The 2018 $M_S$ 5.9 Mojiang Earthquake: Source model and intensity based on near-field seismic recordings

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Abstract: On September 8, 2018, an $M_S$ 5.9 earthquake struck Mojiang, a county in Yunnan Province, China. We collect near-field seismic recordings (epicentral distances less than 200 km) to relocate the mainshock and the aftershocks within the first 60 hours to determine the focal mechanism solutions of the mainshock and some of the aftershocks and to invert for the finite-fault model of the mainshock. The focal mechanism solution of the mainshock and the relocation results of the aftershocks constrain the mainshock on a nearly vertical fault plane striking northeast and dipping to the southeast. The inversion of the finite-fault model reveals only a single slip asperity on the fault plane. The major slip is distributed above the initiation point, ~14 km wide along the down-dip direction and ~14 km long along the strike direction, with a maximal slip of ~22 cm at a depth of ~6 km. The focal mechanism solutions of the aftershocks show that most of the aftershocks are of the strike-slip type, a number of them are of the normal-slip type, and only a few of them are of the thrust-slip type. On average, strike-slip is dominant on the fault plane of the mainshock, as the focal mechanism solution of the mainshock suggests, but when examined in detail, slight thrust-slip appears on the southwest of the fault plane while an obvious part of normal-slip appears on the northeast, which is consistent with what the focal mechanism solutions of the aftershocks display. The multiple types of aftershock focal mechanism solutions and the slip details of the mainshock both suggest a complex tectonic setting, stress setting, or both. The intensity contours predicted exhibit a longer axis trending from northeast to southwest and a maximal intensity of VIII around the epicenter and in the northwest.

Keywords: 2018 $M_S$ 5.9 Mojiang Earthquake; near-field seismic recording; finite-fault model; intensity prediction; focal mechanism solution

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1. Introduction

On September 8, 2018, the China Earthquake Network Center (CENC) reported that an $M_S$ 5.9 earthquake had struck Mojiang, a county in Yunnan Province, China (hereafter referred to as the 2018 $M_S$ 5.9 Mojiang Earthquake), with an epicenter location of 23.28°N, 101.53°E and a focal depth of 11 km (Figure 1). As an emergency response to the earthquake, the CENC soon released preliminary information on the hypocenter location and the focal mechanism solution of the mainshock, as shown in Tables 1 and 2.

According to the local government, 168 villages were affected by the 2018 $M_S$ 5.9 earthquake, and of this number 28 were seriously affected. Nearly 30,000 rooms were damaged, of which 15,140 suffered serious damage and 149 collapsed. No deaths were reported, but 26 individuals sustained injuries. Soon, more than 1,500 people were sent to the spot for rescue and field investigation, and even to monitor aftershocks. Later, a version of the intensity map was released (http://www.cea.gov.cn/publish/dizhenj/464/478/20180912150642725643903/index.html), and preliminary results of the monitored aftershocks were published (see Figure 1), which look dispersive in space.

The 2018 $M_S$ 5.9 Mojiang Earthquake occurred on the southern margin of the southeastern Tibetan Plateau, one of the most active tectonic regions in Mainland China (Molnar and Tapponnier, 1975). The GPS observation shows that this region rotates in a clockwise manner with respect to the eastern Himalayan syntaxis and is dominated by a southeastward extrusion (Zhang PZ et al., 2004; Gan WJ et al., 2007; Jin HL et al., 2019; Zhang KL et al., 2019). This region is characterized by complex tectonic structures and strong seismicity (Yin A and Harrison, 2000). The occurrence of the 2018 $M_S$ 5.9 Mojiang Earthquake sequence provides an opportunity to obtain information on the geometry and kinematics of the seismogenic fault, the regional deformation patterns, and potential mechanical processes in such complex tectonic settings. Investigating the tectonic behavior and seismic properties of this margin is a very important method of revealing the dynamics of the southeastern Tibetan Plateau, as well as for understanding the consequences of the collision between the Indian and Eurasian plates.

The 2018 $M_S$ 5.9 Mojiang Earthquake seems to have occurred on a blind strike-slip fault because no faults cross or run near this
event. Additionally, the distribution of early aftershocks hardly offered any clear constraints on the seismogenic fault plane, even though the intensity pattern released suggested the possibility of trending from northwest to southeast.

To determine the characteristics of the earthquake source and the resulting intensity of the 2018 $M_s$ 5.9 Mojiang Earthquake, we collect and select data from the near-field seismic recordings (Data Management Centre of China National Seismic Network, 2007; Zheng XF et al., 2010). Once more, we carefully identify the hypocenter locations of the mainshock as well as early aftershocks by the time-reversal imaging method (Xu LS et al., 2013a, b; Xu LS et al., 2018) and then process the mainshock and aftershocks by using the double-difference (DD) technique (Waldhauser and Ellsworth, 2000). We also determine the focal mechanism solutions of the mainshock and the aftershocks whose data are acceptable by using the generalized polarity and amplitude technique (GPAT; Yan C and Xu LS, 2014; Yan C et al., 2015), and we invert for the spatiotemporal rupture process of the mainshock by using the finite-fault inversion method (Zhang Y et al., 2012; Zhang X, 2016). Finally, we estimate the intensity pattern based on the inverted fi-

| Table 1. Hypocenter parameters of the mainshock |
|-----------------------------------------------|
| Date and time (UTC) | Latitude (°N) | Longitude (°E) | Depth (km) | Note |
|---------------------|---------------|---------------|------------|------|
| 2018-09-08 02:31:29 | 23.280        | 101.530       | 11.0       | CENC |
| 2018-09-08 02:32:31 | 23.332        | 101.578       | 8.0        | USGS |
| 2018-09-08 02:31:33 | 23.240        | 101.630       | 12.0       | GCMT |

1CENC, China Earthquake Network Center; USGS, U.S. Geological Survey; GCMT, Global CMT Project.

| Table 2. Focal mechanism solutions of the mainshock |
|-----------------------------------------------|
| Plane I | Plane II |
| $\varphi$ (°) | $\delta$ (°) | $\lambda$ (°) | $\varphi$ (°) | $\delta$ (°) | $\lambda$ (°) | Note |
| 219 | 68 | –3 | 310 | 88 | –158 | USGS $M_{sw}$ |
| 215 | 83 | 3 | 125 | 87 | 173 | USGS $M_{wb}$ |
| 216 | 89 | 11 | 126 | 79 | 179 | GCMT |
| 216 | 88 | 9 | 126 | 81 | 178 | IPGP |

1USGS, U.S. Geological Survey; $M_{sw}$ from W-phase inversion; $M_{wb}$ from body-wave inversion; GCMT, Global CMT Project; IPGP, Institut de Physique du Globe de Paris; $\varphi$ is strike; $\delta$ is dip; $\lambda$ is rake.
nite-dynamic model of the mainshock (Xu LS et al., 2016).

2. Hypocenter Locations

Within the first 60 hours of the earthquake, we collect three-component recordings from 13 seismic stations with epicentral distances of less than 150 km to determine the hypocenter locations of the mainshock and aftershocks, as shown in Figure 2a. The velocity model (Wang CY et al., 2003) used here (see Table 3 for details) is ideal for this area because it was specifically verified with human-made events in a previous study (Xu LS et al., 2013b). As a

| Depth (km) | \( V_p \) (km/s) |
|-----------|------------------|
| 0.0       | 5.87             |
| 1.0       | 5.88             |
| 10.0      | 6.45             |
| 30.0      | 7.75             |
| 50.0      | 7.80             |
| 65.0      | 8.05             |

Table 3. Regional velocity model

![Figure 2](image). Distribution of the stations used to relocate the mainshock and early aftershocks as well as the relocated events and their travel-time residuals. (a) The triangles indicate stations and the red dots indicate relocated events. The purple triangles denote the stations used for inverting the focal mechanism solutions in Figure 3, and the green squares denote the major cities and counties in this region. (b) Map view of the relocated events. Fitting of the epicenter locations gives an optimal direction of 26°. (c) A cross section of the relocated events along the profile B–B‘ in subplot (b). The fitting of the hypocenter locations produces an optimal dip of 71°. (d) The graph indicates the distribution of the travel-time residuals before (gray) and after (blue) relocation. Note that only P arrival times are used in the relocation. DD, double-difference technique.
result, the mainshock and 48 aftershocks ($M_L \geq 2.0$) are relocated (Table 4). We should point out that other aftershocks included in the raw catalogue could not be relocated because of insufficient data. To better understand the structure of the seismogenic fault, we process the relocation data of the 48 events by using the DD technique (Waldhauser and Ellsworth, 2000). As a result, the processing output becomes only 28 events, which include the mainshock and 27 aftershocks (see Figure 2 and Table 5 for details). We note that the aftershocks are characterized by a trend from northeast to southwest (Figure 2). The distribution of the travel-time residuals before and after relocation are compared in Figure 2d. Relocation leads to smaller residuals and a more symmetrical distribution. Next, we estimate the strike and dip of the seismogenic fault by fitting the DD-location data as the mainshock is constrained on the fault plane. As shown in Figure 2b and 2c, the optimal strike and dip are N26°E and 71°, respectively. These events are distributed about 8 km along the strike, and they are between 3 and 9 km in depth.

Table 4. Locations of the relocated mainshock and aftershocks

| No. | Date and time (UTC) | Latitude (°N) | Longitude (°E) | Depth (km) | Magnitude |
|-----|---------------------|---------------|----------------|------------|-----------|
| 0   | 2018-09-08 02:31:30.3 | 23.264        | 101.575        | 8.0        | 5.9       |
| 1   | 2018-09-08 02:32:08.7 | 23.268        | 101.577        | 0.8        | 4.2       |
| 2   | 2018-09-08 02:34:26.2 | 23.282        | 101.567        | 0.4        | 4.6       |
| 3   | 2018-09-08 02:35:58.9 | 23.262        | 101.569        | 0.5        | 5.1       |
| 4   | 2018-09-08 02:38:54.6 | 23.278        | 101.590        | 24.1       | 2.2       |
| 5   | 2018-09-08 02:42:10.6 | 23.333        | 101.533        | 8.0        | 2.4       |
| 6   | 2018-09-08 02:48:44.6 | 23.285        | 101.590        | 11.5       | 2.2       |
| 7   | 2018-09-08 02:49:13.3 | 23.292        | 101.588        | 15.8       | 2.0       |
| 8   | 2018-09-08 02:49:49.8 | 23.299        | 101.593        | 17.6       | 2.3       |
| 9   | 2018-09-08 02:53:16.1 | 23.308        | 101.594        | 19.4       | 2.1       |
| 10  | 2018-09-08 02:55:02.4 | 23.266        | 101.576        | 0.5        | 3.2       |
| 11  | 2018-09-08 02:57:29.0 | 23.275        | 101.584        | 9.6        | 2.3       |
| 12  | 2018-09-08 03:01:55.8 | 23.282        | 101.563        | 1.6        | 3.0       |
| 13  | 2018-09-08 03:07:41.7 | 23.279        | 101.563        | 1.3        | 2.0       |
| 14  | 2018-09-08 03:24:32.4 | 23.285        | 101.580        | 9.7        | 2.1       |
| 15  | 2018-09-08 03:26:26.2 | 23.283        | 101.577        | 9.8        | 2.2       |
| 16  | 2018-09-08 03:35:14.6 | 23.268        | 101.553        | 8.2        | 2.2       |
| 17  | 2018-09-08 05:04:32.7 | 23.285        | 101.587        | 11.7       | 2.1       |
| 18  | 2018-09-08 05:07:04.8 | 23.273        | 101.563        | 17.9       | 2.0       |
| 19  | 2018-09-08 05:10:07.2 | 23.288        | 101.580        | 12.2       | 2.0       |
| 20  | 2018-09-08 05:20:42.3 | 23.280        | 101.559        | 9.8        | 2.6       |
| 21  | 2018-09-08 05:27:19.7 | 23.267        | 101.554        | 12.1       | 2.1       |
| 22  | 2018-09-08 06:02:11.6 | 23.298        | 101.532        | 8.1        | 2.2       |
| 23  | 2018-09-08 06:08:53.3 | 23.294        | 101.571        | 8.5        | 2.5       |
| 24  | 2018-09-08 06:32:29.9 | 23.309        | 101.601        | 10.9       | 2.1       |
| 25  | 2018-09-08 07:11:37.2 | 23.267        | 101.568        | 0.7        | 2.5       |
| 26  | 2018-09-08 07:17:50.9 | 23.301        | 101.530        | 4.9        | 2.4       |
| 27  | 2018-09-08 07:31:36.7 | 23.276        | 101.564        | 12.1       | 3.5       |
| 28  | 2018-09-08 08:06:14.2 | 23.289        | 101.597        | 20.7       | 2.1       |
| 29  | 2018-09-08 09:20:51.5 | 23.257        | 101.567        | 16.0       | 2.4       |
| 30  | 2018-09-08 14:51:56.6 | 23.268        | 101.563        | 0.5        | 2.0       |
| 31  | 2018-09-08 23:29:58.7 | 23.278        | 101.575        | 0.6        | 2.3       |
| 32  | 2018-09-09 00:05:04.7 | 23.313        | 101.597        | 9.8        | 2.2       |
| 33  | 2018-09-09 00:25:07.6 | 23.301        | 101.583        | 2.7        | 2.0       |
3. Focal Mechanism Solutions

As we know, the focal mechanism solutions of the aftershocks are helpful for understanding the rupture properties of the mainshock and the stress setting. Thus, we collect three-component recordings from 11 stations for the focal mechanism solutions, as shown in Figure 2a. These stations are less than 150 km from the events because the quality of the recordings is reduced at stations farther away. We adopt the GPAT as was done before (Yan C and Xu LS, 2014; Yan C et al., 2015) and eventually obtain focal mechanism solutions for 34 events, which include 33 aftershocks and the mainshock, as shown in Table 6 and Figure 3.

The GPAT utilizes polarities not only of the first P arrival, but also the maximum amplitudes of other phases, as well as values of the maximum amplitudes of all the phases, so more data are used to constrain the focal mechanism solutions. In fact, this technique has generally been shown to produce satisfactory results (Yan C and Xu LS, 2014; Yan C et al., 2015).

When we simply divide the aftershocks into three groups for normal-slip events, thrust-slip events, and strike-slip events, we find that most of them are in the strike-slip group followed by the normal-slip group, and only a few are in the thrust-slip group. It is interesting that more normal-slip events occurred in the northeast, whereas more strike-slip events took place in the southwest. More interesting is that the major aftershocks around the mainshock have solutions similar to the mainshock. The spatial complexity of the focal mechanism solutions is certainly indicative of the spatial complexity of the local tectonics, local stress, or both.

Here, we must stress that our inverted results show that the fault plane of the mainshock clearly dips to the southeast, as the aftershock fitting indicates, instead of northwest or nearly vertical as the others suggest (Table 2). One possible reason for this discrepancy is the relatively poor resolution of the far-field data, although more than one factor may cause uncertainty in the focal mechanism solutions (Yan C and Xu LS, 2014; Yan C et al., 2015).

4. Rupture Process of the Mainshock

Teleseismic waveform data are usually used in the inversion to determine the rupture process of an earthquake (Lay et al., 2010; Zhang X and Xu LS, 2015; Zhang X et al., 2017a, b), but for the 2018 Ms 5.9 Mojiang Earthquake (a moderately sized event), the teleseismic recordings are unusable. Thus, we collect three-component seismic waveform data recorded by 19 broadband seismic stations whose epicentral distances are within 200 km. As Figure 4 shows, the nearest station is about 50 km from the epicenter, and the azimuthal coverage of the stations is sufficient. Before being used, all the recordings are filtered with a band-pass filter of 0.0333 to 0.1 Hz to reduce the site effects involved as much as possible (Graizer, 2006; Wang RJ et al., 2013). The Green’s functions or synthetic recordings corresponding to the observed recordings are computed by the orthonormalization method (Wang RJ, 1999), and all the synthetic recordings are kept in the same frequency band as the observed recordings.

We adopt our inversion method (Zhang Y et al., 2012, 2014; Zhang X, 2016) to obtain the spatiotemporal rupture process because it does not require a priori constraints on shapes of the subfault moment rate functions, which instead are determined through an iterative process by means of the conjugate gradient method (Ward and Barrientos, 1986). It also allows subfault rakes to vary within a range of ±45° with respect to the given rake. This method has been used successfully to study the 2009 L’Aquila Ms 6.3 earthquake (Zhang Y et al., 2012), a moderately sized earthquake similar to the 2018 Ms 5.9 earthquake at Mojiang. In addition, smoothing constraints in both time and space (Yagi et al., 2004; Zhang Y et al., 2012) are imposed, as well as the constraint of minimizing the scalar seismic moment (Hartzell and Heaton, 1983;
The inverted rakes exhibit a slight thrust and normal components, varying smoothly from one subfault to another, but generally the slips are along the strike direction, with an average of 2.2°, indicating a nearly pure strike-slip event. To display the instantaneous rupture, we take snapshots of the slip rate. As Figure 5c shows, the rupture begins at a greater depth and then propagates upward and outward.

It should be pointed out that all the available focal mechanism solutions of the mainshock suggest a nearly strike-slip event, and this result is in agreement with what the finite-fault inversion portrays. The focal mechanism solutions of the aftershocks also indicate a normal-slip setting in the northeastern fault plane, which is consistent with the results of the finite-fault inversion.

To understand the extent to which the observed data are explained by the inverted model, we calculate the synthetic recordings for all the observed recordings with the inverted model. As shown in Figure 6, in general the fit is remarkably good. The stationings for all the observed recordings with the inverted model. As explained by the inverted model, we calculate the synthetic recordings for all the observed recordings with the inverted model. As shown in Figure 6, in general the fit is remarkably good. The stationings for all the observed recordings with the inverted model.
We observe that the strike N44°E and dip 52° of the mainshock given by the focal mechanism inversion are different from those determined by the spatial distribution of aftershocks, so we make another attempt, this time using an initial model defined with the strike and dip. No changes are made in the other parameters. The inversion results are shown in Figure 7. We can see by comparing Figure 5 with Figure 7 that the two results are very similar. Figure 8 displays a comparison of the observed recordings with the corres-
Figure 3. Focal mechanism solutions of the mainshock and selected aftershocks. The red, green, and blue beach balls denote the type of event: strike-slip, thrust, and normal, respectively. The red dots denote the relocated mainshock and selected aftershocks.

Figure 4. Distribution of the stations used to invert to determine the spatiotemporal rupture process of the mainshock (red star).

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ponding synthetic recordings. We find that they are very similar and that the similarity is as good as that shown in Figure 6. The change in strike and dip does not obviously change the inversion result, which means that the inversion result is stable.

To further verify the stability and reliability of the inversion result, we perform a numerical test. We calculate synthetic recordings at the stations where the observed recordings are available by using the inversion result or source model. We then disturb the synthetic recordings with random noise until the variance between the synthetics and the disturbed synthetics is reduced to 60%, which is the variance reduction reached when the real observed data are inverted. Next, keeping all the inversion parameters unchanged, we conduct an inversion process by using these disturbed synthetics as “observed data.” Figures 9 and 10 illustrate two sets of inversion results and comparisons of the observed recordings with the synthetic recordings, respectively. Both figures strongly suggest that the primary characteristics can be successfully recovered despite the change in the strike and dip or the disturbance involved in the observed data. This result indicates that the primary characteristics of the inverted model for the 2018 $M_{S}$ 5.9 Mojiang Earthquake are stable and reliable.

5. Estimation of Intensity

The postearthquake intensity is a simple but comprehensive description of the ground motion, as well as a direct characterization of the earthquake hazard (Wald et al., 1999a, b). Rapid acquisition of the earthquake intensity is critically important for emergency rescue, so we propose a technique for estimating the intensity based on a finite fault model (Xu LS et al., 2016). Here, we use the two inverted finite models to estimate the spatial pattern of the intensity. As shown in Figure 11, the two models yield very similar intensity patterns, with the longer axes of the intensity ellipses being along the strike direction and the maximum of the intensity reaching nearly VIII. In general, the larger seismic hazard is northwest to the epicenter.

6. Discussion

6.1 Seismogenic Fault

As shown in Figures 1 and 2, the 2018 $M_{S}$ 5.9 Mojiang Earthquake
Figure 6. Comparison between the observed waveform data (black) and the synthetic recordings (red). The letters E, N, and Z represent the three components, east-west, north-south, and vertical, respectively. The station name is shown at the top right for each group of three-component recordings. The three numbers on the left are correlation coefficients between the observed data and the corresponding synthetic recording.

Figure 7. The inversion result of the mainshock rupture process with a strike of N44°E and a dip of 52°. (a) Inversion of the moment rate function. (b) Inversion of the coseismic slip pattern. The black circles indicate aftershocks. (c) Snapshots of the slip rate.
Figure 8. Comparison of the observed waveform data (black) with the synthetic observations (red). See Figure 6 for details.

Figure 9. Results of the numerical test with a strike of N26°E and a dip of 71°. See the preceding figures for additional details.

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is not on an already-mapped fault, and no obvious trend is found on the spatial distribution of preliminarily located aftershocks, but the aftershocks relocated here (Figure 2b) apparently distribute along northeast-southwest, which is consistent with one of the nodal planes indicated by the focal mechanism solutions (Tables 2 and 4 and Figure 1).

Figure 10. Results of the numerical test for a strike of N44°E and a dip of 52°. See the preceding figures for additional details.

Figure 11. Map view of the intensity predicted based on the inverted finite-fault models. (a) Based on the model with a strike of N26°E and a dip of 71°. (b) Based on the model with a strike of N44°E and a dip of 52°. The red stars denote the mainshock, and the dots refer to the relocated aftershocks. The red dashed lines show fault traces.
It is stressed that the focal mechanism solutions determined by inverting the near-field recordings in this study suggest a seismogenic fault dipping to the southeast instead of dipping to the northwest or being nearly vertical, as suggested by others (Table 2). In addition, the cross section of the relocated aftershocks (Figure 2c) supports the result of dipping to the southeast. This discrepancy should be attributed to the limitation of the far-field data resolving such a moderate earthquake.

All the strikes (Table 2), especially the one obtained by our inversion (Table 5), show similar trends, but the trend of the aftershock distribution (N26°E) differs by about 15°. We believe that this deviation is indicative of the geometric complexity of the seismogenic fault.

6.2 Spatiotemporal Process of the Mainshock

With the relocated aftershocks and the inverted focal mechanism solutions based on the near-field seismic data, we set up initial plane models for the source of the 2018 M5.9 Mojiang Earthquake, and invert 19 stations of three-component recordings for the spatiotemporal rupture process. We attempt two sets of strike and dip and find no substantial difference between the inverted results, which means that the inverted result is not sensitive to such uncertainty in the strike and dip. We perform a numerical test to verify the reliability of the inversion result and find that all the characteristics are recovered nearly perfectly. This means that the inversion result is reliable, although the observed data are explained at a level of about 60%.

6.3 Seismic Intensity

As stated in the previous section, intensity is a simple but comprehensive description of earthquake ground motion and is a direct characterization of an earthquake hazard. This method provides a comprehensive indication of the source effect, medium effect, site effect, and even building effect. However, in this study only the source effect is considered, including the magnitude, dimensions, rupture direction, and velocity (Xu LS et al., 2016). We observe that the intensity pattern predicted here is significantly different from the one obtained by the field investigation (http://www.cea.gov.cn/publish/dizhenj/464/478/20180912150642725643903/index.html). This difference could possibly be explained by the administrative effect or the complex medium and site effects, or both.

7. Conclusions

Relocation of the mainshock and aftershocks, as well as inversion of the focal mechanism solution of the mainshock, suggests that the seismogenic fault strikes northeast and dips to the southeast. The strike is between azimuths of 26° and 44°, the dip is between 52° and 71°, and the rake is between 2° and −17°. The inversion of the finite-fault models indicates that the event lasts no more than 6 s and releases a scalar seismic moment of 6.0 × 10^{17} Nm, corresponding to a moment magnitude of M_w 5.8. Only one slip asperity appears on the fault plane, with a peak slip of approximately 22 cm. The asperity is about 14 km long in the strike direction and about 14 km wide in the down-dip direction. The rupture begins at a deeper depth and then propagates upward and outward. The rupture does not seem to reach the ground surface, and the centroid is located at a depth of about 6.8 km. According to the intensity pattern predicted with the inverted model, the longer axis of the pattern falls along the northeast-southwest and the maximum intensity reaches nearly VIII, which is largely situated near and northwest of the epicenter.

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