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ACCELERATED SYNERGISM ALONG A FAULT: A POSSIBLE INDICATOR FOR AN IMPENDING MAJOR EARTHQUAKE

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Abstract: It is generally accepted that crustal earthquakes are caused by sudden displacement along faults, which rely on two primary conditions. One is that the fault has a high degree of synergism, so that once the stress threshold is reached, fault segments can be connected rapidly to facilitate fast slip of longer fault sections. The other is sufficient strain accumulated at some portions of the fault which can overcome resistance to slip of the high-strength portions of the fault. Investigations to such processes would help explore how to detect short-term and impending precursors prior to earthquakes. A simulation study on instability of a straight fault is conducted in the laboratory. From curves of stress variations, the stress state of the specimen is recognized and the meta-instability stage is identified. By comparison of the observational information from the press machine and physical parameters of the fields on the sample, this work reveals differences of temporal-spatial evolution processes of fault stress in the stages of stress deviating from linearity and meta-instability. The results show that due to interaction between distinct portions of the fault, their independent activities turn gradually into a synergetic activity, and the degree of such synergism is an indicator for the stress state of the fault. This synergetic process of fault activity includes three stages: generation, expansion and increase amount of strain release patches, and connection between them.. The first stage begins when the stress curve deviates from linearity, different strain variations occur at every portions of the fault, resulting in isolated areas of stress release and strain accumulation. The second stage is associated with quasi-static instability of the early meta-instability when isolated strain release areas of the fault increase and stable expansion proceeds. And the third stage corresponds to the late meta-instability, i.e. quasi-dynamic instability as both the expansion of strain release areas and rise of strain level of strain accumulation areas are accelerated. The synergism is accelerated when the quasi-static expansion transforms into quasi-dynamic expansion, with interaction between fault segments as its mechanism. The essence of such transformation is that the expansion mechanism has changed, i.e. expansion of isolated fault segments is replaced by linkage of the interacting segments when the fault enters the critical state of a potential earthquake. Based on the experimental results, coupled with data on the temporal-spatial evolution of earthquakes along the Laohushan-Maomaoshan fault, west of the Haiyuan fault zone in northwestern China, the synergism process of this fault before the 6 June 2000 *M*6.2 earthquake is analyzed.

Key words: meta-instability stress state, accelerated synergism, information indicative of sure earthquake occurrence, short-term and impending precursor.

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УСКОРЕННЫЙ СИНЕРГИЗМ ВДОЛЬ РАЗЛОМА: ВОЗМОЖНЫЙ ИНДИКАТОР НЕИЗБЕЖНОГО КРУПНОГО ЗЕМЛЕТРЯСЕНИЯ

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Аннотация: Обычно принято считать, что причиной землетрясений земной коры является внезапное смещение вдоль разлома при наличии двух основных условий. Первое условие связано с высоким синергизмом разлома, когда при достижении предельного уровня напряжений отдельные участки разлома очень быстро соединяются друг с другом, способствуя быстрому смещению более длинных участков данного разлома. Второе условие заключается в значительном напряжении, накопленном на отдельных участках разлома, при котором может быть преодолено сопротивление смещению высокопрочных участков разлома. Исследование таких процессов может помочь в выявлении краткосрочных неизбежных предвестников, проявляющихся перед землетрясениями. В лабораторных условиях проводится моделирование состояния нестабильности прямого разлома. Полученные кривые вариаций напряжений позволили установить состояния напряжений модели и выявить стадию метанестабильности. В данной работе проведено сравнение данных, полученных путем наблюдения процесса на модельной установке, с физическими параметрами полей образца и выявлены различия процессов пространственно-временного развития разломных напряжений по стадиям, когда отмечены отклонения напряжений от линейности и метанестабильности. Результаты исследования показали, что вследствие взаимодействия отдельных участков разлома их независимая активность постепенно переходит в синергетическую активность, и такой синергизм является показателем состояния напряжений разлома. Процесс синергетической активности разлома проходит три стадии развития: возникновение небольших участков, где высвобождаются напряжения, расширение и увеличение размеров таких участков высвобождения напряжений и соединение участков, где идет высвобождение напряжений. Первая стадия начинается, когда кривая напряжений отклоняется от линейности, при этом на каждом участке разлома имеют место вариации напряжений, в результате чего появляются отдельные изолированные участки, где происходит высвобождение и накопление напряжений. Вторая стадия связана с квазистатической нестабильностью ранней метанестабильности, когда отдельные участки разлома, где идет высвобождение напряжений, увеличиваются в размерах и продолжается их стабильное расширение. Третья стадия соответствует поздней метанестабильности, т.е. квазидинамической нестабильности, поскольку ускоряются как расширение участков высвобождения напряжений, так и усиление уровня напряжений на участках накопления напряжений. Синергизм ускоряется, когда квазистатические трансформации переходят в квазидинамическое расширение, при этом действует механизм взаимодействия между участками разлома. Суть такой трансформации заключается в изменении механизма расширения участков – расширение изолированных участков разлома сменяется на слияние таких участков при их взаимодействии, когда разлом входит в критическую стадию потенциального землетрясения. На основе данных, полученных экспериментальным путем и дополненных информацией о пространственно-временной эволюции землетрясений вдоль разлома Лаохушан-Маомаошан в западной части разломной зоны Хайюань в Северо-Восточном Китае, проанализирован процесс синергизма данного разлома перед землетрясением магнитудой 6.2, которое произошло 6 июня 2000 г.

Ключевые слова: метанестабильность, состояние напряжений, ускоренный синергизм, информация, свидетельствующая о неизбежном наступлении землетрясения, краткосрочный неизбежный предвестник.

1. Introduction

In recent years, due to disaster threat on human caused by major earthquakes, it is increasingly desired that scientists should offer definite information on seismic hazard to public. However, it is often noted that “the predicted quake is reluctant to come, while unexpected seismic events caught Earth scientists off guard” [*Zhang Guomin, 2013*]. For example, after the December 2004 Sumatra *Mw*9.1 earthquake, China Earthquake Administration held a meeting on future earthquake trends in mainland China in early 2005, and all the researchers attending the meeting accepted that major events would occur on the North-South seismic zone in central China in view of the geodynamic context. Intensified studies and monitoring were conducted along this potentially hazardous zone. But such expected shocks did not happen in the following three years. Another regular meeting of the Administration was held in early 2008, when some people began to doubt the previous prediction and thought that an expected major event was unlikely to occur in the near future. Unfortunately, several months later, the 12 May 2008 Wenchuan *M*s8.0 (*M*w7.9) earthquake hit Longmenshan, the central part of this zone. Among the complicated reasons for this failure in the effort of earthquake prediction, one is that the experts usually provide answers as “possible or impossible” rather than “yes or no”, i.e. cannot determine which fault will surely generate a major quake, or what time such predicted events will take place given its location and magnitude can be estimated in advance.

Actually, people know little about regularities of earthquakes as seismology is a young science. During the past nearly 30 years, models of quasi-periodicity and characteristic earthquakes for some faults were suggested [*Fedotov, 1968; Sykes, 1971; Shimazaki, Nakata, 1980; Nishenko, 1991*] and served as a primary basis for long-term earthquake prediction, i.e. forecasting the occurrence time of an event in the future. The actual events did not, however, coincide with the expected cases. For instance, *M*7 events occurred at Tokai, Japan in 1707 and 1845, respectively, showing an interval 138 years. Following the assumed recurrence model, in 1978 Japanese scientists inferred that a *M*7 or greater shock should occur at any time in Tokai [*Mogi, 1981; Matsumura, 1997; Science…, 2007*]. In fact such an event, however, did not appear by now more than 30 years since then. In the Parkfield area, California, US, six *M*6 events were recorded with a maximum interval 38 years and minimum 12 years, 22 years on average or largest variation +45 % ~ –72 % [*Schwartz, Coppersmith, 1984; Bakun, Lindh, 1985; Shearer, 1958; Ben-Zion et al., 1993*]. This observation led to the characteristic earthquake model and a forecast in 1984 that claimed a *M*6 shock would happen in Parkfield before the year 1993. In fact, such an event did not come till 2004, implying an error as big as 11 years. So many similar examples reveal such a common truth that the prediction of the occurrence time for a future quake based on quasi-periodicity has a large uncertainty, although it can help estimate the earthquake trend for a long-term period. Laboratory research shows that in the same conditions, including driving force, loading rate, fault plane and experimental sample, the yielded quasi-periodicity of fault stick-slip has errors 5~11 %, which corresponds to errors 15~33 years for a 300-year cycle in nature. In fact, recurrence intervals of earthquakes are affected by many factors, of which the most important is that a fault is not an isolated existence, instead merely a boundary of a block, so its motion is jointly controlled by other boundaries of the block. For crustal motion, such errors are tiny, while too big to be acceptable for hazard reduction in human society, much less the errors in nature should exceed far more than that in the laboratory.

With hindsight to previous earthquakes, it was stated that some abnormal phenomena appeared before earthquakes, which were summarized as “seismic precursors”. Unfortunately, such claimed precursors did not occur in subsequent events, instead other distinct phenomena were observed. Is it possible to find out diagnostic precursors that are bound to appear prior to earthquakes? To answer this question, much effort was invested in studies involving many observational items such as crustal deformation, underground water, seismicity, geomagnetism, geoelectricity, and gravity. But the diagnostic precursors that have been rigorously confirmed are quite a few [*Wyss, 1991, 1997; Cicerone et al., 2009; Chen, 2009; Johnson, 2009; Beroza, Ide, 2009*]. The possible seismic precursors that can appear at one place are associated with geological setting and stress field conditions there. From other angle of view, the stress field will change correspondingly after a major earthquake takes place on a fault, so that the next event on the same site may be different from the last one. Probably this is just one of the reasons why the search for diagnostic precursors is highly challenging. “In spite of extreme difficulties in earthquake prediction, people do not stop or give up their efforts toward this goal” [*Chen, 2009*].

It is widely accepted that earthquake prediction can be made in long-, intermediate-, and short-term and impending time scales. It is, however, not clear how to define such scales using a certain criterion. As different faults have their specific recurrence intervals, they can have different behaviors in the same time scale. In laboratory observations, on a stress-strain curve, the meta-instability stage begins from the peak stress point and ends at the instability point, which is the key period prior to the fault rupture [*Ma Jin et al., 2012*]. For some faults with long recurrence intervals, the meta-instability stage can exceed one year; while for other faults with very short recurrence intervals, one year may account for 1~10 % of the interval which contains the stages of stress deviating from linearity and meta-instability as well as the transform process into instability. Therefore, it is more reasonable to study the seismic risk of a fault from its stress state than from its time scale. The key problem is how to link the field information with the critical moments during the stress-strain process in time.

The laboratory research has such an advantage that information from the press machine can be compared with observed information of physical quantities of a field, which allows us to find out the features of the meta-instability stage from observations of multiple physical fields. Following this approach, we have conducted observational studies on temperature, fault slip and strain fields in the laboratory. Several individual experiments [*Ma Jin et al., 2012; Zhuo Yanqun et al., 2013; Ren Yaqiong et al., 2013; Liu Yuanzheng et al., 2014*] show that like specimen analysis, description of the regional overall stress state should not be based on data from single stations, instead the overall evolution of the deformation field should be considered. The instable slip of a fault is a transform process from independent activity of each fault part into synergism activity of all parts of the fault. When such synergism reaches a certain degree, the fault enters the meta-instability stage. Meanwhile deviating of the stress-time curve from linearity marks the start of stress release. From this moment, isolated weakening patches begin to appear on the fault and increase gradually. In the meta-instability stage of the fault, stress release becomes gradually dominant, and synergism is accelerated and tends to be completed.

The precursor prior to the impending instability is one of the target issues in earthquake research. The laboratory studies mentioned above are of importance for understanding mechanisms of faults and earthquakes as well as seismic precursors. When the stress-strain curve deviates from linearity, stress release on the fault begins and increases with time gradually. The key issues include how to recognize characters of stress release in different deformation stages, how to determine the information indicating that the earthquake is inevitable, and how to combine these research results with data on real seismic precursors. In the following sections of this paper, these issues are addressed based on our laboratory experiments and field observations.

2. Experimental conditions

Experimental specimen and arrangement of measurement sites: The experimental specimen is a 300 mm × × 300 mm × 50 mm granodiorite from Fangshan district, Beijing. It is cut along the diagonal to simulate a straight fault plane. Thirty strain gauges are stuck nearby along the

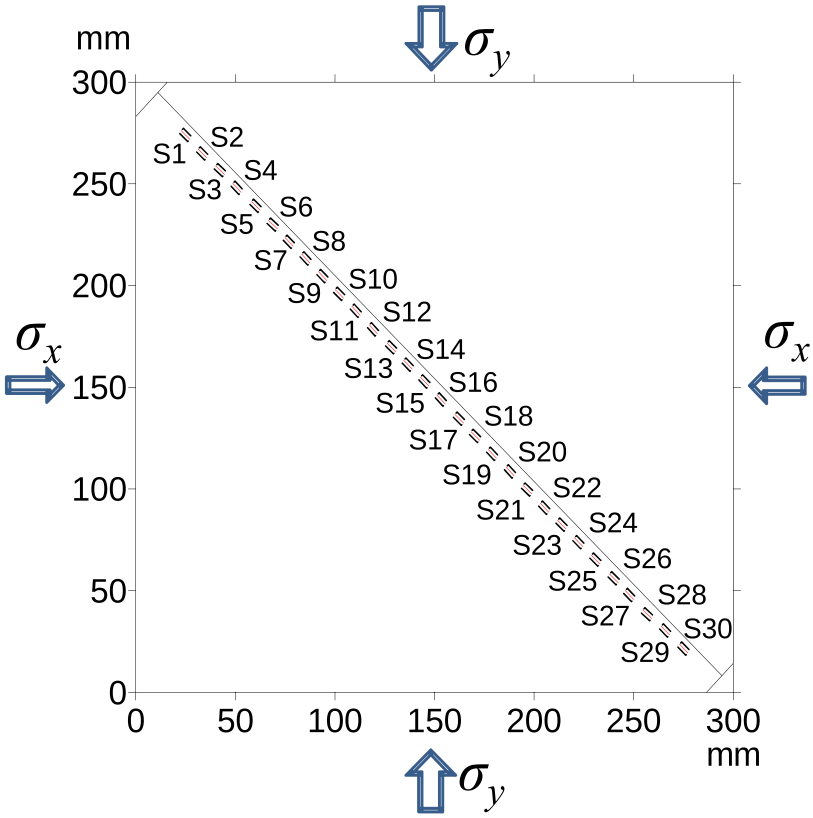

Fig. 1. Specimen structure, loading directions and arrangement of strain gauges.

Small black-and-red boxes along fault denote strain gauges. Black numbers S1 to S30 are serial numbers of strain measurement points.

Рис. 1. Структура модели, направления приложения нагрузки и расположение датчиков напряжений.

Датчики напряжений, установленные вдоль разлома, показаны как черные прямоугольники с красной полосой. Номера S1-S30 означают серийные номера точек замера напряжений.

fault to measure variations of the strain field (Fig. 1), which have resolution 1 με and a sampling rate 100 Hz. These measurements enable us to analyze the temporal-spatial process of strain nearby the fault prior to its instability. We define that shortening (compressive strain) and elongation (extensional strain) of gauges are positive and negative values, respectively.

Loading conditions: Experiments are conducted on a dual-direction servo press machine, of which pressure and displacement are controllable. During tests, a constant pressure (5 *MP*a) is applied in X direction and controllable displacement at a constant rate (0.1 $\mu m/s$) is applied in Y direction. As the included angle between the fault trend and the loading direction is 45°, an average shear stress on the fault is

$$\tau = \frac{\sigma_y - \sigma_x}{2},$$

where τ is an average shear stress on the fault plane, σ_y and σ_x are average stresses at either end of Y and X directions, respectively.

Measurements during tests on the press machine yield data on the average shear stress-time process of the fault (lower right in Fig. 2). An enlarged curve of its last stage is given below to show details of its deformation from the time 660s to 700s (Fig. 2), on which point O is stress peak, N-O denotes the stage seriously deviating from linearity, OAB_2 is the meta-instability stage of which OA is quasi-static release stage, AB_2 is quasi-dynamic release stage, and B_2 marks the beginning of real instability.

3. Features of strain variations along the fault in meta-instability stage

The curve of average shear stress with time (Fig. 2) illustrates several critical moments, N, O, A, B_1 and B_2, of deformation on the specimen. It is noted that this curve based on data from the press machine represents variations of all portions of the whole fault, while each site records strain processes of different portions. Below we analyze strain measurements of different sites at the critical moments on the curve of the average shear stress versus time.

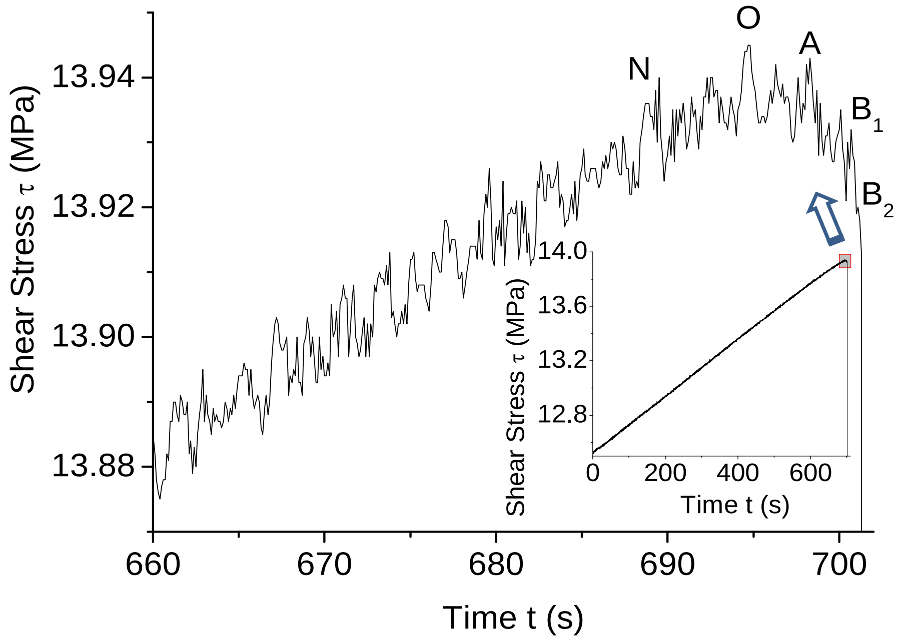

Fig. 2. Curve of mean shear stress versus time (lower right) and enlarged view of the final stage (small red box with blue arrow above).

Letters denote moments of significant deformation. See text for detail.

Рис. 2. Кривая среднего напряжения сдвига относительно времени (график в нижнем правом углу) и увеличенный график последней стадии (красный квадрат с голубой стрелкой в верхней части графика).

Буквами обозначены моменты значительной деформации (см. пояснения в тексте).

Overall, all site strains (hereafter abbreviated as SS) along the fault accumulate in the beginning stage (positive, compression). After the average shear stress-time curve deviates from linearity (about 500 s), strain variations at different sites begin to diverge. Some sites are of accelerated compression, while other portions turn into relaxation (negative, extension). Their variation amplitudes range from 0 to 65 με. Profound differences among the sites appear relatively later. After ~660 s, the stress-time curve is in proximity to serious deviation from linearity. Therefore, the strain value at moment 660 s is set to be zero to highlight variations of strain increments of different portions of the fault in the meta-instability stage.

After moment 660 s, strains of all portions along the fault can be observed in 4 segments: sites 1 to 8, 21 to 24, 9 to 19, and 25 to 30. In terms of similarity, sites 1 to 8 and 21 to 24 are in one category, and sites 9 to 19 and 25 to 30 are in another category.

In the upper segment of the fault (sites 1 to 8), compression strain is observed as slowly increasing and accelerating; then it rises up suddenly, and this sudden increase is followed by inversion and final instability (Fig. 3, *a*). Specifically, as shown by curves 6 and 7, compression rates increase at moment N, and continue increasing further at moment O. At moment A, the distance between curves 4 and 5 reduces. At moment B, curves 1, 2, and 3 all rise nearly vertically. By moment B_2, curves of all sites exhibit instability with large stress drops, of which instability of sites 1 and 2 is behind that of sites 4 and 5 by about 0.2~0.3 s with small stress drops. As sites 6 and 7 begin to release strain, strain accumulation at sites 4 and 5 accelerates. And when site 5 turns into strain release, strain accumulation at sites 2, 3, and 4 speeds up. These processes imply that compressive strain between the sites propagates along the fault at a rate that accelerates after the stress peak (see Fig. 3, *a*).

On the middle segment of the fault (sites 9 to 19) (Fig. 3, *b*), strains rise (sites 9 to 13) or are stationary (sites 14 to 19); then they drop slowly, invert, rise fast close to instability, and finally reach complete instability (except site 19). At moment N, when deviating from linearity, compression strain accumulation on sites 9 to 13 changes into strain release. More sites experience strain drops at moment O. Moment A is the time that many sites begin to speed up their strain release, among which site 19 is most obvious. By moment B_1, strain on most of the sites, except site 19, lowers to the minimum and then rises again. And after the culminating moments, the sites enter instability state (see Fig. 3, *b*).

The lower segment of the fault can be subdivided further into upper and lower parts. In the lower part, i.e. sites 25 to 30, strain declines steadily and does not recover till

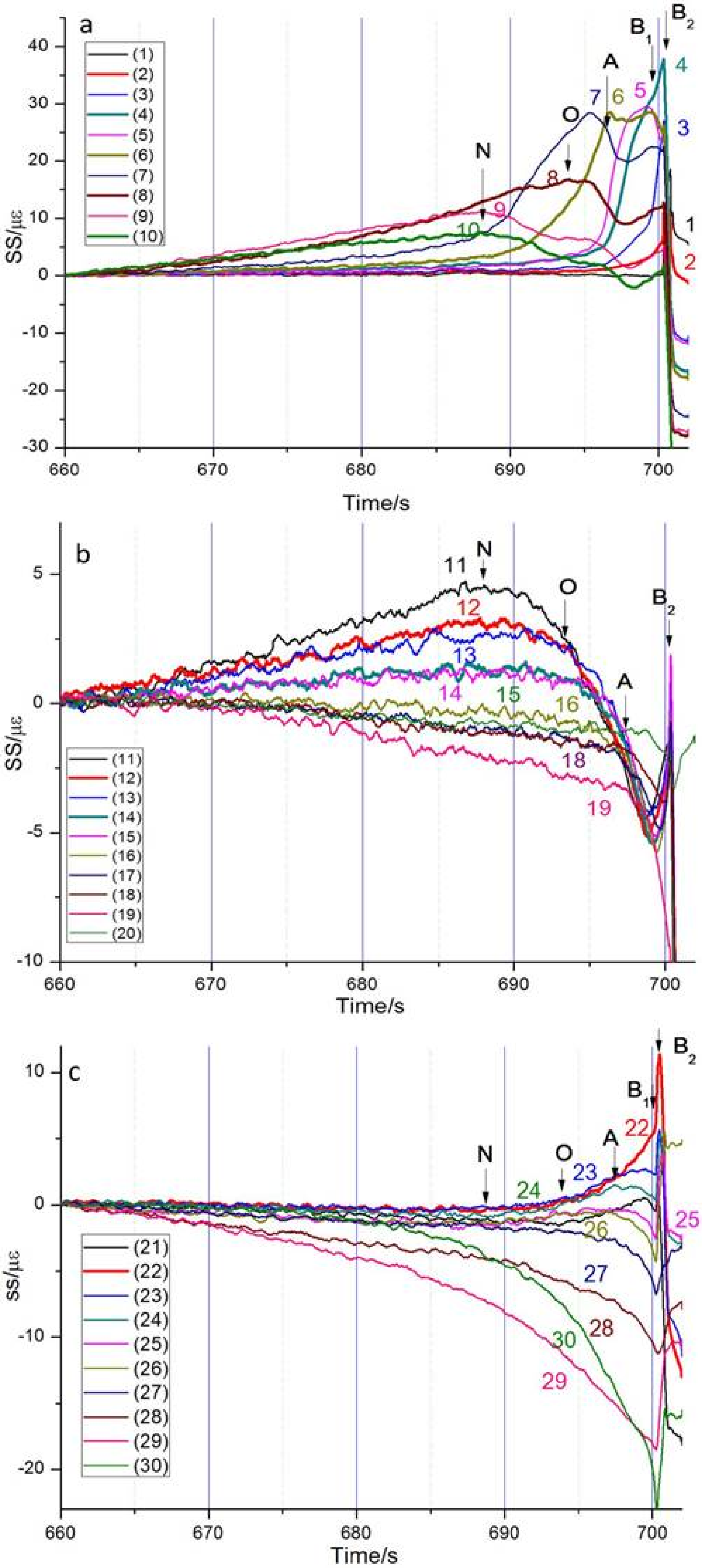

Fig. 3. Variations of strain increments (SS) along fault after moment 660s with time at points in the upper (*a*), middle (*b*) and lower segment (*c*).

Numerals above each curve denote measurement sites. Letters are moments.

Рис. 3. Изменения прироста напряжений (SS) вдоль разлома после 660-й секунды с течением времени в точках на верхнем (*a*), среднем (*b*) и нижнем участках разлома (*c*).

Цифры на каждой кривой означают участки, где производились замеры. Буквами обозначены моменты значительной деформации.

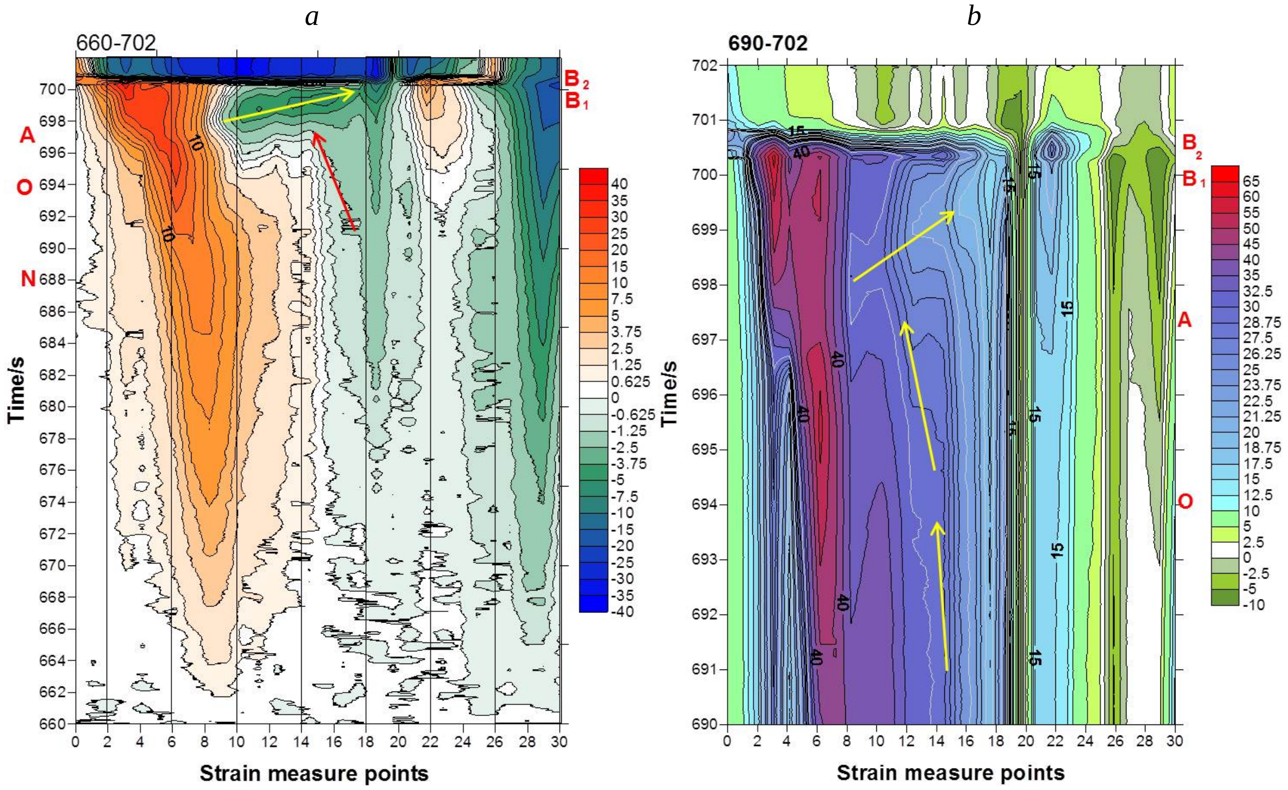

Fig. 4. Variations of strains (SS) at points along the fault in the time intervals 660–702 s (*a*) and 690–702 s (*b*).

Рис. 4. Вариации напряжений (SS) на точках вдоль разлома с течением времени в периоды с 660 по 702 сек. (*а*) и с 690 по 702 сек. (*b*).

instability. Strain of sites 20 to 24 of the upper part, like that of the upper segment (sites 1 to 8), rises slowly, and this increase is followed by slow decline, then sudden rise and abrupt drop take place, in which the amplitude of decline is larger than that of rise (Fig. 3, *c*).

Before instability, amplitudes of strain variations differ in the specified segments of the fault. They are the largest in the upper segment, up to 37 με. The rise amount of the upper part of the lower segment is comparable with maximum 12 με, and decline amplitude of the lower segment is also relatively large with maximum –25 με. Such amplitude of the middle segment is the least, merely 5~6 με for both rise and decline. The sequences of strain variations between the neighboring sites are also variable in the specified segments of the fault. At the early time, increasing compression is observed on all the sites. When deformation intensifies to some degree, differential variations appear on the fault.

4. Strain synergistic process of the meta-instability stage

As evidenced by our laboratory observations and analyses, it is difficult to recognize the stress state of the whole fault from strain processes of its single sites. Variations of the stress state of the fault can be more clearly revealed by integral observation of all the segments of the fault.

In the time interval from 660 s to702 s, sites 26 to 30 of the lower segment are the earliest to start strain release (665 s) (Fig. 4, *a*). This process firstly begins on sites 29 and 30, propagating leftward to site 26. With more release, its range also expands gradually (1.25 mm/s). Meanwhile, the upper segment, centered at site 8, starts to accumulate compressive strain. With increasing accumulation degree, the compressive area expands firstly and reduces afterwards, with gradual leftward shift of the compressive center (1.34 mm/s). Afterwards, the second strain release area appears on site 19 of the middle part of the fault. And from moment N, its range also expands toward the left (2.47 mm/s). From moment O, onsite 10 in the previous strain accumulation area, compression is replaced by extension, implying one more strain release areas. At moment A, this new area expands to the right rapidly (74.1 mm/s) and links with the strain release area centered by site 19. Meanwhile, the earliest strain release areas centered by sites 29 and 30 also expand at moment A. With a further increase of compressive strain, the compression center migrates from site 8 to the left, rapidly reaching sites 5, 6, and 7, and, finally, instability occurs at these sites.

It is clear that as early as the stress curve deviating from linearity, slow release of local strain begins. At mo-

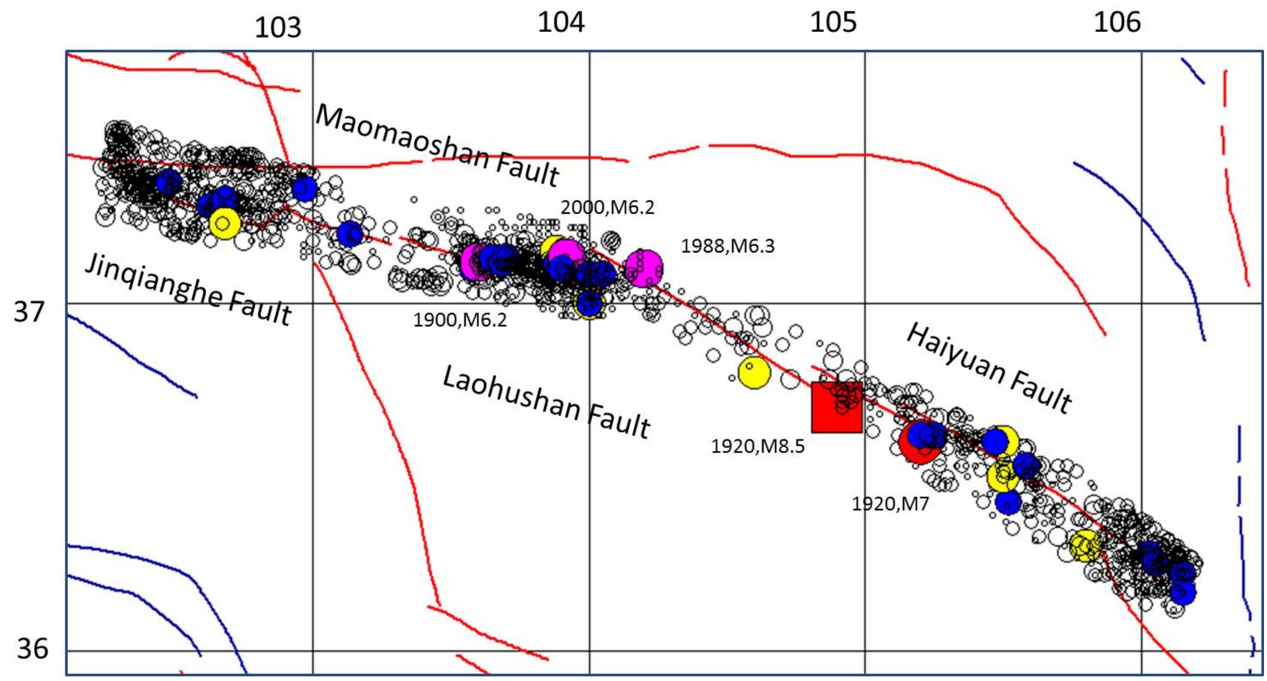

Fig. 5. Laohushan-Maomaoshan fault and distribution of earthquakes since 1920.

Red square is the 1920 Haiyuan *M*8.5 earthquake. Pink, yellow, blue, and red circles show locations of *M*6, *M*5, *M4* and smaller events.

Рис. 5. Разлом Лаохушан-Маомаошан и распределение землетрясений после 1920 г.

Красный квадрат – землетрясение Хайюань магнитудой 8.5, произошедшее в 1920 г. Точки розового, желтого, голубого и красного цвета – землетрясения магнитудой 6, 5, 4 и более слабые.

ment N, when the curve deviates more from linearity, strain release areas increase gradually. From moment O, the strain release areas start to expand. Such a process accelerates at moment A, leading to linkage of the release areas. By this time, instability is irreversible.

We use the term 'synergism' to denote the phenomenon comprising expansion of the strain release areas on the fault and their linkage with each other. The occurrence and increase of such areas indicate that the fault begins to release strain. Their expansion represents the start of the fault's synergistic process. And the accelerated synergism marks that the fault enters the quasi-dynamic meta-instability stage, which is also an indicator that an earthquake is inevitable.

5. Testing the field case

As stated above, the laboratory experiments of faulting reveal a synergistic process including expansion, accelerated expansion and linkage of strain release areas. It is derived from strain measurements in the laboratory conditions that instability slip occurs on a strike-slip fault simulated by a cut rock specimen. The Laohushan-Maomaoshan fault, being a part of the Haiyuan fault zone, is a strike-slip fracture whereat an *M*6.2 earthquake took place on 6 June 2000. Here we attempt to review and analyze small quakes before the major event to explore the synergistic process of this fault.

The Haiyuan fault zone is a large-scale strike-slip structure located west of the Ordos block. It comprises nine fault segments in the NW direction. It can be subdivided into three sections that differ in terms of active behaviors and geomorphology [*The Haiyuan fault zone, 1990*; *Zhang et al., 2005*]. Of them the middle and western sections are left lateral strike-slip, and the eastern section is left-slip with thrust component. The 16 December 1920 *M*8.5 earthquake ruptured the middle section. In the same month, an *M*5 event occurred at Baiying northwest of Haiyuan, followed by a *M7* shock in southeast. Another group of faults arranged in a left step manner is located west of the Haiyuan fault zone, nearby Jingtai (Fig. 5). It includes Laohushan, Maomaoshan, and Jinqianghe faults that are reviewed below as comprising the Laohushan-Maomaoshan fault zone. These faults are striking nearly east-west, with an included angle about 5° with respect to the Haiyuan fault zone, and also a left-step pattern with a 10 km distance between fault ends parallel and perpendicular to the overall strike. In view of their proximity to the Haiyuan fault zone (also left slip), the impact of the 1920 Haiyuanmajor earthquake on the Laohushan-Maomaoshan fault zone and its seismic hazard are issues of high concern.

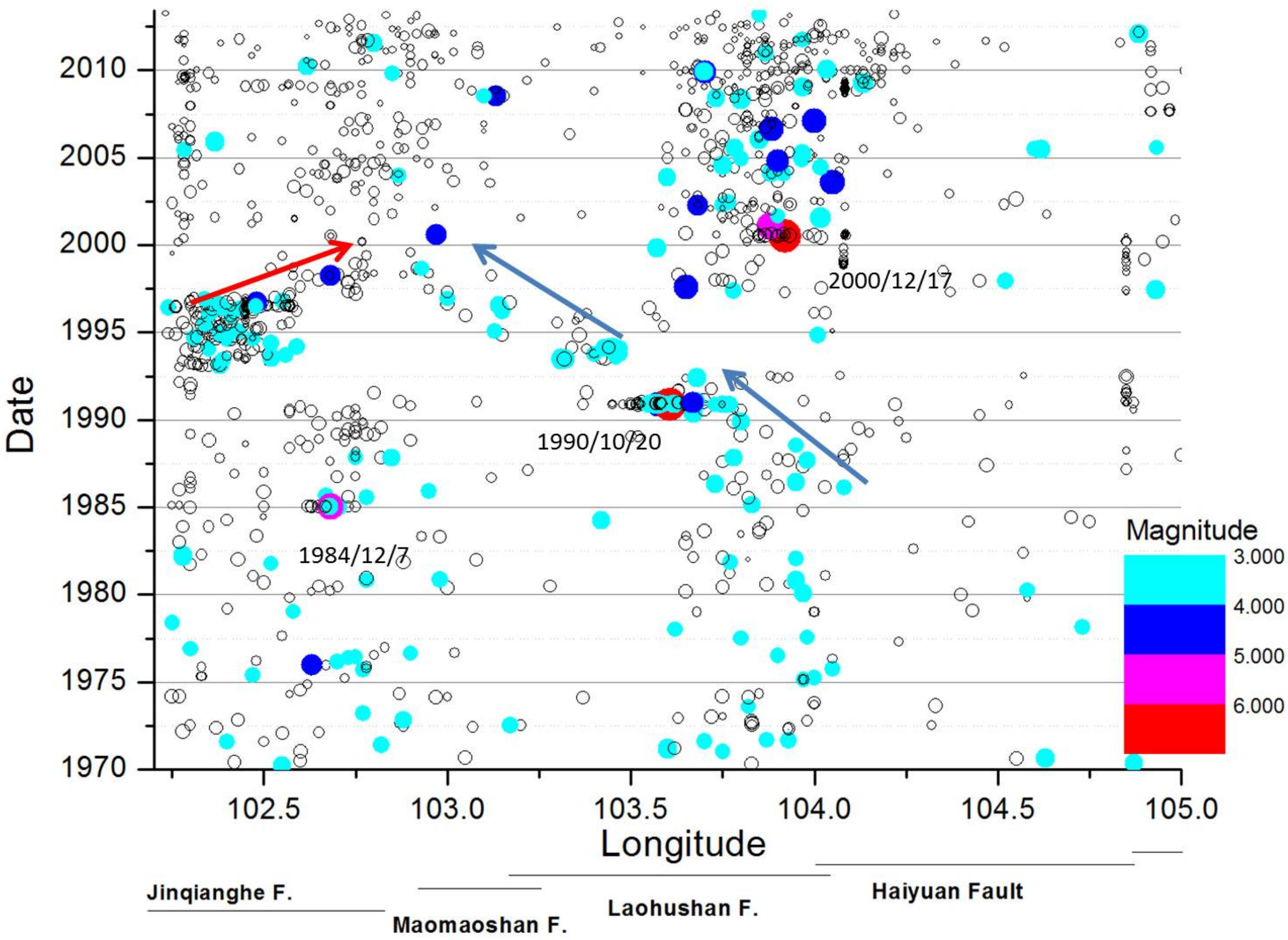

Fig. 6. Temporal-spatial distribution of earthquakes along Laohushan-Maomaoshan fault zone.

Red, rose, dark blue, cyan and open circles denote *M*6, *M*5, *M*4, *M*3 and smaller earthquakes, respectively.

Рис. 6. Пространственно-временное распределение землетрясений вдоль разломной зоны Лаохушан-Маомаошан.

Точки красного, розового, темно-синего, голубого и белого цвета – землетрясения магнитудой 6, 5, 4, 3 и более слабые, соответственно.

Seismic activity of the Laohushan-Maomaoshan fault zone in the period from 1920 to 1958 is unknown as earthquake records are lacking. From 1959 to 1961, three *M*5 events occurred at the extensional jog area of the right part of the fault zone. As the earthquake catalogue since 1970 is continuous and complete, the following analysis is primarily based on this dataset. From 1960, both the Haiyuan and Laohushan-Maomaoshan fault zones were characterized by moderate seismic activity, except two *M*6.2 events in 1990 and 2000, respectively. In the period from 1970 to 1990, seismic activity of this region gradually increased, while after 2000, it continued to decline. The relatively active period started with the *M*5.1 event at the Jinqianghe fault on 7 December 1984; afterwards, moderate-size events migrated from west to east. A seismic swarm with maximum *M*6.2 occurred in the Laohushan fault zone on 20 October 1990. Afterwards, *M*6.2 and *M*5.2 took place in the jog area of the right side of the Laohushan fault on 6 June 2000 and 27 December 2000, respectively, in addition to several *M*4 events during the same period. And since 2000, seismicity of this region turned into decline.

The temporal-spatial migration of epicenters (Fig. 6) shows low seismicity along the Haiyuan fault zone, while seismicity at the Laohushan fault and in the jog area eastward of the fault was relatively active in the decade of 1990–2000. Before and after this period, frequent seismic events took place at same locations, very few migrating along the fault, which is indicative of independent activity of individual fault segments. But close to the relatively active period of seismicity, especially before the 2000 *M*6.2 event in the extensional jog area, there was a synergistic process of fault activity. Around 1990, an *M*3 earthquake belt (shown in cyan in Fig. 6) propagated from southeast (Laohushan) toward northwest with time. After 1997, an *M*3 and *M*4 belt striking from west to east appeared at the Jinqianghe fault; its pattern of epicenters was dense. Thus, activity along the Maomaoshan-Laohushan fault entered the synergistic state, which provided the instability condition for a strong earthquake, and the *M*6.2 event occurred on 6 June 2000. After this earthquake, the activity level of the jog area east of Laohushan became relatively higher. It can be inferred that the synergism, that propagated westward at a stable rate along the Laohushan-Maomaoshan fault, commenced earlier and was accelerated by the eastward propagation of seismic activity at the Jinqianghe fault after 1996. As a consequence, the *M*6.2 earthquake occurred on 27 December 2000. This process is very similar to the strain variations prior to instability which were observed in the laboratory studies described above.

6. Discussion

1. One of most profound characters of faults is complexity of their geometry and heterogeneity and anisotropy of rock as their host media, which yields the complex mechanic nature of faults at any scale [*Konca et al., 2008*]. Like other materials, rocks obey laws of mechanics, but exhibit highly variable behaviors [*Jaeger, Cook, 1979*]. Usually, in a non-uniform medium, a fault consists of relatively weak and strong segments. Under stress, its weak segments are first to become area of strain release, while its strong segments accumulate strain and, finally, become the areas where instability starts fast. Nucleation of a fault might begin by connection of multiple points, rather than necessarily from one point toward outside.

2. The laboratory research shows that as strain accumulates to the stage deviating from linearity, strains on the fault begin to diverge, resulting in segmentation, i.e. segments characterized by high and low strain values are formed. Our studies indicate that when a small quake or slip occurs at one segment of the fault, no matter a quasi-static action [*Stein*, 1999] (displacement) or a dynamic action [*Gomberg et al., 2003; West et al., 2005*], it can cause strain changes in other segments of the fault. Usually, the process of deformation and instability of a fault takes place in three stages as follows: generation of strain release areas, expansion and increase amount of these areas, and their linkage. In the first stage, small-size strain-release areas are formed. As stresses become more intense, the strain-release areas are expanded, and this is indicative of the second stage. Such expansion proceeds slowly within a limited range. When the stress reaches a certain level, the strain-release areas become sufficiently long, distances between these areas become very short, and these areas begin to link up with each other, and this marks the third stage. In the stage of deviation from linearity, both the strain-release and strain-accumulation areas are generated along the fault. And steady expansion and increase of the strain-release areas are associated with quasi-static instability stage. When subsequently the fault enters the quasi-dynamic instability stage, the number of the strain-release areas is sufficient, expansion of the existing strain-release areas reaches some degree, and interaction between these areas is enhanced, such factors jointly make them expand at an accelerated rate [*Du Yijun et al., 1989*].According to the laboratory experiments, in the three above-mentioned stages, the rates of expansion of the strain-release areas along the fault are ~1 mm/s, ~2.5 mm/s, and ~74 mm/s, respectively. Apparently, the rates of the former two stages represent a stable increase, while that of the third stage is an increase of orders of magnitude. The accelerated synergism begins when the quasi-static expansion transforms into quasi-dynamic expansion. Its essence is that the expansion mechanism changes which means that independent expansion of isolated weak fault segments is replaced by linking of the fault segments during their interaction. And from this moment the fault enters the stage within which an earthquake will be surely generated.

3. As stated above, the temporal-spatial evolution of the earthquakes along the Laohushan-Maomaoshan fault zone shows that the fault remains in the stage of deviation from linearity within which dense moderate and small quakes that occurred at many places were not associated with each other at the fault. As these events propagated steadily toward northwest along the fault from Laohushan, the fault should have entered the early meta-instability stage, i.e. the stage of quasi-static instability. The accelerated propagation of moderate and small events at the fault from Jinqianghe to northeast marks the later meta-instability stage, or the quasi-dynamic instability stage. The accelerated synergism of the fault is the indicator of entering the later meta-instability stage. It implies that this fault will surely generate an instability event, probably manifested as a major earthquake, although its time of occurrence is unknown yet.

4. Our experimental results demonstrate that during strain release at some fault segments, strain accumulation takes place at other fault segments. With the expanding range of strain-release areas and enhancement of release degree, the range of strain-accumulation areas reduces while strain accumulation degree increases. As the range and degree of strain release reaches the maximum, meanwhile the strain-accumulation areas become reduced to the least range with the maximum accumulation degree, dynamic instability takes place nearby high-gradient zones of strain. It indicates that the synergism and instability process is just the interaction between the fault segments, that have different mechanical properties, and during such a process, high strain-accumulation areas are not of pre-existence. Besides, the length of the fault segments that cause dynamic instability is much less than that of the fault in the state of instability [*Jordan et al., 2011*].

5. Such events take place in a cascade mode, i.e. they are triggered by previous ones in a continuous sequence. Through many episodes of stepwise amplification, an ori-

ginally weak input signal changes into a very strong output signal [*Ellsworth, Beroza, 1995; Ma Shengli et al., 2002, 2003*]. In the experiments, the weak segments of the fault firstly release strain, which cause stress variations in the neighboring segments through stress adjustment. The strain release of some weak segments of the fault can lead to strain release in other weak segments as well as increase of the strain level of strong segments of the fault. Under such repeated chain-mode reaction, the total length of strain-release segments reaches the critical value and the stress level of the strain-accumulation segments becomes extremely high, so that intense instable slip occurs along the fault. Due to extreme complexity of faults and their behavior in the cascade mode [*Noda et al., 2013*], many factors are uncertain, but need to be taken into account in earthquake prediction.

7. Summary

In this publication, we focus on deformation features of a fault in its meta-instability stage and draw the following conclusions:

1. There exist relatively weak and strong segments of a fault. The former are usually firstly weakened, as expressed by pre-slip, slow temblors, or small shocks, indicative of the start of strain release; while the latter are the places where the fault is locked and ruptured fast in an instable manner.

2. The difference between the stage of deviation from linearity and the meta-instability stage is as follows: once the stress-time curve deviates from linearity, strain release and strain accumulation areas occur successively on the fault, which are relatively independent from each other. In the early meta-instability stage, strain-release areas expand and their number increases, while the ranges of strain-accumulation areas are reduced and their strain level becomes higher. In the late meta-instability stage, the strain-release areas accelerate to expand, link with each other, and finally occupy the entire fault. The accelerating expansion of strain-release areas is an indicator for an impending earthquake.

3. The expansion and linkage of strain-release areas of the fault exhibit the synergism degree of fault activity and indicate instability of the site and temporal proximity of a seismic event. But, actually there are two kinds of instabilities during stick-slip of the fault, of which the former is related with strain release of weak portions of the fault, while the latter results from fast strain release of strong portions, exhibiting a major earthquake. And accelerated expansion of the former facilitates the occurrence of the latter.

Our research is still underway, and many problems remain to be studied further. For instance, we suggest that identification of the meta-instability stage and accelerated synergism can indicate that the instability event is impending, but it cannot specify its location and/or magnitude. The occurrence moment of a major quake means a dynamic burst, while neither the rupturing velocity of the fault nor inertia conditions required for seismic velocity are clear yet. Faults are not isolated features; interaction between different boundaries of a block can influence instability; different dynamic conditions may cause distinct variations, and these are only a few problems requiring further, more detailed studies.

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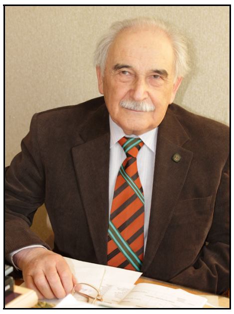

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