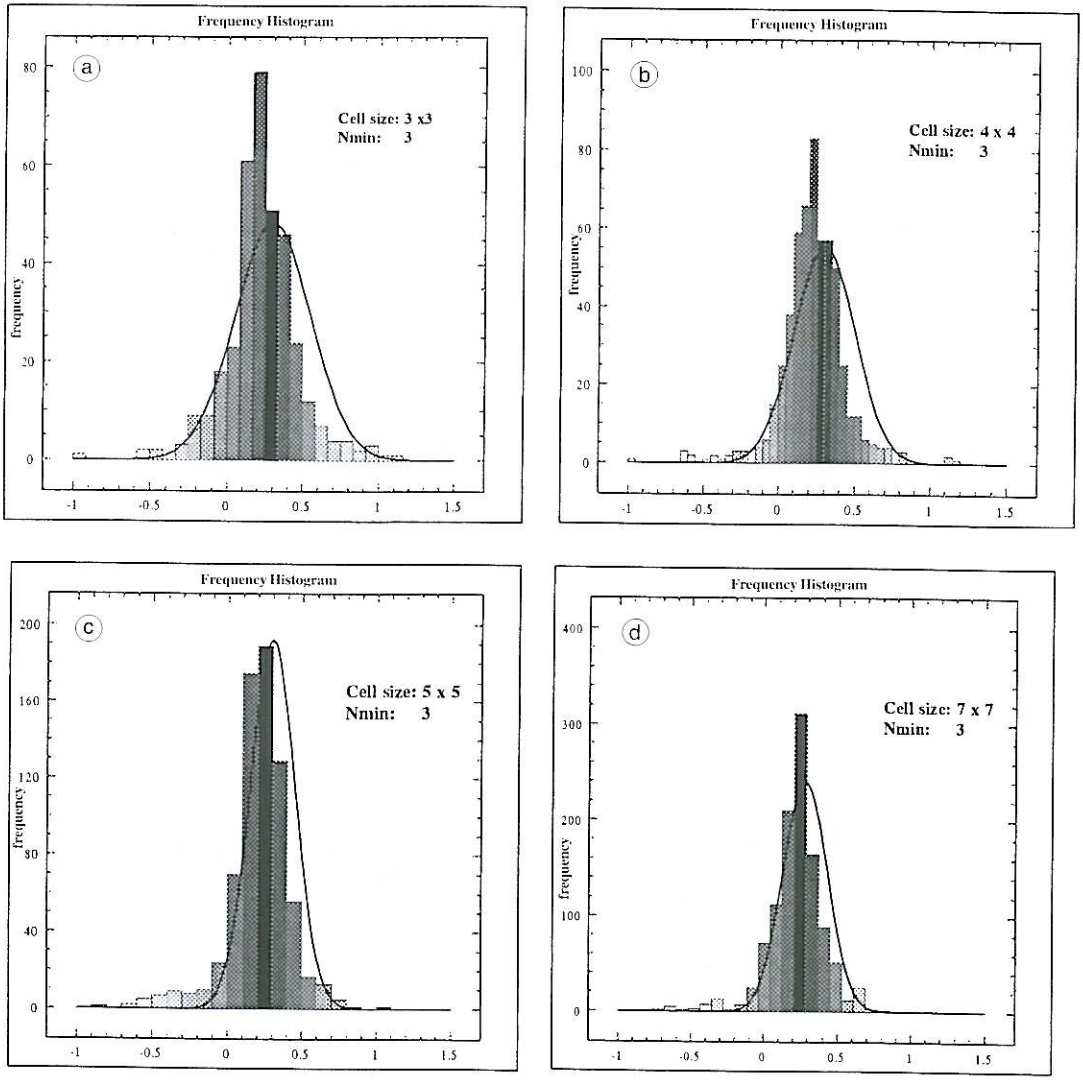


Fig. 4a-d. Frequency histograms of *c* values obtained with minimum observation number equal to 3 for the cell area: a) 3° × 3°; b) 4° × 4°; c) 5° × 5°, and d) 7° × 7°, respectively.

As we did with the simplified time predictable model, different sizes of the regions, different minimum magnitude thresholds and different magnitude range were tested to study the stability of the C values. It was found that, for whatever changes in the above factors, the average C value is always between -0.23 and -0.30 (fig. 6a-d, and fig. 7a-d) which is in excellent agreement with the values obtained by previous research (Papazachos *et al.*, 1997; Papazachos and Papadimitriou, 1997).

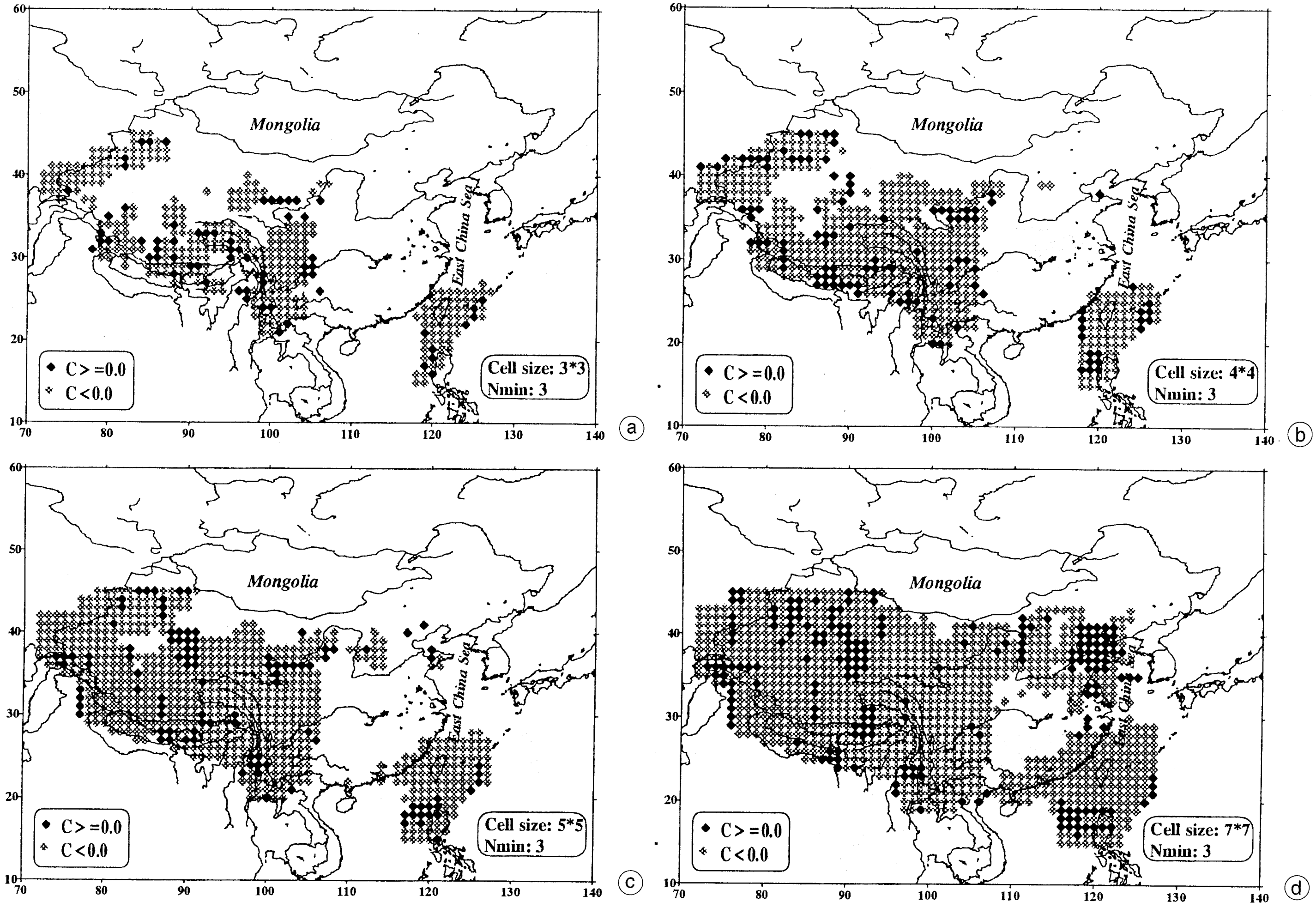


Fig. 5a-d. The *C* value distribution for four different cell sizes. The minimum number of observations is 3. The gray and black diamonds plotted at the center of each cell denote negative and positive *C* values, respectively. Cell area is equal to: a) 3° × 3°; b) 4° × 4°; c) 5° × 5°, and d) 7° × 7°, respectively.

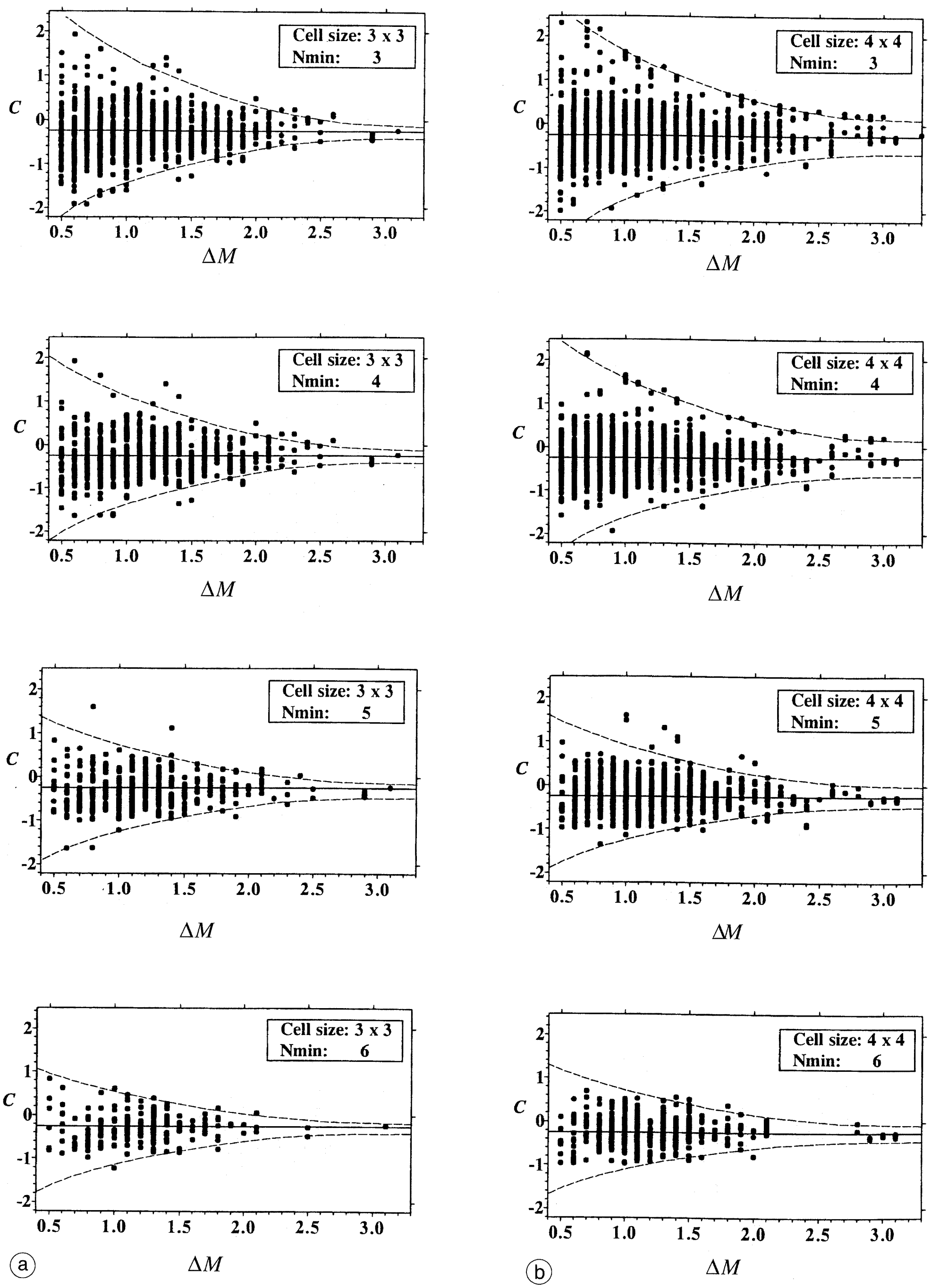
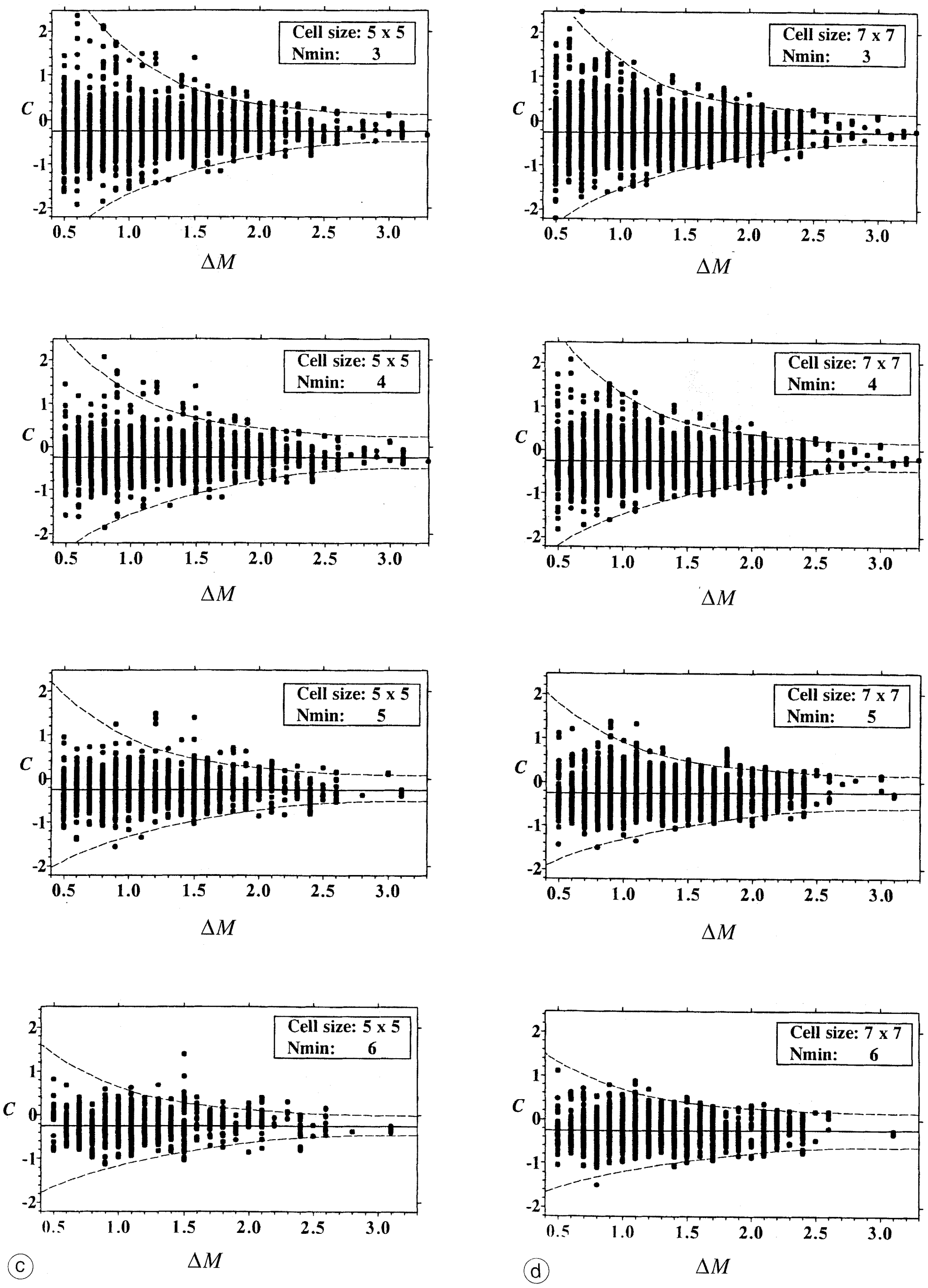


Fig. 6a-d. The C value *versus* magnitude range for four different minimum observation numbers



and four different cell sizes. Straight line was put at $C = -0.25$.

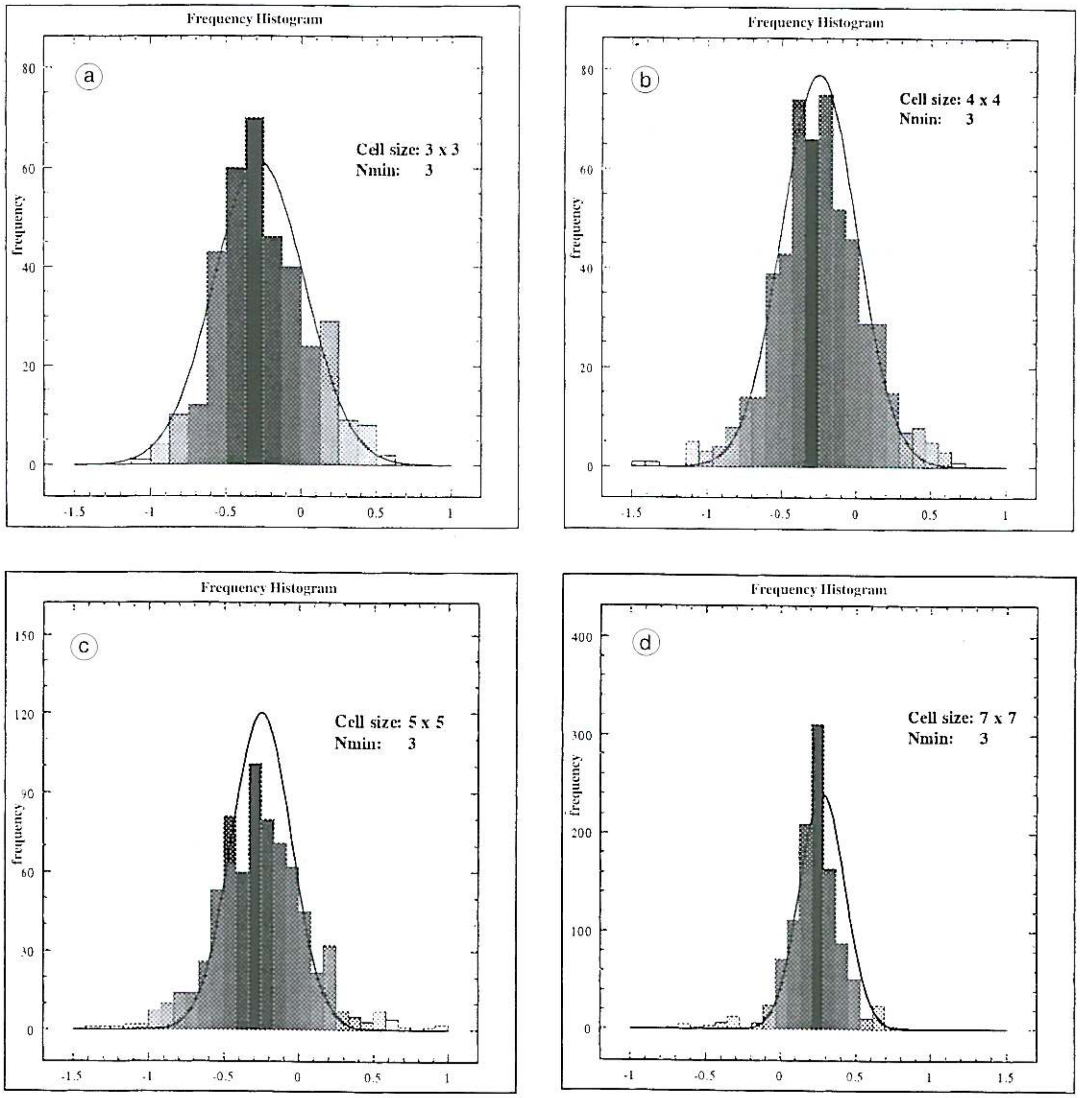


Fig. 7a-d. Frequency histograms of C values obtained with minimum observation number equal to 3 for the cell area: a) 3° × 3°; b) 4° × 4°; c) 5° × 5°, and d) 7° × 7°, respectively.

5. Discussion and conclusions

The regional time and magnitude predictable model reduced to the same level of seismicity and rate of tectonic loading was tested throughout the territory of China. The aim of this research was to examine if this model is appropriate to describe the behavior of mainshock occurrence. The results presented above validate the idea that the magnitude of a mainshock controls the time interval till the occurrence of the next one as well as its magnitude.

More specifically, the larger the magnitude of the previous mainshock is the longer the time till the occurrence of the next one and the smaller its magnitude.

All the above results were derived from the simplified model expressed by relation (2.1) because the magnitude of the previous mainshock is the main term of the regional time and magnitude predictable model. If we separate the model into three parts: the minimum magnitude, $M_{\min}$, the logarithm of the moment rate $\log m_0$ and the size of the previous event, M_p, and if we consider the minimum magnitude term as the one which describes the known classic Gutenberg and Richter law and the moment rate term as the one which expresses the average seismicity, the size of the previous mainshock should be understood as the critical factor of the model.

Although the discussion was concentrated on the simplified form (2.1) of the regional time and magnitude predictable model, the results should be the same as the ones for the complete expressions because many constraints were made. First, the small surface cell that is assumed to be homogeneous was used so that the moment rate term in the cell was kept unchanged. Second, observations based on different seismicity levels were used to fit relation (2.1) separately and, in this way, this term would not influence the results at all. On the other hand, the minimum observation number was set to ensure the stability of the results.

The results of the regional time and magnitude predictable model do not strongly depend on the accurate definition of seismogenic regions because the model has already considered the influence of the momente rate which is believed to reflect the information on tectonics. However, correct zonation will enhance the effectiveness of the model.

The validation of the model became obvious from the dominance of the positive c values and negative C values for all the sizes of the cell surface selected. It is noteworthy that the c and C values, which do not obey this pattern, are mainly concentrated around the low seismicity areas or transition zones where the tectonic loading rate changes. The parameter c tends to a definite value (0.33) and parameter C lies in a very narrow region (– 0.30, –0.23), in accordance with previous research work (Papazachos and Papadimitriou, 1997). Although the above c and C values were obtained from the simplified model, under strict and reasonable constraints, these values are in very good agreement with those obtained from the actual model (Papazachos *et al.*, 1997).

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