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Some Characteristics of Seismicity and Stress State in the Korean Peninsula Using the Korean Seismic Data of the Past and the Present

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요약/Abstract

역사지진 카탈로그 즉, 1960년대 전과 이후 1995년까지의 지진관측을 이용해서 한반도의 지진활동과 응력 상태가 연구되었다. 이씨왕조의 처음 1400−1600년대의 200년동안 역사지진 카탈로그는 크게 완성되었다. 그 후부터 카탈로그는 거의 강진만 완성하는데 주력했다. 강진분포를 볼때 한반도 지진대는 서울−평양 지진대, 남부지진대, 그리고 북부지진대로 나눌 수 있다. 이들 강진의 초동 메카니즘은 그리드 테스팅 방법(grid testing method)에 의해서 재분석되었다. 지진메카니즘 결과는 압축방향이 동서방향을 따라서 수평으로 놓여 있음을 발견했다.

Seismicity and stress state in the Korean peninsula are studied using the catalogue of historical earthquakes and that from the seismological observations before the 1960s, with the aid of instrumental catalogue up to 1995. It seems that the completeness of the historical catalogue has a significant enhancement during the first two hundred years of the Yi dynasty, i.e., from the 1400s to the 1600s. From then on the catalogue may be regarded as near to complete for strong earthquakes in an overall sense. From the distribution of strong earthquakes, three seismic zones may be identified. From the south to the north, those are the southern seismic zone (남부지진대), the Seoul−Pyongyang seismic zone (서울−평양지진대), and the northern seismic zone (북부지진대). The mechanisms of some earthquakes obtained using first motion readings are reevaluated with a grid testing method. The results indicate that the compressional axis is nearly horizontal along the EW direction.

Key words : seismicity, focal mechanism, Korean peninsula, historical earthquakes

Introduction

Locating near to the boundary of the Eurasian plate and the Pacific plate, the Korean peninsula has been subjected to earthquakes since the ancient time. In the view of seismic engineering, it is extremely dangerous to consider the Korean peninsula as a 'quiet' area. In fact the risk of seismic loss is increasing in recent years with the rapid development of economy.

In the assessment of seismic disasters, historical literatures and the seismological data in the past play important roles providing the information about the earthquakes in the past. To some extent, the analysis of historical data is the only way in obtaining the long-term seismicity of a certain region.

The historical records of earthquakes in the Korean peninsula can be traced back to as early as 2 A.D. Since the Koryo (918-1391) and Yi (1,392-1910) dynasty many historical documents have been kept. Several studies have been carried out since the beginning of this century on the earthquake data in the past time, accordingly some catalogues have been compiled and published (e.g., Wada, 1912 ; Musha, 1951 ; DPRK Institute of Seismology, 1986r;Kim, 1987, 1993 ; Kang and Choi, 1993). This paper aims to draw some conclusions about the seismicity and stress state in the Korean peninsula through the reexamination and analysis of these catalogues as well as some conclusions obtained from the seismological recordings in the past.

Discussions on the historical earthquake catalogue

From 2 A.D. to 1900, some 1,843 earthquakes have been registered in the historical catalogue. The catalogue containing most earthquakes (DPRK Institute of Seismology, 1986) is chosen for the analysis, with the reference of other data (Kim, 1987, 1993). Corrections on the locations and magnitudes of some strong earthquakes are made according to more reliable evidences. In the analysis attention is focused on the shallow earthquakes, and the deep earthquakes are not considered. According to modern seismological recordings, it may be concluded that the deep earthquakes are mainly located in the north East Sea, reflecting the subduction of the Pacific plate under the Eurasain plate. But from historical records, few information can be obtained about the deep earthquakes. Seismic observations since the beginning of this century have recorded a few deep earthquakes, which will not be discussed either. Accordingly the 'earthquakes' mentioned in this paper are regarded as shallow ones.

Magnitudes in two of the catalogues (DPRK Institute of Seismology, 1986 ; Kim, 1993) estimated by different quantification schemes are compared. The comparison concludes that different estimation methods have led to the magnitude difference of average $\frac{1}{2}$. The catalogue used for this analysis seems to have a higher magnitude estimation. For instance, the M7.0 earthquakes mentioned in the analysis may correspond to the M6.5 ones in other catalogues.

From the temporal distribution of earthquakes with magnitude larger than or equal to 6.0 in the catalogue, as shown in Figure 1, apparently there exists a seismic active period from the 15th century to the 18th century. It is pointed out that this seismic active period is correlated with the seismic active period in the north China (Kang and Choi, 1993). From the M-t diagram the existence of the seismic active period seems persuasive, however, it is not assured whether before that time the Korean peninsula can be regarded as 'quiet'. As shown in Figure 2a, 2b and 2c, the locations of the registered earthquakes have a clear tendency of 'spreading' from 1400 A.D. to 1600 A.D. After that time, the 'spreading' is seen to be 'saturated'. A possible explanation of such 'spreading' might be the increase of seismicity during that time. However, another competing possibility has at least the equal importance : the enhancement of

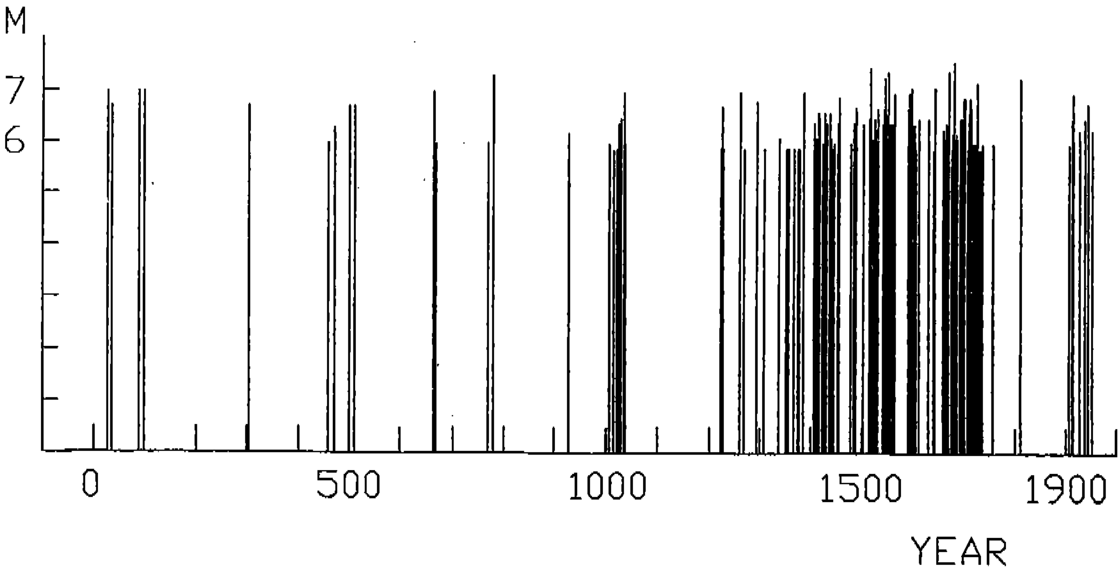
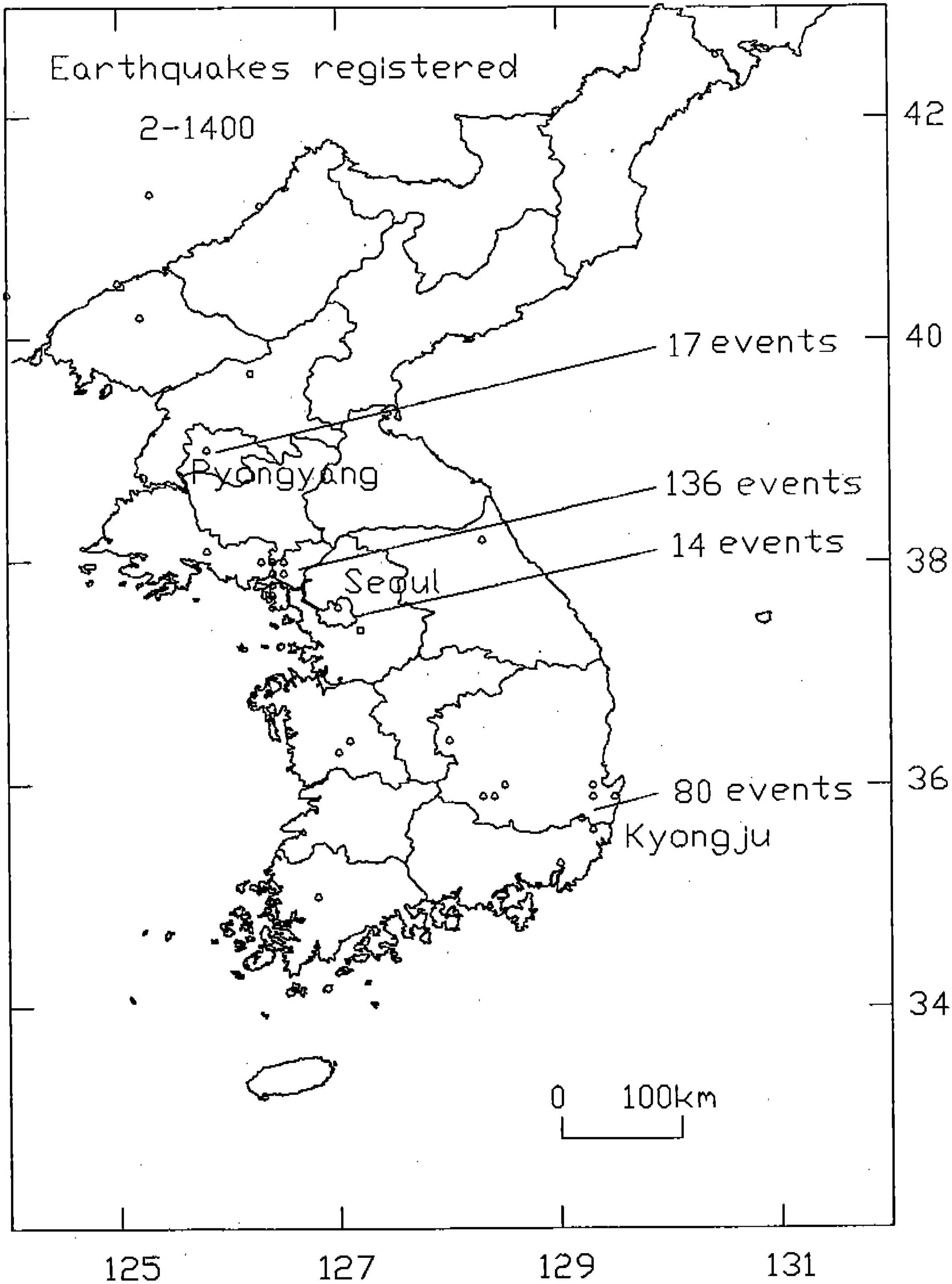


Figure 1 M-t diagram for earthquakes in the Korean peninsula with $M \geq 6.0$ from 2 A.D. to 1960. See text for the discussion on the overestimation of magnitudes in the catalogue used in this study.

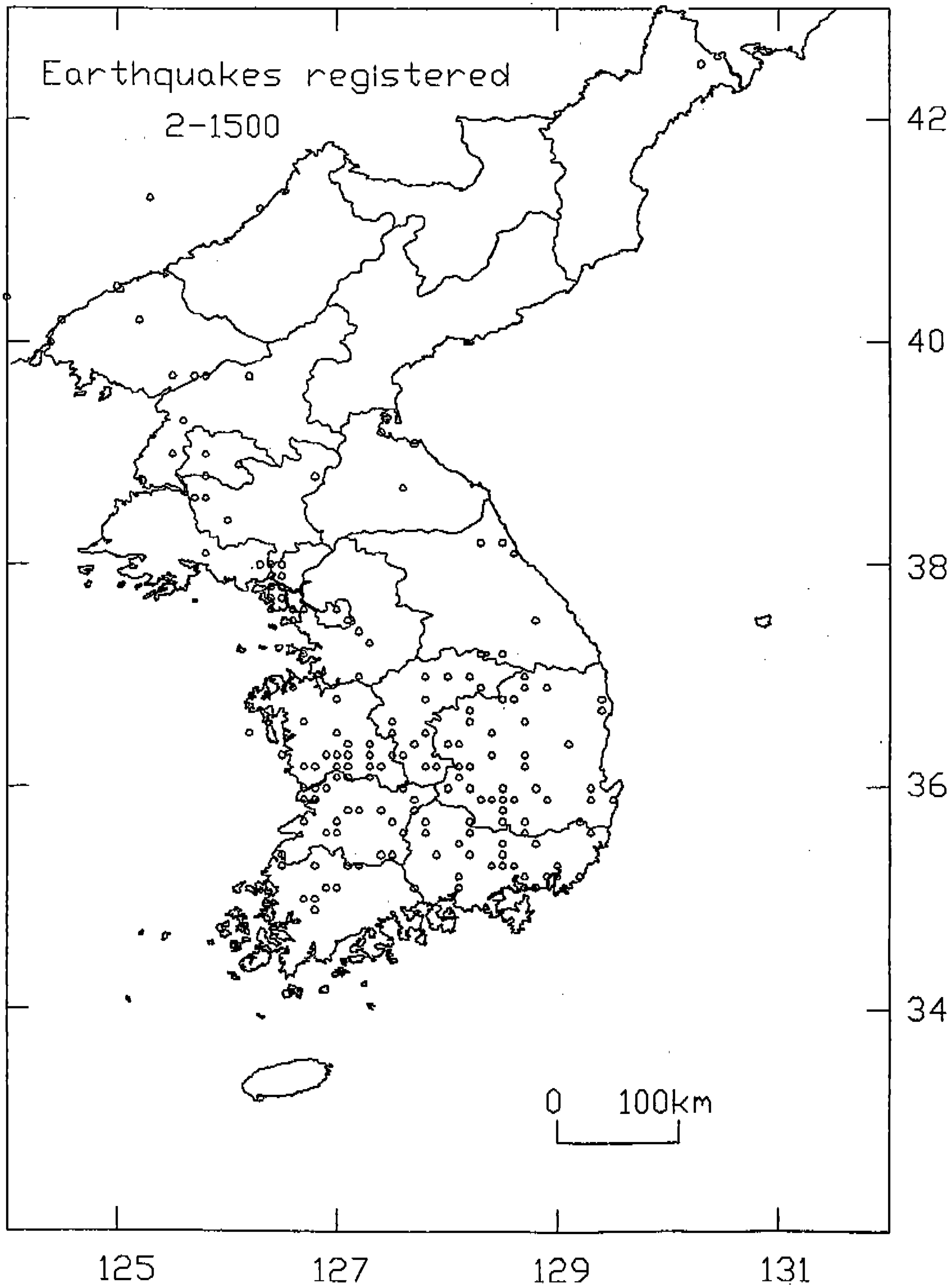
the level of recording earthquakes. In fact from Figure 2a it may be seen that the 'seeds' of such spreading concentrate mainly in the Kyongju, Seoul, and Pyongyang region, strongly suggesting that stimulated by the increasing seismicity, people at that time began to pay more and more attention to earthquakes, accordingly the level of recording earthquakes had a significant enhancement from the beginning of the 15th century to the 16th century. As a result, the earthquake literatures after that time may be considered as reliable for strong earthquakes in an overall sense. On the other hand, it is not reasonable to regard the time before the 14th century as 'quiet' period.

To determine the magnitude threshold above which the catalogue may be considered as near to complete, the occurrence frequency as a function of magnitude is shown in Figure 3a. Inspite of the uncertainties in the estimation of magnitudes, the distribution can still provide some information about the completeness of the catalogue. In the figure a single peak distribution is shown. On the left hand side of the peak (shown in the figure as zone Ⅰ) the record is determined mainly by the distribution of the recording sites ; near to the peak (shown in the figure as zone Ⅱ) the record reflects a mixed effect of the distribution of earthquakes and the distribution of recording sites ; and on the right hand side of the peak (shown in the figure as zone Ⅲ) the record mainly reflects the distribution of earthquakes, which generally obeys the Gutenberg–Richter's relation except for very large magnitudes. It may be seen that the number of earthqaukes with the same magnitude from 2 A. D. to 1400 counts almost the same as that within a single century after 1400, implying that before 1400 it is hard to regard the catalogue as complete for any magnitude. From the distribution of occurrence frequency it can also be seen that the magnitude threshold is near to 6.0, i.e., the catalogue of earthquakes with magnitude larger than or equal to 6.0 since 1600 A.D. may be considered as near to complete in an overall sense.

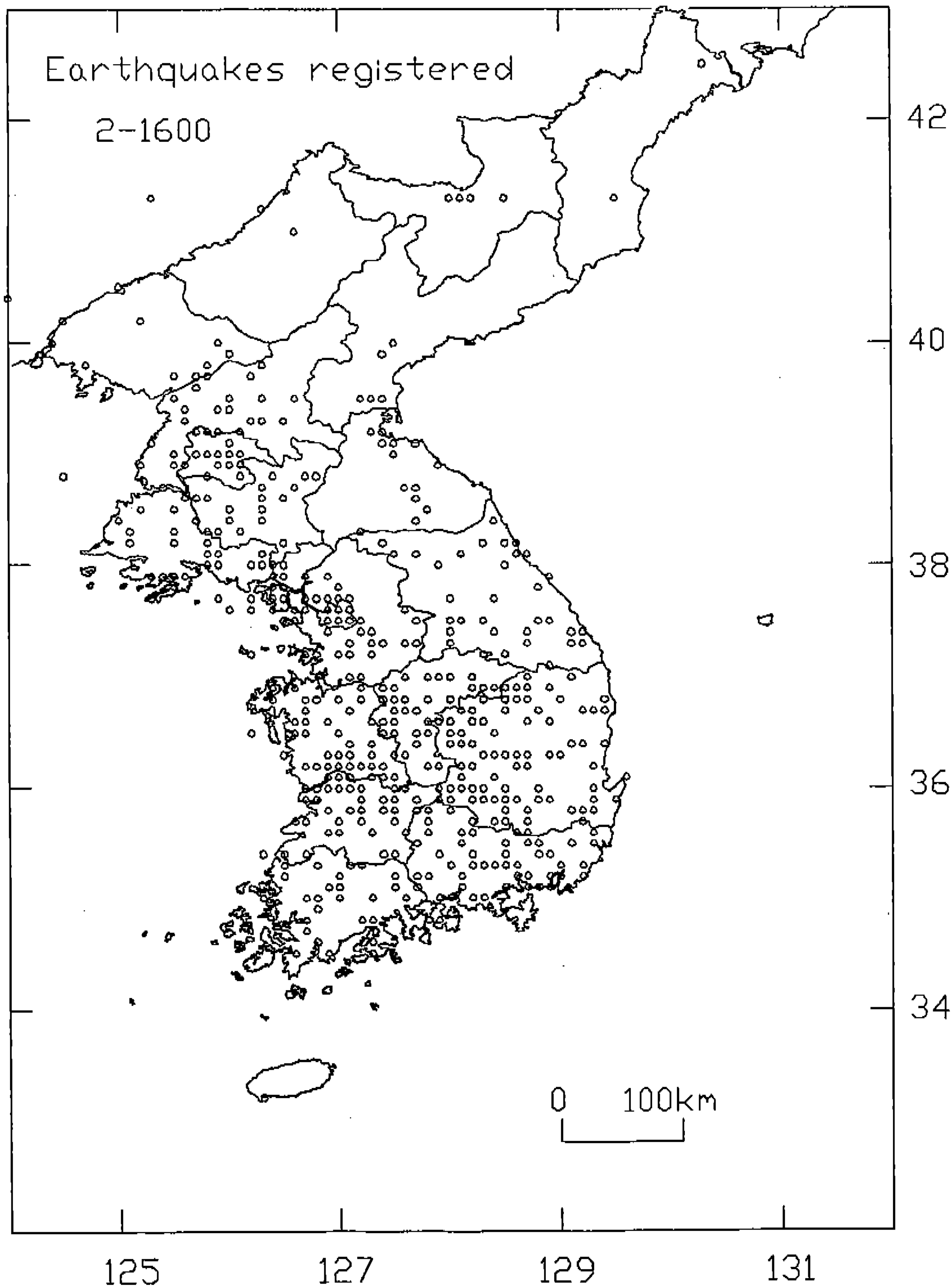
From 1900 to 1960 there are 224 earthquakes registered, with 85 of them having reliable locations. Figure 3b shows the magnitude–frequency relation of these earthquakes. As a comparison, the magnitude–frequency distribution of earthquakes



(a) 2 A.D.-1400 A.D.
Figure 2 Distribution of earthquakes registered for different time periods.


Earthquakes registered
2-1500
42
40
38
36
34
0 100km
125
127
129
131

(b) 2 A.D.-1500 A.D.


Earthquakes registered
2-1600
42
40
38
36
34
0
100km
125
127
129
131

(c) 2 A.D.-1600 A.D.

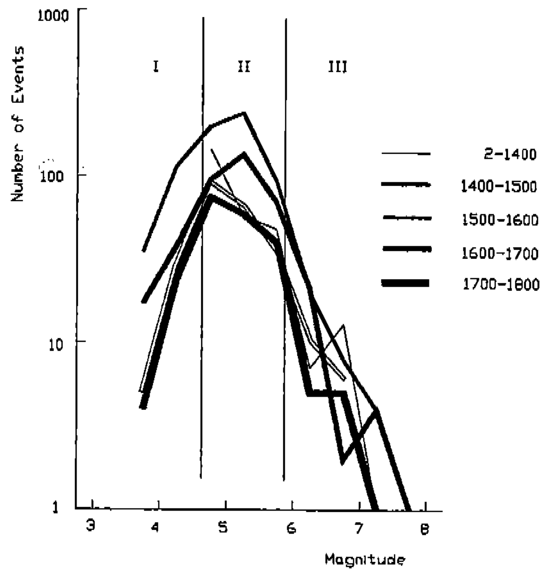


Figure 3a Occurrence frequency as a function of magnitude for earthquakes in different time periods.

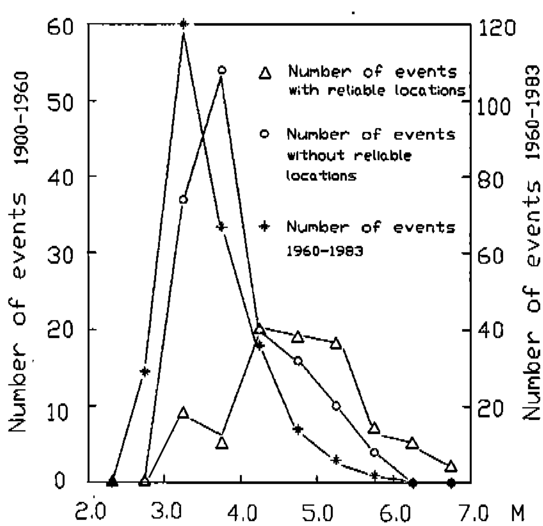


Figure 3b Occurrence frequency as a function of magnitude for earthquakes in this century.

recorded from 1960 to 1983 is also shown in the figure. It can be seen that because of the limitation of instrumentations and the recording site distribution, the earthquake catalogue from 1900 to 1960 still can not be considered as complete for earthquakes with magnitude less than 6.0. For example, for the magnitude interval of 5.5−6.0, there are still 50 percent of earthquakes without reliable locations. On the other hand, however, the earthquakes with magnitude above 6.0 might be considered as reliable.

From 2 A.D. to 1400, there are 272 earthquakes registered. From 1400 to 1900, in contrast, there are 1571. Since most of the earthquakes in the catalogue are contributed after the time when the catalogue of earthquakes above the magntiude threshold began to be reliable, the whole result about the strong earthquakes can be regarded as reliable, in which the earthquakes before the time when the catalogue began to be reliable and those below the magnitude threshold act as auxiliary information. On the other hand, it should be kept in mind that such a distribution only reflects the time period in which the records were reliable. For the Korean peninsula, it reflects only the seismic characteristics since the Yi dynasty, rather than that since the first century.

Since the development of culture and population is inhomogeneous in nature, also it seems possible to obtain more information for some special regions. As we have stated before, from Figure 2a it may be seen that the recordings form 2 A.D. to 1400 concentrates mainly in three regions : the Seoul region, the Pyongyang region, and the Kyongju region, reflecting the development of culture in the ancient time. Accordingly it may be deduced that for these three regions, the catalogue since 1400 A.D. may be considered as near to complete for strong earthquakes, while for the other regions the time when the catalogue can be regarded as near to complete is around 1600. A plausible hypothesis is that some regions, especially the Seoul region, the Pyongyang region, and the Kyongju region, had been ready to have a complete strong earthquake catalogue by 1400 because of their development, while stimulated by the increasing seismicity from the 15th century, the whole peninsula enhanced its recording level gradually, and by the latest 1600 the whole peninsula had been able to have a strong earthquake catalogue which is near to complete. Considering the difference in magnitude estimation, the overall reliability level of the Korean historical earthquake catalougue for the time period from the Yi dynasty to the beginning of this century may be estimated as approximately near to the same, probably a little bit lower, comparing to that in the north China (Gu, 1983).

Distribution of earthquakes

Figure 4a shows the distribution of earthquakes with magnitude larger than or equal to 6.0 in the catalogue from 1400 to 1600, while Figure 4b shows the distribution of earthquakes with magnitude larger than or equal to 6.0 since 1600. As we have mentioned in the above discussions, Figure 4a can be considered as reliable for the region of Seoul, Pyongyang, and Kyongju, and the other regions have a lower reliability due to the incompleteness of the catalogue, while Figure 4b may be considered as reliable for the whole peninsula. In the analysis to account for the phenomena that some earthquakes are located at the same place, and such coincidence are mainly due to the uncertainties of the location, we plotted such coincident events with slightly different coordinates. From the figures it may be seen that from 1400 to 1600 two seismic zones can be identified : the Seoul–Pyongyang seismic zone locating near to the Seoul region and the Pyongyang region, extending near to the NW direction, as shown in the figure by Zone I, and the southern seismic zone locating in the southern part of the peninsula and extending near to the NE direction, as shown in the figure by Zone Ⅱ. From Figure 4b two seismic zones may be identified from the distribution of strong earthquakes since 1600 : the southern seismic zone extending nearly in two conjugate directions, and the Seoul–Pyongyang seismic zone kept being active.

As a summary, the earthquakes with magnitude larger than or equal to 6.0 are shown in Figure 4c. As we have mentioned before, the seismicity shown in the figure mainly reflects the seismicity since the Yi dynasty. Through the above analysis of the distribution of earthquakes, with the aid of the auxiliary information of the earthquakes before the 15th century, the seismicity pattern of the Korean peninsula can be described as being composed of three seismic zones, as shown in the figure. The Seoul–Pyongyang seismic zone, as shown by Zone I in the figure, is located from the Seoul region in the south to the Pyongyang region in the north, characterized by its high and persistent seismicity. According to the distribution of earthquakes, this seismic zone can be further divided into two seismic belts : the Seoul seismic belt, and the Pyongyang seismic belt. Figure 5a shows the detailed pattern of seismicity of the Seoul–Pyongyang seismic zone. It may be seen that the two seismic belt have some correlations in their seismicity. The southern seismic zone, as shown in Figure 4c by Zone Ⅱ 0.4, includes the peninsula to the south of 38°N except the region belonging to the Seoul–Pyongyang seismic zone. Comparing with the background seismicity, relatively higher seismicity concentrates in the center part of this seismic zone. Still another seismic zone is the northern seismic zone, as shown in Figure 4c by Zone Ⅲ 0.4, including the peninsula to the north of 38°N except the region belonging to the Seoul–Pyongyang seismic zone. In this seismic zone the seismicity is relatively lower. What is interesting is that if we link the regions with higher seismicity by straight lines, the orientations of such lines are near to the orientation of the tectonic boundary in that region (Masaitisa, 1964) or its conjugate. This phenomena, although having arbitrariness to some extent, may provide some clues of the tectonics in this region.

The southern seismic zone and the northern seismic zone have different levels of seismicity. However, analysis shows that the seismicities in these two seismic zones have similar scale invariant properties. To show such similarity, box–counting is taken for the two seismic zones. In the box counting the size of the box is taken as 1°, $\frac{2^{1/2}}{1°}$, $\frac{2}{1°}$

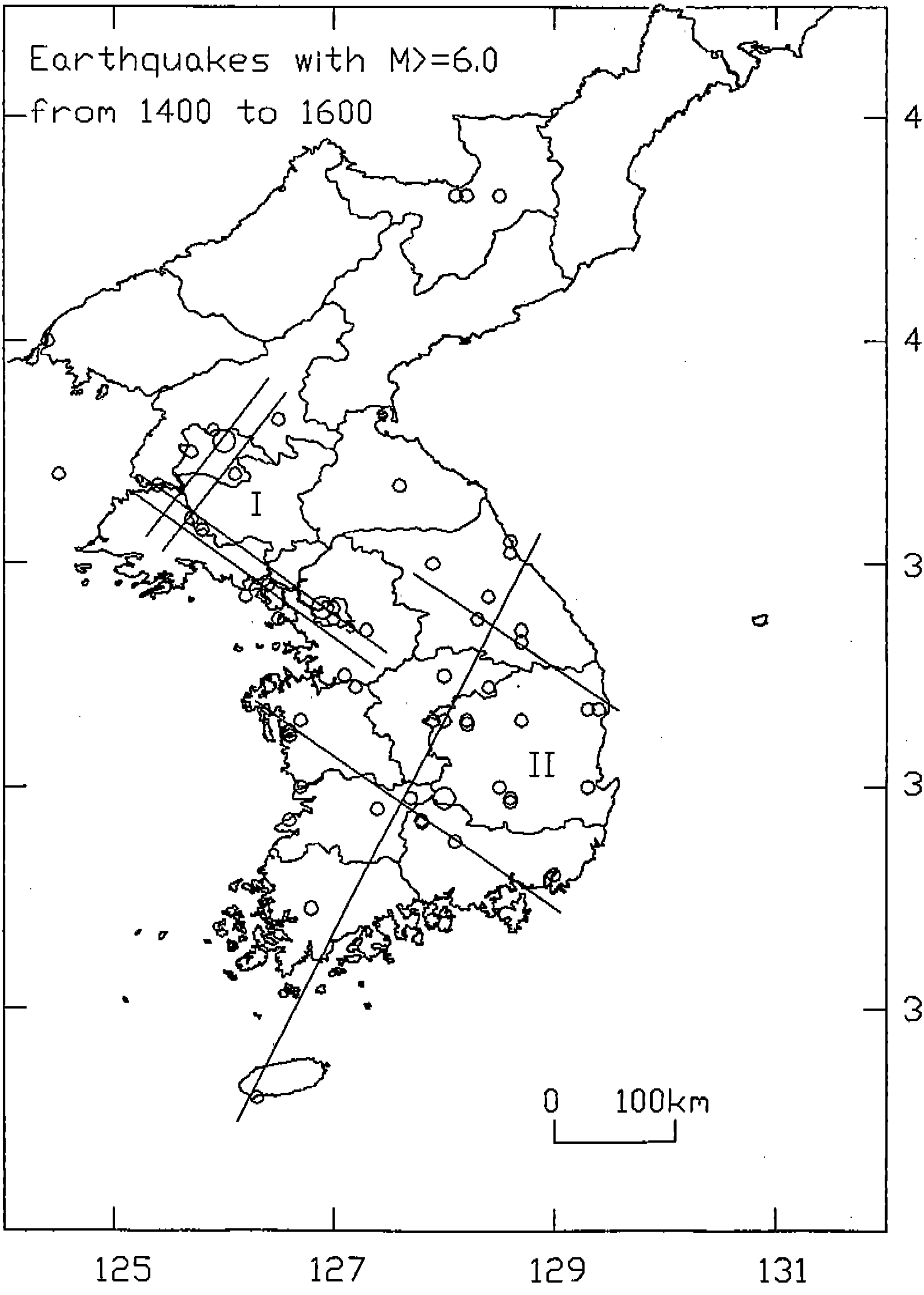


Figure 4a Earthquakes with M>=6.0 from 1400 A.D. to 1600 A.D.
I The Seoul—Pyongyang seismic zone(서울—평양지진대)
II The Southern seismic zone(남부지진대)

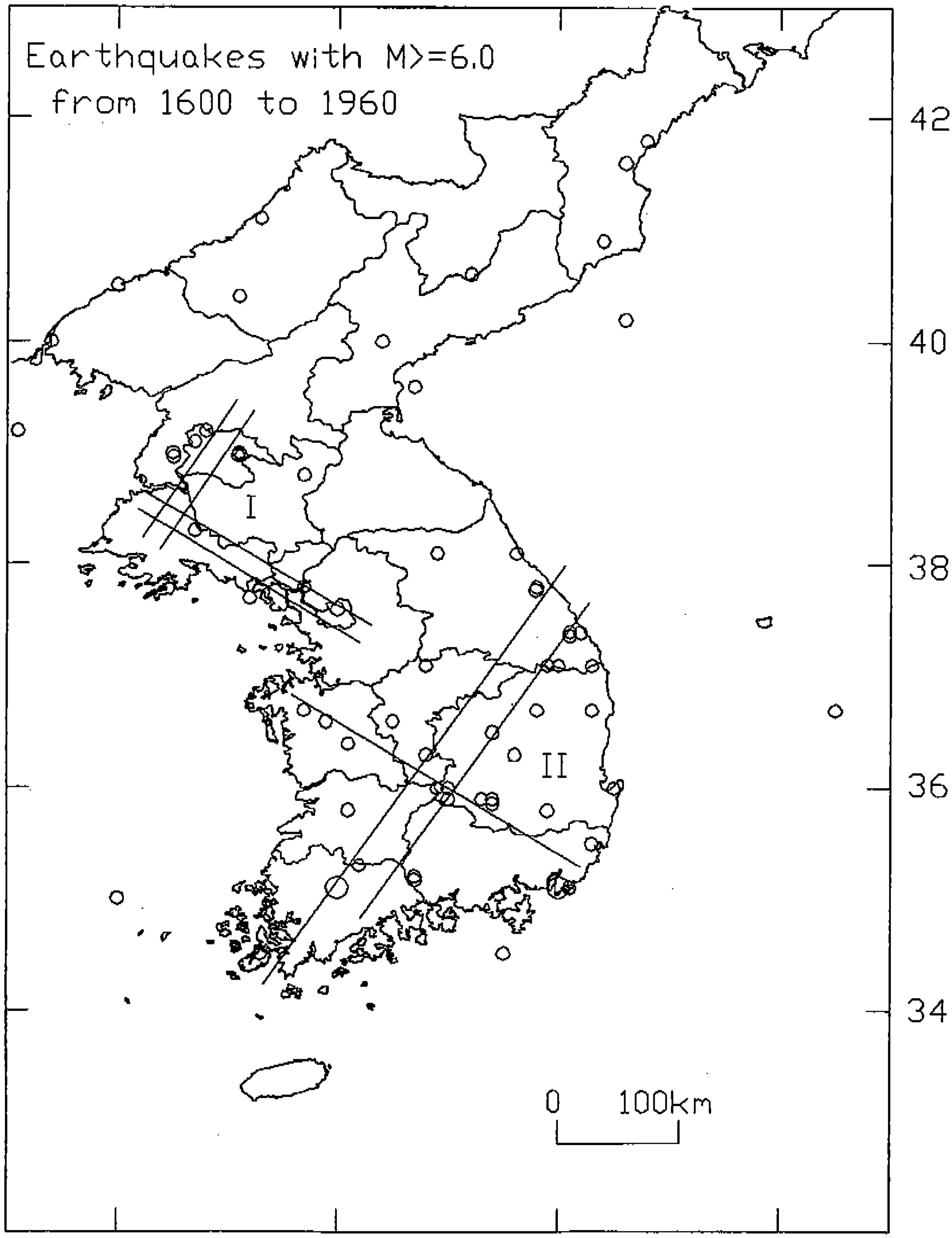


Figure 4b Earthquakes with M>=6.0 since 1600 A.D.
I The Seoul—Pyongyang seismic zone(서울—평양지진대)
II The Southern seismic zone(남부지진대)

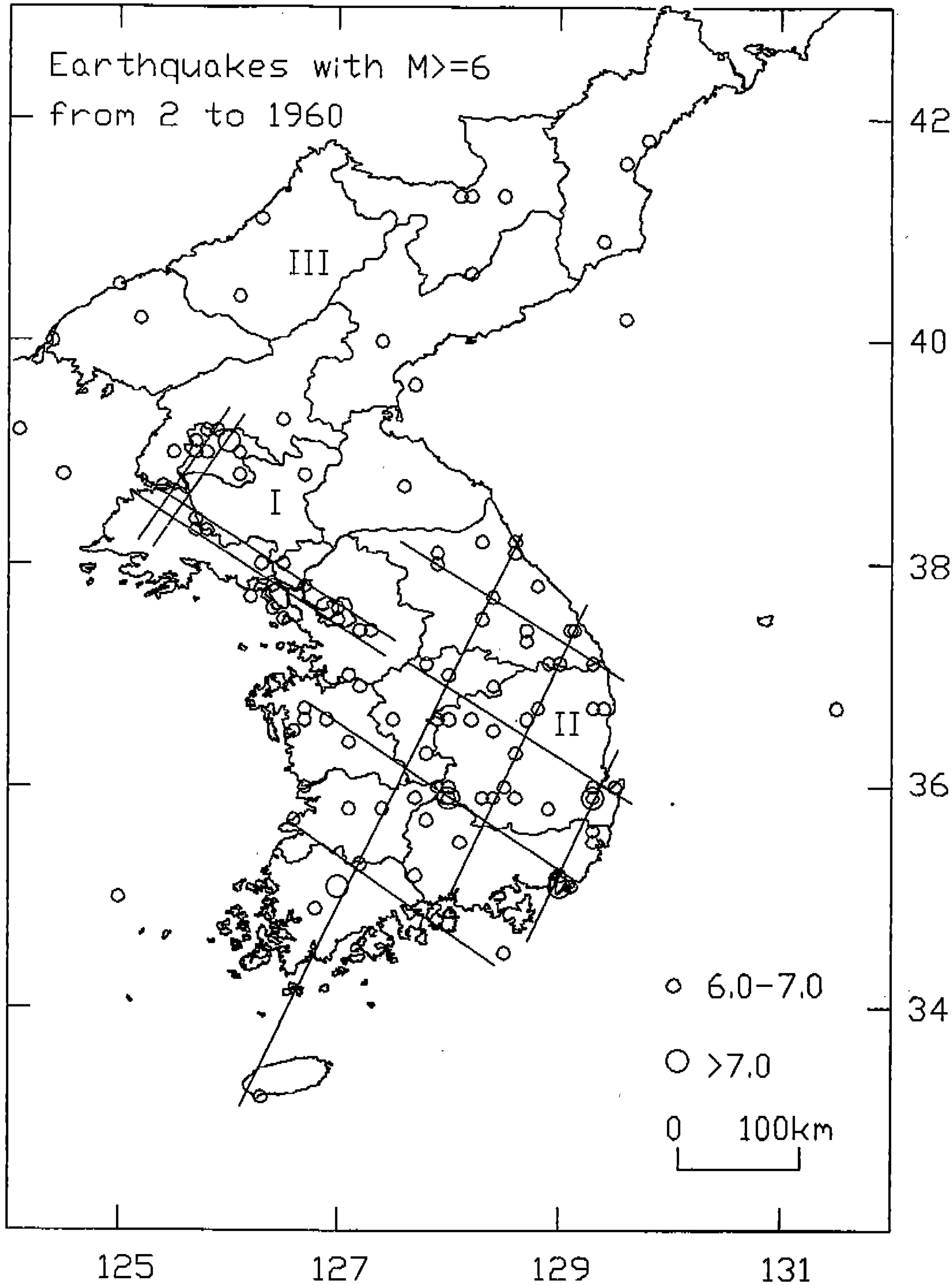


Figure 4c Earthquakes with M>=6.0 from 2 A.D. to 1960. Three seismic zones may be identified from the distribution.
Ⅰ The Seoul—Pyongyang seismic zone(서울—평양지진대)
Ⅱ The Southern seismic zone(남부지진대)
Ⅲ The Northern seismic zone(북부지진대)

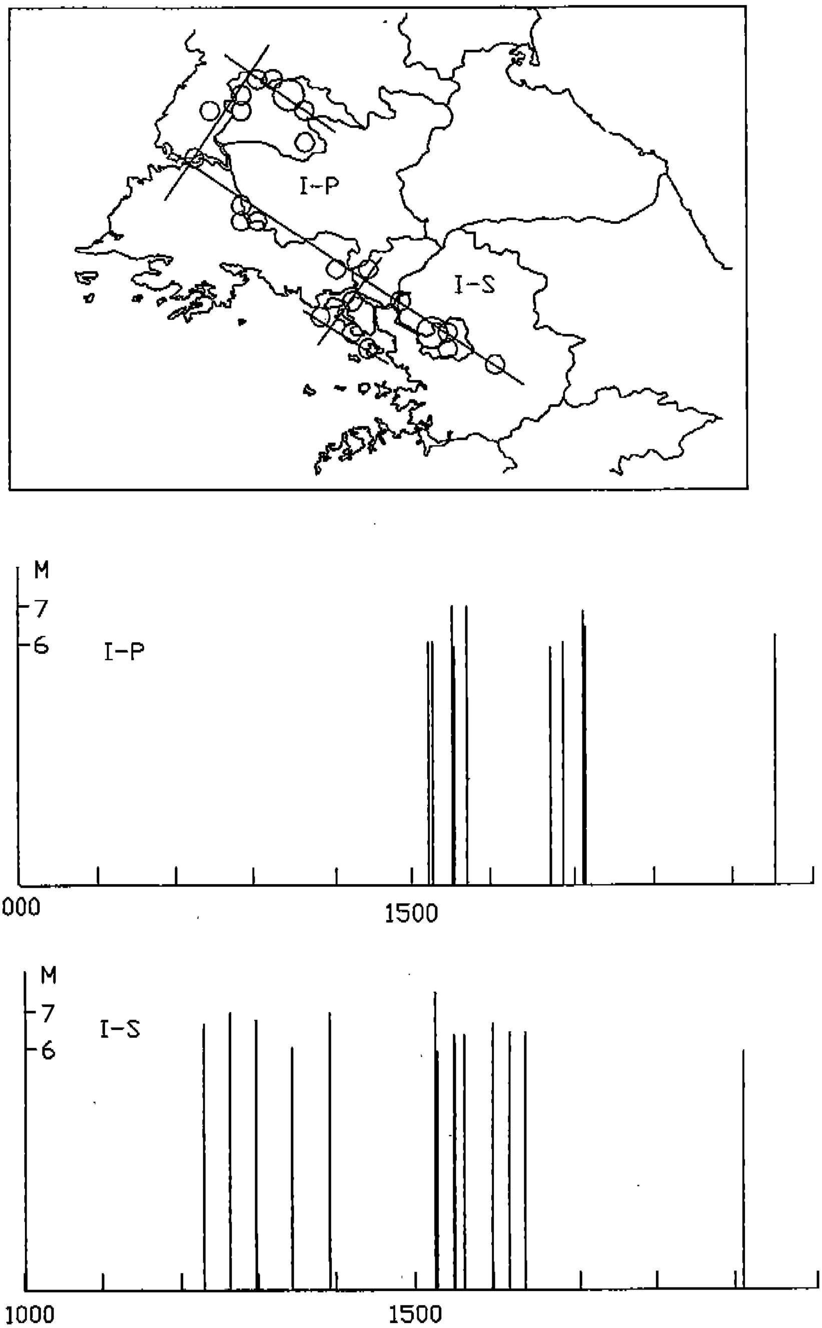


Figure 5a Detailed pattern of seismicity of the Seoul—Pyongyang seismic zone. The seismic zone is subdivided into two seismic belt :
I—S : The Seoul seismic belt
I—P : The Pyongyang seismic belt
M—t diagrams are for the two seismic belts, respectively, showing the correlation of seismicity of the two belts. Earthquakes after 1200 A.D. with magnitude larger than or equal to 6.0 are used in the diagram.

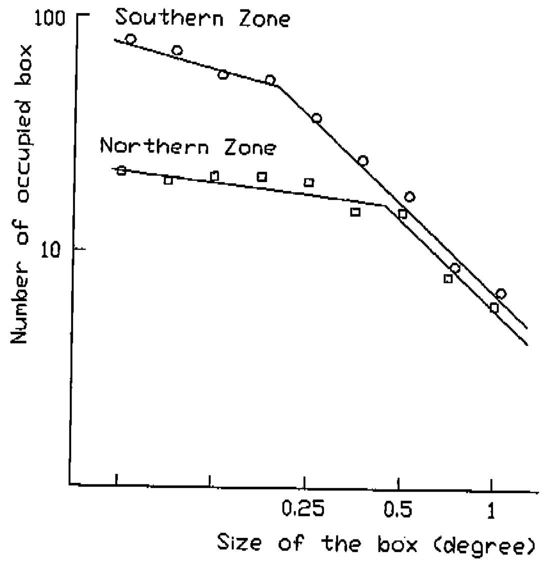


Figure 5b Box—counting results for two seismic zones. See text for detail.

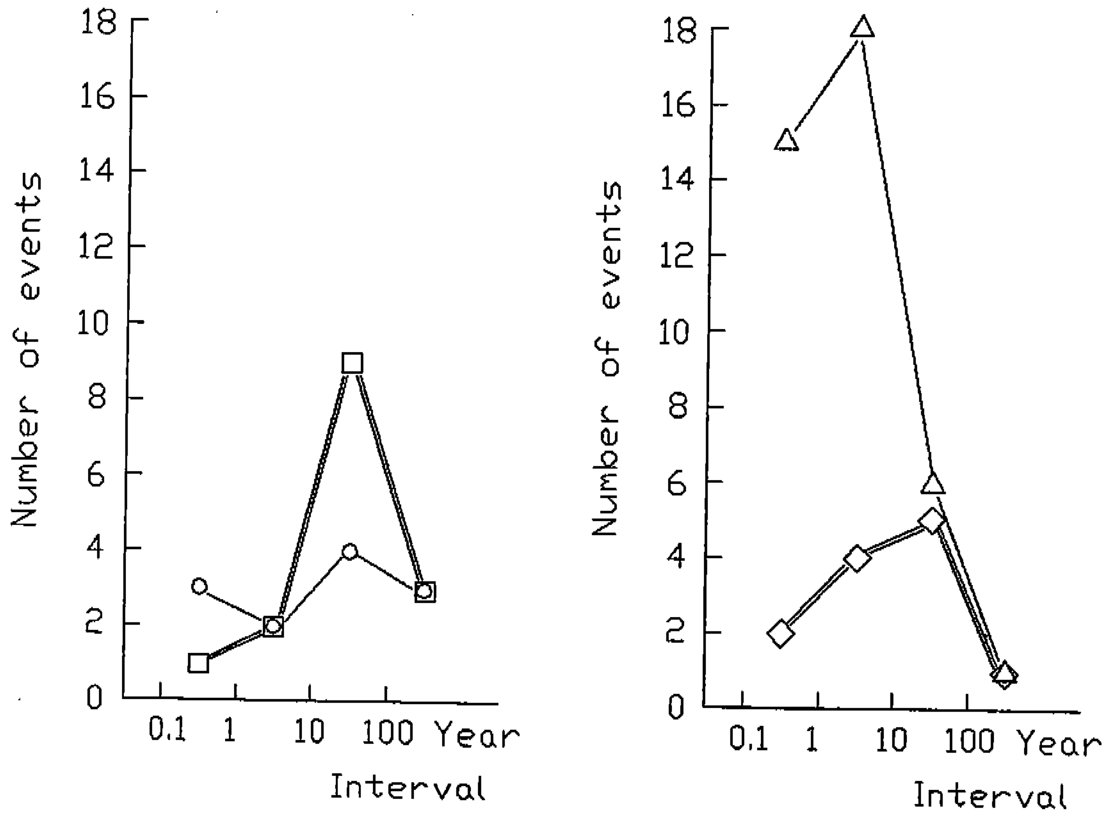


Figure 5c Interval between consequent strong events for different seismic zones. See text for detail.
□ Seoul Seismic Zone, since 1200 ○ Pyongyang Seismic Zone since 1400
△ The Southern Seismic Zone since 1600 ◇ The Northern Seismic Zone since 1600

, $\frac{2^{3/2}}{1°}$, ⋯, respectively, and the number of non−vacant boxes (boxes occupied by at least one earthquake) is counted for different sizes, respectively. Generally the number of the non−vacant−boxes as a function of box−size has three parts. As the size of the boxes becomes very large, the number of non−vacant boxes becomes 1, which is omitted as trivial. As the size becomes smaller than the distances between different events, the number converges to the number of earthquakes. If there are some earthquakes happened in the same place, the number of non−vacant−boxes will converge to the number of 'earthquake places'. As the size varies between a certain range, the number−size relation may be represented as

$$N \propto L^{-D}$$

in which N is the number of the non−vacant−boxes, L is the box size, and D is a constant reflecting the scale−invariance clustering characteristics of the seismicity. To some extent D may be regarded as an approximation of the fractal dimension of the seismicity, reflecting the fractal geometry of the seismogenic deep fault system. In the view of seismicity, the size at which the number of the non−vacant−boxes changes from a constant to a scale−invariant distribution reflects the average distance between different events (or 'event places'), while the constant D reflects the scale−invariance property of the cluster. Figure 5b shows the box−counting results for the two seismic zones. It may be seen that the difference of the two zones in their average distances between different events (or more exactly the distance between different 'event places') is very clear, reflecting the difference of seismic activity. Seen in the perspective of the scale−invariance of the clusters, on the other hand, the two seismic zones have no distinct difference, implying that the seismogenic deep fault systems in these two regions have similar structure. And probably we can further suppose that although having distinct differences in their seismic activity, the whole peninsula may be controled by a common seismogenic deep fault system under an integral stress field. The difference in seismicity reflects only the difference between different parts of the fault system and the different parts of the stress field.

Since the catalogue has significant incompleteness, and the magnitude estimation has considerable uncertainties, it is not approporiate to assess the seismic risk through the b−value analysis, at least at the present stage. As an alternative approach, Figure 5c shows the statistics of the time intervals between two consequent moderate and strong earthquakes (the magnitudes of these events equal or exceed 6.0 in the catalogue, approximately corresponding to the earthquakes with magnitude larger than or equal to 5.5 in general, as discussed in the above section). The 'integration' of such 'spectra' reflects the intensity of seismicity, while the shape of the 'spectra' reflects the recurrence of moderate and strong earthquakes for a certain seismic zone. To compare the relative seismicity one has to account for the normalized result, i.e., the integration divided by the area of the seismic zone, while the recurrence period is not comparable among different seismic zones unless the areas of the seismic zones are near to the same. For the Seoul seismic zone and the Pyongyang seismic zone which are small in size, the first point in the figure may correspond to strong foreshocks and/or strong aftershocks, which occurred within one year before or after another stronger earthquake. As these numbers are small, making no discriminations of foreshocks and aftershocks will not affect the result.

Reevaluation of the focal mechanism solutions obtained using the seismological data in the past

Few strong earthquakes have occurred in the Korean peninsula since the begining of this centruy, still less earthquakes have modern seismological recordings enough to determine the focal mechanism, making the determination of the stress state by earthquakes extremely difficult. In this point of view the few existing records are worth to be reevaluated. At present, the determination of focal mechanisms in the perspective of seismic moment tensors has become a routine job in the seismological observations. On the other hand, as looking back at the earthquakes in the past, considerable uncertainties may be found due to the limitations of both the quality and the quantity of the data. For example, Xu et al. (1994) redetermined the fault plane solutions of 229 Chinese earthquakes during 1933−1972 using a grid testing algorithm. Their results conclude that only for 47 earthquakes relatively reliable solutions could be obtained. For all other earthquakes the data are of poor quality and far not enough to constrain the solution to an acceptable range. In their grid testing algorithm all of the possible nodal planes are plotted on a single projection sphere. In our approach, a modified representation is taken, and the solution is represented by the function

$$S(\phi_s, \delta, \lambda) = \sum_{n=1}^{N} f_n(\phi_s, \delta, \lambda, Az_n, i_n) F_n w_n$$

in which ϕ_s, δ, and λ are the strike, dip, and rake of the fault plane, respectively, $f_n(\phi_s, \delta, \lambda, Az_n, i_n)$ is the theoretical P−wave first motion symbol at the n−th station with azimuth Az_n and take−off angle i_n, F_n is the actual P−wave first motion symbol, and the weight w_n is taken reversely propotional to the number density of stations, to put emphasis on the azimuthal coverage of the observation sites. In the plotting the function S is normalized by its maximum.

Figure 6 gives the distribution of earthquakes reexamined in this paper. The parameters of the earthquakes are listed by Kim (1993). Figure 7 gives the result for the April 15, 1981 earthquake. In figure 7a the S function is plotted in the $\phi_s-\lambda$ plane for different δ values. In the figure from the left top to the right bottom, the small figures correspond to δ=0°, 10°, 20°, 30°, ..., 90°, respectively. In each small figure, the horizontal axis corresponds to ϕ_s form 0° to 360° from the left to the right, while the vertical axis corresponds to λ from −180° to 180° from the top to the bottom. The grid testing step is taken as 10° for ϕ_s, δ, and λ. The black points in the plots correspond to S=1, while the other two kinds of points with different grey scales correspond to $S\geq0.9$ and $S\geq0.5$, respectively. In Figure 7b, the S function is plotted for different P and T axis on the lower−sphere of equal−area−projection, in which the black blocks with three different sizes represent the location of P axis at which S=1, $S\geq0.9$ or $S\geq0.5$, respectively, and the grey blocks represent the position of T axis at which S=1, $S\geq0.9$ or $S\geq0.5$, respectively. On the projection sphere the P−wave first motion readings are also plotted, with cross representing compression and circle representing dilatation. It may be seen from the figure that although the number of readings is limited, the focal mechanism and the stress axis are acceptably constrained. Figure 8 shows the composite result of the February 14, 1982 earthquake and the March 16, 1937 earthquake, while Figure 9 shows the composite result of all of the earthquakes shown in Figure 6 except the April 15, 1981 earthquake. It may be seen that in spite of the lack of the first motion readings, the solutions are still constrained to an acceptable extent, and the results given in previous studies (Kim, 1993) seem reliable. The results indicate that the compressional axis is nearly horizontal along the EW direction, which might be originated from the compression of the Pacific plate.

Discussion

From the analysis in this paper, in the perspective of historical earthquakes and focal mechanisms, the regime of the seismicity and stress state of the Korean peninsula may be described by Figure 10, in which the compression comes from the interaction between the Eurasian plate and the Pacific plate, and the straight lines represent the ap-

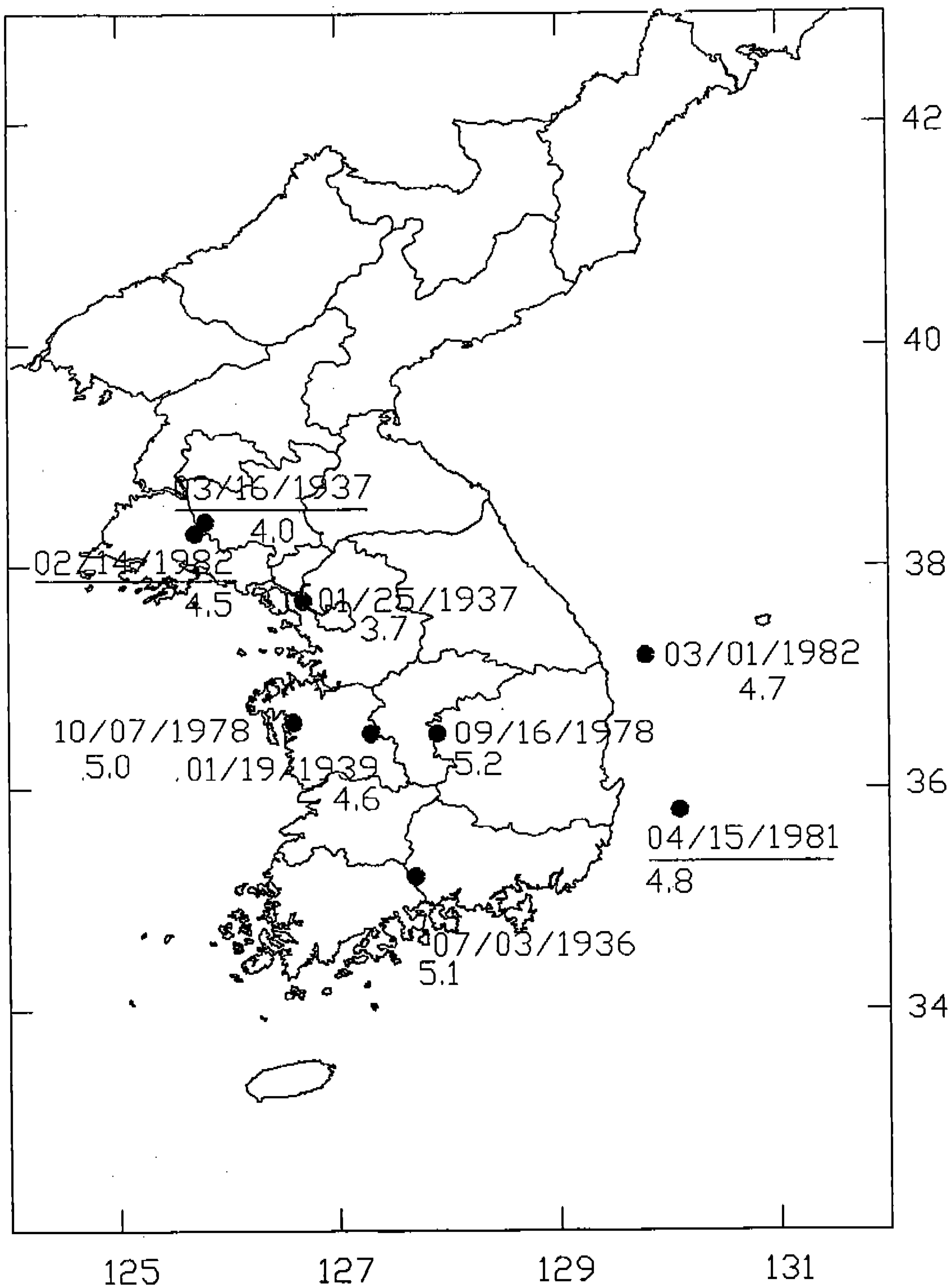
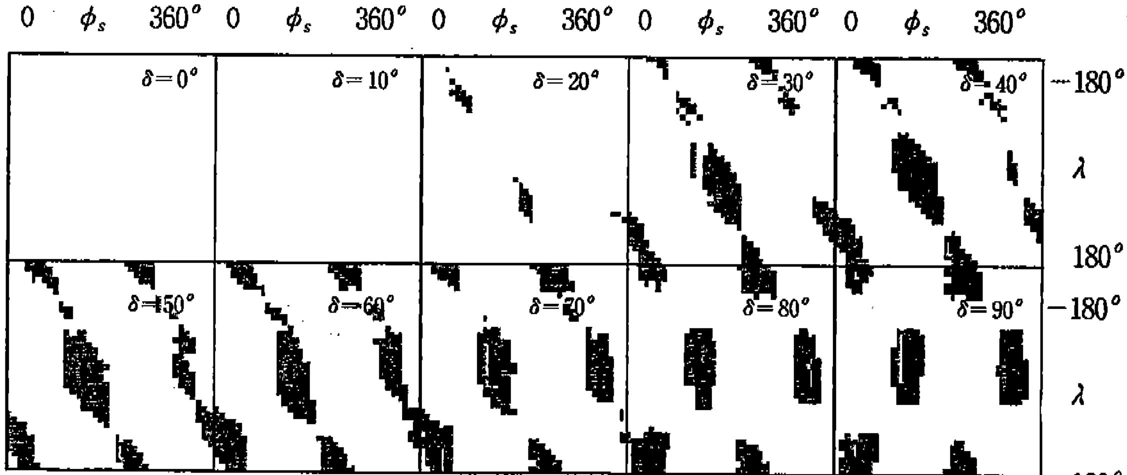
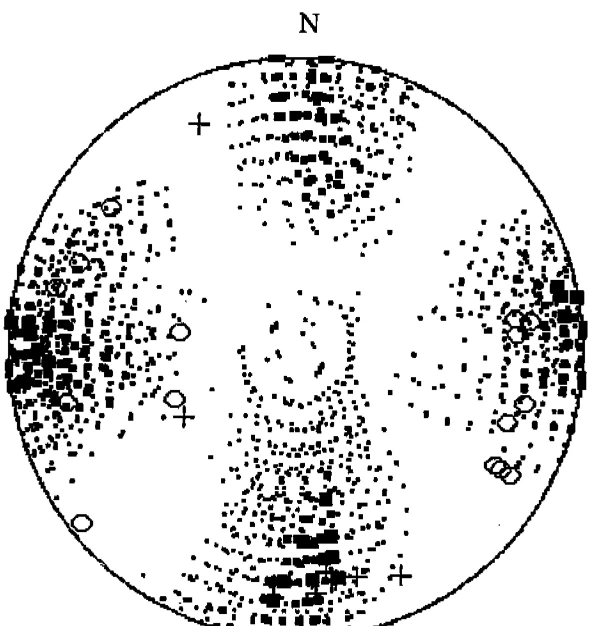


Figure 6 Distribution of earthquakes reexamined in this paper. The parameters of the earthquakes are given by Kim (1993). Numbers near the events denote the magnitude and date of the earthquake.

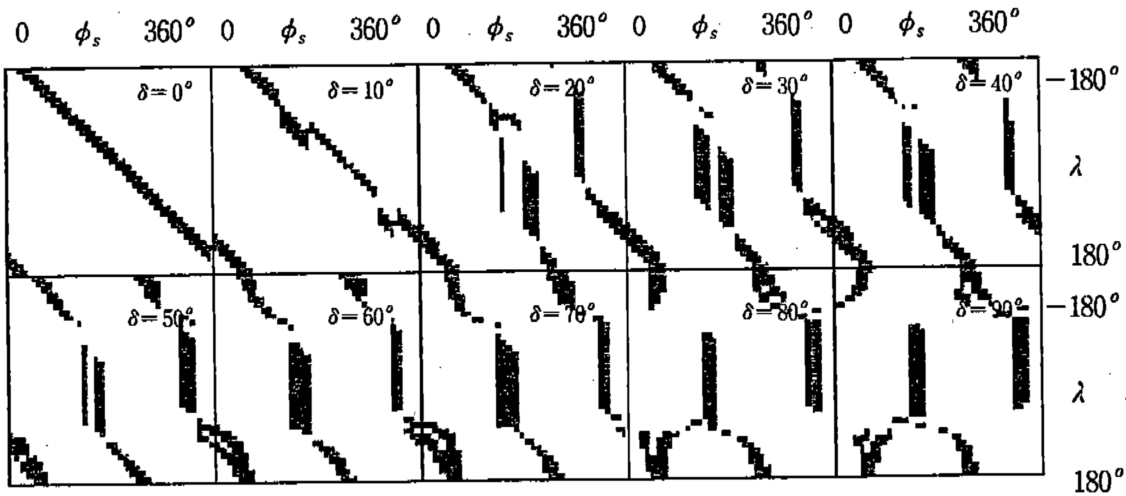


(a)

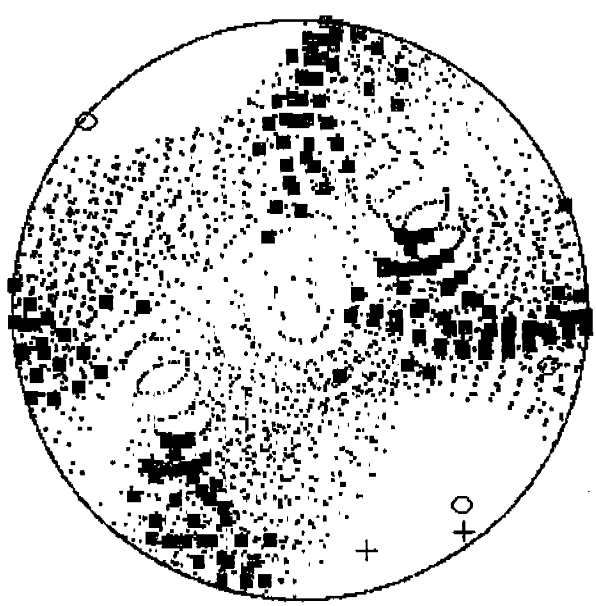


(b)

Figure 7 The grid testing result for the April 15, 1981 earthquake.
(a) S function in the ϕ_s-λ plane for different δ.
From the left top to the right bottom, the small figures correspond to $\delta=0°$, $10°$, $20°$, $30°$, ..., $90°$, respectively. In each small figure, the horizontal axis corresponds to ϕ_s from 0° to 360° from the left to the right, while the vertical axis corresponds to λ from −180° to 180° from the top to the bottom. The grid testing step is taken as 10° for ϕ_s, δ, and λ. The black points in the plots correspond to $S=1$ while the two grey scales correspond to $S\geq0.9$ and $S\geq0.5$, respectively.
(b) Sfunction for different P and T axis on the lower-sphere of equal-area-projection. The black blocks with three different sizes represent the location of P axis at which $S=1$, $S\geq0.9$ or $S\geq0.5$, respectively, and the grey blocks represent the position of T axis at which $S=1$, $S\geq0.9$ or $S\geq0.5$, respectively. On the projection sphere the P-wave first motion readings are also plotted, with cross representing compression and circle representing dilatation.

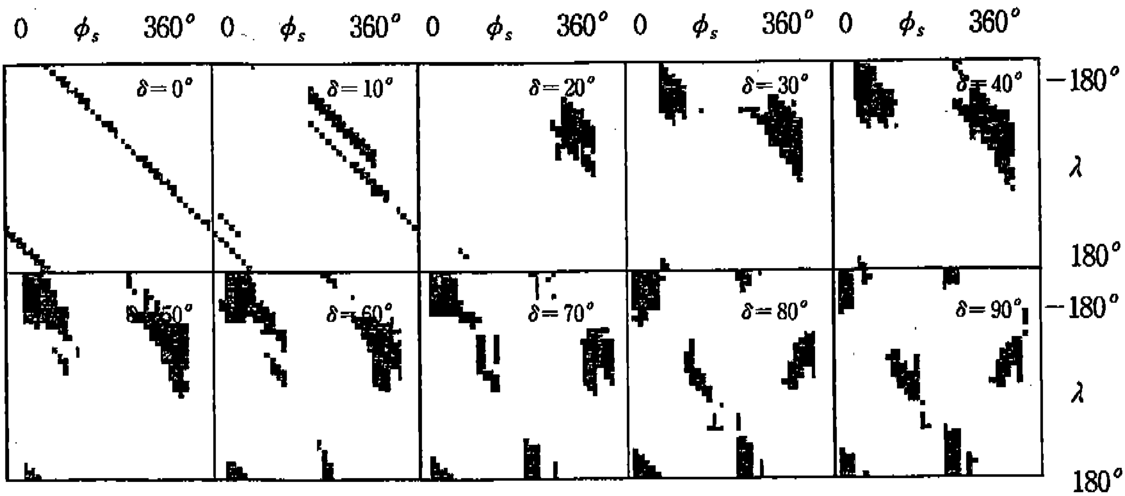


(a)

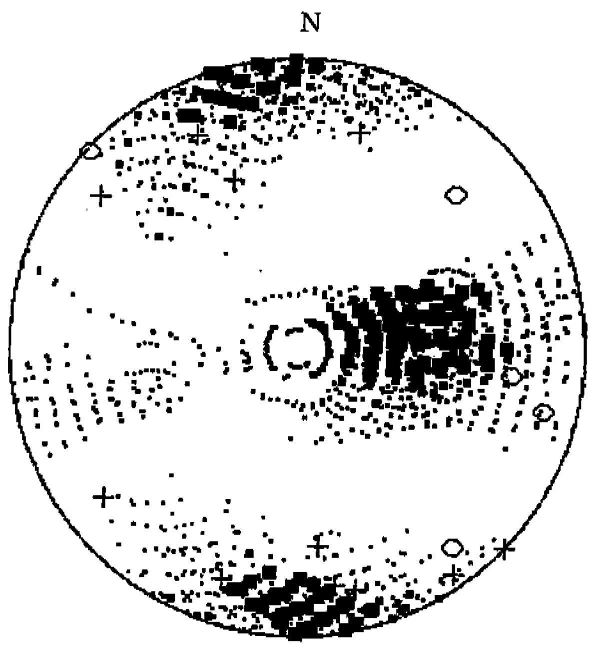


(b)

Figure 8 The composite result of the February 14, 1982 earthquake and the March 16, 1937 earthquake. See Figure 7.



(a)



(b)

Figure 9 The composite result of all of the earthquakes in Figure 6 except the April 15, 1981 earthquake. See Figure 7.

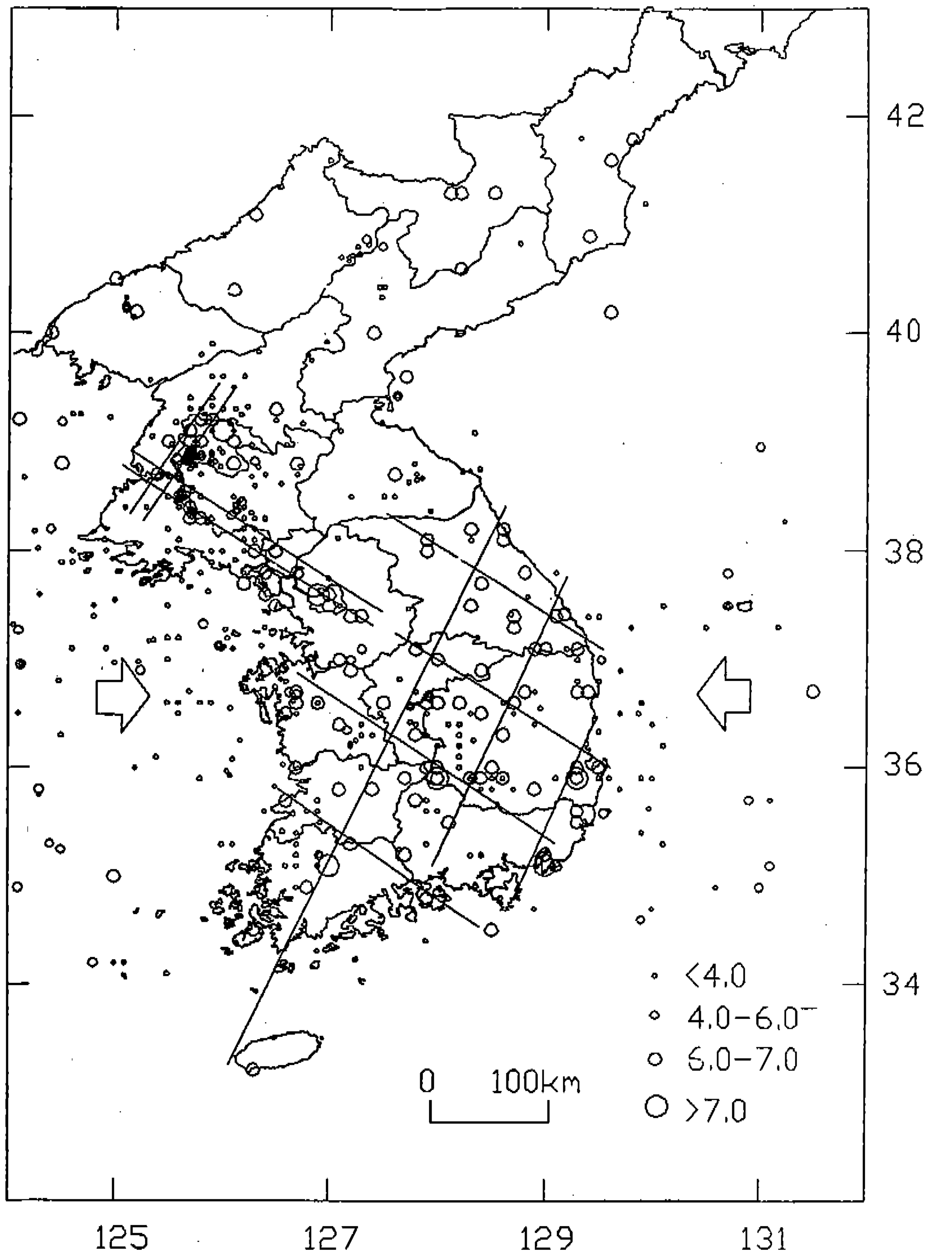


Figure 10 Earthquakes from 2 A.D. to 1960 A.D. with magnitude larger than or equal to 6.0, together with seismicity from modern seismological observations, showing the regime of seismicity and stress state of the Korean peninsula.

proximate orientation of the preferred fracture. In the figure the earthquakes from 2 A.D. to 1960 with magnitude larger than or equal to 6.0 and the earthquakes from 1960 to 1977 (DPRK Institute of Seismology, 1986) as well as those from 1978 to 1992 (Kim, 1993) recorded by the seismic stations in the peninsula are plotted. The data from 1993 to August 1995 from the Korean Meteorological Administration (KMA) are also added to the map. Comparing to Figure 4, it seems that the spatial pattern of seismicity has had some consistency since the 15th century.

From the above analysis it may be seen that the historical documents and the seismological records in the past time may provide the study of seismicity with some useful information. On the other hand, as have seen in the discussions, the incompleteness of the catalogue and the uncertainty of the magnitude estimation are the main problem affecting the reliability of the analysis. Considering that since the beginning of this century the Korean peninsula has been in the period of 'seismic quiescence', the historical data is of most importance to reveal the seismic characteristics of this region. It is clear that more detailed studies on certain earthquakes and further reexaminations of the historical recordings are needed in probing the nature of the seismicity as well as that of the seismological records in the old times.

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