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Active normal faulting and the seismogenic fault of the 1739 M ~8.0 Pingluo earthquake in the intracontinental Yinchuan Graben, China

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Abstract:

The NNE-trending Yinchuan Graben is one of several intracontinental grabens that have developed in the extensional environment around the Ordos Block, northern-central China, and is bounded by active normal faults at both its eastern and western margins. In this study, we present new evidence for the Holocene activity and paleoseismicity of the active normal faults developed in the Yinchuan Graben. Interpretations of high-resolution WorldView and Google images, field investigations, trench excavations, seismic data, and radiocarbon dating results reveal the following: i) two main active fault zones, the Helanshan Piedmont Fault Zone (HPFZ) along the western margin of the graben and the Huanghe Fault (HHF) along the eastern margin, are characterized by conspicuous fault scarps developed on both Holocene alluvial fans and terrace risers; ii) the active faults are dominated by normal faulting; iii) the Holocene normal slip rate is estimated to be ~2–3 mm/yr, and the recurrence interval of morphogenic earthquakes is estimated to be ~1500–2000 yr for both the HPFZ and HHF; and iv) the HHF is the most likely seismogenic fault for the triggering of the 1739 M
~8.0 Pingluo earthquake. Our results show that the HPFZ has the potential to produce a destructive earthquake in the near future, because no large earthquake has occurred on this fault during the past ~1500 years. This contrasts with previous findings that the fault scarps of the HPFZ were caused by the 1739 Pingluo earthquake and that therefore the likelihood of a large and destructive earthquake on that fault in the near future is relatively small because of the <300 years elapsed since the earthquake. Therefore, it is necessary to reconstruct the model of faulting, tectonic activity, and paleoseismicity of the intracontinental graben and to reassess the seismic hazard of the active normal faults for the densely populated Yinchuan region.

**Keywords:** active normal fault, Yinchuan Graben, 1739 M ~8.0 Pingluo earthquake, Helanshan Piedmont Fault Zone, Huanghe Fault, Ordos Block
1. Introduction

Active normal faults generally occur in places where the crust is being stretched under an extensional regime (e.g., Jackson, 1987; Jackson and White, 1989; Yeats et al., 1997; Rao et al., 2014). The Yinchuan Graben is one of several intracontinental tectonic grabens in which many active normal faults have developed in the extensional regime around the Ordos Block in northern-central China (Figure 1). Therefore, investigating the activity and kinematic characteristics of active normal faults in the Yinchuan Graben should provide a better understanding of the seismotectonic features and tectonic evolution of active extensional grabens around the Ordos Block. The Yinchuan Graben has long attracted research attention on account of its high levels of historical paleoseismicity and its normal faulting regime sustained since the early Eocene (Liao and Pan, 1982; Liao et al., 1982; Li and Wan, 1984; Zhang et al., 1986; Deng and Liao, 1996; Zhao et al., 2007; Fang et al., 2009; Feng et al., 2011).

A marked offset of the Great Wall of China, which was built at the northern end of the graben in AD 1531, is considered to have been produced by
the 1739 M ~8.0 Pingluo earthquake along the Helanshan Piedmont Fault Zone (HPFZ), which is developed along the western margin of the Yinchuan Graben (He, 1982; Liao and Pan, 1982; Deng et al., 1984; Zhang et al., 1986; Deng and Liao, 1996); that is, the HPFZ is considered to have been the source seismogenic fault of the 1739 earthquake. Furthermore, the morphologic evolution of fault scarps, and paleoseismicity including the recurrence intervals and slip rates of large earthquakes, have been documented for the HPFZ based mainly on the proposal that the fault scarps of the HPFZ are associated with 1739 earthquake (e.g., Zhang et al., 1986; Deng and Liao, 1996).

However, our recent fieldwork has demonstrated that the Great Wall was not offset by the M ~8.0 Pingluo earthquake of 1739 as reported previously, but was actually built on preexisting active fault scarps, and that the 1739 earthquake was not triggered by the HPFZ (Lin et al., 2013). Therefore, it is necessary to reevaluate the current activity of active normal faults in the graben and to re-identify the source seismogenic fault that triggered the 1739 M ~8.0 Pingluo earthquake in order to assess the seismic hazard in the densely populated...
In this study, we present new evidence demonstrating the Holocene activity of the active normal faults developed in the Yinchuan Graben and discuss the paleoseismicity, including the 1739 M ~8.0 Pingluo earthquake.

2. Tectonic setting

The study area, the Yinchuan Graben, is located on the western side of the Ordos Block, northern-central China. The graben is bounded by the NNE-trending Helan Mountains to the west and the NNE-flowing Huanghe (Yellow River in English) to the east, and is ~150 km long and 50–55 km wide (Fig. 1). Geologic evidence and seismic reflection data show that the graben contains more than 7000 m of Tertiary sediments and ~1200–1400 m of unconsolidated Quaternary sediments, indicating a long period of subsidence in an extensional tectonic environment (Feng et al., 2011). The basement consists of pre-Cenozoic metamorphic rocks (Figure 1b). The main active faults in the graben strike NNE–SSW, parallel to the orientation of graben, and include (from east to west) the Huanghe (HH), Yinchuan–Pingluo, Luhuatai, and Helanshan.
Piedmont (HP) faults (Fig. 1b). Seismic reflection data show that the HHFZ, which runs along the eastern margin of the Helan Mountains, is the main fault forming the western boundary of the graben (Fig. 1b and c; Fang et al., 2009; Feng et al., 2011). The Huanghe Fault (HHF), along which the Yellow River flows to the NNE, is inferred to be a blind fault and its recent activity is unclear (Deng and Liao, 1996). The Yinchuan–Pingluo and Luhuatai faults are inferred faults for which there is no morphotectonic evidence, and therefore their current activity is also unknown (Zhang et al., 1986; Deng and Liao, 1996). The HPFZ is considered to be a major active normal fault zone with a dextral displacement component, and is thought to be the source seismogenic fault of the 1739 M ~8.0 Pingluo earthquake, based on the apparent offset of the Great Wall (He, 1982; Liao and Pan, 1982; Zhang et al., 1982; Deng et al., 1984; Deng and You, 1985; Zhang et al., 1986; Deng and Liao, 1996). The average recurrence interval of destructive earthquakes on the HHFZ has been estimated to be thousands of years to ten thousand years (Zhang et al., 1986) or ~2300–3000 yr (Deng and Liao, 1996).
Historical records show that four large (M > 6) earthquakes, the 1143 M 6.5, 1471 M 6.5, 1921 M 6.0, and 1739 M ~8.0 Pingluo earthquakes, have occurred in the Yinchuan Graben during the last millennium (Zhang et al., 1986; People Network, 2014). The 1739 M ~8.0 Pingluo earthquake occurred on 3 January 1739 and caused more than 50,000 deaths (Zhang et al., 1986; Bai et al., 2005; People Network, 2014). Based on the damage and ground deformation features recorded in historical documents, the strongest ground motion caused by this earthquake was concentrated in a narrow zone around the Huanghe and Yinchuan–Pingluo faults on the eastern side of the Yinchuan Graben, where seismic intensities of up to X–XI (on the Chinese XII-point seismic intensity scale) have been estimated (Fig. 1b).

3. Study methods

To detect and identify tectonic topographical features associated with the active faults in the study area, we processed perspective remote-sensing images by draping over the high-resolution WorldView over the digital elevation model.
(DEM) data and Google images (Figs 2–6). This method made it possible to identify tectono-topographical features, including fault scarps, in the study area. The active fault traces identified using this method were confirmed in the field by detailed mapping, measurements of topographical profiles, trench investigations, and the excavation of fault outcrops (Figs 2c and d, 3b–d, 5c and d, and 6a). To observe fault-zone structures, we also followed fault outcrops along fault traces identified from the images and from topographical features in the field. In representative outcrops, we excavated and cleaned the fault outcrop exposures and then sketched the structural features in detail, as also done for trenching.

To determine the ages of topographical surfaces and alluvial deposits that have been offset and deformed by faulting, we collected carbonate materials from the unconsolidated deposits of both alluvial fans and terrace risers. A total of 25 radiocarbon dating samples were taken from the alluvial deposits and were analyzed at Beta Analytic Inc. USA using accelerator mass spectrometry. Dendrochronologically calibrated calendar ages were obtained following Stuiver
et al. (2003). Radiocarbon dating results and calibrated ages are listed in Table 1. To measure the amount of offset and to evaluate the recent activity of the active faults in the study area, we divided the alluvial surfaces, including the terrace risers and alluvial fan surfaces used as surface deformation markers, into four levels: T0 (lowermost surface), T1 (lower surface), T2 (middle surface), and T3 (high surface), based on their distribution, continuity, and height from the current channel (Figs 3a–c, 4, and 5a–c). The T0 surface is the lowermost surface and is developed within the current river channels as sand dunes. The T1 surface is the lower surface and is bounded mainly by the current river channels. The T2 surface is widely developed on the alluvial fans across a zone extending for ~10 km and is bounded by the eastern piedmont area of the Helan Mountains. The T3 surface is limited to the narrow areas at the heads of alluvial fans and is bounded by the Helan Mountains piedmont. Radiocarbon dating results of carbonate materials contained in the alluvial deposits show that the T0, T1, T2, and T3 alluvial surfaces formed at <=1000, ~1000–2000, ~2000–8000, and ~8000–12,000 yr BP, respectively (Table 1, Figs 3–6), suggesting that these
alluvial surfaces formed during the period of global warming that started at
12–13 ka (e.g., Fairbanks, 1990; Lehman and Keigwin, 1992). During the
fieldwork, we made in-situ measurements of the topographical profiles across the
fault scarps developed on both the alluvial fans and terrace risers, and calculated
the amounts of vertical offset (Table 2), details of which are described below.

4. Structural features of active faults

4.1. Identification of active faults

On the basis of analytic results of the topographical features and the fault
deformation structures, we identified two main active fault zones in the Yinchuan
Graben: the Helanshan Piedmont and Huanghe fault zones, which are developed
along the western and eastern margins of the graben, respectively (Figure 1b).

Previous studies have identified two other inferred faults in the graben: the
Luhuatai and Yinchuan–Pingluo faults, identified using seismic reflection data
(Fig. 1b and c; Cai et al., 2006; Wang et al., 2007; Fang et al., 2009; Feng et al.,
2011; Yang et al., 2011). However, the topographical analysis and field
investigations of the present study show no conspicuous topographical or
golographic evidence for tectonic deformation features on the alluvial surfaces,
including the terrace risers and alluvial fans, which formed during the Holocene
along the Luhuatai and Yinchuan–Pingluo faults (Fig. 1b). On the basis of the
lack of both topographical features and geologic deformation structures, we
suggest that the Luhuatai and Yinchuan–Pingluo faults are blind faults but have
been morphogenically inactive during the Holocene (see Discussion for details).
Therefore, there are only two main morphogenic active fault zones in the
Yinchuan Graben: the Helanshan Piedmont (HP) and Huanghe (HH) fault zones.
The topographical and fault structural features of these two fault zones are
described below.

4.2. Topographical features

4.2.1. The Helanshan Piedmont Fault Zone (HPFZ)

Topographically, the HPFZ is characterized by conspicuous fault scarps
developed along the topographical boundary between the NNE-trending Helan
Mountains and the Yinchuan Graben (Fig. 1b). The HPFZ is composed of two main faults: the Helanshan Piedmont and Suyukou faults. The Helanshan Piedmont Fault (HPF) is ~130 km long, which is developed along the piedmont of the Helan Mountains, and generally shows irregular and discontinuous traces that are concentrated in a zone ranging from several meters to 500 m wide (Figures 1, and 3–5). In the northeastern part of the graben, in the vicinity of the Great Wall, the fault zone is composed of three subfaults that form a small graben structure (Figure 5) where the Great Wall has been recently demonstrated to be built on the fault scarps (Lin et al., 2013) but not offset by the 1739 M ~8.0 Pingluo earthquake as reported previously by Zhang et al. (1986) and Deng et al. (1996).

In contrast, the Suyukou Fault (SYF), which lies 5 km east of the HPF, extends for only ~18 km and generally shows a continuous fault trace along alluvial fans, easily recognized as conspicuous white-gray lineaments in the high-resolution WorldView and Google images (Figure 2a–c). The fault scarp along the SYF shows a conspicuous shape with a fresh surface facing southeast.
Fig. 2d and e), similar to the surfaces of coseismic fault scarps produced by the 2008 Mw 7.9 Wenchuan earthquake (Lin et al., 2009, 2010).

The HPF offsets the T1, T2, and T3 alluvial surfaces (Figures 3 and 4), for which the amounts of vertical offset calculated from the topographical profiles measured in situ range from 0.6 to 1.4 m, 3.2 to 6.1 m, and 14.3 to 22 m, respectively (Table 2; Figures 3–5). In contrast, the SYF offsets surfaces T1 and T2, for which the amounts of vertical offset range from 1.4 to 2.5 m and 3.2 to 11.2 m, respectively (Table 2; Figure 2), similar to the values measured along the HPF. These results indicate that the older the alluvial surface, the larger the amount of offset, demonstrating an accumulation of vertical displacement over time on the surface features cut by the fault scarps.

4.2.2. The Huanghe Fault (HHF)

The HHF is developed at the eastern margin of the Yinchuan Graben, where it extends for >120 km and is bounded by the Ordos Block to the east (Figure 1b). The fault runs mainly along or near the Yellow River channel in the
study area, but in the southern part it is mostly covered by desert dunes on the
Ordos Block and is difficult to observe in the field. Only in the central part, along
the western margin of the Ordos Block, the HHF can be observed in the field
(Figs 1b and 6), where terrace risers are developed along the eastern side of the
Yellow River (Fig. 6a–c). The terrace risers can be divided into three levels: the
lower (T1), middle (T2), and high (T3) terraces based on their distribution and
height above the channel of the Yellow River (Fig. 6c and d). The T1 surface is
bounded by the Yellow River channel, T2 is limited to a narrow belt parallel to
the fault scarp of the HHF, and T3 is bounded by the western edge of the Ordos
Block. The fault scarp along the fault has been eroded in many parts and is intact
only locally (Fig. 6c). The topographical profiles measured in situ show that the
amount of vertical offset is 9–11 m on T2 and >16 m on T3, because the fault
scarp has been eroded on T2, and T3 has been covered by younger alluvial
deposits on the downthrown (western) side of the HHF (Fig. 6b–d).

4.3. Structural features of the fault deformation zone
In this study, a number of fault outcrops found along the fault scarps of the HPFZ and HHF were excavated and cleaned to observe the fault deformation structures. Seven typical fault outcrops were revealed at Locs 1–7 along the HPFZ and five along the HHF (Locs 8–12). Locs 1–4 were exposed on the boundary between the T3 and T2 terrace risers, and Locs 5–7 on the T2 alluvial riser along the HPF (Figs 7–11), with one trench exposure excavated in the T2 terrace riser across the SYF (Fig. 12; see Fig. 2 for the location). Locs 8–12 were exposed on the terrace risers on the eastern side of the Yellow River, and show fault shear zone structures and evidence of Holocene seismic activity. The features found at these various locations are described below (see Figures 2b, 4a, and 6 for locations).

4.3.1. The Helanshan Piedmont Fault Zone (HPFZ)

Locs 1–4 were exposed in the southwestern part of the HPFZ on the T3 alluvial surface along the boundary between the Helan Mountains and the Yinchuan Graben (Fig. 4). The fault offsets alluvial deposits composed of
interbedded layers of sand–pebbles sourced from the Helan Mountains; these

layers were originally titled to the southeast but are now tilted to the northwest
towards the mountains) at angles ranging from 6° to 45° (Figs 7–9).

Radiocarbon dating results show that the alluvial deposit surfaces formed during
the early Holocene (10,990–11,290 yr BP, CA10 and Ca11; Table 1; Figure 7).

The main fault planes strike northeast and dip southeast generally at angles of
50°–60° although locally with angles of <30° (Figs 7–9). The fault zone is 10–20
m wide and is composed of two or three subfaults that form a graben structure
(Figs 7–8). The main fault planes occurring in the basement rocks are marked by
thin fault gouge zones (3–10 cm thick) and are gray-brown and yellow-brown in
color (Fig. 9). Slickenside striations developed on the main fault planes bounded
by the fault gouge zone show normal-slip-dominated displacement (Fig. 9d and
g).

Locs 5–7 were exposed in the northeastern part of the HPF, in the alluvial
sediments on which the Great Wall was built (Figs 10 and 11; see Fig. 5a for
locations). The fault has displaced the T1 and T2 alluvial deposits of
sand–pebbles sourced from the Helan Mountains, which are overlain by undeformed surface talus deposits (Figs 10 and 11). The main fault planes strike N10–20°E and dip southeast, generally at angles of 40°–60°. The alluvial pebble deposits bounded by the main fault planes have mostly been reoriented to parallel or subparallel to the fault planes, and a wedge structure has formed in the fault deformation zone (Figs 10 and 11). Radiocarbon dating results show that the T2 alluvial deposit surfaces formed during the late Holocene (~3300–2300 yr BP, C03–05, C09, and C11; Table 1; Figs 10 and 11), and that the talus deposits overlying the alluvial deposits and covering the fault planes formed at ~2060 yr BP (C10 and C12; Table 1 and Fig. 11). These data indicate that the most recent faulting event occurred at this site between 2300 and ~2060 yr BP.

A trench (Trench 1) was excavated at the fault scarp of the SYF on the T2 alluvial surface (Fig. 12; see Fig. 2c for the location), the northern wall of which has been reported previously (Deng and Liao, 1996). To identify the paleoseismic events corresponding to those identified from the outcrops, we cleaned, observed, and sketched the southern exposed wall and collected
radiocarbon materials for dating. The main fault plane is exposed along the boundary between the gray sand–gravel deposits and the deformed layers of sandy soil and sandy gravel deposits, and is covered by surface talus deposits; the fault plane strikes northeast and dips southeast at an angle of 82° (Fig. 12). On the downthrown side (footwall), the alluvial deposits have also been offset and disturbed by five subfaults, which are found in a deformation zone >5 m wide (Fig. 12c). Radiocarbon dating results show that the alluvial deposits in the lower part of the downthrown side formed during the early Holocene (10,630 ± 60 yr BP, CA06; Table 1; Fig. 12c), and that the upper part of the exposed southern wall in the trench formed at 3960 ± 30 yr BP (C07; Table 1; Fig. 12c).

4.3.2. The Huanghe Fault (HHF)

Five representative outcrops (Locs 8–12) were found in alluvial deposits sourced from the Yellow River, located along the fault scarp, which is sharply bounded by the western edge of the Ordos Block as shown in high-resolution Google Earth images (Figs 13–15; see Fig. 6 for locations). These outcrops
contain various fault deformation structures of the HHF, as described below.

At Locs 8 and 9, the fault offsets the silt–sand and sand–pebble layers upon distinct fault planes (Figs 13 and 14). The main fault planes strike northeast and dip to the northwest at angles of 32°–56°. Liquefied silt–sand deposits are injected into both the country sand and sand–pebble layers as veins and networks that are then cut by faults (Figs 13b and 14b). The faults and liquefied sand-silt veins occurred in a zone ~5 m wide, in which the alluvial deposit layers are disturbed and tilted to the west at angles of 20°–30° (Fig. 14). Radiocarbon dating results reveal that the disturbed, tilted sand layers formed between 11,050 and 6170 yr BP (CA15 and C12; Table 1; Figs 12b and 14b), and that the upper part of the offset sand layer formed at 2570 ± 30 yr BP (CA14; Table 1; Fig. 14b).

From these results, it is inferred that the most recent faulting event occurred during the past ~2570 years. No fresh fault scarp is observed along the HHF because the fault scarp has been strongly eroded, showing either a uniform slope or a step-shaped profile (Figs 6 and 13–15).

At Locs 10 and 11, the fault has displaced sand–silt layers with thin
sand–pebble layers that are tilted to the west on the downthrown side at angles of 40°–50° (Fig. 15). At Loc 12, a ~15-m-wide graben structure is formed within the fault zone (Fig. 13c), in which the sediment layers have been disturbed and tilted towards the central part of the graben. The tilting of the alluvial deposit layers on the downthrown side, the fault structural features, and the graben structure together indicate that normal faulting occurred in an extensional environment along the HHF, similar to that along the HPFZ in the western marginal zone of the Yinchuan Graben.

5. Discussion

5.1. The seismogenic fault of the 1739 M ~8.0 Pingluo earthquake

Previous studies have reported that the HPFZ was the source seismogenic fault that triggered the 1739 M ~8.0 Pingluo earthquake, based on the apparent offset of the Great Wall (He, 1982; Liao and Pan, 1982; Deng et al., 1984; Zhang et al., 1986; Deng and Liao, 1996). However, our recent study demonstrates that the Great Wall is not offset by faulting along the HPF but was built on the fault
scarp developed on the alluvial surfaces (Lin et al., 2013). Based on historical records, the strongest seismic intensity of up to X–XI (on the Chinese XII-point seismic intensity scale) is inferred to be distributed in the central-eastern area around the inferred Yinchuan–Pingluo Fault and the HHF (Fig. 1b; Bai et al., 2005). Historical records made within three weeks of the 1739 earthquake document that in the zone of seismic intensity X–XI, buildings were almost completely destroyed and most people died, and that the intense ground deformation included subsidence of 2–3 m over a wide area, liquefaction, and numerous surface fissures in the area around the Yinchuan–Pingluo and Huanghe faults (Bai et al., 2005). In contrast, the seismic intensity in the Helan Mountains piedmont area along the Luhuatai and Helanshan Piedmont faults during the 1739 earthquake was less than VI–VII, leaving buildings only slightly damaged and resulting in no distinct ground deformation (Zhang et al., 1986; Bai et al., 2005). Historical documents record that temples built ~1000 years ago, namely the 15-floor-high towers (Shuang Towers) (Fig. 16a and b) built on the fault scarp of the HPFZ at the site near Suyukou (see Fig. 1b for locations), were not
destroyed during the 1739 earthquake, but that 10-floor-high towers (Chentian Tower and Haibao Tower) (Fig. 16c and d) with similar structures to that of the Shuang Towers built in downtown Yinchuan City were completely destroyed and subsequently rebuilt in the Qing Dynasty (~200–300 years ago). These historical records and the pattern of damage to buildings (including the towers) indicate that the strongest ground motion occurred in the narrow belt of seismic intensity of X–XI on the eastern side of the graben around the Yinchuan–Pingluo and Huanghe faults, and that the zone of weakest seismic intensity (≤VI–VII) occurred in the Helan Mountains piedmont area around the HPFZ (Fig. 1b).

The seismic reflection data show that the HHF is a main fault in the graben, in which the HPFZ and the Yinchuan–Pingluo Fault converge into a single fault zone at ~30 km depth in the lower crust (Fig. 1c). As stated above, there are no morphotectonic features such as fault scarps along the Luhuatai and Yinchuan–Pingluo faults. The seismic profiles and geological sections based on drilling data and trench investigations indicate that i) the Luhuatai Fault is a blind fault which is buried at a depth of >25 m under the late Pleistocene silt-sand and
soil layers formed before 124 ka (Wang et al., 2007); and ii) that

Yinchuan-Pingluo Fault is mostly buried at a depth of >1.5 m under the Holocene fluviolacustrine deposit layers formed during ~3200-13600 yr BP (Cai et al., 2006; Wang et al., 2007). If the 1739 earthquake was triggered by the Yinchuan-Pingluo Fault or the Luhuatai Fault, a distinct coseismic fault scarp with vertical offset of >2-3m would occur on the alluvial landforms along the faults due to the large magnitude of M~8. However, as stated above, the topographical, geological, and seismic reflection data show that no fault scarp and no vertical offset in the near surface deposit layers can be recognized. These data indicate that no morphogenic faulting event has occurred along these two faults since the formation of alluvial landforms during late-early Holocene, and therefore support our findings that these two faults have been morphogenically inactive during the Holocene. In contrast, the HHF vertically offsets the Holocene terrace risers of the Yellow River by 16–17 m (Figs 6 and 13–15), and the most recent faulting event occurred within the past ~2570 years (Fig. 14), which indicates that morphogenic earthquakes have repeatedly occurred on the
The epicentral locations of recent earthquake sequences indicate that the microearthquakes occurred mainly in the central-southern part of the Yinchuan Graben and between the HPF and HHF (Fig. 17). On the basis of the fault dip angle of ~45° revealed by seismic reflection data (Fig. 1c), we interpret the perspective views of the epicentral distribution in the central-southern parts of the graben as indicating that the recent microearthquakes occurred mainly on the HHF (Fig. 17b and c). Although it is unclear whether the recent earthquakes occurring on the HHF are aftershocks associated with the 1739 M ~8.0 Pingluo earthquake, the epicentral distribution indicates that the HHF is a current main seismogenic fault in the Yinchuan Graben. On the basis of the above discussion, we conclude that the HHF is the most likely seismogenic fault to have triggered the 1739 M ~8.0 earthquake.

5.2. Recurrence interval of morphogenic earthquakes and normal slip rates

In previous studies, using the apparent offset of the Great Wall, the
conspicuous fault scarps developed on the lower terrace riser were considered to be the coseismic fault scarps that formed during the 1739 earthquake (e.g., Zhang et al., 1986; Deng and Liao, 1996). The recurrence interval of the morphogenic faulting events is inferred to be thousands of years to ten thousand or more years, based on the formation time of the old fault scarps developed on the middle and high terrace risers, as calculated from the fault-scarp diffusion model used by Hanks and Wallace (1985) for the Lake Lahontan shoreline and Beachfront Fault scarps (Zhang et al., 1986). Combining the information on the terrace offset, fault scarp morphology, and $^{14}$C ages, Deng and Liao (1996) suggested that four paleoseismic events have occurred along the HPFZ, in 8400, 6300–4600, and 2600 yr BP, and in AD 1739 (the M ~8.0 Pingluo earthquake). These estimates are based on the idea that the apparent offset of the Great Wall was caused by the 1739 Pingluo earthquake and is considered to be the most recent morphogenic faulting event along the HPFZ. As documented above, we present evidence that the fault scarps that developed along the HPFZ were not formed by the 1739 M ~8.0 Pingluo earthquake as stated above and reported by Lin et al. (2013);
consequently, the estimates of recurrence interval inferred from the apparent
offset event of the Great Wall, as reported in previous studies, are unreliable.

The fault outcrops exposed in the area around the Great Wall show that the
surface talus deposits yielding $^{14}$C ages of 2070–2060 yr BP and overlying the
disturbed and offset alluvial deposits that formed at 2370–2130 yr BP are neither
deformed nor offset by faulting (Figs 10 and 11). This constrains a faulting event
to between 2370 and 2060 yr BP. Furthermore, field investigations reveal that the
T0 alluvial deposits yielding $^{14}$C ages of 1660–1510 yr BP are neither deformed
nor offset by faulting along the HPFZ (Fig. 5). Accordingly, considering the
classification of dating ages, we infer that the most recent morphogenic faulting
event occurred along the HPFZ between ~2300 and 1500 yr BP.

The vertical displacements of the T1, T2, and T3 alluvial surfaces
measured in situ range from 0.6 to 2.5 m with an average of ~1.6 m, from 3.2 to
11.2 m with an average of 5.2 m, and from 13.5 to 22.0 m with an average of ~18
m, respectively (Table 2). Considering the post formation erosion and collapse of
the fault scarp, the offset amount caused by individual faulting events would be
larger than the average offset amount (1.6 m) of the T1 surface. Using a maximum offset of 2–2.5 m on the T1 surface measured in situ as a characteristic offset, we infer that the T1, T2, and T3 surfaces have recorded one, two/three, and seven/eight events on the HPFZ, respectively. Therefore, the recurrence interval of morphogenic faulting events during the Holocene is estimated to be ~1500–2000 years for the HPFZ. Considering the two main fault traces of the HPFZ (the HP and SY faults in the southwestern part of the HPFZ, as shown in Figures 1b and 2a), the characteristic offset caused by an individual event would be the total offset on the HP and SY faults, calculated to be ~3–4 m on average. Accordingly, an average normal slip rate of ~2–3 mm/yr is obtained for the HPFZ. Our results show no evidence for a morphogenic earthquake having occurred in the past ~1500–2000 years along the HPFZ, and therefore the HPFZ has the potential to produce such an earthquake in the near future. This conclusion contrasts with previous interpretations of a recurrence interval of large earthquakes of 2300–3300 years (Deng and Liao, 1996) and of thousands of years to ten thousand years (Zhang et al., 1986), which were based on the view
that the latest event of the HPFZ was the 1739 M ~8.0 Pingluo earthquake. As such, it is necessary to reassess the risk of seismic hazards in the densely populated Yinchuan Graben.

In the case of the HHF, the amount of offset cannot be accurately calculated because of the erosion and collapse of the fault scarps developed on the alluvial terrace risers. Using the limited data obtained in this study, we estimate the vertical displacement on the T3 terrace risers to be ≥16 m (Table 2).

On the basis of the $^{14}$C dating results (~11,000–6100 yr BP, CA15 and C12; Table 1; Figs 13b and 14b) of the alluvial deposits, an average normal slip rate of 1.2–2.5 mm with an average amount of ~2 mm/yr is obtained for the HHF, which is comparable to that of the HPFZ. Given that the characteristic offset amount of ~2–2.5 m produced by an individual faulting event is similar to the offset proposed for the HPFZ, we estimate that six or seven morphogenic faulting events have occurred during the Holocene, indicating an average recurrence interval of ~1500–2000 years, comparable to that of the HPFZ. The similarity on the recurrence interval and slip rate between the HPFZ and the HHF may be
caused by the same strain stress sourced from the lower crust where two faults
join into the same fault zone (Fig. 1c).

More work is required on the Huanghe Fault if we are to better understand
the deformation characteristics of the source seismogenic fault of the 1739
earthquake and to improve our ongoing assessment of seismic hazard in the
densely populated area of the Yinchuan graben, central China.

6. Summary

On the basis of the field investigations completed as part of this study, the
following conclusions can be drawn.

1) The Helanshan Piedmont and Huanghe fault zones are the main active normal
faults developed along the western and eastern boundaries of the Yinchuan
Graben, respectively.

2) The slip rate during the Holocene is estimated to have been ~2–3 mm/yr for
both the HPFZ and the HHF.
3) The recurrence interval of large earthquakes is estimated to be ~1500–2000 years for both the HPFZ and the HHF.

4) The HHF is inferred to be the source seismogenic fault to have triggered the 1739 M ~8.0 Pingluo earthquake, and the HPFZ has the potential to produce a large earthquake in the near future.

Our findings differ from those of previous studies, which considered the HPFZ to have been the source seismogenic fault of the 1739 earthquake and which estimated a recurrence interval for morphogenic earthquakes of >2300–3300 years. Therefore, it is necessary to reassess the seismic hazard of the densely populated Yinchun region, central China.

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Data for this paper may be obtained by contacting the corresponding author.

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**Figure captions**

Figure 1. Index map showing the tectonic setting and features of the study area.

(a) Landsat image showing the location of the study area; (b) geologic map of the study region [modified from Li and Wan (1984) and Lin et al. (2013), and with seismic intensity data from Bai et al. (2005)]; and (c) seismic reflection profile, showing the subsurface geologic structures of the Yinchuan Graben [modified from Fang et al. (2009)].


Figure 2. Landsat images (a–d) and photographs (e, f) showing the topographical characteristics and distribution of morphotectonic features in the southwestern part of the HPFZ. (a, b) Google Earth images showing the distribution of morphotectonic features of the HP and SY faults developed on the alluvial fans bounded by the piedmont of the Helan Mountains (see Fig. 1b for the location). Black solid squares indicate the sample locations of radiocarbon dating material with the...
corresponding dating results. P-4 to P-9 indicate the locations of
topographical profiles measured in situ. (c) WorldView image showing
the fault traces of the SY Fault. (d) Close-up view of the SY Fault shown
in (a). Conspicuous fault traces characterized by white-gray lineaments
are prominent in the image. (e) Photograph showing the SY and HP fault
scarps. (f) Close-up view of the SY fault scarp.

Figure 3. Google Earth image (a), topographical division map (b), photograph
(c), and topographical profiles (d) showing the tectonic landforms and
gometry of the HPF in the area near Suyukou (see Fig. 2a for the
location). (a) Google Earth image and (b) corresponding topographical
division map of alluvial surfaces and the topographical features of the
HPF. The $^{14}$C ages indicate that the T2 terrace riser formed between 5040
and 4729 yr BP (Ca-02 and Ca-01). (c) Photograph showing the three
levels of terrace risers that have been offset by the HPF. (d)
Topographical profiles measured in situ [see (c) for locations]. The T1,
T2, and T3 terrace risers are vertically offset by 14.3, 4.4, and 1.2 m,
respectively.

Figure 4. Google Earth images (a, b) and corresponding topographical division map of alluvial surfaces (c) showing the tectonic landforms and geometry of the HPF in the northeastern part of the Yinchuan graben (see Fig. 1b for the location). (a) Google Earth image showing the configuration and deformation features of the HPF in the area near Suyukou (see Fig. 3 for the location). The fault trace shows an irregular lineament along the piedmont of the Helan Mountains, where seven main fault outcrops (Locs 1–7) were observed (see text for details). (b) Close-up view of the area around Loc. 1. (c) Topographical division map of alluvial surfaces in the area shown in (b).

Figure 5. Topographical map and photograph showing the tectonic landforms and configuration of the HPF in the northeastern part of the study area around the Great Wall (see Fig. 1b for the location). (a) Google Earth image. (b) Topographical division map of alluvial surfaces in the area shown in (a). (c) Photograph showing the fault scarp developed on the
alluvial fan, on which the Great Wall was built. (d) Topographical profiles measured in situ [see (b) for locations]. The T1 and T2 terrace risers are vertically offset by 1.0 and 2.2–4.5 m, respectively.

Figure 6. Topographical maps showing the tectonic landforms of the Huanghe Fault in the eastern margin of the Yinchuan Graben (see Fig. 1b for the location). (a, b) Google Earth images. (c) Topographical division map of surfaces in the area shown in (b). (d) Topographical profiles measured in situ [see (a) for locations]. The T2 and T3 terrace risers are vertically offset by 9–11 and 16–17 m, respectively.

Figure 7. Photograph (a) and corresponding sketch (b) showing the deformation structures of the HPF at Loc. 1 (see Fig. 4 for the location). The alluvial sand–pebble layers are deformed and tilted to the northwest at an angle of ~45° within a graben structure bounded by two faults. Half arrows indicate the movement sense of the fault. $^{14}$C ages indicate that the alluvial terrace riser formed between 10,090 and 11,490 yr BP (CA-11 and CA-10).
Figure 8. Photographs showing the deformation structures of the HPF at Loc. 2 (see Fig. 4 for the location). (a) Fault outcrop exposed under the fault scarp. (b) Close-up view of (a). The alluvial sand–pebble layers have been deformed by faults and dip to the northwest at an angle of ~25°.

Figure 9. Photographs showing the deformation structures of the HPF. (a–c) Fault outcrop at Loc. 3. (d) Stereo projection of the striations measured on the main fault at Loc. 3. (e, f) Fault outcrop Loc. 4 (see Fig. 4 for the location). (g) Stereo projection of the striations measured on the main fault plane at Loc. 4. The T3 alluvial terrace riser has been offset and tilted to the northwest. Fault gouge zones, 5–10 cm thick, are observed at these two fault outcrops. Striations on the main fault planes at the two locations indicate a normal, slip-dominated sense of movement.

Figure 10. Photograph (a) and corresponding sketch (b) showing the deformation structures of the HPF at Loc. 5 (see Fig. 4 for the location).

Figure 11. Photographs and corresponding sketches showing the deformation structures of the HPF at Locs 6 and 7 in the northeastern area of the
graben in the vicinity of the Great Wall (see Fig. 4 for locations). (a, b)

Fault outcrop at Loc. 6. (c, d) Fault outcrop at Loc. 7. The alluvial sand–gravel deposits forming a wedge structure and yielding $^{14}$C ages of 2310–2310 yr BP (samples C9 and C11) have been offset and deformed by faulting, whereas the surface talus deposits yielding $^{14}$C ages of 2060–2070 yr BP (samples C9 and C11) have been neither offset nor deformed by faulting.

Figure 12. Photographs and sketch of Trench 1 (see Fig. 2c for the location). (a) Overview of the fault scarp at the trench site. (b) Exposed trench wall. (c) Close-up view of the deformation zone of the main fault. (d) Sketch of the exposed trench wall of (b).

Figure 13. Photographs showing the fault structure of the HHF at Loc. 8 (a, b) and Loc. 11 (c). The alluvial sand–pebble layers have been deformed and a graben structure is bounded by two main faults (c).

Figure 14. Photograph (a) and corresponding sketch (b) of the fault outcrop showing the fault structure of the HHF at Loc. 9. The alluvial sand–gravel
deposits containing carbonate materials yielding $^{14}$C ages of 2570 and 6170 yr BP (CA12 and CA14 samples) have been offset and deformed by faulting. The silt–sand deposits have been liquefied and injected into the country alluvial deposits and in turn have been cut by faulting.

Figure 15. Photographs and corresponding sketches of fault outcrops showing the fault structure of the HHF at Loc. 10 (a–c) and at Loc. 11 (d–f). The fault scarps have been eroded and alluvial sediment layers have been tilted towards the downthrown side at an angle of 30°–45°.

Figure 16. Photographs showing the locations and situation of towers built ~1000–1200 years ago in the Yinchuan Graben. (a, b) The 15-floor-high towers (Shuang Towers) were built ~1200 year ago on the uplifted side of the fault scarp of the HPFZ at the site near Suyukou (see Fig. 1b for the location), and were not destroyed during the 1739 earthquake, which were rebuilt several times in the Qing Dynasty (~200–300 years ago). (c, d) The 10-floor-high towers of Chentian Tower and Haibao Tower, which have similar structures to that of the Shuang Towers, were built in
downtown Yinchuan City ~1000 years ago and were completely destroyed during the 1739 earthquake and later rebuilt in the Qing Dynasty.

Figure 17. Epicentral distribution of instrumentally recorded earthquakes (1.0 ≤ M ≤ 5.0). (a) Plan-view map. (b) Perspective view of the central part (Profile I–I’) of the Yinchuan Graben towards the northeast, showing major faults and instrumentally recorded seismicity. (c) Perspective view of the southern part (Profile II–II’) of the Yinchuan Graben towards the northeast, showing the major faults and instrumental record seismicity. Earthquakes recorded from 1970–2014 were obtained from the seismicity catalog (China Earthquake Data Center, 2014).
Figure 8

(a) Fault scarp tilting to NW at ~7° dip angle.

(b) Fault traces and dip directions.

F: N50°E/60°SE  F: N18°E/56°SE
<table>
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<th>Sample no.</th>
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<th>Sample material</th>
<th>$^{14}$C age (yr BP)b</th>
<th>Conventional age (yr BP)c</th>
<th>$2\sigma$ calendar aged</th>
<th>Sampling locatione</th>
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<td>4720 ± 3</td>
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<td>car.</td>
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<td>5040 ± 30</td>
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<td>2370 ± 30</td>
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<td>1260 ± 30</td>
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<td>770 ± 30</td>
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<td>7500 ± 40</td>
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<td>2370 ± 30</td>
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<td>BC5562-5464</td>
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<td>20130715-C06</td>
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<td>10,630 ± 50</td>
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<td>11,490± 50</td>
<td>BC11482-11236</td>
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<td>2,570 ± 30</td>
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<td>11,050 ± 50</td>
<td>BC11054-10783</td>
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car.: Carbonate material.

a) All samples were analyzed at Beta Analytic Inc. USA, via accelerator mass spectrometry (AMS).
b) Radiocarbon ages were measured using accelerator mass spectrometry referenced to the year AD 1950. Analytical uncertainties are reported at 2σ.
c) Conventional radiocarbon age was calculated using an assumed delta $^{13}$C.
d) Dendrochronologically calibrated calendar age using Method A from CALIB Radiocarbon Calibration Version 7.0 (Stuiver et al., 2003).
e) Sampling location: carbonate material was taken from the alluvial sediments under the alluvial surface. T0-T3 surface: Lowermost, lower, middle, and high alluvial surfaces from the current river channel, see text for details.
Table 2. Amounts of offset of alluvial surfaces. T1, T2, and T3 offset (m) indicates the amounts (m) of offset of the T1, T2, and T3 alluvial surface, respectively.

### Table 2a. Helanshan Piedmont Fault (HPF).

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<th>Location</th>
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<td>20.0</td>
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<td>4.4</td>
<td>1.2</td>
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<td>Site-7</td>
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<td>Site-7</td>
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<td>Site-8</td>
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### Table 2b. Suyukou Fault (SYF).

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### Table 2c. Huanghe Fault (HHF).

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<td>Profile 12 (Fig. 6)</td>
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