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DILATION-CREEP MODEL OF EARTHQUAKE SOURCE DEVELOPMENT AND THE TANGSHAN EARTHQUAKE

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Abstract

The article has made a simple exposition of the dilation-creep model of earthquake source development (abbreviated DC). Inelastic volumetric dilation of rock masses and fault creep are considered as two basic physical processes in the DC model. The physical mechanism of precursors of the M=7.8 Tangshan earthquake has also been analysed and discussed in this paper. The results show that the precursors of the Tangshan earthquake were not caused by only one factor and the precursors observed in and around the epicentral area prior to this earthquake can be grouped in to three types. Type I precursors may be causally related to rock dilatancy. Type II precursors result from fault creep. Type III precursors may be associated with some sort of upward migration of mass in the crust or the upper mantle, and/or may be attributed to large scale stressing process accommodated by some combination of stable slippage and discontinuous brittle rupture (namely small earthquake) along the faults. It was suggested that repeated dilation and discontinuous creep occurred during the process of source development of the Tangshan earthquake and the preparatory process of the Tangshan earthquake can be divided into the following six phases: elastic stress accumulation (from 1954 to 1967); early inelastic dilation (from 1968 to 1969); early fault creep (from 1970 to 1973); the second dilation (from the end of 1973 to the first half of 1975); the second evident fault creep (from the second half of 1975 to the end of Apr. 1976); and fault creep just before the main shock (from the end of Apr. 1976 to the occurrence of the Tangshan earthquake). It is regarded hat the preparatory process of the Tangshan earthquake, as one of the

intraplate events, may be controlled jointly by the upward migration of deep mass and large scale intraplate stress field. This characteristic probably is different from that of earthquake along plate boundary.

Introduction

Seismologists in China have reported a variety of effects premonitory to the disastrous Tangshan earthquake such as crustal movements and anomalous changes in such phenomena as tilt, fluid pressure, electrical resistivity, radon emission, the frequency of occurrence of small local earthquake (N value), the ratio of the number of small to large shocks (b value), the ratio of the seismic compressional velocity to the seismic shear velocity (V_P/V_S) and others. The Tangshan earthquake may be one with the largest number of independently measured precursory phenomena of any single seismic event up to now. In this paper, we will qualitively discuss the physical mechanism of precursors and the process of source development of the Tangshan earthquake. The results will show that the independently measured precursory phenomena of the Tangshan earthquake can be explained by the dilation-creep model (abbreviated DC) we put forward. Local observations by my colleagues are discussed in detail because the geographical distribution of the measurements is of importance. However, I have no personal knowledge of the details of these data, which are simply taken from the referenced articles.

Because the DC model has been published in Chinese (Niu and Su, 1976; Niu, 1978), and is poorly understood outside China, it begins with a recapitulation of the essential concepts of the DC model.

The DC model——a recapitulation

The essential concepts of the DC model may be summarized as follows:

1)Earthquake is the result of the unstable extension of fault.

2)Dilatancy—the non-elastic increase in volume caused by stress—may occur in site and it is recoverable. Both dilatancy and its recovery are strongly time dependent.

3)Creep on varisized weak or discontinuous surfaces—quasi-stable slip and slow spread of the surfaces, as well as the coalescence of the surfaces of small size under approximately constant stress is a basic physical process during earthquake source development.

4)Immediately before earthquake occurrence, a slow failure of intact rock or locked fault will dramatically transit to the rapid unstable rupture of earthquake within a short time.

5) The random distribution of weak or discontinuious surfaces (the main fault, small faults, joints, grain boundaries and even crystal boundaries etc.) results in the complicated distribution and evolution of dilatant zones as well as of fault creep.

On the basis of these concepts, the temporal-spatial course of the earthquake preparation can be visualized as follows. For the convenience of brief description of the course, we assume that there exists only a main fault AO in the region of earthquake source development (Fig.1). In Fig. 1, the dash line OB represents an unfractured zone or "locked zone".

Under the influence of tectonic stress the creep on the main fault AO occurs resulting in the stress concentration at the tip O. The creep occurs also on small weak or discontinious surfaces. As the sizes of these surfaces are one and even several orders of magnitude smaller than that of the main fault, we consider only its statistical effects on the deformation of a rock unit instead of local detail. During this period stress is increasing but dilatant cracks have ont yet begun to open or form.

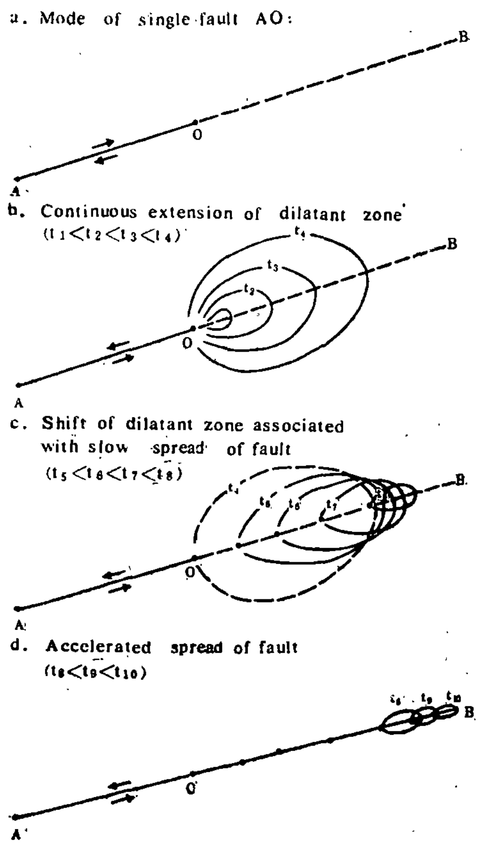

Fig. 1 Schematic illustration of earthquake source development of a single fault.

When the difference between the largest principal stress and the smallest one reaches a centain critical value—the elastic limit, dilatant cracks begin to form. The development of earthquake source transits from stage Ⅰ—the elastic strain accumulation to stage Ⅱ—the dilation. In the stage, dilatant zone forms in the surrounding volume at the tip O of the fault AO. In the dilatant zone, dilatancy causes the changes in the various properties like velocity and resistivity (Tocher, 1957; Matsuchima, 1960; Brace and Orange, 1968; Brace, 1968; Scholz, 1968; Brace, 1977; Mogi, 1962; Chen, 1979; Lai et al., 1979; Chen et al., 1975 and The group of hydrochemistry, the seismological brigade of Beijing, 1977). The dilatancy governed by differential stress is the strongest in the vicinity of the fault andweaker in other raase) Fig. 1,b).This kind of dilatancy patterns has already been observed in laboratory experiments of rock fracture (Chen etal., 1979).

When the differential stress at the tip O reaches the fracture strength of rock (or the ultimate frictional stress on the locked fault), slow fracture in rocks (or locked fault) begins to take place. The development of earthquake source enters stage Ⅲ—the slow spread of the main fault (the creeplike fracture). The slow spread of the main fault results in the decrease of stress level in the surrounding volume of the newly—formed fault; as a result, the dilatancy in this volume is recovered. In dilatancy—recovery zone, with closing of the dilatant cracks, restoration of many original characteristics of rock takes place. In this stage, stress concentration occurs at the tip of spreading fault and dilatant zone forms in the surrounding volume of this moving tip. It should be emphasized that, in this stage and stage Ⅱ, the formation and growth of dilatant cracks and the slow spread of the main fault could all be controlled by loading.

If this process leads to the earthquake, then there must be, by definition, stage Ⅳ—the sharp acceleration of spread of the main fault. In this stage the stress field in the region of earthquake source development changes rapidly with the accelerated movement of the fault tip. The region behind the moving tip is rapidly unloaded but the region in front of the tip is rapidly loaded. The dilatancy recovery zone expands rapidly with the acceleration of the tip movement. Because of the time dependence of dilatancy (the stress required to initiate significant dilatancy should increase with loading rate), the dilatant zone shrinks rapidly with the acceleration of the tip movement. Thus, it can bessen that, in the local zone near the main fault inelastic deformation, fault spread and slip become more and more violent, while in the surrounding zone the load drops and the dilatancy and the deformation recover (Fig. 1, d). Since this process results from the work done by elastic strain energy stored in the body, the spread of the main fault will be no longer controlled by loading, namely that the spread enters an unstable state. Shear brittle fracture occurs this moment. This is stage Ⅴ—the occurence of earthquake. The process of earthquake source development includes another stage (stage Ⅵ)—the stress adjustment after the earthquake. In Ⅵ many aftershocks and fault creep may occur accompanied with the changes in rock properties.

The form of precursors which correspond to the process under discussion are shown in Fig.2. It should be noted that the form of precursors depends not only on the amount of dilatancy but on the size of dilatant zone. In fact, the instantaneous magnitude of the precursory anomalies are connected with the integral of dilatancy over the volume of the detected region.

The earthquake precursors resulting from dilatancy will be called the precursors Type I and those resulting from fault creep will be cesignated as the precursors Type Ⅱ.

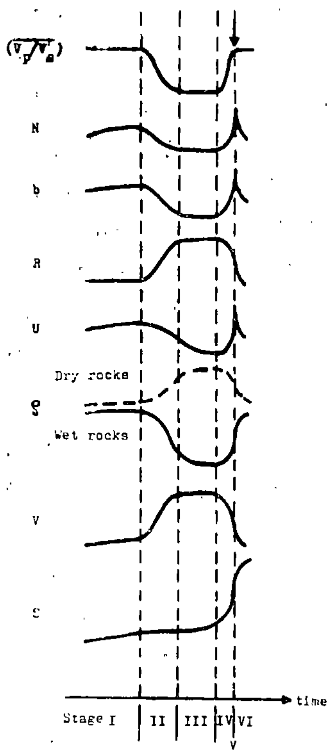

Fig. 2 General view of temporal course of earthquake qrecursors which corresponds to the diagram in Fig. 1. $(\overline{V_P/V_S})$—the ratio of the seismic comqressional velocity to the seismic shear velocity; N—number of seismic events; b—slope of the frequency vs magnitude plot; R—radon emission; U—ground water level; ρ—electric resistivity; V—volumetric strain; S—fault slip. Stage Ⅰ—elastic strain accumulation; Ⅱ—inelastic volumetric dilation; Ⅲ—slow spread of the main fault; Ⅳ—sharp acceleration of the main fault; Ⅴ—earthquake; Ⅵ—stress adjustment after the earthquake.

Physical Mechanism of Tangshan Earthquake Precursors

A number of premonitory phenomena were observed at the stations in and around the epicentral area prior to the Tangshan earthuqake. Fig. 3 is a figure showing the main earthquake, the aftershock area, all place names used, and observation sites. The preliminary study shows that these phenomena are related to the preparation and the occurrence of this earthquake (Mei et al., 1982). The questions here are whether these phenomena result from the same physical mechanism and whether they are due to the changes occurring in the focal region of the earthquake. Here we have collected the main anomalies observed prior to this earthquake and made a classification and futher study on them. The results will be shown in the following.

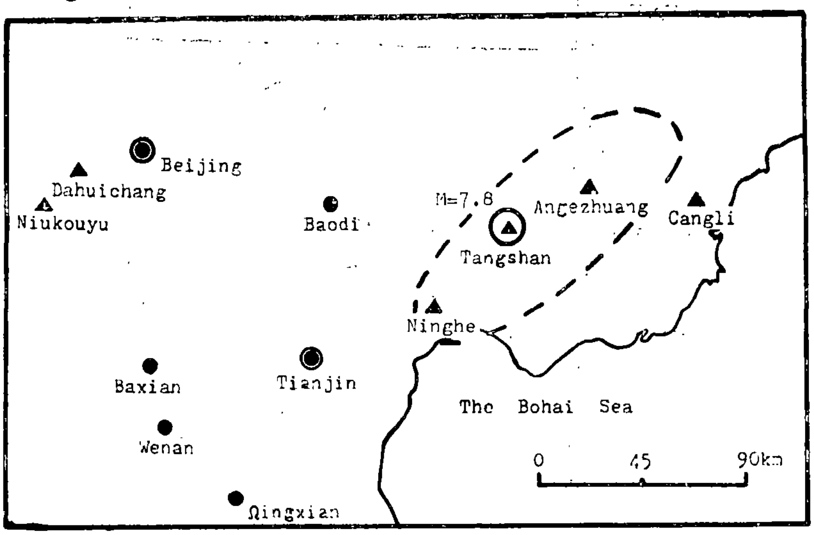

Fig. 3 Map of the Beijing-Tianjin-Tangshan area showing the main earthquake (vacant circle), the aftershock area (dashed line), place names used (solid circle), and observation sites (solid triangle).

1. Evidences for Inelastic Dilatancy in Source Development Region of the Tangshan Earthquake—Precursors Type I

In terms of the data available, the evidences for inelastic dilatancy in the focal region of the Tangshan earthquake are as follows.

Anomalous uplift occurred in the epicentral region in 1968—1969. At the same time, anomalous changes in mean V_P/V_S took place with an amplitude of 10% in this region (Mei et al., 1982). Both seem that dilatancy took place in the focal region of this earthquake in this period. Unfortunately, it is not possible to give a further proof of it because no comparable observed data.

It appears that the significant dilatancy occurred for the second time in the focal region of the Tangshan earthquake from about the end of 1973 to May 1975. In this period, observation of various earthquake precursors was conducted in Beijing-Tianjin-Tangshan region. Fig. 4 shows the main anomalies appeared in Tangshan and its surrounding areas at the end of 1973 or so.

Comparing Fig. 4 with Fig. 2, we can see that the anomalous changes in Fig. 4 can be interpreted in terms of the occurrence of dilatancy in and around the focal region of the Tangshan earthquake. We assume here that rocks in the vicinity of the focal region of this earthquake were saturated by water and dilatancy began at the end of 1973. In fact, excepting the

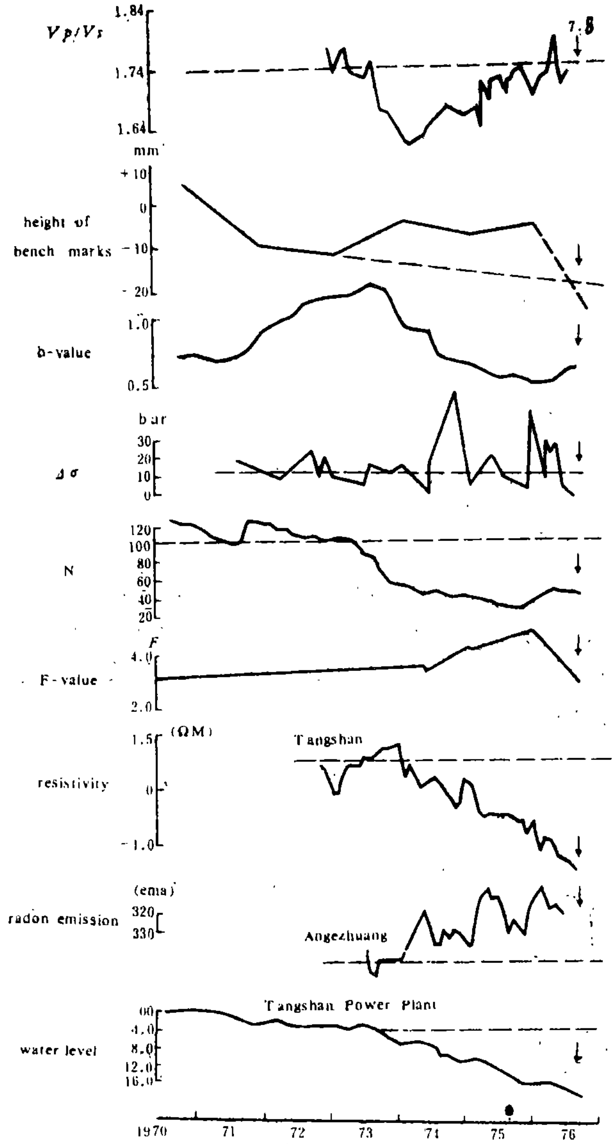

Fig. 4 Contrast patterns of various premonitory anomalies.

stress drop of small earthquake $\Delta\sigma$ and the F-value, the form of the anomalies in Fig. 4 has been predicted in Fig. 2 In addition, since increase in rock strength due to dilatancy hardening will cause increase in stress-drop of small shocks, the increase in stress drop $\Delta\sigma$ after the end of 1973 can be also interpreted a result of rock dilatancy. Zheng et al. (1978) gave a definition of the F-value: $F = M_S - \log S$, where M_S is the surface wave magnitude, S is the fault area. Aki (1972) obtained a expression for S: $S^{3/2} = CM_O/\Delta\sigma$, where M_O is the seismic moment, $C = 4.0$. Therefore, $F = \frac{2}{3}\log\Delta\sigma + (M_S - \frac{2}{3}\log M_O) - \frac{2}{3}\log C$. The F-value will change in the same way as $\Delta\sigma$. The increase in the F-value after the end of 1973 indicates that dilatancy occurred in and around the focal region of the earthquake after the end of 1973.

The other precursor is that the earthquake M≥2 shaped an elliptical gap with a major axis of 90 km nearby the focal region since July 1973 (Fig. 5). This precursor also supports the hypothesis that the significant dilatancy once took place near the focal region because the gap just shows dilatancy hardening

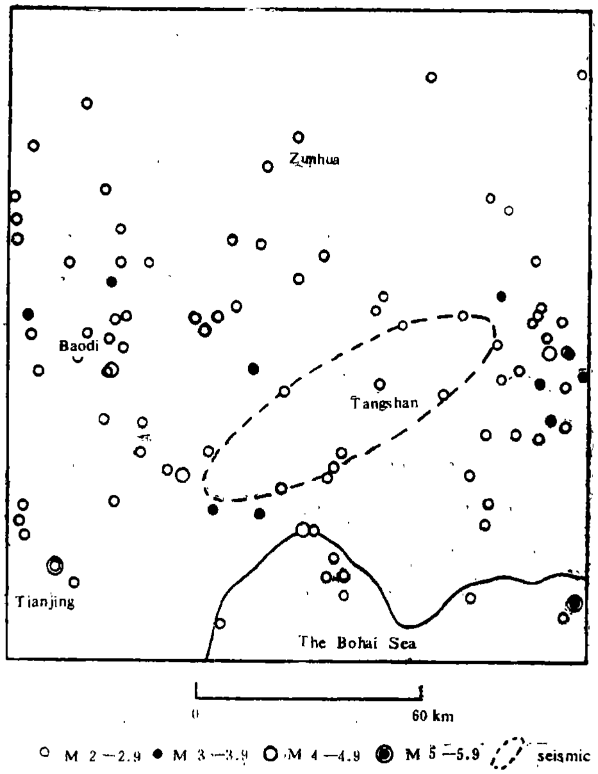

Fig. 5 Distribution of $M_L \geq 2$ earthquake prior to the Tangshan earthquake.

In summary, the above ten kinds of observations from Tangshan and its nearby region support the hypothesis that rocks in and around the focal region of the Tangshan earthquake were saturated by water and the significant dilatancy began there at about the end of 1973.

2. Clues to Fault Creep in the Region of Earthquake Development preceding the Tangshan Earthquake—Precursors Type Ⅱ

It was mentioned in the last section that the creep on weak or discontinuity surfaces, large or small, in the region of earthquake source development is a basic physical process of earthquake source development. Here we present some clues to show that creep had occurred in the region of earthquake source development before the Tangshan earthquake.

1)The short leveling in aftershock region of the Tangshan earthquake was obtained and first hand evidences were also done for fault creep in the source development region before and after this earthquake. Inversion of short leveling data a-Ninghe (Fig. 6) by the use of the dislocation model of Maxwell body indi-cates a precursory slip in upper crust in this area before the main shock Such aseismic slip remained still after this earthquake (Zhao and Zhang, 1981).

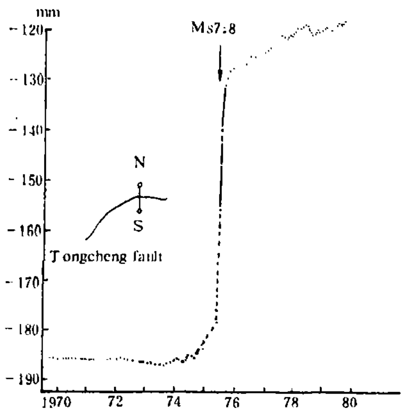

Fig. 6 Short leveling changes at Ninghe station forerunning the Tangshan earthquake.

2)Phenomena of wall inclination of a well for earthquake observation and dislocation of cement pipes of this well at No.10 Middle School, Tangshan, deformation of steel pipes (or hole deformation) in other holes at Tangshan as well as many times eruption of disposal oil well No.11 in Gingxian 120km away from Tangshan after June 1976 are evidences for the preseismic creep in the source development region.

3)A pair of upwarded and subsided regions which distributed antisymmetrically took form at Ninghe and Cangxian respectively at the both enns of active segment of Cangdong fault mainly between 1072 and 1975 (Fig. 7). Zhao et al. (1980) thought that they resulted from the slip on the north part of Cangdong fault. Using a theoretical fault model of viscoelastic medium, Zhao et al. inferred the length of the creep fault = 150km, the upper bound d = 1 km, the lower bound D = 20km and the total slip = 61km.

4)Through analysis of eleven times of repeated leveling data for Tangshan district, Zhang (1981) deemed that aseismic slip took place on both Tangshan and Jiyunhe faults near the epicentral region prior to the Tangshan earthquake. On basis of the elasticity theory of dislocation, she derived the parameters of creep fault and the rates of slip and strain accumulation on the two faults. From her estimates, the strike α of the creep segment of the Tangshan fault is 47°, the dip angle θ of creep plane 87°,

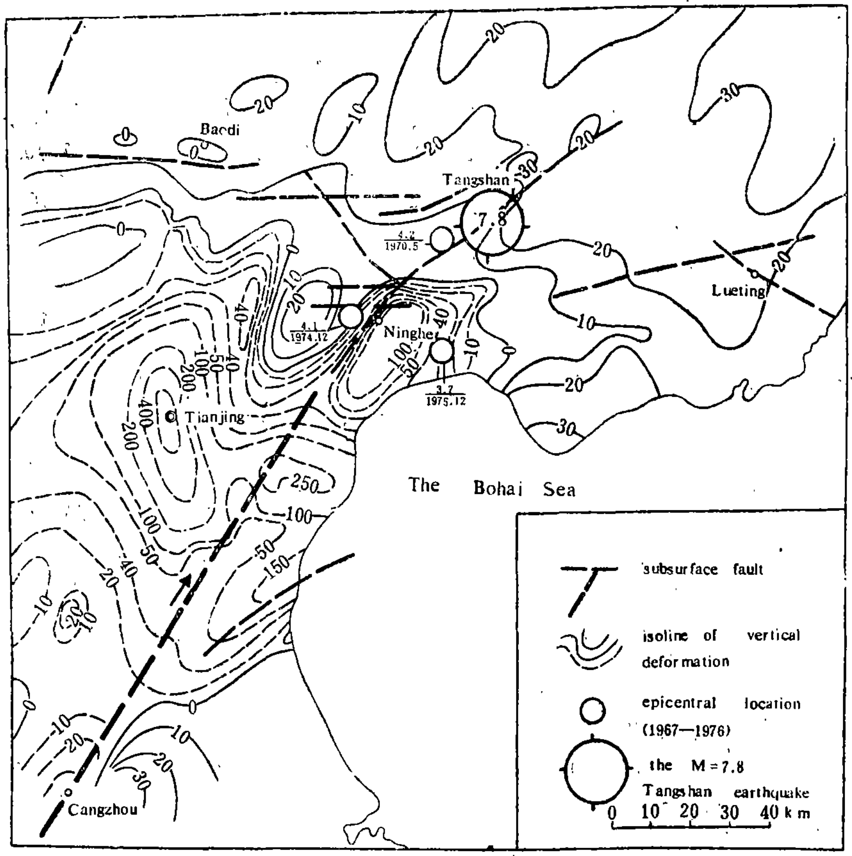

Fig. 7 Map of vertical deformations nearby the Tangshan region in 1968, 1969—1975.

the upper bound of creep plane is 2 km and the lower bound D 8 km respectively. The spread of creep plane is shown in Table 1. This table shows that the spread rate of creep fault was roughly uniform in 1972, 10.2km a year on an average, but it markedly decreased between 1973 and 1975. The slip rate slowed down and the strain accumulation became a strain release.

As for the Jiyunhe fault, the strike α of creep segment is 130°, the dip angle of creep plane 78°; the upper bound d of creep plane is 1.7km and the lower bound D 2.5km. The spread of creep plane is shown in Table 2. It can be seen in Table 2 that, similar to the Tangshan creep fault, the slip rate of the Jiyunhe fault had decreased and the strain accumulation had become a strain release two years before the earthquake.

5)The short leveling data observed at Dahuichang and Niukouyu stations show that the marked creep might appear on the faults in the range of 200km outside the epicentral region in 1975 (Fig. 8).

Observations of crustal deformation, in summary, indicate that aseis-

Table1. Rates of spread, slip and strain accumulation on the Tangshan fault.

Year	Spread rate of creep plane (km/year)	Rate of strike slip (cm/year)	Rate of dip slip (cm/year)	Rate of strain accumulation (10^{-7}/year)
1969—1971	Length of creep plane 3.2km	20.8	1.6	0.5
1971—1972	1.6	22.2	1.7	1
1972—1973	1.8	22.9	1.8	8
1973—1975	0.7	8.6	0.6	-1

Table2. Rates of spread, slip and strain accumulation on the Jiyunhe fault.

Year	Spread rate of creep plane (km/year)	Rate of strike slip (cm/year)	Rate of dip slip (cm/year)	Rate of strain accumulation (10^{-7}/year)
1969—1973	Length of creep plane 1.4km	26.7	8.9	2.2
1973—1975	0.3	21.5	7.2	-1.0

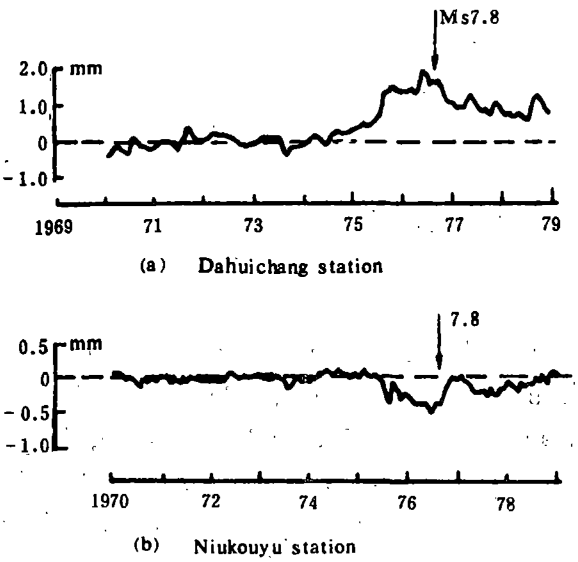

Fig. 8 Short leveling changes at Dahuichang and Niukouyu stations.

mic creep had occurred on the faults in the nearby region of the epicentre before the Tangshan earthquake. Comparison with the curves of changes in ($\overline{V_P/V_S}$) (Fig. 4) suggests that ($\overline{V_P/V_S}$) slowly returns to its normal value or so when the aseismic creep appeared on the faults. This shows that dilatancy recovery is associated with fault creep. According to the DC model, anomalous fault creep and other related anomalous changes are designated as precursors Type Ⅱ. Therefore, the recovery ofe($\overline{V_P/V_S}$) can be regarded as one of precursors Type Ⅱ.

The other changes corresponding to the recovery of ($\overline{V_P/V_S}$) in Fig. 4

also belong to precursors Type Ⅱ.

3. Indications of Migration of Deep Mass and Evolution of Stress Field on a Large Scale

The mobile gravity survey from Beijing to Shanhaiguan was begun in 1971, the results of which show that the gravity value of Tangshan slowly increased relative to Beijing before the earthquake, it slowly decreased after the earthquake (Fig. 9). The changes in gravity occurred mainly near the focal region of the future great earthquake. Such changes in gravity certainly did not result from dilatancy. It seems that they can not be explained as the changes in ground level. They may be related with the migration of deep mass (Chen, 1980).

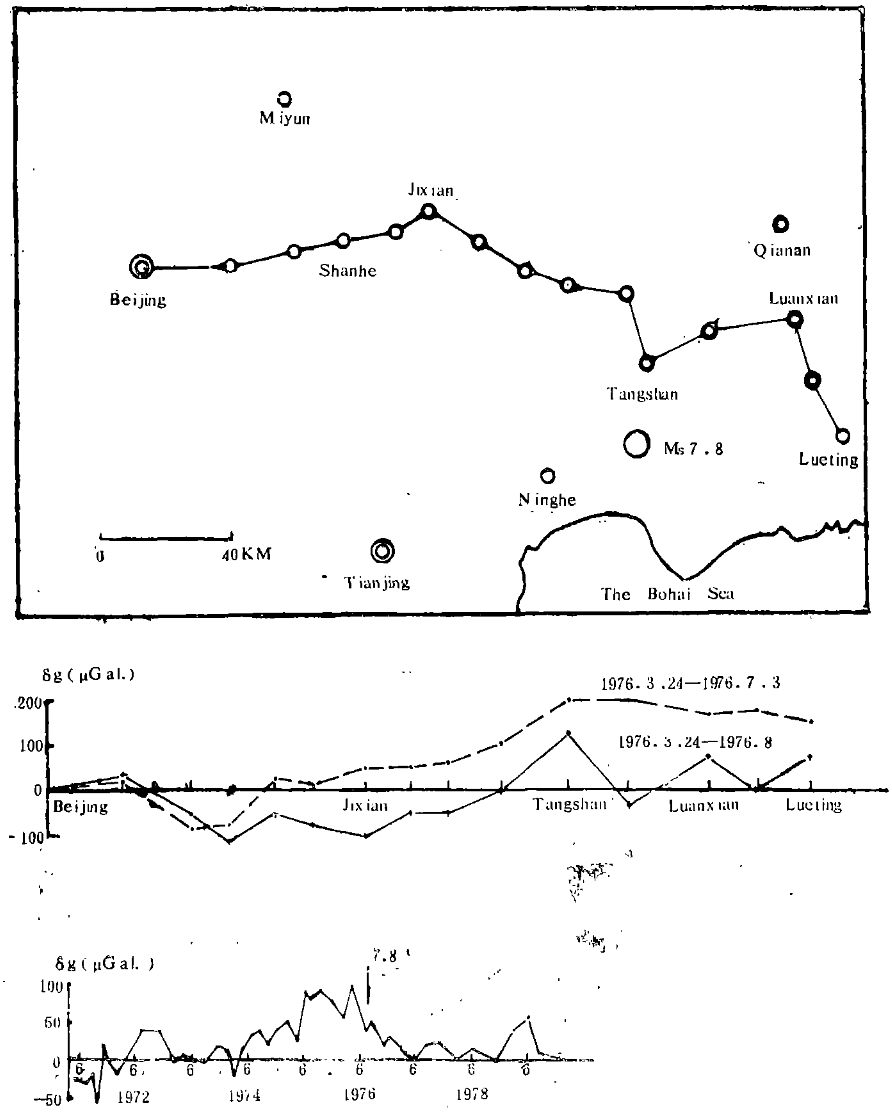

Fig. 9 Gravity changes before the Tangshan earthquake.

The synchronous changes in water temperature, water level and apparent resistivity at Changli station prior to the Tangshan earthquake appear to be consequence of upward heat fluid in the lower crust (Fig.10).

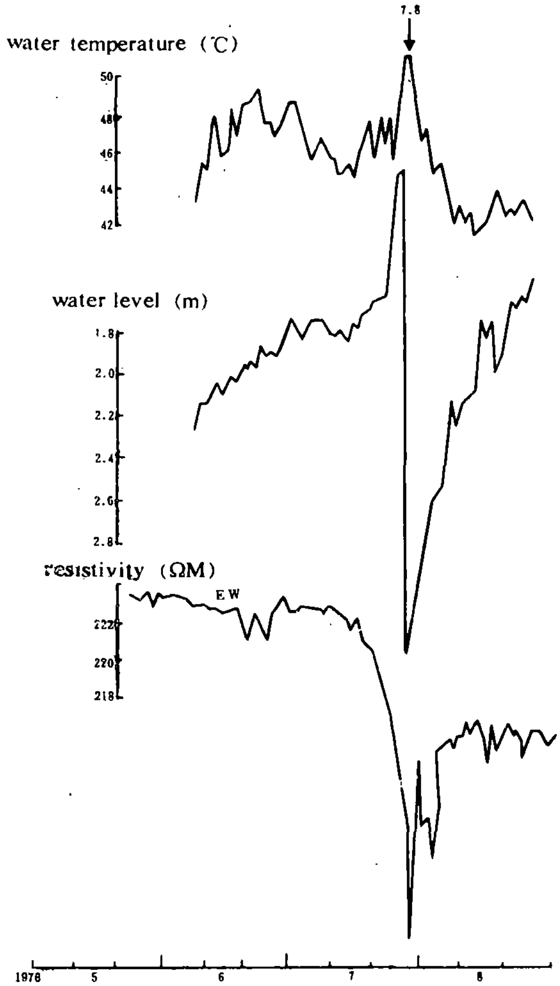

Fig.10 Changes in water temperature, water level and electric resistivity at Canglii mpending the Tangshan earthquake.

The changes in the spatial distribution of the earthquake $M_L \geqslant 4$ took place before the Tangshan earthquake (Fig.11). In fact, the distribution was somewhat disordered in 1970—1971, without the presence of a belt-like distribution. The earthquake $M_L \geqslant 4$ distributed regularly in two belt-like zones in 1972—1976. Between 1972 and the first half of 1973, the earthquake $M_L \geqslant 4$ occurred mainly on the WE belt. After that period, the earthquake activated frequently on the NE belt.The Tangshan earthquake is located just at the intersection of the two belts. The changes in seismicity pattern may show the evolution of stress field on a large scale.

By synthesizing the analysis in this section we can see that the precursors of the Tangshan earthquake were not caused by only one factor. Some of them may orignate from dilatancy in rock, some were probably

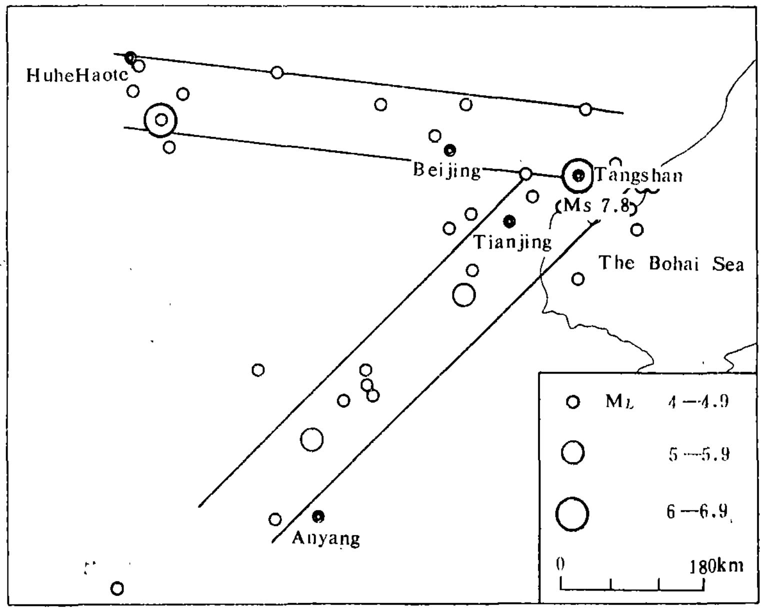

Fig.11 Distribution of $M_L \geqslant 4$ earthquakes in north China in 1972—1976.

due to the stable and/or quasi-stable sliding on weak or discontinuity surfaces and still some may reflect the evolution of stress field in a lahge area and the migration of deep mass. Therefore, when studying their internal relations, initiations, spatial distribution and manners of anomalies etc., we must distinguish the types of them. If we pay attention to this in detection and study of earthquake precursors, we would be greatly helped in realizing the regularities of precursors so as to promote the development of earthquake prediction.

It shows also that not all the anomalous changes prior to earthquake are signals from earthquake source. They contain the changes generated by the evolution of stress field on a large scale and the migration of deep mass. Although the latter is closely related to the former, the direct indications of the latter and the effects of the latter on the changes in medium property and local changes of stress field in source development region are two different concepts. For study on the process of earthquake source decelopment and the causes of earthquake, it is important to correctly distinguish the precursors and study their regularities.

Discussion on the Process of Earthquake Source Development

Considering that there are almost no observations to be available in the focal region before 1954, we divide the process of source development of the Tangshan earthquake after 1954 as follows.

1954—1967 is the period of elastic strain accumulation. No evident precursors appeared near the epicentral area in this period.

1968—1969 is the period of early dilatancy. This stage was characterized by anomalous ground uplift and decrease in ($\overline{V_P/V_S}$) in the epicentral region.

1970—1973 is the period of early evident fault creep. In this stage the slip occurred on the Tangshan fault and the Jiyunhe fault respectively. In accordance with the increase in gravity in and around the epicentral area after 1970, we can consider that the evident faulting in this period (aseismic slip or small earthquakes) might be related to the upward migration of mass from the depths to pores in the upper crust to cause increase in pore pressure and decrease in normal stress on fault surfaces.

Although the evident fault creep is a main characteristic of this stage, the stress varying with the fault creep could also result in the local dilatancy. This local dilatancy will be recovered with decrease of the stress. This idea is supported by the following observed facts. ($\overline{V_P/V_S}$) of a swarm of small earthquakes near Baodi was somewhat low in May, 1991-June, 1972. Not long after that, a group of small earthquakes, ($\overline{V_P/V_S}$) of which was low, occurred in east Baxian (Fig.12).

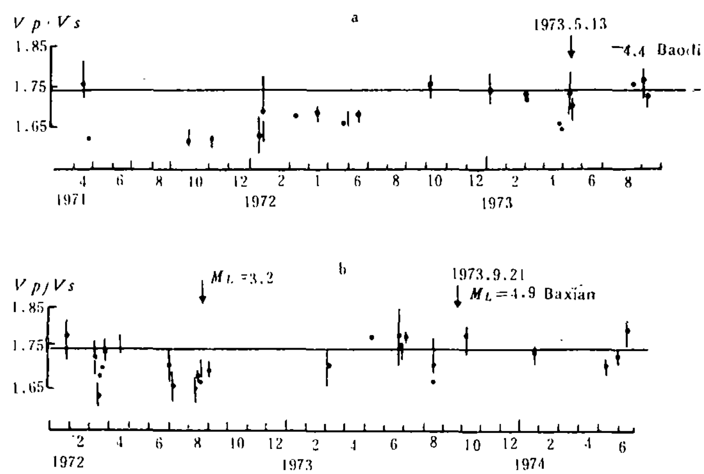

Fig.12　($\overline{V_P/V_S}$) changes with time in the Baodi and Baxian region.

On the basis of scanning results of the b-value, a zone, where the b-value is low, took form in Wenan after May, 1972 and it migrated gradually to Tangshan and its nearby areas along the Cangdong fault (Fig.13). It indicated a process that the stress in this region concentrated gradually to the focal region of the earthquake associated with the fault creep on the north part of the Cangdong fault.

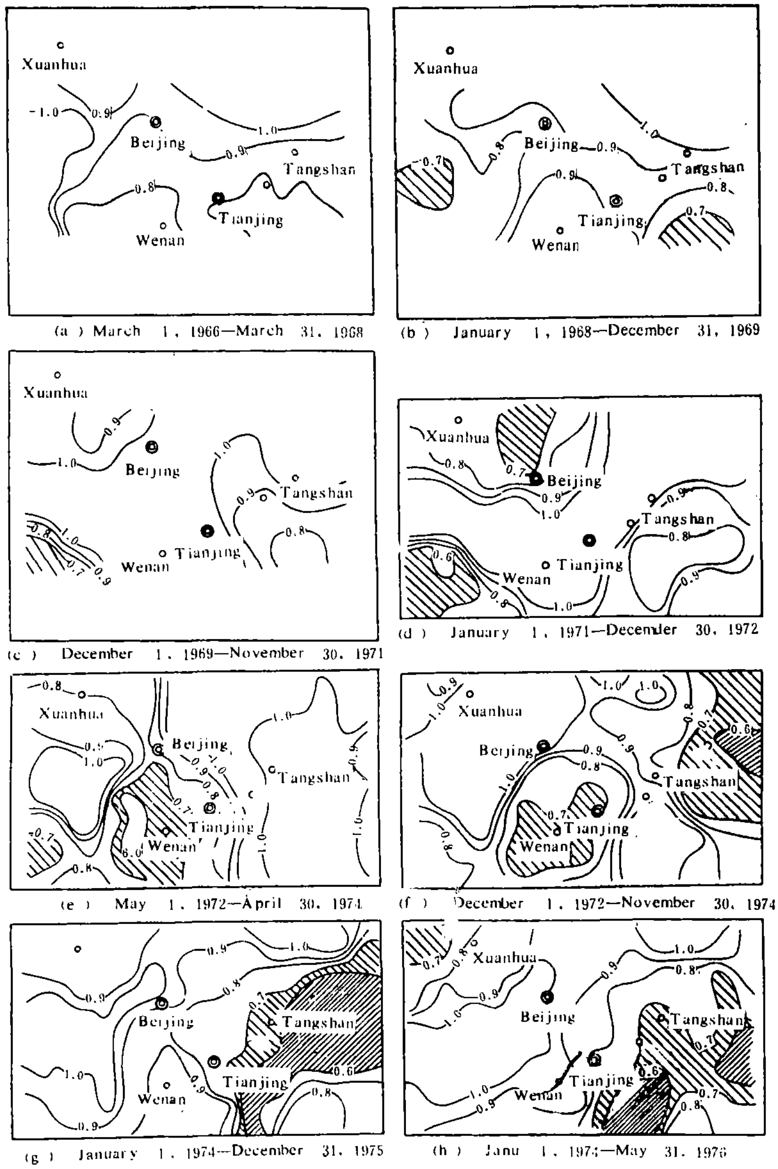

Fig.13 Spatial scanning of the b-value of the whole region in different periods.

The period from about the end of 1973 to the first half of 1975 is the stage of second dilatancy. The results of laboratory experiments suggest that, with a periodic loading, dilatancy can reoccur, and can be recovered, in hysteresis loops. Each loading cycle may produce more dilatancy than the previous one, and it may begin at a lower stress (Scholz et al., 1974). According to the foregoing analysis we can say that another dilatancy occurred in the focal region from about the end of 1973 to May, 1975 after the early dilatancy. Therefore, the various premonitory changes in patterns of seismic activities, ($\overline{V_P/V_S}$), land deformation, resistivity, radon emission and ground water level etc. in the focal region of the Tangshan earthquake and its surrounding area occurred (Fig. 4).

The period from the first half of 1975 to April, 1976 is the stage of second evident fault creep. In this stage, the significant anomalous changes in short leveling and ($\overline{V_P/V_S}$) also increased to its normal value or so. At the same time, the precursors of Type I such as resistivity, radon emission and water level underwent a turn or an acceleration (Fig. 4). it seems that dilatancy was recovered and the dilatant zones shrank with fault creep in this period.

About in April, 1976, the source development entered the stage of fault creep just prior to the earthquake. In this period, accelerated changes were found in observations on the crustal deformation at Ninghe station, which is in the aftershock region. The observed values of short leveling at this station changed 5 mm from September, 1975 to May, 1976, and increased again by 1 mm in June, 1976. It suggests that the fault creep accelerated. The accelerated fault creep may result in other phenomena occurring in this period, such as inclination of well wall, dislocation of cement pipe and eruption of disposal oil well. The development of this process led finally to the Tangshan earthpuake of July 26, 1976.

In summary, the process of source development of the Tangshan earthquake can be divided as follows: elastic strain accumulation (from 1954 to 1967) ; early inelastic dilation (from 1968 to 1969) ; early fault creep (from 1970 to 1973) ; the secood inelastic dilation (from the end of 1973 to the first half of 1975) ; the second evident fault creep (from the second half of 1975 to the end of April 1976); the fault creep just prior to the main shock (from the end of April 1976 to the occurrence of the Tangshan earthquake) etc.

Conclusions and Discussion

From the analyses in the above sections we can come to the following conclusions.

1. Dilatancy of rock mass and fault creep are considered as two basic physical processes in the DC model. The research results on the M=7.8 Tangshan earthquake correspond to the DC model. Just as that the process of source development of the Tangshan earthquake shows, fault creep may intermittently occur and dilatancy may repeat, thus resulting in a complicated process of source development of a strong earthquake.

2. The precursors of the Tangshan earthquake were not caused by only

ene factor. Some of them may result from inelastic dilatancy, some may be causally related to fault creep and still some reflected the process of evolution of stress field on a large scale and migration of dfep mass. There fore, studying their relations, initiations, spatial distribution and manners etc., we must distinguish their types.

3. Repeated dilatancy, discontinuous fault creep, effects of upward migration of deep mass and complex distribution of dilatancy and creep will result in some troubles in determining precursor time, spatial distribution and manners, and will also bring about great difficulties to valid earthquake prediction. Therefore, for successful prediction of earthquake, there is still a long way to go.

4. In the process of source development of the Tangshan earthquake, the upward migration of deep mass may occur in the epicentral region. The preparatory process of the Tangshan earthquake may be controlled jointly by the upward migration of deep mass and intraplate stress field on large scale. This characteristic is probably different from that of strong earthquake along plate boundary.

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