DISPLACEMENT ALONG THE HAIYUAN FAULT ASSOCIATED WITH THE GREAT 1920 HAIYUAN, CHINA, EARTHQUAKE

ZHANG WEIQI, JIAO DECHENG, ZHANG PEIZHEN, PETER MOLNAR, B. C. BURCHFIELD, DENG QIDONG, WANG YIPENG, AND SONG FANGMIN

ABSTRACT

We used a plane table and an aid for detail to construct detailed topographic maps of offset features (stream channels, dry gullies, and old terrace walls) along the fault zone that ruptured during the 1920 Haiyuan earthquake ($M = 8.7$) in Ningxia and Gansu, China. The maximum displacement appears to have reached 10 m at Shikaguan-gou between the Salt Lake and Xianzhou basins in southern Ningxia. The average displacement along the 100 km of the fault that we studied was about 8 m. Assuming that the average slip rate to be between 5 and 10 mm/yr, the recurrence interval for events similar to that in 1920 would be about 800 to 1600 yr.

INTRODUCTION

A basic premise in the evaluation of earthquake hazards is that a knowledge of the characteristics of past seismicity will allow us to predict at least some aspects of future seismicity. Allen (1968) postulated that the historical seismicity of the San Andreas fault may reflect the long-term behavior, such that future large earthquakes will occur where they have in the past. Moreover, the concept of a meaningful average recurrence interval (e.g. Wallace, 1970) is based on the assumption that the amount of slip that occurred in a past earthquake will reoccur in a future earthquake, with the interval between them equal to that amount of slip divided by the long-term average rate of slip in the absence of fault-creep. Measurements of displacement and recurrence intervals for earthquakes that are associated with surface faulting along the Wasatch fault zone suggest that most of the slip has occurred during earthquakes of essentially the same size and therefore with a relatively narrow range of magnitudes (Schwartz et al., 1981; Schwartz and Coppersmith, 1984). The studies of displacements of historical earthquakes and earthquake recurrence intervals along the San Andreas fault zone suggest that the displacements during one earthquake may differ from one segment to another along the fault zone, and that different segments rupture with earthquakes of different magnitude (Sieh, 1978a, b, 1984; Sieh and Jahns, 1984). Nevertheless, offsets at particular localities recur with similar amounts from one event to the next. If the slip rate over a long time period is constant throughout the length of the fault, earthquakes will occur more frequently on segments with small amounts of displacement than those with large amounts of displacement. To discern such variability, however, requires relatively accurate knowledge of the amounts of displacement associated with historical earthquakes.

A 200-km-long left-lateral surface rupture zone formed during the Haiyuan earthquake ($M = 8.7$) of 16 December 1920 in north-central China. This earthquake was responsible for 220,000 deaths and the destruction of thousands of towns and villages (Lanzhou Institute of Seismology and Ningxia Seismological Bureau, 1980). The surface displacement of the 1920 earthquake represented renewed activity along the Haiyuan fault zone, one of the most important left-lateral fault zones in central Asia (e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977).

Our study was carried out only in the eastern half of this fault zone (Figure 1).
The average strike of the Haiyuan fault is about N65°W. At the western end of this area, the Haiyuan fault zone follows the southern foot of Huangjiawa Shan and is marked by a relatively narrow zone along which a series of small streams and ridges are displaced. Where the fault enters the southwest side of the Salt Lake basin, a small pull-apart basin (Figure 1), the displacement along this strand steps over to another strand north of the basin (Zhang et al., 1983; Deng et al., 1984, 1986; Burchfield et al., 1986). Among these strands, displacements were observed only within the step-over zone near Tangjiapo. From the Salt Lake basin to the southeast, the Haiyuan fault follows the northern foot of the Xihua Shan and Nanhua Shan (Figure 1). The surface rupture zone is commonly defined by small scarps and grabens, but in some places it is very difficult to recognize on the ground. From east of Luzigou to the eastern end of the fault zone, surface ruptures become increasingly difficult to recognize, and eventually a continuous trace cannot be seen. A fault trace trending N35°W intersects the main Haiyuan fault zone southeast of Luzigou where the surface ruptures of Haiyuan fault zone become more obscure to the east. The intersecting fault can be followed more than 40 km to the south-southeast. The displacement at the eastern end of the Haiyuan fault zone probably has been partly absorbed by slip on this fault, but we do not call it the Haiyuan fault because its trend differs considerably from that of the main Haiyuan fault zone.

The general geometry of the surface rupture zone and the distribution of displacement during the 1920 earthquake were described preliminarily by Song et al. (1982) and by Deng et al. (1984, 1986). The variability of their tape-measured offsets probably is due to the inclusion of offsets on only one strand where several subparallel strands were active. The goal of this paper is to present more objective data on the amount of left-lateral displacement.

**Displacements Associated with the 1920 Haiyuan Earthquake**

Although the earthquake occurred 65 yr prior to our study, and the loess-covered area has undergone rapid erosion, some of fault scarps of the rupture zone and some
offset features are still visible. Along the zone of surface rupture associated with the 1920 earthquake, many reference features such as stream channels, alluvial fans, topographic surfaces, and some man-made features have been offset. The smallest offsets are probably the result of the 1920 event. This presumes that these topographic features were created prior to the 1920 event but after the youngest previous event. We think that this is a reasonable assumption because of the following reasons.

First, we know that a rupture zone that displaced these features was formed during the 1920 earthquake. During our studies, several old local people pointed out that those ruptures were associated with the 1920 earthquake. In 1983, Ma Jinchao, then an 82-yr-old man who is one of the two survivors of the earthquake in Caiyuan (Figure 1), said that the rupture could be traced along the northern foot of Nanhua Shan all the way to the Yuan River. Tian Baiyou, an 87-yr-old man who lived in Luzigou, said that some "cracks" formed from Luzigou to Shanmen during the earthquake. These "cracks" are, in fact, a combination of grabens, troughs, and fault scarps. In 1983, an unidentified, 82-yr-old man who moved to Shaojiazhuang 3 yr after the earthquake, said that the newly formed scarps could be followed continuously from Tangjiapo to Shaojiazhuang, and his neighbors told him that those scarps were formed during the 1920 earthquake. In addition, we found a fresh portion of the south face of the fault scarp with very little vegetation on it at the western end of a dry stream east of Shaomayin (Figure 2). Its exposure was probably produced by slip during the 1920 earthquake, for the sharp contrast in vegetation

![Figure 2](image_url)

**Fig. 2.** Left-lateral offset of the east side of a small dry stream that begins in the lower right, passes across the photo, and then flows northeast across the Haiyuan fault at the left edge of the photo. View is toward the north. The fault passes along the opposite bank of the stream and is marked by the ridge in the center of the photo. The fault scarp produced during the 1920 Haiyuan earthquake can be seen on the bare area in the left center of the photo. The fresh face near the left end of the gully with very little vegetation on it was formed by left-lateral displacement of 8 to 9 m, which is the horizontal distance between the top of the escarpment and the edge of the vegetation to the right.
could not be due to fault creep or displacement several hundred years ago. The amount of displacement is 8 to 9 m. We will discuss it in the following section.

Second, the reference features that have been offset are newly formed. In the loess-covered area, the small channels that we studied, which are about 1-m wide and less than ½ m deep, could have been formed within several hundred years. Similar channels cross the boundaries of now unused farming terraces that, according to the local historical documents, probably were ploughed 200 to 300 yr ago in the late Qing Dynasty (Figure 3). Because the sizes of these channels are about the same as, or even larger than, the channels offset about 10 m, the ages of these offset channels probably are no more a few hundred years.

Third, the first historical earthquake documented in this area was in 1219 with magnitude 5.0 (Li, 1960). No large earthquake \((M > 7)\) is reported in this area between 1219 and 1920. Perhaps no significant large earthquake occurred 400 to 500 yr before 1219, because the area is only 300 km from Xian, the capital city and cultural center of China during that time. If large earthquakes occurred in this area, people probably would have known and recorded them in the documents.

Finally, the seismic moment of the 1920 Haiyuan earthquake was calculated to be \(1.2 \times 10^{23} \) N-m from spectral densities measured by Chen and Molnar (1977) from long-period Rayleigh waves at two stations (Deng et al., 1984). For a fault area of \(A = 220 \text{ km} \times 20 \text{ km} = 4.4 \times 10^5 \text{ m}^2\) and \(\mu = 33 \text{ GPa}\), this value of seismic moment corresponds to an average slip \(\Delta u = M_0/\mu A = 8.3 \text{ m}\). Although uncertain by a factor of two or more, the amount is consistent with the smallest offsets that we measured along the Haiyuan fault. Therefore, we think that the smallest offsets of several to 11 m along the rupture zone result from left-lateral slip during the 1920 Haiyuan earthquake.

None of these arguments prove that all of the displacements that we measured

---

**Fig. 3.** Channels developed across the boundaries of farming fields. According to local documents, these fields probably were ploughed 200 to 300 yr ago (late Qing Dynasty). The age of these channels must be younger than those boundaries.
could not include fault creep before or after the 1920 earthquake, but the sharpness of most offset features suggests that offsets were abrupt and not gradual. Thus, we are confident that the major portions of each offset occurred in 1920, and we suspect that if fault creep has contributed to the offsets it has been small and probably negligible.

To measure the displacements associated with the 1920 earthquake, we used a plane table and alidade to construct topographic maps of offset features at six widely spaced sites along the surface rupture zone (Figure 1). These sites were chosen because offsets were relatively clear, because only one or two principal strands of the fault seemed to have been active in 1920, and because the amounts of offset are believed to have formed during the 1920 earthquake.

Site 1. The westernmost offset that we mapped is about 3 km west of Gaowenzi (Figure 1) where an offset stream channel is clearly present (Figure 4). The fault scarp at this channel is still identifiable in most places at this site. The upper stream channel is located on northern side of the fault; it is straight, sharply incised, and aligned almost perpendicular to the fault. A downstream channel can be found 4.4 ± 0.5 m along the fault scarp to the east. Both its depth and its width, however, are two or three times smaller than the upstream channel.

Another, beheaded channel is presented on the downstream side of the fault, 11.6 m southeast of the upstream channel (Figure 4). The size of this beheaded downstream channel begins about 4 m downslope from the fault scarp; a small landslide on the northern side of the fault has buried the part of the stream channel near the fault scarp. It is unlikely that before the small landslide formed there was a preexisting channel upstream of the fault from the place where the landslide is located now, and that later the preexisting channel was buried or destroyed by the landslide. Moreover, because the landslide is located at the nose of a ridge, the channel cannot have formed at such a location. Because the channel has not incised into the landslide material, but instead the landslide material has filled in and covered the buried part of channel, it is also unlikely that the channel is newly formed and that its head reaches only to the landslide. Therefore, we think this downstream channel was beheaded from the main upstream channel and offset about 11.6 ± 1 m from it.

A small ridge that blocks the upstream channel to form a sag pond lies about 3.9 m west-southwest of the ridge, making the west bank of the upstream channel, but because of the irregularity of the small hill an accurate measurement of offset is impossible. The similarity of the distance of 3.9 m to the offset of the neighboring stream may be fortuitous, but we did obtain several offsets of 4 to 6 m nearby.

Since we do not know the age of the small downstream channel, two possibilities exist. The first is that this beheaded channel was displaced 7.2 ± 1.5 m from the upstream channel during a pre-1920 event and 4.4 m in 1920. A second possibility is that the total offset of 11.7 ± 2 m was associated with 1920 earthquake, a point of view supported by the similar sizes of the upstream and beheaded downstream channels. The apparent offset of the small ridge and the other offsets of 4 to 6 m, however, are inconsistent with this inference. The choice of the possibilities depends on the assumption that before the 1920 event, or perhaps before the previous large event, no deflection of this channel existed. At present, no evidence requires a definite choice, and among ourselves, we disagree whether only 4 m of slip occurred in this area in 1920 or as much as 10 m occurred.

Site 2. About 700 m east of Gaowenzi, a small stream channel incised into the Haiyuan group of metamorphic rocks has been offset 9 ± 3 m (Figures 1 and 5). An
offset small ridge has blocked the upstream channel to form a sag pond. The length of offset ridge forming the southern wall of the sag pond is about 9 m, which is comparable to the amount of offset of the stream in the same place. Both probably formed during the 1920 earthquake. Because both upstream and downstream channels are not perpendicular to the fault, part of the displacement may be due to meandering of the stream. Thus, the amount of the offset at this site cannot be measured as well as at some other sites.

Site 3. About 1.5 km west of Tangjiapo, a village 2 km west of the Salt Lake (Figure 1), the main strand of the surface rupture zone displaces a series of stone walls that bound old, now unused farming terraces (Figure 6). There are 18 walls in the mapped area, as well as some other features such as stream channels, that cross...
the rupture zone and were offset. In places, the walls are clearly offset by narrow strands of the fault, but in others the fault zone is complicated by the existence of tension cracks and mole tracks (Figure 6). Most of the walls were offset at two or more localities, with the combined offset of 6 to 8 m. For each, our estimate of the displacement was obtained by measuring the distance between the crests of the walls at the ruptures. The edges of the walls were not used to determine the displacement because modification of them is much greater than that of the crests. The uncertainty for each offset was estimated to be either the width or half-width of the wall, depending upon how clear the crest of the wall was and how extensive the modification has been. Obtaining an exact or precise estimate of the offset at this locality is very difficult because the walls were not initially straight. Conseq-
Fig. 6. Map of offset stone walls once used to support farming terraces in Tangjiapo (site 3). This detailed map of 18 stone walls that have been offset in 1920 shows two or three splay of the fault. Offsets at particular localities are probably underestimates because permanent strain near the walls could not be detected. Sums give both offsets at particular strands and the total for each wall.

sequently, if the measurements were taken only at the places where the rupture displayed segments of the wall from one another, we probably obtained a minimum amount of displacement because we failed to include simple shear strain across the fault zone.

According to the local county historical documents, many people immigrated into this area to farm in the late part of the Qing Dynasty (200 to 300 yr ago). The walls were probably built by those people. The walls were offset during the 1920 earthquake; in the early 1970's, some of the older people in Tangjiapo told some geologists working in this area that the offset of those farming walls occurred at the time of the 1920 earthquake (Lanzhou Institute of Seismology and Ningxia Seismological Bureau, 1980).

In the middle part of Figure 6a, a very young alluvial fan represents the outwash from a small and deeply incised young channel to the northeast. The fault scarp of the 1920 earthquake has been covered by this young fan, which has not been offset
at all. This probably implies that there is at least no significant offset along the rupture zone since 1920 earthquake. Fault-creep has not been reported at any locality along the Haiyuan fault. Furthermore, the walls were unlikely to have been offset more than 200 to 300 yr before 1920 because they probably had not been built by then. Since there have been no large earthquakes reported in this area in the 200 to 300 yr before 1920, we think that the entire offset of the walls can be associated with the 1920 earthquake.

Site 4. About 1.5 km northwest-west Fangjiahe, a small village located next to the Haiyuan fault (Figure 1), there are several small stream channels that have been offset apparently during the 1920 earthquake (see Figure 6 in Deng et al., 1984). Three among them were mapped (Figure 7), and the observed amount of displacement is about 10 m.

All of these offset channels are located geomorphically on the surface of a terrace above a westward-flowing large stream. The fault scarp that formed during the 1920 earthquake has not been preserved, but a series of offsets of stream channels and

![Diagram of offset stream channels](image)

**Fig. 7.** Contour map of offset stream channels at Shikaguangou (site 4). Three gullies have been displaced about 10 m, presumably in 1920. The larger of the three, the western gully, may have been displaced by an earlier event; the northwest bank is offset about 20 m at the fault trace.
some depressions clearly delineate a narrow zone of surface rupture. The small stream channels are displaced left-laterally so that the drainage has been blocked, and the runoff periodically has ponded on the upstream (south) side of the fault.

The stream on the right (west) side of Figure 7 has the largest channel and the smallest sag pond among these streams. It has deeply incised the terrace and the slope of the hill. The upstream channel is clear and well-defined. Its downstream channel is wide and shallow, but the main channel is clearly present. The match of the main channels gives $10 \pm 1$ m of left-lateral offset. The northwest edge of this channel is also offset, and one can argue that there has been $20 \pm 5$ m of offset.

The other two stream channels are much smaller than the one in the west (Figure 7), and their associated sag ponds are shallow and large. Springs developed at the heads of both of these gullies, so that the centers of the channels are clearly defined. The match of the channels yields $9.6 \pm 1.0$ m and $10.2 \pm 1.0$ m of left-lateral offset for the eastern and central channels, respectively. Moreover, the two gullies have well-defined banks, and the matches of them also give about $10$ m of displacement, but with large uncertainties.

We think that the 10-m offsets of these three gullies probably occurred during the 1920 earthquake, largely because we associate comparable offsets farther east with that earthquake. The $20 \pm 5$ m offset of the western wall of the western stream channel might represent two offsets of $10$ m, one associated with the 1920 earthquake and the other with its predecessor. This is the only place where we may have found multiple offsets, but the evidence is not very convincing. Thus, we cannot be certain that the 1920 earthquake was typical of major earthquakes on the Haiyuan fault.

**Fig. 8.** Contour map of an offset stream channel and the Haiyuan fault about 700 m east of Shaoyan (site 5). A small stream flows northeast but is deflected at a small ridge that marks the Haiyuan fault. This channel is displaced about 30 m. East of the stream, the fault scarp traverses a low saddle, and the surface rupture there has defined a small graben. The vertical component of slip is only about 0.5 m. Thus, the displacement was primarily strike-slip. At the northwest end of the ridge that marks the scarp, the southwest side of the ridge is bare of vegetation (Figure 2). We presume that this bare region was formed by left-lateral slip in 1920, and from its dimensions, we estimate that 8 to 9 m of slip occurred.
Site 5. Between Shaomayin and Dagoumen along the Haiyuan fault, offsets of minor streams and dry stream beds also clearly show 8 to 9 m of left-lateral offset. About 700 m east of Shaomayin (Figure 1), a minor dry stream appears to be offset about 30 m (Figures 2 and 8). Both the upstream channel on the southwestern side and downstream channel on the northeastern side of the fault trend about N30°E, almost perpendicular to the fault. As the stream reaches the fault, it turns to N60°W, the general orientation of the Haiyuan fault. A well-defined fault scarp forms the northern bank of the stream, and to the east it connects with the boundary fault of a small graben associated with the 1920 earthquake rupture zone. Only 0.4 to 0.5 m of vertical displacement were measured at the flat place east of the stream (Figure 8); thus, the slip along this part of the fault was almost entirely strike-slip. There is very little vegetation on a fresh portion of the south face of the scarp at the western end of the dry stream valley, but to the east beyond the fresh face, the

![Contour map of offset stream channels and a small ridge near Luzigou (site 6). The fault in the eastern part of the area shown seems to consist of only one strand, but in the western part, there seems to be two strands. A deeply incised channel in the eastern part seems to be offset left-laterally, but the low relief in the field north of the scarp makes it difficult to determine the total offset accurately. A small gully in the western part is clearly offset nearly 5 m by the southern strand and possibly another 3.6 m at the northern strand.](image-url)
vegetation covered all of the slope of the channel bank, so the boundary between them is very sharp (Figure 2 and Figure 10 in Deng et al., 1984). Its exposure was probably produced by slip during the 1920 earthquake. If there has been fault-creep, the boundary between the vegetation and bare segments of the scarp would not be so sharp. 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.

**Site 6.** At Luzigou, a small village located about 7 km from the eastern end of the west-northwest-striking portion of the Haiyuan fault (Figure 1), the fault scarp still can be recognized in the farming fields. Several small channels along the scarp have been offset, and we mapped two of them (Figure 9). The upstream channel of the eastern gully is deeply incised and well-defined, but its downstream continuation from the fault is very shallow and poorly defined. North of the scarp, there appear to be two small, shallow channels which join 4 to 5 m from the scarp. If we matched the eastern channel with the upstream gully, then the displacement would be 5.2 ± 1 m. Otherwise, matching the western channel yields 9.2 ± 1.5 m.

The fault scarp to the west seems to curve to the west-northwest, and a small ridge that defines it has blocked a small gully flowing from south to north and

![Image of contour map](image-url)  

**Fig. 10.** Contour map of offset stream southeast of Luzigou (site 7). A well-defined stream channel is offset about 7.5 m at a southwest facing scarp (see Figure 11).
caused a small sag pond to form (Figure 9). The offsets of the gully and the ridge are $4.8 \pm 0.5$ m and $5.6 \pm 1$ m, respectively. To the north, the deflection of same gully may be due to faulting but could also be due to meandering of the stream that has no tectonic significance. Thus, the total offset in this site is poorly defined and could be as little as $4.5$ m or as large as $10.5$ m.

*Site 7.* About $7.5$ km southeast of Luzigou, another strand of the fault developed with an average orientation of about N35°W. This strand crosses the Nanhua Shan and extends about $40$ km southeast to a small pull-apart basin on the south side of Nanhua Shan. We mapped a stream offset on a strike-slip fault strand just north of this pull-apart basin (Figure 1). According to the local people, the well-defined fault scarp in this place is associated with the 1920 earthquake. A straight stream channel has been offset $7.5 \pm 1.0$ m where it crosses the fault scarp (Figures 10 and 11). The widths of the bottoms of the channels, both upstream and downstream from the fault, are typically about 1 m, and depths are about $0.5$ m. The segment of the channel parallel to the fault has a typical width of only about $0.5$ m and a depth of $0.2$ m or even less. It is clear that this segment of the channel formed after the offset occurred, which we think was in 1920.

**Conclusions**

The smallest offsets along the Haiyuan fault are probably associated with the 1920 earthquake. This assumption is supported by several reasons. Three old local people who lived in western, middle, and eastern parts of our studied area, respectively, pointed out that the ruptures that offset the smallest reference features were formed during the 1920 earthquake. By comparing with the channels of known age, the smallest offset channels are probably formed within the several hundred years before 1920. The historical seismicity studies (Li, 1960) show that no large earthquake occurred in this area between 1219 and 1920, and probably no great earth-
quakes occurred 400 to 500 yr before 1219. The seismic moment (Chen and Molnar, 1977; Deng et al., 1984) suggests that the average slip during the 1920 earthquake is about 8 m, a value consistent with the amounts of the smallest offset that we measured along the Haiyuan fault.

The displacements associated with 1920 earthquake in Ningxia and the westernmost Gansu range from possibly as little as 4.4 m to as much as 11 m. The maximum displacement that can be demonstrated convincingly is about 10 m, at Shikaganguogou between the Salt Lake and Xianzhou basins. From Gaowenzi to the Xianzhou basin, the amount of displacement associated with 1920 earthquake is probably between 7 and 10 m. Smaller amounts may have occurred southeast of Caiyunan and northwest of Gaowenzi, but the evidence is not clear. Thus, the average slip probably was 8 ± 2 m.

Burchfiel et al. (1986) found that the average rate of left-lateral slip on the Haiyuan fault during Quaternary time was about 7.5 ± 2.5 mm/yr. Preliminary analysis of Holocene offsets yields a similar range of values (Zhang et al., in preparation, 1986). For an average amount of displacement for 1920-type events of 8 ± 2 m, the recurrence interval of this type of event would be about 1000 yr: less than 1600 yr and more than 800 yr.

ACKNOWLEDGMENTS

We thank Zhang Yuzheng and Wang Zhenguang, for their help in the field with the plane table mapping and S. Gardner for her help in the preparation of the manuscript. We are grateful to an anonymous referee for his/her comments and suggestions that improved this paper greatly. This work was part of an exchange between the People's Republic of China and the United States on seismological studies of earthquake hazards and has been supported by the National Science Foundation through Grant EAR-8306863 and by the State Seismological Bureau of China.

REFERENCES


NINGXIA SEISMOLOGICAL BUREAU
NINGXIA-HUI AUTONOMOUS REGION
YINCHUAN, CHINA (Z.W., J.D.)

INSTITUTE OF GEOLOGY
STATE SEISMOLOGICAL BUREAU
BEIJING, CHINA (D.Q., W.Y., S.F.)

DEPARTMENT OF EARTH, ATMOSPHERIC
AND PLANETARY SCIENCES
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139
(Z.P., P.M., B.C.B)

Manuscript received 18 April 1986