Mann-Kendall Mutation Analysis of Temporal Variation of Apparent Stress in Qinba Mountains and Its Adjacent Areas

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Abstract. In this abstract, we use the Mann-Kendall Mutation analysis to determine the source parameters of 125 earthquakes in the Qinba Mountains and its neighboring areas between 1997 and 2013. Seismic moments, apparent stress, and seismic radiant energy of the earthquakes were calculated. The Mann-Kendall mutation test was used to analyze the temporal data of the apparent stress. The results indicate that there occurred three downward mutation points in apparent stress in June 1998, October 1998 and March 1999, and then only one earthquake, Wudu 4.5 earthquake with magnitude greater than 4 occurred in this area till September 2001. The average apparent stress decreases from 0.16 MPa from July 1997 to March 1999 to 0.15 MPa from April 1999 to September 2001. After the rising mutation point in apparent stress in October 2001, the average apparent stress increases from 0.15 MPa from April 1999 to September 2001 to 0.18 MPa from October 2001 to December 2013. A series of moderate to strong earthquakes with ML4.9, ML6.0, ML5.9, and ML5.2 then occurred in April 2003, May 2008, July 2008 and September 2009. The results demonstrate that the Mann-Kendall mutation analysis can fairly reflect the trend of apparent seismic stress, which is helpful for seismic activity prediction.

1. Introduction
Seismic radiant energy and seismic moment are two basic parameters describing the source of an earthquake. The ratio of these two parameters is related to apparent stress. The above three parameters describe the characteristics of the seismic source from different aspects [1,5,10]. Seismic apparent stress was proposed in the 1960s and has been studied in various aspects in recent years [4,18]. One of the aspects is the research of earthquake prediction, which has been taken mainly in mainland China for nearly 20 years [3,9,19-20]. The increase in apparent stress, especially sudden changes in apparent stress, may indicate an increase in the risk of earthquakes. However, how to accurately and reasonably detect the mutation point of apparent stress is still a challenge. The Mann-Kendall method is a rank-based nonparametric test that can be used to detect monotonic trends in a time series. Whether the time series trend is linear or the data follow a normal distribution, the Mann-Kendall method can be used to determine the trend of incomplete data, and can effectively reduce the impact of data uncertainty [7, 14]. Therefore, compared with the parametric testing methods requiring data normality and sensitivity to data bias, such as linearity and other regression, the Mann-Kendall method has more advantages in determining the mutation points and change trends of the data [6,8].

Qinba Mountains and its adjacent areas are the tectonic boundaries between eastern and western China. They are also the adjustment zones for the differential movement of tectonic blocks such as the north and south part of China. The seismicity of this area is weak in history, but it has increased in recent years. Series of strong earthquakes such as Ningqiang6.0 earthquake on May 27, 2008, the Ningqiang 5.9 earthquake on July 24, 2008, and several earthquakes with magnitude greater than 5 occurred in this
area. Some preliminary researches have been done for the source parameters of earthquakes in this area, but the seismic radiant energy is basically estimated from the relationship between magnitude and energy, so the parameters such as radiated seismic energy and apparent stress are not determined directly [11, 16-17]. In this paper, by using the digital seismic data recorded in Shaanxi Digital Seismic Network from 1997 to 2013, seismic moments, radiant energies, and apparent stress of 125 earthquakes with magnitudes from 1.2 to 6.0 in the Qinba Mountains and its adjacent areas were determined separately. The Mann-Kendall mutation then analyzed the temporal series of the apparent stress.

2. Data
One hundred twenty-five earthquakes records were selected through the regional earthquakes recorded by the Shaanxi digital seismic network from July 1997 to December 2013, with clear waveforms, low background noise, and high ratios of signal-to-noise. More than 4 stations record each earthquake. After zero drift, line drift correction, instrument response correction, and propagation path attenuation correction to the seismic waveforms, the low-frequency amplitude, corner frequency, and high-frequency attenuation rate of the seismic source spectrum were measured. According to the Brune disk dislocation model, the seismic moment, stress drop, source scale, and corner frequency were obtained, and seismic radiant energy is determined through spectral integration of seismic waveform [18]. Then apparent stress is determined by the formula given by Wyss and Burne. The stations and the epicenters of the selected earthquakes are shown in Figure 1.

![Figure 1. The distribution of events used in the analysis](image)

3. Methods
Using the Brune dislocation model, the source spectrum is obtained after instrument response correction, geometric diffusion correction, and medium attenuation correction, and the zero-frequency limit $\Omega_0$ and corner frequency $f_0$ are measured. Then earthquake moment $M_0$, stress drop $\Delta \sigma$ and focal rupture radius $a$ are obtained according to the following formula [18]:

\[ a = \frac{2.34V_s}{2\pi f_0} \]  
\[ M_0 = 4\pi \rho V_s^3 \Omega_0 d/R \]  
\[ \Delta \sigma = \frac{7}{16} \cdot \frac{M_0}{a^3} \]
Where \( d \) is the distance between seismic focus and receiver, \( R \) is the radiation factor, \( V_s \) is the velocity with value of 3.5 km/s, \( \rho \) is density with the value of \( 2.7 \times 10^3 \) kg/m\(^3\). Radiated seismic energy is given by \([12]\)

\[
E = 4\pi \rho \beta \int X^2(f) df
\]

(4)

Where \( X(f) \) is the corrected seismic spectrum, \( \beta \) is seismic velocity.

Seismic apparent stress is given by

\[
\sigma_a = \mu \frac{E_S M_0}{M_0}
\]

(5)

Where \( \mu \) is the rigidity with the value of \( 3.13 \times 10^4 \) MPa and \( E \) is the radiated seismic energy.

4. Results and Discussion

In this study, seismic moments, radiant energies, and apparent stress of 122 earthquakes with magnitude from 1.2 to 6.0 in studied areas are determined from July 1997 to December 2013, and the apparent stress was analyzed by Mann-Kendall mutation test. The temporal curve of apparent stress is shown in Figure 2.

The average apparent stress during the study period in this region is 0.16 MPa, and the variance is 0.50 MPa. If the changing of the apparent stress from the mean value is more than twice the variance, these points are seen as abnormal points. Combined with the M-T diagram of the region, there are no abnormal points of the apparent stress before Shiquan 4.9 earthquake on April 24, 2003, Ningqiang 6.0 earthquake on May 27, 2008, Ningqiang 5.9 earthquake on July 24, 2008, and Ningqiang 5.5 earthquake on September 19, 2009. If the value of apparent stress is seen as abnormal when it exceeds the average value, there are too many abnormal points in the curve, and shows no corresponding relationship between earthquake activity and their abnormal points.
The Mann-Kendall mutation test was then used to analyze the change of the apparent stress from July 1997 to December 2013 in the studied areas. The results are shown in figure 4. The M-K test shows five mutation points during this period. These five mutation points are divided into three swarms, and the middle three points are divided into the same group because they are very close together. The first swarm included one mutation point in November 1997, and the second swarm contains three mutation points, which are in June 1998, October 1998 and March 1999. Finally, the last swarm involved one mutation point in September 2001. The first swarm is not used for analyzing because the previous data is too little. The second swarm shows a decreasing trend, and the third swarm shows a clear increasing trend. Shortly after the three mutation points in the second swarm, Wudu 4.5 earthquake occurred on April 15, 1999, and then no other earthquakes greater than magnitude 4 occurred till September 2001. Thus, the apparent stress generally decreased after the mutation point in March 1999, so the average apparent stress between July 1997 and March 1999 was 0.16 MPa, and the average apparent stress between April 1999 and September 2001 was 0.15 MPa. After the mutation point of apparent stress indicating an increasing trend on September 2001, Shiquan earthquake with magnitude 4.9 on April 24, 2003, Ningqiang earthquake with magnitude 6.0 on May 27, 2008, Ningqiang earthquake with magnitude 5.9 on July 24, 2008, and Ningqiang earthquake with magnitude 5.5 on September 19, 2009,
occurred in this area. Therefore, the average apparent stress from October 2001 to December 2013 was 0.18 MPa, which was greater than the average apparent stress of 0.15 MPa from April 1999 to September 2001. The results show that the Mann-Kendall mutation test method can fairly predict the trend of seismic apparent stress, and has a certain ability to predict seismic activity changes.

![Figure 4](image.png)

**Figure 4.** The change of apparent stress in the studied areas obtained by the Mann-Kendall mutation test

5. Conclusions
This study aimed to identify the trends in seismic activity in the Qinba Mountains area and its adjacent areas, Shaanxi, China, from 1997 to 2013. Seismic moments and seismic radiant energy of the earthquake were calculated, and the temporal curve of apparent seismic stress in the studied area was obtained. The Mann-Kendall mutation test was used to analyze the temporal data of the apparent stress in the area. After the mutation points of apparent stress indicating a decreasing trend in June 1998, October 1998 and March 1999, only one earthquake with a magnitude greater than 4 occurred in this area before September 2001. Therefore, the average apparent stress decreases after the mutation point. After the mutation point of apparent stress indicating an increasing trend in September 2001, a series of moderate to strong earthquakes occurred in this area. And the average apparent stress in the region rises. The results show that the Mann-Kendall mutation test method can fairly predict the trend of apparent seismic stress, which is helpful for seismic activity prediction.

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