



Equidistant Ordering of Shallow Earthquakes ($M \geq 7.5$) in and around Japan since 1890

Xu, Dao-Yi

大内, 徹

(Citation)

神戸大学都市安全研究センター研究報告, 2:141-158

(Issue Date)

1998-03

(Resource Type)

departmental bulletin paper

(Version)

Version of Record

(JaLCD0I)

<https://doi.org/10.24546/00317482>

(URL)

<https://hdl.handle.net/20.500.14094/00317482>



EQUIDISTANT ORDERING OF SHALLOW EARTHQUAKES ($M \geq 7.5$) IN AND AROUND JAPAN SINCE 1890

Dao-Yi Xu 1)

Toru Ouchi 2)

Abstract: Using the method described in (Xu et al., 1994, 1997) the spatial ordering of 28 large shallow earthquakes ($M \geq 7.5$) occurred in Japan since 1890 is studied. The distances between each pair of these earthquake epicenters show a significant peak in the range of 400–599 km. Most of earthquakes are characterized by equidistant ordering. Each earthquake can be related to many other earthquakes with different equidistant orderings. A total of 22 ordered series are found, and they are classified into six type of orderings. The relationships among 28 shallow earthquakes seem to indicate that they are the phenomena of a multi-level network-like system.

Key words: Large earthquake, Spatial ordering, Network feature

1. INTRODUCTION

Large earthquakes are complex and rare phenomena. As they occur in the crust or deeper, they are difficult to observe directly. It is generally considered that large earthquakes appear rarely and are distributed randomly or irregularly. Seismic activity in and around the Japan Islands, characterized by the appearance of many large earthquakes ($M \geq 7$), has been investigated by numerous seismologists (Mogi, 1968, 1969, and others). Mogi (1968) indicated that the crust is highly fragmented and has block structures, and regional occurrences of earthquakes are not random. Recently, Mogi (1993) gave a review about some long-term spatiotemporal regularities of seismicity pattern including that in Japan.

Relationships between large earthquakes can be formalized in the idea of ordering. The distance between two earthquakes may be one of significant relationships which has been more or less ignored before. A number of evidences provided by the studies on large and great earthquakes occurred in China (Xu et al. 1994; Xu et al., 1997) and Aegean region (Xu et al., 1998) support that the concept of equal distance between two epicenters could provide valuable information about the main features of large earthquakes. The aim of this present work is to apply this method to study the spatial distribution of shallow large earthquakes in and around Japan.

2. DATA SET

In order to examine the spatial ordering of large earthquakes in more detail, earthquake catalogue of high quality data is required. Recently, an authorized catalogue of destructive earthquakes in and near Japan was published (Usami, 1996). From this book, a total of 28 shallow depth ($h < 60$ km) earthquakes ($M \geq 7.5$) were collected (Table 1) during 1890–1995 years.

Table 1 List of large earthquakes ($M \geq 7.5$) with shallow depth in Japan since 1890.
(Latitude North, Longitude East)

Date			Epicentral location		Magnitude	Focal depth	
Year	Month	Day	Latitude (deg.)	Longitude (deg.)	Locality	(Ms) (km)	
1891	Oct.	28	35.6	136.6	Mino-Owari	8	
1894	Mar.	22	42.5	146	West-south off Nemuro	7.9	
1896	June	15	39.5	144	Sanriku-Oki	8.5 #	
1897	Aug.	5	38.3	143.3	Sendai-Oki	7.7	
1901	June	24	28	130	Amami-Oshima-kinkai	7.5	
1909	Mar.	13	34.5	141.5	Choshi-Oki	7.5	
1915	Nov.	1	38.3	142.9	Sanriku-Oki	7.5	
1918 A	Sep.	8	45.5	152	Off Urup	8	
1918 B	Nov.	8	44.5	150.5	Off Urup	7.7	
1923	Sep.	1	35.2	139.3	Kanto	7.9	16 *
1931	Mar.	9	41.2	142.5	South-east off Aomori	7.6	
1933	Mar.	3	39.23	144.52	Sanriku-Oki	8.1	10
1936	Nov.	3	38.15	142.13	Kinkazan-Oki	7.5	40
1938	Nov.	5	37.33	142.18	East off Fukushima	7.5	30
1940	Aug.	2	44.25	139.47	Kamuimisaki-Oki	7.5	10
1944	Dec.	7	33.8	136.62	Tonankai	7.9	30
1946	Dec.	21	33.03	135.62	Nankaido	8	20
1952	Mar.	4	41.8	144.13	Tokachi-Oki	8.2	15 *
1963	Oct.	13	44.89	149.56	Off Etorofu, Russia	8.1	40 *
1964	June	16	38.35	139.18	Niigata	7.5	40
1966	Mar.	13	24.24	122.67	East Off Taiwan, China	7.8	42
1968 A	Apr.	1	32.28	132.53	Hyuganada	7.5	30
1968 B	May	16	40.73	143.58	Tokachi-Oki	7.9	26 *
1969	Aug.	12	43.44	147.82	East off Hokkaido	7.8	41
1983	May	26	40.35	139.07	Nihonkai-Chubu	7.7	14
1993	July	12	42.78	139.18	Hokkaido-Nansei-Oki	7.8	35
1994 A	Oct.	4	43.37	147.72	Hokkaido-Nansei-Oki	8.1	23
1994 B	Dec.	28	40.43	143.75	Far off Sanriku	7.5	

● *The depth value is taken from Pacheco and Sykes (1992).

● # The M value is taken from National Astronomical Observatory (1997).

Their spatial distribution is shown in Fig. 1. Their occurrences show linear trends along the Japan Islands. Among 28 earthquakes there are 8 great earthquakes with $M \geq 8$. The year when the earthquake occurred represents the event for the sake of convenience in this paper. When two earthquakes appeared in one year, A and B are added after the year number to distinguish them each other. In this list large aftershocks are not included. The reason to choose the lower limit of earthquake magnitude at 7.5 is to expect more reliable epicenter parameters.

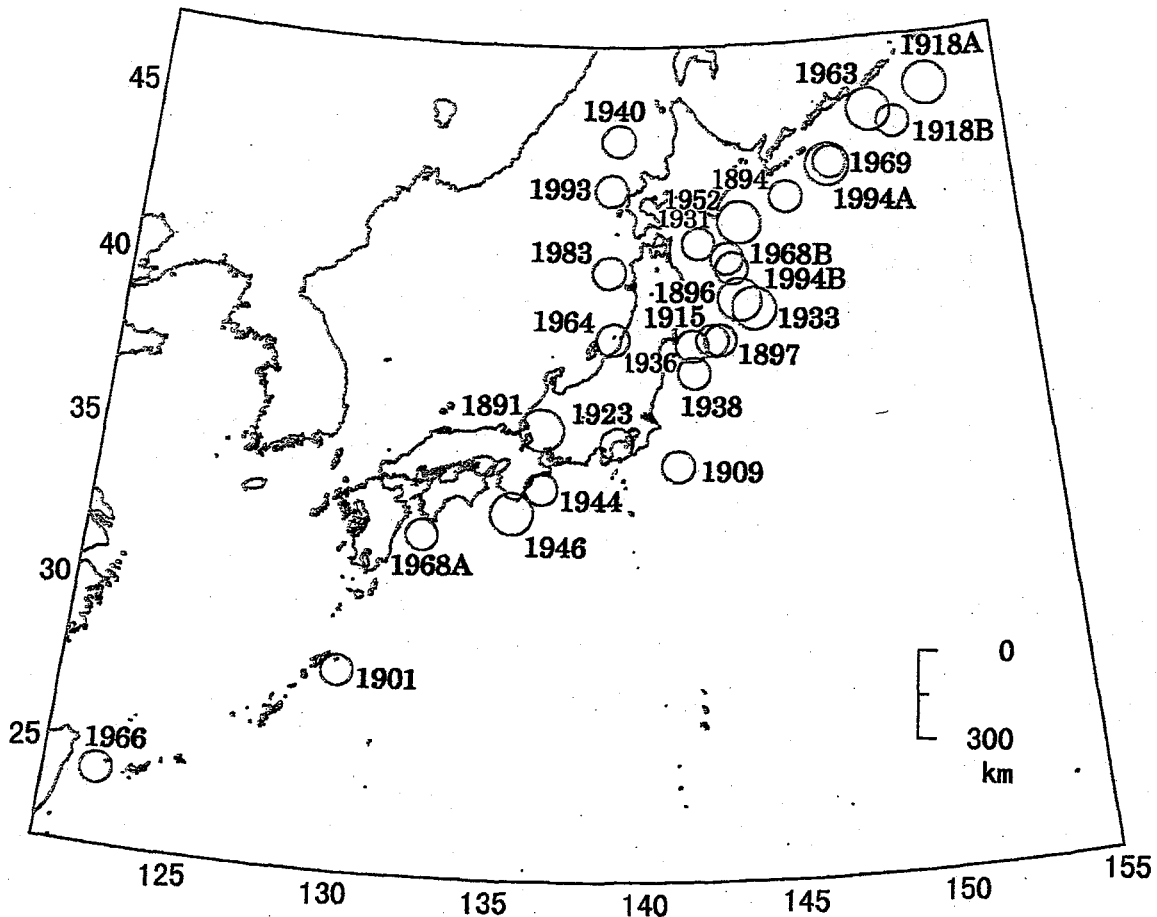


Fig. 1 The distribution of 28 shallow depth earthquakes ($M_s \geq 7.5$) in Japan. The epicenters are denoted by circles.

In the present paper only shallow earthquakes are concerned, and another article will treat earthquakes with deeper depth in Japan. D values larger than 250 km were selected, because the allowances of location errors are relatively small.

3. HISTOGRAM OF DISTANCES

The distance between two epicenters (defined as D later in this text) is one of the main features for studying the relation between them. This D value is computed by the formula described in (Xu et al., 1994). The distances between each pair of all 28 earthquake epicenters are computed and the histogram of these distances (Fig. 2) shows a significant peak in the range of 400–599 km. Minor peaks can be seen in the ranges of 700–799, 900–999, 1300–1399 and 1800–1899 km, respectively. It

seems the last two numbers are about three or four times larger than that of the largest peak. It means there are multiple relations among peaks. In general, large earthquakes are separated each other by several hundreds km, and the dominant distances are about 400–600 km.

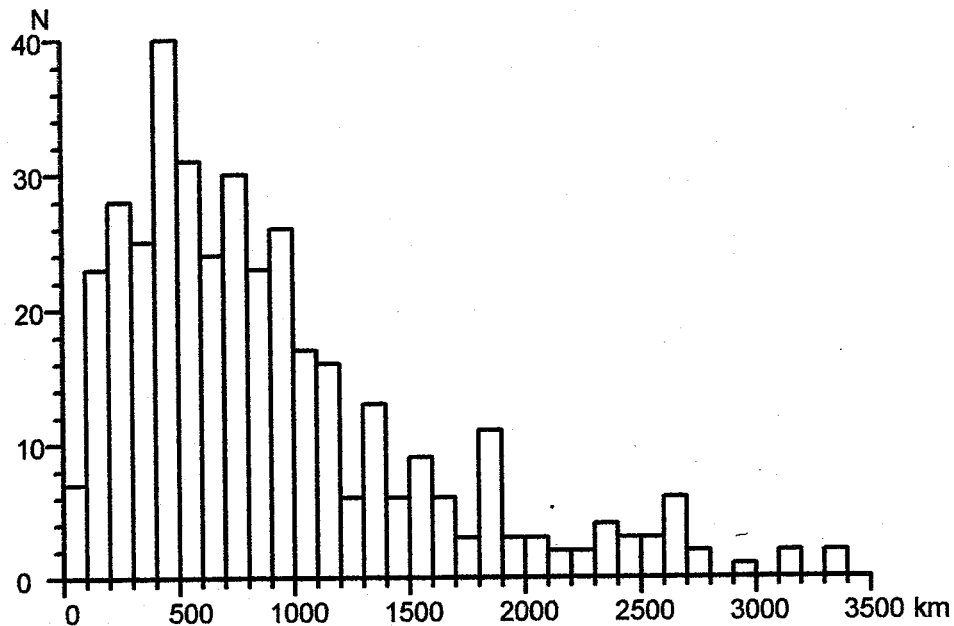


Fig. 2 Histogram of distances between every two earthquakes of 28 shallow depth earthquakes.

4. ORDERING

Due to the complex features of spatial distribution of large earthquakes in Japan, the application of conventional methods seems impractical and has more or less theoretical limitations. Recently, we use equal distance method in studying spatial patterns of earthquakes occurred in China (Xu et al., 1994 , 1997), which seems quite efficient.

Spatial relationship between two earthquakes can be analyzed in the idea of equidistant ordering. As earthquake locations have an accuracy of 0.1 degree both for latitude and longitude, respectively, we regard two distances are equivalent if their difference is less than 40 km, which will be called as allowance limit of equivalence (AL).

Most of earthquakes are characterized by equidistant ordering. Here, an ordered pair is defined when two distances are equal among three earthquakes (members). An ordered series (S) consists of one or more ordered pairs with equal distances. In the simplest case, an ordered series consists of 2 equal distances ($L = 2$) among 3 earthquakes ($m = 3$). The L value represents the number of equal distances in a series. The m value is usually larger than L and can not be less than L. The ratio value (R) equals $(m-L)/m$. The three parameters (R, m and L) can be used to describe the states of structure in that series. Every series has its own combination of m, L, and R values. In a series, the maximum difference (MDIF) among distances describes the deviation of D values, and will be less than 80 km (two time of AL). Another parameter is the average value of all differences (ADIF) between adjacent distances in a series.

Six types of spatial ordering can be recognized based on the above-mentioned data set for large earthquakes in Japan. Below we briefly discuss main features of each type:

1) **Linear ordering:** Several earthquakes with equal distances can be connected and extend along one predominant direction to form a long chain. Figs. 3A – 3D show several linear orderings. Among them the longest one is that in Fig. 3A. This series (S1, named in Table 2, and so forth) consists of six earthquakes, including 3 great earthquakes ($M \geq 8$). Probably, S1 presents one of the basic linear structures of seismic activity for the last 100 years in Japan. Locations of six earthquakes represent its main segmentation.

Table 2 Parameters of 22 ordered series shown in Figs. 3 – 8.

Figure	Series (S)	Length (L)	Member (m)	MDIF (km)	ADIF (km)	D range (km)
Fig. 3A	S1	5	6	33	15	524–557
Fig. 3B	S2	3	4	18	9	686–704
Fig. 3C	S3	3	4	14	13	555–569
Fig. 3D	S4	2	3	1	1	1042–1043
Fig. 3D	S5	2	3	29	29	1159–1188
Fig. 4A	S6	5	6	20	9	455–475
Fig. 4B	S7	4	5	26	16	414–440
Fig. 4C	S8	2	3	6	6	384–390
Fig. 4C	S9	2	3	18	18	403–421
Fig. 4C	S10	2	3	2	2	414–416
Fig. 5A	S11	5	5	26	15	558–584
Fig. 5B	S12	6	6	37	17	429–466
Fig. 6	S13	4	4	16	9	419–435
Fig. 7A	S14	3	4	22	15	1304–1326
Fig. 7B	S15	5	6	35	10	324–359
Fig. 7B	S16	2	3	1	1	299–300
Fig. 8A	S17	5	6	18	11	656–674
Fig. 8B	S18	2	3	4	4	1992–1996
Fig. 8B	S19	2	3	9	9	1829–1838
Fig. 8C	S20	3	4	17	9	801–818
Fig. 8C	S21	2	3	3	3	904–907
Fig. 8D	S22	4	5	14	10	992–1006

2) **Isosceles triangle:** There are many examples for isosceles triangle ordering. Several of them are illustrated in Figs. 4, 5, 7, and 8. There, only two equal sides of a isosceles triangle are shown, and the base side of each triangle is not shown for emphasizing equal sides. Many of them have small sizes ($L=2$, Fig. 4C). In some cases, several isosceles triangles with equal distances are connected each other through one or more common members and form larger series. Fig. 4A shows the longest series of isosceles triangles, which includes six earthquakes (2 great earthquakes) and is formed by four isosceles triangles. Three of six earthquakes are located on the east side of the Japan Islands, and the other three earthquakes – on the west edge.

3) **Equilateral triangle:** This kind of ordering shows a particular situation, i.e. two isosceles triangles share all three common earthquakes. An equilateral triangle can be seen separately as three isosceles triangles (Figs. 5A and 5B). It appears rarely in the actual situation.

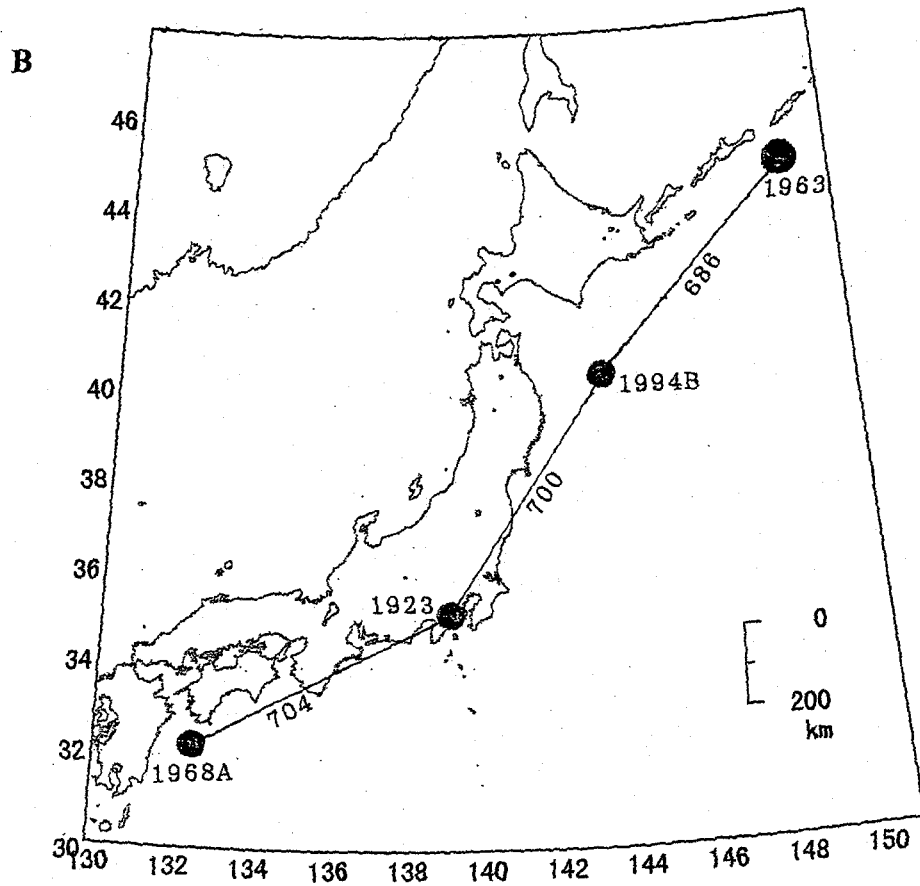
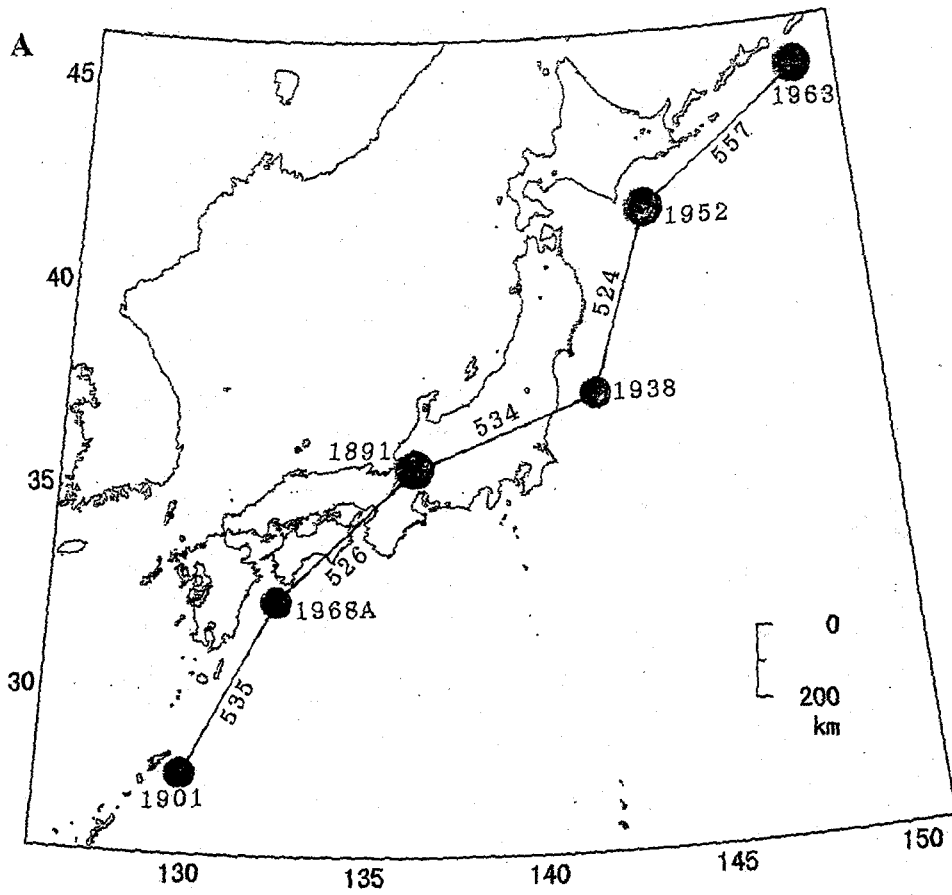


Fig. 3 Linear ordered pairs and series. The number along the line denotes the distance (km) between two earthquakes, indicated by solid circles.

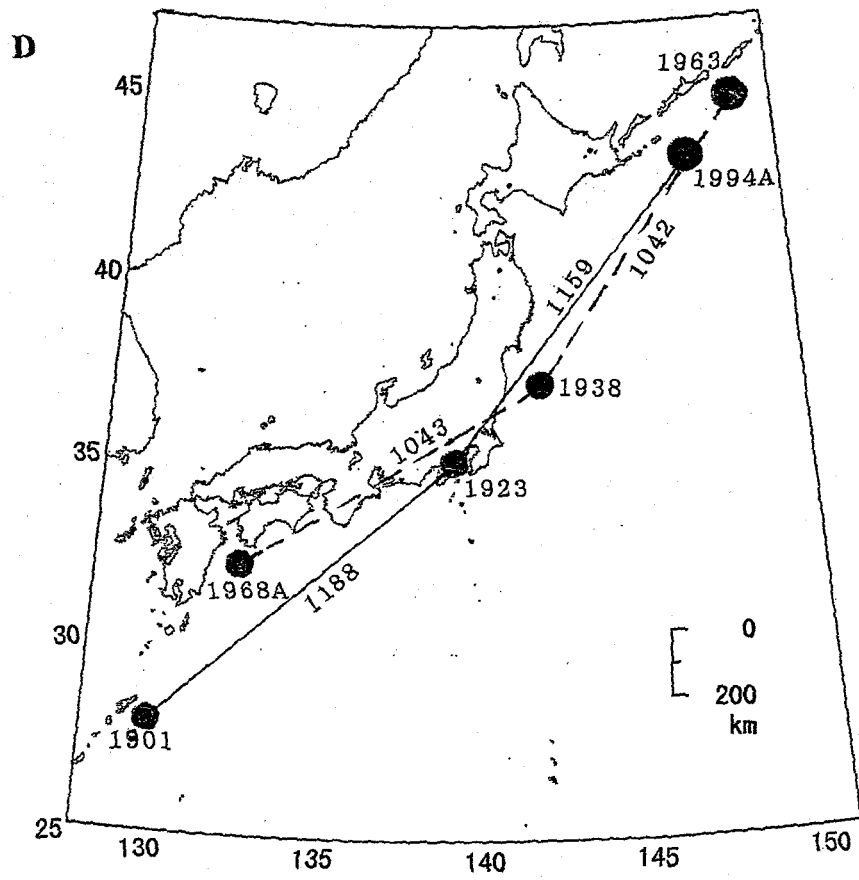
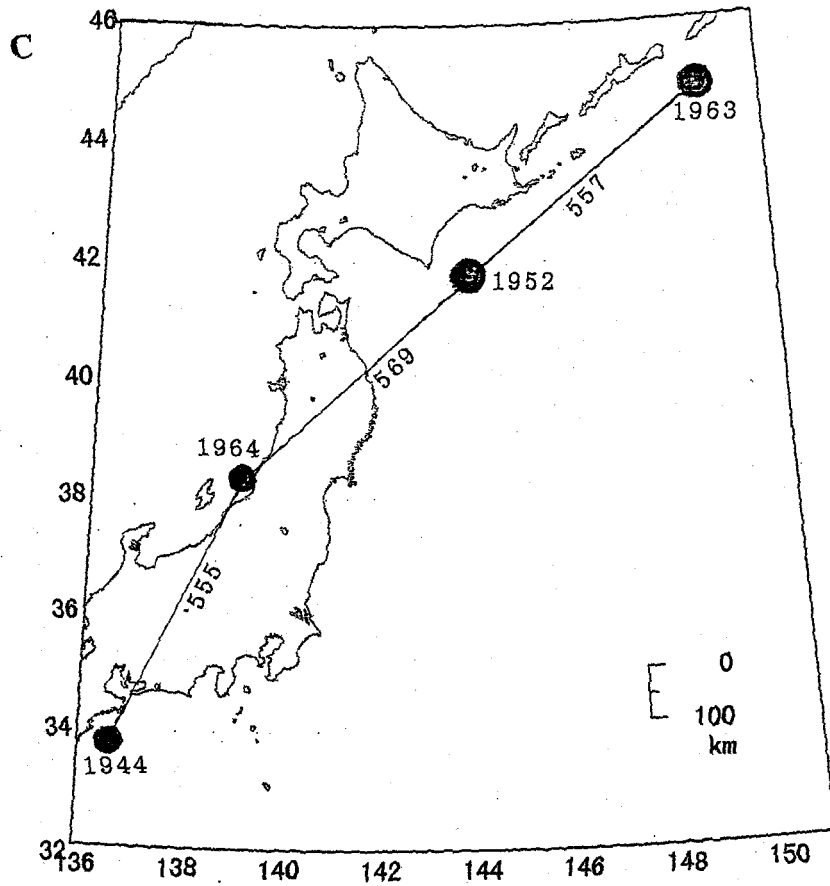


Fig. 3 (Continued)

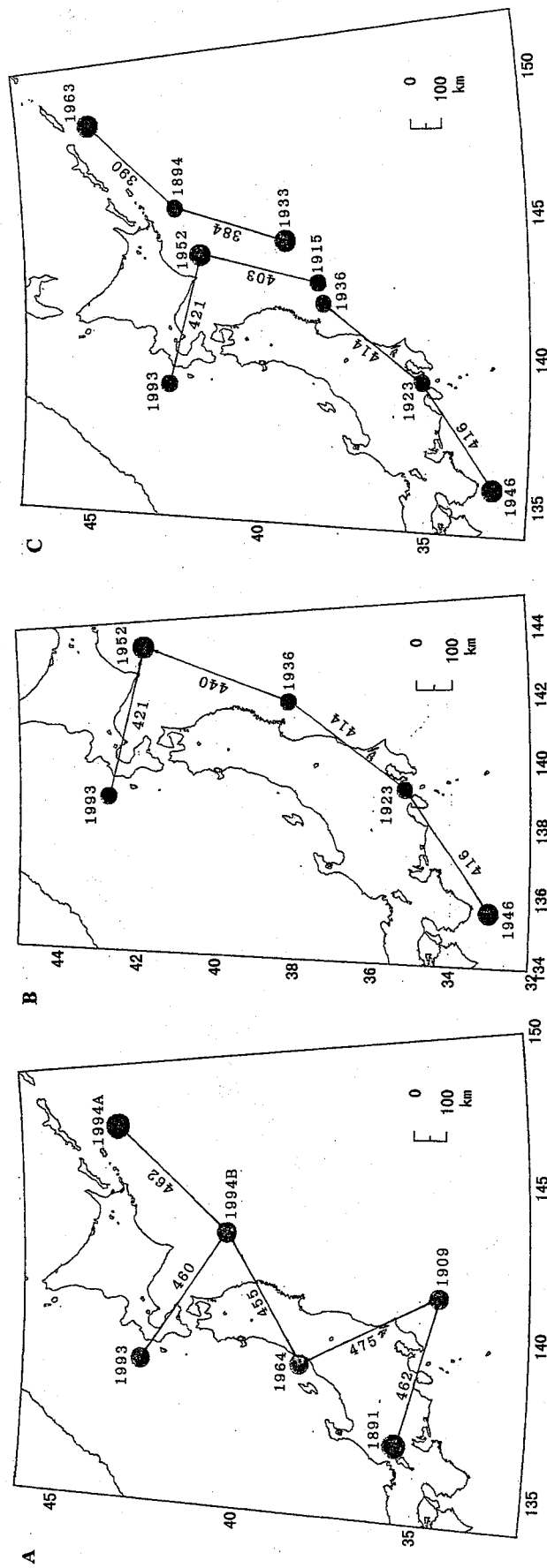


Fig. 4 Isosceles triangles and related ordered series. The number along the line denotes the distance (km) between two earthquakes, indicated by solid circles.

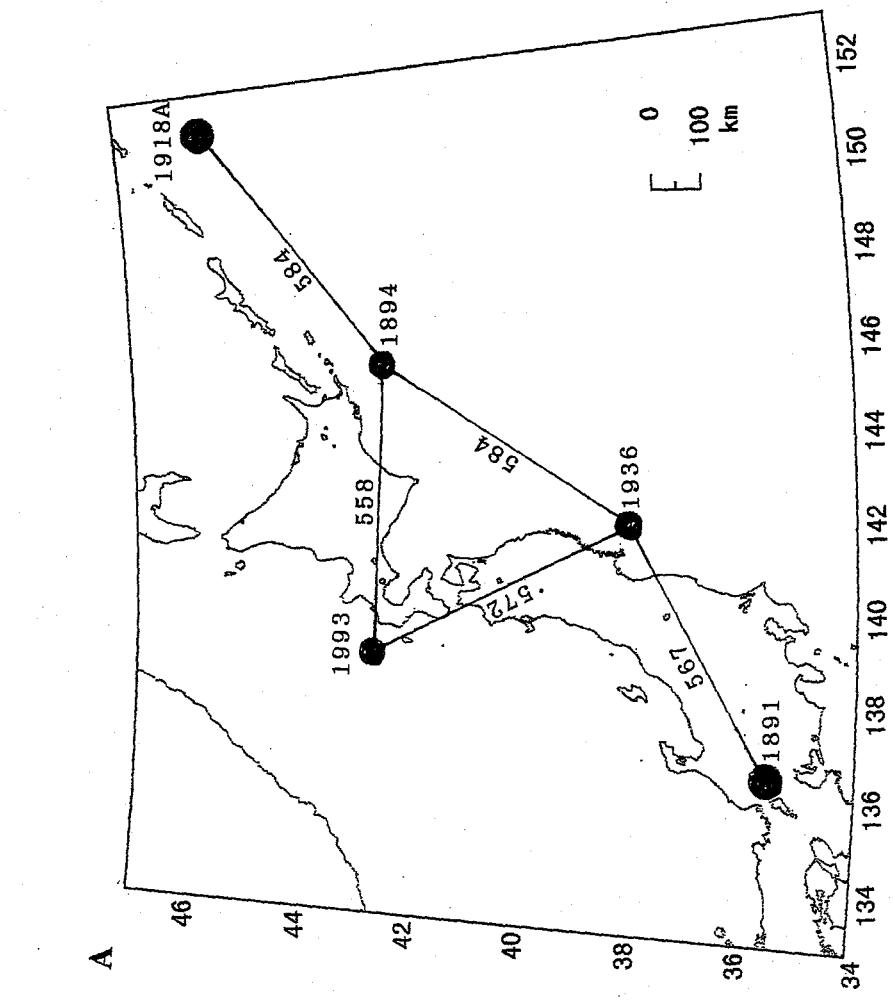
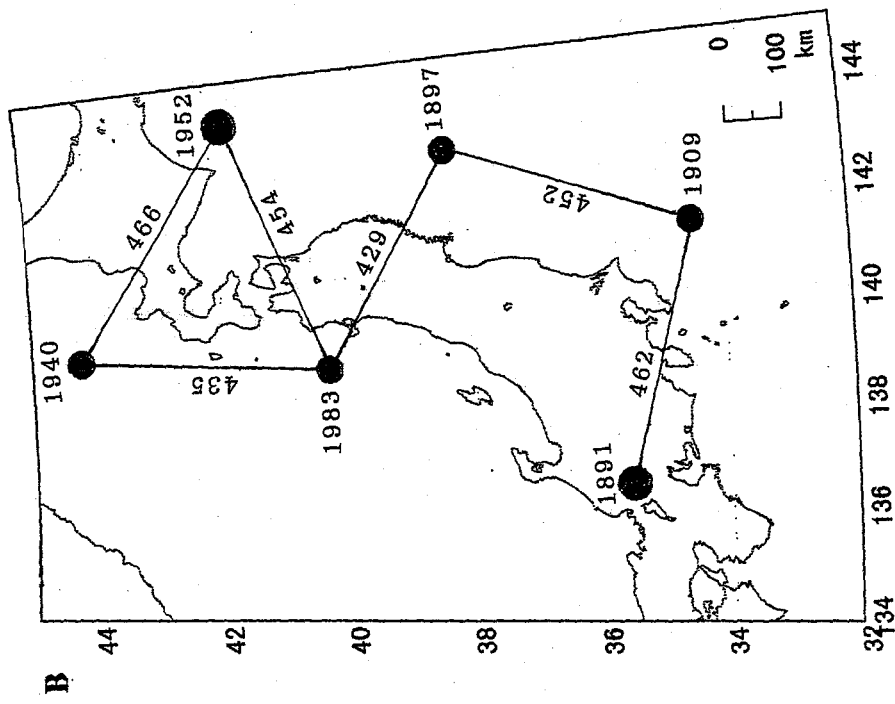


Fig. 5 Two equilateral triangles and related ordered series. The number along the line denotes the distance (km) between two earthquakes, indicated by solid circles.

One equilateral triangle formed by 1940, 1952 and 1983 earthquakes is illustrated in Fig. 5B. Another example (formed by 1894, 1936 and 1993 earthquakes) located in the middle part of Fig. 5A, represents a symmetric axis of the ordered series (S11, see Table 2).

4) **Rhombus ordering:** Another rare case of equal distances of four earthquakes is rhombus ordering. Four large earthquakes (1931, 1938, 1940 and 1983 earthquakes) form a typical rhombus series (S13 in Table 2 and Fig.6).

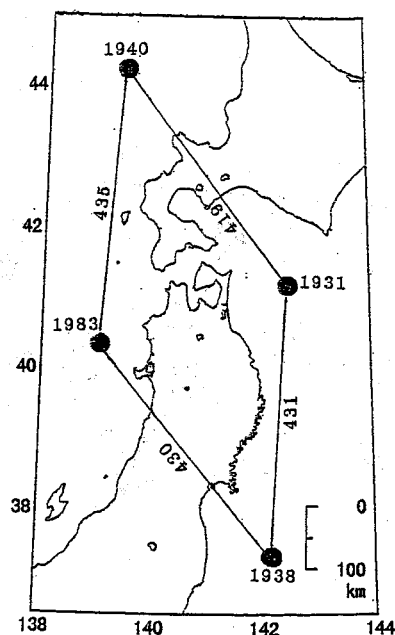


Fig. 6 Rhombus ordered series

5) **Circular ordering:** Circular ordering is an ordered series around an earthquake (as the center with three or more earthquakes of same distances from that earthquake. At least, this needs four earthquakes to form a circular ordering as shown in Fig. 7A. Four earthquakes in the upper part of Fig. 7B (1894, 1897, 1993 and 1931 earthquakes) forms a circular ordering, which at the same time can be seen as three isosceles triangles. In the upper part of Fig. 9D, the 1952 earthquake located in the center of a series and has equal distances with 1940, 1993, 1983, 1936 and 1915 earthquakes. In the case of circular ordering, all ordered pairs share one common earthquake in the series.

6) **Irregular ordering:** Various combinations of different ordered pairs form irregular ordering as shown in Fig. 8. In Fig. 8A, S17 consists of one isosceles triangle and two linear ordered pairs, and in Fig. 8D three isosceles triangles with D values about 1000 km can be identified for S22.

In Table 2, the basic parameters of 22 series illustrated in Figs. 3 - 8, are listed, and the index numbers (S1 - S22) for each series are also given. The MDIS values give the maximum differences among distances in the series. Most of MDIS values are small in comparison with the limit of the allowance error, and even smaller than a half of the limit, which shows fairly good agreement of D values in all series. All of the AMIF values listed in Table 2 show also small values.

Various types of ordered pairs can be connected to form an ordered series sharing equal distances and, at the same time, one or more common earthquakes. For example, S7 (Fig. 4B) includes one linear ordered pair and one isosceles triangle, and S12 (Fig. 5B) - one equilateral triangle and two isosceles triangles.

The 3rd and 4th types series are characterized by zero values of R, while m is equal to L. It means these kinds of series have more compact structures than other series. Large values of L and m present more complicated structure than that of small ones. However, the 5th type has a rather compact structure, whose R value is still larger than zero. Additional parameter is needed in the future.

Almost all of the listed ordered types have been found either in China and the Aegean region, or in Asia (Xu et al. 1994, 1997, Xu and Ouchi 1998). This indicates that they have general significance for understanding the real features of large earthquakes.

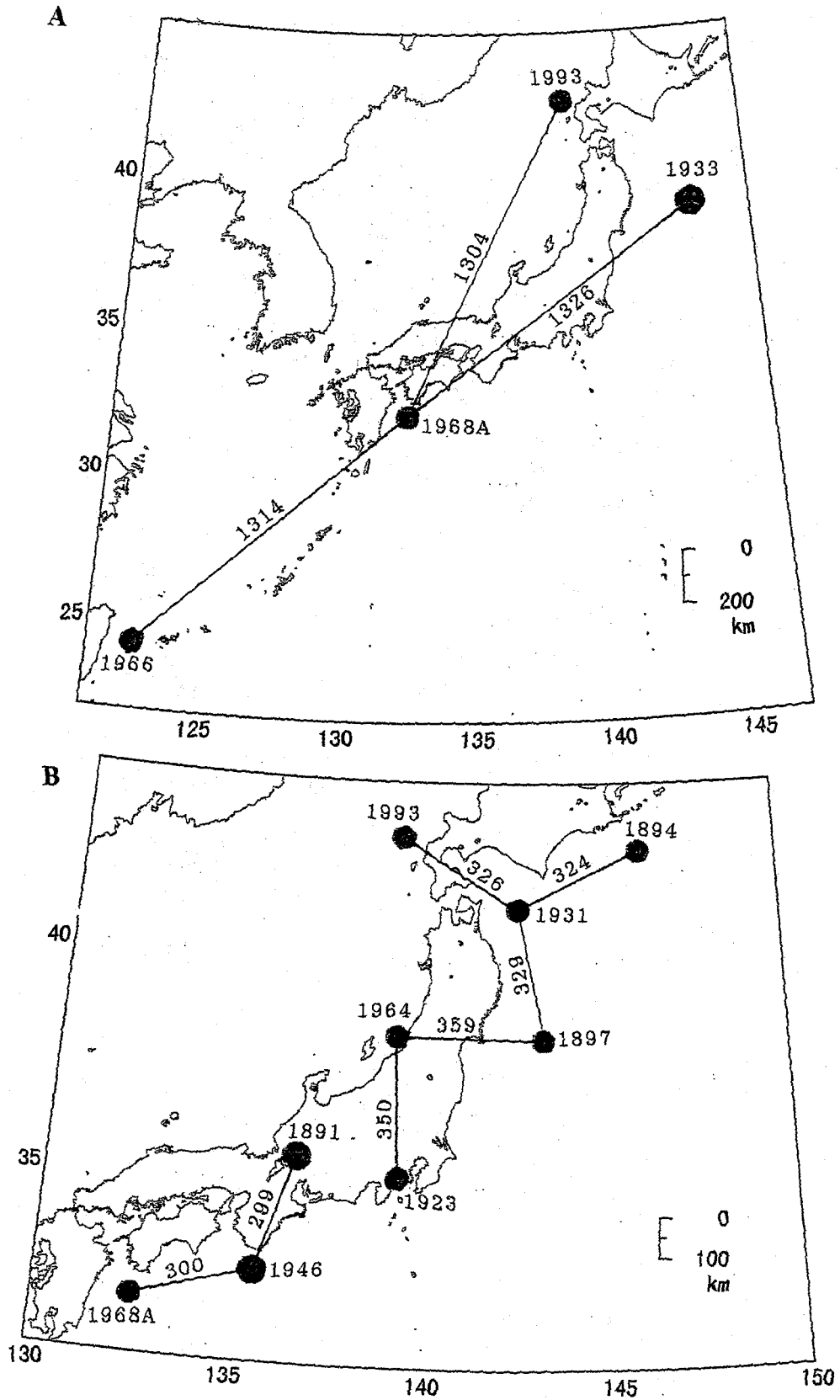


Fig. 7 Circular ordered series. The number along the line denotes the distances (km) between two earthquakes, indicated by solid circles.

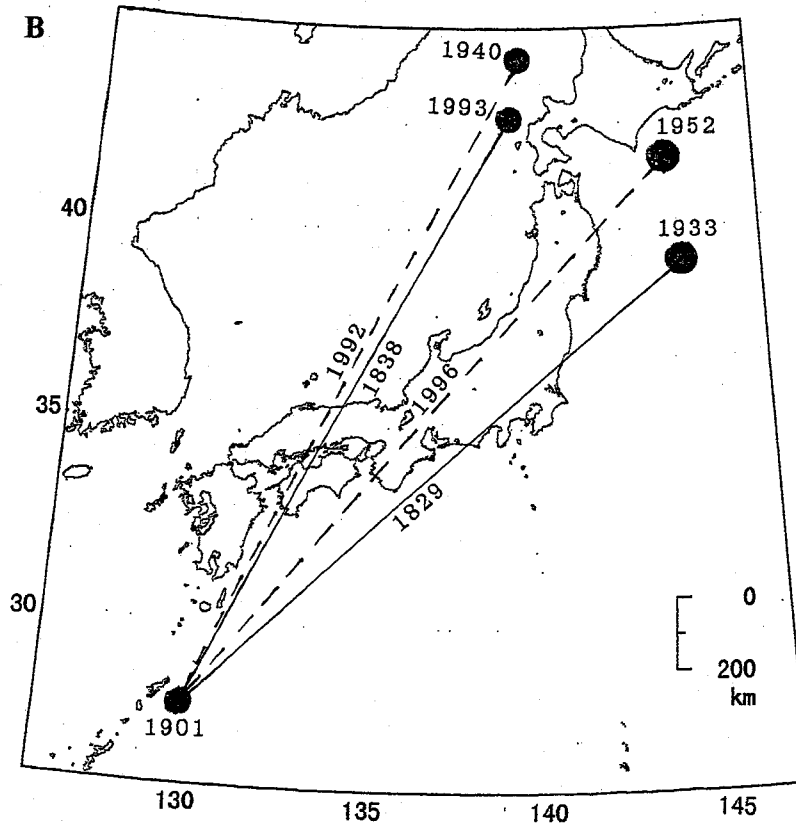
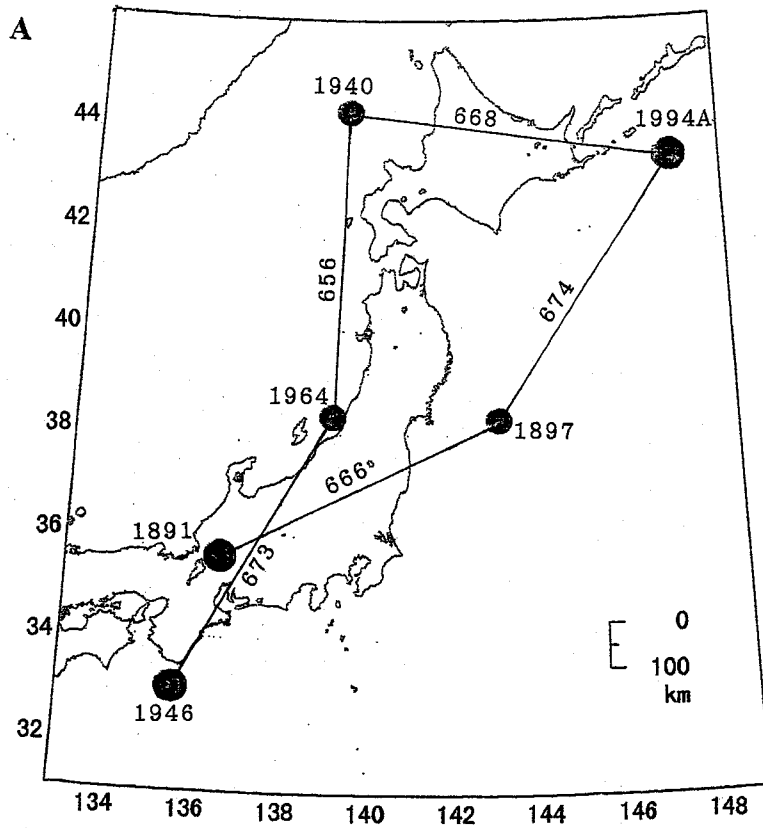


Fig. 8 Irregular ordered series. The number along the line denotes the distance (km) between two earthquakes, indicated by solid circles.

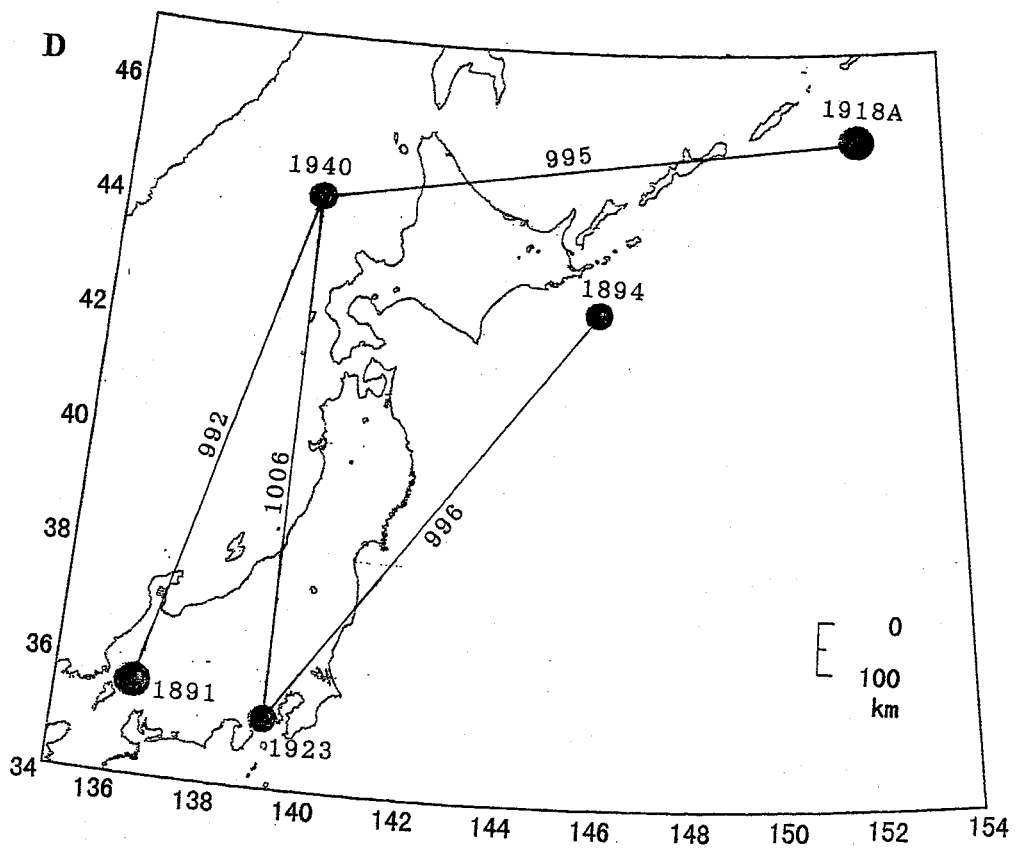
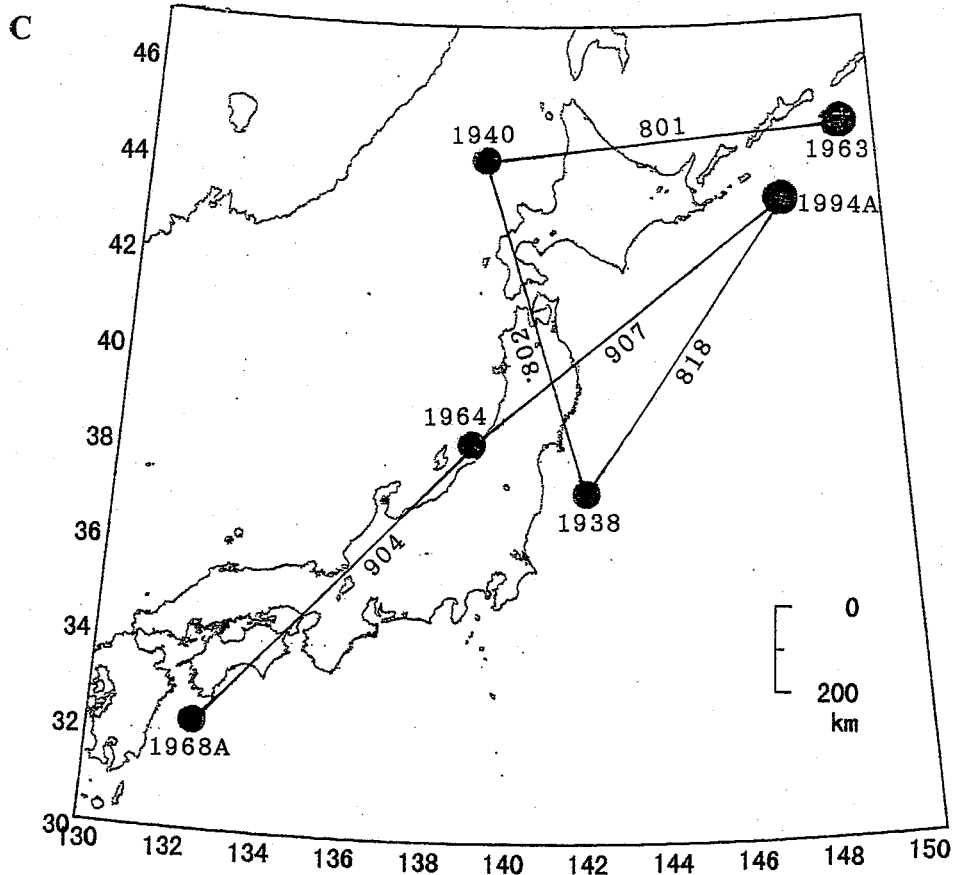


Fig. 8 (Continued)

5. NETWORK OF RELATIONSHIPS

Several ordered series can be combined into higher level of ordering — network of relationships (NWR). Due to the fact that one earthquake appears in many series with different D values (Figs. 3 – 8), each of 4 significant earthquakes (1891, 1923, 1946 and 1952 earthquakes) is regarded as the main node of its network, and therefore, four networks are formed (Fig.9). It means that all ordered pairs listed in Figs. 3 – 8 and related to one earthquake (such as the 1923 earthquake), compose a higher level network (such as Fig. 9B). Main features of these four networks are summarized in Table 3.

Table 3 Some parameters of four networks

Figure	NWR	L	M	D Range	Central earthquake
Fig. 9A	NWR1	12	13	299–995 km	1891
Fig. 9B	NWR2	12	13	350–1188 km	1923
Fig. 9C	NWR3	8	9	299–775 km	1946
Fig. 9D	NWR4	12	13	403–1996 km	1952

The famous 1891 Mino–Owari earthquake has ordered relations with 12 earthquakes, and may form eight ordered pairs (Fig.9A). Among them several pairs share two common earthquakes with different distances. For example, 1891, 1946 and 1968A earthquakes form an isosceles triangle, and 1968A, 1891, 1938 and 1952 earthquakes present a linear series. Two series are connected each other by two common earthquakes. NWR1 shows a more complex structure than individual series.

The 1923 Kanto earthquake is related to 12 earthquakes with 350, 359, 414, 416, 440, 686, 700, 704, 996, 1006, 1159 and 1188 km, respectively (Fig. 9B), which is located at the middle part of the network (NWR2). In terms of ordered types, NWR2 consists of two isosceles triangles and four linear ordered pairs. Hence, this delineates a narrow belt. NWR2 covers almost main Japan. Among 12 earthquakes, only 3 earthquakes (1894, 1897 and 1901) occurred before the 1923 earthquake.

The 1952 Tokachi–Oki earthquake is located in the center of 5 earthquakes with distances in the range of 403–466 km (Fig. 9D, indicated by solid lines) and that of 3 earthquakes — 524–569 km (Fig. 9D, indicated by dashed lines). The network NWR4 consists of 13 earthquakes, and has longest equal distances up to 1996 km (Table 3). The 1952 earthquake seems to be significant for the seismic activity in Japan during 20th century, particularly, in north Japan. Thus, main features of NWR4 agree well to the fact that the 1952 earthquake is characterized by the second maximum magnitude among 28 earthquakes (Table 1).

The network based on the 1946 Nankaido earthquake includes only 9 earthquakes with narrow coverage (Fig. 9C). Most of them (6 of 8 earthquakes) occurred before the 1946 earthquake.

6. DISCUSSION

(1) All of the 28 earthquakes listed in Table 1 are included in the ordered series described in Figs.3 – 8, except 1896, 1918B, 1968B and 1969 earthquakes. These four earthquakes are close to the other earthquakes, their ordered relations to other earthquakes are ignored in this paper. For example, the latitude and longitude of the 1969 earthquake differ from those of the 1994A earthquake

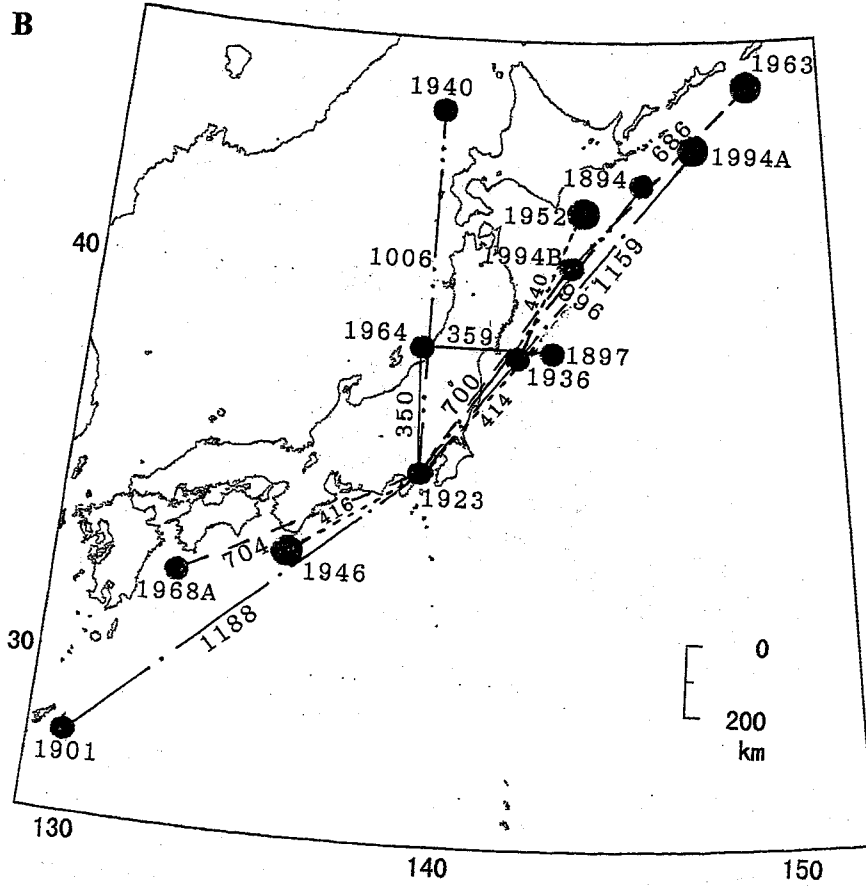
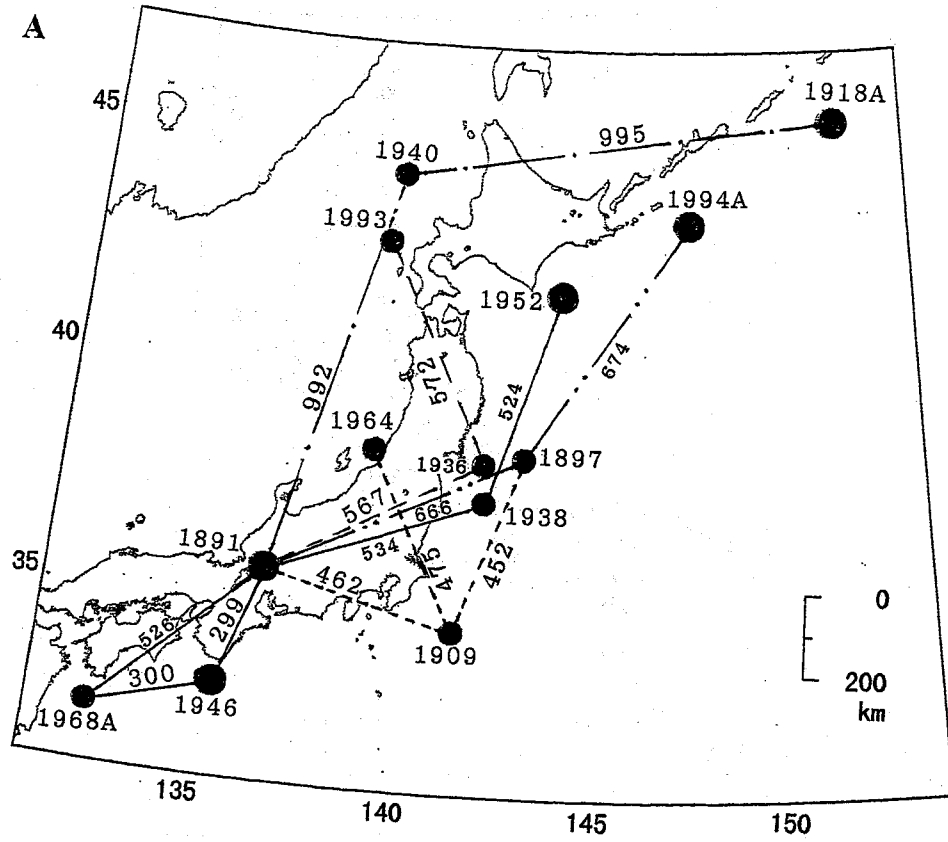


Fig. 9 Four ordered networks based on (A) 1891 earthquake, (B) 1923 earthquake, (C) 1946 earthquake, and (D) 1952 earthquake.

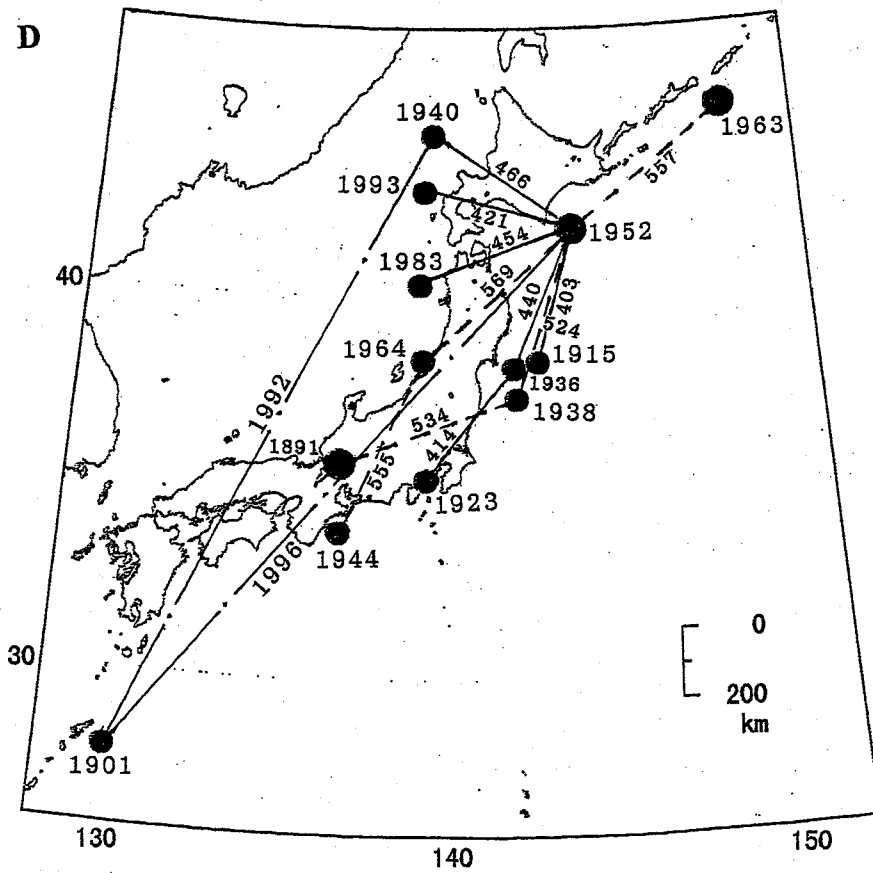
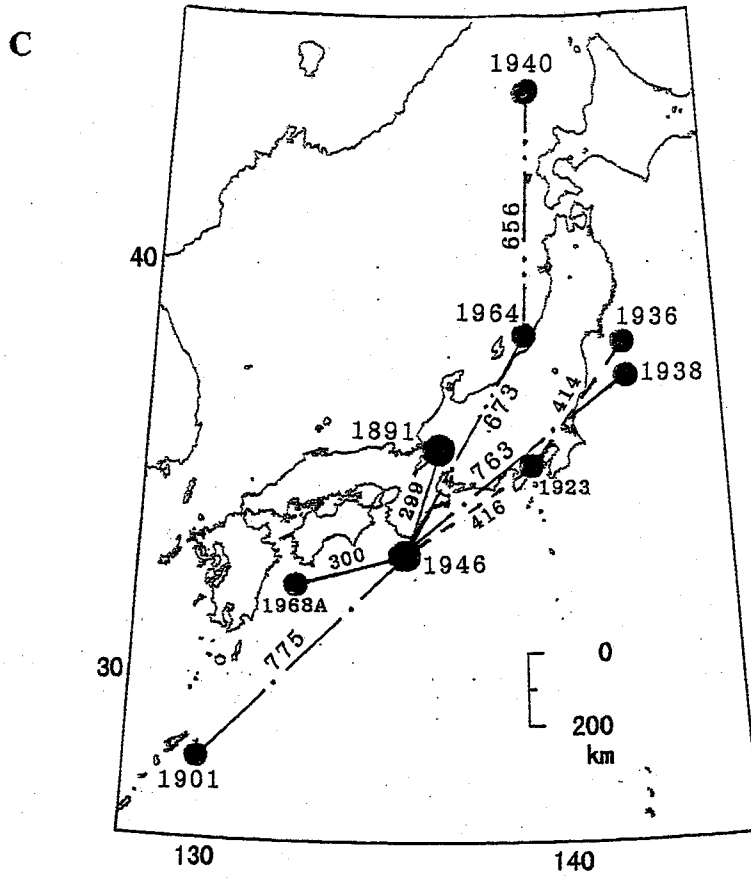


Fig. 9 (Continued)

by less or equal to 0.1 degree. Although the 1896 Sanriku-Oki earthquake has the largest magnitude in Table 1, we prefer to use the 1933 Sanriku-Oki earthquake, since the location parameters of this event is more reliable.

(2) A series of simple geometrical forms (isosceles and equilateral triangles, circles, etc) are applied to describe the relationships among large earthquakes. This method has the advantage that it requires less presumptions and will reveal more real situations in nature. Main assumption is the equivalence of two distances within the suggested limit (AL). The concept of equivalence is used to express and measure orderings. Our results show that this method is suitable for explaining several major behaviors of seismic activity of large earthquakes in Japan. Moreover, the ordered occurrence of large earthquakes reflects also the ordered structure of the crust, including the upper part of the mantle (Xu and Ouchi, 1998).

(3) Our studies of ordering of large earthquakes either in space or in time, however, show evidence of some network features in the Earth's interior (Xu and Ouchi, 1997). It means that the occurrence of large earthquakes is not limited locally as many seismologists imagined earlier, and an earthquake can be viewed as a node of a certain dynamic network, which covers more broad area and is characterized as an open system in nature. Each large earthquake may be connected to some distant earthquakes by direct effects or indirect processes through visible or invisible channels over long distances. At the same time, we think local processes may have only much less effects to it. An important feature of the network concept is that a network is composed of a number of discrete elements connected by chains or channels, analogous to the neural network in human body or internet in communication. This kind of idea about the formation of large earthquakes is, obviously, different from conventional concepts.

In Chinese medicine, a similar network concept is known as meridians (jing luo), by which various organs are connected. Lomnitz (1994) has compared the conceptual models of precursors of the earthquake process to that of Chinese medicine, and indicated their analogies: "A symptom (Chinese medicine) may seem to be wholly unrelated to the illness; it may appear at some remote spot of the body, connected to the diseased organ by invisible channels or meridians (jin luo); a fluid, usually called energy, circulates in these channels. A pattern of symptoms, or syndrome, precedes every ailment, but we cannot know in advance which syndrome will be present in a particular patient.A given collection of earthquake precursors was likened to a syndrome, related to the unknown disturbance that caused the earthquakes." (Lomnitz, 1994, p.18) The Lomnitz's understanding of precursors describes well the generation of earthquake process based on above mentioned network patterns.

The network concept of earthquake generation may give some interesting insight for theoretical understanding about the physics of earthquakes.

The rather regular pattern of earthquakes in space can be served as a good representation of the new physical concept "Nature is seen as an interconnected dynamic network of relationships" mentioned recently by F.Capra as one of important aspects in bootstrap theory (Capra, 1991, p.333). The natural phenomena are described in terms of a network concept instead of isolated field. It is a significant type of dynamic systems. Moreover, it agree well to the new tendency in science that the classical science is going to the end of certainty, and we need not only fundamental laws, but also events (Prigogine, 1997). Network concept is helpful for scientists to explore the time-irreversible world and its complexity, as well as the earthquake phenomena.

7. CONCLUSION

The analysis of 28 shallow large earthquakes ($M \geq 8$) in Japan shows clear spatiotemporal ordering, which reveals one of main features of seismicity in this region. A total of 22 ordered series can be recognized, which are summarized into six types of ordering. Thus, it is suggested that the relationship among 28 shallow earthquakes can be considered as results from a multi-level network, and each earthquake is considered as a node in the network. We argue that the suggested network properties of large earthquakes are significant for understanding the formation of large earthquakes and may be used to improve earthquake prediction research.

REFERENCES

- Capra, F. The Tao of Physics. (3rd edition), Shambhala Publications, Inc. 366p., 1991.
- Lomnitz, C. Fundamentals of earthquake prediction. John Wiley & Sons, Inc., 1994.
- Mogi, K. Sequential occurrences of recent great earthquakes. Jour. Phys. Earth, Vol.16, pp.30-36, 1968.
- Mogi, K. Some features of recent seismic activity in and near Japan (2). Bull. Earthq. Res. Inst., Vol. 47, pp. 395-417, 1969.
- Mogi, K. Some regularities of seismicity pattern: A review. Proceeding of International Symposium on "Continental Earthquakes", Beijing, China, IASPEI Publ. Ser., Vol. 3, Seismological Press, pp.31-61, 1993.
- Pacheco, J.F. and Sykes, L.R. Seismic moment catalog of large shallow earthquakes, 1900 to 1989. Bull. Seis. Soc. Amer., Vol.82, No.3, pp.1306-1349, 1992.
- Prigogine, I. The end of certainty: time, chaos, and the new laws of nature. First Free Press, 1997.
- Usami, T. Materials for Comprehensive List of Destructive earthquakes in Japan [revised and Enlarged Edition]. University of Tokyo Press. 493p, 1996.
- Xu Dao-Yi, Asteriadis, G. and Arabelos, D. Equidistance ordering of large earthquakes in the Aegean and surrounding areas. (in press), 1998.
- Xu Dao-Yi and Ouchi, T. On the network features of large earthquake occurrences that appear in the spatio-temporal distribution. Programme and Abstracts, The Seismological Society of Japan, 1997, No.2, A54, 1997.
- Xu Dao-Yi and Ouchi, T. Spatiotemporal ordering of great earthquakes ($M \geq 8$) in Asia during 1934 - 1970 Years. (this volume), 1998.
- Xu Dao-Yi, Zheng Bin-Hua, Wang Xiang-Nan and Ouchi T. Spatial ordering of $M \geq 8$ earthquakes in the China continent and its adjacent areas. The Institute of Statistical Mathematics, Cooperative Research of Reports, 52, Mathematical Seismology (VIII), pp.155-164, 1994.
- Xu Dao-Yi, Zheng Bin-Hua, Zhang Cun-De, Asteriadis, D. Arabelos, D. Equidistance ordering of large earthquakes in North China. Survey Review, Vol. 34 (No.263), pp.19-30, 1997.

Authors: 1) Dao-Yi Xu, Guest Professor, Research Center for Urban Safety and Security, Kobe University; 2) Toru Ouchi, Associate Professor, Research Center for Urban Safety and Security, Kobe University.