Which velocity model is more suitable for the 2017 *M*_S7.0 Jiuzhaigou earthquake?

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Abstract: On Aug. 8, 2017, an M_S7.0 earthquake struck Jiuzhaigou, a county of Sichuan province, China. A number of investigations and studies have been conducted, some of which involved local velocity models. However, the suitability of these models has not been properly addressed. Here we collect 11 already-existing models, including those used in studies of the 2017 M_S7.0 Jiuzhaigou earthquake, choose 10 local stations surrounding the earthquake, and employ the same technique (TRIT) to relocate the hypocenter. And furthermore, we choose a more suitable model from the 11 already-existed models by analyzing the relocation process and the relocated results for reasonability. Finally, our conclusion is that the model Fang2018 is more suitable and the hypocenter parameters, 103.801°E, 33.192°N and 15.8 km for longitude, latitude and depth, respectively, and 2017-08-08 13:19:46.66 for its origin time, based on this model should be recommended for the 2017 M_S7.0 Jiuzhaigou earthquake.

Keywords: the 2017 M_S7.0 Jiuzhaigou earthquake; the more suitable velocity model; the relocation of the mainshock

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1. Introduction

On Aug. 8, 2017, an M_S7.0 earthquake occurred in Jiuzhaigou, a county of Sichuan province, China (named the 2017 M_S7.0 Jiuzhaigou earthquake). As the China Earthquake Networks Center (CENC) reported, the event was located at 33.20°N, 103.82°E, with a depth of 20 km and an origin time of 21:19:46.7 Beijing Time (Figure 1). The earthquake resulted in the maximal intensity IX (Zhang X et al., 2017; Han LB et al., 2018) causing 25 deaths and 525 injuries (Zhang X et al., 2017).

For several months, field investigations (Xu XW et al., 2017) and preliminary studies (Ji LY et al., 2017; Yi GX et al., 2017; Yang YH et al., 2017; Zhang X et al., 2017; Zheng XJ et al., 2017; Fang LH et al., 2018; Han LB et al., 2018; Xie ZJ et al., 2018) were conducted. Focal mechanism of the mainshock was determined using different datasets and various methods (Yang YH et al., 2017; Yi GX et al., 2017; Han LB et al., 2018); relocation of the aftershocks was carried out by different researchers (Yi GX et al., 2017; Fang LH et al., 2018; Xie ZJ et al., 2018); and rupture process of the mainshock was imaged by means of different approaches and using different datasets (Ji LY et al., 2017; Zhang X et al., 2017; Zheng XJ et al., 2017; Xie ZJ et al., 2018). It has been suggested, this event produced a bilateral rupture at azimuth of about 150°, and broken zone extending about 40 km along strike direction and about 20 km in depth direction. The dip of the seismogenic fault is around 75°, and the slipping is nearly horizontal. All of these have formed

a frame basically characterizing the event. However, there are still some questions or issues remained to be clarified more carefully. The focal depth is still in argument (Yi GX et al., 2017; Fang LH et al., 2018; Han LB et al., 2018; Xie ZJ et al., 2018). The spatial pattern of the aftershock distribution remains interesting (Yi GX et al., 2017; Fang LH et al., 2018; Xie ZJ et al., 2018). Apparent difference still exists in the results of the inverted rupture process (Ji LY et al., 2017; Zhang X et al., 2017; Zheng XJ et al., 2017; Xie ZJ et al., 2018).

In order to clarify the above issues, we have to answer a question: which velocity model is more suitable for the 2017 M_S7.0 Jiuzhaigou earthquake. This question is very important and critical because the velocity model relates to hypocenter location of the mainshock, location and pattern of the aftershock cloud, and tempo-spatial rupture process of the mainshock, and further will affect geometrical and kinematic characteristics of the event and even understanding of the event's dynamic process.

In this paper, we focus on the local velocity model. We collect 11 already-existing models from the literature (Dziewonski and Anderson, 1981; Zhao Z and Zhang RS, 1987; Kennett and Engdahl, 1991; Kennett et al., 1995; Bassin et al., 2000; Wang CY et al., 2007; Laske et al., 2013; Yi GX et al., 2017; Fang LH et al., 2018), including those used in studies of the 2017 M_S7.0 Jiuzhaigou earthquake; we then choose data from 10 local stations that were located around the region of the earthquake, and employ with each model the same technique TRIT (Xu LS et al., 2013a, b) to relocate the hypocenter of the mainshock. Next, we test for reasonableness of the relocation process and the relocated results in order, finally, to choose the most suitable model from among the 11 already-existing models, and make a suggestion regarding the hypocenter parameter of the 2017 M_S7.0 Jiuzhaigou earthquake.
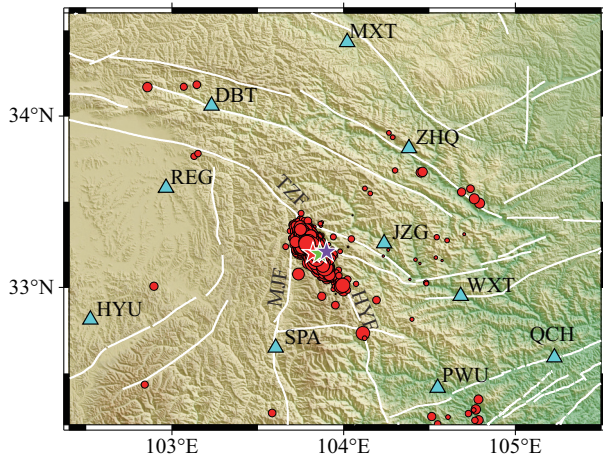
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Figure 1. Tectonic settings of the 2017 M_S7.0 Jiuzhaigou earthquake, the aftershocks within 1 month since the mainshock and the stations used in this study. White lines are major faults, such as Tazang fault (TZF), Minjiang fault (MJF), Huya fault (HYF), red dots are the aftershocks, and cyan triangles are the stations. The three stars show the epicenter locations determined by CENC (red), USGS (green) and GCMT (purple), respectively.

2. Method and Data

2.1 Method

The time-reversal imaging technique (TRIT) is used in this study because of its special advantages (Xu LS et al., 2013a, b). A concise description of TRIT follows:

Assuming ξ_0 is the centroid of hypocenter, τ_0 is the origin time, x_m is the location of the station m, t_m is the arrival time at station m, and S_n^m is used to represent the component n of the recordings at the station m, which may be direct P-, direct S-wave, or their envelopes, now we consider the following function,

$$S_0(x,t) = \frac{1}{N \times M} \sum_{m=1}^{M} \sum_{n=1}^{N} S_n^m (x_m - \xi_0. \, t_m - \tau_0), \qquad (1)$$

and an integration

$$E = \int_0^{T_w} S_0^2(x,t)\,\mathrm{d}t, \qquad (2)$$

in which, M is the number of stations, N is the number of components, and T_w is the effective duration time of the used P- or S-wave or its envelope. Note, the integration value will reach the maximum only as $\xi_0 = x_m$ and $\tau_0 = t_m$, which means the hypocenter centroid and the origin time become known.

In practice, the solution of equation (2) is usually paired values ξ_i and τ_i instead of unique values ξ_0 and τ_0 due to uncertainty in velocity models and/or errors in observation data; thus we use

$$\Delta\xi_{\max} = \max(|\xi_i - \xi_0|) \qquad (3)$$

to describe resolution of the hypocenter centroid ξ_o, while

$$\Delta\tau_{\max} = \max(|\tau_i - \tau_0|) \qquad (4)$$

is used to describe resolution of the origin time τ_o, and use stand-

ard deviation of the difference between observed and theoretical arrival time to express uncertainty of the hypocenter location.

If any observation wave is represented with $S_n^m(\xi_0^l, \, \tau_0^l)$ as returning to the hypocenter centroid, then the difference of the observed arrival time from the time predicted by theory is just

$$\Delta\tau_0^l = \tau_0^l - \tau_0. \qquad (5)$$

Ordering

$$\Delta\bar{\tau} = \sqrt{\frac{\sum\limits_{l=1}^{L} \Delta\tau_0^{l2}}{L}}, \qquad (6)$$

if τ_0^c and ξ_0^c are used to describe uncertainties of τ_0 and ξ_0, then the uncertainties are expressed as

$$\tau_0^c = \begin{cases} \Delta\tau_{\max}, & (\Delta\tau_{\max} \geq \Delta\bar{\tau}) \\ \Delta\bar{\tau}, & (\Delta\tau_{\max} < \Delta\bar{\tau}) \end{cases} \qquad (7)$$

$$\xi_0^c = \begin{cases} \Delta\xi_{\max}, & (\Delta\tau_{\max} \geq \Delta\bar{\tau}) \\ \dfrac{\Delta\xi_{\max}}{\Delta\tau_{\max}}\Delta\bar{\tau}. & (\Delta\tau_{\max} < \Delta\bar{\tau}) \end{cases} \qquad (8)$$

Here we would like to stress that the theoretically most conservative estimate was presented in the previous paper (Xu LS et al., 2013a), and actually the uncertainties given by the equations (7) and (8) are good enough in most cases.

2.2 Seismic Data

We collected vertical component data from 10 stations as shown in Figure 2 (Data Management Centre of China National Seismic Network, 2007; Zheng XF et al. 2010). These stations are closest to the instrument epicenter (Figure 1), with minimum distance of 38 km and maximal distance of 148 km. It is lucky that these stations cover the epicenter nearly perfectly. Only 1 s-long P-waves after first motion are used in determining the location of the hypocenter because almost all of the recordings are clipped and S-arrivals are not clear, as shown in Figure 2.
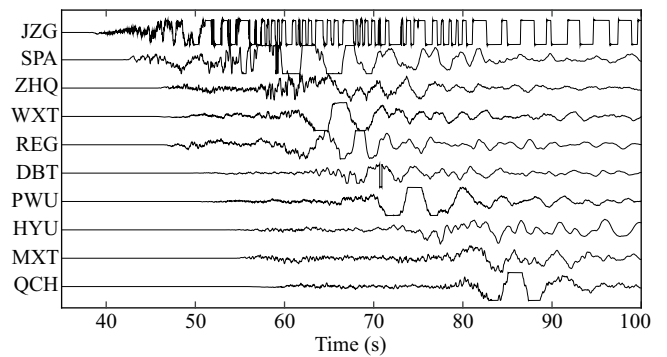

Figure 2. Vertical components of the broadband recordings from the stations shown in Figure 1. Most of them are clipped due to short epicenter-distances.

3. Comparison of Models

3.1 Velocity Models

We collected 11 velocity models for this study, including three

global models: PREM (Dziewonski and Anderson, 1981), IASPEI91 (Kennett and Engdahl, 1991) and ak135 (Kennett et al., 1995); two regional models: Crust2.0 (Bassin et al., 2000) and Crust1.0 (Laske et al., 2013); and six local models from individual investigations: ZhaoA1, ZhaoA2, ZhaoA3 (Zhao Z and Zhang RS, 1987), WCYW (Wang CY et al., 2007), Fang2018 (Fang LH et al., 2018), and YGX (Yi GX et al., 2017). As Figure 3 shows, these models exhibit significant differences from each other.
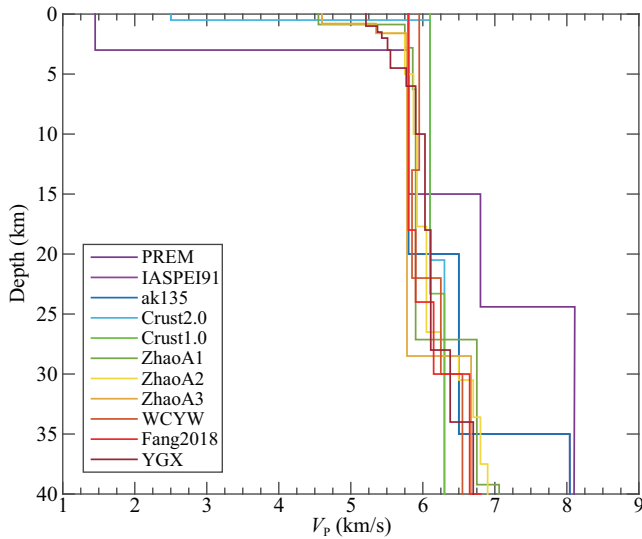

Figure 3. Layered models of P velocity used in this study. Global models PREM, IASPEI91 and ak135; regional models Crust2.0 and Crust1.0; and local models ZhaoA1, ZhaoA2, ZhaoA3, WCYW, Fang2018, and YGX.

3.2 Relocation Based on Various Models

The 2017 M_S7.0 Jiuzhaigou earthquake is relocated using the 11 velocity models and the 10 stations of seismic data by means of the TRIT. It is stressed that altitudes of the stations are removed in doing this. The relocated parameters are presented in Table 1, and

for convenience of direct view and analysis, all the information on the relocation is shown in Figure 4.

Subplots (a1)–(k1) in Figure 4 show the epicenter locations determined by using the different models. It is noticed that different models give different locations, but most agree with the epicenter location issued by the CENC to 2 km or less. However, the associated uncertainties of these calculated epicenters, which range among models from a minimum of 0.35 km to a maximum of 1.13 km, are an indication of model suitability.

Compared with epicenter locations, the focal depths differ more widely among models, ranging from a minimum of 0.8 km to a maximum of 16.0 km, and the associated uncertainties also vary over a large range, from a minimum of 1.2 km to a maximum of 6.7 km. To emphasize the difference in focal depth and its uncertainty, vertical and horizontal pillars are used in subplots (a2)–(k2). It is clear that the focal depths and their uncertainties are strongly dependent on the details of the velocity models.

It is stressed that, for all of the models, data from two of the stations had to be abandoned due to singular residuals (much larger than 0.3 s) compared with the other stations (usually smaller than 0.3 s), as shown on the insets of the subplots (a1)–(k1). That residuals would be different from one station to another is understandable, due to heterogeneity of the propagation medium, but large residuals are a reason to reject data because they imply large deviation of the model from reality.

3.3 Model selection

Table 1 and Figure 4 present the relocation data yielded by the various velocity models. At first glance it is not obvious which model best fits the 2017 M_S7.0 Jiuzhaigou earthquake. However, it becomes clearer when layering of medium, spatial distribution of stations, and reasonableness of focal depth are taken into account.

First of all, it is unacceptable that velocity of medium sharply changes with increasing depth, and there exist many velocity layers with obvious velocity discontinuity. For examples, the model

Table 1. Source parameters of the 2017 M_S7.0 Jiuzhaigou earthquake determined based on various velocity models

Date (yy-mm-dd)	Time (hh:mm:ss)	Δt/s	ϕ/°N	$\Delta\phi$/(°)	λ/°E	$\Delta\lambda$/(°)	Δd/km	H/km	ΔH/km	Model
2017-08-08	13:19:45.03	±1.75	33.208	±0.003	103.802	±0.002	±0.3	14.4	±1.2	PREM
2017-08-08	13:19:46.70	±0.07	33.194	±0.003	103.800	±0.004	±0.5	16.0	±2.6	IASPEI91
2017-08-08	13:19:47.04	±0.07	33.216	±0.003	103.801	±0.003	±0.4	13.5	±2.8	ak135
2017-08-08	13:19:47.78	±25.29	33.220	±0.003	103.818	±0.003	±0.4	1.6	±2.2	Crust2.0
2017-08-08	13:19:47.96	±0.14	33.208	±0.009	103.821	±0.006	±1.1	0.8	±5.5	Crust1.0
2017-08-08	13:19:46.86	±0.09	33.190	±0.005	103.799	±0.007	±0.8	13.0	±5.4	ZhaoA1
2017-08-08	13:19:46.84	±0.07	33.191	±0.004	103.799	±0.007	±0.8	10.5	±2.9	ZhaoA2
2017-08-08	13:19:46.78	±0.07	33.213	±0.003	103.799	±0.003	±0.5	15.9	±2.6	ZhaoA3
2017-08-08	13:19:47.35	±0.06	33.192	±0.004	103.799	±0.004	±0.5	1.6	±6.7	WCYW
2017-08-08	13:19:46.66	±0.09	33.192	±0.004	103.801	±0.004	±0.5	15.8	±3.6	Fang2018
2017-08-08	13:19:46.91	±0.06	33.194	±0.004	103.800	±0.004	±0.6	7.1	±3.9	YGX

Notes: Δt is uncertainty of the origin time, ϕ is latitude, $\Delta\phi$ is uncertainty of the latitude, λ is longitude, $\Delta\lambda$ is uncertainty of the longitude, Δd is uncertainty of the epicenter location, H is depth, ΔH is uncertainty of the depth.
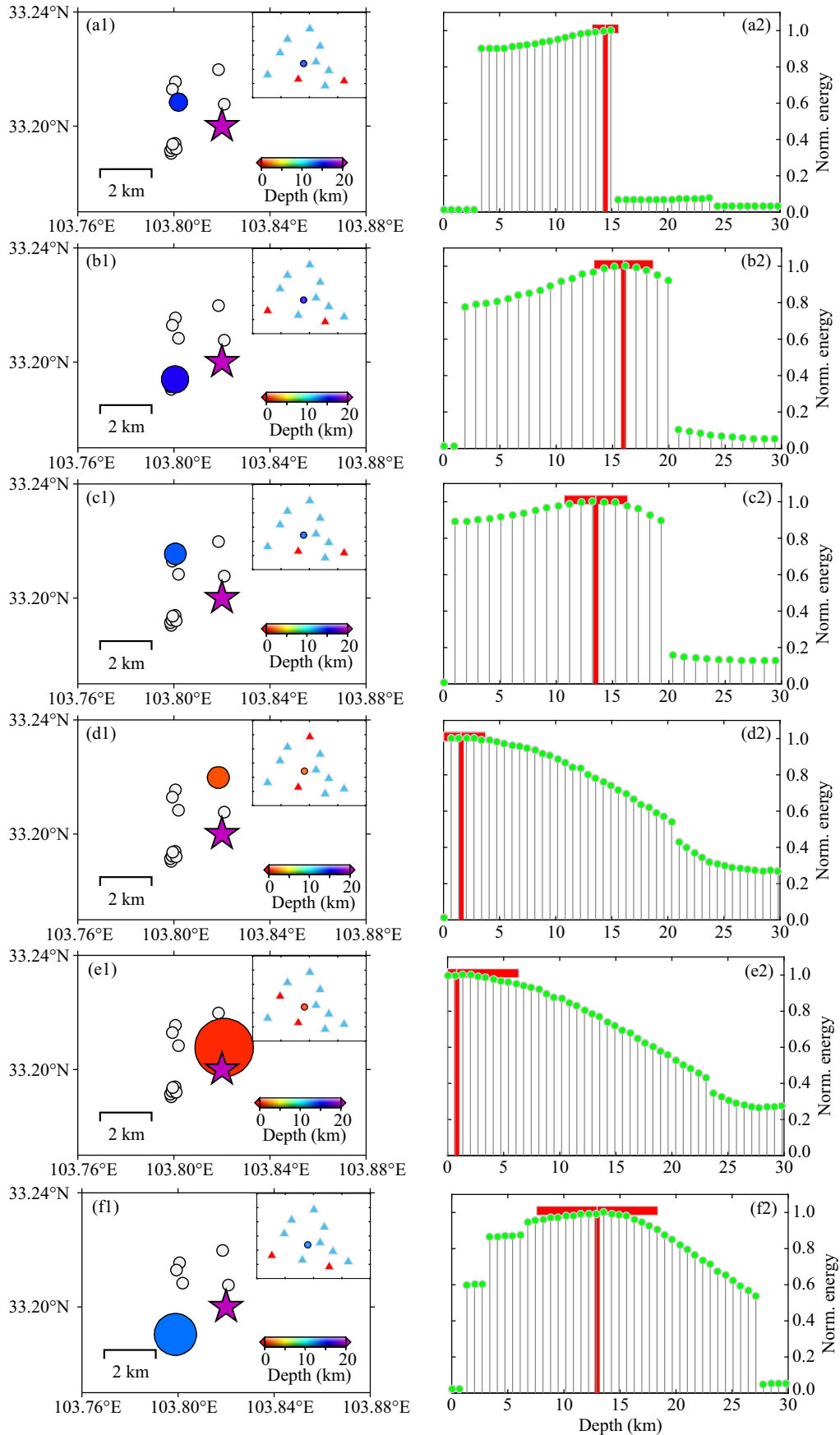
Figure 4A. Relocation of the 2017 M_S 7.0 Jiuzhaigou earthquake based on various velocity models. The details of subplots see Figure 4B.
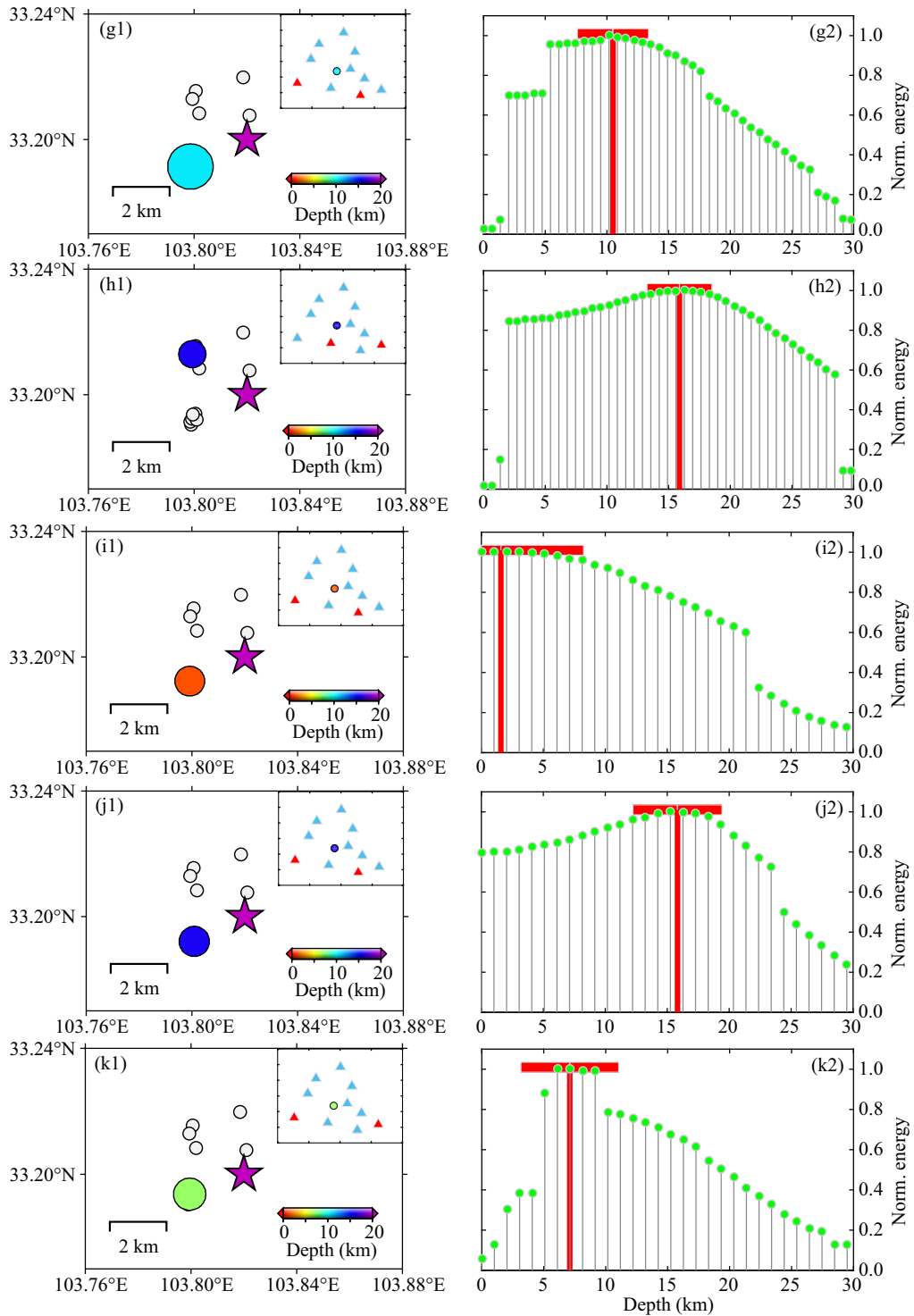
Figure 4B. Relocation of the 2017 M_S 7.0 Jiuzhaigou earthquake based on various velocity models. In subplot (a1), the purple star denotes the epicenter location issued by the CENC while the empty circles show the locations determined based on the various velocity models involved in this study. The color-filled circle emphasizes the location determined with velocity model of PREM, where the color and size indicate focal depth of the hypocenter and uncertainty of the epicenter location, respectively. The inset on the upper-right corner shows the epicenter location (cyan dot) and the stations used (cyan triangles) and abandoned (red triangles) due to too large residuals. Subplot (a2) shows the normalized energy varying with the focal depths, where the red pillar and the red bar at its top are used to emphasize the best depth and its uncertainty range, respectively. Successively, subplots (b1) and (b2) are for the model of IASPEI91, (c1) and (c2) are for the model of ak135, (d1) and (d2) are for the model of Crust2.0, (e1) and (e2) are for the model of Crust1.0, (f1) and (f2) are for the model of ZhaoA1, (g1) and (g2) are for the model of ZhaoA2, (h1) and (h2) are for the model of ZhaoA3, (i1) and (i2) are for the model of WCYW, (j1) and (j2) are for the model of Fang2018, and (k1) and (k2) are for the model of YGX, respectively.

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ZhaoA2 makes the depth-dependent variation of energy change sharply several times, many layers of the model YGX exhibit discontinuous energy variation.

Next, azimuth coverage of the stations with respect to the epicenter should be good enough, for a good model is the best approximation of reality. In our case, the relocated hypocenter should stand properly with the stations without singular residuals but with good azimuth coverage. For example, the model CRUST2.0 requires that data be abandoned from the stations of north and south of the epicenter.

At last, it is believed to be unreasonable that the hypocenter of a large earthquake would be close to ground surface, because large earthquakes are usually accompanied with large accumulation and release of stress. Here we specially collected data from earthquakes with magnitudes larger than M_S5.0 and depths smaller than 70 km, as well as earthquakes with magnitudes between M_S6.5 and M_S7.5, and calculated the ratio of various depth-bands, as shown in Figure 5. We found that only a small percentage of these earthquakes occurred at depths less than 10 km. Therefore, models such as Crust2.0, Crust1.0, and WCYW that yielded shallow depths appear unsuited to the 2017 M_S7.0 Jiuzhaigou earthquake.
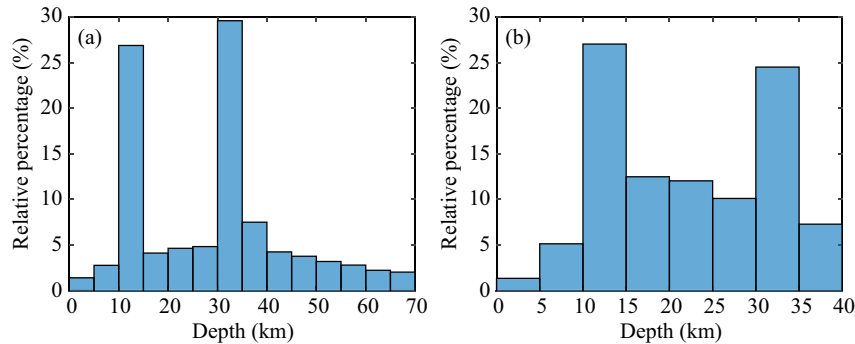

Figure 5. Percentage of the earthquakes distributed in the world from Jan. 1, 1970 to Dec. 31, 2017. Note: most of them have depths larger than 10 km. (a) Earthquakes with magnitudes larger than 5.0 and depths less than 70 km. (b) Earthquakes with magnitudes between M_S 6.5 and M_S 7.5 and depths less than 40 km.

Using the above criteria, we believe that the model Fang2018 is the best choice for the 2017 M_S7.0 Jiuzhaigou earthquake, because it presents a smooth depth-dependant variation of energy change (in spite of a little discontinuity around depth of 24 km), it does not obviously change the azimuth coverage of stations, and it yields a focal depth of 15.8 km, which is not close to ground surface. Looking back at the source of the model Fang2018 (Fang LH et al., 2018), we find that the model was derived from a seismic profile close to that of the 2017 M_S7.0 Jiuzhaigou earthquake (Wang CY et al., 2007). The other models were dismissed because of combinations of the above criteria. PREM and ak135, for instance, are rejected because of the first and second criteria; IASPEI91 because of the first criterion; CRUST2.0 because of the second and third; CRUST1.0 because of the third; Zhao1 and Zhao2 because of the first; Zhao3 and YGX because of the first and third; and WCYW because of the third criterion.

3.4 Hypocenter Parameters of the 2017 M_S7.0 Jiuzhaigou Earthquake

Having selected velocity model Fang2018, the hypocenter parameters become available: Fang2018 gives 103.801°E for longitude, 33.192°N for latitude and 15.8 km for depth (Table 1). For convenience of comparison, these parameters are again presented in Table 2 together with those from other sources.

Recently, Fang LH et al. (2018) relocated the hypocenter of the 2017 M_S7.0 Jiuzhaigou earthquake based on a 3-D velocity model (Table 2). The epicenter was located at 103.806°E and 33.201°N and the depth was 20.4 km with respect to local ground surface

Table 2. Parameters of the epicenter and depth of the 2017 M_S7.0 Jiuzhaigou earthquake

Source	Latitude (°N)	Longitude (°E)	Depth (km)
CENC	33.200	103.820	20.0
USGS	33.197	103.861	9.0
GCMT	33.210	103.900	14.9*
Han LB et al. (2018)	—	—	14.0*
Xie ZJ et al. (2018)	—	—	6.0*
Yi GX et al. (2017)	33.195	103.817	5.0*
Fang LH et al. (2018)	33.201	103.806	16.4
This study	33.192	103.801	15.8

Note: "*" indicates centroid-depth.

(16.4 km with respect to sea-level). In addition, they noted that, based on the time difference between S- and P-wave recorded at a strong-motion station about 30 km away from the epicenter, the depth with respect to ground level ranges from 14.3–32.5 km. It is clear that our result is very close to the one determined by Fang LH et al. (2018) using the 3-D model, so we strongly suggest that 103.801°E, 33.192°N and 15.8 km with respect to see-level be taken as longitude, latitude and depth of the 2017 M_S7.0 Jiuzhaigou earthquake, and 2017-08-08 13:19:46.66 be accepted as the origin time of the event.

4. Conclusions

An analysis of the relocation results of the 2017 M_S7.0 Jiuzhaigou

earthquake calculated by use of 11 velocity models applied to data from 10 local broadband stations indicates that the model Fang2018 (Fang LH et al., 2018) which was developed for application to a seismic profile close to the Jiuzhaigou event (Wang CY et al., 2007) is the most suitable of the 11 to this event, and the hypocenter parameters yielded from this velocity model should be the best estimates at this time. These parameters are as follows: 103.801°E, 33.192°N and 15.8 km for longitude, latitude and depth, respectively, and 2017-08-08 13:19:46.66 for the event's origin time.

Acknowledgments

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