Stress, strain and earthquake activity

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There are 13 papers in this special issue on stress field, crustal deformation and seismicity. The great Wenchuan earthquake is a grievous disaster, but Chinese scientists are trying to learn more from the event in order to understand better the physics of earthquakes for future hazard mitigation planning. Rapid development of GPS technology provide the possibility in the first time in history to monitor the crustal deformation in a wide range and high accuracy, however, it is an important lesson learned from the Wenchuan earthquake, that GPS deformation alone is insufficient for forecast of major earthquakes. The Longmenshan fault zone is of low strain rate and relatively low historical seismicity in comparison with a number of strike slip faults in the western Sichuan region, such as the Xianshuihe fault, Xiaojiang fault, etc. However, the Wenchuan earthquake broke out in Longmenshan fault zone as a surprise to most Chinese seismologists. Guo et al (2009) happened to make hydrofracture stress measurement at the northeastern part of the Longmenshan fault one week before the great Wenchuan earthquake, and was able to make repeated measurement after the earthquake. They found stresses were high close to the fault zone than those from boreholes farther away from the fault zone before the main quake, indicating that stress may accumulate and exceed strength of rock mass even though the strain rate is low. In contrary, high strain rate may not necessarily lead to great earthquakes if stress can be rapidly released from a number of media or strong earthquakes as well as slow or quiet earthquakes. Therefore, this issue of stress field, crustal deformation and seismicity emphasis a new point of view to investigate both strain and stress in relation to earthquake activity.

Reliable stress measurement is expected to become a priority in earthquake related network construction. Chi reported deployment of 40 sets YRY-4 four-component borehole strainmeters in China as part of the National “Digital Seismic Observation Network Project”. The new generation instrument has a strain resolution of 5×10^{-11} , response frequency range of

DC-20Hz, and can record solid tidal strain clearly. The four-component of strainmeter provide a way to cross check reliability of the measurements, since three components are enough to determine the horizontal strain tensor components. The author was trying to show several pre-seismic strain anomalies had been observed before large earthquakes. I hope the raw data can be used to calculate ε_θ , ε_ϕ , $\varepsilon_{\theta\phi}$ and σ_θ , σ_ϕ , $\sigma_{\theta\phi}$ in the future to help us understand the long term stress tensor variations.

There are three papers discussing different aspects of Wenchuan earthquake in this issue. Numerous aftershocks of Wenchuan earthquake provide an opportunity to study the b -value characteristics, especially the depth distribution of b -value for aftershocks after accurate relocation of the focus. Feng et al not only find out the b -value variation at different segment of the Longmenshan fault, but also find out the b -value variation with depth. The b -values show an increase from <5 km to 5–10 km and decrease >10 km. It is interesting that the stress envelope during brittle-ductile transition in the crust show similar pattern. The physics behind the phenomena is worth to be studied throughly.

Horizontal coseismic deformation of Wenchuan earthquake has been widely discussed since GPS data are now relatively easy to be obtained. Preseismic and postseismic repeat leveling are more difficult to carry out, but Wang et al provided valuable coseismic vertical deformation of the $M_s 8.0$ earthquake from such repeat leveling observation. With respect to the reference point at Pingwu county town, they found the hanging wall of the Yingxiu-Beichuan-Nanba thrust fault coseismic uplift with a maximum of 4.7 m at a site 100 m west of the fault scarp in Beichuan county. The foot wall of the Yingxiu-Beichuan-Nanba thrust fault subsides with a maximum subsidence of 0.6 m near the rupture. With a listric dislocation model to depth of 18 km and uniform thrust-slip of 5.6 m, they can explain the observed coseismic vertical deformation very well.

Wenchuan earthquake is believed to occur on a listric thrust fault, its dip varies with depth. Erslev (1991) proposed the trishear fault-propagation folding model to interpret listric thrust fault formation. Hardy and Ford (1997) further developed numerical modelling of such trishear fault-propagation folding. Bradshaw and Zoback (1988), on the other hand, suggested changes of mechanical properties to produce stress refraction and variations of the state of stress to produce listric normal faulting. In this volume, Xie et al use a 2-D finite element model to investigate the effect of the depth variation of Poisson's ratio on the state of stress. They found that if the Poisson's ratio in the fault increases, the angle between the maximum principal stress and the fault plane will decrease. They attribute the seismogenic process of the Wenchuan earthquake to a decrease of the fault strength associated with an increase in Poisson's ratio. They also use a lateral depth-dependent displacement boundary condition, which assumes horizontal displacement increases linearly with depth in the crust. Many researchers have been wondering about how deep the GPS observation can be extrapolated to deep crust, the suggestion of Xie et al may arouse more discussions.

GPS observation has been widely applied to determine coseismic deformation of large earthquakes in China, Jin and Wang applied Hori's inverse method which is based on spectral decomposition to estimate coseismic slip distribution on the rupture plane of the 14 November 2001 $M_{\text{S}}8.1$ Kunlun earthquake using GPS survey results. A smoothed fault is plotted on a grid of 2106 elements for numerical computations. The results show purely left-lateral strike-slip mainly concentrated along the eastern segment of the fault rupture, with a maximum about 7 m. Their results constrained by geodetic data are consistent with seismological results. They believe that Hori's method for GPS inversion is effective, but relies closely on the density of GPS sites around the fault, therefore, combination of GPS and InSAR data may lead to more useful results.

Earthquake slip produce coseismic changes in stress field and the variation of stresses may affect subsequent occurrence of other earthquakes. The background stress field, however, is not well known, therefore idea of Coulomb failure stress change has been proposed and widely applied in China for stress triggering or stress shadow analysis. In this volume, Wang et al analyzed the static Coulomb failure stress changes produced by the Yutian $M_{\text{S}}7.4$ earthquake and Wujia $M_{\text{S}}6.9$ earthquake. They confirmed that $M_{\text{S}}\geq 3$ earthquakes did

occur in the positive Coulomb stress change region in the central segment of Tianshan Mountain, Kalpin block and Kashi-Wujia joint region. It should be noted that Coulomb failure stress is a way to get around the difficulty of unknown background stresses; however, regions of largest Coulomb stress change may not be close to failure if the background stresses are low. The best way for estimation of future earthquake activity still is the direct measurement of the tectonic stress field. Even for accurate calculation of shear stress variations on the fault during Coulomb stress computation, understanding of the tectonic background stress is necessary (Shi and Cao, 2009).

Characteristics of tectonic stress field before major earthquakes are discussed by Wan et al. In this issue they investigate the focal mechanism orientations of small earthquakes in southern California from 1982 to 1999, and find that for the two large earthquakes occurred in southern California, the 1992 $M_{\text{W}}7.3$ Landers and the 1999 $M_{\text{W}}7.1$ Hector Mine, the orientations of regional seismicity focal mechanisms tend to converge to a state with principal stress direction promoting seismic rupture about half-year before its occurrence, suggesting that the tectonic stress field gets more organized in favor of the rupture of the forthcoming event. It is a direction in future study to combine investigations of both background stress field and coseismic Coulomb stress changes.

In the calculation of Coulomb failure stress change, pore pressure is an important, but not well known, parameter. Zhang et al tried to calculating the Skempton's coefficient B from groundwater data. Based on linear poroelastic theory of ordinary isotropic, linearly poro-elastic solid and under the undrained condition, they deduced equations for calculating the Skempton's coefficient B directly from the relationship between water level and tidal strain. They applied their method to Changping station before and after the Wenchuan $M_{\text{S}}8.0$, and found out there's a slight change of the value of B after the seismic waves passed by. This may lay light on the mechanism of earthquake triggered in the far field by great earthquakes, such as the remote triggered earthquake swarms in Yellowstone by the $M_{\text{W}}7.9$ Denali earthquake (Husen et al, 2004).

The overall tectonic stress field and tectonic movement of China are of basic importance in the study of earthquake activities in China. In this issue, Wang et al summarize Chinese 1 683 GPS data and Quaternary faults data, divide the Chinese continent into 31 blocks,

and apply a method developed by McCaffrey (2005) and Wallace et al (2004) to analyze the block motion of China. Their study supported a mainstream thinking in Chinese seismological community (e.g. Zhang and Zhu, 2000): Chinese mainland is cut by active fault zones into blocks, significant deformation is localized along fault zones of 50–100 km wide with slip rates in a range of 6–18 mm/a for the major faults in Tibet and its margins and 1–4 mm/a in eastern China, strains inside the blocks are quite small at a level of $\sim 10 \times 10^{-9}/a$.

Tectonic and stress environment are related to earthquake occurrences. Xu and Zhao discuss the relation between normal fault earthquakes and geothermal active regions in Tibet. The E-W extension of crust in the southern Tibet crust may produce both the active geothermal feature and the normal fault earthquakes in the upper crust. However, catalogs used by Xu and Zhao suggest normal earthquakes also occur in the lower crust and upper mantle in the same region, this is in conflict to the common belief that the Tibetan lower crust is ductile and not in favor of occurrence of brittle failure of earthquakes, and the mantle earthquakes may be related to the underthrust cooler Indian lithosphere. Therefore, it is very important to confirm the accuracy of focal depths. If the focal depths are reliable, the physics is a very interesting problem to explore.

Accurate locating of earthquake is important for research of seismicity, earthquake geology, and earthquake physics. Lou et al employ a double-difference algorithm (hypoDD) to relocate the shallow and intermediate-depth earthquakes beneath the Pamir-Hindu Kush Region in the period of 1964–2003 reported by the International Seismological Center (ISC). The improved hypocentral locations delineate a double-layered Wadati-Benioff zone in the eastern Hindu Kush intermediate seismic belt. They propose that the intermediate-depth earthquakes beneath the Pamir-Hindu Kush region may occur in two collided subduction zones with opposite dip directions.

A doublet of earthquakes, $M_{6.2}$ earthquake of 21 July, 2003 and $M_{6.1}$ earthquake of 16 October, 2003 occurred in Dayao, Yunnan province. Wang et al noticed their aftershocks are different not only in depths, but also in earthquake mechanism. They use the maximum amplitude ratios of vertical component of P and S waves recorded by a regional network to determine the 921 focal mechanisms of Dayao earthquake doublet sequence (389 focal mechanisms of the first and 532 focal mechanisms of the second quake). A focal-mechanism

consistent parameter a is defined to describe the similarity of mechanisms of different earthquakes. The focal mechanisms of the first aftershock sequence are more consistent than those of the second. This doublet provides insights into earthquake clustering, triggering and stress cycling

Earthquake forecasting is an important task for institutes of China Earthquake Administration, Therefore, in China, studies in stress, strain and seismicity often seeks connections with the goal of earthquake forecasting. Wang et al present two statistical methods of earthquake corresponding relevancy spectrum (ECRS) and sliding mean relevancy (SMR). A η -value is defined for the deviation between the actual magnitude-frequency curve and the Gutenberg-Richter relation. They test the method by taking the time sequence of η -value in the northern Tianshan region as original data. The result shows that with a time-interval of 18 months, the precursor anomaly can be identified better. The anomaly corresponding rate can reach 83 percent; the earthquake corresponding rate is 86 percent. They also try a multi-parameter comprehensive analysis for Kalpin tectonic block in Xinjiang region, and analyze the spatial and temporal abnormal characters of multi-parameter sliding extreme-value relevancy (MSER) before mid-strong earthquakes. The result indicates that ECRS and SMR sequence in different time-intervals can not only be used to identify the precursor anomaly of single-item data, but also offer the data of quantitative single-item anomaly for comprehensive earthquake analysis and prediction.

In pure elastic media, stress and strain are simply linearly related according to Hooke's law. Unfortunately, lithosphere is not purely elastic, but with complex rheological features; and crustal deformations are not continuous, but cut by faults. Therefore, both stress and strain must be independently measured, and their characteristics and rheology of the crust must be integrated studied. This volume touches many of the frontier issues in the research of stress field, crustal deformation and earthquake activities, and is hopefully to attract comments from seismological community.

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