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地震成因的综合模型和强震预报

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摘要

根据以往研究的地震孕育和发生的 3 个模式提出了地震成因的综合模式、地震前兆指标和预报方法。综合模式由 7 个单元组成:震源、震源端部的 2 个调整单元、震源顶部和底部的 2 个软弱层(这些单元均位于上岩石圈)以及下岩石圈的两个深部剪切蠕滑断层(一个与震源断层面垂直立交,另一个与震源断层面同面立接)。这 7 个单元组成了导致强震后果的结构。在构造力源作用下每一个单元围绕震源运动。最终使震源区破裂和发生强震。根据这个模式各种地震前兆异常区的演化与模式中震源与其它各个单元之间的差异性有关,与调整单元、调整层、深部剪切蠕滑断层之间的差异性有关。这种差异性使不同时间或同一时段多个异常区、带边界的交汇点或连接区预示未来强震位置。

在孕震后期,震源系统某些单元之间的相互作用增强,并形成正反馈,前兆异常随时间的变化出现起伏加剧。根据总结,强震大多发生在第 3 次起伏加剧的峰值处和峰值后并得到

$$M = 4.29 + 0.11t$$

式中 t 为起伏加剧的异常时间,以月为单位。由上述指标可以作出强震的中短期预报。在文章最后我们以唐山地震为例展示了综合模式在地震预报中的应用。

主题词: 震源孕育模式 地震前兆 地震预报 异常区边界交汇法 起伏加剧

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COMPREHENSIVE MODEL OF EARTHQUAKE FORMING MECHANISM AND STRONG EARTHQUAKE PREDICTION

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Abstract

On the basis of previous research on three earthquake source preparation and occurrence models, the comprehensive model about earthquake forming mechanism, earthquake prediction indexes and prediction methodology have been suggested in the present paper. Comprehensive model consists of 7 major units: the earthquake source, two adjustment elements at ends of source region, two weak medium layers above and below the source body, which are located in upper lithosphere, and two deep shear creep faults in lower lithosphere, in which one is perpendicularly stereoscopically crossed with the seismogenic fault and another parallel to it in the same plane. The 7 basic units compose a structure having strong earthquakes.

According to this model, the differentiation between the source region and the other units and the differentiation among the adjustment elemonts, adjustment layers and deep shear creep faults can lead to temporal and spatial evolution of earthquake source and the boundary of various seismic precursory anomalies regions will pass through the source region. The intersection region of several boundaries of various seismic precursory anomalies regions in various time interval is epicenter of future strong earthquake.

During latter preparation period, the interaction between some units of the model intensifies and forms positive feedback, and the fluctuation intensification anomalies of precursor change with time. According to our study, the main shock occurs generally just at the third peak of fluctuation intensification of precursor or after it, and fluctuation intensification displays certain periodicity. Therefore we can estimate roughly the third peak time and get formula

$$M = 4.29 + 0.11t$$

t indicates anomalous time interval of fluctuation intensification, in month. According to above mentioned indexes, the moderate and short term prediction of strong earthquake may be made. At the end of this paper, we take the 1976 Tangshan earthquake as an example to show the application of the comprehensive model in the earthquake prediction.

Key words: **Focal development pattern, Earthquake precursor, Earthquake prediction,** Anomaly region boundary intersection method, Fluctuation intensification

1 Comprehensive Model of Strong Earthquake Forming Mechanism

The comprehensive model of strong earthquake forming mechanism is a physical model considering the interaction between earthquake source environment, tectonic force and earthquake source during earthquake preparation, occurrence and after occurrence. This model synthesizes, in fact, the combination model[1], the interlayer decoupling model[2] and the stereoscopic cross model[3] and is the combination of the above three models. The comprehensive model consists of 7 major elements: the earthquake source area (seismogenic fault F_3), the adjustment elements C and D at both ends of the source, sedimentary layer A and low velocity layer (or low resistivity layer) B which are the upper and lower adjustment layers to the source body, the deep creep slip fault F_1 which is the same plane to the seismogenic fault and the deep creep fault F_2 in lower lithosphere, which is perpendicular to the seismogenic fault. Fig. 1 illustrates simply the comprehensive model.

C and D in Fig. 1 are two adjustment elements, such as slip fault, fractured area in medium, high temperature area and low density area in medium etc. at both ends of the source. Because of the low strength of medium, or low rigidity of medium, adjustment movement takes place under the tectonic regional force which adjusts and shifts stress to both ends of the source and causes stress concentration and forms the strong earthquake source stress field. Sedimentary layer A and low velocity layer B are weak medium interlayers in the crust of several kilometers in thickness. For the low strength of medium, moderate earthquake or strong earthquake generally dont't occur within it. The two weak layers restrain the preparation and occurrence of the earthquake source in earthquake preparing layer between them. If sinking, uplift or vertical differential movement takes place in lower lithosphere beneath the source, interlayer decoupling may occur due to the differential deformation of soft interlayer and hard earthquake source layer, which affects the preparation and occurrence of earthquake source. Lower lithosphere beneath the earthquake source is in a state of high temperature and high pressure and relatively plastic, shear creep fault in lower lithosphere propagates beneath seismogenic fault in upper lithosphere and makes an angle of 45° with the direction of regional tectonic pressure. Coupling may occur if above mentioned shear creep movement takes place, the movement of F_2 (perpendicular to the seismogenic fault F_3) may cause lock of fault F_3. But the movement of F_1 (F_3 in the same plane) may unlock F_3. Movements of deep faults F_1 and F_2 offer dynamic tectonic force for earthquake source. As F_1 and F_2 are very close to the source area, they are also an important major force for the preparing and occurrence of strong earthquake. Earthquake source is the core of comprehensive model which is a relatively homogeneous area of high strength and higher rigidity and also the source area where drastic dislocation occurs and disaster is induced at the last. During the preparing process before strong earthquake, the source area is the most stable place, the other elements around the source play an active role in this process and their adjustment movements cause failure in source area and induce disaster finally. It is obvious that the model is near mostly to real source structure in crust. We call the complex source structure the source system.

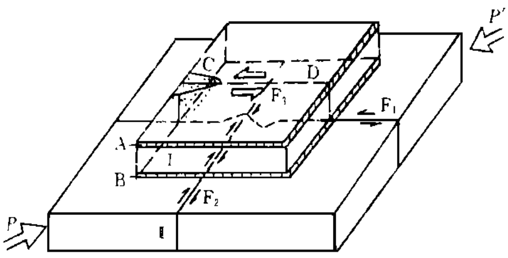

Fig. 1 Schematic of the comprehensive model.
I upper lithosphere; II lower lithosphere;
A, B top and bottom layers of source region;
C, D adjustment elements;
F1, F2 deep shear creep faults; F3 active fault

As above mentioned, the structure of the comprehensive model has disaster inducing effect. Under the effects of horizontal and vertical forces, elements of the model may move around the source (it is a stable body, exhibits rare precursor and could be treated as an unmovable point before earthquake). The individual movement of each element, or combined movement, coordinated movement among elements and field tectonic faults forming the temporal and spatial evolution of source precursory field. Composing of the comprehensive model and the evolution pattern of strong earthquake precursor may help research the whole process of strong earthquake preparation and set up physical basis for the index system of strong earthquake prediction. Such movement propagation displays as the chain pattern seismicity and the spatial propagation pattern of precursors, and induces the inhomogeneous regional precursory development in a larger area.

What should be pointed out is that the horizontal stress field is base field in China plate, the vertical force is often in local region and the deep shear creep fault movements are linear with long distance. The latter two kinds of force do not certainly exist for some source area in various time. In this case, the combination model in the comprehensive model is both independent and synthetical during the long preparation process. The' independent' here means that the combination model is sufficient in consideration of vertical force is weak and the deep fault has not pass through beneath the source region, the ' synthetical' here means to make the combination model with other one or two models. For example, if vertical force is rather strong and the movements of deep faults do not pass through beneath source region, both the combination model and the interlayer decoupling model should be considered, if vertical force is weak and the deep faults pass through beneath the source region, both the combination model and the stereoscopic cross model should be considered, and the three models should be considered synthetically if the horizontal and vertical forces are prominent and interaction occurs between deep and shallow faults. From above discussions, we may say the combination model is the foundation of the comprehensive model. As the deformation in source area reaches top and bottom of the source area, the deformation of asperities occurs on source fault plane, the pre-displacement takes place on source fault plane and when close to the occurrence of main shock, the comprehensive model must be taken into consideration in this period. It is obvious that the evolution of precursory anomalies is rather complicated, but we may identify the site and time of strong earthquake occurrence in the complicated precursory field by applying the differential between various elements in behaviour of the comprehensive model and the source region shall be located at the edges of various anomaly regions caused by adjustment elements movement trace.

2 The Differentiation between Various Elements in the Comprehensive Model and the Site Prediction of Strong Earthquake

The earthquake source in comprehensive model is called as accumulation element, other elements are called as adjustment elements. The differentiation among elements includes two parts: the differentiation between accumulation element and adujstment element, and the differentiation between adjustment elements. For the first part, the accumulation element is stable body with homogeneous medium, relatively higher strength of rock, higher frictional strength and higher rigidity in which there is the least amount of precursors before earthquake, while the adjustment element is unstable body with relatively lower strength of medium, fractured medium, lower rigidity and easy to be deformed and adjustment movement may occur frequently within it and the movement causes stress concentration at ends of accumulation elements. The second part of the differentiation displays as the differentiation of the adjustment effects between adjustment elements, and the difference of dynamic composing pattern of adjustment movement caused by the differences of stress level, medium property, strength, rigidity, volume and location of each adjustment element.

The above mentioned two differentiations may cause spatial and temporal evolution of anomaly around the earthquake source and form complicated composing anomaly pattern, and the intersecting area between the composing patterns is the possible site of future strong earthquake. There would be more precursors during the various preparation stages, such as locked stage, unlocked stage[5]. Besides, in the early preparation stage, adjustment movement of various elements is independent. The anomaly appears mainly in single region and in single seismic belt. During the intermediate preparation stage, anomalies will appear alternatively between single region and double regions and will be alternatively active for conjugate seismic belts. During latter preparation stage, anomalies appear mainly in double regions and are active in conjugate seismic belts and order seismic pattern. During the period just before occurrence of earthquake, strain at the source area propagates upward to its top and causes deformation in upper adjustment layer and the much shallower tectonics also join in the activity, precursors appear at the future epicentral region. So, the transition of seismicity pattern from simple to complicated is the qualitative index of strong earthquake developing from preparation stage to occurrence.

The following indexes for site identification of strong earthquake may be concluded from above discussions:

(1)Strong earthquake occurs along the rim of single anomaly rigion in different stages, within single anomaly belt or zone in different stages. Site of future strong earthquake is the intersection area of anomaly regions and belts or zones in different stages are superimposed.

(2)Strong earthquake occurs in the area where the difference of anomalies is the greatest, or areas where double regions, belts or zones are conjugated.

(3)Strong earthquake occurs in the rim of single anomaly region, or between double anomaly regions with higher anomaly frequency, the intersection area between dynamic seismic gaps, intersection area of swarms activity traces.

For site prediction of strong earthquake, the dynamic pattern of the seismicity anomalies must be applied in above mentioned indexes. Static pattern of anomalies may conceal the source area in the average anomaly area.

Evolution pattern of dynamic anomalies must be taken as the basis for analysis in the site prediction of strong earthquake. In previous studies, we suggested several methods to give out the dynamic evolution pattern according to seismicity such as the method of modulation ratios of small earthquakes[7-10], the method of dynamic seismic gaps and the method of spatial and temporal evolution of swarm chain etc. which had been applied to the practice of strong earthquake site prediction. By applying the above indexes, other dynamic precursory pattern such as the temporal and spatial evolution of infrared radiation anomaly, the temporal and spatial evolution of air temperature, air presssure and ground temperature could also be used to predict the site of future strong earthquake.

3 Comprehensive Model and the Magnitude and Time Prediction of Strong Earthquake

During the process determining the site of strong earthquake, the preparation stage of strong earthquake has been qualitatively identified in fact. But such identification is far from enough. We should study at least two aspects. One is to study the lock beginning time and unlock time on source fault plane from the whole preparation time T to determine the magnitude and occurrence time. The other is to determine the magnitude and occurrence time from the time history curve of earthquake precursory anomalies. Magnitudes and occurrence time estimated by these two aspects should be well-matched. In fact, more aspects may appear during the whole earthquake preparation period. In the present paper, only the above mentioned two aspects were mainly studied.

3.1 Determination of the Lock Bebinning Time and Unlock Time of Strong Earthquake

3.1.1 Lock beginning time discussed in the stereoscopic cross model

The lock beginning time may be determined by the following indexes according to the stereoscopic cross model.

(1) Moderate-strong earthquake gap may appear the intersection area between active fault and earthquake migration zone with linear and long distance.

If deep creep fault stretches beneath active fault and stereoscopically crosses perpendicularly the active fault, it may cause asperities on the active fault plane and make it lock. Indexes of deep fault activity are: seismicity of small and moderate earthquakes displays linear pattern and distribute in a long distanec, linear epicenter migration in a long distance and short period crossing different tectonic units. If the linear distribution belt of seismicity crosses active fault and seismic gap of moderate-strong earthquake is formed afterwards, the above mentioned earthquake migration time may be determined as the beginning time of active fault to be locked.

(2) Strong earthquake induces the movement of deep fault which is stereoscopical to the source fault in the same plane in lower lithosphere (F1 in Fig. 1), the movement of deep fault leads to some active fault to be locked in the near field of strong earthquake occurred and forms small and moderate earthquake belt at the same time. The belt perpendicularly crosses the active fault and forming seismic gap of moderate and strong earthquake. That is another method to determine lock beginning time and suppose strong earthquake occurrence time is as the lock time. Considering the dynamic action of strong earthquake, the effect distance does not exceed 500 km.

3.1.2 The lock beginning time t_0 in the combination model

Stereoscopic cross tectonic condition doesn't certainly exist in the source area for some strong earthquakes, especially for moderate-strong earthquakes. Asperities two block of active fault plane have not meeting, and the meeting of asperities may form lock during intensive tectonic movement. So, the lock beginning time is the time when the active fault becomes active abruptly and then stops movement, and at the same time the seismicity is intensified and then the seismic gap is formed.

3.1.3 Discussions on time index t_n of unlock of earthquake source fault plane

During the latter time of preparation, the asperities on fault plane may be deformed, become weak, break and induce the activity of the conjugate seismic belts along the strike of souce fault plane and perpendicular to it. Activities of these two belts condition each other, their activities are alternative, this is one kind of unlocked index. The other kind of unlocking index is intensified the moderate strong earthquake activity at the ends of the strong earthquake source, which is unlocked time of seismogenic fault. According to our statistics, strong earthquake occrus generally 1—4a after the appearance of above index.

Magnitude M and preparating time T(a) and possible occurrence time t_x of strong earthquake may be estimated by the statistical fromulaes[5]

$$T = T_n - T_0 + (1+4) \quad (1)$$

$$M = 5.06 + 1.308\log T \quad (2)$$

$$T_x = T_n + (1-4) \quad (3)$$

3.2 Magnitude and Occurrence Time Estimated by the Variation Curve of Precursors with Time

According to statistical physics, the critical index of stable failure of a complex system is the apppearance of intensification of fluctuation, critical slowness etc. We choose the index of fluctuation intensification here. For earthquake prediction, fluctuation intensification is the result of positive feedback formed by the interaction among adjustment elements of the earthquake source system. According to the research of modulation ratios of small earthquakes, before strong earthquake the main shock occurs generally just at the third peak of fluctuation intensification of precursor or after it, and fluctuation intensification displays certain periodicity. So, we can roughly estimate the third peak occurrence time [t_3] and we take the t_3 as t_x of strong earthquake occurrence time. The statistical relationship between duration t_1 of fluctuation intensification and M[10] is

$$M = 4.29 + 0.11t_1 \quad (4)$$

where t_1 is interval time (in month) from beginning anomaly to third peak occurrence time. In fact, in the above mentioned formula we have hypothesized that the duration time of fluctuation intensification is related to M. When magnitude M calculated from formula(4) is near to the M from formula (1), we take t_x into formula(4), the preparation duration T is verified, the preparation duration T should be

$$T = t_x - t_0 \quad (5)$$

put T from (5) into (1), M from (1) can be modified.

The above mentioned combination of long term, immediate and short term predictions is very important, which may decrease the error of prediction. It should be pointed that the fluctuation intensification of most precursors appear generally after the above mentioned unlock indexes. For example, the number of dynamic seismic gap and seismic belt of small earthquakes increased, anomalies of the modulation ratio of small earthquake appear by the way of fluctuation intensification with time etc.

The above discussions is our practice on site, magnitude and time prediction of strong earthquake by the comprehensive model of earthquake source preparation. The method may be also applied to the case of several earthquake sources in different preparation stages within the crust. But the evolution pattern of precursor is more complicated for the case of several sources than that of single case, the precursory anomaly of each source should be separated from sources and then the following prediction for one earthquake source of them may be really realized.

4　The Prediction Problem Discussion of the 1976 Tangshan Great Earthquake

For spreading and application of the prediction model, idea and method discussed in the present paper, we take the 1976 Tangshan great earthquake ($Ms=7.8$) as an example and use several figures to exhibit some prediction indexes of various stages in preparation of source.

The schematic map of the comprehensive model of the 1976 Tangshan earthquake is shown in Fig. 2 where P is horizontal tectonic force, its direction is near to EW; V is vertical tectonic force. Other symbels in the figure are the same as that in Fig. 1.

It is not convenient to illustrate the interlayer decouple process in Fig. 2, we show th process in Fig. 3.

In Fig. 3, the interlayer decouple process is divided into six stages: (1) the no bending stage of various layers; (2) the stage during which only layer Ⅱ bend; (3) the stage during which the low velocity layer B consequently bend; (4) the stage during which the layer Ⅰ bend (In this stage, a sink basin formed, shear stress and tensile stress become high around the rim of basin and in the center of the basin. In this case, foreshocks are active around the rim and in the center of the basin. Because the center of the basin is plain in the Tangshan region, the foreshocks are quiescent in this position.); (5) the stage of bending of sedimentary layer A (Because the layer A is rich in water and gas, both number and amplitude of anomalies become very big and display jump precursors.); and (6) the stage of occurrence of the 1976 Tangshan great earthquake and after it (In this stage, all layers sink down and its adjustmentary process accompanies a lot of aftershocks.).

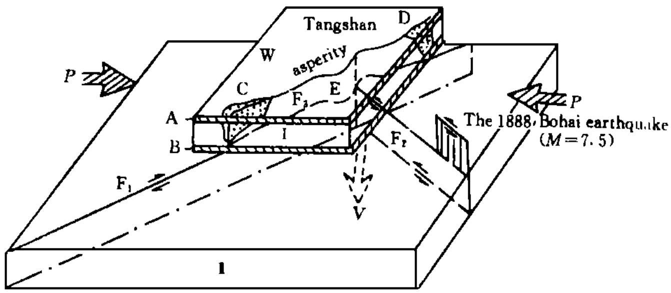

Fig. 2　Schematic of the comprehensive model of the 1976 Tangshan earthquake (M 7.8).

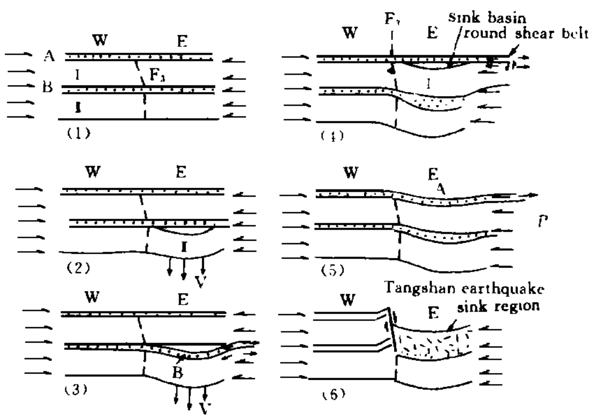

Fig. 3　The interlayer decouple process under horizontal and vertical tectonic force before and after the 1976 Tangshan earthquake.

In Fig. 4, the active seismogenic fault F3 was locked by fault F2 on which a large earthquake occurred in 1888. According to our model of earthquake preparation, the beginning time from which the active seismogenic fault F3 was locked is 1888. If we put $T=88$a into the formula (2), then the magnitude is 7.6, which is near the real magnitude of the 1976 Tangshan earthquake.

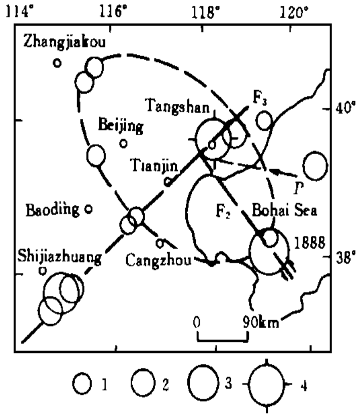

Fig. 4 An active fault (F3) locked in 1888.
1 $5.0 \leq M \leq 5.9$; 2 $6.0 \leq M \leq 6.9$;
3 $7.0 \leq M \leq 7.9$; 4 main shock

According to the comprehensive model, the unlocking indexes are the small and moderate earthquake activities, which are caused by shear creep fault F1 and fault F2 in the lower lithosphere. From 1972, such earthquake activity pattern appeared, which is shown in Fig. 5.

It means the Tangshan earthquake is near to occur in moderate time interval scale. About 4—5a before the 1976 Tangshan earthquake a conjugation of seismicity belts appeared in the region of source, which is shown in Fig. 6.

In our model, since the seismogenic fault F3 was locked in 1888, the seismic gap of stronger earthquake gradually formed. About 3a before the Tangshan earthquake, the seismic gap of small and moderate earthquakes displays, which is show in Fig. 7.

In this figure, regions C and D are two adjustmentary elements at the ends of Tangshan source region, in which small and moderate earthquakes concentrated. The length of the seismic gap is equel to 100km, we use $L = 100$ km and the following formula to calculate the magnitude of Tangshan earthquake to be 7.5. The formula is

$$M = 3.3 + 2.1\log L \qquad (6)$$

Other predicting indexes and a kenetic monitory method which is proposed by us are omitted here. In the following we introduce the indexes of predicting occurrence time of the Tangshan great earthquake.

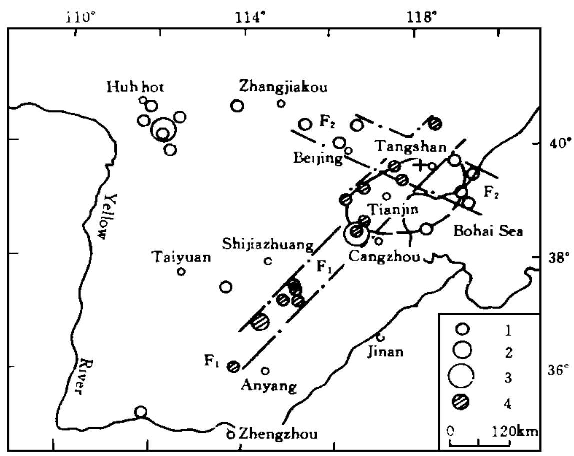

Fig. 5 Seismogenic fault (F3) unlocked by deep shear creep faults F_1 and F_2 in 1972.
1 $4.0 \leq M_L \leq 4.9$; 2 $5.0 \leq M_L \leq 5.9$;
3 $6.0 \leq M_L \leq 6.9$; 4 unlocked belt

According to the critical phenomena of phase change in statistical physics, immediately before the great earthquake, the fluctuation intensification of the modulated small earthquakes by tidal force appeared, which is shown in Fig. 8. In this figure, the r_m indicate the ratio of the number of modulated small earthquake to the total number of earthquakes month by month. From our study, after third fluctuation peak, the main shock occurred. Based on the curve in Fig. 8, the total anomalous duration is equal to 30 months. Using this data and formula (4) we got $M_x = 7.6$, which is near to the real magnitude of the great Tangshan earthquake.

Fig. 9 shows three anomalies regions, in the fluctuation intensification term. In Fig. 9, there

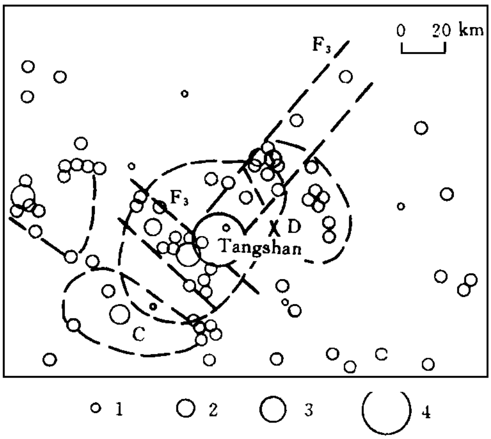

Fig. 6　Conjugation of seismicity belts (1970— 1972) in the source region before the 1976 Tangshan earthquake.
1　$2.0 \leqslant M_L \leqslant 2.9$;　2　$3.0 \leqslant M_L \leqslant 3.9$;
3　$4.0 \leqslant M_L \leqslant 4.9$;　4　$5.0 \leqslant M_L \leqslant 5.9$

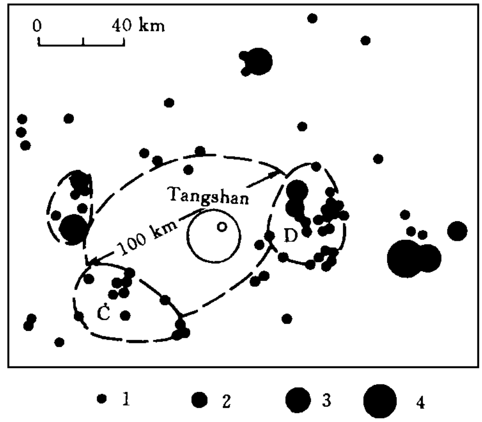

Fig. 7　Seismic gap and intensified earthquakes activity at the ends of the 1976 Tangshan earthquake source region.
1　$2.0 \leqslant M \leqslant 2.9$;　2　$3.0 \leqslant M \leqslant 3.9$;
3　$4.0 \leqslant M \leqslant 4.9$;　4　$5.0 \leqslant M \leqslant 5.9$

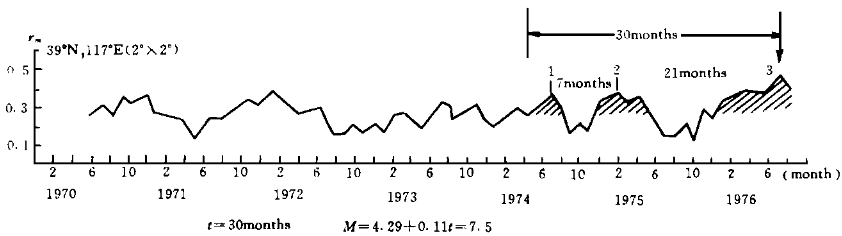

Fig. 8　The fluctuation intensity of r_m with time.

are two intersection points, one is the Tangshan epicenter region, which is located between C and D regions, the other is located between C and E regions. According to statistics, the first intersection is stable and the second one is instable, which is not considered as a prediction region.

The above mentioned indexes in various stages before the 1976 Tangshan earthquake are accordant with the comprehensive model to a greater degree. Therefore we consider that the comprehensive model may serve as a physical base of earthquake prediction in some degree. we believe by combining the model with the realistic precursors the expection of predicting strong earthquake is not in vain in future.

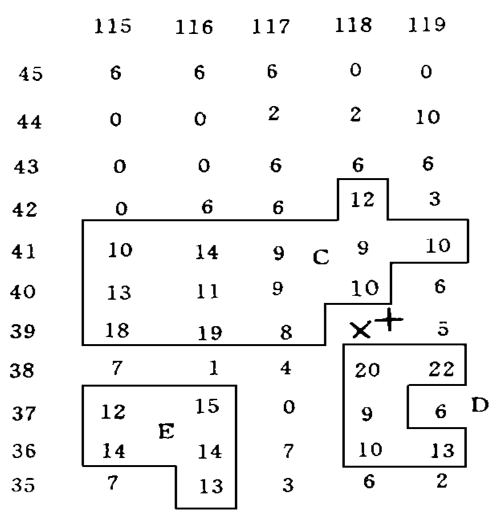

Fig. 9　R_S anomaly regions before the Tangshan earthquake. R_S is frequency of r_m anomaly.