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# Wenchuan aftershocks as an example of self-organized criticality

Kai Shi [a,b,*], Baofeng Di [c], Chunqiong Liu [a,b], Zhengwen Huang [d], Bin Zhang [e]

[a] *Key Laboratory of Ecotourism's Application Technology of Hunan Province, Jishou University, Jishou, Hunan 416000, China*
[b] *College of Biology and Environmental Sciences, Jishou University, Jishou, Hunan 416000, China*
[c] *Department of Architecture & Environment, Sichuan University, Chengdu, Sichuan 610065, China*
[d] *Town and Country Construction College, Chengdu University, Chengdu, Sichuan 610106, China*
[e] *Land and Resources College, China West Normal University, Nanchong, Sichuan 637009, China*

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ABSTRACT

Analysis of the magnitude and temporal distributions, described by the Gutenberg–Richter and Omori laws respectively, in the sequence of aftershocks of the Wenchuan Ms8.0 earthquake occurred on Longmenshan tectonic zone of Sichuan Province in China, has been performed. The power exponent $b = 0.71 \pm 0.13$ and $p = 2.08 \pm 0.29$ in the form of the Gutenberg–Richter and Omori laws respectively. Dose there exist a simple mechanism which can explain these statistical relations of Wenchuan aftershocks together? In order to provide a possible explanation for these observed distributions, we develop a new self-organized criticality (SOC) model by introducing stress decay coefficient and anisotropic diffusion factors into Olami–Feder–Christensen model of earthquakes. The self-organized criticality properties of the model are discussed. The model displays a robust power law behavior in certain stress decay coefficient region. The model can give a good prediction of the Gutenberg–Richter and Omori laws in Wenchuan aftershock together. The high correspondence of the simulated results to observations shows that Wenchuan aftershock is an example of a SOC process. It is SOC of Wenchuan aftershock process that makes it is impossible to give a fairly accurate forecast of large aftershocks.

## 1. Introduction

The Wenchuan Ms8.0 earthquake occurred on Longmenshan tectonic zone of Sichuan Province in China. The abundant aftershocks occurred after the main event (Huang et al., 2008). Understanding the physical mechanism of Wenchuan aftershocks is of great practical importance. By improving our understanding of the aftershock process, we can gain important insight into the physics of Wenchuan earthquake in general.

An important trend for these aftershocks is that they seem to be occurring along the fault propagating toward a narrow zone (Wang, 2008). Recent detailed analysis of the fault mechanism indicates the relation between Wenchuan aftershocks and focal strike-slip faulting (Zheng et al., 2009). These studies are, however, conceptual and it remains an open question what mechanisms can explain detailed statistical patterns of observed seismicity.

Generally, some empirical relationships for the occurrence of aftershock in a given area are well-known. One of these is the Gutenberg–Richter law (Kalyoncuoglu, 2007). The law shows earthquake energy (magnitude) follows a power-law distribution. It has the form $\log N(M) = a - bM$, where $N(M)$ is the cumulative number of earthquakes with a magnitude greater than $M$, $a$, $b$ are positive constants. The other is the famous Omori law (Utsu et al., 1995). This law specifies a temporal decay of aftershock rates and possesses a power-law scaling. It has the form $n(t) = K(c + t)^{-p}$, where $t$ is the time from the main earthquake and $K$, $c$ and $p$ are constants.

Currently, various models have been proposed to explain the two main laws governing the temporal distribution of aftershock. For example, the Omori law can be explained by viscoelastic relaxation in the fault zone (Hainzl et al., 1999), fault weakening after a block slips (Ito and Matsuzaki, 1990), pore fluid flow (Nur and Booker, 1972), rate-state friction (Dieterich, 1994), and damage rheology (Shcherbakov and Turcotte, 2004). These models can yield the Omori law, but by construction they use rather than explain the Gutenberg–Richter law. The Gutenberg–Richter law can be reproduced by Burridge–Knopoff model and Olami–Feder–Christensen model based on avalanches of stress redistribution, following the idea of self-organized criticality (SOC) (Olami et al., 1992). In these cases, aftershocks are not observed. When the stress transfer on the fault becomes very weak, Hergarten and Neugebauer (2002) show that Olami–Feder–Christensen earthquake model can exhibits sequences of aftershocks. However, since their results are consistent with Omori's empirical law, the $p$ value of the law predicted by the model is unrealistically lower than observed in nature.

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* Corresponding author at: College of Biology and Environmental Sciences, Jishou University, Jishou, Hunan 416000, China.

*E-mail address:* einboplure@163.com (K. Shi).

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In the previous research (Zhang et al., 2012), we found that Wenchuan aftershocks series are in accordance with the Gutenberg–Richter and Omori laws statistically. Does there exist a simple mechanism which can explain the two statistical relations of Wenchuan aftershocks together? In this study, firstly, we investigated the typical earthquake distributions about Wenchuan aftershocks. Secondly, we developed a modified Olami–Feder–Christensen earthquake model based on the SOC theory, which can explain the Gutenberg–Richter and Omori statistical distributions of Wenchuan aftershocks. Finally, we illuminate that the earth's crust is in a self-organized critical state and the generation of Wenchuan aftershocks is an example of a SOC process.

## 2. Typical Wenchuan aftershocks distributions

We analyzed the aftershock sequence of Wenchuan main earthquake that occurred at May 12, 2008 with magnitude 8.0. The examined aftershock sequences occurred at locations with latitude 30.0–33.5°N and longitude 102.7–106.3°E (the Wenchuan earthquake epicenter was located at latitude 31.0°N and longitude 103.4°E) during the period of 12 May 2008–12 October 2008. The length of the occurrence sequence is 2752. In this aftershock sequence, the maximum magnitude of completeness is 6.4 and the minimum magnitude of completeness is 2.0. The time sequence of the aftershocks is displayed in the previous research (Zhang et al., 2012). Fig. 1 shows the special distribution of aftershocks. They seem to be occurring along the fault propagating toward the northeast direction.

### 2.1. Magnitude distribution of aftershocks

A general observation in seismology is that small earthquakes occur more frequently than large earthquakes. The Gutenberg–Richter law is a well established empirical law in seismology. We fitted by the least-squares method the cumulative Gutenberg–Richter law by a straight line, whose slope has been estimated to give the *b* value. The Gutenberg–Richter analysis gives $b = 0.71 \pm 0.13$ (Zhang et al., 2012).

### 2.2. Temporal distribution of aftershocks

The Omori law for aftershocks is another well established empirical law in seismology, describing that the rate of aftershocks decays with some power of the time after the main shock. We applied a nonlinear fitting procedure to fit the Omori law. The Omori law fit has furnished $p = 2.08 \pm 0.29$ (Zhang et al., 2012).

## 3. The model

Olami–Feder–Christensen (OFC) earthquake model (Olami et al., 1992) may be the simplest self-organized critical model, which exhibits a phenomenology resembling real seismicity. OFC model has long been known to reproduce the Gutenberg–Richter law, using only one simple local interaction between discrete fault elements. Although recently it has also been shown to qualitatively exhibit Omori law, the exponents predicted by the model are lower than observed in nature (Hergarten and Neugebauer, 2002). Therefore, the OFC model must be amended in order to simulate the statistical distributions of Wenchuan aftershocks.

For the creation of real Wenchuan aftershocks patterns, we believe that two aspects are important and are not described by the OFC model algorithm. One is that aftershock sequences reflect the gradual decaying process of the total earthquake energy relaxation. The other is the spatial distribution characteristics of aftershocks, which seem to be occurring along the fault propagating toward a narrow zone. It reflects local interactions between blocks in the fault are anisotropic. By this motivation, we obtain a continuous, non-conservative, attenuated, anisotropic cellular

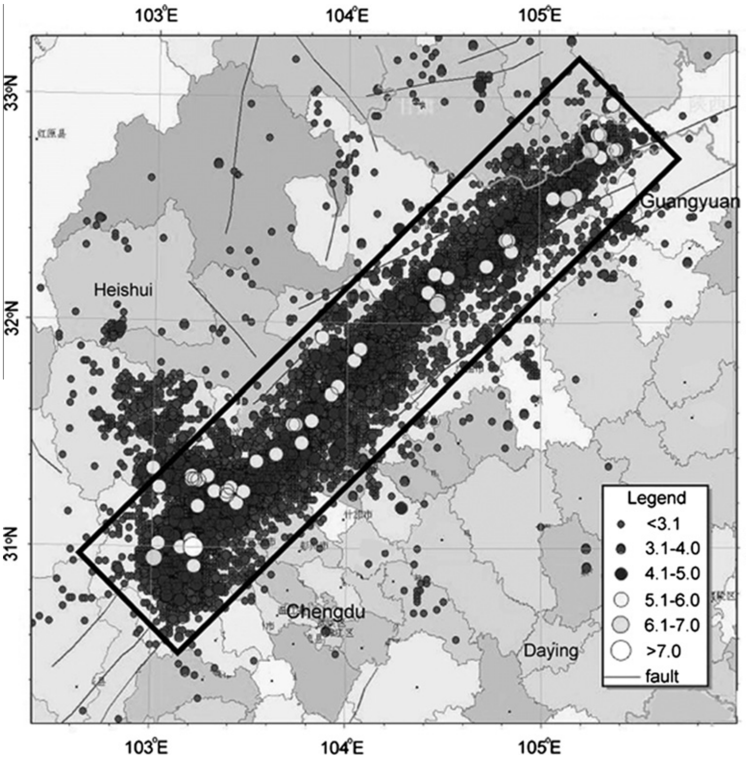

**Fig. 1.** The special distribution map of Wenchuan aftershocks during the period of 12 May 2008–12 October 2008. The minimum magnitude of completeness is 2.0. These aftershocks approximately distribute a rectangular area that rate of length and width is 5:1.