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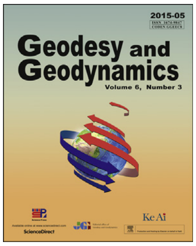

Cognitions and questions regarding crustal deformation and location forecasts of strong earthquakes

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ABSTRACT

Using Global Positioning System(GPS) data to analyze the earthquake preparation characteristics of the Kunlun Ms8.1 and the Wenchuan Ms8.0 earthquakes, we review the main research developments of earthquake forecasting and the mechanisms of earthquake preparation using crustal deformation data from recent periods, and discuss the similarities and differences in the scientific approaches adopted by the Chinese and foreign scholars. We then analyze the deformation characteristics of earthquake preparation, with respect to slip and dip-slip faults. Our results show that, in order to understand the relationship between crustal deformation and earthquake preparation, research focus should be expanded from fault-scale to larger scale regions. Furthermore, the dynamic deformation characteristics associated with earthquake preparation must be considered as a multiscale, spatial-temporal process, in order to obtain the necessary criteria for strong earthquake forecasts.

1. Introduction

The application of Global Positioning System (GPS) equispaced Earth observation technology is facilitating a greatly increased ability to monitor large- and mid-scale crustal deformations, which further enables us to study the development and occurrence processes of strong earthquakes from the large-scale, and to the mesoscale and fault scale of developing earthquakes. For over 10 years, beginning with the establishment and operation of the Crustal Movement Observation Network of China (CMONOC) in 1998, the China mainland has suffered from the Kunlun Mountain Pass West Ms8.1 earthquake in 2001 and the Wenchuan Ms8.0

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earthquake in 2008. In particular, any "premonitions" about the impending occurrence of the Wenchuan earthquake and the great calamity it would bring were not obvious, and were clearly beyond the existing capabilities of seismologists. Allusions to the characteristic faulting rate of the Longmen Mountain fault zone being low, as reflected by the GPS observation, led one observer to suggest that the GPS observation result had misled our scientific understanding. In this paper, we analyze the characteristics of crustal deformation at different scales and propose the processes of development and occurrence of the Kunlun Mountain Pass West earthquake and the Wenchuan earthquake that were reflected by the GPS observation. We also combine our analysis with a review of our basic understanding of crustal deformation in the earthquake development process over the past decades. We discuss and extract some knowledge on the analysis of the dynamic characteristics of the crustal deformation of developing earthquake from a multi-spatial-temporal scale and propose some research ideas.

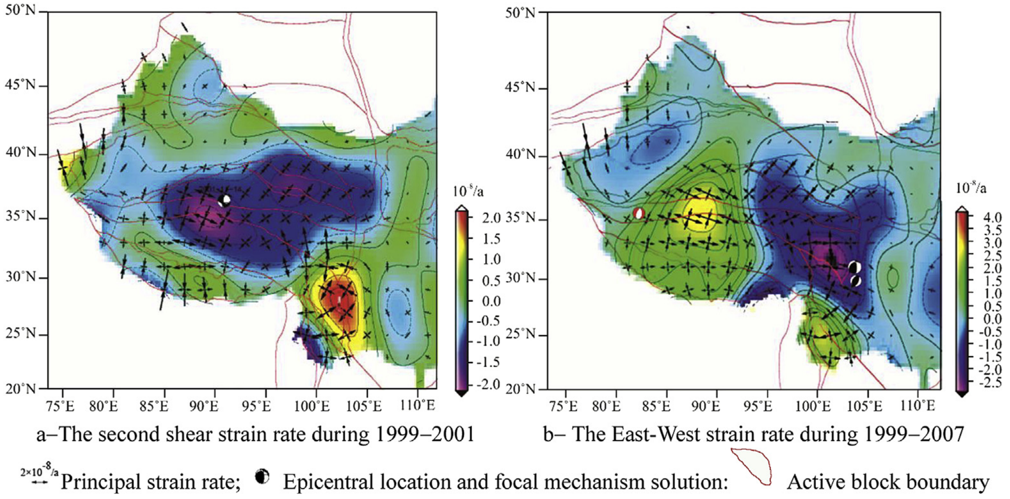
2. Dynamic characteristics of crustal deformation in the development and occurrence processes of violent earthquakes

(1) Characteristics of crustal deformation in the development and occurrence processes of the Kunlun Mountain Pass West Ms8.1 earthquake

On November 14, 2001, the Kunlun Mountain Pass West Ms8.1 earthquake took place. Because this earthquake occurred in a depopulated zone in the middle of the Qinghai–Tibet Plate, it did not result in a severe human disaster. However, it was the largest earthquake in the past 50 years in China mainland. The CMONOC (which includes a regional network of 1000 stations, a basic network of 81 stations, and a fiducial network of 26 stations) [1] was established in 1998, and began conducting comprehensive observations over the GPS regional network in 1999. To judge earthquake tendencies by applying GPS observation for reference support, the academician Ma Zongjin presented a special report for the 2001 annual earthquake tendency conference, launched in December 2000, on behalf of the CMONOC [1]. According to Ma's report, the second shearing strain rate parameter of the strain rate field, as computed by China mainland's GPS data for the 1993–2000 period, shows a large-scale negative value region inside the Qinghai–Tibet Plate. Most of the fracture zone of the Kunlun Mountain Pass West Ms8.1 earthquake that occurred on November 14, 2001 fell into the northeast edge of the extreme value region of the large-scale negative value region of the second shearing strain rate (Fig. 1). The negative high value region of the second shearing strain rate indicates a deformation rate that occurred close to the east and west, and then revolved and sheared towards the left, or close to the south and north, and continued to revolve and shear toward the right in this area. This pattern accords with that of the Kunlun Mountain Pass West Ms8.1 earthquake's East Kunlun fault zone, which was close to the east and west, and revolved, sheared, and ruptured towards the left. An understanding has thus been reached that violent earthquakes may occur at the edges of high value shearing strain rate regions, which is consistent with our understanding of tectonic deformation. [2,3]

According to the principal strain distribution diagram of the strain field, as calculated using GPS data, the value of the principal stretching strain rate (i.e., the maximum principal strain rate) that occurred in the northwest area of the Kunlun Mountain Pass West earthquake was slightly larger than the strain rate of the principal pressing strain rate (i.e., the minimum principal strain rate) in the north and east. In other words, this earthquake occurred in a region in which the surface strain rate was slightly stretching. [4] This crustal deformation characteristic would have been beneficial for the full release of the strain close to the east and west, and its revolving and rupture toward the left during the process of the violent earthquake, This contributes to our understanding of the phenomenon that suggests that the rupture scale of this Ms8.0 earthquake was obviously too long (reaching a length of 426 km) and the strength of the aftershock was relatively lower (no earthquake with a magnitude of more than 6.0).

We processed the basic network data (81 stations) of the CMONOC, and adopted changes in the 1998–2006 base line



a–The second shear strain rate during 1999–2001

b– The East-West strain rate during 1999–2007

Principal strain rate; Epicentral location and focal mechanism solution: Active block boundary

Fig. 1 – Field distribution of strain rate in Midwestern China.

formed by all the simultaneous observation stations, based on whether or not a change was consistent with the associated influence of the revolving and rupture toward the left of the violent earthquake, after the 2001 Kunlun Mountain Pass West Ms8.1 earthquake. We then analyzed the Kunlun Mountain Pass West Ms8.1 earthquake and its scope of influence (see area encircled by the bold green line in Fig. 2, which is in the Report on Large Situation Tracking and Tendency Prediction Study of Earthquakes in Chinese Mainland in 2007–2009 by the 2007 Annual Earthquake Tendency Conference), which shows the large scope of the GPS station distribution of the response to the influence of this violent earthquake process. Our analysis also showed that obvious changes influenced by the Kunlun Mountain Pass West earthquake occurred at many stations inside the borders of the Sichuan–Yunnan Plate, while its influence is not obvious at the JB34 station, situated at the eastern area of the Banyan Kara Ulla Plate close to the Longman Mountain fault zone (at a distance of about 130 km).

The base station in the crustal movement continuous observation network nearest to the fracture zone of the Kunlun Mountain Pass West earthquake is the DLHA station (Fig. 2). It is 300 km away from the eastern side of the fracture zone and the perpendicular distance between it and the fracture zone in which earthquake occurred is about 200 km. We used data from the DLHA and the LHAS stations, and the XIAA and the LUZH stations, which are relatively near to the fracture zone of the 2001 Kunlun Mountain Pass West Ms8.1 earthquake, to calculate a time series of the second shearing strain parameter (Fig. 3). This time series shows a continuous decreasing tendency over the long term, which reflects a revolving wrench deformation towards the left in the east and the west, and towards the right in the south and the north. The wrench deformation in the several months prior to the Kunlun Mountain Pass West Ms8.1 earthquake was in a state of stagnation or slight reverse. According to data accumulated over many years, during this period, the deviations from the typical relatively stable tendency are obvious. However, if we extract the data from the DLHA station, which is nearest to the earthquake fracture zone among all the calculation data, there is no observable change. Such a change before an earthquake manifests as a pause or slowdown of the relative movement of crust from the accumulated strain over a long period of time.

Further, utilizing the DLHA station data, as well as the DXIN and XNIN stations, which are relatively close to the DLHA station, to compute a time series of the strain parameter. Fig. 4 shows the time series (as for the XNIN station, its antenna movement in April 2001 was deducted using the estimated parameter) of the first shearing strain parameter (shear deformation that whirled toward the left in the north and east and toward the right in the north and west). Seen over the long term, the first shearing strain parameter, computed for the three GPS stations located in the northeast of the Kunlun Mountain Pass West earthquake fracture zone, increases continuously, but was in a static state for nearly one year before the occurrence of the Kunlun Mountain Pass West earthquake. This indicates that the DLHA station moves toward the west of the other two stations under normal circumstances, but this relative movement was once stagnant. The change of such abnormality and the change resulting from the rupture process of the earthquake occurrence are reversed in direction, which can be interpreted as a display of the frustration of the left-whirling twist deformation. This change prior to the earthquake also indicates that the relative movement of the Earth's crust accumulated either by long-term strain pauses or by slowing down.

(2) Characteristics of crustal deformation in the processes of development and the occurrence of the Wenchuan Ms8.0 earthquake

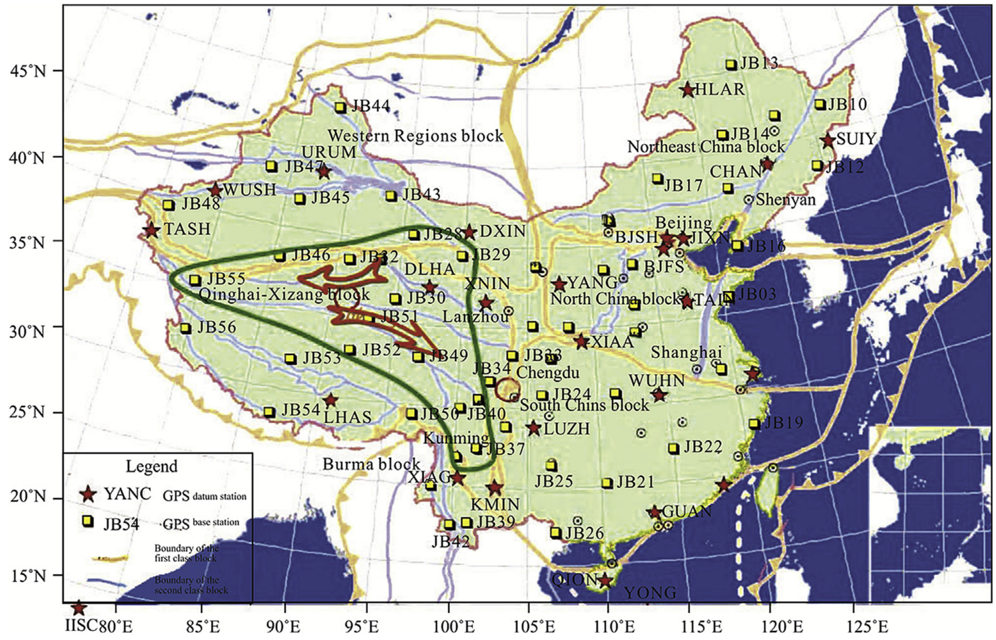


Fig. 2 – **Division of active block and distribution of GPS data (base) stations (GPS stations in the area encircled by the bold green line had a certain response to the Kunlun Mountain Pass West Ms8.1 earthquake).**

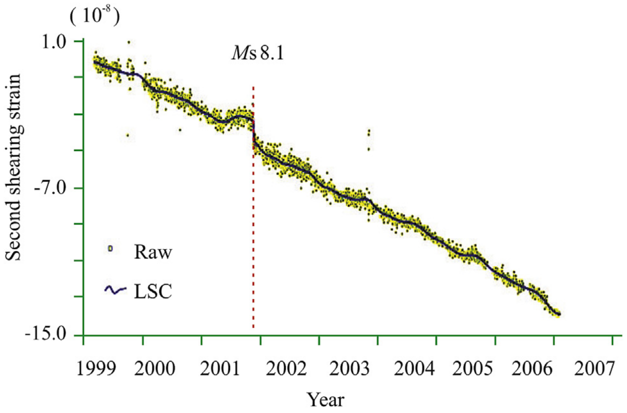


Fig. 3 – Time series of the second shearing strain by LHAS–DLHA–XIAA–LUZH station data. Raw: the calculated result; LSC: fitting curve by the least squares collocation.

On May 12, 2008, the Wenchuan Ms8.0 earthquake occurred in the Qinghai–Tibet Plate with strong tectonic deformation and in the Longmen Mountain fracture zone in a boundary strip of the stable South China Plate. The Wenchuan earthquake conditions were such that our earthquake department nearly detected it. However, the department's monitoring ability over Longmen Mountain and the neighboring area is relatively low and not good enough for detecting abnormal foreshadow activity. But the Kunlun Mountain Pass West Ms8.1 earthquake took place in a depopulated zone in the middle of the Qinghai–Tibet Plate in 2001, and Sichuan was able to detect some outstanding abnormities prior to the earthquake. While no abnormities were detected prior to the Wenchuan earthquake, we continue to be inspired by the thought of it.

According to the GPS observation results, prior to the Wenchuan earthquake the GPS system did not detect any deformation of the Longmen Mountain fracture zone or of the Chengdu Plain situated at its east side (its size is smaller than the millimeter-sized observation error). However, the east part of the Bayan Kara Ula Plate, located in the west of the Longmen Mountain fracture zone, reveals a large-scale slow deformation in which the crust cuts down, comparatively, the Longmen Mountain fracture zone, mainly revolving and wrenching it towards the right, while the compressional deformation is smaller. The annual gross deformation from revolving and wrenching towards the right of the Longmen Mountain fracture zone and of the parallel fracture zone, on a spatial scale of 500 km from its northwest side between 1999 and 2007, is approximately 10.7 ± 0.8(mm/a). The relative deformation rate is 2.1 ± 0.2(10^{-8}/a), the average yearly deformation, in which the crust shortens the perpendicular fracture zone, is −3.5 ± 0.6 (mm/a), and the relative deformation rate is 0.7 ± 0.1(10^{-8}/a). In total, these deformations reflect large-scale strain accumulations. Compared with the magnitude of the revolving and wrenching towards the right of the Longmen Mountain fracture zone and of the parallel fracture zone, on a spatial scale of 500 km from its northwest side between 1999 and 2004 that during the period 2004–2007 increased by 1.6 ± 1.5 (mm/a). The deformation of revolving and wrenching towards the right in the area neighboring the Longmen Mountain fracture zone also increased (about 0.8 mm/a), but this observation is not indisputable with respect to observation accuracy.[5]

The distribution of the Chinese Mainland strain rate field mainly reflects the crustal deformation of a relatively low-frequency range, Among the various strain parameters, the distribution of the negative value of the east-west component strain rate and the first shearing strain rate have a relative relation at the site of the Wenchuan earthquake. Specifically, the east-west component strain rate (Fig. 1b) has an extremely high negative value region in the east of the Bayan Kara Ula Plate, which reflects the obvious east-west deformation in which the crust cuts downward. Its distribution range is large and the quantity value is high, which is very similar to the large-scale negative value region in the middle of the Qinghai–Tibet Plate of the second shearing strain rate of the Chinese Mainland prior to the Kunlun Mountain Pass West earthquake. The Wenchuan earthquake took place in the east edge of the extreme value region of the negative east-west component strain rate, which shows that the construction power source of the Wenchuan earthquake is pushing the Bayan Kara Ula Plate towards the east. If seen from the perspective of the strain rate field of the Sichuan–Yunnan area, it mainly reflects the increased compressive strain rate of the south section of Longmen Mountain fracture zone in the 2004–2007 period. Apart from its microscopic epicenter, most of the Wenchuan earthquake fracture zone was still in a zone characterized by a low strain rate.[5]

The time series of the GPS base line, as it spreads towards the north and east and stretches across the North-South Seismic Belt several years before the Wenchuan earthquake, and especially in 2006, reflects the relative movement in which the crust cut down was relatively enhanced.[5] The time series of the east-west base line also displays that relative movement of the east-west crust cut down being in an enhanced state. However, the time series of the east-west base lines between the Qinghai–Tibet Plate and the GPS station at its edge, and the TASH station and WUSH station

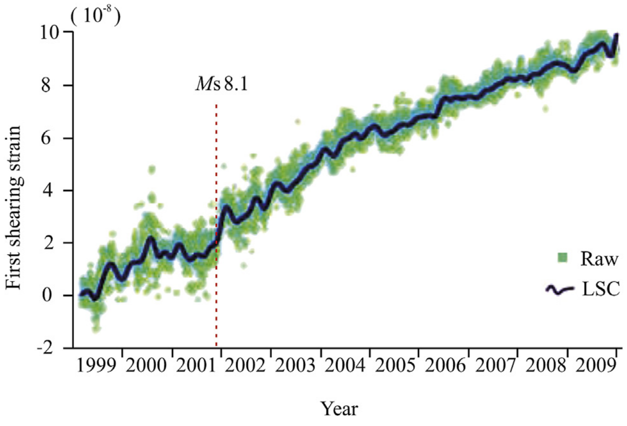


Fig. 4 – Time series of the first shearing strain by DLHA–XNIN–DXIN station data. Raw: the calculated result; LSC: fitting curve by the least squares collocation.

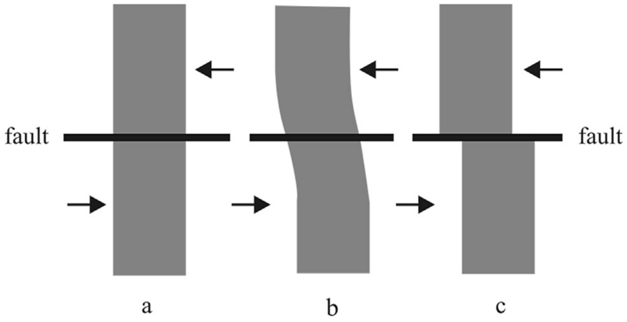
in Xinjiang, show a stretching exchange that was basically synchronous with the base line shortening of the North-South Seismic Belt. This indicates that the change in the enhanced shortening of the north-east and east-west base lines, as composed by the GPS base stations, was not caused by error influencing the scale factor in the GPS resolution, but may reflect a change in the relatively large-scale relative movement of the crust. This is because the enhancement of the relative movement of this crust shortening of the North-South Seismic Belt is fundamentally consistent with the relative crustal movement due to long-term strain accumulation in the North-South Seismic Belt. It reflects, from the large-scale crustal movement that the relative movement of regional crust was enhanced prior to the Wenchuan earthquake. But the continuous observation data of the GPS base stations did not obtain the crustal deformation or the background of the long-term strain accumulation, similar to that of the Kunlun Mountain Pass West earthquake (as shown in Figs. 3 and 4), or the change (or slowdown or pause), which was the reverse of the relative movement of earthquake rupture. Although the LUZH station, which is nearest to the Wenchuan earthquake fracture zone, is only 300 km from the Longmen Mountain fracture zone, the above-mentioned characteristics were not observed. This maybe because this station is situated in the interior area of the stable South China block.

According to the crustal deformation characteristics of the Longmen Mountain fracture zone and its neighboring area prior to the Wenchuan earthquake, as shown by the GPS observation data, in addition to the low movement frequency of the Longmen Mountain fracture zone, and the low strain accumulation rate, some problems are worthy of consideration. For example, the crustal deformation observed by the GPS data prior to the earthquake is non-corresponding with co-seismic crustal deformation. The elastic strain released by an earthquake is elastic strain that has accumulated for a long time prior to the earthquake. Therefore, generally, the deformation characteristics prior to a violent earthquake and those of co-seismic deformation when an earthquake occurs include reverse or complementary characteristics, which are very different from each other. Co-seismic deformation faulting is staggered while the faulting during strain accumulation prior to an earthquake is a continuous deformation, and is also thought to convey the deformation field of a developing earthquake.[3,6] The non-correspondence between the crustal deformation prior to the Wenchuan earthquake and the co-seismic displacement is mainly reflected in this way: co-seismic displacement basically accords with the presentation of damping in the power function with the displacement of distance leaving the fracture zone. This is most obvious in the neighborhood of the fracture zone in which an earthquake occurs. The crustal deformation in the neighborhood of the Longmen Mountain fracture zone prior to the earthquake was extremely imperceptible, and obvious deformation occurred inside the Bayan Kara Ula Plate. The co-seismic displacement shows that one side of the Sichuan Basin, located in the east side of the Longmen Mountain fracture zone, also shows deformation released upon compressive strain, which accords with elastic resilience. Compressive strain accumulation, however, has not been observed prior to an earthquake. Co-seismic displacement mainly occurs in deformation released from compressive strain when the crust on two sides of a fracture zone stretches. The large-scale deformation in the east of the Bayan Kara Ula Plate, located in the northwest side of the Longmen Mountain fracture zone, which was observed prior to the earthquake, primarily parallels the deformation of revolving and shearing towards the right side of the Longmen Mountain fracture zone as the principal stress. This observation likely indicates that the crustal deformation of the Longmen Mountain fracture zone and its neighboring area over the most recent ten years, as observed by the GPS prior to the Wenchuan earthquake, has been in an abnormal condition that differs from the condition of crustal deformation accumulated by long-term strain. In other words, the obviously low strain rate of the fracture zone and its neighboring area may be characteristic of the last phase of development of a violent earthquake.

3. Relevant knowledge of crustal deformation reflecting earthquake preparation

As is well known, the world's first theory of the earthquake preparation and occurrence process—the elastic-rebound theory—drew its conclusions after studying geodetic data from the San Francisco earthquake in 1906 (as well as the 1851–1865 and 1874–1892 periods and three sets of triangulation data about the San Francisco earthquake). The theorists comparatively analyzed crustal deformation characteristics before and after the earthquake.[7] The theory states that the presence of relative movement on both sides of the San Andreas Fault, and the locked state of the fault, led to the accumulation of elastic strain energy of the Earth's crust nearby the fault. Therefore, when the strain reached a critical point, fracture dislocation occurred, and the fault rebound generated seismic waves (Fig. 5). According to this theory and its long-term predictions, one of the most fundamental problems to be solved in the anticipation of an earthquake is to obtain the crust elastic strain accumulation, and especially the state of strain accumulation in the seismogenic fault zone.

After many years of research, knowledge about crustal deformation and earthquakes has continuously developed and progressed. We now recognize that elastic strain accumulation in the brittle layer of the upper crust provides the foundation for earthquakes. Consequently, the gestation process of earthquakes is closely associated with the toughness of the mantle and lower crust layers [8] (Fig. 6). A basic understanding of the deep ductile lower crust layer is based on the long-term stability of the relative motion with no blocking. Brittle upper crust layers will lead to strain accumulation, because the relative motion is impeded by fault locking, and the relative motion of the upper crust is closer to that of deep ductile layer due to elastic strain released by the same earthquake. This can be seen as an extension or development of the elastic rebound theory. In fact, the understanding of the mechanism of earthquake preparation should be extended to the deep underground from the observation of surface phenomena. And the



a–No slip potential accumulation

b– Interseismic slip potential accumulation (fault locking)

c– Coseismic slip potential release

Fig. 5 – Elastic-rebound theory model [7].

understanding of simple elastic deformation and spring, based on the brittle crust layers (Fig. 5), can be linked to our understanding of the deep ductile layer (Fig. 6). The international community attaches great importance to geodetic data as providing a constraint for studying the seismogenic fault strain accumulation rate, by which the study of the strain accumulation state can provide a basis for long-term earthquake prediction.

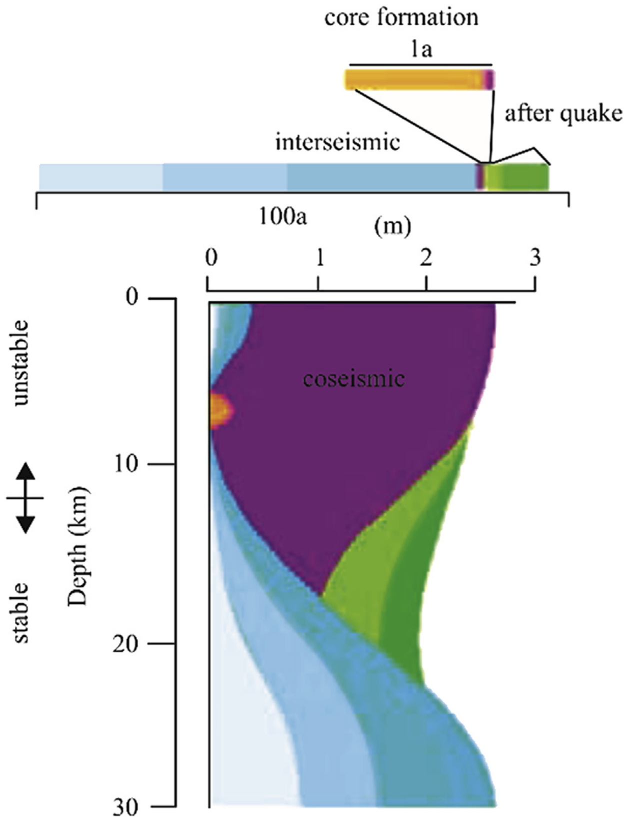


Fig. 6 – Model of earthquake fault movement changes with time and depth [8].

On the basis of the elastic-rebound theory, Savage et al. [9] combined the displacement velocity distribution of both sides of strike-slip faults to reflect the elastic strain faults during an earthquake and the relative motion of the dislocations and faults of a block on its two sides at a relatively early time [10,11] (Fig. 7). This work clarified the different deformation characteristics during early and late seismogenic stages [9,11] (Fig. 8). The healed fault begins to accumulate strain after the earthquake. The early deformation occurs in a very narrow range near the fault. The deformation of the two sides of the fault become more gentle with increasing range in the advanced stage (closer to the next earthquake period), and the speed of this deformation after leaving the fault is determined by the degree of depth of the fault. [9] With this basic understanding, the relative motion and deformation that can be observed in the vicinity of the fault are significantly reduced as the next earthquake approaches.

The Russian Krakow first proposed dividing into three stages the earthquake preparation process, based on the geoidal changes that occur. [12] Fig. 9b summarizes the Yoichiro Fujii earthquake preparation, based on its crustal deformation α–β–γ phase morphology characteristics during the occurrence process, as obtained from 30 well-known earthquake cases.[13] The graphed curve reflects the change process from strain accumulation to instability, which corresponds to rock mechanics test results. (In Fig. 9a, we see that the strain significantly accelerated and entered the non-linear B–C segment, after passing through the stable elastic strain accumulation segment A–B. The instability and stress drop after point C.) Therefore, we know that the early stages of the α stage is the easily deformed section, occurring after the fault is healed. This is followed by the longer-term stability of the normal linear strain accumulation stage. After crustal deformation accelerates into β_1 and then β_2, at this time unstable changes occur before entering the γ stage, until lastly, the earthquake happens. The understanding represented by this crustal deformation mode is based on the analysis of multiple sets of crustal deformation data from earthquake cases that showed a large degree of crustal deformation.

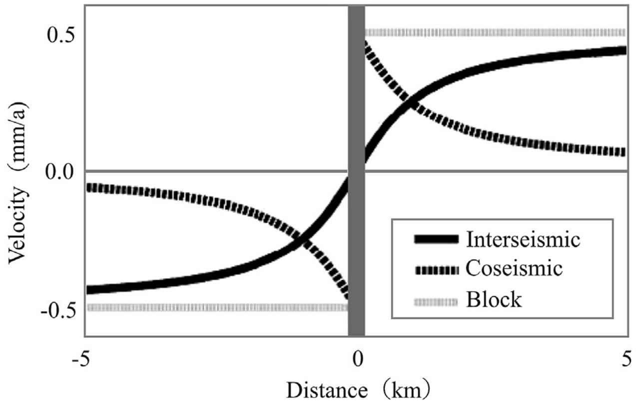


Fig. 7 – Velocity projection cross fault (parallel component), (interseismic, co-seismic, and block movements).

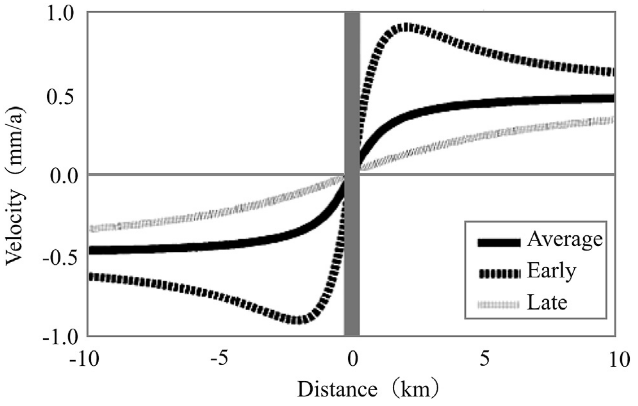


Fig. 8 – Velocity projection cross fault in different seismic time periods (parallel component), (early, late, and average).

4. Discussion and conclusions

4.1. *Discussion and understanding of deformation characteristics of earthquake crust preparation occurring in the course of large earthquake preparation*

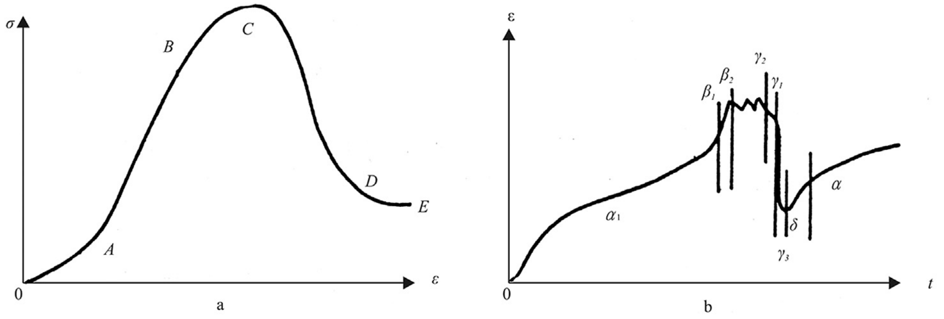
To understand the physical nature of a large earthquake preparation process from multi-scale crustal deformation data, and to establish a basis from which to predict hazardous large-scale earthquake locations for several years, based on dynamic data, the following discussion and summary is offered:

(1) The basis for understanding crustal deformation in the seismogenic process must be expanded to encompass a larger area around the seismogenic fault

Although the elastic-rebound theory can explain earthquake preparation, the accumulated elastic strain, and the release mechanism, it is insufficient with respect to the analysis of the fault scale. Strong earthquakes and earthquake gestation processes show that abnormal changes may occur at greater spatial scales. The crustal deformation α–β–γ phase changes reveal patterns that occur in the process of earthquake preparation (Fig. 9), and can be obtained by combining rock mechanics experiments with crustal deformation earthquake case data. Although we can obtain large amounts of observational data in China, including fault deformation timing curves, it is still insufficient to observe only the time process. Time and spatial distribution research should be combined to obtain a more complete understanding. By doing so, we can observe the parallel speed projection of the direction of a cross-fault at different stages of the earthquake cycle, as shown in Fig. 8. There are significant differences in the direction of fault attenuation characteristics in the early accumulation phase from those in the late phase of crustal deformation. [10,11] Although we can reveal the differences between the early and late stages of strain accumulation of the same earthquake fault, as well as its average state, it also provides an idea that inspires the analysis of the problem from the perspectives of both space and time. The actual existence of different fault segments that occur as a result of strong earthquakes are in the different strain accumulation stages, or strain accumulation stages have significant differences due to the different lengths of elapsed time. At the time of crustal deformation or during continuous dynamic change, the faults at different states of strain accumulation have corresponding impacts. Given that fault strain accumulation is caused by relative motion on both sides of the fault block, it follows that the association of fault and block movement dynamics should be carefully studied. Because the strain of an earthquake can affect multiple blocks in a larger area (as occurred in the area affected by the great earthquake of west Kunlun Mountain, shown in Fig. 1), a large earthquake preparation process is also associated with a large area. Therefore, a better understanding of the process of earthquake preparation is needed which involves the expansion to larger spatial and time scales.

(2) Seismogenic deformation field characteristics in strike-slip earthquake fault zone areas

Seismogenic fault segments from the near-field and its vicinity can be used to qualitatively analyze possible regional seismogenic deformation field characteristics. The first assumption must be that the fault's relative movement constraints on both sides of the block are consistent, in order to reveal the space distribution of the crustal deformation. Fig. 10a is drawn from the view given in Fig. 8a straight east-west strike-slip fault—and the degree of strain accumulation



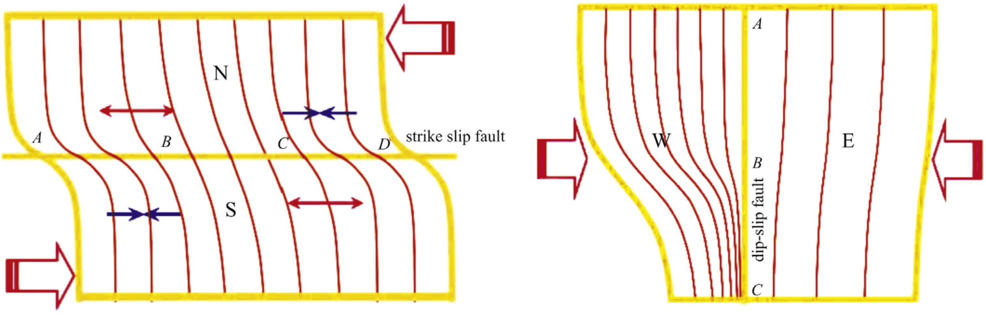
a– Sign of the rock stress–strain constitutive relation b–Phase characteristics of precursory deformation

Fig. 9 – Stage curve of strain before and after earthquake [13].

and state of the different sections in the presence of significant differences. The *B*–*C* segment in the figure indicates the late strain accumulation between the earthquake and the fault has reached the locked state. Since the fault segment can bear sinistral shear elastic deformation, which nears the limit, the crustal sinistral shear strain is relatively gentle and the deformation bandwidth becomes larger, so that the non-cross-fault deformation at the cross-fault difference is not very significant. The adjacent *A*–*B*, *C*–*D* segments are still in the early stages of strain accumulation, which are less than the *B*–*C* segment fault locking strength. The crust shear deformation of the Earth's crust caused by the relative movement of the fault on both sides are focused on a narrow range near the fault, and to cross the most significant deformation at the fault, the shear deformation will be faster with increasing the fault attenuation distance. This shows that the relative motion and deformation of the field near the fault zone is significantly higher than in the middle *B*–*C* segment under the same tectonic force, which falls into the easy deformation segment. Further, we assume that if it inherits the tectonic force enhancement, the response to this will be different in different segments. The *A*–*B* and *C*–*D* segments are more yielding segments, so the tectonic deformation force will more significantly enhance the response. In the middle segment, however, as a result of the *B*–*C* elastic deformation being relatively closer to the ultimate level, the tectonic deformation force enhancement to the response will be lower than in the adjacent segments. However, overall, the total sinistral twist on both sides of the fault may be balanced, under the circumstance of an enhanced role of inherited tectonic stress. If we calculate the large regional deformation strain field, which reflects relatively low frequency, the area near the fault zone a, as shown in Fig. 10, may render the shear strain rate values of the entire area. Therefore, a strong strike-slip earthquake may occur when its strain accumulation is consistent with its background shear strain rate value area.

(3) Regional seismogenic deformation field characteristics of dip-slip earthquakes fault zones

Fig. 10b assumes a dip-slip fault, whereby there are significant differences on both sides of the dielectric block, and wherein block E is relatively rigid, and block W is relatively elastic. The *A*–*B* segment at the end of the seismogenic fault's strong locking segment, due to the continuing role of long-term accumulated strain and elastic deformation tectonic forces deformation, tends to have limited deformation pushed by the block, and is very smooth and distributed over a very wide range. The locked degree of the fault in the *B*–*C* segment is relatively low, and the degree of crustal strain accumulation in this section is not high. These crustal deformation states are relatively prone to occur, and significant crustal shortening deformation is mainly concentrated in the vicinity of the fault. To carry the analysis further, if the inherited tectonic force is enhanced, the enhancement of the deformation response of the tectonic deformation force in the *B*–*C* segment will be more significant. But since the elastic deformation of the *A*–*B* segment is relatively close to the limit, the enhanced role of the tectonic deformation response force will be lower than in the adjacent segments. This can be understood as the large-scale EW compressive strain negative high value area from 2004 to 2007 (in which the Wenchuan earthquake occurred in the extreme eastern edge). Furthermore, the strain rate field of the Sichuan–Yunnan region mainly displays an increased compressive strain rate high value area in the southern section of the Longmen Mountain, which is the zone of most earthquake rupture and is a low strain rate zone. So, we can begin to understand the impact of the *Ms*8.1 earthquake west of the Kunlun Mountain, in which multiple sites inside the Sichuan and Yunnan apparently respond to change, and the fault of the JB34 station in the eastern Bayan Har block, which is close to the Longmen Mountain fault zone (a distance of about 130 km), showed no obvious change by the great earthquake. This indicates that the stress and strain caused by a major earthquake can adjust in uncoordinated low response areas. It is the elastic deformation of the crust that tends to limit the area's high-risk earthquake zone. Elastic crust deformation of a thrust-type earthquake during final earthquake preparation tends to be limited and shows low strain, which may last a long time. For instance, GPS observations from nearly a decade of data show that the fault zone maintained a relatively consistent strain rate. Even more than 30 years of cross-fault measurement data show that the fault activity velocity of Longmen Mountain is the lowest in the North-South Seismic Belt.



a–Area of strike slip fault

b–Area of dip-slip fault

Fig. 10 – Schematic diagram of regional crustal deformation fault zone with significant differences in the strain accumulation states.

(4) Understanding seismogenic deformation dynamics of strong earthquakes from the multi-scale spatial and temporal processes

The relative motion and deformation characteristics to the west of the Ms8.1 Kunlun Mountain and Ms8.0 Wenchuan earthquakes, as reflected by current GPS observations data, showing high-risk of crustal deformation rates or low-risk issues can be understood with a basic answer: seismogenic fault segments and their vicinities in late approaching earthquake seismogenic crustal deformation periods reflect a weakening trend of strain accumulation several years before the big earthquake. This is consistent with the long-term strain accumulation, whose relatively large-scale crustal deformation may increase, but the crustal deformation of certain earthquake fault zone areas may enhance uniformly.

(a) Seismogenic fault segments and their local areas, or the relatively small-scale crustal deformation of a greater earthquake may slow down, or remain in a low crustal deformation state. This may involve a relatively long and slow process. In the dip-slip fault accumulation of the elastic strain of an extrusion, in particular, in which this phenomenon will be more prominent, it may involve longer time scales. Furthermore, at times much closer to an earthquake occurrence, the range of slowed strain accumulation of crustal deformation may expand.

(b) Relatively large-scale crustal deformation, which is consistent with the strain accumulation of a few years or long-term before great earthquakes, may increase. This will occur at a relatively large-scale, which means the scales much greater than that of the rupture zone as shown in the situation to the west of the Kunlun Mountain and Wenchuan earthquakes. Regarding the general physical mechanisms of continuous deformation caused by the long-lasting effects of crust tectonic forces, seismogenic faults are also in an enclosed pressure environment. Hence, when the strain accumulation and elastic deformation tend to be limited, or in a critical state, if it continues to strengthen an earthquake may occur, or it is possible to delay earthquakes for weakening.

(c) The crustal deformation non-uniformity of certain areas associated with seismogenic fault segments may be enhanced. Of the existing observation data, only the current GPS data can observe this phenomenon in front of the earthquake fault zone of the Wenchuan earthquake and Longmen Mountain. The local compressive strain at the Longmen Mountain from 2004 to 2007 was significantly enhanced, and most of the earthquake rupture zone of the Wenchuan earthquake was under a low strain state. However, from the analysis of the physical mechanism, due to the tectonic force effect enhancing the relatively large-scale structure, and the different strain accumulations from the different stages, some belong to the easily deformed sections between the earlier stages of earthquake fault segments. The elastic deformation of a fault tended to be limited. The enhancement of a relatively large-scale tectonic force shows a significantly different response, resulting in a certain region of enhanced crustal deformation non-uniformity. As proposed by Zhou, the scientific thinking from a system image dynamics perspective, namely the whole space distribution of crustal deformation of the earthquake preparation process reflects a system evolution that has proceeded as follows: “quasi-uniform →inhomogeneous, earthquakes →quasi-uniform.” [14]

Huge earthquake rupture events are more prominent, and reflect more prominent seismogenic features. Despite the Mar.11 2011 *Ms*9.0 earthquake in Japan being located in a subduction zone 150 km away from land, due to its large magnitude, the GPS data station on land was able to observe certain characteristics. From this huge earthquake a few years ago, the continuous GPS observation time series shows the relative motion of crustal shortening west and east of the area of large-scale enhancement (the 2010, 2011 annual reports of the National Research earthquake situation report that the westward subduction of the Pacific Plate is being continuously enhanced, as observed from 2006). The rupture zone near the regional scale earthquake is observed to be slowing down, and the subduction zone of the entire Japan Trench shows enhancement, with flat, slow, segment difference variations from north to south, [15] which also supports the above perspective.

4.2. *Study on dynamic processes and prediction criteria of strong earthquakes from the large spatial and temporal tectonic forces dynamics process*

The development of the capacity for crustal deformation observation, especially the introduction of the GPS Earth observation technology from space, has allowed the study of the gestation of earthquakes by looking at the larger spatial and temporal scales of crustal movement and deformation. In the key project study of the “Eleventh Five-Year Plan,” the National Technology Support Program of the “strong earthquake prediction research dynamic motion picture,” a large regional research-based power structure has been proposed to understand the dynamic processes of large regional tectonic forces, to extract useful information to better predict earthquakes. China mainland has many seismogenic tectonic zones where strong earthquakes may occur, and there are thousands of other potentially strong sources. The last earthquake predicted to lock the elastic strain accumulation tended to lock the dangerous seismogenic tectonic zone sections where the elastic strain accumulation entered the nonlinear deformation stage. Under the dynamic effects of boundary action, the dynamic field of large regional changes, and some relative local areas that are enhancing strain-concentrated areas, there are some regions in stress–strain mitigation areas that are under stress–strain enhancement. Seismogenic zones with a centralized structure, especially those in which high levels of stress and strain have already accumulated and are tending to reach the limits of elastic deformation, the seismic hazards of these seismogenic zones have been further enhanced. The changes in the nonlinear instabilities of these seismogenic zones should be captured. Closely combining tectonic settings, according to border force analysis and the multidisciplinary field of multi-scale dynamics, could facilitate the determination of the stress–strain accumulation enhancement in concentrated areas. By better understanding the gradually locking of strong earthquake high-risk segments in seismogenic zones, we can predict the risk associated with the locked segments based on the short-term dynamics information. The study of crustal movement and deformation, based on GPS data, to determine the future location of strong earthquakes, offers more specific criteria to determine strong earthquake risk from the different spatial and temporal scales of crustal movement and deformation dynamics.

Strong earthquake prediction includes low to medium-term (several years scale) prediction levels, and the number of years required for predicting hazardous areas of strong earthquake risk is also an important environmental constraint in earthquake prediction. If we can do better in this respect, by being able to identify dangerous strong earthquake areas a few years in advance, a clear objective emerges to strengthen our tracking and monitoring activities for short-term prediction. Medium-term forecasting of strong earthquakes still has many scientific problems to be solved. The basic problem in solving earthquake prediction is, first, to make progress in correctly understanding the physical processes occurring in earthquake preparation systems, and, second, to be able to use certain models using a variety of observation techniques to obtain information and parameters that reflect the seismogenic process. To achieve a more comprehensive and in-depth understanding, the Earth surface must be linked with its deep regions for a comprehensive study of the tectonic dynamics process.

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REFERENCES

[1] Ma Zongjin, Chen Xinlian, Ye Shuhua, Lai Xian, Wei Ziqing, Chen Junyong, et al. GPS study of current crustal movement of China Mainland. Chinese Sci Bull 2001;46(13):1118–20. 5307.

[2] Jiang Zaisen, Ma Zongjin, Zhang Xi, Wang Qi, Wang Shuangxu. Horizontal strain field and tectonic deformation of China mainland revealed by preliminary GPS result. Chinese J Geophys 2003;46(3):352–8 [in Chinese].

[3] Jiang Zaisen, Yang Guohua, Wang Min, Zhang Xi, Wu Yun, Fang Ying, et al. On crustal movement in China continent and its relationship with strong earthquakes. J Geodesy Geodyn 2006;26(3):1–9.

[4] Jiang Zaisen, Zhang Xi, Zhu Yiqing, Zhang Xiaoliang, Wang Shuangxu. Regional tectonic deformation background before the Ms8. 1 earthquake in the west of the Kun lun Mountains Pass. Sci China (Series D) 2003;33(Supp.):163–72.

[5] Jiang Zaisen, Fang Ying, Wu Yanqiang, Wang Min, Du Fang, Ping Jianjun. The dynamic process of regional crustal movement and deformation before Wenchuan Ms8.0 earthquake. Chinese J Geophys 2009;52(2):505–18 [in Chinese].

[6] Jiang Zaisen, Yang Liming, Chen Hong. Study on the physical foundation and its application of new technology about Strong earthquake prediction. Beijing: Seismological Press; 2008.

[7] Reid HF. The mechanics of the earthquake, the California earthquake of April 18, 1906, report of the State Investigation Commission, vol. 2. Washington DC: Carnegie Institution of Washington; 1910. p. 16–28.

[8] Scholz CH. Earthquakes and friction laws. Nature 1998;391:37–42.

[9] Savage JC, Burford RO. Geodetic determination of relative plate motion in central California. Geophys Res 1973a;78:832–45.

[10] Savage JC, Prescott WH. Precision of Geodolit distance measurements for determining fault movements. J Geophys Res 1973b;78:6001–8.

[11] Brendan J Meade, Bradford H Hager. Block models of crustal motion in southern California constrained by GPS measurements. J Geophys Res 2005;110:B03403. http://dx.doi.org/10.1029/2004JB003209.

[12] Rikitake Tsuneji. Translation. In: Feng R, Zhou XH, editors. Earthquake prediction. Beijing: Seismological Press; 1978.

[13] Zhou Shuoyu. What is the nature of earthquake prediction? J Seismol 1993;1:39–43.

[14] Shuoyu Zhou, Shirong Mei, Shunying Shi. Research on the reproducibility of earthquake precursors, papers on the sixth annual meeting of the seismological society of China. Beijing: Seismological Press; 1996.

[15] Chen Guangqi, Wu Yanqiang, Jiang Zaisen, Liu Xiaoxia, Zhao Jing. Characteristics of seismogenic model of Mw9.0 earthquake in Tohoku, Japan reflected by GPS data. Chinese J Geophys 2013;56(3):848–56 [in Chinese].

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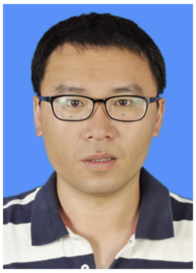

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