A possible seismic gap and high earthquake hazard in the North China Basin

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ABSTRACT

In this study we use combined historical records and results of early paleo-earthquake studies to show that a 160 km seismic gap has existed along the northeast-striking right-slip Tangshan-Hejian-Cixian fault (China) over more than 8400 yr. The seismic gap is centered in Tianjin, a city in the North China Basin with a population of 11 million and located ~100 km from Beijing, which has a population of 22 million. Current data indicate that the recurrence interval of major earthquakes along the Tangshan-Hejian-Cixian fault is 6700–10,800 yr. This implies that a large earthquake with an estimated magnitude of ~M 7.5 is either overdue or will occur within the next 2000–3000 yr along the inferred seismic gap if it is ruptured by a single event. Alternatively, the seismic gap may be explained by aseismic creeping, strain transfer between adjacent faults, or much longer recurrence times than the current knowledge indicates.

INTRODUCTION

Intracontinental earthquakes have caused the most fatalities in human history (Dubar et al., 1992), yet their controlling mechanisms remain poorly understood (e.g., Obermeier et al., 1991; Stein et al., 2012). This issue is well illustrated by the North China Basin, in which there were 24 devastating earthquakes with M ≥ 6 in the past millennium, along buried faults below thick (300–1200 m) Quaternary sediments with no or little surface expression (Xu et al., 1996). For example, the active faults responsible for the 1966 M 7.2 Xingtai and 1976 M 7.8 Tangshan earthquakes were not known until after the earthquake disasters (e.g., Xu et al., 1996). Despite this challenge, north China is an ideal place to examine spatiotemporal patterns of major historical earthquakes along slow-moving (<2–3 mm/yr) faults, because the region has more than 4000 yr of written records of preinstrumentation seismic events (Min et al., 1995). In this study we show that a 160-km-long seismic gap has existed along the right-slip Tangshan-Hejian-Cixian fault zone (Fig. 1B) in the past 1000 yr and possibly over the past 8400 yr.

REGIONAL BACKGROUND

Among estimated M ≥ 6 historical earthquakes since 2300 B.C. across north China (Fig. 1A), those that occurred in the past 1000 yr are the best located (Fig. 1B) (Min et al., 1995). Estimating preinstrumentation earthquake magnitudes in this study is based on an empirical relationship that converts the maximum seismic intensity to seismic magnitude in the North China Basin. The relationship was tested against instrumentally recorded events with a magnitude uncertainty of ±0.5 (Min et al., 1995). Bakun and Wentworth (1997) proposed a model that converts seismic intensity to seismic magnitude based on recorded intensity observed at single locations; their method is ideal for regions such as the western United States with sparse intensity data, which is not the case for north China. In addition, the model depends on local geology that would require additional calibration if applied to north China. For these reasons, we chose to use the empirical relationship of Min et al. (1995) rather than the Bakun and Wentworth (1997) model. The uncertainties of locating preinstrumentation earthquakes in the North China Basin are 20–100 km (Min et al., 1995) (see the GSA Data Repository[1]).

Nearly all of the M ≥ 6 earthquakes in the past millennium occurred along the northeast-striking Sanhe-Laishui and Tangshan-Hejian-Cixian faults in the northern North China Basin. The Sanhe-Laishui fault in the mountainous regions has well-expressed morphology (Xu et al., 2002), whereas the Tangshan-Hejian-Cixian fault is buried below Quaternary sediments (Xu et al., 1996), recognizable only through seismic-reflection profiling (e.g., Xu et al., 2002), examining clustering of small earthquakes (e.g., Shen et al., 2000), drill-core surveys (e.g., Chen et al., 2004), and trenching (e.g., Guo et al., 2011). Because GPS data show no detectable fault motion across the Tangshan-Hejian-Cixian fault within the uncertainties of data (1–2 mm/yr) (Fig. 2), the current slip rate of the Tangshan-Hejian-Cixian fault must be slower than 1–2 mm/yr. A broad east-trending left-slip shear indicated by a southward increase in eastward GPS velocities across the North China Basin (Fig. 2A) may have driven current right-slip motion along northeast-striking faults via bookshelf faulting (Fig. 2B).

SPATIOTEMPORAL PATTERNS OF SEISMIC RUPTURE

Because of a general lack of surface ruptures for most major historical earthquakes in the North China Basin (Xu et al., 2002), we plot the distributions of subsurface rupture length along the Sanhe-Laishui and Tangshan-Hejian-Cixian faults using the scaling relationship of Wells and Coppersmith (1994) (Fig. 3). The plot incorporates uncertainties of locating and estimating the magnitude of historical earthquakes (see the Data Repository). Assuming symmetric rupture, which was the case for the A.D. 1976 Tangshan earthquake (Butler et al., 1979), the plot reveals a 160 km seismic gap centered at Tianjin that has not ruptured in the past 1000 yr (Fig. 3). This gap can be projected onto the seismically active section of the Sanhe-Laishui fault, dominated by the A.D. 1679 M 8 Sanhe earthquake rupture. The duration of the Tianjin seismic gap may extend to ~4000 yr ago, based on the known written records of historical earthquakes in the region (Chen et al., 2004, 2010). However, the large uncertainty (>100 km) in locating ancient earthquakes and estimating their magnitudes prior to A.D. 1000 (Min et al., 1995) makes the usefulness of this inference questionable. This prompts us to examine the paleo-earthquake activities in the Tianjin area along the Tangshan-Hejian-Cixian fault zone.

In Tianjin the northeast-striking North Tianjin and South Tianjin faults are linked by the northwest-striking Haihe fault (Fig. 4A) (Chen et al., 2010). The Haihe fault extends ~40 km southeastward with left-slip kinematics (Chen et al., 2004). A drill-core study shows that the base of the youngest marine layer (MB1) in the region is nearly flat (~13 ± 2 m below the surface), whereas the older marine marker beds (MB2, MB3, and MB4) have variable thicknesses and basal-contact depths (Fig. 4B). This observation has been used to suggest that the last major earthquake in Tianjin occurred between deposition of MB1 and MB2, dated as 8415 ± 115 ^{14}C yr B.P. and 36–39 ka (optically stimulated luminescence ages), respectively (Chen et

[1]GSA Data Repository item 2015023, historical earthquake locations, and uncertainties of locating them and estimating their magnitudes, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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al., 2004). This interpretation implies that the Tianjin seismic gap may not have ruptured for at least 8400 yr, assuming that the observed relationship applies to the entire section of the 160 km seismic gap.

We note that the 1624 Luanxian earthquake (M 6.5) was followed by the 1976 Tangshan earthquake (M 7.8) ~50 km to the south, whereas the 1830 Cixian earthquake (M 7.5) was followed by the 1966 Xingtai earthquake (M 7.2) ~100 km to the north. These four earthquakes are the largest seismic events along the Tangshan-Hejian-Cixian fault zone in the past 400 yr and their progressive migration toward the Tianjin seismic gap may be interpreted in two ways: (1) the pattern is accidental in a random process (Swafford and Stein, 2007), and (2) the pattern was controlled by a deterministic stress-transfer mechanism generated by sequential seismic events along the fault zone (Stein et al., 1997).

DISCUSSION AND CONCLUSIONS

The available data suggest that the 160 km Tianjin seismic gap may have not been ruptured by M ≥ 6 earthquakes in more than 8400 yr. Whether this apparently long-lasting seismic gap represents a seismic threat depends on our knowledge of the characteristic time of the earthquake cycle on the Tangshan-Hejian-Cixian fault (Swafford and Stein, 2007). For example, if the duration of the earthquake cycle is much longer than the currently known duration of the seismic gap, then our observation would not be able to differentiate whether the gap was already filled by rupture events before our time constraints (i.e., prior to 8400 yr). Trenching of the Tangshan-Hejian-Cixian fault zone north of the Tianjin gap revealed that the return times of major earthquakes were between 6700 and 10,800 yr in the past 75,000 yr (Guo et al., 2011). If the Tianjin section shares the same temporal evolution of major earthquakes, it would imply that the seismic gap is either ~1700 yr overdue for a major earthquake, as suggested by the shortest return time, or that the next major event will occur within ~2400 yr, as required by the longest return time. The magnitude of this potential earthquake is estimated to be ~M 7.5, assuming a rupture length of 160 km, a rupture depth of 20 km, a shear modulus of 3×10^{10} Pa, a slip rate of 1 mm/yr constrained by the GPS data, and a slip accumulation period of 8000 yr.

The accumulated seismic energy at the Tianjin gap could alternatively be explained by energy release via multiple smaller earthquakes, aseismic creeping over a wide zone (i.e., outside the region investigated by drill-core surveying shown in Figure 4), strain transfer between adjacent faults (Liu et al., 2011), or much longer recurrence intervals than current knowledge indicates. The strain-transfer mechanism explains well the projection of the

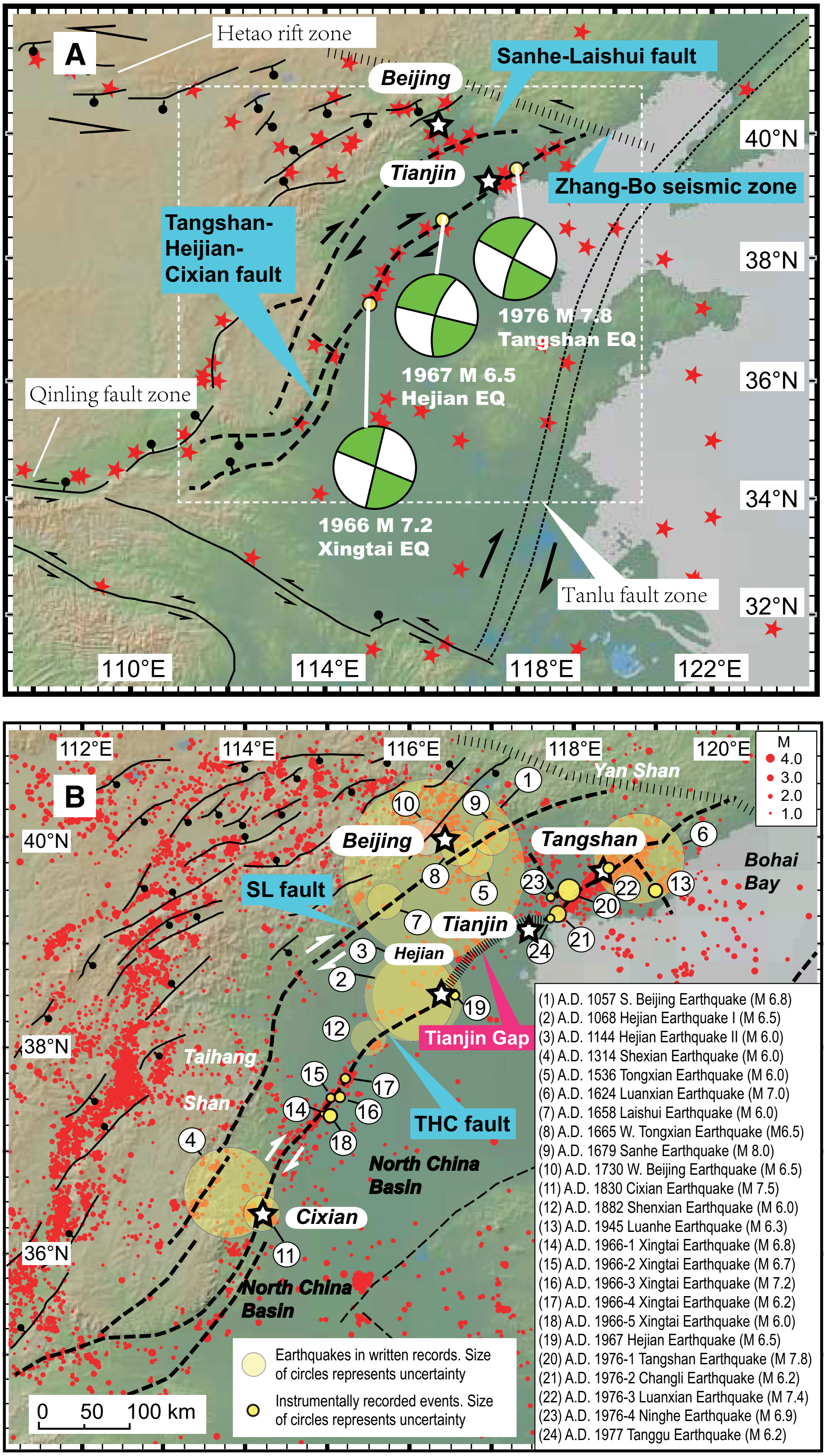

Figure 1. A: Preinstrumentation historical earthquakes (EQ) with M ≥ 6 across north China (after Min et al., 1995) and focal mechanisms of the A.D. 1966 Xingtai, 1967 Heijian, and 1976 Tangshan earthquakes (from Xu et al., 1996). B: M ≥ 6 earthquakes from A.D. 1000 to the present in the North China Basin against a background of microseismicities between 2009 and 2013. Preinstrumentation data are from Min et al. (1995); instrumentally located major earthquakes are from both the China Earthquake Administration and the U.S. Geological Survey. THC—Tangshan-Hejian-Cixian fault; SL—Sanhe-Lushui fault. For earthquakes that occurred in the same year, they are labelled sequentially, such as 1966-1, 1966-2, 1976-1, and 1976-2.

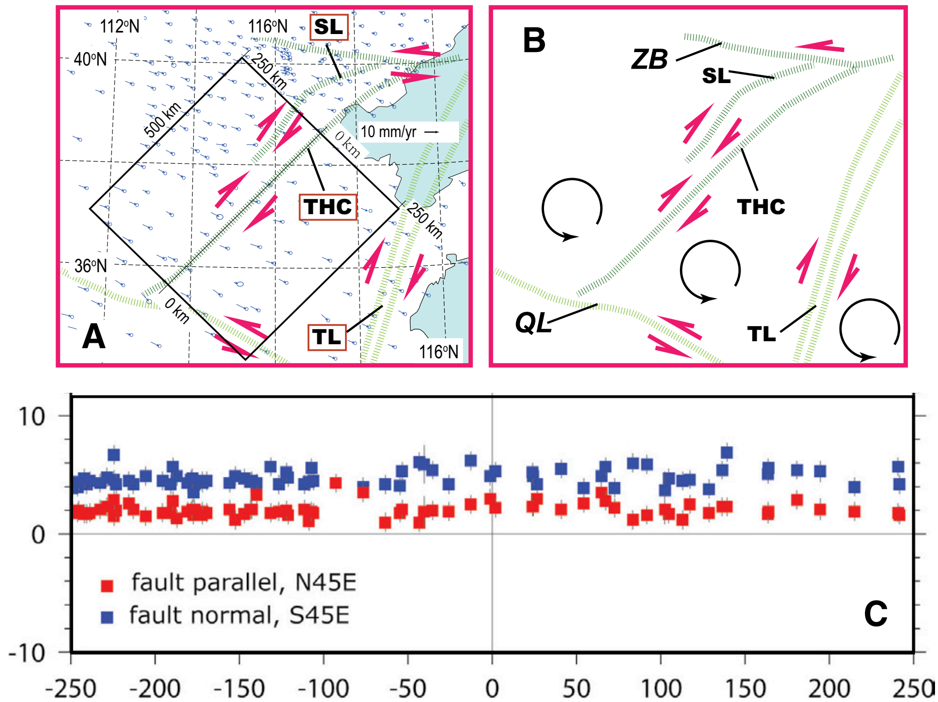

Figure 2. A: Global positioning system velocities derived from 10 yr of campaign occupations of the Crustal Movement Observation Network of China from 1999 to 2009. (Data observed after that could have been affected by the 2011 Tohoku earthquake sequence and thus are not included.) The velocities are referenced to the stable Eurasia plate, and the error ellipses represent the 70% confidence level. THC—Tangshan-Hejian-Cixian fault zone; SL—Sanhe-Lushui fault; TL—Tanlu fault. B: The eastward velocities increase southward, suggesting distributed east-west–trending left-slip shear. This shear may be the cause for right-slip faulting along the northeast-striking faults in north China (Shen et al., 2000). QL—Qinling fault zone; ZB—Zhang-Bo fault zone. C: To avoid the effect of left-slip shear along the east-trending Zhang-Bo and Qinling zones, the fault-parallel and fault-perpendicular velocity components plotted are from the central region of the North China Basin (shown in box in A). The THC fault zone is located approximately along the 0 km line in the box.

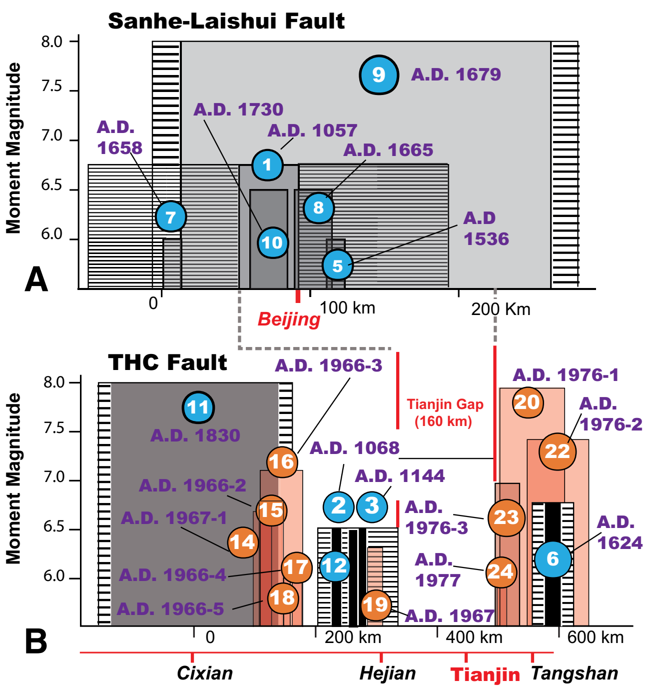

Figure 3. A: Distribution of subsurface rupture length along the Sanhe-Laishui fault, north China. Only the location uncertainties are considered in this plot as the A.D. 1679 Sanhe earthquake dominates this fault segment. Circled numbers correspond to those shown in Figure 1B. B: Distribution of maximum subsurface rupture length corresponding to maximum estimated earthquake magnitudes along the Tangshan-Hejian-Cixian (THC) faults. Gray and red boxes associated with blue and red circled numbers, respectively, represent historical and instrumentally recorded seismic events, and circled numbers correspond to those shown in Figure 1B. For earthquakes that occurred in the same year, they are labelled sequentially, such as 1966-1, 1966-2, 1976-1, and 1976-2 (same as those labelled in Figure 1B). Regions with black horizontal lines indicate location uncertainties of historical earthquakes.

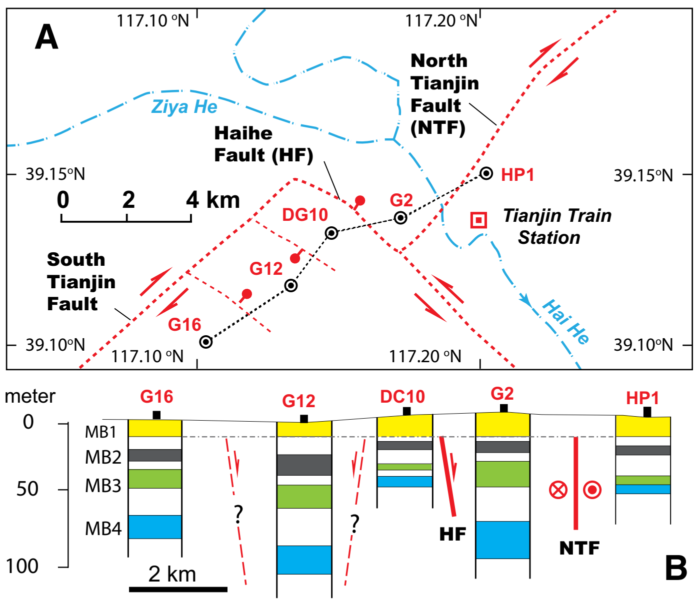

Figure 4. A: Simplified active fault map of the Tianjin area (north China) modified from Chen et al. (2004). B: Simplified stratigraphic sections revealed by a series of drill cores (shown as black dots inside black circles; drill-core numbers are labeled in red) across the Tangshan-Hejian-Cixian fault zone in the Tianjin area. Data are from Chen et al. (2004).

Tianjin seismic gap onto the seismically active section of the Sanhe-Laishui fault in the past 1000 yr (Figs. 1B and 3), but validation of this model requires further analysis of their geometric and kinematic links.

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