Earth and Planetary Science Letters 479 (2017) 231–240

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Shallow microearthquakes near Chongqing, China triggered by the Rayleigh waves of the 2015 M7.8 Gorkha, Nepal earthquake

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ARTICLE INFO

Article history:
Received 2 March 2017
Received in revised form 31 August 2017
Accepted 8 September 2017
Available online 4 October 2017
Editor: R. Bendick

Keywords:
dynamic triggering
Rayleigh waves
Gorkha earthquakes
induced earthquakes

ABSTRACT

We present a case of remotely triggered seismicity in Southwest China by the 2015/04/25 M7.8 Gorkha, Nepal earthquake. A local magnitude M_L3.8 event occurred near the Qijiang district south of Chongqing city approximately 12 min after the Gorkha mainshock. Within 30 km of this M_L3.8 event there are 62 earthquakes since 2009 and only 7 $M_L > 3$ events, which corresponds to a likelihood of 0.3% for a $M_L > 3$ on any given day by a random chance. This observation motivates us to investigate the relationship between the M_L3.8 event and the Gorkha mainshock. The M_L3.8 event was listed in the China Earthquake National Center (CENC) catalog and occurred at shallow depth (∼3 km). By examining high-frequency waveforms, we identify a smaller local event (∼ M_L2.5) ∼ 15 s before the M_L3.8 event. Both events occurred during the first two cycles of the Rayleigh waves from the Gorkha mainshock. We perform seismic event detection based on envelope function and waveform matching by using the two events as templates. Both analyses found a statistically significant rate change during the mainshock, suggesting that they were indeed dynamically triggered by the Rayleigh waves. Both events occurred during the peak normal and dilatational stress changes (∼10–30 kPa), consistent with observations of dynamic triggering in other geothermal/volcanic regions. Although other recent events (i.e., the 2011 M9.1 Tohoku-Oki earthquake) produced similar peak ground velocities, the 2015 Gorkha mainshock was the only event that produced clear dynamic triggering in this region. The triggering site is close to hydraulic fracturing wells that began production in 2013–2014. Hence we suspect that fluid injections may increase the region's susceptibility to remote dynamic triggering.

1. Introduction

Earthquakes can be triggered by static, dynamic or quasi-static stress changes from nearby earthquakes (Harris, 1998; Freed, 2005). At long-range distances, only dynamic stresses from seismic waves are large enough to trigger seismicity (e.g., Hill and Prejean, 2015; and references there in). Remotely triggered seismic activity is mostly observed in tectonically active regions (Hill et al., 1993; Gomberg et al., 2001; West et al., 2005; Prejean et al., 2004; Tape et al., 2013), and the magnitudes are generally less than M5 (Parsons and Velasco, 2011; Johnson et al., 2015). In addition to triggering microseismic events, large distant earthquakes are capable of triggering deep tectonic tremor (Peng and Gomberg, 2010) and slow-slip events (Hirose et al., 2012; Zigone et al., 2012; Peng et al., 2015).

Remote triggering is also documented in relatively stable intraplate regions with low background seismicity rates (Hough et al., 2003; Gomberg et al., 2004). Velasco et al. (2008) conducted a systematic global survey and found that remote dynamic triggering is a ubiquitous phenomenon, independent of the tectonic environment of the triggering mainshock or the triggered events. In continental China, remotely triggered seismicity is mostly observed near active faults in different tectonic settings (e.g., Jiang et al., 2010; Lei et al., 2011; Li et al., 2016) or active volcanoes (Lei et al., 2011; Liu et al., 2017). Near the Fangshan Pluton southwest of Beijing, dynamically triggered microearthquakes have been detected during the surface waves of several large distant earthquakes (e.g.,

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http://dx.doi.org/10.1016/j.epsl.2017.09.024
0012-821X/

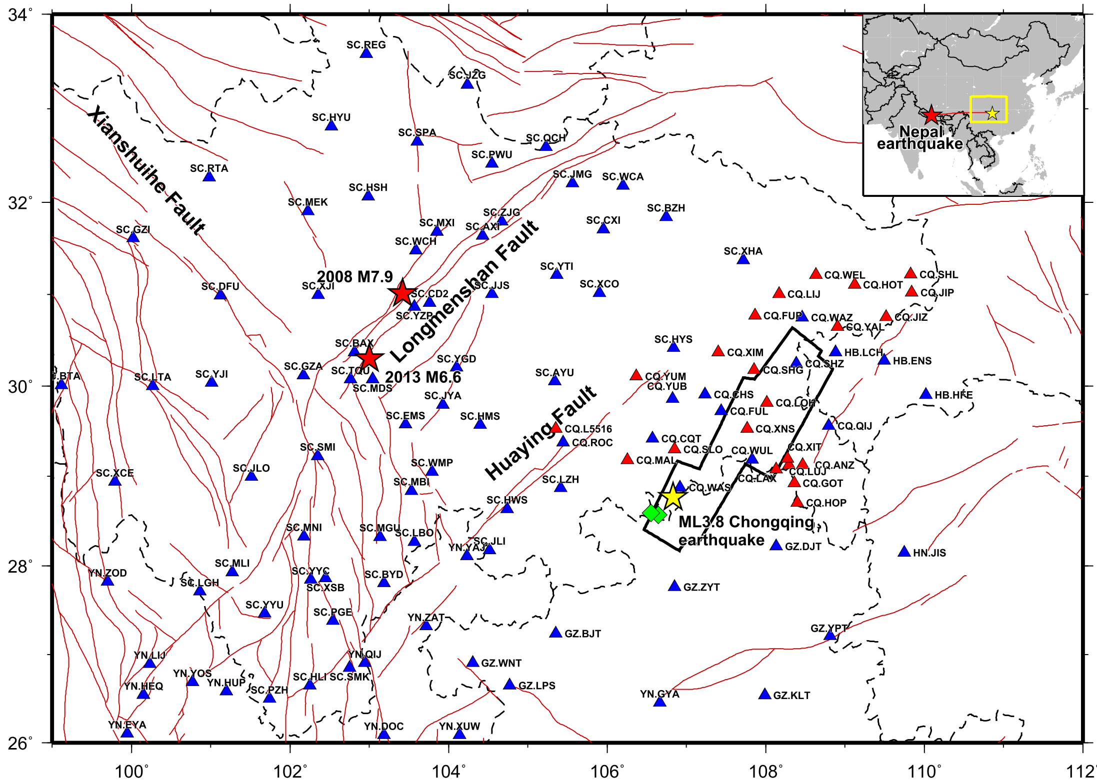

Fig. 1. Map view of the study region in Chongqing, Southwest China. The red stars indicate the 2008 Wenchuan M7.9 and 2013 Lushan M6.6 earthquakes. The yellow star denotes the M_L3.8 event reported by CENC. The blue triangles are broad-band stations and red triangles are short-period stations. The red lines mark active faults in the study region. The black thick lines mark major shale gas blocks where hydraulic fracturing is in operation (Lei et al., 2017), and the green squares are hydraulic fracturing wells. The inset on the top right marks the study region in a larger map of Asia. The Gorkha mainshock and the great circle path are marked as a red star and red line, respectively. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Wu et al., 2011, 2012). Wang et al. (2015) suggested that local coal-mining activities may perturb subsurface stress conditions, resulting in a near critical state of stress that is highly susceptible to dynamic triggering (Brodsky and van der Elst, 2014).

Here we report another case of remotely triggered seismicity in Southwest China that is close to the region with underground anthropogenic activities (Fig. 1). The study area is located in the Qijiang district south of Chongqing city within the Eastern Sichuan Fold Belt at the western margin of the South China Block. The tectonic framework of this region is dominated by NE-striking chevron anticlines and NW-verging thrust faults (Li et al., 2015a). Coal has been mined in this region for more than 50 yr. In recent years, the regions to the south and southeast of Sichuan basin (Fig. 1) is the location of shale-gas hydraulic fracturing (Lei et al., 2017), and Qijiang was among the first region for shale gas development (e.g., http://www.gov.cn/gzdt/2009-08/25/content_1400707.htm). Two wells (DY1HF and DY2HF) were successfully drilled to the depth of ∼5700 and ∼3300 m, and completed in 2013/09 and 2014/03, respectively (Zhao and Yang, 2015; Lei, X., per. communication, 2017/08).

In this study we focus on this region because the largest event since 2009 (local magnitude $M_L = 3.8$; moment magnitude $M_W = 4.1$) occurred here approximately 12 min after the 2015/04/25 M7.8 Gorkha, Nepal earthquake. According to the China Earthquake Network Center (CENC) historic earthquake catalogue, only one $M \geq 5$ event (estimated magnitude 5.5) occurred in this region since 1854/12/24. From 2009/01 to 2016/12 there are 132 seismic events ranging from M_L1.0 to M_L4.0 in our study region (E106.4°∼107.4° in longitude and N28.4°∼29.2° in latitude) reported by the CENC (Fig. 2).

The Gorkha earthquake is the largest event occurring along the Himalaya frontal thrust since the 1950 M8.6 Assam-Tibet earthquake (Avouac et al., 2015). The Gorkha mainshock was followed by numerous aftershocks near the epicenter (Adhikari et al., 2015) as well as several moderate-size normal faulting earthquakes in southern Tibet (Li et al., 2016). The largest event was the 2015/05/12 Mw7.2 Kodari earthquake. The timing of the M_L3.8 event coincides with the passage of the large-amplitude surface waves from the Gorkha mainshock located ∼2200 km away, with a corresponding apparent velocity of ∼2.92 km/s. We relocate this event and quantify the triggering relationship with the passing surface waves and associated dynamic stresses. Additionally, we examine patterns in the seismicity over longer periods before and after the Gorkha mainshock and other large distant earthquakes to better understand the physical mechanisms and conditions for remote dynamic triggering in this region.

2. Analysis procedure

The analysis procedure generally follows Peng et al. (2014) and Yao et al. (2015), and is briefly described here. We first search for evidence of triggered earthquakes using 62 broadband stations (Zheng et al., 2010) from Chongqing and Sichuan regional seismic networks (Fig. 1). We apply a 2–16 Hz band-pass filter to suppress long-period teleseismic waves of the Gorkha mainshock in the broadband recordings and visually identify stations that recorded high-frequency events during the passage of large-amplitude teleseismic waves. We also compute the spectrogram for station CQ.WAS and convert the seismic data into audible range (Kilb et al., 2012) to identify potential changes in high-frequency radiations immediately before and after the mainshock (Fig. 3; Movies S1).

For stations with potential high-frequency events during the surface waves, which we define as the time windows correspond-