Bounds on the Holocene Slip Rate of the Haiyuan Fault, North-Central China

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We measured the offsets of six stream valleys, of 30 to 90 m, along the northwest–southeast trending, left-lateral Haiyuan strike-slip fault, in north-central China. Minimum ages of these offsets were determined to estimate lower bounds for the Holocene slip rate. The most reliable bounds are 7.6 ± 1.0 and 6.7 ± 1.0 mm/yr, with three others that are smaller (3.4 ± 0.7, 3.5 ± 0.9, and 4.1 ± 0.4 mm/yr) and one large value (16.4 ± 5.9 mm/yr) that we doubt. Thus, the average Holocene slip rate of the Haiyuan fault is larger than 6 mm/yr and probably exceeds 7 mm/yr. If the average slip rate of 5 to 10 mm/yr for the Quaternary Period is applicable to the Holocene Epoch, the average rate is 8 ± 2 mm/yr. © 1988 University of Washington.

INTRODUCTION

Following its collision in early Tertiary time, India has penetrated into Eurasia causing widespread deformation throughout central and eastern Asia in front of India’s path. Much of this penetration has been absorbed by crustal shortening and crustal thickening, but, at least in late Cenozoic time, lateral extrusion of material out of India’s northward path has enabled India to continue its penetration without further crustal thickening in front of it (e.g., Molnar and Tapponnier, 1975). The lateral extrusion is most clearly reflected by active strike-slip faulting; several major left-lateral, roughly east–west trending faults emanate from the Tibetan plateau, and slip on them allows material to slide eastward relative to Siberia (Fig. 1). Quaternary and/or Holocene slip rates on the three principal fault systems, the Altyn Tagh, the Kunlun, and the Xianshuihe faults, exceed 10 mm/yr (e.g., Allen et al., 1988; Kidd and Molnar, 1988, Molnar and Deng, 1984; Molnar et al., 1987; Peltzer, 1987). Rates for other more minor strike-slip faults between these major ones or farther east are smaller, but for several faults, they reach several millimeters per year (Burchfiel et al., 1987; Kidd and Molnar, 1988; Peltzer, 1987; Peltzer et al., 1988). In this paper, we discuss the rate of slip for one such fault, the Haiyuan fault (Fig. 1).

In 1920, a major earthquake, the Haiyuan earthquake ($M = 8.7$), ruptured the eastern 200 km of the Haiyuan fault (Deng et al., 1984; Lanzhou Institute of Seismology and the Seismology Brigade of the Ningxia-Hui Autonomous Region, 1980), and an average left-lateral displacement of 8 m can be associated with that earthquake (Zhang Weiqi et al., 1987). The 220,000 deaths caused by this earthquake, the dimensions of the rup-
Fig. 1. Map of eastern Asia showing major faults. Quaternary or Holocene average slip rates exceed 10 mm/yr on the Altynt Tagh (Peltzer, 1987), Kun Lun (Kidd and Molnar, 1988), and Xianshuihe faults (Allen et al., 1988; Molnar and Deng, 1984). Slip rates on other strike-slip faults between these or east of them appear to be smaller, but for many, like the Haiyuan fault, rates reach several millimeters per year.
ture zone, and the large average displacement attest to a great significance of the Haiyuan fault in any evaluation of the seismic hazard of the Ningxia region. Accordingly, one of the motivations of the present study was to put a bound on the average rate of slip during the last few thousand years, so that this bound could, in turn, be used to evaluate the recurrence intervals of great earthquakes on the Haiyuan fault (Zhang Peizhen et al., 1988).

The Haiyuan fault is particularly clear on the Landsat imagery, and displacement, not only that associated with the 1920 earthquake, has obviously been primarily left-lateral strike-slip (Deng et al., 1984; Tapponnier and Molnar, 1977). Stream valleys have been displaced from tens of meters to as many as 1 or 2 km (Deng et al., 1984), and conglomerates deposited in stream valleys in Quaternary time have been displaced several kilometers from source areas of distinctive cobbles in the conglomerates (Burchfiel et al., 1987). The total left-lateral offset on the fault is between 10 and 15 km, with markers of Paleozoic, Eocene, and latest Pliocene or early Quaternary age all offset the same amount (Burchfiel et al., 1987). Thus, the average rate of slip for the Quaternary Period has been between about 5 and 10 mm/yr. The present study, which considers offsets accumulated only during the Holocene and latest Pleistocene Epochs, complements the results reported by Burchfiel et al. (1987).

METHOD

The key to determining an average Holocene slip rate along a fault is finding landforms and deposits that can be dated and that can be related to slip on the fault. Streams incised into the landscape and ridges between them are often displaced varying amounts depending upon both the dates when incision began and the rate of slip. Dating such incision, or the ages of landforms in general, is usually difficult, and there are very few faults for which accurately dated, offset landforms have been used to determine Holocene or late Pleistocene slip rates (e.g., Sieh and Jahns, 1984; Weldon and Sieh, 1985). Bounds on maximum ages, however, can be obtained by dating deposits that later were sculpted into the present landforms. With this in mind, we gathered organic material for radiocarbon dating from depositional terraces and colluvial deposits later incised by streams whose valleys have been offset by slip on the Haiyuan fault. Thus, the quotient of measured offset divided by such ages gives a lower bound for the slip rates.

To estimate the offset, we measured the component of the distance parallel to the fault between the offset upstream and downstream channels. In some cases, the present stream, where it crosses the fault, does not flow parallel to the fault, presumably because of continuing lateral incision concurrently with slip on the fault. For such cases, we measured the orientation of the stream at the offset and then calculated the component of displacement parallel to the fault from the measured distance between the upstream and downstream channels (Fig. 2). Because the measured offsets include the contribution of displacement associated with the 1920 earthquake, the average offset of 8 m associated with that
earthquake (Zhang Weiqi et al., 1987) was subtracted from the measured offsets to obtain the offset that occurred since the stream channel was incised but before 1920. To determine a lower bound on the rate of slip, we divided these corrected offsets by the age of the organic material in 1920, so that we ignore the large recent amount of slip associated with the 1920 earthquake.

**RADIOCARBON DATING**

All of our samples of organic material were pretreated and dated by Beta Analytic Inc. in Coral Gables, Florida. Using the traditional half-life of 5568 yr, Beta Analytic calculated an age before 1950 A.D. and an uncertainty given as one standard deviation. We then corrected these ages (Table 1) both for a revised half-life of carbon-14 of 5730 yr and for variations in the rate of formation of carbon-14 in the atmosphere with time (Klein et al., 1982). Carbon-14 dating of tree rings of known ages has yielded a relation between the measured carbon-14 ages and corrected ages calibrated to the tree ring chronology for the past 8000 yr. For radiocarbon ages younger than 8000 yr, the corrected ages and uncertainties equivalent to two standard deviations were taken from Klein et al. (1982). For ages older than 8000 yr, we simply recalculated ages using a carbon-14 half-life of 5730 yr, and the errors were taken to be 1000 yr or more, as suggested by Klein et al. (1982). We ignore the possibility that charcoal was derived from wood that had lived and died long before it burned. Organic soil containing decayed grass may yield ages that are more representative than those from charcoal, if the grass lived for a relatively short time and was accommodated directly into the organic material. In any case, since we are dealing with the ages from 5000 to 17,000 yr, we treat the ages of charcoal and organic soil as the same throughout our study.

**HOLOCENE SLIP RATE OF THE HAIYUAN FAULT**

At six locations we were able to find organic material beneath erosion surfaces later incised by streams offset by slip on the Haiyuan fault (Fig. 3). Here we discuss these localities individually.

Fangjiaha. The westernmost locality from which we collected organic material for dating a stream offset is near the village of Fangjiaha (Fig. 3). The amount of offset was measured to be about 70 ± 15 m. The stream is aligned perpendicular to the trend of the fault, and its deflection occurs where the stream crosses the geologically mapped fault. The width of the fault zone itself is about 15 m. Thus we are confident that the deflection of the stream is due to faulting.

On the downstream (north) side of the fault, the stream has incised a deep valley, with some colluvial deposits adjacent to it, but with no clear depositional terraces. The

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Age (yr B.P.)</th>
<th>Date (95% Confidence)</th>
<th>Corrected Age&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF84SMY1</td>
<td>Shaomayin</td>
<td>4,540 ± 180</td>
<td>3775–2890 B.C.</td>
<td>5,295 ± 445</td>
</tr>
<tr>
<td>HF84SMY2</td>
<td>East Shaomayin 1</td>
<td>4,780 ± 80</td>
<td>3820–3360 B.C.</td>
<td>5,540 ± 230</td>
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<tr>
<td>HF84SMY3</td>
<td>East Shaomayin 1</td>
<td>4,630 ± 110</td>
<td>3700–3050 B.C.</td>
<td>5,325 ± 325</td>
</tr>
<tr>
<td>HF84SMY4</td>
<td>East Shaomayin 2</td>
<td>5,550 ± 100</td>
<td>4650–4110 B.C.</td>
<td>6,330 ± 270</td>
</tr>
<tr>
<td>HF84YHP1</td>
<td>Yehupo</td>
<td>11,930 ± 200</td>
<td>12,280 ± 1000</td>
<td></td>
</tr>
<tr>
<td>HF85FJH2</td>
<td>Fangjiaha</td>
<td>17,190 ± 140</td>
<td>17,690 ± 1000</td>
<td></td>
</tr>
<tr>
<td>HF85DGM1</td>
<td>Dagoumen</td>
<td>15,061 ± 130</td>
<td>15,400 ± 1000</td>
<td></td>
</tr>
<tr>
<td>HF85SMY5</td>
<td>East Shaomayin 2</td>
<td>4,470 ± 95</td>
<td>3495–2905 B.C.</td>
<td>5,150 ± 295</td>
</tr>
</tbody>
</table>

<sup>a</sup> Corrected age assumes a half-life of 5730 yr; uncertainty estimate based on Klein et al. (1982).
Fig. 3. Simplified topographic map of the Haiyuan area with the locations of features and villages mentioned in the text. The contour interval is 200 m.
deposits have been further modified by farming, and a relationship between these deposits and the evolution of the valley is not likely to be simple. Thus we did not use material from this side of the fault.

The upstream channel lies in a broad valley, but the present channel has incised into the northwestern side of the valley. A well-developed depositional terrace lies southeast of the upstream reach, and this terrace clearly was deposited before the present channel was incised. Because the present stream channel is very straight until it reaches the fault but the broad valley in which it flows lies mostly to the southeast of this channel, we presume that the 70-m offset occurred after the material comprising this terrace was deposited. Unfortunately we found no organic material in these terrace deposits.

On its northwestern side, the upstream channel has incised deeply into colluvial gravel at the foot of the steep hill near the fault and into bedrock somewhat farther from the fault; there is no terrace on this side of the stream. Approximately 20 m southwest of the fault on the northwest side of the stream we found organic material, consisting of small pieces of charcoal, within a gravel layer. A sample was taken from about 2 m above the present stream channel and from 6 to 8 m below the top of this gravel layer. The gravel appears to have been deposited within the colluvial apron at the foot of the hills. From the elevation of these deposits, which is lower than the top of the terrace on the southeastern side of the stream, we infer that the organic material was deposited before the top of the terrace on the southeastern side formed. Therefore this material predates both the present incision of the stream into the terrace and the 70-m offset.

The age of the organic material should give a minimum age of the stream offset at Fangjiahe. Using the corrected radiocarbon age of 17,660 ± 1000 yr before 1920 for 62 ± 15 m of slip (Tables 1 and 2), the resulting slip rate must be at least 3.5 ± 0.9 mm/yr.

Shaomayin. Shaomayin is a small village that straddles the Haiyuan fault about 3 km southeast of Fangjiahe (Fig. 3). A large stream flows northwest through Shaomayin, nearly parallel to the Haiyuan fault and with a relatively wide, flat depositional terrace on both sides of the stream channel. To the south and west of Shaomayin, the terrace grades into the erosion surface on the northern slope of the adjacent mountain (Fig. 4). At the northwest end of this terrace, a small stream flows northeast from the Xihua Shan across both the terrace and the Haiyuan fault. The small stream channel has incised about 4 m into both the terrace and the erosion surface, and its valley shows a clear V-shaped cross section. At the fault this small valley is offset 48 m, which was measured by matching the axes of the channel. We take the 4 m width of the channel bottom as the uncertainty of the offset.

Because the small stream channel was entrenched only after both the surface of the high terrace and the erosion surface formed, a lower bound for the age of initial incision of the small stream can be esti-

<table>
<thead>
<tr>
<th>Location</th>
<th>Total offset (m)</th>
<th>Pre-1920 offset (m)</th>
<th>Age (years before 1920)</th>
<th>Slip rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fangjiahe</td>
<td>70 ± 15</td>
<td>62 ± 15</td>
<td>17,660 ± 1000</td>
<td>3.5 ± 0.9</td>
</tr>
<tr>
<td>Shaomayin</td>
<td>48 ± 4</td>
<td>40 ± 4</td>
<td>5,265 ± 445</td>
<td>7.6 ± 1.0</td>
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<tr>
<td>East Shaomayin 1</td>
<td>30 ± 2</td>
<td>22 ± 2</td>
<td>5,325 ± 325</td>
<td>4.1 ± 0.4</td>
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<tr>
<td>East Shaomayin 2</td>
<td>92 ± 30</td>
<td>84 ± 30</td>
<td>6,300 ± 270</td>
<td>13.3 ± 4.8</td>
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<tr>
<td>Dagoumen</td>
<td>61 ± 10</td>
<td>53 ± 10</td>
<td>5,120 ± 295</td>
<td>16.4 ± 5.9</td>
</tr>
<tr>
<td>Yehupo</td>
<td>90 ± 10</td>
<td>82 ± 10</td>
<td>15,370 ± 1000</td>
<td>3.4 ± 0.7</td>
</tr>
</tbody>
</table>
estimated from the age of either the erosion surface or the terrace of the main Shaomayin stream. The stratigraphy of the terrace in the place excavated by the small stream consists of a thick sequence of coarse-grained sand and pebbles, interbedded with fine-grained redeposited loess. Although we found no organic material in the sequence of sediments exposed in the deeply incised valley offset by the fault, we did obtain organic material 1.8 m below the surface of the terrace about 100 m east of where the stream enters the main Shaomayin stream. The organic material consisted of peat with a few pebbles and some roots, which we removed before sending the sample to be dated. The black peat was in a lens-shaped layer with a maximum thickness of 30 cm, and about 7 to 8 m in horizontal extent. We think that it was deposited in a small depression while the sediment in the high terrace was deposited. Therefore it yielded the age of a layer that once was the surface of the terrace.

The corrected radiocarbon age of this sample, which gives an upper bound for the age of the top surface of the terrace, is 5295 ± 445 yr B.P. (Table 1), and therefore 5265 ± 445 yr before 1920 (Table 2). Because the amount of stream offset includes the contribution by the 1920 earthquake, the pre-1920 amount of displacement should be about 40 ± 4 m. Thus, the lower bound on the slip rate is 7.6 ± 1.0 mm/yr. This range is a minimum because of the age of the surface of the terrace should be younger than the age of the material that we sampled, and the onset of entrenchment of the small stream should be even younger than the surface of the terrace.
East Shaomayin 1. About 700 m east of Shaomayin (Fig. 3), a minor dry stream valley appears to be offset about 30 m (Fig. 5). Both the upstream reach on the southwestern side and the downstream reach on the northeastern side of the fault trend about N30°E, almost perpendicular to the fault. The upstream and downstream reaches are deeply incised into reworked loess and colluvium, and both show clear V-shaped cross sections. There are no terraces adjacent to the upstream and the downstream reaches. Where the stream crosses the fault, it turns to trend N60°W, the general orientation of the Haiyuan fault. A well-developed fault scarp forms the northern edge of the channel. Very little vegetation on the south face of the ridge at the western end of the dry stream valley exposes a fresh portion of the scarp that probably was produced by slip during the 1920 earthquake (Deng et al., 1984). The horizontal distance between the northwest end of the escarpment and the edge of the vegetation to its southeast gives a displacement of 8 to 9 m (Zhang Weiqi et al., 1987).

A trench was dug across the fault scarp within the channel in order to obtain the organic material to date the offset as well as to study the earthquake recurrence intervals (Zhang Peizhen et al., 1988). Organic material was found within two layers of sediment in the trench. The corrected radiocarbon age of the younger layer is 5325

Fig. 5. Contour map of an offset stream channel and the Haiyuan fault about 700 m east of Shaomayin (East Shaomayin 1). A small stream flows northeast, but is deflected at a small ridge that marks the Haiyuan fault. This channel is displaced about 30 m. At the northwest end of the ridge that makes a southeast-facing scarp, the southwest side of the ridge is bare of vegetation (Deng et al., 1984). We presume that this bare region formed by left-lateral slip in 1920, and from its dimensions we estimate that 8 to 9 m of slip occurred (Zhang Weiqi et al., 1987). East of the stream the fault scarp traverses a low saddle, where the surface rupture has defined a small graben. The vertical component of slip is only about 0.5 m. Thus the displacement was primarily strike-slip. The rectangular area in the right-center shows the location of the trench discussed by Zhang Peizhen et al. (1988).
± 325 yr B.P., or 5295 ± 325 yr before 1920. Since this layer is clearly older than the 30 ± 2 m offset (Zhang Peizhen et al., 1988), its age yields a minimum slip rate. For 22 ± 2 m of pre-1920 slip, the resulting lower bound on slip rate is 4.1 ± 0.5 mm/yr.

East Shaomayin 2. About 900 m east of Shaomayin (Fig. 3), a large stream flowing northeast from the Xihua Shan reaches the fault and turns to flow in a direction more or less parallel to the fault for about 250 m (Fig. 6). The northerly flowing stream meanders through pre-Silurian schists, and farther north it is incised into the young alluvium and loess. The downstream channel, north of the fault is deeply incised into Tertiary red beds and redeposited loess (Fig. 6). After crossing the fault, the stream turns to flow northeast again.

Within this 250-m apparent offset, the upstream and downstream reaches of the present channel are separated by about 100 m where it crosses the fault. In its offset part, the channel is wide, and has a U-shaped cross section with steep sides. It has incised into old stream deposits (Fig. 7) that have been preserved along the edge of the channel. The Haiyun fault there strikes N60–65W, but the stream flows in a direction of N40W. Thus the angle between them is only 20° to 25° (Fig. 6). Applying the calculation illustrated in Figure 2, the offset along the fault would be between 90 and 94 m. We take 92 m as the average offset. Because the channel is 10 to 20 m wide, and because neither the upstream nor the downstream channel is perpendicular to the fault, however, we take 30 m as the uncertainty of the offset, and we consider it possible that this large value is still an underestimate of the uncertainty. Among the offsets that we measured, this is the least accurate.

The preserved channel deposits form an important sedimentary unit for obtaining a lower bound on the slip rate in this part of

Fig. 6. Left-lateral stream offset of approximately 92-m east of Shaomayin (East Shaomayin 2). View is to the east–southeast along the fault trace. A major stream enters the photo in the upper right, flows parallel to the fault, and then flows northward out the lower left corner of the photo. The dashed line delineates the trace of the Haiyun fault. The stream channel that is marked by the thick white arrow joins the main, offset valley upstream from the 92-m offset. The trapezoid shows the area covered by Figure 7.
the fault, because the offset stream channel has incised into them. Therefore, the stream offset postdates these channel deposits. The distribution of these deposits along the offset part of the large stream channel, however, suggests that the stream had already been flowing subparallel to the fault when the 92-m offset began to develop.

In 1984 we took a sample of organic soil from a site about 5 m southwest of the fault in the upstream reach, and about 2 m below the surface of the terrace. This sample gave a corrected radiocarbon age of 6330 ± 270 yr B.P. (Table 1). For 84 ± 30 m pre-1920 displacement, the slip rate would be 13.3 ± 4.8 mm/yr. When we obtained this age, we thought the sample might have been taken from a slump of younger material from the terrace, and the age might not be reliable. In 1985 we revisited this channel, and we found a very good sample of organic material with charcoal, also about 2 m below the surface, about 15 m southwest of the fault, and along the same upstream channel. The corrected age of this sample is 5150 ± 295 yr B.P. Its resultant lower bound on the slip rate would be 16.4 ± 5.9 mm/yr.

These two estimates for lower bounds on the slip rate are both much larger than the others that we obtained and larger than Burchfiel et al.’s (1987) average rate for the Quaternary period. We include discussion of them here because they constitute a part of our work, but we doubt their reliability for two reasons. First, because the stream has been flowing roughly parallel to the fault since before the organic material was deposited, the measured offset might not be representative of the displacement since their deposition. Second, because the present stream flows at an angle of only 20°
to 25° to the fault trace, meanderings of the stream could make the measured offset more uncertain than we had estimated in the field.

Dagoumen. The largest stream in the several hundred meters south of Dagoumen (Fig. 3), which we call the Dagoumen stream, flows from northwest to southeast almost parallel to the Haiyuan fault. A wide, flat high stream is well developed on the southern side of the stream, and gradually grades into the erosion surface of the mountains to its southwest. The height of the terrace is about 10 m above the channel bed, and its width is generally 60 to 80 m. The terrace is composed of layers of gravel mixed with sand and redeposited loess.

Several streams flowing from the Xihua Shan, the mountains southwest of the fault, cut the terrace before reaching the Dagoumen stream. All of these stream channels have been offset where they cross the Haiyuan fault, with the larger of these streams offset more than the smaller ones. We studied the stream channel with the largest and clearest offset; it probably is the oldest of them. The upstream reach south of the fault has deeply incised a U-shaped cross section in the bedrock. The downstream reach, north of the fault, has deeply incised a V-shaped cross section in the terrace of the Dagoumen stream. The bottoms of the upstream and downstream reaches are separated by about 87 ± 10 m at the fault. The Haiyuan fault there strikes about S60E, but the floor of stream channel within the fault zone trends about S15E, so that the angle between the present stream bed and the fault is about 45°. Therefore the amount of displacement along the fault is about 61 ± 10 m. Apparently continued incision of the stream has cut obliquely across the fault as the valley has been displaced by the slip on it.

Because the offset streams have incised into the terrace of the Dagoumen stream and the erosion surface, their incision should be younger than the erosion surface. By using the largest stream offset among them, we obtain the largest among a family of lower bounds on the slip rate. We collected many small pieces of charcoal distributed irregularly within a layer of reworked loess from 3 m below the top of the erosion surface. The corrected age of this sample is 15,400 ± 1000 yr B.P. (Table 1). For 53 ± 10 m of pre-1920 stream offset, the minimum slip rate was estimated to be 3.4 ± 0.7 mm/yr.

Yehupo. At a small village, Yehupo (Fig. 3), a stream flowing north from the Nanhua Shan has been offset about 90 m. We use the width of 10 m of the present stream channel for the uncertainty of the offset (Fig. 8). Adjacent to the stream channel are a higher terrace, a lower terrace, and a bench. The higher terrace is about 3.5 m above the lower terrace and is composed of several thick gravel layers interbedded with two layers of pebbly, redeposited loess and coarse-grained sand. At the top of the higher terrace is a layer of soil about 0.4 m thick. The lower terrace consists entirely of gravel, and only a thin layer of soil has developed on top of it. Its height above the bench of the stream is about 1 m. The bench is less than 0.5 m above the channel bed.

Both the higher and lower terraces are well developed on the northwest side of the upstream reach (southwest) of the fault, but remains of the higher terrace can be found only in a few places on the opposite (southeastern) side of the upstream reach. Downstream from the fault, the lower terrace is well developed on both sides, but remains of the higher terrace can be found only at one place on the northwestern side of the channel (Fig. 8). Along the portion the stream flowing parallel to the fault, only the lower terrace is developed.

The higher terrace apparently had already been deposited and incised before the recent offset of the stream valley began. The pebble imbrication on the higher terrace in the upstream reach shows transport in a direction between N10W to N40E. Near the part of the stream channel within the fault zone, the pebbles in the higher ter-
race are imbricated in the same direction as those in the upstream reach; they do not show any indication of a different direction of transport that might have existed if the stream were deflected at the fault when the material was deposited. The pebble imbrication in the lower terrace, however, shows transport in the direction N90°W to N50°W in the offset part of the stream, but northward in both the upstream and downstream reaches. The variation in the direction of imbrication near where the stream channel is offset suggests that the stream flowed west or northwest when material comprising the lower terrace was deposited. Therefore the 90-m displacement started before the formation of the lower terrace but apparently after the formation of the higher terrace.

A sample of organic soil taken from 1.8 m below the surface of the high terrace within a layer of reworked loess and sand, and therefore 1.4 m below the surficial soil, gives a corrected age of 12,280 ± 1000 years before present (Table 1). With a pre-1920 offset of 82 ± 10 m, the minimum average slip rate during this interval is 6.7 ± 1.0 mm/yr (Table 2).

DISCUSSION

We obtained lower bounds on the slip rate at six localities along the Haiyuan fault (Fig. 9 and Table 2). They range from 3.5 ± 0.8 to 16.4 ± 5.9 mm/yr, but the five that we consider the most reliable are less than 7.6 ± 1.0 mm/yr.

The three smallest bounds on the slip rate are 3.5 ± 0.9 mm/yr from Fangjiahe, 4.1 ± 0.4 mm/yr from East Shaomayin 1, and 3.4 ± 0.7 mm/yr from Dagoumen (Fig. 3). At Fangjiahe the sample of organic material, for which we obtained a radiocarbon date, was taken from a piedmont gravel layer now 6 to 8 m below the surface. At East Shaomayin 1, the sample of organic material was collected from a clay layer inter-
bedded with a widespread gravel layer in that locality and 10 m below the erosion surface incised by the offset stream. In the Dagoumen region, the sample of organic material was collected from 3 m below the erosion surface that grades into a high terrace above the Dagoumen stream and that has been incised by a young offset stream. The large depths of the samples below the erosion surfaces or terraces imply that their ages could be much greater than the ages for the initiation of the corresponding stream offsets. Therefore the ages of these three samples could be so old that the lower bounds for average slip rate estimated from them might be misleading underestimates.

The offsets at both Shaomayin and Ye-hupo are clear and well defined. The samples of organic material were collected from below high terraces incised by these streams. Because the offsets are clear and the organic materials are between 1 and 2 m from the tops of the surfaces incised by the stream channels, we think that the rates of 7.6 ± 1.0 and 6.7 ± 1.0 mm/yr from these two streams, especially that from Shaomayin, are the least disputable among those that we studied (Fig. 9; Table 2). Thus we think that the average Holocene slip rate of the Haiyuan fault is almost surely more than 6 mm/yr and probably more than 7 mm/yr.

At East Shaomayin 2, we obtained a lower bound on the slip rate to be 16.4 ± 5.9 mm/yr. As mentioned above, this bound may not be as reliable as the others because of the uncertain offset and its relationship to the material dated. We assigned a large uncertainty of 30 m to the displacement, but it could be larger, and we included a discussion of this area for completeness, but, in fact, we do trust this estimate.

We think that the average slip rate is not much greater than 10 mm/yr. If the rates were greater than 10 mm/yr, and if slip on the Haiyuan fault were associated with great earthquakes, many great earthquakes should have occurred in the past few thousand years. Our studies of trenches dug across the Haiyuan fault reveal evidence of only two earthquakes in the last 2500 yr, excluding the 1920 event. Thus, if the average displacement were 8 m and the recurrence interval were 800 to 1300 yr, the average slip rate would be 6 to 10 mm/yr. Moreover, we expect that any great earth-
quake that occurred in the last 800 yr would have been recorded in the historic documents of China, because the Haiyuan area is only about 300 km from the ancient capital city of Xian (Zhang Peizhen et al., 1988). For the absence of such a recorded event, we suspect that the Holocene slip rate along the Haiyuan fault has not been much larger than about 10 mm/yr, but we cannot prove this definitely.

The average Holocene slip rate of the Haiyuan fault is larger than 6 mm/yr. If it is less than 10 mm/yr, or in another form, 8 ± 2 mm/yr, then this rate is comparable to the 5 to 10 mm/yr average slip rate for Quaternary time obtained by Burchfiel et al. (1987).

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