Systematic search for repeating earthquakes along the Haiyuan fault system in Northeastern Tibet

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Abstract

Repeating earthquakes have been found at many faults around the world, and they provide valuable information on diverse faulting behavior at seismogenic depth. The Haiyuan fault is a major left-lateral strike-slip fault along the northeastern (NE) boundary of the Tibetan Plateau. Two great earthquakes (1920 Haiyuan, 1927 Gulang) have occurred on this fault system, but the section between the ruptures of the two earthquakes, also known as the Tianzhu seismic gap, remains unbroken. Shallow creep has been observed from geodetic data at the eastern end of the seismic gap. However, the driving mechanism and depth extent of shallow creep are not clear. Here we conduct a systematic search for repeating earthquakes in NE Tibet based on seismic data recorded by permanent stations in ten years (2009-2018). Based on waveform cross-correlations and subsequent relocations, we find several repeating earthquake clusters at Laohushan section. This is consistent with the shallow creep inferred from the geodetic data, indicating repeating earthquakes can be driven by nearby aseismic slip. ~300 repeaters were found within clusters of intense seismicity near the rupture zones of the 1927 M8.0 Gulang and 2016 M6.4 Menyuan earthquakes. Relocation of events in the cluster near the Gulang earthquake delineates two possible unmapped faults orthogonal to the Haiyuan fault. In addition, we also identify several repeating earthquakes generated by mining activities with different waveforms and occurrence patterns. Our study suggests that repeating earthquakes around the Haiyuan fault are mostly driven by postseismic relaxation process associated with 1920 Haiyuan and 1927 Gulang earthquakes.

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Abstract: Repeating earthquakes have been found at many faults around the world, and they provide valuable information on diverse faulting behavior at seismogenic depth. The Haiyuan fault is a major left-lateral strike-slip fault along the northeastern (NE) boundary of the Tibetan Plateau. Two great earthquakes (1920 Haiyuan, 1927 Gulang) have occurred on this fault system, but the section between the ruptures of the two earthquakes, also known as the Tianzhu seismic gap, remains unbroken. Shallow creep has been observed from geodetic data at the eastern end of the seismic gap. However, the driving mechanism and depth extent of shallow creep are not clear. Here we conduct a systematic search for repeating earthquakes in NE Tibet based on seismic data recorded by permanent stations in ten years (2009-2018). Based on waveform cross-correlations and subsequent relocations, we find several repeating earthquake clusters at the Laohushan section. This is consistent with the shallow creep inferred from the geodetic data, indicating repeating earthquakes can be driven by nearby aseismic slip. ~300 repeaters were found within clusters of intense seismicity near the rupture zones of the 1927 M8.0 Gulang and 2016 M6.4 Menyuan earthquakes. Relocation of events in the cluster near the Gulang earthquake delineates two possible unmapped faults orthogonal to the Haiyuan fault. In addition, we also identify several repeating earthquakes generated by mining activities with different waveforms and occurrence patterns. Our study suggests that repeating earthquakes around the Haiyuan fault are mostly driven by postseismic relaxation process associated with the 1920 Haiyuan and 1927 Gulang earthquakes.

Plain Language Summary: Repeating earthquakes usually have a similar magnitude and occur at the same fault patch. Based on the ten years data in NE Tibet, we find ~10 % of events in NE Tibet are repeating events. The repeating earthquakes at Laohushan section of Haiyuan fault mark the boundary between the creep and locked region. The repeating earthquakes at Menyuan follow the moderate-size mainshocks. The intense seismicity at the Gulang seismic zone reveals two possible hidden faults. Mining related repeaters have different waveforms from natural earthquakes and occur dominantly in afternoons, inferring that repeaters along the Haiyuan fault are of earthquake origin and indicators of faulting behavior.

Key points:

1. Repeating earthquakes are found at the creeping Laohushan section of the Haiyuan Fault.
2. Intense seismicity at the Gulang seismic zone reveals two possible hidden faults.
3. Repeating earthquakes along the Haiyuan Fault are likely driven by postseismic processes of large earthquakes.

Introduction

Repeating earthquakes (also known as repeaters) are families of seismic events generated by repeated loading and failure of a single fault patch (e.g., Vidale et al., 1994; Nadeau et al., 1995). Because they are typically driven by aseismic slow slip surrounding them (Beeler et al., 2001), repeaters provide new insight into diverse fault slip behavior at depth, which is usually difficult to characterize from surface observations alone. These include postseismic afterslip, triggered creep and eposodic slow slip events, and steady fault creep during interseismic period (Uchida and Bürgmann, 2019; Uchida, 2019). In addition, repeating earthquakes can be used to quantify temporal changes of seismic velocities (e.g., Poupinet et al., 1984; Schaff and Beroza, 2004; Rubinstein and Beroza, 2004; Peng and Ben-Zion, 2006) or seismic scatterers at depth (Niu et al., 2003; Taira et al., 2009).

Repeating earthquakes was first identified in Central California along the Calaveras Fault (Vidale et al., 1994) and the Parkfiled section of the San Andreas Fault (Nadeau et al., 1995). Since then, they have been found on major plate boundary faults elsewhere around the world, such as the Japan trench (e.g. Igarashi et al., 2003; Uchida et al., 2003), Taiwan (Chen et al., 2007), Tonga (eg. Yu, 2013), Costa Rica (Yao et al., 2017), and Turkey (Peng and Ben-Zion, 2005, 2006). There are also increasing reports on repeating earthquakes in intraplate settings. For example, repeaters have been found in seismic zones in the central United States (Bisrat et al. 2012). Based on cross-correlating of regional seismic waveforms, Schaff and

Richards (2004) found that 10% of seismic events in and around China are repeating earthquakes (with no more than 1 km from each other). In addition, Li et al. (2007) found repeaters in eastern China along the aftershock zone of the 1976 M7.6 Tangshan earthquake, and Li et al. (2011) identified repeaters in the Longmen Shan Thrust Fault zone along the rupture zone of the 2008 Mw7.9 Wenchuan earthquake. Liu et al. (2019) found the repeating earthquake clusters in the aftershock zone of the 2016 Ms6.4 Menyuan earthquake along the northeastern (NE) margin of the Tibetan Plateau.

The Haiyuan fault (HYF) is a major active left-lateral strike-slip fault along the NE edge of the Tibetan Plateau (Figure 1). The western and central sections include the Lenglengling fault (LLLF), Jinqianghe fault (JQHF), Maomaoshan fault (MMSF), Laohushan fault (LHSF), and the eastern section connects with the Liupanshan fault (LPSF) at Madongshan (MDS). Several large earthquakes occurred along the Haiyuan fault system in the past, including the 1920 M7.8-8.3 Haiyuan (Liu-Zeng et al., 2015), the 1927 M~8 Gulang, the 1990 Ms6.2 Jingtai and the 2016 Ms6.4 Mengyuan earthquakes. However, there is not yet the consensus of the slip rate along the HYF. Based on the ages of fault-related, scarp-derived colluvial wedges, Zhang et al. (1998) obtained a slip rate of 8 ± 2 mm/yr along the eastern section of the HYF. Based on offset geomorphic features and age constraints, Li et al. (2009) inferred a slip rate of 4.5 ± 1.0 mm/yr on the same section. However, Lasserre et al. (1999) yielded a high slip rate (12 ± 4 mm/yr) in the middle section, which was recently re-evaluated and updated to be 5-9 mm/yr (Yao et al., 2019).

At the east end of the middle Laohushan section, shallow creep has been observed from geodetic data and is estimated to be 5 ± 1 mm/yr (Jolivet et al., 2012, 2013), close to or slightly smaller than the geologic rate. However, creep in this section is poorly understood as compared to other known creeping faults of fault sections around the world (e.g., Harris, 2017). For example, the depth extent of the creep is not well constrained. In addition, it is unclear whether creep on this section of the HYF is a transient phenomenon following the 1920 Haiyuan mainshock, or reflects a long-term slip behavior (Chen et al., 2018).

In order to better understand the seismicity pattern and fault slip behaviors along the HYF, we conduct a systematic search for repeating earthquakes in this region based on ten years of microseismic data. Specifically, we identify repeating earthquake pairs using waveform cross-correlations, and then we group the pair into clusters. Finally, we use these repeating clusters to better understand the aseismic process and slip rates along the HYF and other faults in NE Tibet.

Data and Methods

Within the following geographic boundaries (longitudes between 96-107°E, latitudes between 36-41°N), there are more than 25,000 M≥1 events from 2009 to 2018 based on the regional catalog archived by the China Earthquake Networks Center (CENC) (Figure 1). The earthquakes are mostly distributed along the HYF and other major faults/boundaries in this region, such as near the eastern end of the ATF, and the western boundary of the Ordos basin. We obtain raw seismogram data (100 Hz sampling rate) recorded by 51 permanent stations from the Data Management Centre of the China National Seismic Network (Zheng et al. 2010). These include 44 stations deployed before 2009, and 7 stations deployed at the end of 2014 (Figure S1).

Hypocenter location and waveform similarity are two main methods to identify repeating earthquakes (Uchida, 2019). Here we use the later one because it is the most frequently used method and we can relocate the events afterwards. Our analysis procedure includes the following six steps. First, we compute the P and S arrival time using the Taup program (Crotwell et al., 1999) according to a local velocity model (Deng et al., 2018; Table S1) modified from isap91 model (Kennett and Engdahl, 1991). Because there are some hand-picked P and S phases in the catalog, we use them when available, and use the computed arrival times for the rest traces. We then apply a 2-16 Hz bandpass filter on the data, which is the predominant frequency range for microearthquakes (Uchida, 2019). Next, we perform a quality control on the raw data, based on the signal-noise-ratio (SNR). We use a 20-s window (5 s before the P wave) as the signal window, and the same 20-s window 25 s before the P wave as the noise window. We choose the data with the SNR higher than 4 and remove the rest seismograms with low SNRs.

We then compute cross-correlations (CCs) among all M≥1 events beneath all stations, and identify repeating event pairs with locations less than 200 km apart with CC value above 0.80. Because the time windows are usually set to contain both P and

S phases to ensure the same P-S time and thus the same hypocentral distance (Uchida et al., 2003), here we choose 2 s before and 18 s after the P arrivals. The predicted P arrival may be not accurate due to the complicated velocity structure and inaccurate epicentral location, so we allow a maximum time shift of 5 s to obtain the highest CC between each waveform pair. Next, we group repeating pairs into clusters using an Equivalency Class (EC) algorithm (Peng and Ben-Zion, 2005; Press et al., 1986). When two pairs have a common event and meet a certain threshold (median CC value ≥ 0.9 with number of at least 2 stations), we group them into the same cluster. Finally, we relocate the repeaters in each cluster using the Growclust program (Trugman et al., 2017) based on the differential arrival times from waveform cross-correlations.

Based on the identified repeaters, we can estimate their cumulative slip according to their local magnitudes M_L. The individual slip d can be estimated by assuming a standard crack model

$$d = \frac{M_0}{\mu\pi r^2} \quad (1)$$

where r is the rupture size, and M_o is the seismic moment. The rupture size r can be obtained from (Kanamori and Anderson, 1975)

$$r = (\frac{7M_0}{16\Delta\sigma})^{1/3} \quad (2)$$

where $\Delta\sigma$ is the static stress drop. The seismic moment M_o can be estimated from the local magnitude M_L with the following equation (Abercrombie, 1996)

$$\log(M_0) = 9.8 + M_L \quad (3)$$

Finally, the average slip rate is computed from dividing the cumulative slip with the total duration of the repeating cluster (Li et al., 2011).

While the local magnitudes M_L can be obtained from the CENC catalog, the stress drops $\Delta\sigma$ for these events are not available. Hence, we use nominal stress drop values of 1, 5 and 10 MPa, respectively (Li et al., 2011).

Results

In total, we identify 929 clusters (~2,500 events) in NE Tibet with at least two repeaters, which accounts for ~10% of earthquakes in this region. Figure 2 shows the spatial distribution of all repeating clusters, together with the background seismicity. Even though the repeaters are widely distributed, clusters with more than 8 events are only found at certain regions along and outside of the HYF. In the following sections, we discuss them in more detail.

1) The creeping section of the HYF (middle Laohushan section) (region 1)

We find the 31 repeating earthquakes within 12 clusters along the LHSF, which is in the central section of the HYF (Figure 3). From the map view, the repeaters are mostly located around 103.7°E, to the west side of the peak creep region as reported by Jolivet et al. (2013). 87 % and 94 % repeaters have the depth shallower than 10 km before and after relocation, respectively. Figure 4 shows an example of waveforms recorded at station GS.JDT for the repeating earthquake cluster with 8 events, which occurred from 2013 to 2017. The waveforms show high similarity from the P and S waves to the coda waves, and their magnitudes are similar, indicating that they likely rupture the same fault patch at depth.

Between the analyzed time period (2009-2019), a total of four events with moment magnitude Mw≥4 occurred in this region, and two of them have focal mechanisms estimated with the gCAP method (Cui et al., 2019). If we include three more events listed in the global CMT (GCMT) catalog, four of them have strike-slip focal mechniams and the other one (2009 M4.3) is a thrust event. We observe an increasing occurrence of repeating events (as well as background events) following the 2014/11/14 M4.9 and 2015/07/15 M4.0 strike-slip events. No obvious change in repeating earthquake (and background event) was found following the 2009/10/27 M4.3 thrust and 2018/05/26 M4.1 event (focal mechanisms not determined).

Table S2 summarizes the estimated slip rates for 6 repeating clusters along the LHSF with three nominal stress drop values. For the cluster with number of events, the corresponding slip rates with 1, 5 and 10 MPas stress drops are 0.77, 2.25, and 3.58 mm/yr, respectively. If we take the results with 5 MPa for later comparison with results along the Wenchuan aftershock zone by Li et al. (2011), the average slip rate of these repeating earthquakes is 2.25 ± 2.24 mm/yr.

2) Aftershock zone of the 2016 Menyuan earthquake (region 2)

A strong earthquake with a magnitude of Ms6.4 occurred at Menyuan, Qinghai Province of China at 2016/01/21, close to the LLLF at the western edge of the HYF. In addition to this event, several moderate-size earthquakes, such as the 1986 M5.4, 1987 M6.5, 1991 M5.2, and 2013 M5.3 earthquakes, also occurred in this region (Li et al., 2016). Based on the matched filter detection and relocation of early aftershocks, Liu et al. (2019) inferred that the 2016 Mengyuan mainshock occurred on a steeply dipping secondary fault rather than the major LLLF. This interpretation is consistent with the geodetic and geological observations (Li et al., 2016). Liu et al., (2019) also found 26 repeating clusters (~172 events) in the aftershock zone of the Mengyuan mainshock.

From ten years of seismic data, we identify 81 events within 37 clusters in this region (Figure 5). Most of them occurred following the 2016 Ms6.4 mainshock. A subtle increase of repeating events is also observed after the 2016 M4.7 and 2017 M4.1 events (likely aftershocks of the Ms6.4 mainshock), but not following the 2013 M5.3 event. Because repeating aftershocks are mostly driven by afterslip (Schaff and Beroza, 2004; Peng et al. 2005), their recurrence times increase following the Mengyuan mainshock (Liu et al. 2019). Hence we do not compute their cumulative slip and average slip rate in this region.

3) Gulang seismic zone, north of the HYF (region 3)

We found 210 repeating earthquakes (75 clusters) that occurred in the Gulang seismic zone near the epicenter of the 1927 Gulang earthquake (Figure 6). From the map view, these repeating earthquakes are located between the strike-slip HYF in the south and the south-dipping Huangcheng-Shuangta fault (HC-STF) in the north. The repeating earthquakes are within the clusters of intensive background seismicity that deneate two nearly N-S striking features. But there are no mapped faults on the surface. These repeating earthquakes occurred every year from 2009 to 2018. We find that repeating earthquake rates increased after the 2011/02/22 M4.1 event, 2014/02/22 M 4.5 event and 2014/03/12 M 4.1 event. In comparison, some repeating clusters are not related with any moderate-size earthquakes. For example, 10 repeating earthquakes occurred in a tight cluster between 2013/07/03 and 2013/07/04 with very short occurrence intervals (marked as C3 in Figure 6). Similar repeating clusters occur on 2009/06/21 (C1), 2012/06/24 (C2), and 2017/06/08 (C4). Since these sequences do not have a clear moderate-size mainshock (earthquakes with $M \geqslant 4$, Figure 6), they may be considered as earthquake swarms (Vidale and Shearer, 2006).

4) Mining related repeaters

In the CENC catalog, there are 332 marked mining explosions at the boundary between Neimenggu and Ningxia Provinces (39.0-39.2°N, 105.95-106.15°E. Marked as region 5 in Figure 2). Because mining explosions almost occur in the same position, the corresponding seismic waveforms have very high similarities and can be detected as repeaters in this study. In our study region we find 136 possible repeating events within 25 clusters that are likely mining related.

We use the following evidence to confirm these events are likely related to mining activities. First, some events listed in the repeating clusters are marked as mining explosion in the CENC catalog. Second, the local times of these events have peaks in the afternoon instead of a uniform distribution (Figure 7), which is consistent with the expected mining explosion schedule (e.g., Ruan et al., 2017). Third, we can identify possible mining related images with Google Map in this region (Figure 8). Finally, the event magnitudes are tightly clustered (Figure 9), and there are no M>4 events in this region.

In addition to this region, we also find three other regions (regions 6-8 in Figure 2) with possible mining explosions. Compared with clear P and S arrivals for regular earthquakes, explosion-generated waveforms have different phases (Figures 3 and 9). We note that the first few cycles of the P waves are not quite the same among these regions (Figure 9), which may indicate different styles of explosions (e.g., delayed versus single fire) (Stump et al., 2002), as well as possible structural difference.

There are also some repeating events in other places, such as MDS that is marked as region 4 in Figure 2. If there are no M>4 events and no marked surface fault, we generally consider them as possible mining explosions.

Discussion

1. The characteristics of repeating earthquakes at LHSF

In this study, we identified 12 clusters with 31 repeating events along and near the Laohushan section of the HYF, where surface creep has been identified (Jolivet et al., 2013). As mentioned before, it is still not clear what is the cause of creep in this region. There is some evidence for the surface-breaking rupture of paleo-earthquakes in this section. In addition, the cumulative slip offset in this region is similar to non-creeping brittle faults (Chen et al., 2018). Based on these observations, Chen et al. (2018) inferred that either the fault is capable of switching between creeping and brittle faulting over time, or the fault is partially creeping, capable of both creeping and surface-rupturing brittle faulting. In the second possibility, the creep on the Laohushan section is a shallow phenomenon, with the fault remaining locked at depth, similar to the Ismetpasa segment of the North Anatolian fault in Turkey (Ozener et al., 2010; Karabacak et al., 2011; Kaneko et al., 2013) and the Hayward fault in northern California (Simpson et al., 2001; Schmidt et al., 2005).

Based on an assumed stress drop of 1, 5 and 10 MPas (Li et al., 2011), we computed the cumulative slip and slip rate of the repeating earthquakes in this region. We found that the largest slip rate is 6.6 mm/yr and the average slip rate is 2.25 ± 2.24 mm/yr. Although with large uncertainties, our estimated slip rate is less than the shallow creep rate of ~5 mm/yr from InSAR observations (Jolivet et al., 2013) and geological rate of 5-9 mm/yr (Yao et al., 2019).

Our estimation of slip rate based on repeating clusters has several limitations. First, we only take the $M \geq 1$ events into account. Hence, seismic slip released by events with smaller magnitudes is not included. Second, the $M \geq 1$ events catalog may be incomplete, which could result in a biased estimation of slip rate. Finally, it is possible that some asperities creep at interseismic time periods (Beeler et al., 2001).

Hence, what we estimate here can be considered as the lower bound of the actual slip rate, although we do not expect to observe several folds increase in the slip rate.

After the relocation, the repeaters are mostly located between 4-8 km depth (Figure 10), which is below the inferred depth of shallow creep (Jolivet et al. 2013). In addition, these repeaters occurred to the west of the peak creep observed from InSAR observation (Jolivet et al. 2013). Our observation suggests that the geodetically observed creep is constrained at shallow depth, while faults at deeper depth remain locked. Hence, these repeating earthquakes likely marked the boundary between the creep and locked region, similar to the Parkfield section of the San Anderas Fault (Nadeau and McEvilly, 1999, 2004; Lengline and Marsan, 2009), the Morgan Hill section of the Calaveras Fault (Rubin, 2002; Schaff et al., 2002; Peng et al., 2005), as well as the Hayward Fault (Bürgmann et al., 2000; Shirzaei et al., 2013). This is also compatible with the observation of earthquake swarms driven by shallow aseismic slip in Salton Trough, California (Lohman and McGuire, 2007), and anticorrections between afterslip and aftershocks (including repeating earthquakes) following the 2012 M7.6 Nicoya, Costa Rica, earthquake (Hobbs et al., 2017; Yao et al., 2017). These studies suggest that while microseismicity (including earthquake swarms and repeating earthquakes) can be driven by nearby aseismic slip, they likely occur in slightly different regions, indicating varying frictional behavior along dip and strike directions.

Considering that the creeping Laohushan section on the HYF is located immediately to the west of 230-km surface rupture of the 1920 Haiyuan M7.8 earthquake, Chen et al. (2018) speculated that long-term post-seismic deformation following the 1920 Haiyuan mainshock might have a heightened effect on creep rate observed recently. The creeping section is also located at the eastern end of the over-200 km long “quite” seismic gap, known as the Tianzhu gap (Gaudemer *et al.*, 1995). Hence, the Laohushan section is somewhat similar to the creeping section of the San Andreas Fault from Parkfield to Hollister in Central California, which was sandwiched between the 1857 Fort Tejon and 1906 San Francisco earthquakes. However, the creeping section of the Haiyuan fault is only 35 km (Jolivet et al. 2012), much shorter than the ~150 km length for the San Andreas Fault. While the creeping section is generally considered as ‘barrier’ to seismic ruptures, Noda and Lapusta (2013) demonstrated that dynamic earthquake ruptures (combined with co-seismic weakening) can break through long portions of creeping faults, indicating the possibility a total rupture on long strike-slip faults such as the San Andreas or Haiyuan Faults.

2. The implication of intense seismicity at the Gulang seismic zone

Another region (region 3 in Figure 3) with intense background seismicity and repeating earthquakes is located near the epicenter of the 1927 Gulang earthquake, north of the HYF (Figure 6). Yang (2017) performed repeating earthquake detections in this region, and found similar patterns of repeating clusters. While there are no corresponding faults mapped on the surface, relocated seismicity is concentrated along two linear zones trending NNW to nearly NS, indicating two possible hidden faults at depth (Figure 6). Such interpretation is consistent with the available focal mechanisms of moderate-size events in this region, which are predominately NNW-SEE trending right-lateral strike slip events.

Wang (2018) named the intensive seismic activity in this region as “Gulang seismic window”, which are stress sensitive regions in the aftershock zones following large earthquakes. Because this region is spatially close to the rupture zone of the 1927 M~8 Gulang earthquake, it is possible that they are extended aftershocks of the Gulang earthquake. This interpretation is consistent with general observations of long-tailed aftershock activity, especially in intraplate regions around the world (Ebel et al., 2000; Stein and Liu, 2009). Even at plate boundary regions, large earthquakes can potentially affect the deformation pattern and cycles of small to moderate-size earthquakes at nearby distances. For example, Ben-Zion et al. (1993) employed 3-D finite-element modeling to infer that the M6-type Parkfield earthquakes are driven by time-dependent loading from the 1857 M8 Fort Tejon earthquake. Hence, we argue that intensive earthquake swarms and repeating earthquakes in this region are likely driven by the relaxation process induced by the 1927 M~8 Gulang earthquake.

Based on seismic velocity inversions, Deng et al. (2018) found that this region is mechanically weaker compared with the North China Craton in the north, and the central Qilian in the south. This is comparable with the earthquake swarms at Belo

Jardim, NE Brazil (Lopes et al., 2010), and the Salton Trough South California (Lohman and McGuire, 2007), which are likely occurred at the pre-existing weak zones.

Conclusions

Based on waveform cross-correlations and relocations, we systematically search for repeating earthquakes in NE Tibet with ten years of seismic data. The repeating earthquakes are found in certain regions. Laohushan section of HYF has several repeating earthquakes, whose epicenters are located to the west of the peak creep region indicated by InSAR observations. The slip rate estimated from the repeating earthquakes is slightly smaller than the geodetic and geological observation. However, our estimation is based on assumed constant stress drops and has several limitations, and hence could be considered as a lower bound for the slip rate. In addition, the relocated microearthquakes are mostly located deeper than 4 km, indicating the geodetically observed creep is constrained at shallow depth, while faults at deeper depth remain locked. Hence, we infer that these repeating earthquakes likely mark the boundary between the creep and locked region. We also find many repeating earthquakes following the 2016 M6.4 Menyuan mainshock. The intense seismicity at the Gulang seismic zone is aligned along two linear zones indicating two possible hidden faults. This region may be intrinsically weak and hence these repeating events can be driven by the long-term relaxation process of the 1927 Gulang earthquake. In comparison, repeating events related to mining explosions in this region have different waveforms from natural earthquakes, and can be readily identified based on several diagnostic features.

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Figure Caption

Figure 1. (a) The geological setting, major faults (pink), microearthquakes (black dots) and station distribution (blue triangles) in NE Tibet. The inset marks the study region in a larger map of Tibet. (b) The focal mechanism of M>3.5 events and GPS velocity in this region. The focal mechanisms are obtained from Cui et al., (2019) and GCMT catalog. HYF: Haiyuan fault; XHF: Xianshuihe fault. The GPS data is sourced from Zheng et al., 2017, JGR. The fault geometry is obtained from

Taylor and Yin (2009).

Figure 2. Distributions of clusters of repeating earthquake in NE Tibet. Events with white colors are background seismicity, and cluster with different numbers in each family is marked with different colors. The detailed information of marked faults is shown in Figure 1. 8 sub-regions are marked for subsequent analysis.

Figure 3. (a) A map view showing the repeating earthquakes along the Laohushan section of the HYF. The M≥4 events are noted in the figure. The red color indicates the cluster with at least 8 events. The blue box indicates the possible creep region (Jolivet et al., 2012). The black box marks the region for calculating the slip rate. The black square indicates the start point (0 km) on (b-c). (b) Along-strike distribution of the average, horizontal fault parallel, creep rate measured on average velocity fields determined by Jolivet et al. (2013). (c) Along-strike distance versus time for both background events and repeating clusters. The radius of circle corresponds to the magnitude/rupture size. The fault geometry comes from the airborne LiDAR (Liu-Zeng et al., 2013). The focal mechanisms are obtained from Cui et al., (2019) and GCMT catalog.

Figure 4. The vertical component waveforms recorded at station GS.YDT for a single cluster with 8 members.

Figure 5. (a) The map distribution of repeating earthquakes and background events around the aftershock zone of the 2016 M6.4 Mengyuan mainshock. (b) The time distribution of repeating

earthquakes and background events at Menyuan. The M≥4 events are noted in the figure. The fault geometry is from Liu et al. (2019). The blue color indicates the cluster with at least 4 events. The focal mechanisms are obtained from GCMT catalog.

Figure 6. (a) The map distribution of repeating earthquakes and background events at the Gulang seismic zone. (b) The time distribution of repeating earthquakes and background events at the Gulang seismic zone. The M≥4 events are noted in the figure. The red color indicates the cluster has at least 8 events. The red arrows (C1, C2, C3, C4) indicate the possible triggered swarms. (c) The relocated background events (including repeaters) at the Gulang seismic zone. The events distribution before and after relocation within the shading region marked in (a) and (c).

Figure 7. The histogram of the event time with local time zone at four regions with likely mining activities.

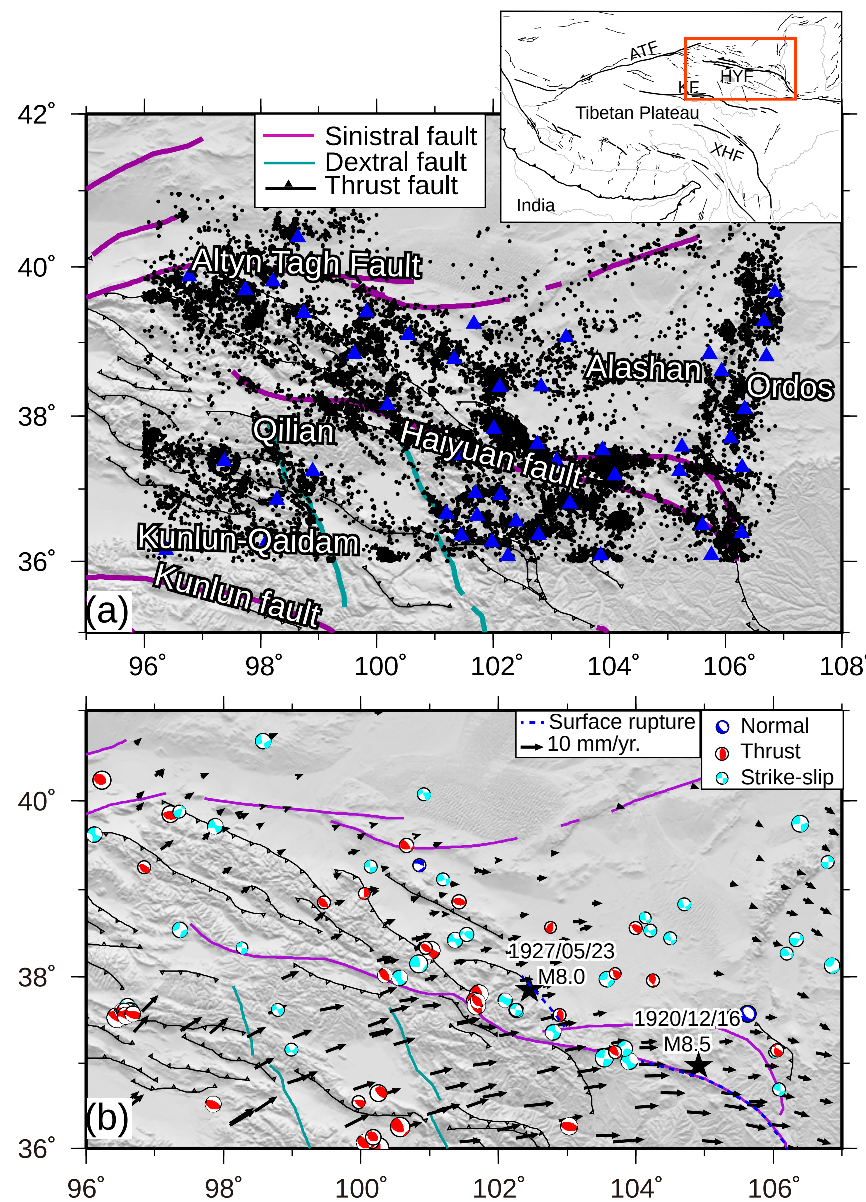
Figure 8. The local topography is shown in Google Map at four regions with likely mining activities.

Figure 9. The vertical component waveforms recorded at stations in four regions with clusters more than 8 events.

Figure 10. The events (a) and repeaters (b) before and after relocation along and across strike in the Laohushan section of the HYF. The events located in the box are marked in Fig. 4. 0 km for

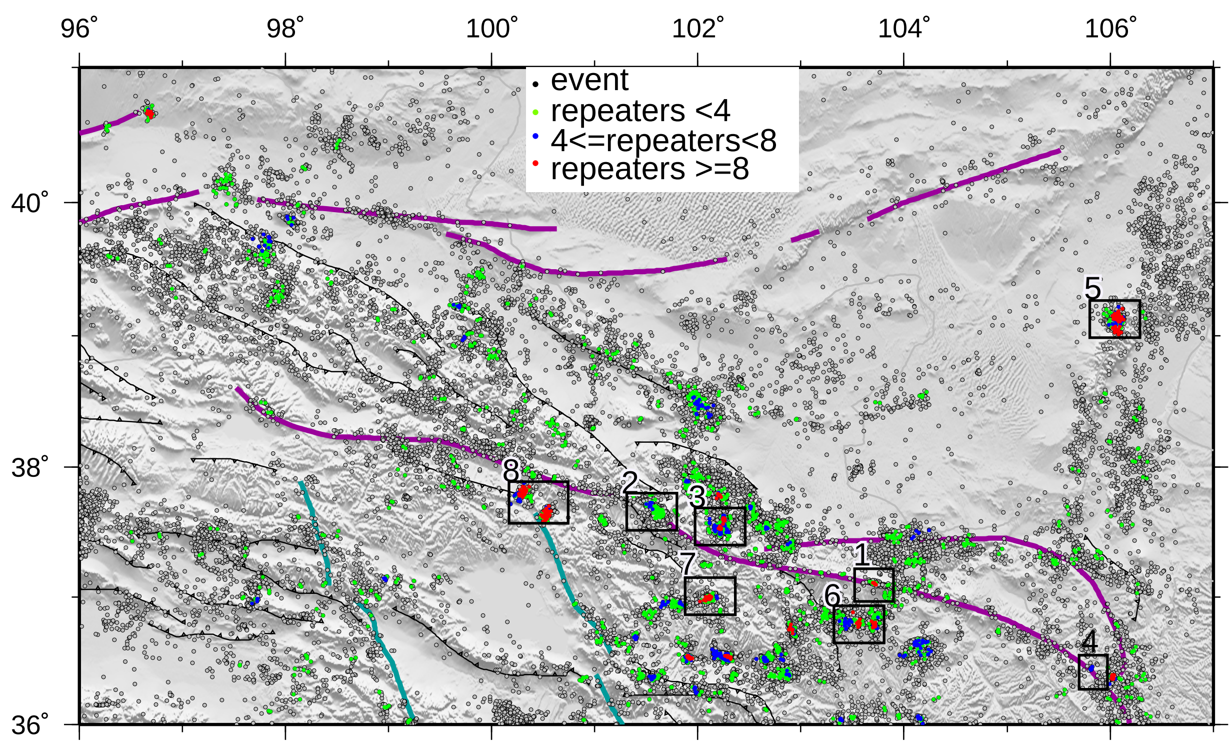
the along strike is the left boundary of the black box at HYF. The shading region indicates the possible creep region. The black dashed lines mark the changes before and after relocation.

Figure1.



Sinistral fault
Dextral fault
Thrust fault
ATF
KF
HYF
Tibetan Plateau
XHF
India
Altyn Tagh Fault
Alashan
Ordos
Qilian
Haiyuan fault
Kunlun-Qaidam
Kunlun fault
(a)
42°
40°
38°
36°
96°
98°
100°
102°
104°
106°
108°
Surface rupture
10 mm/yr.
Normal
Thrust
Strike-slip
1927/05/23
M8.0
1920/12/16
M8.5
(b)

Figure2.



96°
98°
100°
102°
104°
106°
40°
38°
36°
event
repeaters <4
4<=repeaters<8
repeaters >=8
1
2
3
4
5
6
7
8

Figure3.

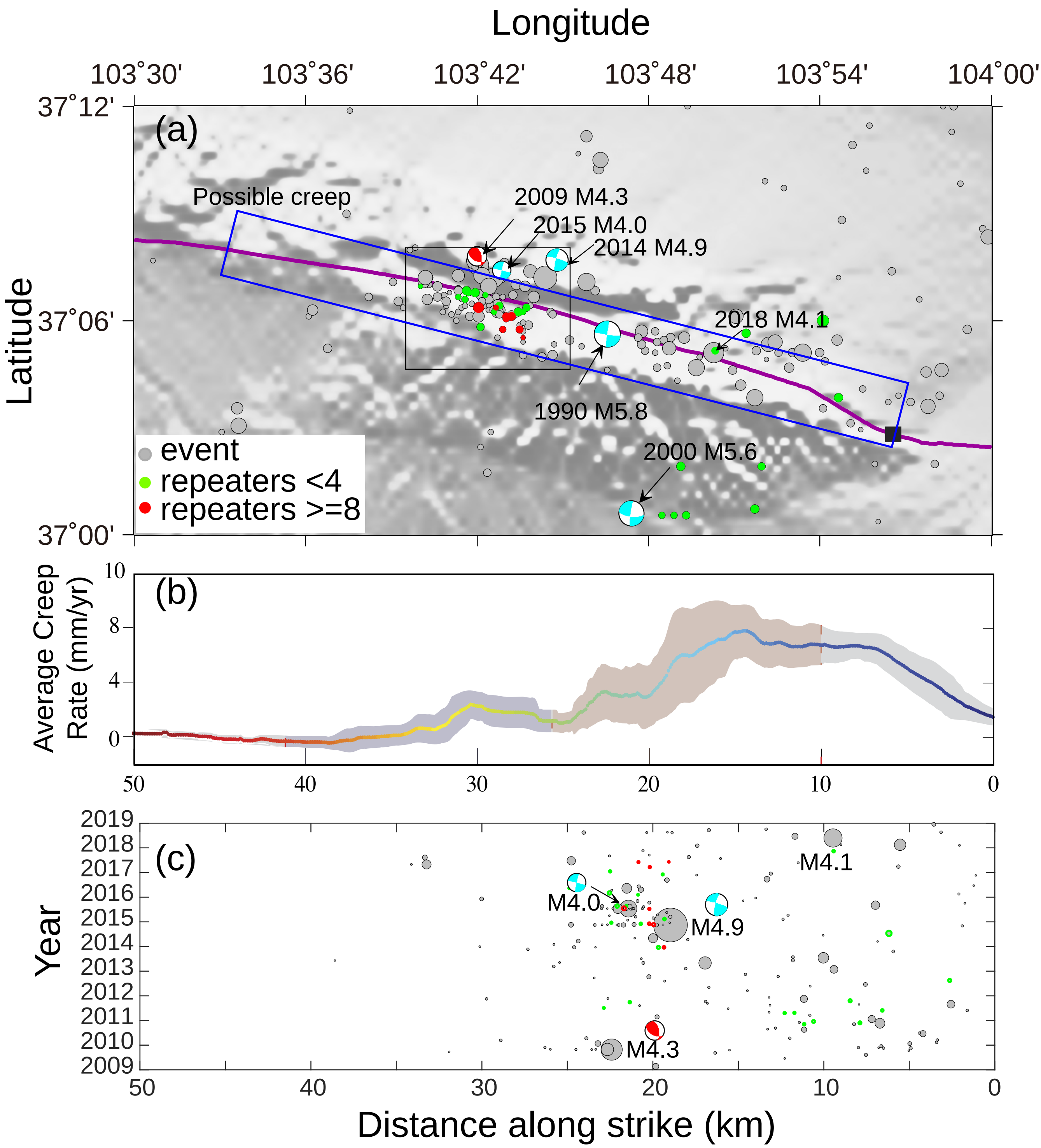

Longitude
103°30'
103°36'
103°42'
103°48'
103°54'
104°00'
37°12'
37°06'
37°00'
Latitude
(a)
Possible creep
2009 M4.3
2015 M4.0
2014 M4.9
2018 M4.1
1990 M5.8
2000 M5.6
event
repeaters <4
repeaters >=8
(b)
Average Creep Rate (mm/yr)
10
8
4
0
50
40
30
20
10
0
(c)
Year
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
M4.1
M4.0
M4.9
M4.3
Distance along strike (km)

Figure4.

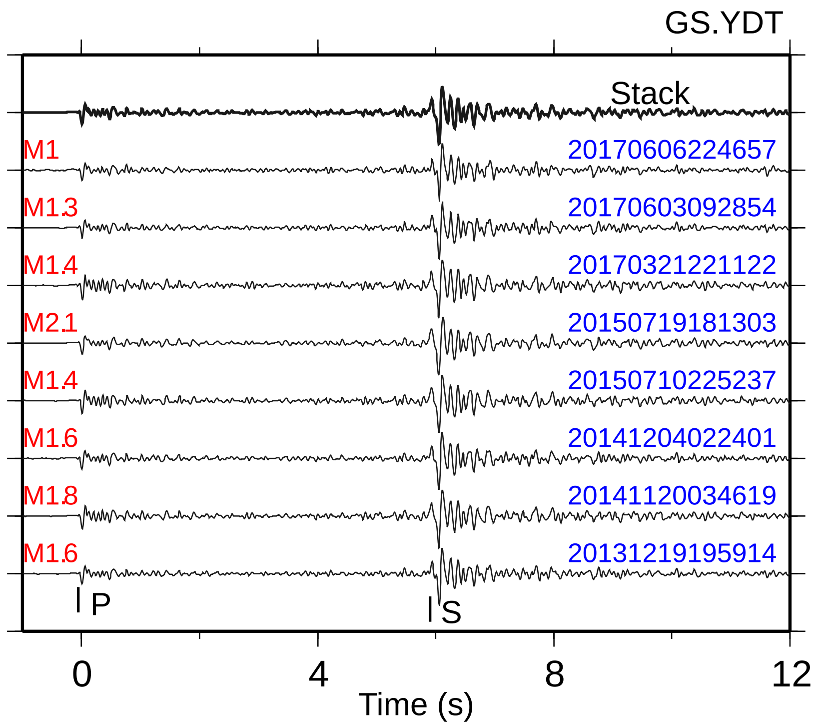

GS.YDT
Stack
M1
20170606224657
M1.3
20170603092854
M1.4
20170321221122
M2.1
20150719181303
M1.4
20150710225237
M1.6
20141204022401
M1.8
20141120034619
M1.6
20131219195914
P
S
0
4
8
12
Time (s)

Figure5.

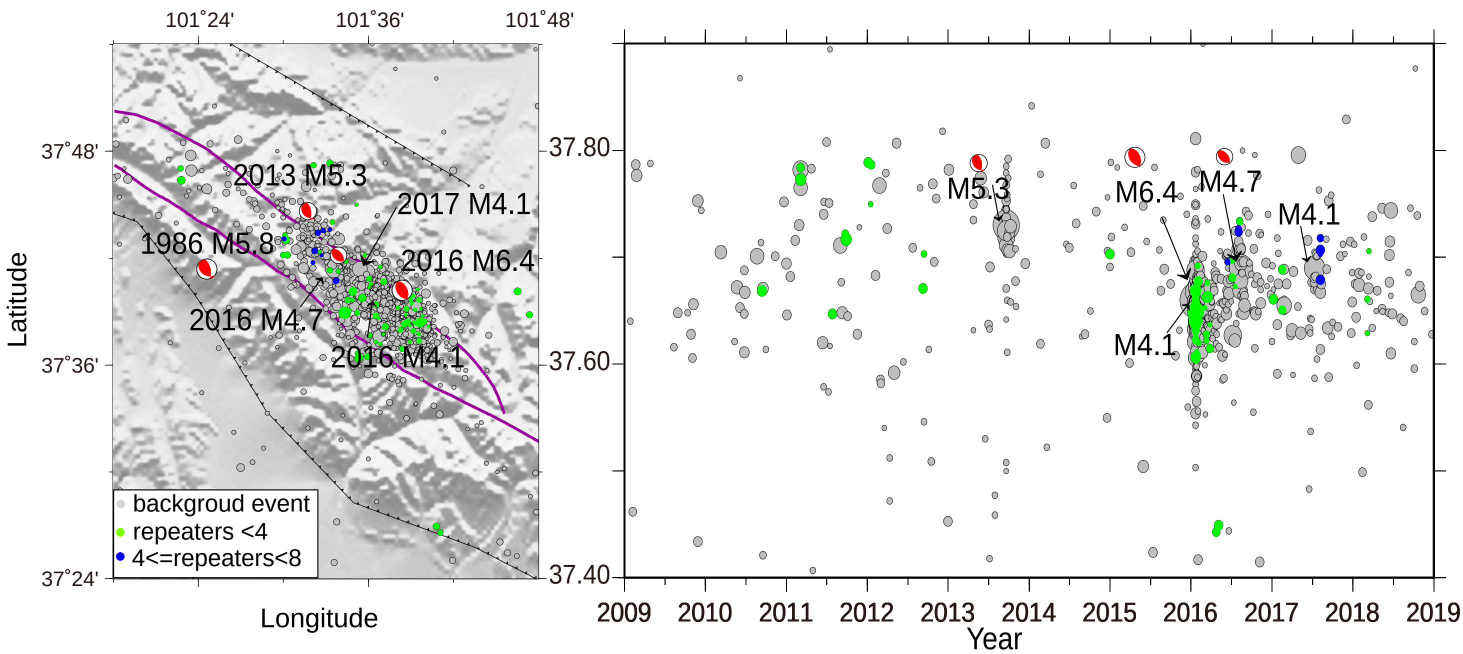
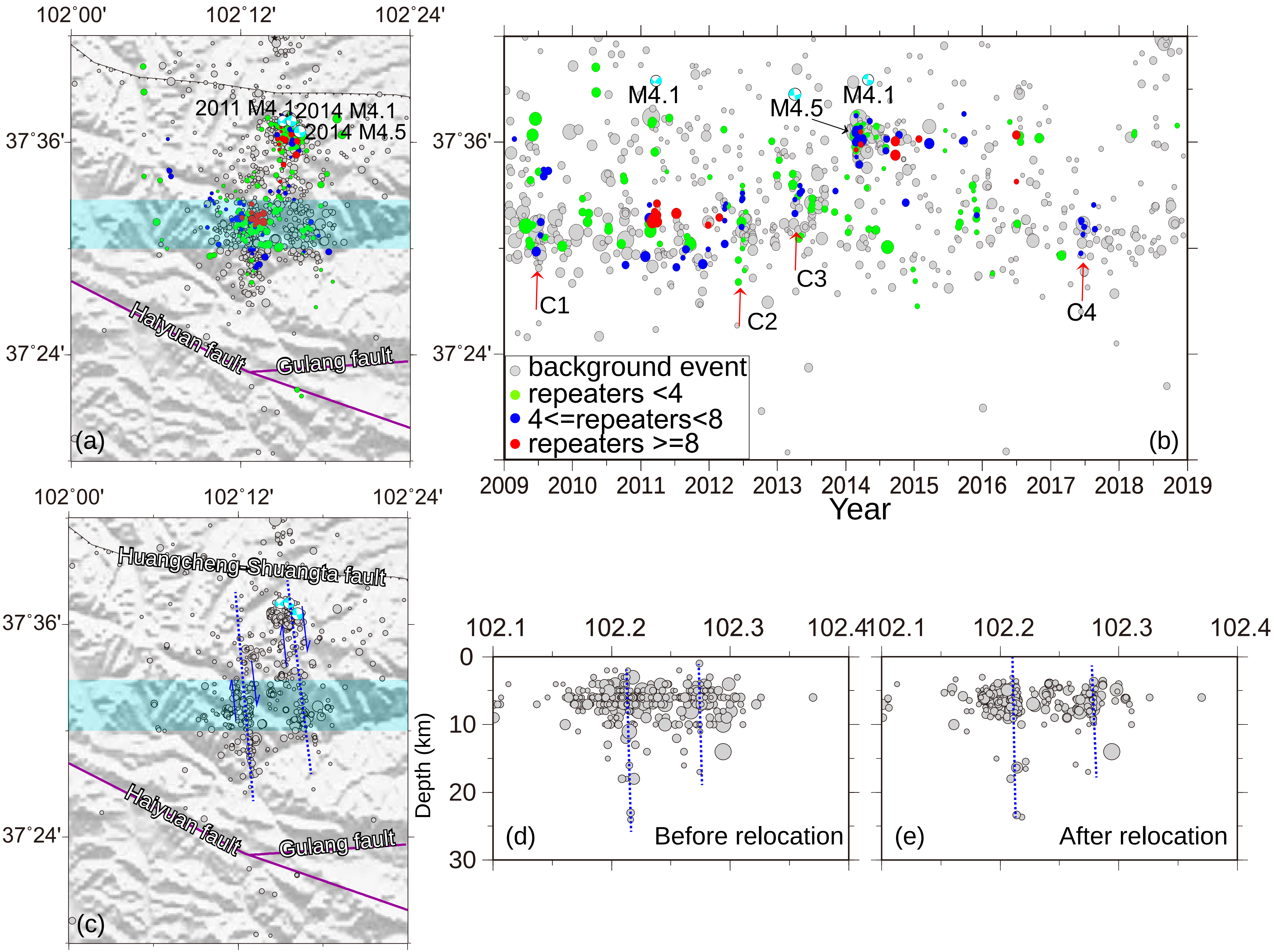

101°24'
101°36'
101°48'
37°48'
37°36'
37°24'
Latitude
Longitude
2013 M5.3
2017 M4.1
1986 M5.8
2016 M6.4
2016 M4.7
2016 M4.1
backgroud event
repeaters <4
4<=repeaters<8
37.80
37.60
37.40
M5.3
M6.4
M4.7
M4.1
M4.1
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year

Figure6.



102°00'
102°12'
102°24'
37°36'
37°24'
2011 M4.1
2014 M4.1
2014 M4.5
Haiyuan fault
Gulang fault
(a)
M4.1
M4.5
M4.1
C1
C2
C3
C4
background event
repeaters <4
4<=repeaters<8
repeaters >=8
(b)
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year
Huangcheng-Shuangta fault
(c)
102.1
102.2
102.3
102.4
Depth (km)
0
10
20
30
(d)
Before relocation
(e)
After relocation

Figure7.

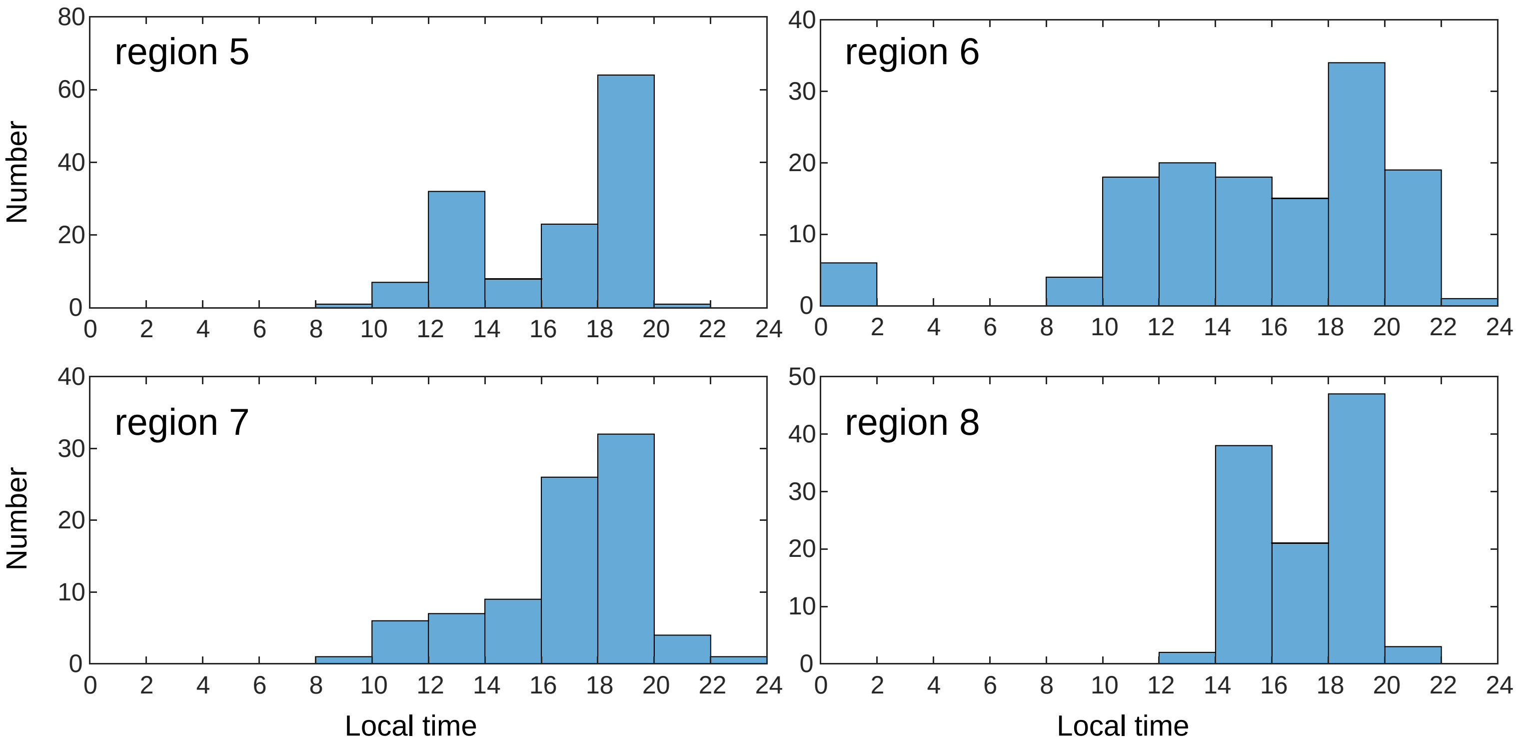

region 5
region 6
region 7
region 8
Number
Number
Local time
Local time

Figure8.

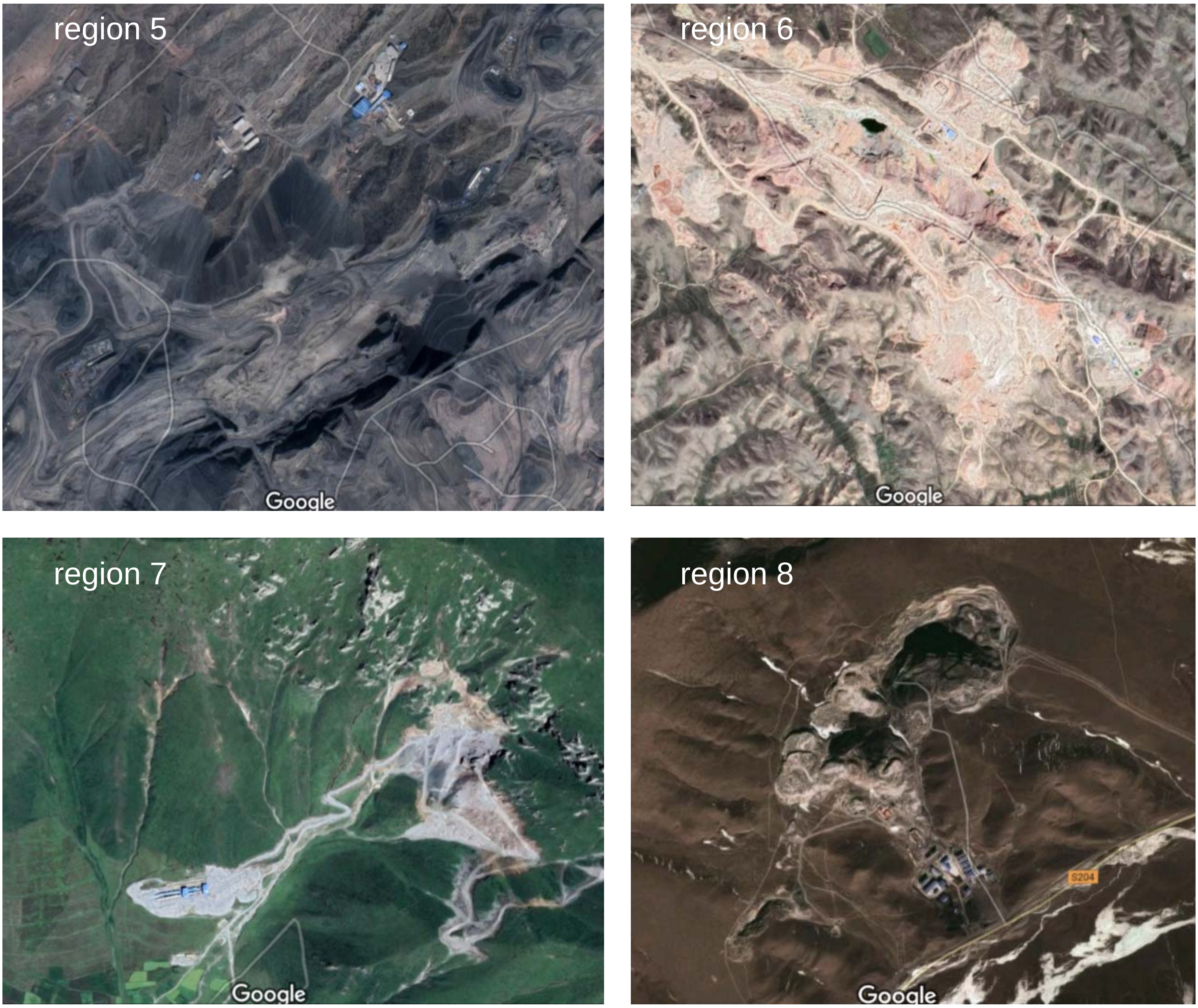

region 5
Google
region 6
Google
region 7
Google
region 8
S204
Google

Figure9.

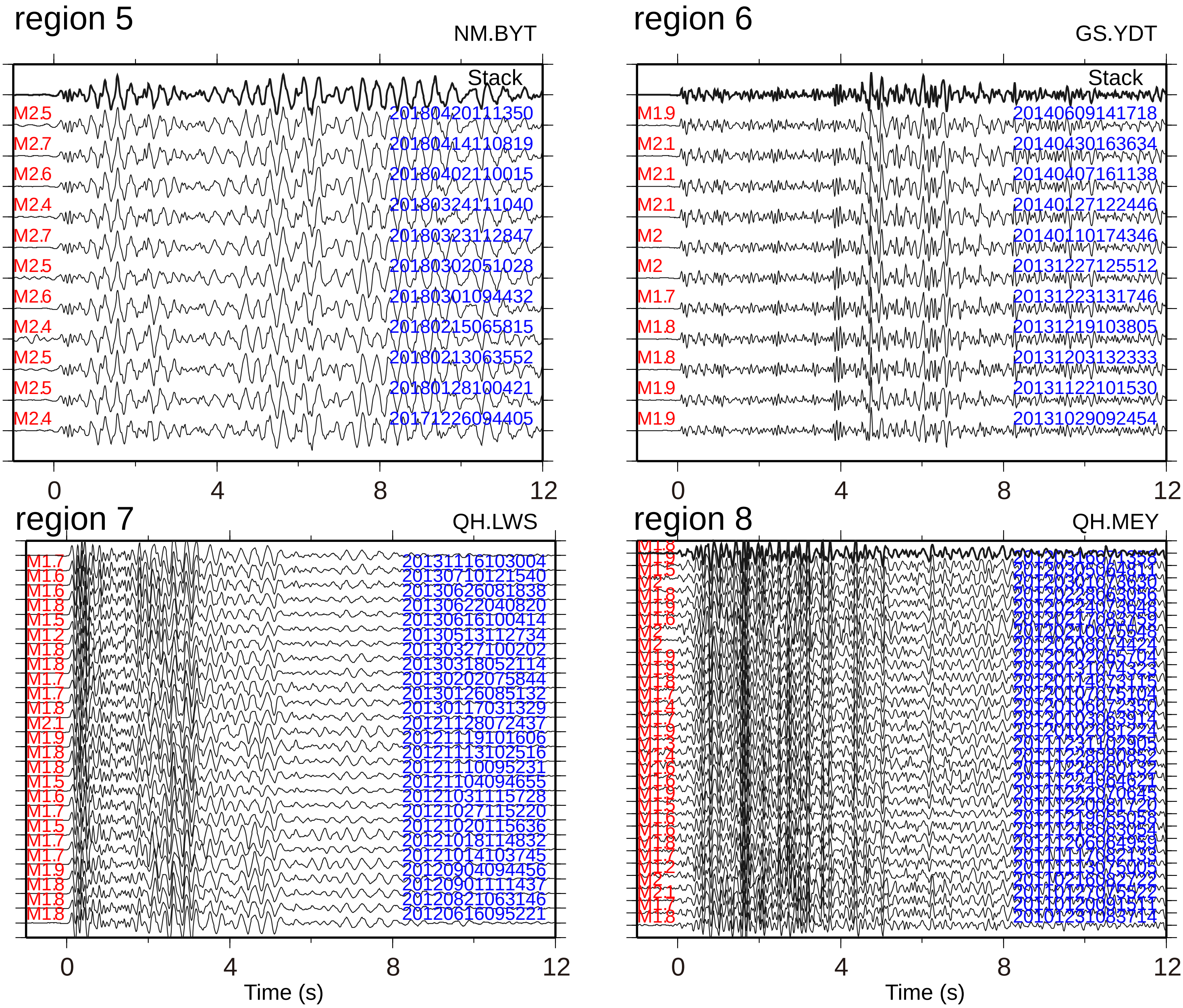
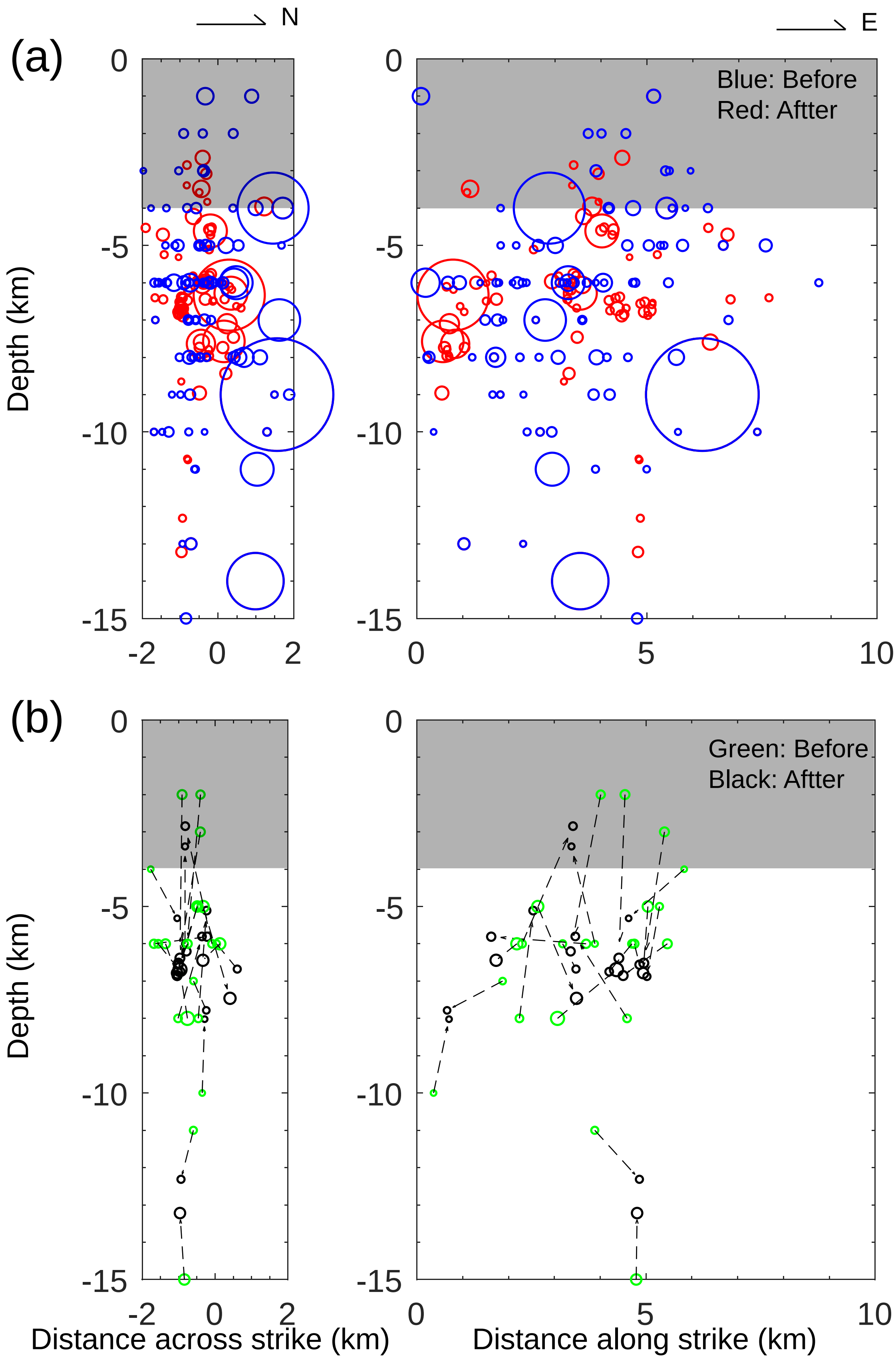

region 5
NM.BYT
Stack
M2.5
20180420111350
M2.7
20180414110819
M2.6
20180402110015
M2.4
20180324111040
M2.7
20180323112847
M2.5
20180302051028
M2.6
20180301094432
M2.4
20180215065815
M2.5
20180213063552
M2.5
20180128100421
M2.4
20171226094405
region 6
GS.YDT
Stack
M1.9
20140609141718
M2.1
20140430163634
M2.1
20140407161138
M2.1
20140127122446
M2
20140110174346
M2
20131227125512
M1.7
20131223131746
M1.8
20131219103805
M1.8
20131203132333
M1.9
20131122101530
M1.9
20131029092454
0
4
8
12
region 7
QH.LWS
M1.7
20131116103004
M1.6
20130710121540
M1.6
20130626081838
M1.8
20130622040820
M1.5
20130616100414
M1.2
20130513112734
M1.8
20130327100202
M1.8
20130318052114
M1.7
20130202075844
M1.7
20130126085132
M1.8
20130117031329
M2.1
20121128072437
M1.9
20121119101606
M1.8
20121113102516
M1.8
20121110095231
M1.5
20121104094655
M1.6
20121031115728
M1.7
20121027115220
M1.5
20121020115636
M1.7
20121018114832
M1.7
20121014103745
M1.9
20120904094456
M1.8
20120901111437
M1.8
20120821063146
M1.8
20120611095221
0
4
8
12
Time (s)
region 8
QH.MEY
20101231083714
0
4
8
12
Time (s)

Figure10.



(a)
N
E
Blue: Before
Red: Aftter
(b)
Green: Before
Black: Aftter
Depth (km)
0
-5
-10
-15
-2
0
2
5
10
Distance across strike (km)
Distance along strike (km)