The 2013 Lushan earthquake: Implications for seismic hazards posed by the Range Front blind thrust in the Sichuan Basin, China

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ABSTRACT

Thrust and reverse faults pose significant earthquake hazards in convergent plate margins around the world, but have proven difficult to study given the complex nature of their ruptures, which often involve multiple along-strike and vertically stacked fault segments. The 2013 M_w 6.6 Lushan earthquake exemplified this complexity, rupturing a blind thrust fault in the southern Longmen Shan, which border the western Sichuan Basin in China. This event occurred 80 km south of the epicenter of the destructive 2008 M_w 7.9 Wenchuan earthquake. The Wenchuan earthquake produced surface ruptures on two parallel fault splays, the Pengguan and Beichuan faults. In contrast, the Lushan earthquake was generated by a ramp in the Range Front blind thrust (RFBT), which is in the footwall of the Wenchuan rupture. We use seismic reflection profiles, petroleum wells, and relocated seismicity to construct a three-dimensional model of this imbricated fault system. Our model illustrates that the 2013 Lushan earthquake ruptured <10% of the RFBT, which extends for 250 km along the Longmen Shan range front and into the western Sichuan Basin. Analysis of growth strata in structures above the RFBT fault along strike shows clear evidence of Quaternary activity and constrains the middle Pleistocene to current slip rate at two locations on the fault. Single segment and multi-segment fault rupture scenarios involving the RFBT suggest the potential for large earthquakes (M7.8) that would affect the densely populated western Sichuan Basin. Assessing the hazards posed by such complex thrust systems, which occur in convergent margins worldwide, requires subsurface characterization of fault segments that can be independently associated with geologic and seismologic evidence of fault activity.

INTRODUCTION

Active thrust and reverse faults, including blind thrusts systems, pose significant seismic hazards in many parts of the world, for example, in the Los Angeles (California, USA) metropolitan area (e.g., Shaw et al., 2002). These hazards were demonstrated in the 20 April 2013 Lushan (surface-wave magnitude, $M_s = 7.0$) thrust fault earthquake, which occurred in western Sichuan Province, China, along the southern Longmen Shan fold-and-thrust belt. This earthquake was located 80 km south of the epicenter of the destructive 2008 M_w 7.9 Wenchuan earthquake. The Lushan earthquake caused nearly 200 deaths, injured at least 11,470 people, and led to $US 14 billion of economic losses. Field investigations reveal that there are no definitive coseismic surface ruptures, but rather sparse, small-scale surface fissuring (Li et al., 2014). This lack of surface rupture combined with the hypocentral locations of the mainshock and aftershock sequence suggest that the Lushan earthquake ruptured a portion of the Range Front blind thrust (RFBT) (Hubbard et al., 2010; Li et al., 2014). This raises concerns about the earthquake hazards posed by the unruptured portions of the RFBT and other faults to the adjacent western Sichuan Basin, and together with the 2008 Wenchuan rupture illustrates the complex nature of thrust-fault earthquake sequences.

The Chengdu Plain in the western Sichuan Basin (Fig. 1) is one of the most densely inhabited areas in China, with a population of nearly 28 million people. Although seismic hazard assessments in the western Sichuan Basin have traditionally been dominated by faults in the Longmen Shan, crustal shortening is also accommodated by active faults within the foothills and in the western Sichuan Basin (Hubbard et al., 2010; Wang et al., 2013a). These faults have more subtle surface expressions. However, because of their locations near large cites, and the prospect for basin amplification of seismic waves, these foreland faults represent significant hazards. To investigate this hazard, in this study we extend our previous interpretations of the RFBT (Hubbard et al., 2010; Wang et al., 2013a; Li et al., 2014) into the interior of the basin, and present the structural and seismological evidence for the presence and activity of the these faults.

GEOLOGICAL SETTING

The Longmen Shan extends for ~500 km along strike in the eastern margin of Tibetan Plateau, forming very steep topography on the margin of the plateau (Burchfiel et al., 1995). The 2008 M_w 7.9 Wenchuan earthquake produced two coseismic surface ruptures in the central and north segments of the Longmen Shan (Lin et al., 2009; Xu et al., 2009). The Wenchuan rupture did not extend into the southern segment of Longmen Shan, however, despite the continuation of the main thrust faults into this region. Historical seismicity, including three M > 6.5 events recorded within the interior of the thrust belt, indicates that the southern Longmen Shan is tectonically active. In addition, there have been many small earthquakes in the southwestern Sichuan Basin, which is next to the southern Longmen Shan, possibly on faults associated with shallow basin detachments that link these two tectonic provinces (Wang et al., 2013a).

DATA AND METHODS

In this study we had access to extensive high-quality two-dimensional (2-D) petroleum industry seismic reflection profiles (see Fig. DR1 in the GSA Data Repository[1] for locations). We also incorporated surface geology and aftershocks that were relocated using the double-difference method (Fang et al., 2013). We constructed a regional seismic reflection profile, A-A′ (Fig. 2; Fig. DR2), from the epicentral zone of the 2013 Lushan earthquake to the Sichuan Basin. We projected the relocated aftershocks onto the section perpendicular to the section trace (±1 km), and interpreted the profile using quantitative fault-related folding theories (Shaw et al., 2005). To characterize the structural relationships of these different faulting levels in the imbricate thrust system, we developed a three-dimensional model of the structures (Item DR3) in the Longmen Shan range front, including the faults that ruptured in the Wenchuan and Lushan earthquakes. To further constrain the activity on the unruptured portion of these faults, we used shallow seismic reflection profiles to image Quaternary strata above thrust faults and fault-related folds. These data were acquired by using a vibroseis seismic source method (see Item DR4). Horizons interpreted on the seismic profiles were correlated with stratigraphic picks from several hydrology exploration wells and geological maps (see Fig. DR3).

[1]GSA Data Repository item 2014321, supplementary figures, methods, and tables, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, October 2014; v. 42; no. 10; p. 915–918; Data Repository item 2014321 | doi:10.1130/G35809.1 | Published online 28 August 2014
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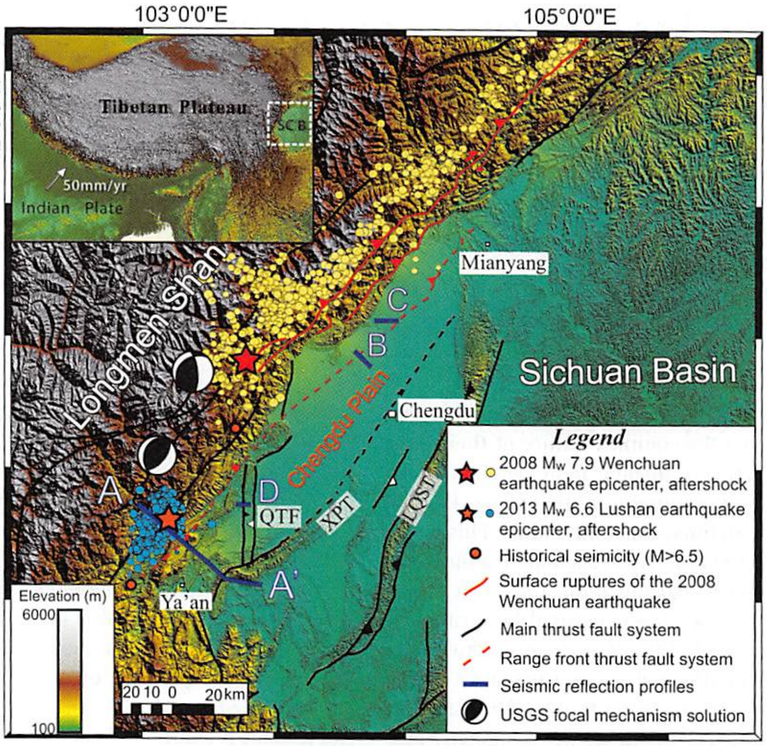

Figure 1. Shaded relief map of Longmen Shan and Sichuan Basin (China) showing epicenter and aftershock locations of the 2008 Wenchuan and 2013 Lushan earthquakes. Red lines are Wenchuan surface ruptures (Xu et al., 2009). Blue lines A-A′, and B, C, and D, are reflection profiles shown in Figures 2 and 4, respectively. QTF—Qiongxi thrust fault; XPT—Xiongpo thrust (black dashed line for the XPT is referenced from Deng et al. [1994]); LQST—Longquan Shan thrust; SCB—Sichuan Basin; USGS—U.S. Geological Survey. Red dashed line for Range Front blind fault is generated by the projection of 8.5 km depth on the surface model.

STRUCTURE

The structure of the southern Longmen Shan range front consists of an imbricate stack of thrust faults. Three major thrusts can be identified on profile A-A′; the Feixianguan fault, the RFBT, and the Hongya fault. The Feixianguan fault dips shallowly to the northwest and is interpreted to merge with the Lingguan fault to the west of section A-A′ at a depth of 4–5 km (Fig. 2) (Wang et al., 2013a). The Lingguan fault represents the unruptured southern segment of the Pengguan fault that slipped in the 2008 Wenchuan earthquake (e.g., Jia et al., 2010). At greater depths, the RFBT is a blind ramp that underlies the Lingguan fault (Wang et al., 2013a). This ramp merges upward with the detachment level in the Sichuan Basin at ~4–6 km depth. This detachment is localized on a Triassic salt layer (Hubbard et al., 2010) and extends to the east into the Sichuan Basin, where displacement on a shallow thrust ramp forms the Xiongpo anticline (Fig. 2). Several migrated seismic reflection profiles image the RFBT as a coherent set of reflectors that dips to the northwest between 28° and 35° (Fig. 2B). Fault cutoffs are aligned along the ramp, and a prominent southeast-dipping forelimb is present in the hanging wall of the thrust (Fig. 2A).

The relocated seismicity of the Lushan earthquake indicates that the focal depth ranges from 10 to 20 km, and that the average hypocenter depth is 15.2 km (Fang et al., 2013; Lü et al., 2013). The focal mechanism solution from the U.S. Geological Survey suggests that the coseismic fault trends 198°, with 33° dip and 71° rake. This coseismic fault dip is consistent with the direct measurements of 28°–35° on the RFBT from the seismic reflection profile. Moreover, seismic data reveal that the rupture initiated at 12.5 km, and propagated downward along the blind thrust fault, and that the peak dip-slip was 1.2 m (Hao et al., 2013). These results indicate that the Lushan earthquake, and many of its aftershocks, occurred on the downdip extent of the RFBT.

The Hongya fault is a shallowly dipping blind thrust fault in the footwall of the RFBT and a Triassic detachment. The upper portion of the Hongya blind fault is well imaged by a coherent set of prominent seismic reflections (Fig. 2C). These seismic reflections suggest that the Hongya fault dips to the northwest between 13° and 16°. The Hongya fault is imaged to the base of

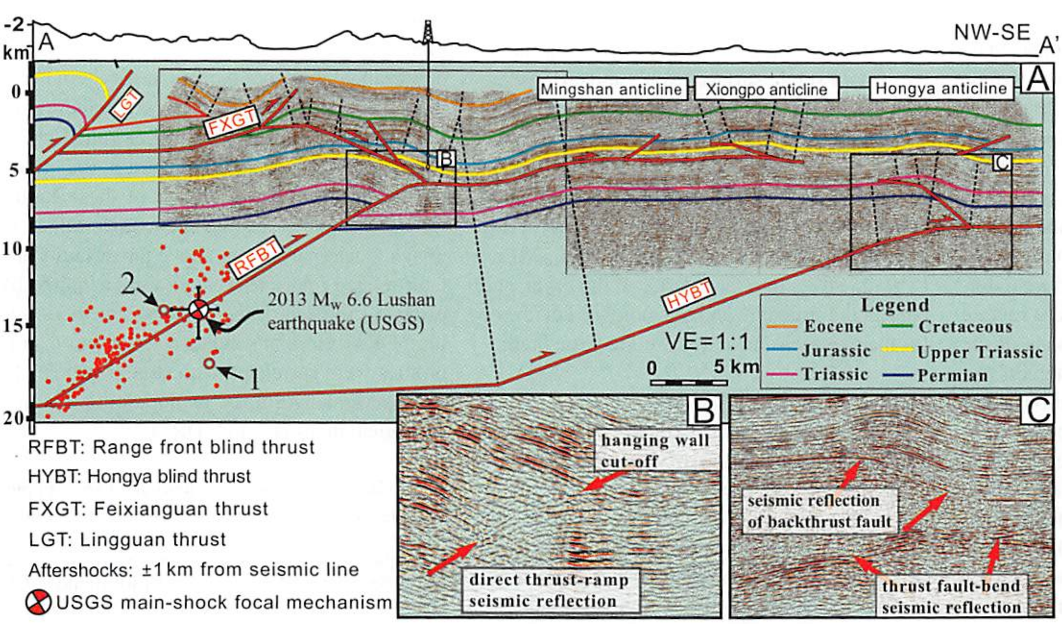

Figure 2. A: Seismic reflection profile imaging the imbricate thrust faults beneath the range front of the Longmen Shan (China), from the hypocenter of the Lushan earthquake into the Sichuan Basin. Red circles 1 and 2 are relocated hypocentral locations from Fang et al. (2013) and Lü et al. (2013), respectively. USGS—U.S. Geological Survey; VE—vertical exaggeration. B: Interpreted fault cutoffs and direct fault plane reflection of the Range Front blind thrust. C: Structural wedge formed by the frontal part of the Hongya fault. USGS—U.S. Geological Survey.

the section A-A′ at ~11 km depth. The presence of structural relief of Paleozoic and younger strata between the north and south sides of the Mingshan anticline suggests that the Hongya fault does not locally sole to a detachment level. Rather, we interpret that the fault ramp extends to a depth of 18–20 km, where it shallows, its dip producing a prominent synclinal fault bend fold that is imaged on section A-A′ just to the southeast of the RFBT.

The spatial relationships and along-strike extents of the Wenchuan rupture, the RFBT, and Hongya faults are illustrated in the 3-D fault model presented in Figure 3. The RFBT extends from Ya'an to Mianyang city, a distance of ~250 km along the western margin of the Sichuan Basin (Fig. 3). The RFBT extends to the east on a shallow detachment within the western Sichuan Basin. Thrust ramps above this detachment form the Qiongxi thrust fault and Longquan Shan anticline (Figs. 1–3). To the west, the RFBT extends downward to ~16–20 km depth, as illustrated by the distribution of relocated seismicity associated with the Lushan earthquake. In our model the RFBT and Hongya fault sole to a basal detachment in the Longmen Shan. The relocated historical seismicity (Zhu et al., 2005) shows a diffuse set of microearthquakes (M < 5) along and within the hanging wall of the Hongya blind fault (Fig. 3). This suggests that the Hongya blind fault is active, implying that the active crustal shortening in the Sichuan Basin is accommodated on both the shallow (3–9 km) detachment and the deeper detachment inferred below the Hongya fault.

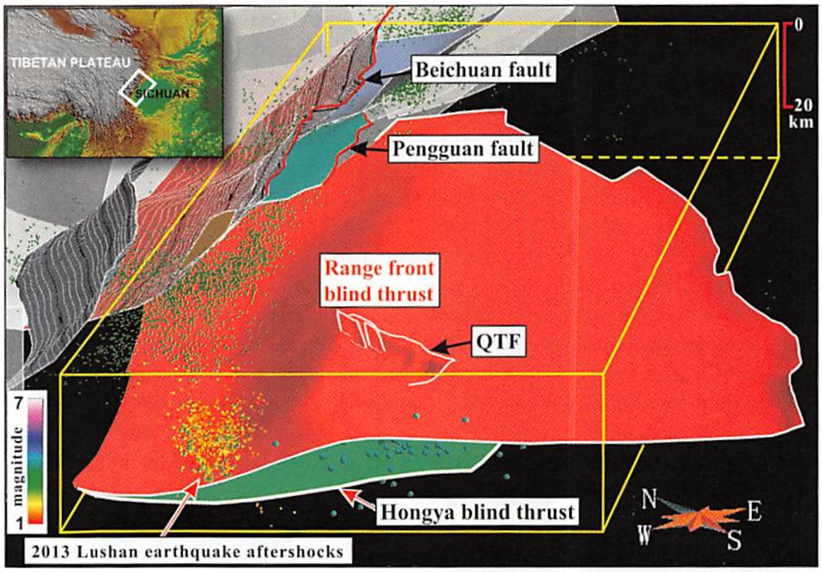

Figure 3. Oblique view of three-dimensional model of imbricate thrust structures in the Longmen Shan (China) fold-and-thrust belt and Sichuan Basin. Red lines are surface ruptures in the Wenchuan earthquake on the Beichuan and Pengguan faults. Green points are aftershocks of the Wenchuan earthquake. Red and yellow hypocenters are aftershocks of the Lushan earthquake (Fang et al., 2013). Blue spheres are hypocenters that were recorded from 1992 to 2002 (Zhu et al., 2005). QTF—Qiongxi thrust fault.

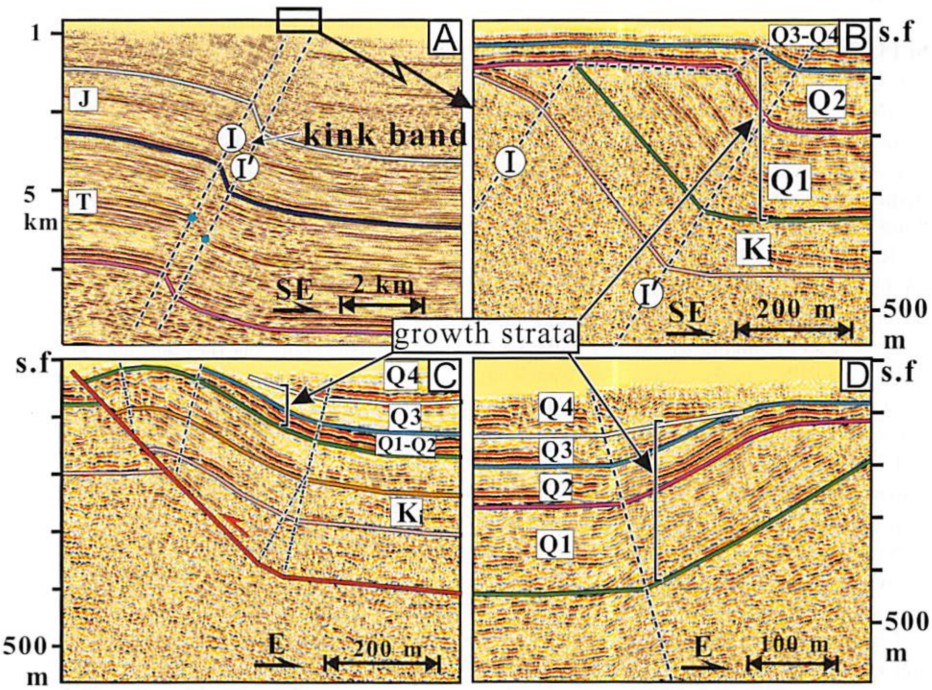

Figure 4. Seismic reflection profiles imaging growth folds associated with thrust splays above the Range Front blind thrust beneath the Chengdu Plain, China. A: Industry seismic reflection profile L2 (Fig. DR4 [see footnote 1]). J—Jurassic; T—Triassic; Ki—Cretaceous interval layer; Q1—Dayi Formation, lowermost Pleistocene (ca. 2.6 Ma); Q2—Ya'an Formation, middle Pleistocene (0.56–1.09 Ma); Q3—upper Pleistocene; Q4—Holocene; s.f—surface.

ACTIVITY

The newly acquired seismic data and previous studies provide three locations along the strike of the RFBT that indicate Quaternary fault activity. Wang et al. (2013a) presented evidence for folding of Quaternary strata in the south, above the Qiongxi thrust fault (Figs. 1 and 4D), which is in the hanging wall of the RFBT; they defined an early Pleistocene to present slip rate on the RFBT of 0.5–1.5 mm/yr. In addition, we present two seismic reflection profiles (B and C, in Figs. 4B and 4C) that are located to the north along strike of the RFBT (Fig. 1).

Previous interpretations of seismic reflection profiles have shown that the ramp of the RFBT rises to a depth of ~8–9 km in the Sichuan Basin and forms a series of kink bands associated with splays in its hanging wall (Jia et al., 2010) (Fig. 4A; Fig. DR4). We imaged one of these structures with seismic reflection profile B (Fig. 4B; Fig. DR3; location shown in Fig. 1). The profile shows Quaternary growth strata that are deformed and thin above this fold limb. This section images a growth triangle (Suppe et al., 1992) located above the projection of the synclinal axial surface of the monocline from depth, based on industry reflection profile L2 (Fig. DR4). The growth triangles include discrete zones of dipping Quaternary strata that narrow upward between well-defined axial surfaces. The shape of the growth triangle implies that the fold developed as a fault-propagation fold or structural wedge associated with a fault splay in the hanging wall of the RFBT (Suppe et al., 1992). The growth triangle indicates that fold growth initiated after the deposition of the base Quaternary (Q1) section and continued through the Holocene (Q4), confirming Quaternary activity on the underlying RFBT. Age control on the Quaternary growth deposit (Q2) is provided by a magnetostratigraphy study, and ranges from 0.56 Ma to 1.09 Ma (see Fig. DR3). This yields an average uplift rate of the fold since the age of the Q2 marker of 0.11–0.21 mm/yr. We translate this uplift rate to a slip rate based on the relationship from Shaw et al. (2002), assuming a fault dip of 33°–56° (fault dip measurements in Fig. DR4). This method constrains the range of slip rate for the RFBT to be 0.13–0.39 mm/yr, but because this growth structure is developed above a single splay in the hanging wall of the RFBT, we consider this slip rate to be minimum estimates for the RFBT.

We present a second profile located in the western margin of Chengdu Plain (Fig. 4C; Fig. DR5; see Fig. 1 for location); profile C images the Quaternary growth strata (Q1–Q4) that thin above, and onlap the crest, and are also folded a series of folds. We interpret this faulting and folding as having formed above the tip-line fold produced by the splay fault of a blind fault splay associated with the RFBT (Fig. DR5). The dip of the Quaternary strata above the fold limb is consistent with activity of the underlying fault and RFBT that have been interpreted along the Qiongxi thrust fault and profile B (Fig. 4B).

SEISMIC HAZARDS

Our study suggests that unruptured parts of the RFBT may pose significant seismic hazards to the population centers in the Chengdu Plain. This is consistent with previous trench excavation studies that have demonstrated that the Qiongxi thrust fault, which is a splay in the hanging wall of the RFBT, ruptured in late Holocene earthquakes (Wang et al., 2013b). Furthermore, instrumental seismicity records suggest that the Hongya fault, a deeper level of blind thrust faulting in the footwall of the RFBT, is also active. The Wenchuan and Lushan earthquakes, along with results from our study, demonstrate that the Longmen Shan and western Sichuan Basin are underlain by an active imbricate thrust system. This suggests that there are several potential sources of large earthquakes in the region, and presents the possibility of multisegment earthquakes that may involve two or more of these faults.

To assess the earthquake potential of the RFBT and Hongya faults, we calculated fault surface areas from our 3-D model. The ramp portion of the RFBT has an area of 7200 km², of which the 2013 Lushan earthquake ruptured ~7%–9%. Using empirical fault area to magnitude relations (Wells and Coppersmith, 1994), rupture of the entire RFBT could source an earthquake with an M_w of 7.8. Using empirical relations between coseismic displacement and moment magnitude (Wells and Coppersmith, 1994), and the slip rate on the RFBT of 0.5–1.5 mm/yr (Wang et al., 2013a), such earthquakes would have average repeat times of 1500–6300 yr. An earthquake that ruptured the entire Hongya fault (1600 km² area) could generate M_w 7.2 events. Alternatively, these faults could rupture in smaller but more frequent earthquakes. Due to effects of seismic wave amplification and the updip source directivity into the basin, large earthquakes on these faults would likely generate severe ground shaking within the western Sichuan Basin.

The 2008–2013 Longmen Shan earthquake sequence also has important lessons about fault and earthquake behavior that can provide information for hazard assessments in other regions characterized by imbricate thrust systems, such as the northern Los Angeles basin (California), the Himalayan thrust front, and Taiwan. First, these events show that large and destructive earthquakes can occur in a short time period on nearly parallel thrust ramps that compose imbricate systems. In the Wenchuan earthquake, this involved simultaneous rupture on two fault splays, whereas the Lushan earthquake ruptured another roughly parallel thrust to the south and in the footwall of the Wenchuan source. This sequence demonstrates that large and destructive earthquakes can occur in the same region on both surface emergent and blind thrust sources. This highlights that different levels of faulting within imbricate thrust stacks can be active and seismogenic. The complexity of these sources emphasizes the value of developing 3-D models that characterize the size, shape, and activity of each fault within these imbricate systems. Moreover, it suggests the need for time-dependent hazards assessments for these sources, given the possibility that destructive events on different thrust segments may occur in sequence.

ACKNOWLEDGMENTS

This research was supported by the National Science and Technology Major Project of China (2011ZX05009-001), the Harvard China Fund, and the Japan Society for the Promotion of Science. We thank the editor James A. Spotila and six reviewers for constructive comments, and A. Lin, P. Zhang, and Z. Li for helpful discussions. We also thank PetroChina for providing seismic data.

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Manuscript received 25 April 2014
Revised manuscript received 5 August 2014
Manuscript accepted 7 August 2014

Printed in USA