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SPATIOTEMPORAL ORDERING OF GREAT EARTHQUAKES (M≧8.0) IN ASIA DURING 1934 –1970 YEARS

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Abstract: During 1934–1970 years there were 12 great earthquakes in Asia, which are characterized by regular spatiotemporal ordering. The temporal patterns observed for six of them show near equal time intervals in the range of 2139–2208 days, and the second level ordering of time intervals have been found for nine great earthquakes. The spatial patterns can be described mainly by ten isosceles triangles, and in rare cases by equilateral triangle and parallel quadrilateral patterns. Our results provide new evidences of recurrence patterns that many great earthquakes might have similar time intervals close to the Saros period.

Keyword: Great earthquakes, Spatiotemporal ordering, Earthquake migration, Saros period

1. INTRODUCTION

Great earthquakes (in this paper, defined as earthquakes with M≧8) are classified to the largest class for the earthquakes. They account for a large fraction of the total seismic energy release in regional seismic activity. Due to the rare occurrence of great earthquakes, few regularities of them have been reported.

Through the study on active periods in the world's major seismic belts, Mogi (1974) emphasized that large earthquakes are frequently coupled into a large scale regular pattern in their spatiotemporal distribution. Utsu (1984) indicated that great earthquakes (M≧8) occurred repeatedly at the plate boundary off the Kii Peninsula and Shikoku. Time intervals between great earthquakes (M ≧8) in China show a rather regular variation in the range of 252–257 years (Xu et al., 1991). Also, the study on the spatial ordering of 28 earthquakes (M≧8) in the China and its adjacent areas provides evidences of equidistant spacing in terms of isosceles and equilateral triangles (Xu et al., 1994).

2. DATA SET

Mogi (1974) indicated that the seismicity of Alpide belt started from Sunda arc and ended to Anatolia and the Mediterranean on the western end may be divided into four periods: 1897–1916, 1917–1933, 1934–1951 and 1952–1970 years based on large earthquakes (M≧7.7). The 1897–1916

and 1934–1951 periods are active, and 1917–1933 and 1952–1970 periods are inactive. This result stimulated us to investigate the seismic activity of great earthquakes in Asia.

Table 1 List of M≧8 earthquakes with shallow depth in Asia during 1934 –1970.

(Latitude North, Longitude East)

Date			Epicenteral location			Magnitude	Focal depth
Year	Month	Day	Latitude (deg.)	Longitude (deg.)	Locality	(M)	(km)
1934	Jan.	15	26.5	86.5	Nepal	8.3	20
1938	Feb.	1	−5.25	130.5	Banda Sea	8.2	40
1941	Jun.	26	12.5	92.5	Andaman, India	8.1	60
1945	Nov.	27	24.5	63.0	Makran	8.25	
1946	Dec.	20	33.03	135.62	Nankaido, Japan	8.0	30
1948	Jan.	24	10.5	122.0	Philippines	8.2	
1948	Jan.	24	10.5	122.0	Philippines	8.2	
1950	Aug.	15	28.5	96.0	Chayu, China	8.6	30
1951	Nov.	18	31.1	91.4	Dangxiong, China	8.0	
1952	Mar.	4	41.8	144.13	Hokkaido, Japan	8.2	15
1957	Dec.	4	45.2	99.2	Bayan, Mongolia	8.3	25
1963	Oct.	14	44.89	149.56	Etorofu, Russia	8.1	40

In the present work, the investigated area is basically the same as the one defined in Fig. 5 of Mogi's paper published in 1974, including a large part of Asia (10° S – 45° N, 35° E – 160° E). A

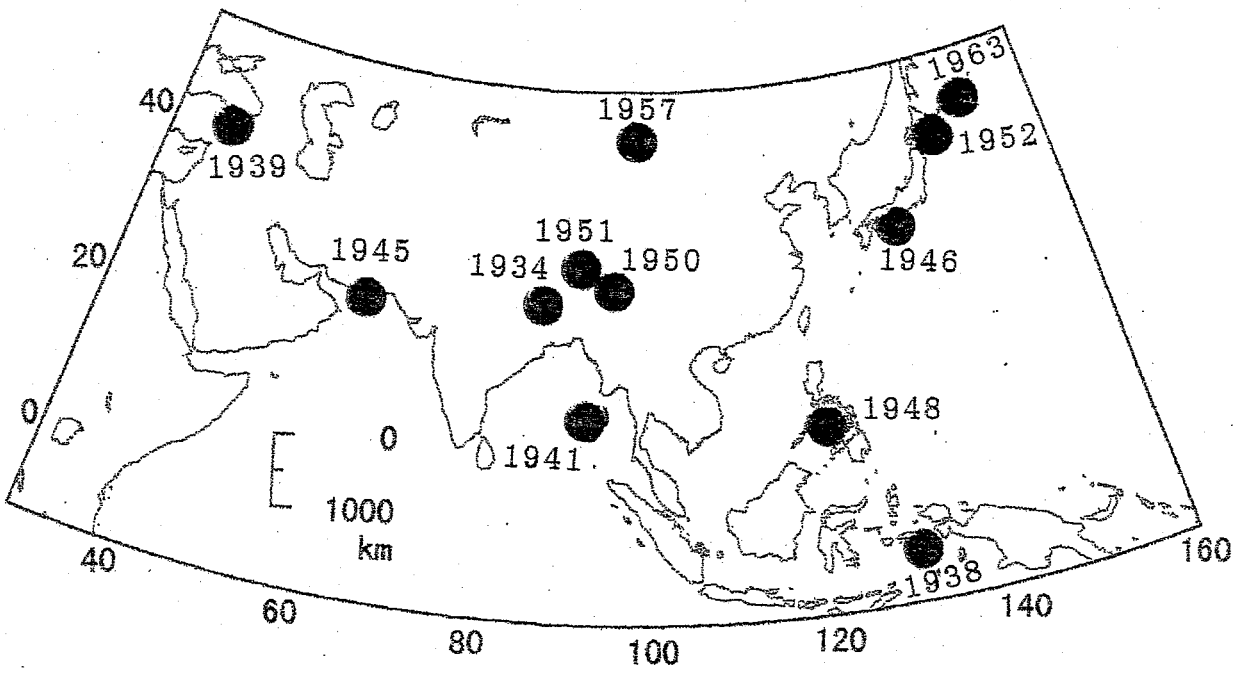


Fig. 1 Distribution of 12 shallow depth earthquakes (Ms ≧ 8) in Asia.

total of 12 shallow great earthquakes appeared in Asia from 1900 to 1970. Entire events of Ms ≧8.0 are listed in Table 1, and their distribution is shown in Fig. 1. This time period of 37 years includes one seismic active period and one inactive period suggested by Mogi and represents a major seismic process in Asia.

As some earthquakes, which were treated as with M ≧ 8.0 or lower in Mogi (1974)'s paper, were corrected later to be lower or larger, the number of great earthquakes is not the same as in Fig. 5 of Mogi's paper. Another limitation is concerned with the depth of great earthquakes. The lower limit of shallow depth is defined as 60 km in the present work. Some great earthquakes have been added into the catalogue in Table 1 according to " World Catalogue of Earthquakes: 1900–1980 years, M≧6 " (Shi et al., 1986), in which revised magnitudes of great earthquakes occurred in 1934–1970 years were given, in addition to that by Usami (1996). The depth values of great earthquakes in Table 1 are mainly taken from Pacheco and Sykes (1992). For the sake of simplicity, the number of the year, when the great earthquake occurred, is used to represent individual earthquake in the present work.

3. TIME ORDERING

During 37 year (12614 days) period there were only 12 great earthquakes. However, six of them present well agreement of almost equal time intervals among them. The T1 sequence in Table 2 show 5 nearly equal time intervals: 2171, 2163, 2182, 2208 and 2139 days between each pair of succeeding earthquakes. The maximum difference among 5 numbers is 69 days, and the minimum one is 8 days. Differences between the average value of 5 numbers and each of them are 2, 10, –9, –35

Table 2 Equal time intervals and equal distance among 6 great earthquakes

Date	1934		1939		1945		1951		1957		1963
	1.15		12.26		11.27		11.18		12.4		10.13
Magnitude	8.3		8.0		8.25		8.0		8.3		8.1
T1 (days)	|	2171	|	2163	|	2182	|	2208	|	2139	|
T2 (days)			|		4345		|		4347		|
D1 (km)	|	4652	|		4832		|		5216		|
D2 (km)			|	2835	|	2883	|	1706	|	3904	|

and 34 days, respectively. Another sequence (T2) presents two time intervals for three great earthquakes (1939, 1951 and 1963 earthquakes): 4345 days and 4347 days, the difference of them is only two days.

Here, three main equal time intervals for 1934, 1939,1945 and 1951 earthquakes can be considered as first level of rhythms, and they are denoted as t1, t2 and t3 respectively. We can see the first two intervals (t1 and t2 in unit of days) between each pair of 5 earthquakes in detail as follows:

1934		1938		1939		1941		1945 (Earthquake)
|	1478	|	693	|	548	|	1615	| (Days)
|	t11	|	t12	|	t21	|	t22	|
|		2171		|		2163		| (Days)
|		t1		|		t2		|

If let m1 = t1/3 = 724 and m2 = t2/4 = 541, the deviations between real time intervals and computed values are:

t11 − 2*m1 = 30; t12 − m1 = −30; t21 − m2 = 7; t22 −3*m2 = −8.

For the first two rhythms (t1, t2) we find rather small deviations.

The t3 rhythm can be divided into 5 units (m3 = t3 / 5 = 442 days). Real time intervals between each pair of five earthquakes are illustrated as follows:

1945		1946		1948		1950		1951	(Earthquake)
	388		400		934		460		(Days)
	t31		t32		t3		t34		
				2182					(Days)
				t3					

The deviations between actual time interval between two earthquakes and computed values are:

t31 − m3 = −48; t32 − m3 = −37; t33 − 2*m3 = 61; t34 − m3 = 24 (days).

These results show the second level ordering of time intervals. The standard error of 8 deviations is about 38 days.

Therefore, all the great earthquakes, except the 1952 earthquake, are characterized by various kinds of equal time interval orderings. This paper could be the first that mentioned the good agreement of time intervals among great earthquakes (repeated five times) in seismology. It provides a new insight for understanding the intriguing features of great earthquake occurrences.

4. EQUIDISTANT ORDERING

The method applied for studying equidistant orderings between great earthquakes is the same as introduced in our earlier papers (Xu et al., 1994, and 1997). D is defined as the distance between two epicenters corrected for the effects of the ellipticity of the Earth.

There are more than ten isosceles triangles illustrated in Fig. 2. Lengths of their equal sides vary in

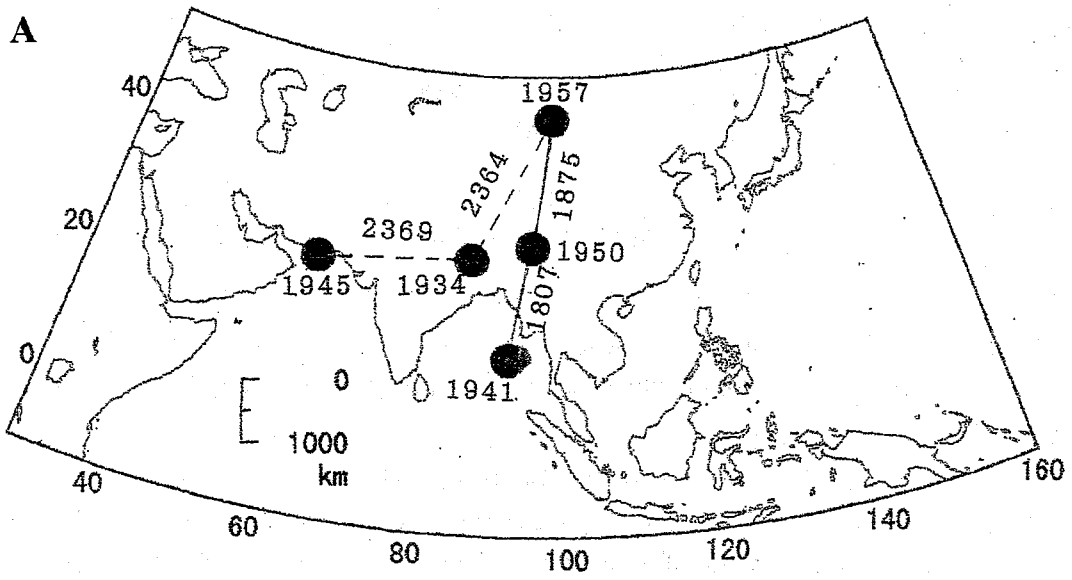


Fig. 2 Ordered pairs and series (Fig. 2A– 2G) of great earthquakes. The earthquakes are denoted by solid circles, the numbers near circles are the years they occurred. The numbers along the lines show distances between two epicenters. Fig. 2B – Fig. 2G are in the next two pages.

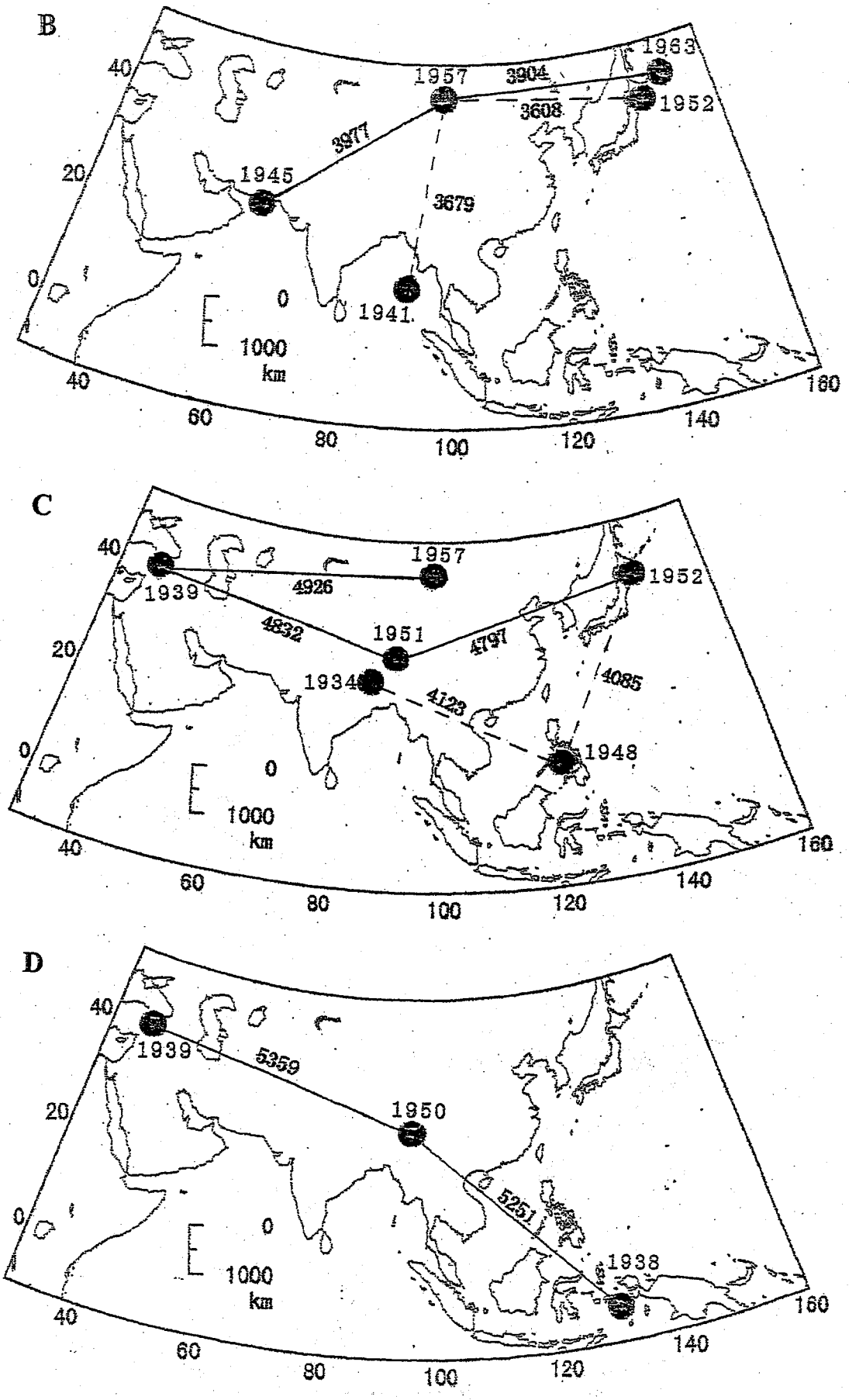


Fig. 2 (*Continued*)

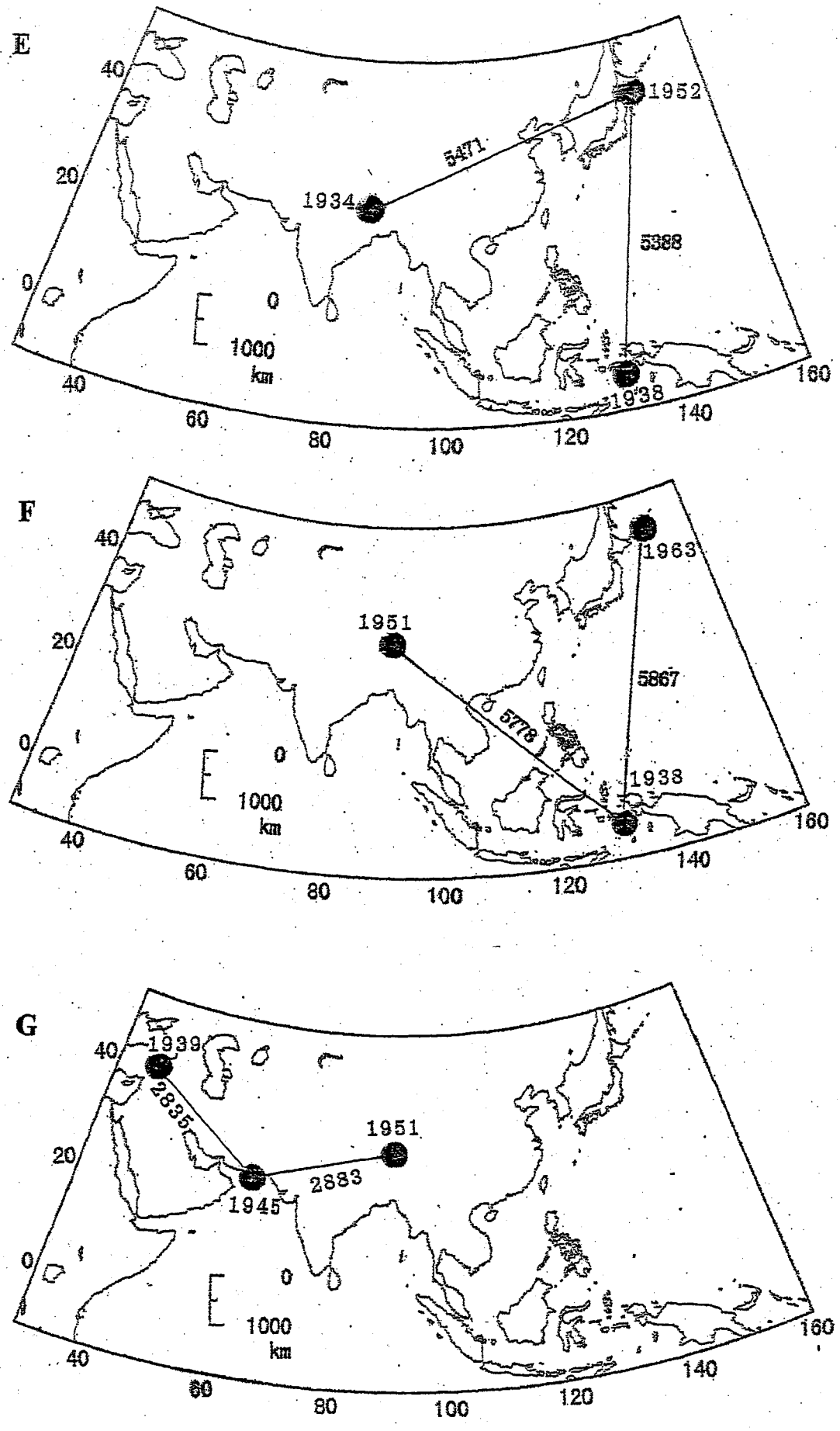


Fig. 2 (*Continued*)

the ranges of 1800–5900 km. A ratio (R) reflects the relative deviation is introduced. This R value equals to the difference of two D values of equal sides of an isosceles triangle divided by the maximum values of these two . The allowance limit for the R values is defined as 0.05. All of 11 computed R values for isosceles triangles are much less than 0.022, except the worse case when R value is 0.036.

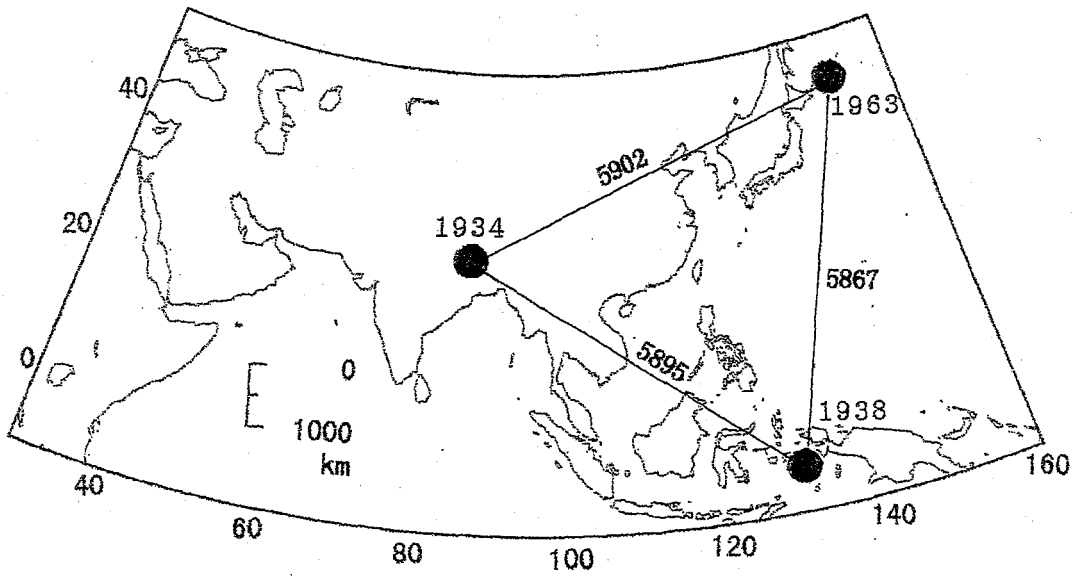


Fig. 3 A equilateral triangle formed by the 1934, 1938 and 1963 earthquakes

One equilateral triangle is found in Fig. 3, formed by the 1934, 1938 and 1963 earthquakes. The differences between pairs of three D values are: 7, 28 and 35 km respectively. They are rather small, as D values are in the range of 5867 – 5902 km. Fig. 4 represents a parallel quadrilateral case. The difference between two opposite equal sides is 12 km, and that between another two opposite sides is 87 kms.

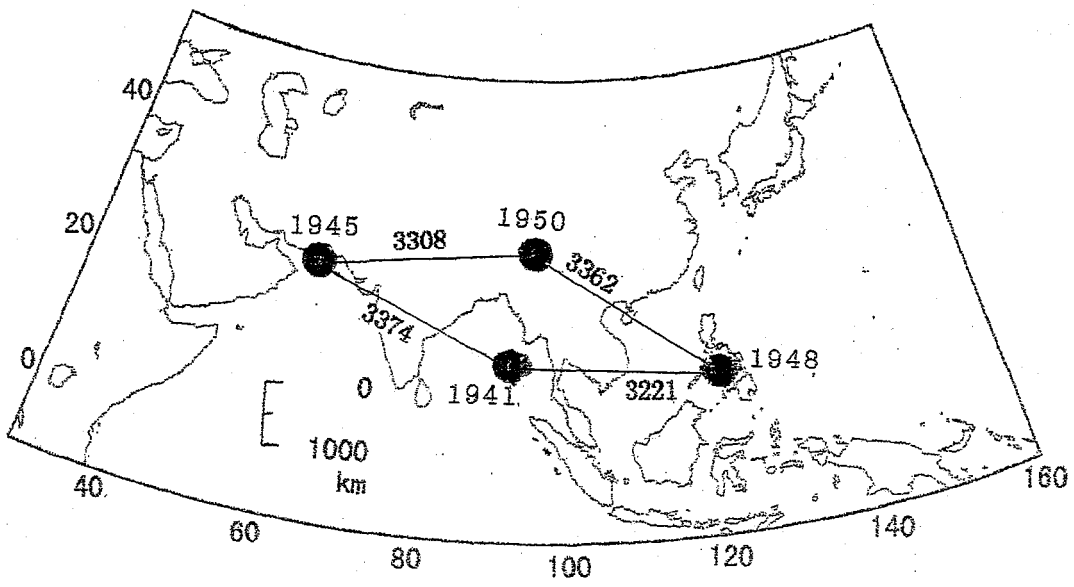


Fig. 4 A parallel quadrilateral formed by the 1941, 1945, 1948 and 1950 earthquakes

In Table 1, the largest earthquakes are the 1950, 1934 and 1957 earthquakes and each of them appears several times in Fig. 2 – Fig. 4. The 1934 earthquake has an equidistant ordering with 6 great earthquakes, the 1950 earthquake with 6 earthquakes, and the 1957 earthquake with 8 earthquakes. All of the 12 earthquakes are involved in Fig. 2 – Fig. 4, except the 1946 earthquake in Japan.

5. SPACE-TIME ORDERING

Only in two cases, ordered features both in space and time appear simultaneously. In Fig. 2B, the D value for the 1939 and 1945 earthquakes (2835 km) is similar to that for the 1945 and 1951 earthquakes (2883 km, Fig. 5). Also, the time interval between the 1939 and 1945 earthquakes is 2163 days, and that between the 1945 and 1951 earthquakes is 2182 days (Table 2), whose R ratio is only 0.017. Another example is shown also in Table 2. Two time intervals (4345 and 4347 days) are surprisingly similar, and the difference between two D values (4832 and 5216 kms) is 384 km, whose R ratio is 0.074.

6. MIGRATION

Migration patterns of earthquakes seem important in understanding the dynamics of the crust. A well known one direction migration pattern of large earthquakes was, first, observed by Richter (1958) in northern Anatolia, Turkey, which started with the 1939 Erzincan earthquake. The direction of migration is from east to west. This migration includes 7 earthquakes according to Mogi (1993), who added several new earthquakes after 1955. All the earthquakes shown , except the 1939 Erzincan earthquake, are smaller than 8.0 in magnitude. The distance between the 1939 earthquake and the last 1967 earthquake (M=7.1) occurred on the west part of Turkey, is about 1000 km or slightly longer.

Our research provides another migration pattern (Fig. 5), which is concerned of five great earthquakes listed in Table 2, with equal time intervals. It is also related to the same 1939 earthquake of M=8.0, and also present regular migration, but, in opposite direction, i.e. each earthquake took place in succession to the eastward. Fig. 5 shows the locations of 6 earthquakes, listed in Table 2, and includes above-mentioned five earthquakes. Their distances are indicated by various lines and numbers on them. Since 1939, earthquakes migrated from east end of Anatolia Fault, across Middle

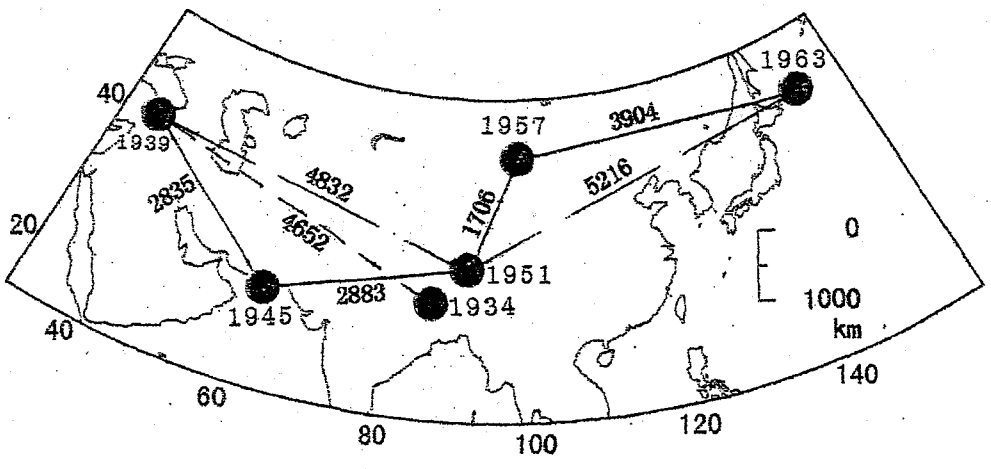


Fig. 5 Distances among 6 great earthquakes, which form regular spatial ordered pairs.

Asia, China, Mongolia, and ended in the eastern most part of Fig. 6. The distance between the 1939 and 1963 earthquakes is about 8411 km. If the 1951 earthquake is taken as a referential middle point, the time intervals and D values before and after the 1951 earthquake are almost same, as mentioned in the previous section.

This fact indicates that the migration pattern of five earthquakes shows more regular spatiotemporal ordering than that along the fault of northern Anatolia. Similar to the westward migration along this fault, this more regular pattern of eastward migration must have physical background (for example, large weak regions where these great events occur, connected each other by potential canals in the crust, as well as in the upper part of mantle), although we have few knowledge about such a situation.

Now, we face a surprising phenomena: since the occurrence of the 1939 earthquake, two migrations of earthquakes started on opposite directions with different magnitudes for more than 20 years. The eastward migration is characterized by larger and wider distributions in scales and more regular patterns in space and time than the westward one. In this respect, the hypothesis that great earthquakes are distributed randomly is not appropriate.

7. DISCUSSION

(1) The 1934, 1950 and 1951 earthquakes occur in a cluster in the middle part of Fig. 1, and the 1950 earthquake has the largest magnitude among 12 earthquakes. According to the seismic moment catalog given by Pacheco and Sykes (1992) the seismic moment of the 1950 earthquake accounts for more moment release than any other 11 earthquakes. In each case of Figs. 2a, 2d and 4, it can be mentioned that the 1950 earthquake is located in the middle point between two ordered pair of earthquakes. Moreover, the 1950 earthquake can be regarded also as an important common node of three isosceles formed by 5 great earthquakes in China continent (Xu et al., 1994). This indicates that the 1950 earthquake occupies the most important location in the spatial distribution of great earthquakes in Asia during 1934–1970 period.

(2) The migration of large earthquakes in northern Anatolia is related to the occurrence of the 1939 earthquake of M=8 class, as mentioned by Mogi (1993). Therefore, it seems adequate to say that other great earthquakes in Table 1 may be also regarded as significant nodes of migration of large earthquakes. The 1946 Nankaido earthquake is also an example of similar migration in Japan (see Xu and Ouchi, 1998).

(3) Utsu (1984) listed four examples of recurrences of large or great earthquakes in Japan, and later he added another two examples from Parkfield, U.S.A., and Hindu Kush in his 1994 paper. All these examples about recurrences of earthquakes at almost equal time intervals are related to earthquakes occurred in small areas or regions. Utsu introduced a parameter (r) to describe the variety of time intervals. This r value is a ratio of maximum time interval to minimum time interval. Among four r values listed in Table 2 of Utsu (1994) the smallest one is r = 1.075 for 5 large Hindu Kush earthquakes in 1950–1993.

The r value for 6 great earthquakes in Table 2 of present paper is only 1.032. Therefore, our results provide a new type of recurrence pattern that great earthquakes might have unexpectedly almost similar time intervals, and such correlation of earthquakes may extend to very long distances over several thousands kilometers.

(4) The regular time intervals among 6 great earthquakes listed in Table 2 stimulated us to search for the physical basis of their formation. We calculated the sums of every three values in T1 sequence in Table 2 and the results are shown in Table 3.

Table 3 Equal time intervals among 6 great earthquakes in Asia (in unit of days)

Earthquakes	Time intervals			
	T1	S1	S2	S3
1934				
	2171			
1939				
	2163	**6516**		
1945				
	2182		**6553**	
1951				
	2208			**6529**
1957				
	2139			
1963				

It is well known that the Saros period in astronomy is 6585.321 days (18 years and 10 days or 11 days depending on leap years), which is near to S1, S2 and S3 values in Table 3. The Saros period is the time that it takes nodes of the Moon's orbit to complete one full circuit of the Earth. The largest deviation between Saros period and S1 is 70 days and it's relative deviation is 1.06%. The smallest deviation between Saros period and S2 is 23 days and it's relative deviation is only 0.35%. Each value of T1 sequence in Table 2 is also near to one third of Saros period (2195 days or 6 years and 3 days). The standard deviation between them is $\pm$35.6 days.

Fedotov et al. (1977) indicated the correlation of seismicity in Kamchatka, Kurile Islands and northeastern Japan, and also Aleutian Islands with the lunar-solar tide with the18.6-year period and 6.2-year period. Later, Kilston and Knopoff (1983) reported the 18.6 period of large earthquakes in southern California. Their method was applied to study on seismicity of major seismic regions over the world, and it was found that most of large shallow earthquakes have statistically significant 18.6-year periodicity (Du, 1994). Similar correlation of 18.6-year periodicity with large deep and intermediate earthquakes also have been reported (Du, 1996).

The 18.6 year (6793.477 days) period is the one of the precession of the line of nodes of the Moon's orbit and should not be confused with the Saros period. The deviations between the 18.6-year period and S values in Table 3 and also those between the 6.2 period (one third of 18.6-year period) and each value in T1 sequences are much larger than those between the Saros period and S values or values in T1 sequence. Therefore, it is reasonable to conclude that the 6 great earthquakes have regular temporal ordering related to the Saros period. We refer the time intervals of earthquakes to the Saros

period, rather than to perfectly periodic occurrence.

The Saros period is exactly 223 times the length of synodic month. It is very near to 19 eclipse years (6585.781 days), to 242 times the length of nodical month (6585.357 days), and also to 239 times the length of anomalistic month (6585.537 days). All four periods are around 6585 days (National Astronomical Observatory, 1997). It reflects an important moment of relative position among the Sun, the Moon and the Earth, while the summing-up attraction of the Sun, the Moon and the Earth had maximum effect for the occurrence of great earthquakes in Asia.

8. CONCLUSION

We have shown that 12 great earthquakes occurred in Asia for the years from 1934 to 1970 show clear spatial equidistant and equal time interval ordering, which seems to be significant facts to understand the real features of earthquake generations. The regular time intervals among 6 great earthquakes in Table 2 and Table 3 should be compared to the Saros period, since these time intervals are quite similar to the Saros period.

If great earthquakes in Asia show ordered distribution, this indicates that their occurrences have no probabilistic features, as many seismologists insisted. If so, we would have more opportunities to predict the future great earthquakes and mitigate the amount of possible damage by great earthquakes.

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