Fine relocation, mechanism, and tectonic indications of middle-small earthquakes in the Central Tibetan Plateau

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Abstract: The medium-small earthquakes that occurred in the middle part of Tibetan Plateau (32°N–36°N, 90°E–93°E) from August 2016 to June 2017 were relocated using the absolute earthquake location method Hypo2000. Compared to the reports of Chinese Seismological Networks, our relocation results are more clustered on the whole, the horizontal location differences exceed 10 km, and the focal depths are concentrated in 0–8 km, which indicates that the upper crust inside the Tibetan Plateau is tectonically active. In June 2017 altogether eight earthquakes above magnitude 3 took place; their relocated epicenters are concentrated around Gêladaindong. The relocation results of $M<3.0$ small earthquakes also showed obvious differences. Therefore, we used the CAP method to invert for the focal mechanisms of the $M \geq 3.0$ earthquakes; results generally tally with the surface geological structures, indicating that the Tibetan Plateau is still under the strong compressional force from the India Plate. Among them the eight earthquakes that occurred near Gêladaindong in June 2017 are all of normal fault type or with some strike-slip at the same time; based on previous research results we conjecture that these events are intense shallow crust responses to deep crust-mantle activities.

Keywords: relocation; focal mechanism solution; compression; Gêladaindong; ground surface response

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1. Introduction
The Tibetan Plateau is not only the highest plateau on the Earth, but also the continent-continent collision orogeny belt of the largest deformation scope and the youngest age (Yin A and Harrison, 2000). At present it is still in the mountain-building process (Ma ZJ et al., 2001), giving rise to frequent earthquakes in its interior and periphery (Figure 1), for example, the great East Kunlun $M_{6.8}$  earthquake of 2001, the Wenchuan $M_{6.0}$  earthquake of 2008, the Nyima, Tibet, $M_{6.0}$  earthquake of 2009, the Yushu $M_{7.3}$  earthquake of 2010, and the great Nepal $M_{8.2}$  earthquake of 2015, etc.

During 2010–2017 there were altogether 144 earthquakes above magnitude 5, 25 above $M_{6}$, and 7 above $M_{7}$; more than 200 earthquakes above magnitude 3 occurred each year in the interior and periphery of the Tibetan Plateau. The plateau is still in a state of intense tectonic activity; therefore, it is considered a natural laboratory for continental dynamics study.

Because of its special geographic conditions, the larger part of the plateau is unpopulated owing to severe natural conditions. Accordingly, permanent seismological stations are sparse; therefore, seismological studies are conducted mainly in the plateau’s northeastern part and periphery (Wang SY et al., 2000; Jiang M et al., 2006; Bai L et al., 2017). Consequently, research on earthquakes inside the plateau is relatively limited and insufficient. In 1991 a Sino-US cooperative study of broadband seismology was carried out along the Qing-Zang road (Owens et al., 1993); since then a large number of mobile broadband seismological observations have been made inside the Tibetan Plateau (Liang XF et al., 2016), providing necessary supplementary data for study of earthquake mechanisms within the plateau. Full utilization of the waveform data recorded by these mobile broadband stations in relocation and focal mechanism studies will tremendously benefit our understanding of the tectonic activity mechanism inside the plateau.

In this paper we obtained China Earthquake Networks Center (http://news.ceic.ac.cn/) data from 14 earthquakes of $M_{3.0}$, (Table 1) and 82 earthquakes of $M_{3.0}$ (78 with clear P and S arrivals, locations in Supplementary Materials Table S1) that occurred in the eastern part of Qiangtang in Tibetan Plateau between August 1916 and June 1917. We selected and sorted waveform data from these events that had been recorded by permanent station networks and the mobile broadband station array along the Amdo-Tuotuo River profile (Figure 1); a one-dimensional velocity structure model was constructed on the basis of previous research results (Figure 2) (Mechie and Kind, 2013; He et al., 2014b), then the Hypo2000 method (Klein, 2002) was used to relocate the 14 events given in Table 1, and the CAP method (Zhu LP and Helmberger, 1996) was used to invert for their focal mechanism...
solutions. The preliminary result (Table 1) indicates that the accuracy of relocated epicenters and focal depths is significantly improved, and the focal mechanism solutions have clearer tectonic meaning, which enriched our understanding of the seismic activity in the middle of the Tibetan Plateau.

2. Geologic Setting
The Tibetan Plateau is composed of a number of blocks pieced together at different geological times (Chang CF et al., 1986); it was formed by rapid uplift in the later stage of continent-continent collision because of the consistent northward subduction and collision of the Indian Plate starting at about 65 Ma ago (Yin A and Harrison, 2000). The geological structures carry distinct features and can be divided into three categories, including near-NS trending suture zones and reverse fault belts caused by north-southward convergence (Chang CF et al., 1986), near-NS rift systems caused by east-westerly extension (Yin A and Harrison, 2000), and widespread magmatism (Chung et al., 2005).

As shown in Figure 1, the earthquakes studied in this paper are mostly located in eastern Qiangtang in the middle part of the Tibetan Plateau. The area is bounded on the south and north by the Bangong-Nujiang suture and Jingshajiang suture, respectively (Chang CF et al., 1986), and is divided in the middle by the Lungmu Co-Shuanghu-Tanggula Mountain suture into two terranes, termed South Qiangtang and North Qiangtang (Li et al., 2006a 2006b). In addition, widespread and intense magmatic and volcanic activities started in the Tertiary and continue to the present (Deng WM et al., 1996; Wang CS, 2001; Chung et al., 2005), such as the Zhentouya, Kenzhuwulaer, and Dogaicoring Qangco super-volcanic rock provinces (Turner et al., 1993; Deng WM et al., 1996, 1999; Williams et al., 2004; Guo ZF et al., 2006). The tectonic origin of these volcanic rocks is considered to be the result of crust-mantle interaction (Turner et al., 1993; Deng WM et al., 1996, 1999; Hacker et al., 2000; Williams et al., 2004; Guo ZF et al., 2006; Chung et al., 2005). Zou et al. (2012) collected and studied data from earthquakes that occurred before 2011, and found that the earthquakes in the northern Tibet plateau were distributed in planes (Teng JW et al., 1980, 1989; Zheng JD and Zheng BH, 1982; Zheng JD, 1986), which was not consistent with geologic structure characteristics in that region. Therefore, utilizing data from permanent and mobile stations to study the earthquakes in that region is beneficial to understanding the mechanism of earthquake occurrence as well as the tectonic background of frequent earthquakes inside the Tibetan Plateau.

In this paper we (1) adopt the absolute location method (Hypo2000) to relocate the above-mentioned 96 earthquakes (14 $M_c\geq3.0$ and 82 $M_c<3.0$), (2) use the CAP method to invert for the focal mechanisms, and (3) discuss the resulting relocations and focal mechanisms.

3. Method and Data
3.1 Hypo2000 Location Method
Hypo2000 earthquake location program is developed on the basis of the traditional Geiger method (Klein, 2002), which makes a
| Event | Date and time (UTC) | M | Before | After | FM (°) | RMS | Depth (km) | CAP | $M_0$(N m) | Mechanism | Region |
|-------|---------------------|---|--------|--------|--------|-----|------------|-----|-------------|-----------|--------|
| 1     | 2016-08-23 05:32:20.30 | 4.0 | 35.870 | 91.420 | 5     | 35.950 | 91.783 | 7.31 | 235, 77, 172 | 5.37E-03 | 17     | 5.82E+22 | Strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | East Kunlun Strike-Slip Fault Belt |
| 2     | 2016-10-01 03:11:24.11 | 3.7 | 34.164 | 90.258 | 9     | 34.267 | 90.400 | 4.11 | 356, 34, –137 | 2.99E-04 | 9.96   | 2.43E+22 | Strike-slip and normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | North margin of Zhentouya volcanic rock area |
| 3     | 2016-12-04 21:34:25.00 | 5.4 | 32.280 | 92.230 | 10    | 32.383 | 92.150 | 18.0 | –60, 86, 177 | 1.37E-01 | 5.27   | 1.01E+24 | Strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Intersection of Tumengela and Little Tanggula Fault |
| 4     | 2016-12-06 18:19:48.07 | 3.8 | 35.992 | 90.233 | 7     | 34.400 | 90.066 | 7.00 | 50, 9, –155 | 3.33E-03 | 15.4   | 2.40E+22 | Strike-slip and normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | North margin of Zhentouya volcanic rock area |
| 5     | 2017-01-27 01:03:02.60 | 3.6 | 32.552 | 91.673 | 6     | 32.617 | 91.616 | 372  | 170, 44, 91 | 7.52E-02 | 3      | 1.72E+22 | Thrust |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | South side of Tumengela Fault Belt |
| 6     | 2017-02-12 16:53:41.94 | 3.5 | 35.958 | 90.216 | 9     | 35.650 | 90.600 | 7.00 | 334, 60, 104 | 5.49E-03 | 1.56   | 1.26E+22 | Thrust |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | South of East Kunlun Strike-Slip Fault Belt |
| 7     | 2017-06-03 05:07:50.13 | 3.7 | 33.524 | 91.351 | 10    | 33.550 | 91.233 | 0.07 | 89, 55, –100 | 1.32E-02 | 8.27   | 2.43E+22 | Normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 8     | 2017-06-05 12:42:45.48 | 3.3 | 33.604 | 91.071 | 10    | 33.550 | 91.267 | 664  | 290, 45, –77 | 3.65E+00 | 3.30   | 6.31E+21 | Normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 9     | 2017-06-08 00:56:53.70 | 4.8 | 33.560 | 91.130 | 10    | 33.300 | 91.600 | 5.67 | 34, 84, –176 | 6.52E-05 | 5.88   | 3.67E+22 | Strike-slip and normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 10    | 2017-06-08 04:31:49.90 | 4.1 | 33.590 | 91.110 | 9     | 33.550 | 91.200 | 232  | 21, 54, –100 | 6.69E-07 | 4.52   | 3.27E+21 | Normal and strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 11    | 2017-06-08 21:24:30.18 | 3.1 | 33.532 | 91.315 | 11    | 33.583 | 91.250 | 5.98 | 216, 25, –124 | 7.34E-03 | 9.90   | 3.16E+21 | Normal and strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 12    | 2017-06-13 19:38:20.50 | 4.8 | 33.550 | 91.700 | 10    | 33.583 | 91.250 | 5.43 | 260, 83, –159 | 1.39E-02 | 13.22  | 2.08E+23 | Strike-slip and normal |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 13    | 2017-06-14 06:04:07.01 | 3.8 | 33.579 | 91.182 | 10    | 33.567 | 91.250 | 3.12 | 25, 54, –100 | 1.52E-02 | 2.07   | 3.43E+22 | Normal and strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |
| 14    | 2017-06-18 06:09:29.89 | 3.9 | 33.580 | 91.172 | 10    | 33.567 | 91.267 | 5.22 | 287, 40, –80 | 3.68E-03 | 6.07   | 2.49E+22 | Normal and strike-slip |
|       |                     |    |         |        |       |      |          |     |             |           |        |          | Gédadaindong |

Table 1. Relocation result and focal slip type of $M \geq 3.0$ earthquakes.
Taylor expansion of the observed travel time $T'$ around the vicinity of the initial value $T$, keeps the first-order approximation, and results in the following equation system:

$$T' = T + \frac{dT}{dx} (x' - x) + \frac{dT}{dy} (y' - y) + \frac{dT}{dz} (z' - z),$$

where $T'$ is the travel time close to $T$.

First we reduce the dimension of the equation system to a normal equation, use the singular value method to decompose the equation system, and use the least-squares method to get the solution. In practical calculation multiple data weighting is adopted. Hypo2000 employs a layered velocity model, and is used mainly for locating near and local earthquakes; the calculation variance is

$$\sigma^2 = E^2_r + (c \cdot R^2),$$

where $\sigma^2$ is the variance, $E^2_r$ is the sum of errors not caused by the model, $c$ is weighting factor, and $R$ is the RMS travel time residuals. Based on the result of Guan et al. (2017) using Hypo2000 to locate the earthquakes in Sichuan Province, we selected the location results of $R \leq 0.5$.

3.2 CAP Method

First we use the frequency-wave number (F-K) method to calculate the theoretical Green’s function. Given a horizontally layered crust model, by integration over frequency and wave number respectively, the F-K method calculates the theoretical Green’s functions of various frequencies for different epicentral distances.

Compared to the focal mechanism method using P-wave first motions, the CAP (Cut and Paste) inversion method utilizing waveforms needs less data and has higher reliability and accuracy (Zhu LP et al., 1997). The CAP method uses near-earthquake waveform data, divides the broadband seismic record into a body wave (Pnl) and a surface wave part, and then, by fitting the calculated waveform $s$ and the observed waveform $u$, searches for the optimum solution in the related parameter space $(0^\circ \leq \phi (\text{strike}) \leq 360^\circ, 0^\circ \leq \delta (\text{dip}) \leq 90^\circ, -180^\circ \leq \lambda (\text{rake}) \leq 180^\circ)$.

This method makes corrections for the epicentral distance (Zhu LP and Helmberger, 1996); the absolute error is expressed as

$$e = \left\| \left( \frac{r}{r_0} \right)^p \| u - s \| \right\|,$$

where $u$ is the observed waveform, $s$ is the theoretical waveform, $r$ is epicenter distance, and $p$ is an exponential factor; generally $p=1$ for the body wave part (Pnl) and $p=0.5$ for surface wave (Zhu LP and Helmberger, 1996; Han LB and Jiang CS, 2012).

3.3 Data Collection

The study area is within 32°N–36°N and 89°E–93°E. The network center report suggested that most earthquakes did not occur on tectonically distinct structures in the study area. In order to understand the seismicity in the middle Tibetan Plateau more accurately, we collected data since July 2016 from 25 permanent stations in Tibet and Qinghai Province (black triangles in Figure 1; Data Management Centre of China National Seismic Network, 2007; Zheng XF et al., 2009) as well as from 30 broadband mobile stations (green triangles in Figure 1) deployed along the Qing-Zang road (Amo-Tanggula Pass-Tuotuohe).

This mobile broadband seismological observation profile crosses the Bangong-Nujiang suture zone, Lungmu Co-Shuanghu suture zone, and the Jinshajiang suture zone from south to north, with an average station spacing about 10 km. We collected the data of 14 $M \geq 3.0$ and 82 $M < 3.0$ earthquakes (Figure 1) that occurred between August 2016 and June 2017, recorded by 55 stations in the study area and its surrounding areas. Considering the effects of station altitude, the elevations of all selected permanent stations are not less than 3000 m above sea level. In the location study we ensured that each earthquake was clearly recorded by at least 8 stations. To ensure greatest location accuracy, we manually selected records of high S/N ratio and with clear P and S arrivals, so as to reduce errors caused by manual picking-up of seismic phases. Figure 2 shows the raw waveforms of the vertical component of Event 3, indicating that the data of permanent and mobile stations have high S/N ratio and clear P and S wave arrivals.

4. Crustal Velocity Model

The development and application of broadband seismological observation technique have allowed gradually deeper understanding of the velocity structure of crust and mantle in the Tibetan Plateau. Li YH. (2006) used the observation data of INDEPTH III Program to carry out waveform inversion and obtained the one-dimensional velocity model, which indicated that the Moho depth in the study area is 65 km with slight variation. Gao R et al. (2013) studied the Moho interface by deep seismic sounding, which led to a similar estimate of Moho depth beneath middle Qiangtang: 68.9 km. Mechic and Kind (2013) obtained a reflection profile in the study area of this paper and surrounding areas; combining the research result of Moho depth and Poisson’s ratio in the Chinese mainland (He RZ et al., 2014b), an 1D crustal velocity model is obtained using the identified P/S arrivals and VELEST calculation (Figure 3; Kissling et al., 1995). The crust is found to be 69 km thick, and is divided into 6 layers from +4 km to –65 km.

5. Result Analysis

5.1 Relocated Epicenters

Utilizing the Hypo2000 method to relocate the 96 earthquakes in the study area, results are shown in Figure 4. Table 1 shows the relocation results for 14 $M \geq 3.0$ earthquakes; relocations for 82 $M < 3.0$ earthquakes are listed in Supplementary Materials (Table S1). The epicenter distribution after relocation shows significant change, all exceeding 0.01°; the relocated epicenter of Event 4 changed by more than 2° (Table 1, Figures 1 and 4). The relocated epicenters are closer to active structures (fault or volcanic rock areas) (Table 1). The aftershocks of Event 3 are along the mainshock rupture; the 8 earthquakes in June 2017 are more concentrated, and the earthquakes at the periphery migrate to the interior of the study area. Figure 4 shows the travel time residuals of mobile stations before and after relocation; after relocation the residuals are significantly reduced, indicating that adding the broadband mobile observations clearly improves the accuracy of earthquake location.

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5.2 Relocated Focal Depths

As shown in Table 1, the focal depths given by the China Earthquake Networks Center are mainly distributed on the planes of depth 5 km and 10 km (Teng JW et al., 1980, 1989; Zheng JD and Zheng BH, 1982; Zheng JD, 1986; Zou CQ et al., 2012). Except for event 3 (focal depth 18 km), most other focal depths are in the range 0–8 km. This is consistent with previous results that earthquakes in middle and west China are rather shallow, 91% shallower than 20 km (Yang ZX et al., 2003; Ma ZJ, 1992). Previous studies indicated that low velocity and high conductivity layers exist in the crust of Tibetan Plateau (Jiang M et al., 2012; Peng M et al., 2012). While the upper crust is brittle, earthquakes mostly take place at the top of a low-velocity high-conductivity layer; the relocation focal depths are consistent with this result.

The focal depth of Event 3 is closer to the result of CMT (see Supplementary Materials, Table S2), indicating the reliability of the method of the present study. The 8 earthquakes in June of 2017 appear to be concentrated; no active fault exists around this concentration area. Profile A-A’ (Figure 7) shows that the focal depths in this area are between 0 and 15 km, except for only one below 15 km. Event 3 and the M>3.0 earthquakes around it occurred below 10 km, and the aftershocks of Event 3 took place mainly near the rupture of the mainshock. Figure 5 shows the time series of the study area earthquakes that occurred in 2017. It can be seen that earthquakes occurred frequently in June, indicating intense
tectonic activity in the upper crust; according to the relocated epicenter distribution, we conjecture that they are a series of related events. Therefore, in order to further study the characteristics of the seismogenic structures, we used the CAP method to invert the waveform data of the 14 earthquakes from permanent and mobile stations, and obtained the focal mechanisms of these 14 events.

6. Focal Mechanism Analysis

We first correct the data for instrument response to get the displacement of ground motion, then rotate the $Z$-$N$-$E$ components to $Z$-$R$-$T$ in the great circle coordinate system, and finally divide the waveform into two parts: Pnl and surface waves (Figure 2); for suppressing noise, the frequency bands of the bandpass filter are respectively 0.02–0.15 Hz and 0.02–0.1 Hz (Han LB and Jiang CS, 2012).

Figure 8 compares the observed and theoretical waveform fitting for Event 3 (Dec. 4, 2016, $M_s$ 5.4). Altogether the data from 11 stations were used in the inversion; for most stations the waveform fitting is good; the correlation coefficients are greater than 0.6 for 76.3% of the total waveforms. For stations XZ.LIZ, XZ.NMU, and XZ.RKZ the fitting of the Pnl wave is relatively poor, which is related to the complex structure of the Tibetan Plateau (Figure 1); that is, the real velocity structure differs from the adopted 1D crust velocity model. Figure 9 shows the variation of waveform fitting with focal depth for Event 3; in the depth range 0–15 km the focal mechanism solution changes insignificantly, indicating that the solution is rather stable. The minimum value is reached at about 5 km, which is the optimum focal depth from CAP inversion and is very different from the relocation result (depth 18 km). This also shows that the adopted crust model deviates from the actual deep structure.

The focal mechanism solutions from CAP inversion indicate that for most stations the fitting between theoretical and observed waveforms is relatively good; thus the corresponding resultant seismic moment is reliable. As shown in Table 1, the strike-slip ruptures of Events 1 and 3 indicate that, in the margin of the study area, EW-trending faults are developed; the focal mechanism solutions of Event 5 in the south of the Tumengela Fault and Event 6 at the East Kunlun Strike-Slip Fault are of reverse faulting type, indicating that this region is still under compression, which accords with the regional tectonic character; all the other earthquakes are normal faulting or with some strike-slip component. Events 2 and 4 are located in the Zhentouya area, while Events 7–14 are in nearby Gêladaindong; their rupture types are similar.
7. Discussion
At present, earthquakes still occur frequently in the Tibetan Plateau and its periphery, indicating that while the Indian Plate is continuously subducting northward, the Tibetan Plateau and its periphery are still tectonically active (Figure 1). Frequent earthquakes caused severe losses of human life and property, such as in the

Figure 6. Relocated epicenters, focal mechanisms (red), and previous results (black, Zhu GH et al., 2017). Red circles are relocated epicenters; black open circles are epicenters of \( M < 3.0 \) earthquakes; A-A' indicates the position of the profile. AKMS-A’nyêmaqên-Kunlunshan suture, JSS-Jinshajiang suture, LSLS-Lungmu Co-Shuanghu-Lancangjiang suture, BNS-Bangong-Nujiang suture, SMKLF-South Margin of Kunlun Fault, TGF-Tumengela Fault, IYS-Yarlung Zangbo River suture. Event 1 to Event 14 are the 14 earthquakes studied in the paper (see Table 1).

Figure 7. Focal depths of earthquakes within 13 km from Profile A-A' (for locations see Figure 6). TGF-Tumengela Fault, LTGLF-Lesser Tanggula Fault, MTGLF-Main Tanggula Fault.
Wenchuan earthquake of May 12, 2008, and the Nepal earthquake of April 25, 2015. Studying the mechanisms of frequent earthquakes in Tibetan Plateau and its periphery, especially those inside the plateau, is one of the best ways to understand the uplifting mechanism of the Tibetan Plateau (Wang CS et al., 2014) and the variation of stresses in its shallow crust.

This paper used the absolute location method Hypo2000 to relocate 96 earthquakes that occurred in the middle Qiangtang basin from August, 2016, to June, 2017, and obtained results for 93 events. The locations before and after relocation differ significantly; the maximum horizontal difference exceeds 200 km. The focal depths of $M_{\geq 3.0}$ earthquakes are mainly in the range of 0–8 km, but not distributed in planes, except for Event 3 at a depth of 18 km. Some of the relocated epicenters are closer to the active faults in the study region than previously estimated; and the previously concentrated events became more clustered. The focal depth profile (Figure 7) shows that the depth does not exceed 15 km. Based on the relocated epicenter distribution and the focal mechanism solutions (Table 1, Figure 6, Figure 7), the 93 earthquakes in this paper are mainly distributed in the following three regions:

1. **Hoh Xil potassium-hyperpotassium volcanic rock region in northern Tibet**
   
   This region has frequent earthquakes. Event 1 and event 6 occurred in the East Kunlun Fault and to its south, generally showing as strike-slip or reverse faulting (Deng QD, 1996), which is similar to the East Kunlun great earthquake of 2001 (Lin AM et al., 2002). On the other hand, Events 2 and 4 occurred in the north margin of the Zhentouya volcanic region, and their focal mechanisms are of strike-slip with normal faulting type. These 4 earthquakes are all located in the east margin of the Hoh Xil potassium-hyperpotassium volcanic rock province in northern Tibet. This may indicate that the crust-mantle interaction beneath the volcanic rocks in northern Tibet is still intense (Williams et al., 2004; He RZ et al., 2014a); that is, large-scale eruption of potassium-hyperpotassium volcanic rocks in this region have occurred since the Neogene (Turner et al., 1993; Deng WM et al., 2001); the present activity is still strong.

2. **Gêladaindong region**
   
   Events 7–14 are concentrated along the northeast margin of Gêladaindong-Quemocuo-south of Kenzuwulaer Mountains (Table 1, Figure 6, Figure 7).

Figure 8. Theoretical (red) and observed (black) waveforms of Event 3 (Dec. 4, 2016, $M_{\text{S}}$5.4). Dis: Epicenter distance; AZ: Azimuth; net: Network code; name: Station name; on the right side of each waveform, the upper figure is the correlation coefficient (percent) of theoretical and observed waveforms, the lower figure is the time shift between the two waveforms.
8. Conclusion
This paper relocated 93 earthquakes that occurred in the middle part of the Tibetan Plateau from August 2016 to June 2017, and obtained the focal mechanism solutions of 14 $M$≥3.0 earthquakes through inversion. The relocation results show significant differences from results reported by the Networks Center—both horizontally and in depth; the maximum horizontal shift exceeds 200 km; the focal depths of the $M$≥3.0 earthquakes concentrated between 0 and 8 km in both studies, but not in a planar distribution. The relocated epicenter distribution and the focal mechanism solutions were concentrated in three regions, namely the Hoh Xil potassium-hyperpotassium volcanic rock region in northern Tibet, the Gêladaindong region, and the intersection of the Tumengela Fault and the Lesser Tanggula Mountains, which accord generally with surface geological characters. In the East Kunlun Fault and its south there were generally strike-slip or reverse faulting mechanisms; in the north margin of the Zhentouyu volcanic rock region and the Gêladaindong region the crust-mantle interaction was intense; the front edge of the subducted Indian lithospheric mantle beneath southern the Tibetan Plateau was just about 200 km under the intersection of the Tumengela Fault and Lesser Tanggula Mountains, and was broken off, resulting in the overall extension environment of this region. This indicates that the northward subduction of India continent continues to the present; that is, that the interior of the Tibetan Plateau is still tectonically active.

Because the geologic structures of the middle part of the Tibetan Plateau are complicated and most areas are unpopulated, this brings tremendous challenge to the deployment of broadband seismological observation equipment, hence the stations in the western part of the study area are sparse, and observation data are insufficient. As monitoring resources improve, further research should continue to advance knowledge of tectonic activity in this important area.

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Supplementary Materials

Table S1. Relocation result of $M$<3.0 earthquakes.

| Events | Before relocation | | After relocation | |
|---|---|---|---|---|
| | Lat(°N) | Log(°E) | D (km) | Lat(°N) | Log(°E) | D (km) | $M$ |
| 1 | 32.60 | 92.23 | 6.00 | 32.6333 | 91.7833 | 25.1 | 0.45 |
| 2 | 35.86 | 92.53 | 8.00 | 35.1667 | 93.85 | 7 | 1.49 |

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Continued from Table S1

| Events | Before relocation | After relocation |
|--------|------------------|-----------------|
|        | Lat(°N) | Log(°E) | D (km) | Lat(°N) | Log(°E) | D (km) | M |
| 3      | 35.90    | 92.04    | 8.00   | 36.1167 | 90.9167 | 7      | 1.14 |
| 4      | 35.91    | 92.02    | 7.00   | 35.2    | 94.7833 | 7      | 2.85 |
| 5      | 35.75    | 92.21    | 10.00  | 33.1667 | 92.0667 | 0.44   | 2.59 |
| 6      | 33.75    | 91.47    | 11.00  | 33.65   | 91.9    | 16.14  | 0.44 |
| 7      | 33.51    | 91.07    | 6.00   | 33.5    | 91.3    | 12.87  | 0.23 |
| 8      | 32.35    | 92.19    | 7.00   | 32.4    | 92.1667 | 18.01  | 0.06 |
| 9      | 32.29    | 92.25    | 7.00   | 32.4    | 92.1667 | 17.46  | 0.14 |
| 10     | 32.56    | 92.16    | 8.00   | 32.6167 | 92.1333 | 12.99  | 0.06 |
| 11     | 32.30    | 92.25    | 6.00   | 32.4    | 92.1667 | 18.45  | 0.13 |
| 12     | 32.33    | 92.18    | 6.00   | 32.3833 | 92.1667 | 17.65  | 0.05 |
| 13     | 32.32    | 92.06    | 6.00   | 32.3833 | 92.1167 | 18.1   | 0.08 |
| 14     | 32.25    | 92.55    | 5.00   | 32.35   | 92.1833 | 17.2   | 0.38 |
| 15     | 32.30    | 92.17    | 10.00  | 32.3833 | 92.15   | 24.35  | 0.09 |
| 16     | 32.34    | 92.48    | 6.00   | 32.4    | 92.1667 | 17     | 0.32 |
| 17     | 32.26    | 92.59    | 8.00   | 32.45   | 91.95   | 7.39   | 0.67 |
| 18     | 32.31    | 92.35    | 6.00   | 32.4167 | 92.1167 | 21.74  | 0.26 |
| 19     | 32.31    | 92.16    | 6.00   | 32.4    | 92.15   | 17.52  | 0.09 |
| 20     | 32.32    | 92.24    | 7.00   | 32.4    | 92.2167 | 17.82  | 0.08 |
| 21     | 32.34    | 92.12    | 6.00   | 32.4    | 92.15   | 17.41  | 0.07 |
| 22     | 32.29    | 92.34    | 6.00   | 32.3833 | 92.1    | 20.99  | 0.26 |
| 23     | 32.31    | 92.24    | 5.00   | 32.3833 | 92.1167 | 28.24  | 0.14 |
| 24     | 32.41    | 92.30    | 9.00   | 32.4    | 92.15   | 16.83  | 0.15 |
| 25     | 32.28    | 92.37    | 7.00   | 32.3833 | 92.1333 | 17.97  | 0.26 |
| 26     | 32.32    | 92.40    | 5.00   | 32.4    | 92.1333 | 23.06  | 0.28 |
| 27     | 32.31    | 92.47    | 5.00   | 32.4167 | 92.1667 | 17.91  | 0.32 |
| 28     | 32.30    | 92.21    | 5.00   | 32.3833 | 92.1333 | 17.49  | 0.11 |
| 29     | 32.29    | 92.23    | 5.00   | 32.4    | 92.1667 | 9.87   | 0.13 |
| 30     | 32.98    | 91.97    | 11.00  | 33.0333 | 92.15   | 10.2   | 0.19 |
| 31     | 32.31    | 92.26    | 8.00   | 32.4167 | 92.1667 | 18.58  | 0.14 |
| 32     | 32.99    | 92.00    | 11.00  | 33.0167 | 92.1333 | 15     | 0.14 |
| 33     | 32.31    | 92.17    | 5.00   | 32.3833 | 92.15   | 17.78  | 0.08 |
| 34     | 32.29    | 92.18    | 6.00   | 32.4167 | 92.1667 | 11.68  | 0.13 |
| 35     | 32.34    | 92.18    | 5.00   | 32.3833 | 92.15   | 17.78  | 0.05 |
| 36     | 32.18    | 92.37    | 6.00   | 32.4    | 92.1333 | 18.31  | 0.32 |
| 37     | 32.36    | 92.14    | 12.00  | 32.4    | 92.1167 | 21.25  | 0.05 |
| 38     | 32.32    | 92.20    | 7.00   | 32.3833 | 92.1833 | 18.79  | 0.07 |
| 39     | 35.90    | 91.98    | 12.00  | 34.3167 | 92.45   | 0.035  | 1.65 |
| 40     | 32.40    | 92.61    | 11.00  | 32.4833 | 92.5833 | 10.02  | 0.09 |
| 41     | 32.32    | 92.27    | 7.00   | 32.4    | 92.1    | 20.92  | 0.19 |
| 42     | 33.91    | 91.29    | 11.00  | 33.9167 | 91.3333 | 3.56   | 0.04 |
| 43     | 32.28    | 92.32    | 10.00  | 32.3833 | 92.1333 | 24.75  | 0.21 |
Continued from Table S1

| Events | Before relocation | After relocation | M |
|--------|-------------------|------------------|---|
|        | Lat(°N) | Log(°E) | D (km) | Lat(°N) | Log(°E) | D (km) |
| 44     | 33.92    | 91.30     | 11.00   | 33.9333 | 91.3     | 2.53   | 0.01 |
| 45     | 32.95    | 91.75     | 9.00    | 32.95   | 92.0167  | 10.49  | 0.27 |
| 46     | 32.85    | 91.86     | 10.00   | 32.9167 | 92.2     | 0.3    | 0.35 |
| 47     | 32.95    | 92.14     | 10.00   | 32.95   | 91.9667  | 11.77  | 0.17 |
| 48     | 32.93    | 91.76     | 8.00    | 32.95   | 92      | 10.46  | 0.24 |
| 49     | 32.29    | 92.19     | 11.00   | 32.3667 | 92.15    | 21.86  | 0.09 |
| 50     | 32.68    | 90.43     | 6.00    | 32.6833 | 90.55    | 8.12   | 0.12 |
| 51     | 32.31    | 92.16     | 8.00    | 32.4167 | 92.1667  | 11.65  | 0.11 |
| 52     | 33.25    | 90.28     | 4.00    | 32.55   | 92.9333  | 0.22   | 2.74 |
| 53     | 32.57    | 91.61     | 6.00    | 32.6167 | 91.5833  | 0.19   | 0.05 |
| 54     | 32.33    | 92.17     | 5.00    | 32.4167 | 92.15    | 17.94  | 0.09 |
| 55     | 32.39    | 90.59     | 5.00    | 32.5333 | 90.5333  | 2.19   | 0.15 |
| 56     | 34.01    | 91.82     | 6.00    | 33.9833 | 91.85    | 13.23  | 0.04 |
| 57     | 32.36    | 92.24     | 6.00    | 32.4    | 92.15    | 19.22  | 0.10 |
| 58     | 33.40    | 90.69     | 6.00    | 33.3333 | 91.0333  | 5.96   | 0.35 |
| 59     | 33.98    | 90.90     | 8.00    | 34.0167 | 90.8167  | 7.19   | 0.09 |
| 60     | 32.33    | 92.29     | 7.00    | 32.4167 | 92.2333  | 14.49  | 0.10 |
| 61     | 32.72    | 92.87     | 10.00   | 33.1    | 91.3333  | 0.03   | 1.58 |
| 62     | 32.73    | 92.81     | 8.00    | 33.0667 | 91.3667  | 0.05   | 1.48 |
| 63     | 33.10    | 91.21     | 8.00    | 33.2333 | 91      | 12.27  | 0.25 |
| 64     | 33.53    | 91.29     | 10.00   | 33.1833 | 92.55    | 0.05   | 1.31 |
| 65     | 34.69    | 92.99     | 9.00    | 33.25   | 90.2167  | 7.001  | 3.12 |
| 66     | 33.49    | 91.28     | 11.00   | 33.15   | 92.5667  | 0.03   | 1.33 |
| 67     | 35.93    | 91.95     | 7.00    | 35.7667 | 93.1833  | 6.78   | 1.24 |
| 68     | 32.51    | 92.16     | 6.00    | 32.5833 | 92.1     | 16.41  | 0.09 |
| 69     | 33.61    | 91.06     | 9.00    | 33.2833 | 92.6667  | 0.44   | 1.64 |
| 70     | 33.50    | 91.23     | 10.00   | 33.2167 | 92.6     | 0.2    | 1.40 |
| 71     | 33.59    | 91.07     | 9.00    | 33.6    | 91.15    | 7.8    | 0.08 |
| 72     | 33.57    | 91.38     | 8.00    | 33.5833 | 91.3167  | 10.66  | 0.06 |
| 73     | 33.58    | 91.11     | 9.00    | 33.6833 | 91.3167  | 18.72  | 0.23 |
| 74     | 33.60    | 91.08     | 10.00   | 33.1833 | 92.5667  | 0.05   | 1.54 |
| 75     | 33.87    | 91.54     | 11.00   | 33.65   | 91.85    | 16.58  | 0.38 |
| 76     | 33.62    | 91.13     | 10.00   | 33.5333 | 91.2833  | 8.14   | 0.18 |
| 77     | 33.64    | 91.14     | 10      | 33.2    | 92.7667  | 0.43   | 1.69 |
| 78     | 33.64    | 91.09     | 9       | 33.1667 | 92.4     | 0.87   | 1.39 |

Table S2. Relocation result of CMT

| Event 3 | Epicenter | FM | M |
|---------|-----------|----|---|
| CMT     | Lat(°N)   | Log(°E) | D (km) | strike | dip | rake | M |
| This study | 32.3833 | 92.1500 | 18.0 | −60 | 86 | 177 | 5.4 |
| CMT     | 32.27    | 92.27   | 17    | 333   | 83 | 174 | 5.3 |

The focal mechanism solutions in the figure are all from the Global CMT Catalog (http://www.globalcmt.org/).
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