

A Review of Aftershock Mechanism Research¹

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In this paper, research of aftershock mechanisms is reviewed, including heterogeneity of medium and stress, mechanical loading, fluid intrusion and stress corrosion, and rate-state dependence. Previous studies have indicated that the heterogeneity of media and stress is the basic premise of aftershocks generated. From the point view of mechanics, transient creep and afterslip can explain the decay of aftershocks in a short time after a mainshock and the relaxation of stress tends to interpret the characteristics of long-term aftershocks. Fluid intrusion and stress corrosion control the evolution process of the aftershocks under certain conditions. The interaction between the faults perturbed by the mainshock always exists during the aftershock activities. All kinds of models and the theories want to comply with the two basic power-law relationships—the G-R law and Omori law to some extent.

Key words: Aftershock sequence; Mechanism research; Medium heterogeneity; Stress relaxation; Modified Omori law

INTRODUCTION

After a large earthquake, more seismic activities are observed in the focal region and its adjacent areas. The obvious increased seismicity is called an aftershock, the greater earthquake before is named the mainshock and a series of aftershocks after the mainshock constitute the aftershock sequence. Generally speaking, the aftershock sequence gradually weakens and sometimes has ups and downs. The time when the aftershock activities begin to mix with background seismicity is known as the aftershock activity duration.

The aftershock sequence is one of the enduring seismology research fields. Aftershock sequence type determination, the maximum magnitude aftershock prediction and sequence activity duration estimation are the most important contents of evaluation of post-earthquake trends, as

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well as the most concerned problems of post-earthquake relief and reconstruction for the government and public. In order to meet actual needs, long-term statistical research for aftershock sequence has been carried out in China and the results play an important role in earthquake emergency response (Wu Kaitong et al., 1990; China Seismological Bureau, 1990; China Seismological Bureau, 1998; Jiang Haikun et al., 2007a). In general, domestic research of aftershocks is based on the statistical analysis of a large number of earthquakes and focuses on practical application, but less on the mechanism of aftershock activities. In fact, since the aftershocks are frequent and their epicenters are concentrated, there are a large number of observations available, so it is an important way to research the observed phenomena of the aftershock sequence and its physical mechanism for the understanding of the earthquake process and seismogenic environment. By contrast, scientists abroad have attached great importance to and have done much research on the mechanism of aftershock activity. The modified Omori law, $n(t) = K(t + c)^{-p}$, is the best description of the frequency decay of the aftershock sequence with time. In his article, published to commemorate the 100th anniversary of Omori law, Utsu et al. (1995) analyzed and summarized the calculations of more than 200 global p -values from 1962 ~ 1965, and found that the p -value distribution was between 0.6 ~ 2.5 and the average was 1.1. Recent further research (Rabinowitz et al., 1998; Stephan et al., 2004; Gentili et al., 2008; Öztürk et al., 2005) is in accord with these findings. Although the relationship between p and mainshock magnitude and the lower limit magnitude of sequence is not obvious, the p -value in different periods after the earthquake is different (Eaton et al., 1970; Lu Yuanzhong et al., 1983; Latoussakis et al., 1994; Drakatos, 2000; Jiang Haikun et al., 2008). The explanation for the c value in modified Omori law has been always controversial. According to past experience, c has a relationship with the time of incomplete records after the mainshock (Kagan, 2004; Kagan et al., 2005; Lolli et al., 2006). Recent research points out that c can not only support physical interpretation for rapid decay of aftershocks a short time after the mainshock (Enescu et al., 2007; Peng et al., 2006; Lindman et al., 2005), but is also related to the mainshock focal mechanism (Clement, 2009), which means that aftershock decay is controlled by stress state. Since strong aftershocks are often accompanied by higher-order ones, that is, sequence activity has the characteristic of "aftershocks triggering others". Ogata (1988, 1989) introduces a self-similar theory to study aftershock sequence activity. According to the thought that any earthquake can produce its own higher-order aftershocks, the ETAS (Epidemic Type Aftershock Sequence) model is established.

The ETAS model is the extension of Omori law, the parameters of which have some regional characteristics and are connected with mainshock size, the type of seismogenic fault and the type of aftershock sequence (Guo et al., 1997; Jiang Haikun et al., 2007b). As a complete earthquake sequence set, it follows G-R law. In most cases, b in G-R law is in the range of 0.6 ~ 1.1 (Utsu, 2002). The b -value is different in other regions and relatively low during strong earthquake activity. The intensity of aftershock activity is proportional to mainshock magnitude. The magnitude difference between mainshock and maximum aftershock is in the range of 0 ~ 3 (Kisslinger et al., 1991). The aftershock distribution scale is roughly the same as the mainshock rupture scale which has a relationship with physical processes, such as stress drop or strain release, so the logarithm of aftershock distribution scale is proportional to mainshock magnitude (Utsu, 1961; Wu Kaitong et al., 1990; Wells et al., 1994; Biasi et al., 2006). From the observation point of view, the aftershock sequence meets two important power law statistical relationships, which are G-R law describing the relationship between magnitude and frequency and Omori law representing aftershock decay with time. At present, one of the main standards to measure whether the model is good or bad is to achieve the two basic laws in most of the research on the mechanism of the aftershock activity.

1 RESEARCH ON THE MECHANISM OF AFTERSHOCK ACTIVITY

1.1 *Result of Tectonophysical Experiment*

The research on aftershock sequence type and activity mechanism originate from tectonophysical experiments, the most important of which are those by Mogi (1962, 1963) and Scholz (1968a, 1968b, 1968c), who first introduced the heterogeneity of medium and stress. Rock fracture experiments by Mogi (1962, 1963) have been widely accepted and referenced. According to the experiments, the uniform, slightly uneven and extremely uneven medium and tectonic conditions respectively correspond to mainshock-aftershock type, foreshock-mainshock-aftershock type and swarm type. Scholz (1968a, 1968b, 1968c) focused on number changes of acoustic emissions with time after instability with rock uniaxial compression experiments. He points out that if a system is no longer pressed after the main-failure, number decay of acoustic emissions with time will follow Omori law. In order to explain the relationship between aftershock and time decay after the mainshock and the result that aftershock frequency decay follows Omori law, Scholz (1972) presented static fatigue or creep rupture, which considers that medium heterogeneity leads to heterogeneity of stress distribution and the stress unit forced heavily is strongly corroded and quickly ruptured. At the beginning, the mean stress is large, so the aftershock activity is strong. With the mean stress decaying, the aftershock frequency also decays gradually. In addition, the fracture experiments of some researchers (Hirata Takako, 1990; Tang, 1997; Tang et al., 1993) addressed the influences of sample heterogeneity on the sequence type of micro-earthquakes, such as the uniaxial compression rupture experiment by Hirata Takako (1990) which uses Murata Basalt in constant stress. The pulse time series also divides into foreshock-mainshock-aftershock type, mainshock-aftershock type and swarm type, and the decay patterns accord with Omori law.

1.2 *Impact of Medium Heterogeneity*

The heterogeneity of seismic faults in geometry, mechanics and physical properties is confirmed in friction experiments and seismic observations (Scholz, 1990). As an important concept describing the difference of rock strength, asperities and barriers in the study of medium heterogeneity influence on the aftershock sequence are often mentioned (Mogi, 1977; Kanamori, 1981; Brune, 1979; Ben-Zion et al., 1993; Somerville et al., 1999; Yamanaka et al., 2004; Hidet et al., 2009). The asperity model illustrates that asperity strength on the fault surface is relatively stronger and bears all the stress (Aki, 1979, 1981, 1984), which can explain precursory seismic activity images, such as background earthquake activity in the focal and adjacent area before the mainshock, seismic quiescence, and foreshock (Kanamori, 1981). The barrier model is based on the idea that strength on the fault surface is different and barriers restrain and suspend the fault rupture (Aki, 1979, 1984). The model is often used to explain the aftershock mechanism (Aki et al., 1977; Aki, 1979; Das et al., 1977; Papageorgiou et al., 1983a, 1983b). If the tectonic stress is relatively high, the barrier is broken as the crack tip passes and the sequence that has few foreshocks and aftershocks belongs to the isolated type. If the tectonic stress is relatively low, the crack tip proceeds beyond the barrier, leaving behind an unbroken barrier, which belongs to the swarm type. If the tectonic stress is intermediate, the barrier is not broken at the initial passage of the crack tip but eventually breaks because of subsequent increase in dynamic stress, hence, forming the foreshock-mainshock-aftershock type.

1.3 Impact of Stress Loading Press

In addition, much research discusses the characteristics of the aftershock sequence activity from the view of stress change. The rupture process of a violent earthquake is usually not more than hundreds of seconds, but strain adjustment of the large land block involved in the linear scale of hundreds of kilometers may not complete the elastic recovery process in a short time. Thus, creep will continue after the mainshock. Benioff (1951) adopts the material rheological model of the elastic creep and explains statistical properties of aftershock activity decaying with time. When the loading stress is repealed and elastic strain appears, the subsequent creep process is known as the decay process of aftershock activity. Thus, time-space variation of aftershock activity may be closely related to the rheological properties of rock. Chen et al. (1987) proposed a complex and patulous earthquake sequence model and its numerical simulation under the inhomogeneous stress field in the viscoelastic medium. He believes that the main mode of crack sliding and growth is a kind of creep. The result shows that the earthquake sequence types are controlled by the stress level and heterogeneity. The isolated type earthquakes usually occur under the high pre-stress or low cracking strength. The foreshock-mainshock-aftershock type earthquakes turn up under intermediate pre-stress and intermediate cracking strength. The swarm type earthquakes emerge under low pre-stress or high cracking strength. Overall, the phenomena of aftershocks rapidly decaying in the early short time after the mainshock can be explained by transient creep and the afterslip model (Benioff, 1951; Mikumo et al., 1979; Perfettini et al., 2004, 2007), then, aftershock activity after a long period of time can be reasonably interpreted by the viscoelastic relaxation of the lower crust and upper mantle (Deng et al., 1999; Freed et al., 2001).

1.4 Aftershock Sequence Simulation Based on the Physical Concept Model of Rheologic Properties

The numerical simulation of a seismic activity process is an important means to study the complexity of seismic processes, and generally is divided into two methods with different characteristics. One kind attempt to really simulate the actual fault and the process of fault movement, analyze the kinematic and dynamic characteristics of a fault system and the relationship with strong seismic activity. The finite element and similar methods are typical representatives of this kind. The rationality of the simulations depends on the initial and boundary conditions and the match with actual situations. Another kind is mainly from the physical concept of holding the key and possible influencing factors of the seismic activity, using the highly generalized, simple physical model and evolution rules to simulate the most essential features of actual seismic processes, such as the spring block model and sandpile model, which are focusing on the most significant statistical characteristics of the seismic activity process, catching hold of the most likely physical essence and simulating the complex seismic phenomenon and group activities of earthquakes based on physical concepts and simple evolution rules. Because the composition of the mainshock fault surface and the stress changes of the aftershock process are extremely complex and aftershock activities are highlighted, consistent statistical characteristics, many researchers carry out aftershock mechanism research on the basis of the physical concept model. On the one hand, this kind of research is based on brittle fracture (Griffith, 1920, 1924) or stick-slip instability (Bowden et al., 1950, 1964; Brace et al., 1966). On the other hand, it is based on the stress relaxation process of viscosity and simulates the aftershock process by stress changes. Burridge et al. (1967) first introduced viscous friction into a simple one-dimensional spring-block model and simulated the aftershock process. Based on the above, Dieterich (1972) verified viscoelastic properties and friction time-dependent influence on aftershocks by numerical

simulation. According to research on the San Andreas fault, Yamashita (1979) pointed out that the stress relaxation process of viscosity is the main cause of aftershocks and put forward the essential conditions of aftershocks: ① local stress field is perturbed during the mainshock; ② the initial creep phenomenon can be observed in the perturbed area; ③ the aftershocks' seismogenic fault has a long time stress accumulation; and ④ the stress adjustment instantly generated by mainshock is close to the static friction value of the fault. Deng et al. (1999) used a finite element model with an elastic upper crust, a weaker viscoelastic lower crust and a stronger upper mantle to model the aftershock sequence associated with the 1994 Northridge thrust-faulting earthquake. Based on a good correlation between aftershock hypocenters and stresses transferred from the viscoelastic lower crust, Deng et al. (1999) concluded that viscoelastic relaxation could have a first-order influence on the triggering of Northridge aftershocks. Most aftershocks within the rupture zone, especially those occurred after the first several weeks of the mainshock, may have been triggered by continuous stress loading from viscous flow. The long-term decay time of aftershocks (about two years) approximately matches the decay of viscoelastic loading, and thus is controlled by the viscosity of the lower crust. Zhang Guomin et al. (2003) put forward the spring-block model of rheologic property and composed of two parts in parallel. The upper part is spring-block in series to model the upper crust with elastic deformation and brittle fracture and the lower part is the Maxwell solid to simulate the lower crust with plastic flow deformation. When the block suddenly slides (fast fracture of seismic source), the stress of the seismic source from the upper crust drops to 0 and the total stress drops to the stress of the lower crust, it means the system evolves to the post earthquake period (aftershock period). The stress from the lower crust (the stress from the Maxwell solid) is transferred to the upper crust through creep, so the upper crust stress gradually recovers. When the stress of the upper crust rises to the strength of the connected section, the section will fracture and generate aftershocks. Gu Jicheng et al. (1979) adopted fracture mechanics criterion of crack instability extension and the upper mantle material rheological model to interpret the time distribution of strong aftershocks. According to their model, the time interval between two strong aftershocks has a double logarithmic relationship with the time after the mainshock. On the basis of the dynamic fracture process of nonuniform friction faults, Mikumo et al. (1979) introduced the shearing stress and strength recovering with time after the main fracture and adopted a standard linear solid composed of Maxwell and elastic spring elements to model the stress recovery mechanism of viscoelastic material. If the external load doesn't change, the stress of sliding unit decrease will recover with time. On the contrary, the high stress on a non-ruptured unit will relax with time. The simulation results show that the magnitudes of aftershocks are decided by the shear stress of the aftershock occurring and medium intensity. Perfettini et al. (2004) evaluated the effect of coseismic stress changes to brittle creeping slip at mid-crustal depths, assuming a velocity-strengthening rheology. Given that the seismicity rate might be considered proportional to the sliding velocity, the model predicts a decay rate of aftershocks that follows Omori's law and results in an inverse relationship between the Omori law parameter c and the magnitude of the mainshock. This implies that the smaller the duration with an initially constant rate, the larger the stress change. Applying the model to the 1999 M_w 7.6 Chi-Chi earthquake in Taiwan, the same depth afterslip model can explain the temporal evolution of both aftershock and postseismic deformation. According to further analysis of postseismic deformation, the occurrence of the 1992 Landers earthquake is a result of frictional afterslip reloading the seismogenic ductile-brittle zone. The temporal and spatial distribution of aftershock sequence is consistent with frictional afterslip (Perfettini et al., 2007).

1.5 The Effect of the Fluid Invasion and Stress Corrosion

As the aftershocks almost appear simultaneously in the entire rupture after the mainshock,

they are unlike the earthquakes happening in front of fluid diffusion and migrating along a certain direction (Scholz, 1990). In addition, the dry rocks under pressure can also produce an acoustic emission sequence just like the mainshock-aftershock type sequence, so fluid is not necessarily the essential factor for aftershocks (Takayuki et al., 1987; Hirata, 1987). However, the slide of the fault causes fluid diffusion and leads to time-related physical reactions around the fault. This time lag dependency is thought to be important in excitation and migration of aftershocks and the process of the earthquake swarm activity (Nur et al., 1972; Rudnicki, 1986). Interstitial fluid causes an earthquake by reducing the rock strength or shear stress intensity of the fault, such as a reservoir (Talwani et al., 1985; Roeloffs, 1988; Pandee et al., 2003), groundwater recharge (Saar et al., 2003), fluid injection (Zoback et al., 1997; Shapiro et al., 2003; Lei et al., 2008) and rainfall induced seismic activity (Husen et al., 2007; Jiang Haikun, 2011). The model that is based on isotropic, infinite elastic space and simple pore fluid diffusion hypothesizes that the aftershock frequency in the focal region is proportional to the partial derivative of pore pressure with time, so the decay of aftershock frequency with time is qualitatively consistent with Omori law (Nur et al., 1972). The relationship between spatial distribution of the actual pore pressure and the coseismic slip distribution is very close. Based on the interstitial fluid diffusion model (Nur et al., 1972), Bosl (2002) simulated the decay process of the 1992 Landers aftershock sequence in combination with the actual situation of the Landers faults. Results show that the interstitial fluid diffusion model can simulate the decay rate of the Landers aftershock sequence, and simultaneously give the non-zero c -value of the Omori law. Miller (2004) studied the migration issues of Umbria-Marche earthquake sequence in the north of Italy, believing in high-pressure CO_2 fluid under the Apennine Mountains, and simulated the fluid flow along the fault with seismological data, with permeability of about 1 km/d. This result explains the temporal evolution of the distribution of the aftershock.

In addition to the triggering or inducing of an earthquake by fluid itself, the stress corrosion under the fluid intrusion is also thought to be the physical mechanism for the weakening, unlocking and delayed rupturing of the residual asperity area on the main rupture surface (Yamashita et al., 1987). Kanamori et al. (2004) believe that the crack tip of the fragile material can naturally develop and expand under the conditions of high temperatures or existence of fluid. When the crack reaches a critical state, the large rupture may come up on the fault plane because of stress corrosion, thus, weakening the crack tip and crack propagation. Based on the subcritical crack growth model, Kanamori (2004) considers loading the stress on a series of cracks under a constant rate, the loading process being controlled by stress corrosion. The stress disturbance will accelerate the crack growth, and the aftershock activity caused by this is consistent with the Omori law. He also obtained a c -value that is inversely proportional to the magnitude of the mainshock. Vinciguerra (1999) gave a good explanation for the active process of the Etna volcanic earthquake sequence in Italy, believing that the earthquake sequence after the Etna volcanic eruption was the result of the magmatic stress corrosion. The magma easily produced a chemical reaction with the country rock under the extremely high temperature, leading to the country rock weakening quickly and the concomitant gas accelerating crack growth. Ojala et al. (2003, 2004) conducted acoustic emission experiments with water injected Permian Aeolian sandstone, and found more small acoustic emission events under the low strain rate loading than that under high rate, thus believing that crack propagation is controlled by stress corrosion under the low strain rate loading.

1.6 The Aftershock Activity Simulation Based on the Rate-state Dependent Friction Law

The rate-state dependence is also used to explain the aftershocks mechanism. Once a fault forms, the further movement will be controlled by the friction. The regular stick-slip phenomenon

can often be observed in rock friction activity. As the earthquake is the recurring active instability along the pre-existing faults, Brace et al. (1966) believed stick-slip was the earthquake mechanism. Velocity weakening is an important reason for rock regular stick-slip under most conditions (Dieterich, 1979a, 1981). The rate-state dependent friction constitutive relationship is thought to be the main physical mechanism for the fault movement and the earthquake (Dieterich, 1994; Marone, 1998; Shibazaki et al., 2007, 2010; Hori et al., 2011). In the description of the earthquake process, the rate-state dependent friction constitutive relationship considers that the friction stress is related to the normal stress, temperature, slip rate and sliding history (Dieterich, 1979b; Ruina, 1983). Dieterich (1994) supposed that the normal stress is a constant, and the mainshock offers a sudden step of shear stress for the aftershock sequence. On this basis, the rate of aftershock activity based on the friction constitutive relationship of the rate-state dependence mainly depends on the stress perturbation amplitude, the physical characteristics of the fault (the constitutive parameters that control the fault rate-state dependent friction), the stress loading rate and background seismicity rate of the study area. The duration of the aftershock is negatively correlated with the loading rate, and the decay of the aftershock frequency with time is consistent with the Omori law. The decay is a constant in a short period of time originally, then shows a relationship of negative exponent with time. The c -value of the Omori law is related to the magnitude change of the static stress; the greater change with the stress, the smaller the c value is. Dieterich (2000) simulated the earthquake activities of Kilauea volcano based on the rate-state dependent friction constitutive relationship as the practical application, and found that the simulation results have a good consistency with the statistical results. Peng (2007) studied the aftershock sequence of 80 earthquakes with $M3.0 \sim 5.0$ recorded by the Japan Hinet network based on the rate-state dependent friction law and ETAS model, and inspected the variation of the p value in a short period after the earthquake. The results show that in the 20 ~ 900 seconds after the shock, $p = 0.58 \pm 0.08$, after 900 seconds, $p = 0.92 \pm 0.04$, the p -value gradually becomes larger by time. Combining the spatial distribution heterogeneity of the coulomb stress, Hainzl et al. (2008, 2010) focused on the impact of the uncertainty of stress on the parameters of the rate-state dependent friction constitutive relationship. Based on the parameters of the model for estimating the early-stage aftershocks of the 1992 Landers earthquake, Hainzl synthesized the static stress triggering and the rate-state dependent friction constitutive relationship to predict the subsequent aftershocks.

2 CONCLUSION AND DISCUSSION

(1) The results of tectonophysics experiments and the various types of numerical simulation studies show that the activity characteristics of the aftershocks are controlled by the structure of the main fault plane and the heterogeneity of the medium and the resulting heterogeneity of the stress. Thus, as the basis for studying the mechanism of aftershock activity, it is particularly important to build the heterogeneous model of the main fault plane. The asperity or barrier model focuses on the heterogeneity of the rock strength distribution of the fault plane. Although the asperity (heterogeneity or fault roughness) of the fault plane before the earthquake can be described by the local static slip and the slip rate of the fault plane after the earthquake (Miyaka et al., 2001; Yamanaka et al., 2004; Hidet et al., 2009), it is found according to the aftershock location results that the aftershocks inside the mainshock rupture plane are distributed mostly in the termination region of the main slip, the edge of the high-slip zone, conversion parts of the high and low slip zone, the edge of the uncracked barrier and the low slip zone (Mendoza et al., 1988a, 1988b, 1989; Hauksson, 2000; Madariaga et al., 2000; Das et al., 2003; Yamada et al., 2000). In fact, between the main slip and the aftershock distribution, there are so far no

deterministic law or characteristics, which bring challenges to building the heterogeneous model of the main fracture plane. The model should satisfy the two basic requirements. The first is to fit to the results of the heterogeneity of existing aftershocks rupture, the second is the intensity distribution of the aftershock sequence caused by the asperity rupture should satisfy the G-R relation in the stress interaction process.

(2) Another key issue for such studies is the fracture criteria set for the residual asperity in the main fault and the reasonable expression of the aftershock density. As a numerical simulation study based on the physical concept model, it goes without saying that the importance of model evolution rules. Enough attention should be given to the two issues: first, the rapid changes of the loading stress with time; secondly, the interaction and impact between the residual asperities of the fault. This interaction and impact could theoretically exist unlimitedly. From the simulation point of view, the area of asperity, the intensity of asperity, the initial stress, the failure stress drop and so on are known. When making a reasonable expression of the aftershock intensity according to these known parameters, we must meet the basic requirements. The first is that the model output aftershock magnitude should not breach the existing relationship between the magnitude, stress drop and rupture scale which is derived on the basis of focal theory, microscopically; and the second is that the aftershock sequence should satisfy the G-R relationship, macroscopically.

(3) Creep or afterslip model, rate-state dependent model and subcritical crack growth model can all explain the Omori law of the aftershocks frequency decay with time under the certain assumptions. Rate-state dependent, creep and afterslip models believe that the fault stress of the mainshock is the main reason for the aftershock, so the origin time of the aftershock has a relationship with the mainshock (Dieterich, 1994; Huc et al., 2003; Henry et al., 2001), but this relationship is not found in the intensive study of some actual aftershock observations (Gasperini et al., 1989; Shaw, 1993; Jones et al., 1998; Helmstetter et al., 2003), or this relationship is very weak (Peng et al., 2009). On the other hand, the stress relaxation process can explain long-term aftershock activity, and the stress relaxation model exists on the basis that the rheological properties of the fault control the decay rate of the aftershock. The study of the Southern California 45 earthquake sequence with mainshock magnitude $M5.0 \sim 7.0$ found that the aftershocks in a short time after the mainshock are related to the stress adjustment of the mainshock; the mainshock or the dynamic stress of the mainshock changes the coefficient of friction and the fault properties; but the late aftershocks are not controlled by the stress adjustment of the mainshock, they are decided by the sliding after the shock (Felzer K. R., 2010). Thus, the actual aftershocks process may not be all explained by a single model, but should be a combined effect with multi-stage and multi-process. Actually, when Perfettini et al. (2004) explained the aftershock process with the stress relaxation model, they adopted the multi-stage simulation process (the rheological model of velocity weakening nucleation and velocity enhancement). Thus, it is clear that in the aftershock activity process, the interaction (brittle fracture or the stick-slip instability) between the faults impacted by the stress perturbation always exists, and we can get the cognition of the decay of the aftershock sequence controlled by the rheological property of the fault only under the premise that it is without regard to the interaction between the faults.

(4) It should be noted that the study of explaining the aftershock sequence simulation with various models or the theories mentioned above, is aimed at the stress changes of the default model, and it is not able to simulate the real aftershock sequence, thus, it is also unable to investigate the similar degree between the theoretical simulation and the actual aftershock activity according to the direct calculation of the aftershock data. The study related to the decay (Omori law) of the aftershock sequence also assumes some kind of relationship between the aftershock

decay rate and the stress directly. For example, Perfettini et al. (2004, 2007) assumed that the aftershock decay rate is proportional to the slip rate of the creep fault, and Nur et al. (1972) assumed the aftershock frequency is proportional to the partial differential of the pore pressure by time, which analyzes and obtains the relationship between the parameter of the Omori law and the model parameters. Based on the heterogeneity of the mainshock's fracture plane, stress loading process and fluid invasion, aftershock sequence data is generated under different conditions simulating the aftershock process. Then, the relationship between the aftershock activity and the simulated physical quantities is investigated and the main influencing factors of the aftershock activity are discussed, which is one way to further study the mechanism of aftershock activity under the current theoretical understanding and simulation conditions.

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