Stress evolution before the 2014 Ludian M6.5 earthquake: Insights from groundwater and geodetic measurement

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Abstract. Because the meta-instability stage before an earthquake can be found in rock-deformation experiments in the laboratory, great expectations are placed on the detection of possible precursors in earthquake forecasting and prediction. However, varietal observations are difficult to compare, and it is very difficult to distinguish to which stage the observed value belongs. The top priority is to study the relationship between the observations and the meta-instability stage in a uniform system of measurement. The 2014 Ludian M6.5 earthquake, which occurred in the southeastern region of the Qinghai-Tibet Plateau, was surrounded by 122 observatories for groundwater, electromagnetism, and surface deformation within a 300-km radius. Many data were observed before and after the Ludian earthquake, which provided a great case to study the relationship between the observations, stress evolutions, and meta-instability stage before the earthquake. We determined the detailed spatiotemporal variations in groundwater temperature, water level, chemical ion measurement, and crust deformation by strain meter and tilt meter. Following the previous study on the relationship between the observations and stress field, we simply classified all these data from 78 observatories into three groups: stress
increased, stress disturbed, and uninfluenced. The results show that the stress field displayed a four-quadrant pattern around the seismogenic structure of the 2014 Ludian earthquake, which is called the Baogunao-Xiaohe Fault and is known as a buried branch fault of the Daliangshan fault. Along with the orientation of fault-block movement, the stress decreased at the back while increasing at the front. In addition, some stress perturbations were found along nearby large active faults, such as the Xianshuhei-Amminghe-Zemuhe-Xiaojiang fault zone, which is a deep-cutting active fault belt confining the Sichuan-Yunnan block. Based on the spatiotemporal evolution of the stress field and distribution of aftershocks, we simplified the seismogenic structure to a set of conjugated strike–slip faults. The nonlinear friction finite-element method was applied to simulate the stress variations before and after earthquake, and the ability of the system to detach earthquake precursors and determine whether the earthquake system is in the meta-instability stage can be distinguished from our simulation. Our research can be used to help predict earthquakes, precursors and determine whether the earthquake system is in the meta-instability stage.

1 Introduction
The ability to observe the meta-instability stage before an earthquake via rock mechanics experiments is expected to become a strong tool for earthquake prediction [1–2]. A real case has been sought to determine whether the meta-instability stage can be trapped. However, the sparse observation sites, lack of observational standards, and ambiguous relationships between the abnormal data and the stress have resulted in few ideal real-world examples.

On August 3 of 2014, the Ludian $M_S 6.5$ earthquake occurred in the Sichuan-Yunnan region. Compared with other moderate to large earthquakes that occurred in the Sichuan-Yunnan region in the last two decades, such as the 2008 Wenchuan $M_S 8.0$ earthquake, 2014 Kanding $M_S 6.3$ and $M_S 5.8$ earthquakes, 2017 Jinggu $M_S 6.6$ earthquake, and 2017 Jiuzaigou $M_S 7.0$ earthquake, we found that the foundation detection work of the 2014 Ludian earthquake was great and the seismogenic structure had been determined by consensus. Most importantly, there were many observation stations around the epicenter of the Ludian earthquake. These stations had recorded groundwater and geodetic measurements before and after the $M_S 6.5$ earthquake. Further, these abnormal data were mostly triggered by the Ludian earthquake because there were no other major events in the local region. Therefore, the observation data before the Ludian earthquake may be a good example with which to study the meta-instability stage.

Using these valuable observation data, this article reorganizes the specific data before the 2014 Ludian earthquake, represented and simulated their spatial characterize, trying to explain these observations using the thesis of the meta-instability stage before an earthquake.

2 Seismic source parameters and Observation stations

2.1. Seismic source parameters
The 2014 Ludian $M_S 6.5$ earthquake struck off the south boundary of the Daliangshan sub-block in the eastern margin of the Tibetan plateau (Fig. 1). Focal mechanism solutions
show that the main event was nearly pure sinistral strike–slip and most aftershocks were strike–slip with similarly nodal planes [3]. The relocated aftershocks indicate that a portion of the conjugate structure was involved in the Ludian earthquake and aftershocks, trending NNW and E–W, respectively [4]. Emergency investigation after the earthquake illustrated that the NNW trending of the Baogunao-Xiaohe fault was the seismogenic structure of the Ludian earthquake. The Baogunao-Xiaohe fault is a branch fault with similar trending to the Daliangshan fault, which is a newborn active fault with very high seismic hazard risk cutting across the Daliangshan sub-block [5]. The Baogunao-Xiaohe fault cuts through the NE trending fault of the Zhaotong-Ludian fault, which comprises the south boundary faults of the Daliangshan sub-block [6].

Figure 1. Observation stations and the epicenter of the 2014 Ludian earthquake

2.2. Observation stations
There are 122 observation stations within 300 km of the epicenter: 79 seismology stations and 79 precursor stations, including 35 monitoring types and 290 items in total, such as water level, water geochemical survey, and crustal tilt. According to previous statistics, there were 48 anomalies from 18 stations before the Ludian earthquake [7–8], although some of these
were found after the earthquake. The number of anomalies is large and they are concentrated within the space.

Based on previous analysis of precursor anomalies [7–8, 9], we determined that the 48 anomalies mainly developed within one year before the earthquake. These anomalies were concentrated along the Zemuhe-Xiaojiang fault and the Zhaotong-Ludian fault, which are two nearby boundary faults of active blocks. All of these anomalies were found in the groundwater and geodetic measure monitor stations. No anomalies were found by the electromagnetism station.

We characterized the anomalies based on the relationship between the monitor items and the stress field. The groundwater level and water temperature are probable signs of stress intensification. Other items are signs of a disturbed stress field, such as fluoride ions, calcium ions, and water-tube tilt. Therefore, we classified the 48 items into two groups, stress intensification and stress distribution, as shown in Fig. 2. The distributions of the anomalies show a pattern similar to the four quadrants commonly found in strike–slip fault propagation.

Figure 2. Reclassification of anomalies and their relationships with stress variations

Simulation of the anomalies before the Ludian earthquake

2.3. Methods
We employed a nonlinear friction finite-element method (FEM, Parallel Adaptive Nonlinear Deformation Analysis System) [10] to simulate the fault behavior and evolution of stress fields before the $M_S$ 6.5 Ludian earthquake. This nonlinear friction FEM has been used to simulate the fault behavior in multiple fault bend models and the seismic cycle evolution of faults, e.g., for the 2008 Wenchuan $M_S$ 8.0 earthquake [11].

Both quasistatic and dynamic finite-element-based solvers and computational models were applied to simulate the dynamics and evolution of multiply faults. The dynamic phenomena were considered, including the slow quasistatic stress accumulation and the rapid dynamic rupture, corresponding stress redistribution due to the accumulated energy release along the multiple fault/plate boundaries. An R-minimum method was used to formulate the contacts between nodes and perform time integration [10].

2.4. Models

Based on the above analysis of anomalies and two branches of aftershock distribution, we built a simplified three-dimensional FEM model with a length and width of 100 km, as shown in Fig. 3. Our model was rotated by an angle of 45°, such that the positive X and Y axes are SE and NE, respectively, and 31548 hexahedral meshes were used. Velocity boundary conditions were applied according to a GPS field. A group of four perfectly symmetrical strike–slip faults with an angle of nearly 45° was set to simulate the fault behaviors of earthquakes and anomalies. All the friction parameters of the nodes on the fault planes were set the same. The model used homogeneous materials with the Young's modulus and Poisson's ratio of granite: 40 GPa and 0.25, respectively.

![Figure 3. (a) FEM Model and (b) corresponding geographical location](image)

2.5. Results

After loading the boundary conditions to 500 steps, our model represented the fault surface offset with a first-order approximation of the Ludian earthquake. We obtained the spatial and time evolutions of the shear stress field, direct stress field, and von Mise stress field, as well
as the relative strain data. Due to length restrictions, we only present and discuss the shear stress velocity (change in shear stress within the cost time in one step) and accumulated shear stress in the XY direction.

3 Discussions

The shear stress velocity field (Fig. 4), which presents the stress change rate per step, illustrates the fault behavior in each step. As the boundary conditions are loaded, several nodes on the fault plane slip off and out of contact. Around every set of propagating fault segments, the disturbed shear stress velocity field displays a six-petal pattern, rather than an eight-petal pattern, because the segments only contain two or three fault nodes out of contact. This means that these small offsets could represent little or no earthquake. Because of the complete symmetry in our model, the shear stress caused by these small offsets showed alternating increment and decrement on different fault planes.

![Shear stress velocity field in XY direction](image)

Figure 4. Shear stress velocity field in XY direction

As the boundary conditions are loaded further, some new fault nodes became out of contact while some fractured nodes returned to being in contact, similar to fault healing. After loading to 300 steps, two longer fault segments, located in the central of the model fractured with a length of about 14 km, which is approximately the length of the aftershock sequence distribution. Therefore, we have confirmed that the moderate offset was the simulation of the Ludian earthquake.

Before the Ludian earthquake, both sides of the fault segments locally ruptured and tended to expand. These fractures of small segments produced positive shear stress variation.
We compared the stress fields with the distribution of anomalies, but the stations were mostly located out of the fault planes of the model. The stress variations near the origin point may have corresponded to the anomalies along the Zemuhe fault; however, the boundary effect cannot be ruled out.

The accumulated shear field in the XY direction (Fig. 5), which recorded all the shear stress accumulated since step 1 of loading, illustrated a similar stress evolution. Before the Ludian earthquake, the local small fault fractures had resulted in a very complex stress field wherein the stress increments and decrements had become intertwined. The region far from the fault plane, where the increased stress anomalies were located, showed that the stress had increased before the Ludian earthquake.

Figure 5. Accumulated shear stress in the XY direction

4 Conclusions
A simplified simulation of the distribution of anomalies before the Ludian earthquake has been presented. The simulation represents the rupture of the Ludian earthquake and the stress evolutions preceding it. It also indicates that the small fault fractures before moderate to large earthquakes may be unstable. The small fault or fractures may experience a complex process of breaking, healing, and breaking again. However, the accumulated stress field is relatively stable and showed a tendency to expand the stress variation in the region, regardless of increments or decrements.

The anomalies before the Ludian earthquake show curve turning corresponding to the meta-instability stage before an earthquake. We suggest that the turning may be connected with the unstable local fault breakage and healing. However, the static stress evolution in this paper only simulates the anomaly distribution. We have only represented the stages before the
meta-instability stage, including the expansion of the abnormal range and the increments of abnormal items.

Therefore, we need to carry out a detailed step-by-step analysis of the stress simulation and spatiotemporal evolution of anomalies to characterize the meta-instability stage before the Ludian earthquake.

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